Grid-Scale Frequency Regulation Using Flywheels

Matthew L. Lazarewicz, Todd Ryan

***Abstract* — The grid frequency regulation function addresses the balance between the network's load and power generated. The intent is to maintain the grid at the target 50Hz or 60Hz operating point. When there is more load than generated power, frequency drops, and vice versa. The system operator generates a signal, Area Control Error (ACE), based on the difference between load and power. Traditionally, frequency regulation is managed by varying the output of fossil fuel or hydro generators connected to the electric grid. The author presents a new method in which electrical energy is recycled to keep the system in balance. First, absorbing energy when it is in abundance, then discharging when there is a power shortfall. The proposed system is based on kinetic energy storage technology in high-speed flywheels. The cost and performance of storage-based regulation can offer significant advantages over traditional generator-based regulation.**

Flywheel-based energy storage is being introduced on a large scale (20 MW) to provide grid frequency regulation in deregulated markets in North America. The ISOs have already introduced, or are in the process of introducing, market rules and tariffs to comply with FERC Order No. 890, which requires that new competitive technologies be permitted to participate in the regulation markets. Analysis of more than 18 months of operating data shows flywheel-based storage can provide superior cost, emissions, and operational performance. Availability of this new grid technology is particularly important, since the rapid addition of variable-generation renewable resources to meet RPS standards is expected to increase the need for regulation.

This paper presents performance data from more than 18 months of operation in an ISO New England (ISO-NE) field trial; describes NYISO and MISO strategies for using fast-response Limited Energy Storage Resources (LESR) for maximum effectiveness; and describes the ISO-NE regulation control methodology that has achieved the lowest (best-in-class) amount of required regulation of any large grid in North America. Charge and discharge cycle requirements for energy storage-based technologies performing regulation are also extrapolated based on real operating data, and a practical definition of overall system efficiency is introduced.

***Index Terms* – Ancillary services, energy storage, flywheels, frequency regulation, power grid.**

I. NOMENCLATURE

AGC	Automatic Generator Control
CAISO	California Independent System Operator
CEC	California Energy Commission
DOE	U.S. Department of Energy
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
ISO	Independent System Operator
ISO-NE	ISO New England
LESR	Limited Energy Storage Resources
MISO	Midwest ISO
NERC	North American Electric Reliability Corporation
NYISO	New York ISO
PJM	PJM Interconnection
PNNL	Pacific Northwest National Laboratory
RTO	Regional Transmission Operator
SOC	State of Charge

Introduction

The prerequisite for stable system frequency is to have instantaneous balance of load demand and generated power. In the most basic terms, the difference of the sum of all real power sources and the sum of all real power sinks is reflected in the increase or decrease of system frequency; set nominally to 60 Hz or 50 Hz in most networks around the world. If there is more power than load on the grid, frequency will be high. If there is too much load, the generator will slow down under the load and frequency will drop. Fundamentally, the entire interconnect is operating at one frequency. Generators support the target frequency by maintaining a synchronous speed. They also provide regulation (following rapidly changing loads, measured in seconds) and are asked to rebalance typically within five minutes – very slow when compared to the time constant of changing load. Figure 1 shows a load profile in a typical network over a 24-hour period. A close-up view of the load curve, at any given hour, brings out the jagged nature of the curve with respect to a smoother line that represents the output from all generating assets. Frequency regulation services address the task of keeping the gap between these two lines in check. As seen in Figure 1, load changes can be very rapid, with many in the sub-second range, whereas generation transients are slow and often lag load variations by minutes. Frequency Regulation is a service

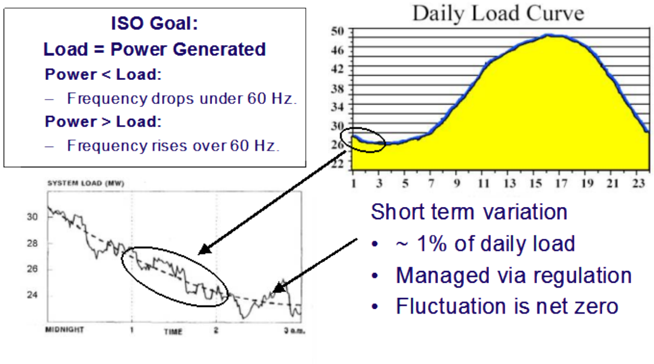

Figure 1. Frequency Regulation Description

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[1] M. L. Lazarewicz is Vice President and Chief Technical Officer of Beacon Power Corporation, Tyngsboro, Massachusetts 01879 USA (email:lazarewicz@beaconpower.com)
T. M. Ryan is an Energy Systems and Markets Analyst for Beacon Power Corporation, Tyngsboro, MA 01879 USA (email:ryan@beaconpower.com)

intended to manage generation to minimize this discrepancy. It is typically in the range of 1-2% of the total power being generated **[1]**.

