Final Technical Performance Report

Grid-Scale Energy Storage Demonstration of Ancillary Services Using the UltraBattery® Technology

Smart Grid Program

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List of Acronyms

A	Ampere
AC	Alternating Current
BESS	Battery Energy Storage System
BMS	Battery Monitoring System
CCGT	Combined Cycle Gas Turbine
CSIRO	Commonwealth Scientific and Industrial Research Organization
CUBS	Containerized UltraBattery® System
DC	Direct Current
EPA	Environmental Protection Agency
HVAC	Heating, Ventilation, and Air Conditioning
ISO	Independent System Operator
kV	kilovolt
kW	kilowatt
MVA	Megavolt ampere
MW	Megawatt
MWh	Megawatt hour
MW*h	Megawatt hour of regulation
PCS	Power Conversion System
pSoC	Partial State of Charge
RegA	Traditional regulation signal
RegD	Dynamic or ‘fast’ regulation signal
RMCP	Regulation Market Clearing Price
RMCCP	Regulation Market Capability Clearing Price
RMPCP	Regulation Market Performance Clearing Price
RTO	Regional Transmission Organization
SCADA	Supervisory Control and Data Acquisition
SoC	State of Charge
SoH	State of Health
V	Volt
VRLA	Valve Regulated Lead-Acid

1. Overview of Energy Storage Project

The collaboration described in this document is being done as part of a cooperative research agreement under the Department of Energy's Smart Grid Demonstration Program. This document represents the Final Technical Performance Report, from July 2012 through April 2015, for the East Penn Manufacturing Smart Grid Program demonstration project.

This Smart Grid Demonstration project demonstrates Distributed Energy Storage for Grid Support, in particular the economic and technical viability of a grid-scale, advanced energy storage system using UltraBattery® technology for frequency regulation ancillary services and demand management services.

Figure 1. Frequency regulation site at East Penn's facility in Lyon Station, PA.

Introduction to East Penn Manufacturing Co.

East Penn is headquartered at Lyon Station, Pennsylvania and operates the world's largest, single-site lead-acid battery manufacturing facility. The facility has over 3.7 million sq. feet under roof on a 520 acre plant site.

East Penn Manufacturing makes thousands of different sizes and types of lead-acid batteries, battery accessories, and wire & cable products for virtually any application. Since 1946, East Penn has developed an enviable reputation for world-class quality products made in state-of-the-art manufacturing facilities.

These facilities include a modern U. S. EPA permitted lead smelter, refinery, and recycling center where virtually 100% of every used lead-acid battery returned to East Penn is recycled.

Project Overview

This project entailed the construction of a dedicated facility on the East Penn campus in Lyon Station, PA that is being used as a working demonstration to provide regulation ancillary services to PJM and demand management services to Metropolitan Edison (Met-Ed).

To achieve the project objectives, the project team designed and constructed a dedicated energy storage facility consisting of an array of UltraBattery® modules. Those modules were integrated in a turnkey Battery Energy Storage System (BESS) engineered and supplied by Ecoult, a subsidiary of East Penn. The UltraBattery® is a hybrid energy storage device, which combines the advantages of an asymmetric ultracapacitor and a lead-acid battery in one unit cell – taking the best of both technologies without the need for electronic controls. In addition to the UltraBattery®, the BESS includes a power conversion system (PCS), a master programmable controller, and a Battery Monitoring System (BMS). An electrical single-line diagram of the system is provided in Figure 2.

East Penn has coordinated with the following partners for the building and operation of the UltraBattery® Energy Storage System.

- Ecoult - Wholly owned subsidiary of East Penn, Energy storage solution provider, supplier of the BESS, including the PCS, the Containerized UltraBattery® System (CUBS), and the battery monitoring system
- PJM - Pennsylvania-Jersey-Maryland Interconnection – regional transmission organization, coordinating wholesale electricity transactions in 13 states
- Noble Energy Solutions - primary responsibilities are providing products and services to retail energy customers and hedging strategies for the company's generation assets. Noble Energy Solutions is the retail energy supplier to East Penn and their responsibilities for this project include the management of battery facility's services in the PJM market
- Met-Ed - A subsidiary of FirstEnergy, 5th largest, investor-owned, electric utility providing services to Ohio, PA, and NJ

East Penn provided the UltraBattery® modules, designed and constructed the Facility and interconnected the Facility to PJM (the regional transmission organization), through Met-Ed's transmission and distribution system. To demonstrate modularity and portability, self-contained, Containerized UltraBattery® Systems (CUBS) have been designed and included as a subset of this project.

The completed energy storage system is designed to provide up to 3 MW of frequency regulation into the PJM Energy Market. In addition to frequency regulation, the system has the capability to provide demand management services to Met-Ed during specified high demand power periods. These services can provide up to 1MWh for 1 to 4 hours. Maximum power is restricted to 0.25-1MW as MWh capacity of the system becomes the limitation when providing up to 4 hours of capacity. Noble Energy Solutions provides the daily management required to bid and schedule ancillary services into the market and provide invoicing with a subaccount. East Penn analyzed the collected data for frequency regulation.

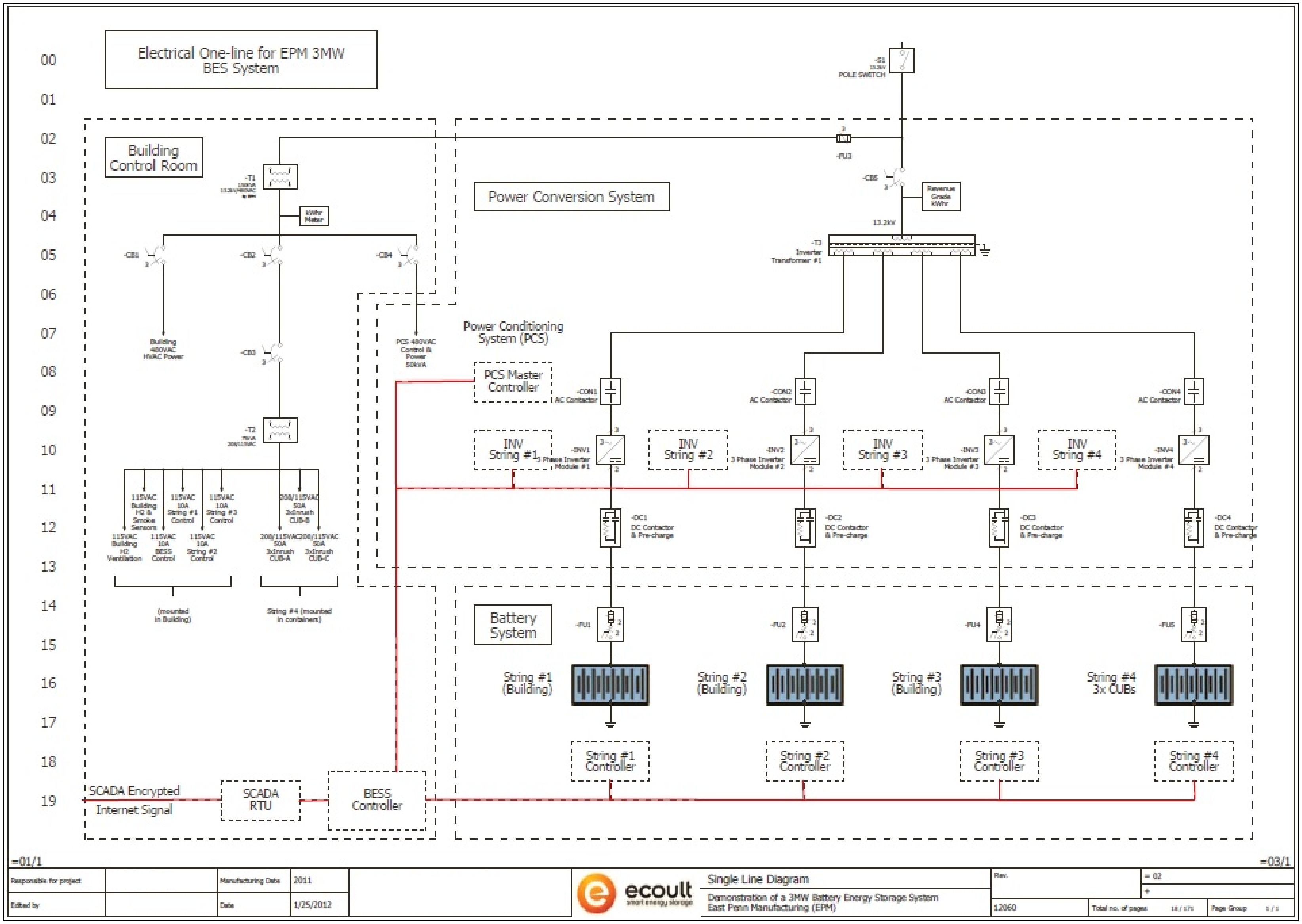


Figure 2. Single line Diagram of UltraBattery® System.

Product Learning and Contribution toward 2nd Generation UltraBattery®

The implementation of the Frequency Regulation Facility at the site of the manufacturer of the UltraBattery® and indeed behind East Penn's own plant load provided several advantages. One of these was that the site also is where EPM maintains its R&D and engineering capability. The proximity to the facility provided a resource for the UltraBattery® engineering team to utilize for the purposes of advancing the product as well as for Ecoult and the project team to gain experience through the implementation and provision of ancillary services. As a result, maximum advantage was taken of the opportunity to capture learning and evolve the technology, products and solution. In the spirit of knowledge sharing of the ARRA projects the results considered most important are set out in this report.

One such product outcome was the recognition that the standard racking system used with the UltraBattery® devices for the projects (normally used for UPS applications where the batteries are held on float against need for reserve power) resulted in a relevant temperature difference being created in the rows of cells rising from the bottom to the top. There is potential for such a difference in temperatures to age the batteries at different rates so it is preferable to keep the batteries in each string at a reasonably constant temperature. A method to equalize the battery temperatures in the strings was devised and added to the project. Making use of this understanding a new racking system that provided passive cooling and temperature equalization was developed by Ecoult for use on subsequent installations.

A second product outcome was the projects contribution into the design considerations that were underway in parallel for a 2nd generation UltraBattery®. The 2nd generation UltraBattery® utilized learning gained from the project to design a 12V UltraBattery® capable of providing frequency regulation at much higher rates than the first generation UltraBattery® products used for the project.

When the project was first designed, it was sized to support 3MW of the original PJM signal and a technical objective of the project was to test performance against a higher density signal. Soon after commissioning, the target PJM regulation services signal changed to the more energy throughput dense fast-responding Dynamic Regulation signal. The demonstration project was able to operate in the PJM market at 3MW against both the original signal and revised signal. However a side effect of the extra energy density of the revised signal was that with the old style racks, the temperature of the higher cells became close to the operating limit that had been established for the project (40C) after about 24 hours of continuous operation. Therefore the system was more typically operated at either 2MW or 2.4MW during the project. Based on the information from this project as well as additional testing data, EPM developed a new format UltraBattery® specifically designed for high rate PSoC applications, called 12UB700. The 12UB700 batteries are designed to operate in the PJM market up to 1.4 times the one hour rate, nearly double the rate the 2V batteries were able to operate continuously in the PJM market.