In deregulated open markets, this regulation is provided as an ancillary service using an auction mechanism. The bidding process employs a clearing price approach that is similar to the one used for wholesale energy procurement.

The purpose of staying at or very near to the target frequency is to maintain grid stability and reliability. If the speed of a specific generator were not synchronized to the rest of the interconnection, internal current flows within the generator could get very high. When the current flow reaches a threshold, that generator would disconnect to protect itself from the high current. Because of the large difference in time constants between typical load changes (seconds) and generator load following requirements (5 minutes), exposure to those high currents could last for minutes. Depending on the size of the generator, this sudden reduction of generated power when the generator drops offline may create a bigger imbalance in the system and could, in extreme cases, cause a blackout as generators sequentially disconnect.

Not all generators can be effectively operated with constantly varying output, and all that are operated in this manner are negatively affected due to increased fuel consumption and maintenance.

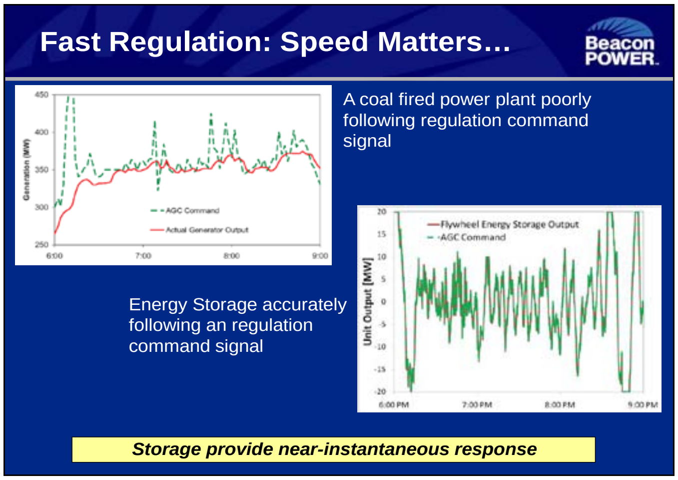
Regulatory and market conditions have molded the frequency regulation function to become a "net zero" short-term correction, on the order of 10-15 minutes where over-generation equals under-generation. This zero-sum characteristic makes it an ideal application for energy storage. Further, the typical time lapses between neutral crossings are measured in minutes, making it a very highly cyclic application. The charge / discharge events will total in the thousands of cycles in the course of a year. Normal operation includes constant charging and discharging at varying rates, from very slow to rapid and deep cycling. In this application, the storage device will very rarely be "resting".

Generators that were used for regulation were also often substituted for other products, such as spinning and contingency reserve. This practice led to market rules that required regulation resources to provide power for long durations, often for an hour, in order to also meet the requirement for other reserve products. Market rules governing generator-based regulation were not applicable to storage.

In 2007, FERC issued Order No. 890 which, in part, mandated that non-generation technologies be allowed to participate in deregulated markets for ancillary services. FERC's intent was to reduce cost and improve performance by increasing competition [2]. This mandate required significant changes to existing market rules, tariff structures and system operating software that had until then assumed that conventional generation was the only technology capable of providing regulation.

Speed of response

One of the attractive characteristics of a storage device is its fast response capability. It can react to its target power setting within seconds, rather than minutes as with a generator.


Fast Regulation: Speed Matters…

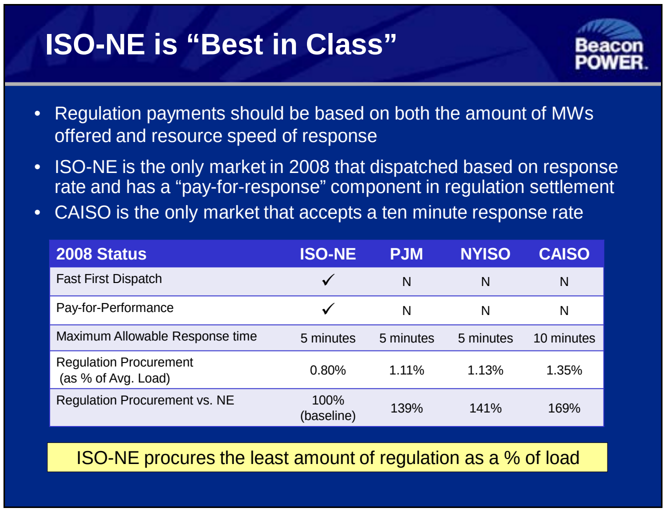
A coal fired power plant poorly following regulation command signal

Energy Storage accurately following an regulation command signal

Storage provide near-instantaneous response

Figure 2. Fast response is important for regulation

Figure 2 shows the importance of fast response in matching generated power to load. In both graphs, the actual instantaneous load is represented by the green dotted line. The red line shows the power output of a generator trying to keep up with the varying load. In the coal plant case, the difference or imbalance between the power and load can still be very high and can last for minutes [1]. The storage example shows the response on top of the demand signal [3]. In that case load and power are perfectly balanced, maintaining the frequency target. The faster the response, the better the performance. Up until recently, most ISOs did not dispatch resources to take into account the fact that some resources may respond more quickly than others and therefore could do more to maintain reliability. For example, PJM, NYISO and CAISO divide the required control action (AGC) among resources equally on *pro rata* basis; i.e., equally on a per-MW basis. This means that a slow unit providing 1 MW of regulation would be expected to provide the same service as a fast unit providing 1 MW of regulation [4-6].


ISO-NE is "Best in Class"

- Regulation payments should be based on both the amount of MWs offered and resource speed of response
- ISO-NE is the only market in 2008 that dispatched based on response rate and has a "pay-for-response" component in regulation settlement
- CAISO is the only market that accepts a ten minute response rate

2008 Status	ISO-NE	PJM	NYISO	CAISO
Fast First Dispatch	✓	N	N	N
Pay-for-Performance	✓	N	N	N
Maximum Allowable Response time	5 minutes	5 minutes	5 minutes	10 minutes
Regulation Procurement (as % of Avg. Load)	0.80%	1.11%	1.13%	1.35%
Regulation Procurement vs. NE	100% (baseline)	139%	141%	169%

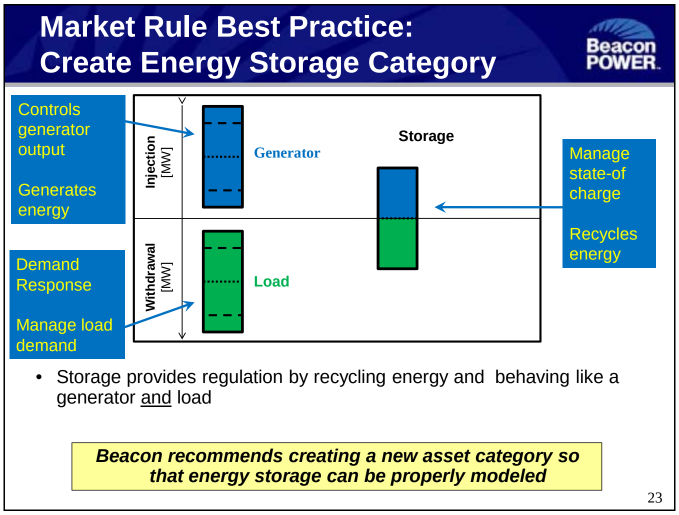
ISO-NE procures the least amount of regulation as a % of load

Figure 3. ISO-NE's "best-in-class" regulation performance

ISO-NE uses a different approach. They assign AGC to the fast-responding assets first and have a portion of each unit's total compensation based on the amount of regulation deployments. The Regulation Service Credit, or "mileage" payment, takes into account how active the resource actually was and pays for the increased speed and service [7]. For example, a resource that takes five minutes to respond would be dispatched less often, and be paid less for mileage than an asset that responds in one minute. This encourages resources to provide more flexibility to the operators. Figure3 shows that ISO-NE required approximately 30-40% less regulation than PJM, NYISO and CAISO [8]. This appears to be a best-in-class operation and is due to ISO-NE's method of utilizing and paying for fast regulation resources.

Storage State of Charge Control

NYISO and MISO both have FERC-approved market rules for Limited Energy Storage Resources (LESR) specifically aimed at addressing the unique characteristics of energy storage [9, 10]. These changes created the LESR asset category and included changes to the scheduling, dispatch, and settlement systems. One key change in both NYISO and MISO was to modify the scheduling of LESRs can provide regulation while acting as a load when charging, and as a generator when discharging. The ISOs concluded that the greatest value could be gained from storage if the ISO considered state-of-charge when scheduling and dispatching storage providing regulation. Figure 4 illustrates how storage should be treated as a separate asset class, different from generation or Demand Response. It has characteristics of both generation and load, but only for a limited time. It should be managed by State of Charge and sometimes provides Regulation like a generator (only injecting energy), sometimes like a load (only withdrawing energy), but primarily as both.