Having achieved the full set of project objectives with the 1st generation UltraBattery®, EPM approached the DOE with a request to push the demonstration further (at EPM's sole cost) by implementing a string of the 2nd generation UltraBattery® and demonstrating the ability of the devices to operate in the PJM regulation market with the batteries being used at power levels equivalent to 1.4C1. By running at the higher rate the service can be provided with a smaller and lower cost battery store. The DOE was supportive of EPM's proposal and EPM proceeded to replace one of the four strings of the 2V batteries with a storage block of the new format 12UB700 batteries during the reporting period of the demonstration project. The project was extended 3 months to allow performance results from the new storage block to be included in this report.

Figure 3 shows the updated electrical single line diagram with the new storage block. The only change is to the battery section where string 3 has been replaced with Storage Block #3 (SB3).

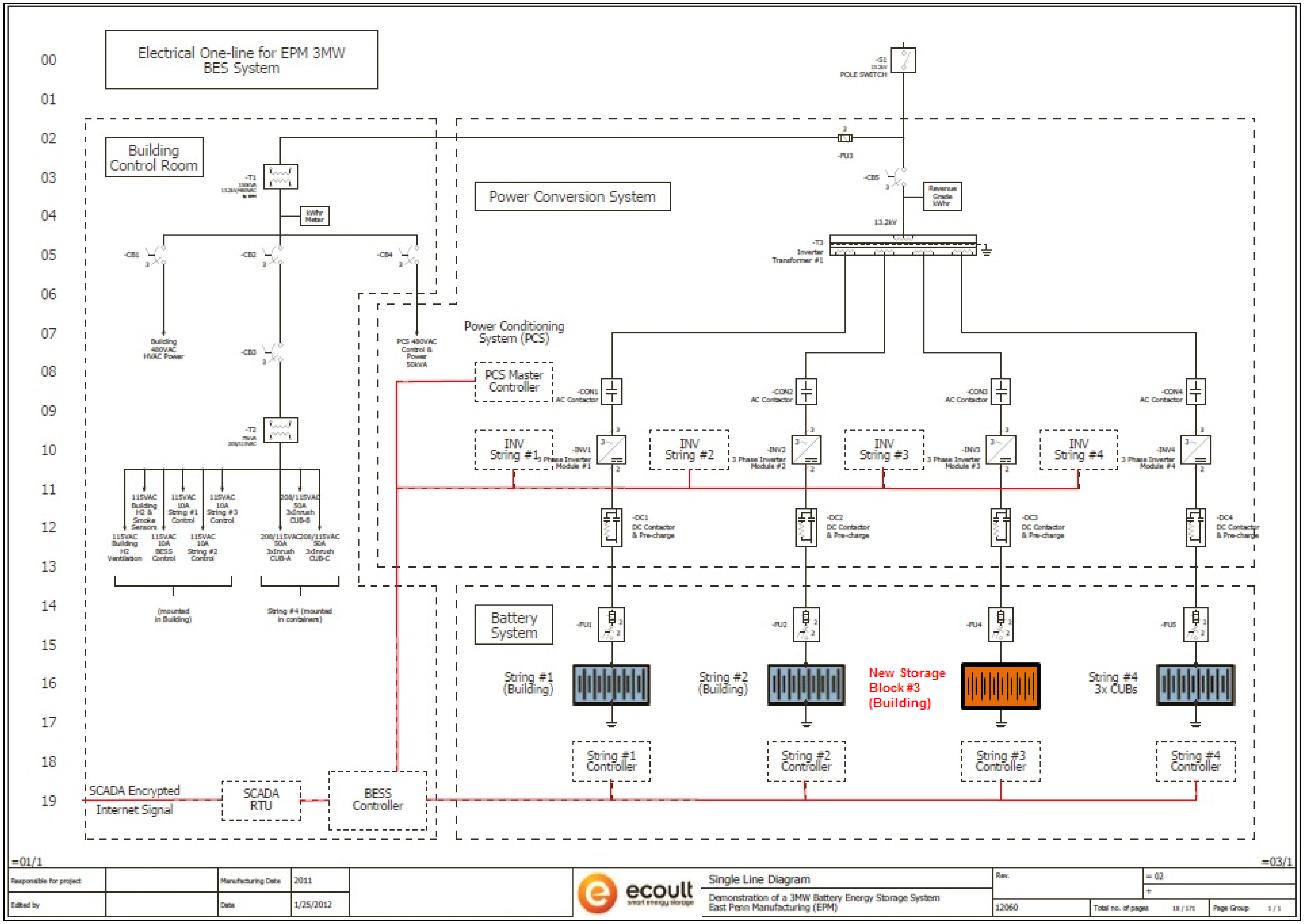


Figure 3. Single line Diagram of UltraBattery® System with new Storage Block #3.

Project Objectives

Overall specific goals and objectives of East Penn's Smart Grid project include:

1. Providing the PJM market with regulation service in response to the network regulation signal.
    - Document the development and running costs of the system to provide network regulation services.
2. The original Metrics & Benefits Plan proposed that (for short periods expected to be two 24hr periods each year, and beginning in the second year of the performance evaluation program) the ability of the system to provide a faster regulation response than is normally required to satisfy PJM requirements would be evaluated.

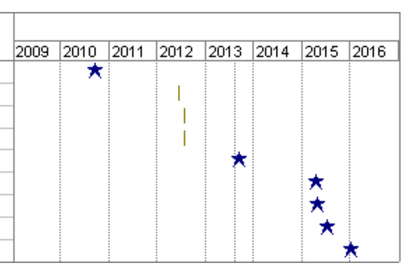
    Since the projects inception, PJM has implemented a fast-responding Dynamic Regulation market for systems such as the East Penn BESS. This is the market in which the system will be operated over the life of the project. The system is now participating in the Dynamic Regulation market.
3. For 100 hours per year, beginning in the second year of the performance evaluation program, the demonstration project will reserve the ability to provide demand management to Met-Ed to allow them to meet the requirements of PA Act 129.
    - Monitor cost of operation to support this application
    - Monitor the mix of energy generation during battery charging and discharging to evaluate the potential for reduction (or increase) of CO_2 emission with battery energy storage

Schedule

Key project milestones and how they are related to system impact goals are included as a list in Table 1.

Table 1. Key Project Milestones and Impact Metrics

ID	Program WBS	Task Name
19		Phase I Complete
199		Phase II Complete
283		PJM Approval Received
284		Commissioning Complete
314		TPR/Data Analysis Report - 12 mo - Submitted
316		TPR/Data Analysis Report - 30 mo - Submitted
317		Final Briefing Complete
318		Phase III Complete
320		Project Complete



- Phase 1 Project Definition and NEPA Compliance
  - Contract negotiations
  - Completed Sept 2010
- Phase 2 Final Design and Construction
  - Engineering, purchasing, construction and installation
  - Completed May 2012
- Phase 3 Commissioning and Operations
  - Commissioning, operations, data collection and reporting
  - Operations end January 2015

In addition, East Penn's key asset deployment schedule, as identified in East Penn's Project Management Plan, is provided as Table 2.

ID	Program WBS	Task Name
1	1.0	**Grid-Scale Energy Storage Demonstration for Ancillary Services using the UltraBattery Techn**
2		**Grant Award**
5	1.1	**Phase I - Project Definition and NEPA Compliance**
19		Phase I Complete
20		
21	1.2	**Phase II - Final Design and Construction**
196		**Decision Point 2 - Operational Readiness Review**
199		Phase II Complete
200		
201	1.3	**Phase III - Commissioning and Operations**
202	1.3.1	**Phase III Project Management and Project Management Plan Updates (SOPO Task 9)**
273	1.3.2	**Commissioning (SOPO Task 10)**
285	1.3.3	**Operations (SOPO Task 11)**
286	1.3.3.1	**Systems Management (SOPO Sub Task 11.1)**
287	1.3.3.1.1	Energy Management (SOPO Sub Task 11.1.1)
288	1.3.3.1.2	**Facility Management (SOPO Sub Task 11.1.2)**
295	1.3.3.1.3	**UltraBattery Management (SOPO Sub Task 11.1.3)**
296		**Thermal Imaging Equipment**
299		**UltraBattery Data Analysis and Checks**
303		**UltraBattery Maintenance**
308	1.3.3.2	**Data Collection (SOPO Sub Task 11.2)**
309	1.3.3.2.1	Systems Monitoring (SOPO Sub Task 11.2.1)
310	1.3.3.2.2	**Data Collection, Analysis and Reporting (SOPO Sub Task 11.2.2)**
311		Baseline Data Collection
312		Baseline Data Analysis and Reporting
313		Operations Data Analysis and Reporting - 12 mo
314		TPR/Data Analysis Report - 12 mo - Submitted
315		Operations Data Analysis and Reporting - 30 mo
316		TPR/Data Analysis Report - 30 mo - Submitted
317		Final Briefing Complete
318		Phase III Complete
319		Final Financial and Project Reports Submitted
320		Project Complete

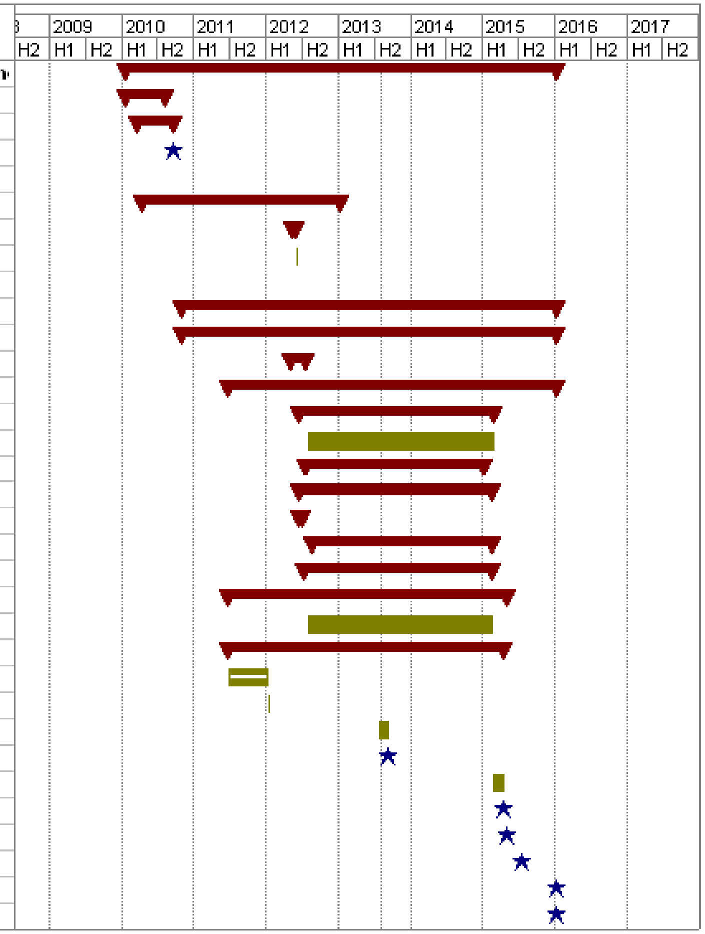


Table 2. East Penn Manufacturing's Integrated Schedule.

Cyber Security

For this project, East Penn Manufacturing and Ecoult have developed and submitted a Cyber Security Plan to the DOE. The cyber security plan describes how EPM will address interoperability and cyber security in every phase of the engineering lifecycle of the project, including design, procurement, construction, installation, commissioning, and operation as well as the ability to provide ongoing maintenance and support. The system has been implemented as per the original Cyber Security plan with the exception of two areas:

The first area involves concerns over access control of the proposed roles in the original plan. The plan intended that access control of such roles would be enforced by physical access tokens. Such tokens were not compatible with the access control hardware at the site and presently access is controlled via user ID, access keys, and passwords. The use of physical access tokens is intended to be the final solution.