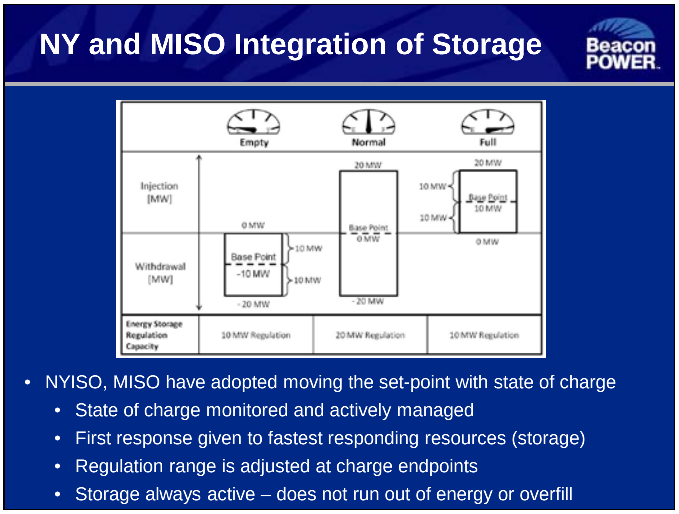
Market Rule Best Practice: Create Energy Storage Category

- Storage provides regulation by recycling energy and behaving like a generator and load

Beacon recommends creating a new asset category so that energy storage can be properly modeled

Figure 4. Storage is neither generation, nor load. It is a separate asset class using management of state of charge

They also recognize that fast assets should be dispatched first. To take advantage of the benefits of LESR in a manner that treats them comparably to other generation facilities and without impacting NYISO's ability to meet all existing reliability criteria, NYISO made changes in three major areas; scheduling, operations and settlements. NYISO created a dispatch mechanism for LESR that involves two-way communication between the resource and the ISO, allowing the ISO to vary the amount of regulation the resource provides every five minutes based on its energy level as expressed by SOC (Figure 5). This mechanism has been designed to extract the greatest usefulness from the resource, while ensuring the highest level of reliability.



NY and MISO Integration of Storage

- NYISO, MISO have adopted moving the set-point with state of charge
  - State of charge monitored and actively managed
  - First response given to fastest responding resources (storage)
  - Regulation range is adjusted at charge endpoints
  - Storage always active – does not run out of energy or overfill

Figure 5. A 20 MW energy storage resource's regulation capacity as a function of its energy level

As shown in Figure 5, the amount of regulation service that can be scheduled on a LESR depends on the amount of energy stored in the device. A LESR can continuously and sustainably provide regulation service if it is dispatched like a generator (around a positive base-point) when it is full of energy, a demand response provider (around a negative base-point) when it is empty, or both a generator and a demand response provider (around a 0 MW base-point) when it is at its midpoint of energy.

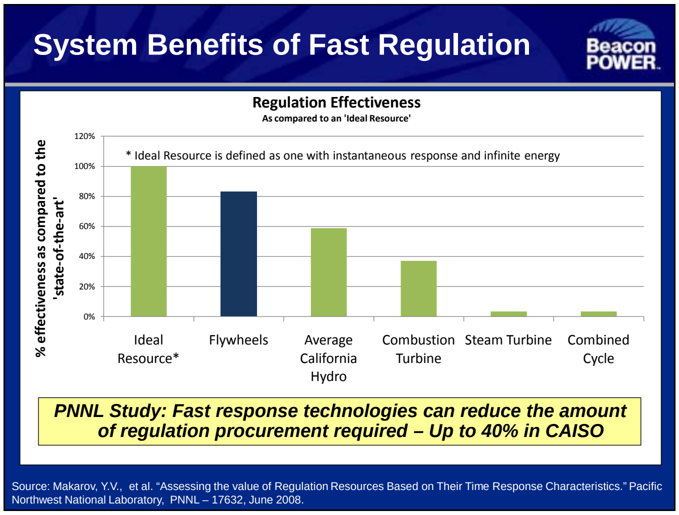
When a 20 MW LESR (which has a 40 MW regulating range) is half full, it has the ability to provide its maximum regulating capacity; i.e., it can absorb or inject 20 MW of power, around a 0 MW base-point. When the LESR is empty, it is able to provide 10 MW of regulating reserve, similar to a demand response resource, around a negative base-point of -10 MW. When the LESR is full, it has the ability to provide 10 MW of regulating reserve like a generator, around a positive base-point of 10 MW.

Thus, an LESR always has the ability to provide regulating reserves, as long as the ISO sets its base-point to the mid-point of its available operating range. Furthermore, this method of dispatching LESR for regulation better positions LESR to provide their full regulating reserve capacity in the next interval.

With this dispatch method, when a LESR is empty, the ISO schedules the resource at a negative -10 MW energy base-point, making the resource more likely to fill up with energy and thus have a greater regulating reserve capacity in the next interval. Also, when the LESR is full, the proposed dispatch will schedule the LESR with a positive 10 MW energy base-point, making the resource more likely to empty its energy and increasing its regulating reserve capacity in the next interval.

Combining speed and unlimited energy

The CEC funded another study by PNNL to evaluate the effectiveness of energy storage [11]. PNNL took the approach of assuming a theoretically perfect (and thus non-existent) regulation asset as 100% effective. The perfect regulation asset has infinite energy and capacity, so it is always available to provide regulation, respond immediately, and deliver the exactly the amount of regulation required, with no over- or undershoots. PNNL then studied several candidate regulation resources and compared the results. Figure 6 shows the summarized findings.


System Benefits of Fast Regulation

PNNL Study: Fast response technologies can reduce the amount of regulation procurement required – Up to 40% in CAISO

Source: Makarov, Y.V., et al. "Assessing the value of Regulation Resources Based on Their Time Response Characteristics." Pacific Northwest National Laboratory, PNNL – 17632, June 2008.

Figure 6. Comparison of regulation effectiveness of various assets

Table 1 shows the characteristics of both generation and energy storage for providing regulation. It shows that generation and energy storage are complementary to one other. Generation is good for long-term balancing and storage is good for fast response. The two, however, have very different control mechanism requirements.

TABLE I
COMPARISON OF GENERATION AND ENERGY STORAGE ASSETS FOR FREQUENCY REGULATION

	Response Time	**Energy**	**Control**	**Adds to Base-Load Generation**
Generation Based	5 Mins	>1 Hr	AGC	Yes
Energy Storage	4 Sec	15 Mins	AGC (w/ Managed SOC)	No

Generators are controlled using AGC, while storage devices, because of their limited energy capacity, use both AGC and SOC. Table 1 also highlights that generators have to provide a certain amount of power while providing regulation. Generators typically need to operate with at least 50-80% of their capacity in the energy market and can thus only deliver 20-50% of nameplate capacity for regulation. This additional energy can be a major disadvantage when more regulation is needed at night and all non-regulating base-load generators are at minimum economic dispatch, for example. Adding generation to the base-load at this condition could (and historically has) led to negative energy pricing. Negative energy pricing means that the generator must pay for a load to take the excess power. Storage-based regulation would certainly alleviate the pricing pressure by providing regulation without adding the unwanted energy. Negative pricing scenarios will probably be more likely in the future when high-penetration, low-cost variable renewable energy such as wind, coupled with low-load variability at night, for example, become major sources of energy.

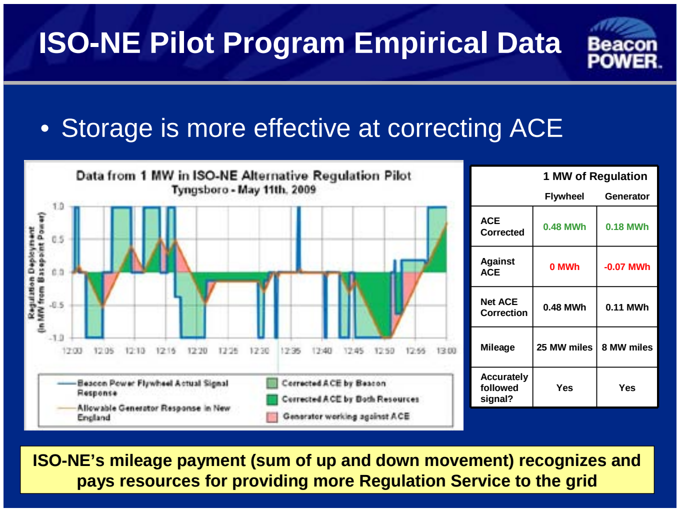
ISO-NE Alternative Technologies Pilot Program

ISO-NE is evaluating storage for regulation using a pilot program and testing various control strategies [12]. They have stakeholder approval for up to 13 MW of storage to be tested. Beacon Power is currently operating 3 MW of flywheel-based storage. The first MW has been in operation since November 2008, the second since July 2009, and the third since December 2009. Figure 7 shows two of the MW systems in ISO-NE service.