Another area involves concerns over the access by suppliers of major subsystems to access equipment for maintenance or monitoring. Open access by suppliers is not desirable. The solution has been to allow access to equipment on an as-needed basis. Access is removed after maintenance is complete.

2. Description of Energy Storage Technology and System

This Smart Grid Demonstration project is located at East Penn Manufacturing's facility in Lyon Station, PA. The battery system consists of four strings; each rated to provide up to 750kW of frequency regulation services to PJM for a total regulation capability of 3MW.

The overall system consists of a building containing the bulk of the cells, an outdoor AC/DC power converter and transformer for interconnection, and a portion of the system cells packaged in ISO shipping containers.

The structure is a pre-engineered steel building which includes heat and air conditioning to keep the batteries within operating temperature. The building is equipped with a sprinkler system in order to meet both insurance and local code requirements. The building contains three strings, each with an approximate footprint of 125 square feet and weight of approximately 126,000lbs (the second generation 12UB700 storage block has an approximate footprint of 155 square feet and a weight of 70,000lbs).

Figure 4. Three strings of batteries installed in the building.

East Penn manufactured the UltraBattery® modules for the project on-site and delivered them directly to the building.

Containerized UltraBattery® System (CUBS)

The Containerized UltraBattery® System (CUBS) contains one string of UltraBattery® modules. Each CUBS weighs approximately 50,000 lbs. The CUBS are standard shipping containers designed with the necessary ventilation/air conditioning systems and integrated battery monitoring to demonstrate a version of the system that can be relocated. The intent of the CUBS is to allow systems to be installed where energy storage is required to compensate for a grid constraint or to allow an existing energy storage system to be easily scaled. If the constraint is subsequently resolved, the energy storage system can be downsized or relocated. A containerized system for the 2nd generation 12UB700 has also been designed which utilizes two 20 ft containers each weighing 45,000lbs to provide 800kW of Dynamic regulation services. East Penn is continuing to advance power density and a 3rd generation 2 volt 2UB700 will be released in early 2016 which will provide a higher power rating from the same footprint and weight.

Figure 5. One string of Containerized UltraBattery® System (CUBS)

Battery Monitoring System (BMS)

A BMS function has been provided within the BESS programmable controller to verify the technical performance of the Battery System. The BMS provides voltage monitoring down to individual cells, cell temperature monitoring of sample cells, and includes the ability to add a pulse test load and monitoring of resulting cell voltage behavior for more accurate cell impedance tracking as required for cell State-of-Health (SoH) and State-of-Charge (SoC) monitoring.

Power Conversion System (PCS)

The PCS design uses mature technology, which is based on previous utility-scale BESS systems. Additionally, these components (primarily the inverters, associated electronics, controls, battery monitoring systems) are commercially available equipment.

The power conversion system is housed in what is called an EHouse. The EHouse contains the entire PCS with the exception of the heat exchanger for the liquid coolant.

The EHouse is divided into three main sections, i) a "Transformer Section", ii) "Conversion Section," and iii) "Control/Cooling Section". Each section has the following features:

i) Transformer Section and Forced Air Cooling

The Transformer Section houses the AC Fused Isolation Switches, the Inverter Transformer. The external entry doors used for maintenance of the Transformer Section are Kirk-Key interlocked with the 69kV breaker for compliance with the safety requirements of the National Electrical Code.

ii) Conversion Section

The totally enclosed Conversion Section is designed and constructed to NEMA 4 / IEC IP65 to house the Inverter Modules, AC Filters, AC Contactor and Pre-Charge Circuits, DC Filters, Main DC Contactors and the DC Fused Isolation Switches. Conversion of power from DC to AC and AC to DC is by inverter type, Power Electronic Building Blocks (Inverter PEBBs). There is one inverter module for each UltraBattery® string.

iii) Control/Cooling Section

The totally enclosed Control/Cooling Section is designed and constructed to NEMA 4 / IEC IP65 to house the programmable controller, the closed loop cooling circuit, and AC circuits to power the PCS and battery pre-charge circuit. Closed loop cooling through an external liquid to air heat exchanger is used to cool the inverters. An externally mounted air conditioning unit is used to maintain the internal ambient temperature in the EHouse at 40°C to maximize life of the PCS components.

Grid Connection and Switchgear

The PCS is connected to an existing 13.2kV bus that is connected to the utility's 69kV subtransmission system through a 69kV/13.2kV oil filled transformer. The secondary of this transformer is connected to a 13.2kV feeder breaker and the PCS wiring that runs underground and enters the PCS from the bottom.

Data Measurements & Data Acquisition

System data measurements are provided as part of the vendor-supplied system from Ecoult. This system logs around 150kB of system variable data each hour and the data is logged to an Ecoult fileserver that is remotely located from the project system. Therefore, the data logs are not dependent on any on-site archive capability. Most data is low-level system monitoring data and the points that are applicable to the project TPR are the following:

2sec sampling
PJM regulation control signal
PJM regulation response signal
AC Power Flow to/from PCS (MW)
10sec sampling
Operational mode, including manual modes
State of Charge (SoC) of entire battery of the BESS

The AC Power Flow to/from the system is measured by a 13.2kV revenue-grade meter – model specified by the local connection authority, Met-Ed. This meter is located at the 13.2kV PCS grid connection point.

The PJM regulation control signal is supplied by a PJM-defined Supervisory Control And Data Acquisition (SCADA) interface unit. The PJM regulation response signal is generated by the Ecoult control system. The AC Power Flow equals the PJM regulation response signal plus any power drawn by the system to provide for system losses.

Demand management was never called for by Met-Ed during this project. Demand management operations was planned to be implemented by a manual charge and discharge at requested durations and power levels.

New Storage Block #3

The new storage block is composed of 6 parallel strings of 80 12UB700 batteries. Ecoult developed a new monitoring and control system for the 12V storage block and integrated with the existing system controller. Based on experience gained through the initial part of the project, a new racking system was designed to facilitate better battery temperature consistency through passive cooling. The experience in operating the 12V storage block will be discussed at the end of section 4 of the report.

Figure 6. Storage Block #3 utilizing new rack design and new battery design.

3. Description of Analysis Methodologies

3.1 Analysis Objectives

The primary objective of this project is to demonstrate the economic and technical capability of UltraBattery® technology to provide frequency regulation ancillary services to PJM. Frequency regulation maintains the system frequency by matching load and generation in real time. To provide frequency regulation in the PJM area, a resource will follow a regulation signal provided by PJM. This demonstration system follows PJM's dynamic regulation signal (RegD).

As a secondary objective, the project has the capability to provide the local utility (Met-Ed) with demand management. This service was available to Met-Ed beginning in the second year of the project, but was never utilized.

The following metrics will be utilized to assess this project's technical and economic capability in the frequency regulation market:

- **Regulation Services - Average Energy Storage Efficiency**
  Round trip efficiency of demonstration system while operating in frequency regulation mode. Metric will be calculated using 13.2kV revenue meter power flows in/out logged to a database.

- **Regulation Services – Average Energy Storage Accuracy**
  Accuracy of the energy storage system will be determined by the PJM performance score. This score will be calculated at the end of each month as the percentage of credited MW*h compared to bid MW*h.

- **Regulation Services - Annual Storage Dispatch**
  Accumulated MW*h of ancillary services provided in a year. The metric will be derived by East Penn based on system logs.

- **Regulation Services - Average Power Level**
  Magnitude of the average power level experienced during frequency regulation operation. The calculation will be performed using Power Converter (PCS) power logged to a database.

- **Regulation Services - Capacity Turnover/Day**
  Daily charge energy accepted is reported as a percentage of system capacity. Turnover will be calculated using PCS power logged to a database.

- **Regulation Services - Auxiliary Loads**
  Power consumption of the support equipment, HVAC, lighting, etc, is logged by East Penn using a separate meter.

- **Capacity**

Total energy capacity of the system is measured periodically throughout the project life. Capacity will be calculated using PCS power logged to a database while the system is taken through a full charge /discharge cycle.

- **Response Time**
  The measured time from receipt of a 3MW PJM command until the system's response is held within 2% of 3MW. The calculation will be performed using PCS power and PJM requested power logged to a database during PJM qualification tests.

- **Cell Resistance**
  The resistance of each cell will be periodically measured by East Penn to indicate the health of the cells.

- **Cell Temperature Range**
  The temperature range between the warmest and coolest cells in the stack is recorded.

3.2 Methodologies for Determining Technical Performance

In the following descriptions of the calculations, the relevant system variables from the logged data are in bold.

The cost figures are from East Penn's accounts and from Noble Energy Solutions' accounts of the regulation service benefits to PJM. The system implementation costs are split into one-time, specific to the demonstration site and costs associated with a replicate system at a new site. The latter is more relevant to a commercial basis of operation.

The average power level of the system during regulation services mode or load shifting is determined by an average of the **AC Power Flow**.

System capacity in MWh is determined periodically by running the system through a full discharge, charge and discharge cycle and integrating the **AC Power Flow** output over time for the final discharge phase.

System uptime, downtime due to SoC limit, and system faults are determined by analysis of the time spent in each **Operational Mode**.

The capacity turnover per day is determined by the following formula:

$$\text{Capacity Turnover} = \frac{\text{Charge Energy}}{\text{3MWh} \bullet \text{Measurement Period}}$$

Measurement Period is in days and Charge Energy is in MWh.

The efficiency when providing regulation services or demand management is determined by the following formula:

$$MWh_{comp} = \left(SoC_{start} - SoC_{end}\right) \bullet 3MWh$$

$$\eta = \frac{MWh_{out} + MWh_{comp} \bullet \sqrt{\eta}}{MWh_{in}}$$

SoC_{start} is system **State of Charge** at beginning of test
SoC_{end} is system **State of Charge** at end of test
MWh_{comp} is an adjustment factor added to make SoC_{end} equal to SoC_{start}
MWh_{out} is integrated **AC power flow** out of the system
MWh_{in} is integrated **AC power flow** into the system
η is system efficiency

This calculation assumes that input/output efficiency to SoC is split and this simplification is acceptable if MWh_{comp} is not a dominant factor in the calculation.

The calculation of losses when providing regulation services or demand management are similar to the above where:

$$losses = MWh_{in} - \left(MWh_{out} + MWh_{comp} \bullet \sqrt{\eta}\right)$$

The auxiliary power losses are determined by separate power metering on the auxiliary power to the system.

The response time of the system was determined from the AC Power Flow during the PJM system acceptance test. The PJM test at the time of system commissioning was based on a rectangular test waveform consisting of an idle period, full-power, back to idle, negative full-power, and back to idle test. The system data logs allow calculation of both a response time and provision of a raw response waveform figure.

Projected Performance Parameters

The major performance factor that requires projection beyond project completion is the longevity of the system components. This allows comparison of the energy storage solution with existing or other emerging technologies.

The PCS and other system components, aside from the UltraBattery® energy storage, have known longevity characteristics designed for the 10-20 year life spans required by utility customers. The duration of the smart grid demonstration project was not sufficient to provide relevant visibility into longer-term longevity for the UltraBattery® cells but East Penn will continue to operate the facility beyond the project conclusion and to gather further results around longevity performance to combine with their own accelerated life and cell testing on the UltraBattery® and that which has been performed by other parties such as Sandia, CSIRO, Furukawa, and Ecoult.

3.3 Methodologies for Determining Grid Impacts and Benefits

Specific smart grid benefits supported by East Penn's Energy Storage Project and aligned with the DOE are:

- **Ancillary Service Revenue**

  The PJM Regulation Market Clearing Price (RMCP) during periods of operation is used to determine Ancillary Service Revenue.

- **System Costs**

  The installation and operating costs associated with this demonstration project will be reported. The long-term maintenance costs will be estimated.

- **Optimized Generator Operation**

  The small scale of this demonstration project will not be sufficient enough to influence the PJM RMCP; however, if a large proportion of regulation services was based on the UltraBattery® BESS technology, the overall regulation capacity required will decrease.

- **Reduced CO_2, SO_X, NO_X, and PM-2.5 Emissions**

  The CO_2 emissions calculation is not based on direct system measurements. When in demand management role, the emissions associated with generation mix during charging periods will be compared to the generation mix during discharge (peak demand) periods to estimate reduction in emissions. When in ancillary services mode, the emissions associated with operation of gas turbine at lower operating point (lower efficiency) are used to estimate reduction in emissions. The percent allocation for representative sample days of summer peak demand days over 24 hours will be recorded. The values will be averaged for a 24-hour 'summer' mix and used to determine relative emissions during the charging versus the discharge periods. Round-trip efficiency of the energy store is also included. The generation mix for different days and gas turbine emissions will be taken from industry publications.

- **Demand Management Revenue**

  Demand Management was never called for by Med-Ed, therefore there is no revenue from this application.

4. Technology Performance Results

In this demonstration project, the BESS has been operating to provide frequency regulation to PJM. The system follows PJM's dynamic regulation signal, RegD. Over the course of the demonstration, the system has been operating at various power levels and durations. Although the majority of operation covered in this report is at 2.0 or 2.4MW, the system has been operated in the PJM's Dynamic regulation market up to 3MW. Figure 7 and Figure 8 illustrate the system's accuracy and range of charge while following a 3MW signal.

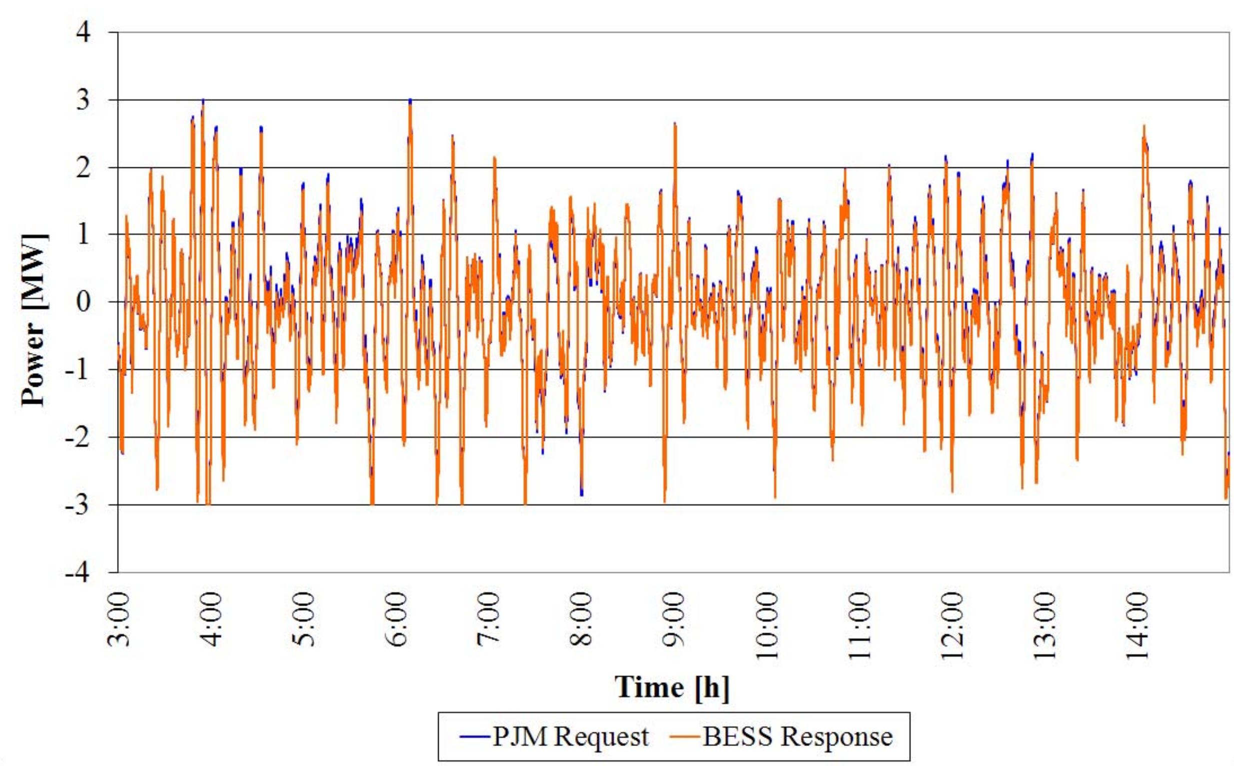


Figure 7. System's response to 3MW regulation signal.

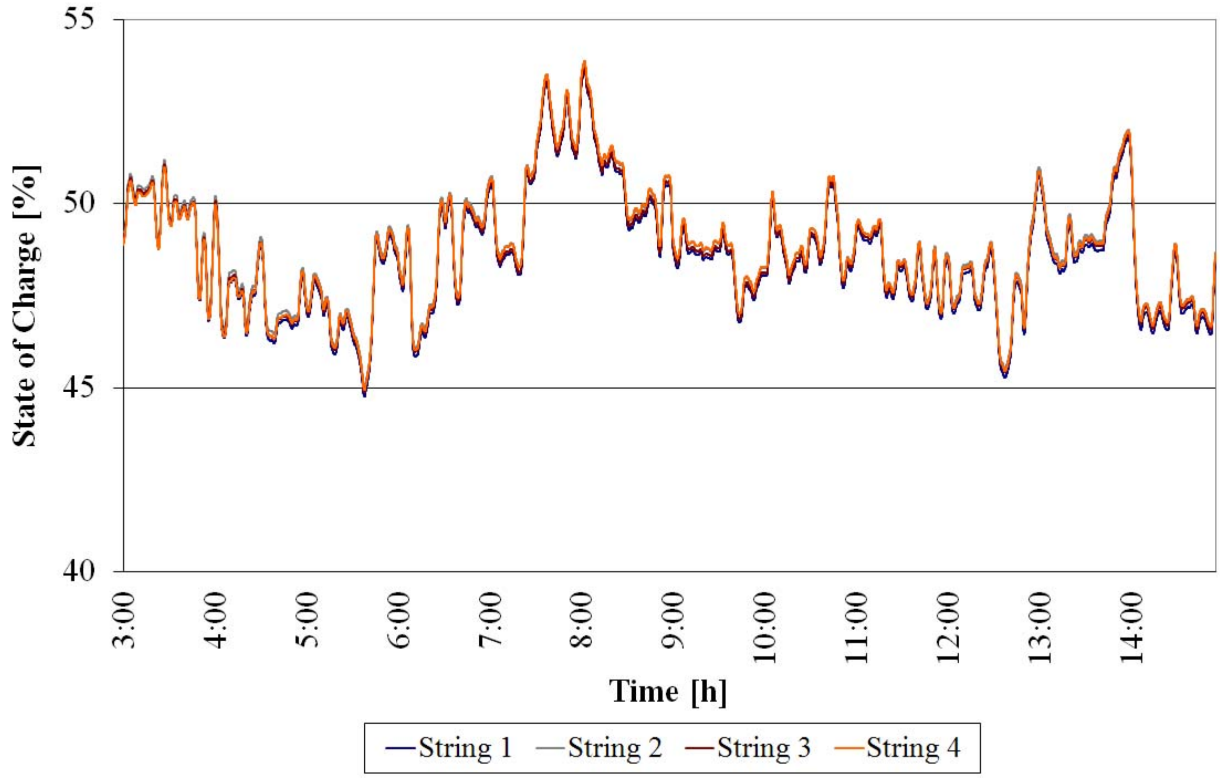


Figure 8. System's SoC range for regulation profile in Figure 7.

As shown in Table 3, the system operated in the PJM regulation market approximately 53% of the time from July 2012 through April 2015. The majority of the time the system was offline was scheduled downtime primarily to test operational enhancements including methods to manage air flow to bring the temperature of the cell rows during operation into tighter alignment. Additionally the system was initially operated for 8 hours a day while gathering experience and gradually ramped to continuous operation.

Table 3. Breakdown of system time

Metric	Results
Regulation Services – total regulation-time	53.4%
Regulation Services – SoC limit down-time	0.0%
Regulation Services – scheduled offline time	38.0%
Regulation Services – planned maintenance down-time	4.3%
Regulation Services – fault down-time	4.3%

Over the reporting period, several issues leading to interruption in regulation service have been identified. Shown as faults in Table 3, these events accounted for less than 5% of total project time.

Battery Storage

False alarms occurred due to: (i) noise pickup of sensing lines from power circuits; (ii) use of a smoke detector that was unsuitable for battery room environments. The noise pickup has been resolved by improved noise immunity of alarm sensing inputs, and the smoke detectors have been replaced.

Wiring/sensor issues and system controller issues were experienced and have been reduced significantly. In particular challenges had to be overcome around using a CAN-bus with the long strings. (Resolved)

Cell under/over-voltage alarms are related to the temperature management of the cells. As noted previously, PJM increased the energy density of the signal with the introduction of Dynamic Regulation (by about 20%) after the system was designed. This had an effect of increasing the range of cell temperatures within a string, compounded by the use of the standard racks which resulted in higher temperatures in the higher rows. East Penn and Ecoult investigated a number of options for temperature management discussed later in this section.

Power Conversion System

The power converter faults were due to initial hardware issues followed by noisy communication signals between the PCS and BESS.

PJM Communications

PJM communication faults indicate a loss of communication with PJM, which initially required manual intervention to resume system operation. Various improvements have been made on both the EPM/Ecoult software and on the PJM system to the point where manual intervention is not required and communication is normally restored within 5 minutes.

Average Energy Storage Efficiency

Table 4 shows a summary of operation and AC-AC efficiencies (recorded by the revenue meter) for each month from commissioning in July 2012 through the end of the project in April 2015. The average AC-AC efficiency of the system was calculated to be 80.6%. The low efficiency months are due to short run times, where small SoC inaccuracies and variations in the net energy of the PJM signal are magnified, or low operational power where the core losses of the transformer are a higher percentage of the total energy input.

Table 4. Operation summary and efficiency calculations for regulation runs.