Figure 7. Two MW Beacon Power flywheel storage in frequency regulation service in ISO-NE

ISO-NE is also evaluating several different SOC-based methodologies to be combined with their "use the fast assets first" and "pay for performance" strategies. Figure 8 shows a comparison of the amount of energy delivered by the fast-acting flywheel system and compares it to the amount of regulation that would have been delivered by a generator asset responding at a 5-minute response rate [13]. The area under the curves is the amount of energy actually used to neutralize the load imbalance. It is easy to see why the storage-based system is much more effective for short transient imbalances.

Constant operation over more than a year has provided significant operating data that helps create a product specification for what is required to maximize benefit to the system. Operation such as that shown in Figure 9 can be performed by any storage system capable of providing 1 MW for 15 minutes [14]. What was surprising was how much cycling the storage device has to be able to perform for a 20-year service life in ISO-NE. Figure 9 shows a typical SOC profile of a 1 MW/250kWh flywheel storage system in a 24-hour period.



ISO-NE Pilot Program Empirical Data

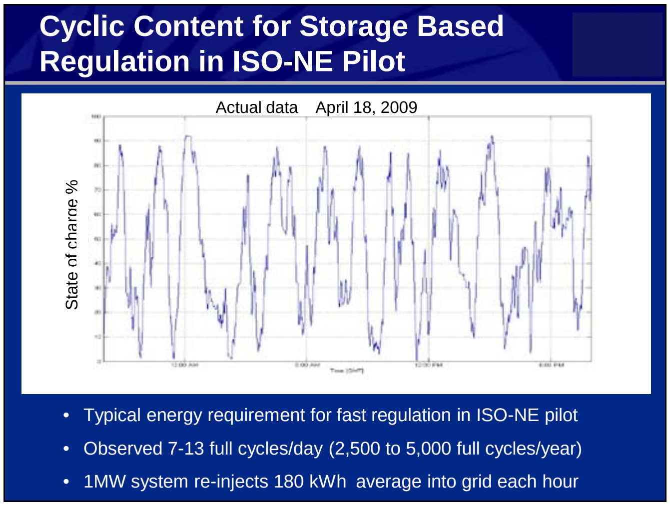
- Storage is more effective at correcting ACE

	1 MW of Regulation	
	Flywheel	Generator
ACE Corrected	0.48 MWh	0.18 MWh
Against ACE	0 MWh	-0.07 MWh
Net ACE Correction	0.48 MWh	0.11 MWh
Mileage	25 MW miles	8 MW miles
Accurately followed signal?	Yes	Yes

ISO-NE's mileage payment (sum of up and down movement) recognizes and pays resources for providing more Regulation Service to the grid

Figure 8. Comparison of fast flywheel-based and slow generator-based regulation.

On a daily basis, there are from 7-13 roughly 80% depth-of-discharge cycles and many smaller ones. A common way to calculate the cyclic equivalency of the entire mix of cycles is to measure how much energy actually was returned to the load and divide by the effective capacity of the storage system. On average, the 1 MW system injects 180 kWh per hour (range is between 110kWh and 230 kWh/hour).



Cyclic Content for Storage Based Regulation in ISO-NE Pilot

Actual data April 18, 2009

- Typical energy requirement for fast regulation in ISO-NE pilot
- Observed 7-13 full cycles/day (2,500 to 5,000 full cycles/year)
- 1MW system re-injects 180 kWh average into grid each hour

Figure 9. Cyclic content of ISO-NE pilot program

<u>Annually, a 1 MW system injects</u>

Annual energy = 180kWh/hour x 8760 hours/year (1)
Equivalent cycles = 1,577MWh/year / 0.250 MWh/cycle
= 6,300 cycles/year (2)

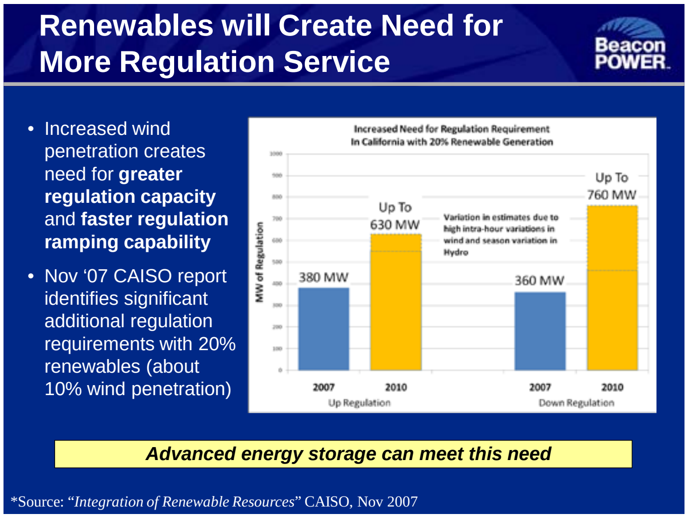
Over a 20-year life of the system, the storage device will see approximately 125,000 full charge/discharge cycles. Much of this operation is at full power.

This cyclic requirement is a very challenging one. As an example, electric vehicles are expected to have a range of 250 miles. For the 250,000-mile life of a car, the car's battery system will need to have 1000-cycle life capability. That requirement is approximately two orders of magnitude less demanding than the frequency regulation application. Flywheels are ideally suited for this application because they are mechanical devices that have the capability to meet the cyclic life requirements with no replacement.

The ISO-NE pilot will continue until permanent market rules are developed, and approved by FERC, that successfully address the issue of integrating storage into the ISO-NE market.

Impact of Renewables

The California Energy Commission (CEC) funded a study to evaluate the amount of regulation that will be required when California achieves 20% RPS penetration. Figure 10 shows similar results shows that 20% more generated power will require about 75-100% more regulation than was needed in 2007. The report further states that the outlook is uncertain as to whether there will be enough generation-based regulation assets to provide the required amount of regulation [15].



Renewables will Create Need for More Regulation Service

- Increased wind penetration creates need for **greater regulation capacity** and **faster regulation ramping capability**
- Nov '07 CAISO report identifies significant additional regulation requirements with 20% renewables (about 10% wind penetration)

Advanced energy storage can meet this need

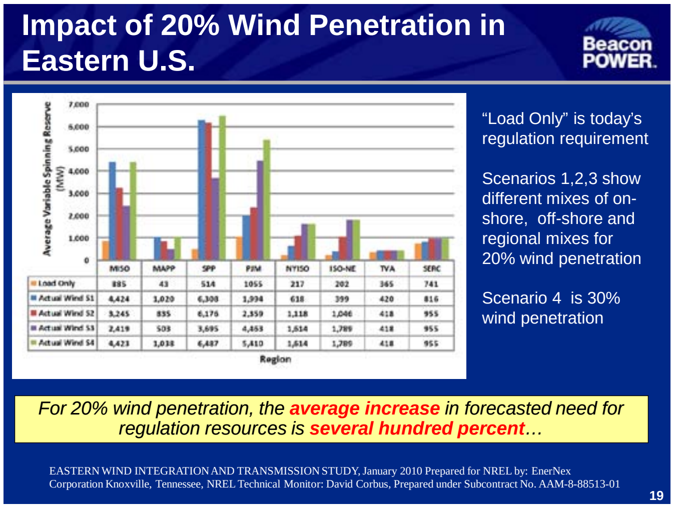
*Source: "*Integration of Renewable Resources*" CAISO, Nov 2007

Figure 10. Renewables will create need for more regulation service

Pacific Northwest National Laboratory (PNNL) conducted a study funded by the California Energy Commission. It estimated that with the proper mix of generation and storage-based regulation assets, CAISO could reduce its regulation requirement by 40% [11].

CAISO is in the final stages of preparing its market rules for submission to FERC.

NREL recently completed a study that evaluated the integration impact of 20% penetration of wind on the Eastern U.S. Interconnect. Figure 11 shows the resulting regulation requirements. The base case with today's requirement is shown on the first bar. Three different scenarios of on-shore, off-shore and combined wind installations all indicate that significant increases in regulation will be required[16]. Flywheels were rated as 82% effective as compared to the ideal resource. That is approximately 35% more effective than the average California hydro plant and about twice as effective as a combustion turbine. A combined cycle plant was estimated at only 6% or 7% as effective as an ideal resource. The PNNL study also concluded that CAISO could procure up to 40% less regulation if it had faster-responding resources. Today, with the exception of ISO-NE, each of these resources receives the same compensation despite providing different qualities of regulation. The PNNL study is supported by the empirical data in ISO-NE (Figure 3) that shows that fast resources are more effective at providing regulation. It also shows that ISOs can procure less regulation if they incentivize and utilize faster, more effective regulation resources. This data adds to the growing consensus that regulation should be paid for performance [17].