Month	Run time [hrs]	Avg. Regulation Operation Level [MW]	AC-AC Efficiency
Jul-12	45	2.5	71.9%
Aug-12	263	2.4	77.2%
Sep-12	273	2.0	83.1%
Oct-12	272	1.5	81.7%
Nov-12	221	1.4	81.1%
Dec-12	345	2.0	82.2%
Jan-13	129	1.1	83.8%
Feb-13	420	2.1	81.1%
Mar-13	686	2.0	81.6%
Apr-13	450	2.0	82.9%
May-13	54	2.0	81.4%
Jun-13	602	2.0	81.4%
Jul-13	468	1.8	81.1%
Aug-13	719	2.1	80.8%
Sep-13	503	2.0	81.2%
Oct-13	159	2.0	84.0%
Nov-13	707	2.2	81.1%
Dec-13	627	2.3	80.5%
Jan-14	573	2.2	81.3%
Feb-14	406	2.4	80.8%
Mar-14	652	2.4	81.0%
Apr-14	558	2.2	80.7%
May-14	633	2.1	80.4%
Jun-14	352	0.6*	75.4%
Jul-14	237	1.5*	81.2%
Aug-14	358	1.2*	79.0%
Sep-14	574	1.7*	79.8%
Oct-14	367	1.2*	79.6%
Nov-14	385	0.6*	75.3%
Dec-14	390	1.1*	79.2%
Jan-15	116	0.4*	71.7%
Feb-15	214	1.2*	83.1%
Mar-15	175	1.2*	81.5%
Apr-15	68	1.0*	82.8%
Totals	**13,001**		
Averages		**1.8**	**80.6%**

*Lower operating rates in the orange highlighted period were due to the preparations for replacement of Block3 with the new storage block using the 2nd generation 12UB700. During this period access to the battery room was needed for construction and typically only 1 or 2 strings were available for operation.

Average Energy Storage Accuracy

The accuracy of the frequency regulation system is measured using the performance score calculated by PJM. PJM calculates an hourly score for each resource ranging from 0-100%. From the time PJM began calculating performance scores in October 2012, the PJM performance score has averaged 94.2% as shown in Table 5. During normal operation, there is a small percentage difference between the PJM signal and the system's response to account for losses and to maintain the system's SoC. Some performance scores are lower than expected due to the fault and alarm issues previously described; however, typical performance scores are expected approximately 96-98%.

Table 5. Monthly PJM performance scores

Month	Avg. PJM Performance Score [%]
Oct-12	91.3%
Nov-12	94.3%
Dec-12	81.4%
Jan-13	92.5%
Feb-13	96.5%
Mar-13	97.2%
Apr-13	96.3%
May-13	91.0%
Jun-13	95.2%
Jul-13	81.8%
Aug-13	98.7%
Sep-13	97.9%
Oct-13	97.8%
Nov-13	97.9%
Dec-13	89.5%
Jan-14	95.5%
Feb-14	92.2%
Mar-14	93.4%
Apr-14	95.3%
May-14	92.6%
Jun-14	91.4%
Jul-14	96.1%
Aug-14	96.0%
Sep-14	92.8%
Oct-14	92.9%
Nov-14	76.7%
Dec-14	80.3%
Jan-15	N/A
Feb-15	92.1%
Mar-15	98.1%
Apr-15	98.0%

Project Average	94.2%

Annual Storage Dispatch

The data indicates a round-trip AC-AC efficiency figure of 80.6% and an average regulation level of 1.8MW. In a commercial system, this 1.8MW average, with an assumed performance score of 96% and 90% availability, would result in an Annual Storage Dispatch figure of 13,623 MW*h of regulation service.

Regulation Services - Average Power Level

The average power level is calculated from AC data logged by the PCS. While operating at a frequency regulation level of 2MW, the system's average power level is approximately 520kW or 130kW per string. When the system provides its rated 3MW of regulation, the average power level is approximately 780kW or 195kW per string.

Regulation Services - Capacity Turnover/Day

Energy data logged by the PCS is used to calculate the daily capacity turnover. The average daily capacity turnover while operating at 2MW is 240%. Daily capacity turnover for 3MW operation is 360%.

Regulation Services - Auxiliary Loads

Auxiliary loads are measured using a separate meter that records power provided to HVAC, lighting, controls, and management systems. The installation of the auxiliary meter was completed in February 2013. During operation from February 2013 to April 2015, average system auxiliary loads were calculated to be approximately 12.3% of the total energy required by the system as shown in Table 6. Several months the system was operated at reduced rates using only one or two strings, increasing the average auxiliary loss percentage. Performing the same calculation for months where the average operation was above 2.0MW gives average auxiliary loads as approximately 9.2%.

Table 6. Auxiliary loads calculations

Month	Avg. PJM Bid [MW]	AC-AC Efficiency	Auxiliary Loads	System Efficiency Including Aux Loads
Jul-12	2.5	71.9%	-	-
Aug-12	2.4	77.2%	-	-
Sep-12	2.0	83.1%	-	-
Oct-12	1.5	81.7%	-	-
Nov-12	1.4	81.1%	-	-
Dec-12	2.0	82.2%	-	-
Jan-13	1.1	83.8%	-	-
Feb-13	2.1	81.1%	7.1%	75.4%
Mar-13	2.0	81.6%	7.4%	75.6%
Apr-13	2.0	82.9%	7.8%	76.5%
May-13	2.0	81.4%	10.8%	72.6%

Jun-13	2.0	81.4%	10.8%	72.6%
Jul-13	1.8	81.1%	13.4%	70.5%
Aug-13	2.1	80.8%	11.9%	71.2%
Sep-13	2.0	81.2%	10.5%	72.5%
Oct-13	2.0	84.0%	8.8%	76.7%
Nov-13	2.2	81.1%	7.3%	75.3%
Dec-13	2.3	80.5%	9.4%	72.9%
Jan-14	2.2	81.3%	8.8%	74.1%
Feb-14	2.4	80.8%	7.8%	74.4%
Mar-14	2.4	81.0%	7.7%	74.7%
Apr-14	2.2	80.7%	10.3%	72.5%
May-14	2.1	80.4%	11.2%	71.3%
Jun-14	0.6	75.4%	26.0%	55.9%
Jul-14	1.5	81.2%	15.8%	68.2%
Aug-14	1.2	79.0%	20.3%	63.6%
Sep-14	1.7	79.8%	14.8%	68.2%
Oct-14	1.2	79.6%	15.7%	67.1%
Nov-14	0.6	75.3%	22.6%	58.5%
Dec-14	1.1	79.2%	17.0%	66.1%
Jan-15	0.4	71.7%	46.6%	38.8%
Feb-15	1.2	83.1%	20.8%	64.1%
Mar-15	1.2	81.5%	17.2%	67.6%
Apr-15	1.0	82.8%	15.4%	70.3%
Averages	**1.8**	**80.6%**	**12.3%**	**70.7%**

Response Time

The PJM qualification tests were successfully completed on June 5, 6, and 12, 2012. An example of the PJM test profile and system response is shown below in Figure 9. Since this project's commissioning, PJM has revised their qualification test for RegD to make it more representative of the dynamic signal.

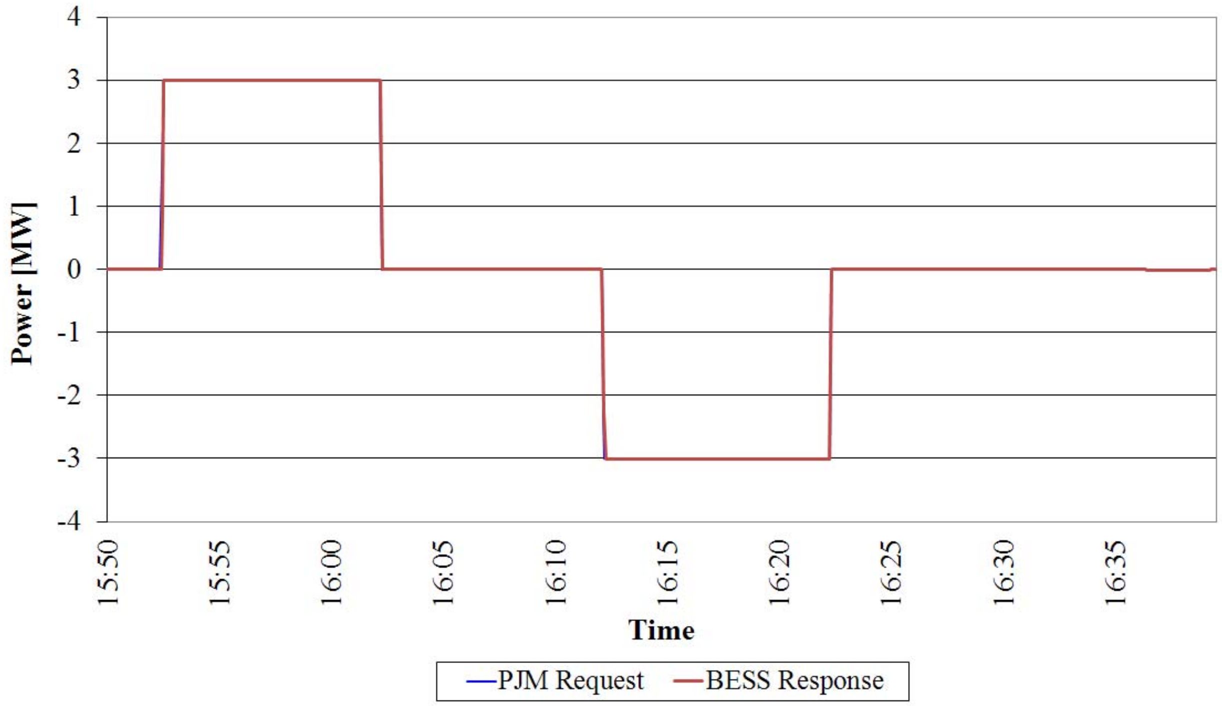


Figure 9. Example of PJM qualification test performed.

Using PCS power data and the PJM command signal, logged every 2 seconds, the response time of the system to a 3MW command was determined to be less than 4 seconds, or 0.75MW/s. The response time was determined by a rate limit on the PCS as well as latency in the system controller and communications. The system response is more than sufficient to provide very accurate dynamic frequency regulation as the high PJM performance scores indicate. UltraBattery® systems are capable of a much faster response and have recently demonstrated 50ms response time in another project.

The ramp rate requirements of the PJM RegD signal were analyzed for January 2014, one of the more aggressive months due to particularly cold weather and natural gas shortages. Figure 10 shows a histogram of ramp rates the demonstration system experienced while operating that month, normalized to 1MW. The maximum ramp rate was 0.1 MW/s, occurring less than one thousandth of one percent of the time. Over 90% of the time ramp rates were below 0.1MW/s.

Scaling the ramp rate of 0.1MW/s for a 1MW system to a 3MW system equates to 0.3MW/s, less than 50% the measured ramp rate for this demonstration system.

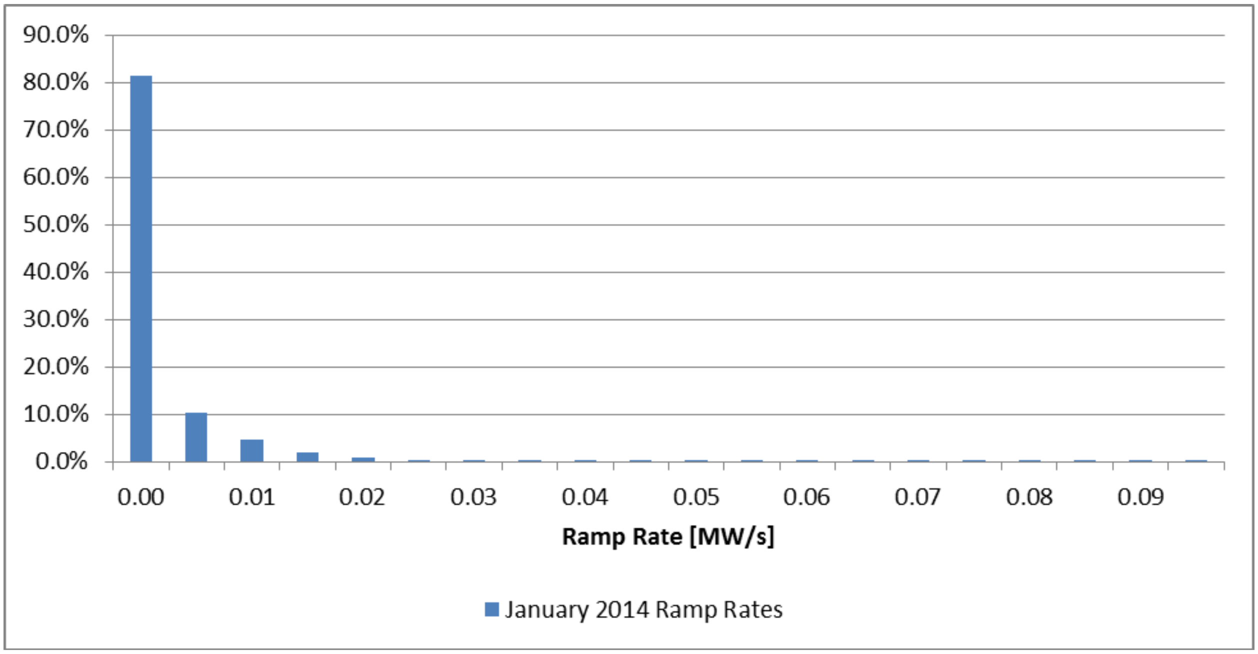


Figure 10. Histogram of PJM RegD ramp rates for 1MW signal in January 2014.

Cell Resistance

Cell resistance measurements are periodically taken on every cell in the system as a measure of the health of each cell. The first set of measurements occurred before commissioning. The latest measurements were performed in December 2014. Figure 11 shows the cell resistance trend up to this point.

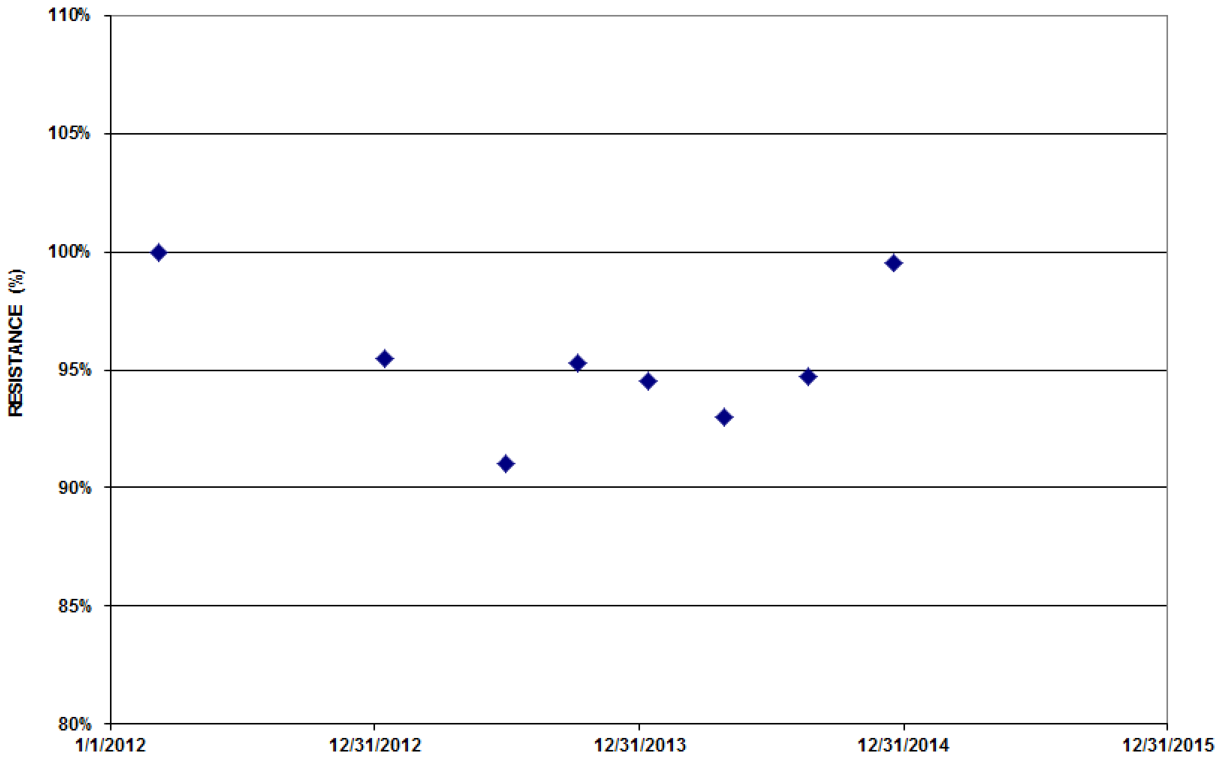


Figure 11. Measured cell resistance as a percentage of initial resistance.

Typically as cells age their resistance will increase; however, it is not uncommon to see resistances drop initially before they begin to increase. The average cell resistance is expected to continue to rise as the cells age.

Cell Temperature Range

The general rule for lead-acid batteries held on float is that every 10°C above room temperature will result in a 50% reduction of life. This follows from the Arrhenius equation, which describes the doubling of a chemical reaction rate for every 10°C above room temperature. In the case of batteries on float, the relevant reaction is the rate of corrosion of the positive grid. The rate of positive plate corrosion is a function of several factors in addition to temperature but particularly it is a function of voltage. UltraBattery® technology is operated in the pSoC region where average voltage is lower than that of a battery held on float. EPM and Ecoult have ongoing tests aimed at discovering the impact of temperature on the life of the UltraBattery® in the pSoC.

Participating in the PJM frequency regulation market, the system is continuously responding to charge and discharge commands from PJM. The system operates at an average power level of 520kW, as reported above, leading to increased cell temperatures when compared to an idle system.

As well as absolute temperature being a relevant factor, the variation in temperature of individual cells in a string is considered relevant as it may result in individual cells aging at different rates. Cell temperature deltas within a stack of 10 cells were measured to be 14°F when the project was first commissioned. Cell temperatures in the high/middle of the stack were the warmest while the uppermost row and lower rows were the coolest.

Efforts were initiated to identify the causes of the cell temperature differentials and to provide solutions to reduce the delta over the stacks. Several solutions were implemented, and the range of cell temperatures was reduced to under 4°F.

Future UltraBattery® installations will utilize temperature management methods identified in this project to minimize cell temperature differentials.

East Penn generates weekly reports to track system performance and document system issues that do not allow the system to run within the scheduled parameters. An example of the report is shown in Figure 12.

Weekly Operation Report

March 11, 2013 to March 17, 2013

Availability

$$Availabilty = \frac{hours run}{hours\ scheduled}$$

**168 hours in a week*

Scheduled Hours	System Hours Run	String 1 Hours	String 2 Hours	String 3 Hours	String 4 Hours
168	168	168	168	168	168
Availability	100%	100%	100%	100%	100%

Performance

$$Performanc\ e = \frac{MW * h\ delivered}{MW * h\ possible}$$

Where: *MW*h is 1MW of regulation for 1 hour*
Maximum regulation level is 3MW

Max System MW*h	System MW*h delivered	String 1 MW*h Delivered	String 2 MW*h Delivered	String 3 MW*h Delivered	String 4 MW*h Delivered
504	336.0	84.0	84.0	84.0	84.0
Performance	67%	67%	67%	67%	67%

Weekly Schedule

	Scheduled Hours	Hours Run	Rate [MW]	Description
Monday 3/11/13	24	24	2	–
Tuesday 3/12/13	24	24	2	–
Wednesday 3/13/13	24	24	2	–
Thursday 3/14/13	24	24	2	–
Friday 3/15/13	24	24	2	–
Saturday 3/16/13	24	24	2	–
Sunday 3/17/13	24	24	2	–

Fault Description

Fault Description	Date/Time	Reduced Availability (h)	Action
--	–	–	–

Figure 12. Example of the Weekly Operation Reports.

New 12UB700 Storage Block (SB3)

PNNL Frequency Regulation Profile

As part of the commissioning process of the new Storage Block, the 24hr profile outlined in the PNNL Energy Storage Protocol was run on Storage Block #3 (SB3) to verify short term operation following a regulation profile. The 12UB700 batteries ran the profile very well as illustrated in Figure 13. The figure shows a 6 hour segment of that operation covering both average and aggressive portions of the profile.

The AC-AC efficiency of the Storage Block for this run was calculated to be 79.3% using the methods described in section 3. This is slightly lower than the average efficiency of the 2V strings over the course of the project. However, it is approximately 4% higher than the months where the 2V strings were operated at an equivalent rate (0.6MW).

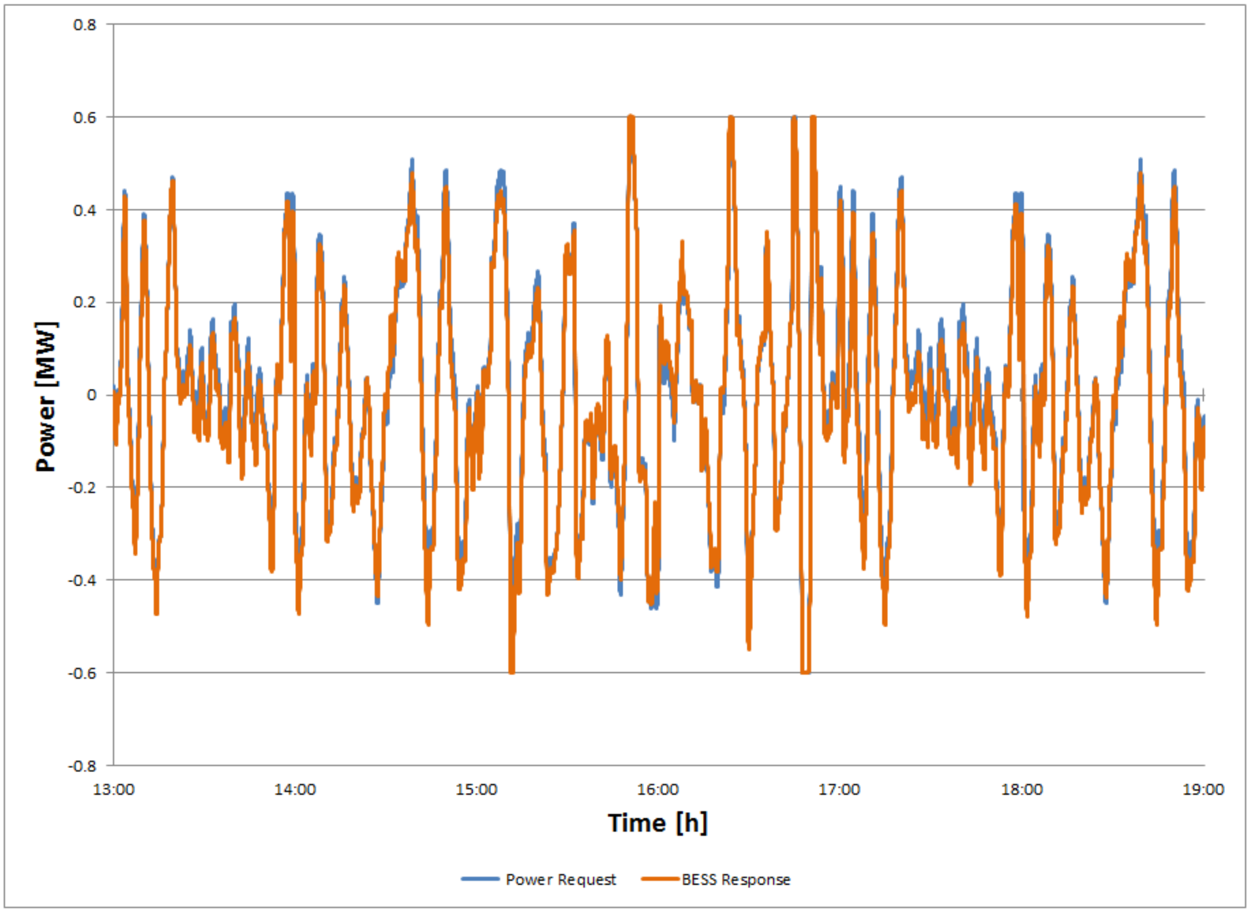


Figure 13. PNNL Energy Storage Frequency Regulation profile on Storage Block #3.