Impact of 20% Wind Penetration in Eastern U.S.

Beacon POWER

	MISO	MAPP	SPP	PJM	NYISO	ISO-NE	TVA	SERC
Load Only	885	43	514	1055	217	202	365	741
Actual Wind S1	4,424	1,020	6,308	1,994	618	399	420	816
Actual Wind S2	3,245	835	6,176	2,359	1,118	1,046	418	955
Actual Wind S3	2,419	503	3,695	4,453	1,614	1,789	418	955
Actual Wind S4	4,423	1,038	6,487	5,410	1,614	1,789	418	955

"Load Only" is today's regulation requirement

Scenarios 1,2,3 show different mixes of on-shore, off-shore and regional mixes for 20% wind penetration

Scenario 4 is 30% wind penetration

*For 20% wind penetration, the **average increase** in forecasted need for regulation resources is **several hundred percent**…*

EASTERN WIND INTEGRATION AND TRANSMISSION STUDY, January 2010 Prepared for NREL by: EnerNex Corporation Knoxville, Tennessee, NREL Technical Monitor: David Corbus, Prepared under Subcontract No. AAM-8-88513-01

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Figure 11. Impact of 20% wind penetration on Eastern U.S. Interconnect

Efficiency

The economics of this application are dependent on the net energy used to provide regulation service. FERC-approved market rules used to calculate settlement cost of lost energy were defined as the difference between energy supplied to the storage device minus the energy returned to the grid. The energy measurements are actually made at the transformer connecting the system to the transmission line. The obvious practical definition of efficiency was simply stated as:

$$\text{Efficiency} = \frac{\text{total energy returned to grid in a period of time}}{\text{energy absorbed by storage in a period of time}} \qquad (3)$$

This definition is very different from the traditional one normally quoted for a battery. The efficiency of a battery or storage device is usually measured as energy withdrawn divided by energy used to charge the battery, measured at the DC posts in a single charge/discharge cycle. Specific parameters are usually fixed; such SOC range, power level, temperature, depth of discharge, and hold time. The measured round-trip efficiency value could change significantly if those environmental parameters were varied, as they naturally would in the regulation application. It is very important to include the effects of the ancillary systems such as cooling, heating, interconnection equipment and power electronics that convert the DC to useable AC in the quoted efficiency rating.

It is highly recommended to universally adopt the definition in equation (3) using the total net energy calculation approach to quote grid storage efficiency, and not rely on laboratory component measurements that cannot be easily related to total billable losses.

Status of two 20 MW Regulation Plants

DOE has been very helpful in the funding of the first two 20 MW flywheel energy storage plants, the first of which is now being built in Stephentown, New York. All the necessary permits and FERC-approved market rules are in place. Funding is partially provided by a $43M DOE loan guarantee commitment supplemented with a $2M NYSERDA grant. Groundbreaking was held in November 2009. Revenue operation is expected to begin in Q4 2010, and a completed 20 MW plant in spring 2011. Figure 12 shows an artist's rendering of the Stephentown plant.

Figure 12. Rendering of the 20MW regulation plant in Stephentown, NY

$24M Recovery Act Smart Grid stimulus grant, will be used to help build a second 20 MW plant within PJM territory.

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III. BIOGRAPHIES

Mr. Matthew L. Lazarewicz has been with Beacon Power since 1999, where he serves as Vice President and Chief Technical Officer. His responsibilities include company representation within various industry organizations and associations; oversight of the company's intellectual property portfolio, and primary technical interface to academic and government institutions. Prior to joining Beacon, Mr. Lazarewicz worked for 25 years for General Electric in various engineering and managerial capacities in Power Systems and Aircraft Engines. He holds B.S., M.S., and M.B.A. degrees from the Massachusetts Institute of Technology and is a Registered Professional Engineer in Massachusetts. He serves on the Board of Directors of the Electricity Storage Association, and is a member the IEEE Power Engineering Society, American Society of Mechanical Engineers, CIGRE (the International Council on Large Electric Systems), and NEMA's Energy Storage Council.

Mr. Todd M. Ryan works as an Energy Systems and Markets Analyst for Beacon Power Corporation. He models how Beacon's flywheel energy storage system interact with the electricity grid with respect to each region's specific rules and regulations. Previously Todd worked as a Process and Systems Engineer for Nuvera Fuel Cells developing hydrogen fuel cell and automotive fuel-reformering systems. Todd received his B.S. in chemical engineering from Tufts University.