<u>PJM Frequency Regulation Operation</u>

An example of SB3 operating in the PJM market is shown in Figure 14. Similar to the PNNL profile in Figure 13, the new storage block follows the signal very well, with only small deviations from the PJM command. As with the 2V system, these inaccuracies are due to the control system working to maintain the system SoC in its optimal range and enable appropriate response to charge and discharge commands.

The average AC-AC efficiency of SB3 while operating in the PJM market was calculated to be 78.9%. As with the PNNL profile, this is slightly lower than the average efficiency of the 2V, but higher than the periods the 2V system was operated at the same power level. If all strings were replaced with 12UB700 batteries, the average efficiency is expected to increase.

As mentioned previously, when a single string is operated, AC-AC efficiency is expected to decrease because transformer core losses are no longer distributed among the 4 storage blocks. Assuming 25% of measured core losses (as would be the case when all 4 storage blocks are operating), the AC-AC efficiency of 78.9% rises to approximately 83%.

The average performance score of SB3 as calculated by PJM is 94%. This is slightly lower than expected, however there were several PJM communication issues that reduced the overall performance score. The range of performance scores during normal operation is from 94.4%-98.8% with the average being 97.7%.

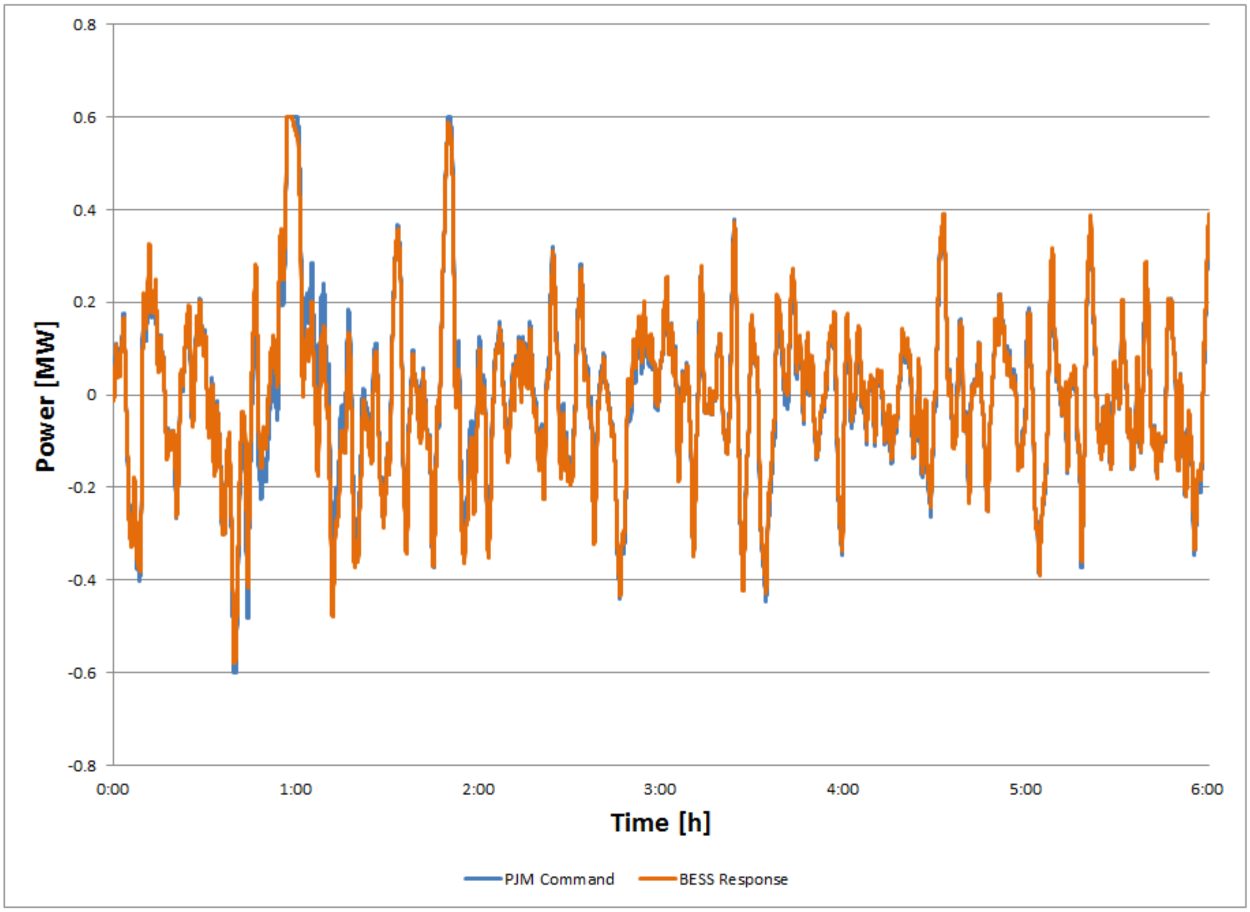


Figure 14. PJM Frequency regulation profile running on Storage Block #3.

<u>PJM Frequency Regulation Operation – 800kW</u>

In addition to running at 600kW, the system was also operated 800kW, or 1.4 times the one hour rate. Figure 15 provides an example of 6 hours of operation in the PJM market at 800kW. Over the period of operation at 800kW, the AC-AC efficiency of the system was calculated to be 78.3%, slightly lower than the same system operating at 600kW, but in line with system efficiencies calculated throughout the project.

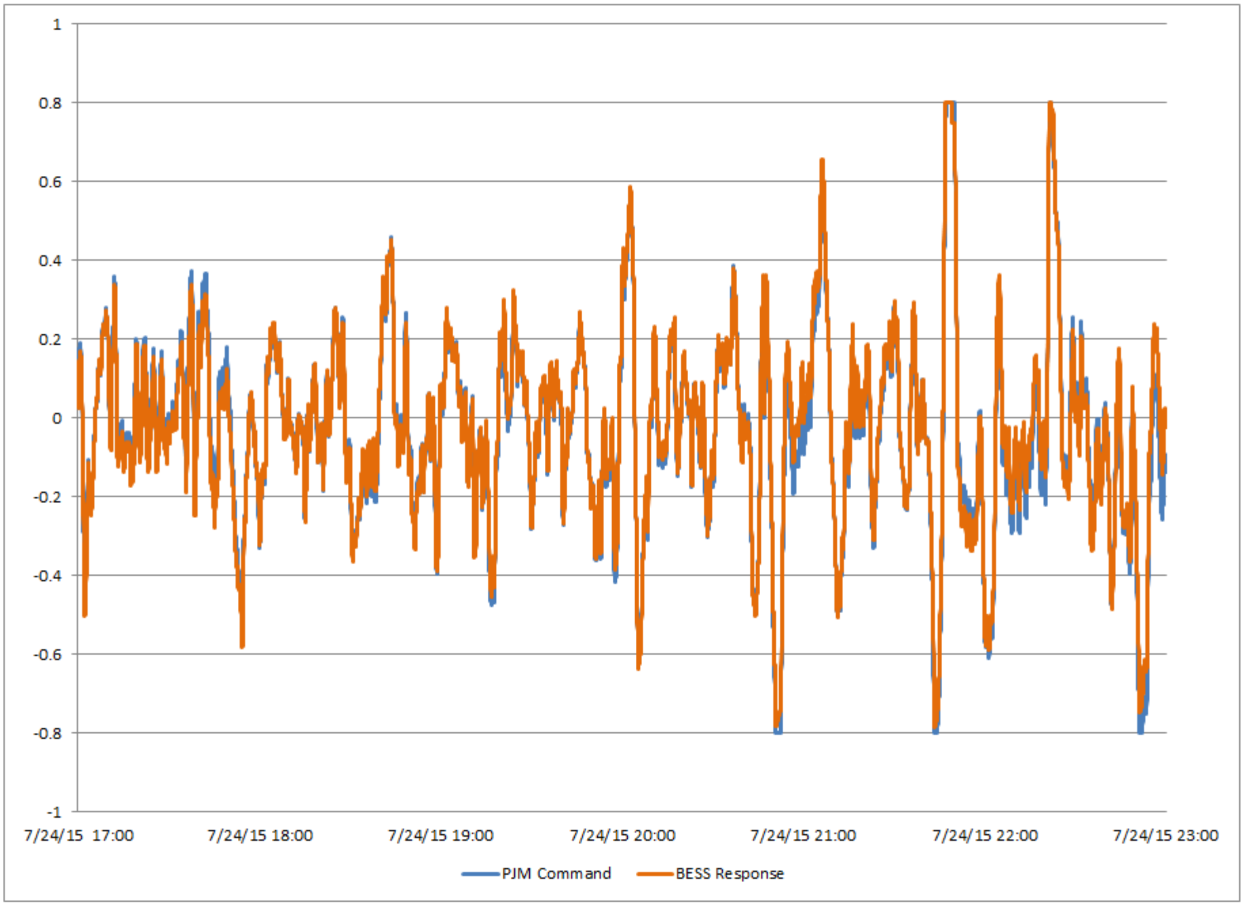


Figure 15. PJM Frequency regulation profile running on Storage Block #3 at 800kW.

<u>UltraRax for 12UB700</u>

Ecoult developed a new rack design, shown in Figure 6, to better manage battery temperatures via passive cooling. In addition to passive air flow, fans are included to increase air flow should battery temperatures exceed their temperature or variation threshold. The initial results show battery temperatures were maintained below 100°F during peaks, with average battery temperatures of the warmest string being just above 90°F.

5. Grid Impacts and Benefits

Ancillary Services Revenue

Since the start of this project, PJM has created a new class of regulation service, Dynamic Regulation.

Beginning in October 2012, under Dynamic Regulation (RegD) the payment scheme for an energy storage system has been revised. This payment structure includes a Regulation Market Capability Clearing Price (RMCCP) component and a Regulation Market Performance Clearing Price (RMPCP) component. The change recognizes that a more accurate resource provides additional benefits to the grid. Table 7 shows the project's PJM payments for the period July 2012 through April 2015. The last column of Table 7 depicts the average payment for providing 1MW (capability) of regulation services for one hour with 100% PJM performance score.

Table 7. PJM regulation payments.

Month	Payment	MW*h	Avg Payment per MW*h
Jul-12	$ 1,742.59	108.9	$ 16.00
Aug-12	$ 10,758.69	621.7	$ 17.31
Sep-12	$ 7,056.22	542	$ 13.02
Oct-12	$ 15,193.39	355	$ 42.77
Nov-12	$ 12,664.15	289	$ 43.76
Dec-12	$ 13,168.47	521	$ 25.29
Jan-13	$ 7,687.90	138	$ 55.63
Feb-13	$ 22,165.24	850	$ 26.07
Mar-13	$ 38,995.44	1329	$ 29.34
Apr-13	$ 21,571.24	871	$ 24.77
May-13	$ 6,293.65	104	$ 60.81
Jun-13	$ 31,821.30	1144	$ 27.81
Jul-13	$ 32,588.15	722	$ 45.16
Aug-13	$ 37,638.90	1449	$ 25.97
Sep-13	$ 22,570.80	965	$ 23.39
Oct-13	$ 6,118.52	299	$ 20.45
Nov-13	$ 42,857.22	1542	$ 27.79
Dec-13	$ 41,441.28	1258	$ 32.93
Jan-14	$ 228,928.10	1224	$ 187.05
Feb-14	$ 55,996.27	912	$ 61.38
Mar-14	$ 144,150.43	1489	$ 96.80
Apr-14	$ 43,083.56	1148	$ 37.54
May-14	$ 51,817.30	1256	$ 41.26
Jun-14	$ 6,354.07	181	$ 35.18
Jul-14	$ 14,071.50	345	$ 40.83
Aug-14	$ 10,188.51	398	$ 25.62
Sep-14	$ 27,186.82	891	$ 30.51
Oct-14	$ 16,348.66	422	$ 38.73
Nov-14	$ 5,520.25	168	$ 32.78
Dec-14	$ 8,647.93	319	$ 27.10
Jan-15	$ 1,269.21	42	$ 30.04

Feb-15	$ 20,879.26	249	$ 83.95
Mar-15	$ 8,541.71	180	$ 47.44
Apr-15	$ 3,368.26	67	$ 55.55
Totals	**$ 1,018,684.99**	**22,401**	
Averages			**$ 45.48**
Average Oct 12-Apr 15			**$ 47.29**

The average payment received from October 2012 through April 2015 is $47.29 per MW*h.

The average payment per MW*h (after Oct. 2012) together with the Annual Storage Dispatch figure of 13,623 MW*h (calculated in Section 4) provides an expected annual revenue of $619,574 for a commercial system operated at 1.8MW.

System Costs

The combined cost of equipment and installation from project start to July 2012 is reported in Table 8.

Table 8. Equipment and installation costs

Components	Cost
Battery	$ 1,416,709
Power Conversion System	$ 1,186,910
Building	$ 593,248
CUBS	$ 436,040
Balance of Plant	$ 421,292
Total	$ 4,054,199

Maintenance and labor costs for the demonstration system have been tracked and are reported in Table 9. Additional labor costs from scheduling and monitoring are not included. Costs are split into pilot costs (associated with a smaller one-off demonstration project) and long-term costs for replicated commercial systems. A pilot system often incurs more development costs so the long-term costs are more indicative of future commercial systems.

Table 9. Summary of operating costs for demonstration system.

Metric	Value	Results
Distribution Connection		
Equipment Failure Incidents	/kW-month	none
Maintenance Labor Cost – pilot	$/kW-month	none
Maintenance Material Cost – pilot	$/kW-month	none
Maintenance Labor Cost - long-term	$/kW-month	none
Maintenance Material Cost - long-term	$/kW-month	none
Power Converter		
Equipment Failure Incidents	/kW-month	0.000028; rupture of DI filter in PCS cooling system

Maintenance Labor Cost – pilot	$/kW-month	$0.06
Maintenance Material Cost – pilot	$/kW-month	$0.07
Maintenance Labor Cost - long-term	$/kW-month	$0.06
Maintenance Material Cost - long-term	$/kW-month	$0.07
Battery Storage		
Equipment Failure Incidents	/kW-month	none
Maintenance Labor Cost – pilot	$/kW-month	$1.28
Maintenance Material Cost – pilot	$/kW-month	$0.37
Maintenance Labor Cost - long-term	$/kW-month	$0.86
Maintenance Material Cost - long-term	$/kW-month	$0.08

In addition to the maintenance costs of the equipment, there are also electricity costs associated with auxiliary loads and energy purchased to offset losses in the system. The monthly energy costs during operation are shown in Table 10. Auxiliary load costs were estimated until the auxiliary meter was installed in February 2013. These costs are calculated using EPM's average cost of electricity over the period from July 2012 to April 2015.

Table 10. Operational energy costs.

Month	Reg. Energy Cost	Auxiliary Energy Cost	Total Energy Cost
Jul-12	$ 94.82	$ 94.59	$ 189.41
Aug-12	$ 873.32	$ 553.00	$ 1,426.32
Sep-12	$ 875.76	$ 659.72	$ 1,535.47
Oct-12	$ 772.50	$ 460.83	$ 1,233.33
Nov-12	$ 589.88	$ 386.34	$ 976.22
Dec-12	$ 1,225.80	$ 587.30	$ 1,813.10
Jan-13	$ 200.44	$ 228.68	$ 429.12
Feb-13	$ 1,790.45	$ 697.09	$ 2,487.54
Mar-13	$ 2,550.29	$ 1,130.28	$ 3,680.57
Apr-13	$ 1,545.60	$ 815.90	$ 2,361.49
May-13	$ 137.86	$ 139.52	$ 277.38
Jun-13	$ 2,296.42	$ 1,452.70	$ 3,749.12
Jul-13	$ 1,501.64	$ 1,296.61	$ 2,798.26
Aug-13	$ 2,663.77	$ 1,864.19	$ 4,527.96
Sep-13	$ 1,862.99	$ 1,169.75	$ 3,032.74
Oct-13	$ 385.11	$ 412.25	$ 797.36
Nov-13	$ 2,945.81	$ 1,055.50	$ 4,001.31
Dec-13	$ 2,396.18	$ 1,462.14	$ 3,858.32
Jan-14	$ 2,559.96	$ 1,303.39	$ 3,863.35
Feb-14	$ 1,922.36	$ 616.20	$ 2,538.56

Mar-14	$ 3,220.16	$ 384.76	$ 3,604.92
Apr-14	$ 2,435.64	$ 1,512.12	$ 3,947.76
May-14	$ 2,711.00	$ 1,702.97	$ 4,413.97
Jun-14	$ 531.02	$ 753.47	$ 1,284.49
Jul-14	$ 704.87	$ 692.94	$ 1,397.80
Aug-14	$ 895.68	$ 1,074.08	$ 1,969.77
Sep-14	$ 1,854.72	$ 1,655.06	$ 3,509.77
Oct-14	$ 847.97	$ 703.23	$ 1,551.20
Nov-14	$ 542.88	$ 718.98	$ 1,261.87
Dec-14	$ 769.60	$ 752.42	$ 1,522.02
Jan-15	$ 91.94	$ 415.35	$ 507.28
Feb-15	$ 470.22	$ 689.71	$ 1,159.93
Mar-15	$ 416.62	$ 409.83	$ 826.45
Apr-15	$ 105.31	$ 111.31	$ 216.62
Totals	**$ 44,788.58**	**$ 27,962.21**	**$ 72,750.80**

Optimized Generator Operation

A 2011 KEMA report, commissioned by PJM, found that including fast responding regulation resources can reduce PJM's overall requirement for regulation while maintaining the same system performance[1]. This is expected to lead to an overall reduction in system costs for procuring regulation. In fact, since the project's commissioning, PJM has reduced their regulation requirement from 1% to 0.7%, both on- and off-peak.

CO_2 Emissions and NOx Emission Reduction

As part of reporting to the DOE, the project's potential greenhouse gas reduction is estimated by a comparison against the baseline of providing the same services using conventional fossil-fuel generators. Reductions are estimated by comparing BESS losses with the additional losses a Combined Cycle Gas Turbine (CCGT) would see when operating at a reduced level to provide frequency regulation. Losses are then translated into CO_2 and nitrous oxide (NO_X) emissions based on typical emission levels for CCGT plants.

The reporting is to span both demand management and supply of ancillary services. The system did not provide demand management services to Met-Ed, only ancillary services. The ancillary services calculation is as follows:

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[1] KEMA Inc. December 2011, KERMIT Study Report. Web. August 27, 2013. http://www.pjm.com/~/media/committees-groups/task-forces/rpstf/postings/pjm-kema-final-study-report.ashx

The project is demonstrating round-trip efficiency of around 80%. For a 3MW system, the PJM signal requires approximately 10.7MWh of energy input over a 24-hour period. At 80% efficiency, losses are approximately 2.14MWh per day. Adding losses due to auxiliary loads gives a total loss of 3.46MWh per day. A 300MW Combined Cycle Gas Turbine (CCGT) providing ±30MW of frequency regulation would need to operate at 270MW or 90% of its full load capacity. When regulation services are provided by even high-efficiency fossil-fuel generators such as CCGT, the operation of such systems at the lower levels (90%) required to support regulation typically results in an efficiency drop of 1%[2]. Losses due to supporting regulation would be approximately 1% of 270MW. This is 2.7MW or 64.8MWh/day for ±30MW of regulation or 6.48MWh/day for ±3MW of regulation. Compare this 6.48MWh of losses with the 3.46MWh of losses through the East Penn UltraBattery® demonstration project. At typical CCGT emissions[3], a daily savings of 3.02MWh translates to approximately 1,100kg of CO_2 and 90gm of NOx.

Demand Management Revenue

The system has successfully performed several demand management tests discharging at 1MW for an hour and 0.25MW for four hours. Per the project plan, participation in the Met-Ed peak load market was scheduled for the second year; however, the system was not been called upon to perform this function.

[2] Sources of Flexibility and Their Limiting Factors: Conventional Power Generation. Web. December 18 2013. http://www.smartpowergeneration.com/spg/discussion/sources_of_flexibility_and_their_limiting_factors_conventional_power_generation

[3] Gas Fired Power. Energy Technology Systems Analysis Programe. Web. December 18 2013. http://www.iea-etsap.org/web/E-TechDS/PDF/E02-gas_fired_power-GS-AD-gct.pdf

6. Major Findings and Conclusions

UltraBattery® technology is well suited for providing dynamic frequency regulation service to (ISO/RTOs). The capability of UltraBattery® to operate in the partial state of charge (pSoC) region allows it to respond to both charge and discharge commands required to follow the dynamic regulation signal from PJM. By operating in the pSoC, this UltraBattery® regulation system is able to show high round-trip efficiencies. The fast accurate response of the system achieved very high performance scores as calculated by PJM.

The new performance based pricing structures introduced by PJM have led to higher revenues for accurate and fast responding regulation resources like the UltraBattery® system. In addition PJM has made pricing changes that factor the 'quantity of regulation' each resource provides into the payment.

Another major finding in this project is that the UltraBattery® does not produce significant amounts of H_2 during normal operation in the pSoC region. Limited H_2 evolution occurs in conventional lead-acid batteries at higher cell voltages typically when they are brought to 100% SoC or maintained on float. A test was performed to measure any H_2 expelled by the cells while following the frequency regulation signal. The results of the test confirmed that, while following the regulation signal and operating in the pSoC region, little to no H_2 was measured.

Lessons Learned

During operation, the range of individual cell SoCs was found to be larger than expected. This SoC variation lead to occasional cell voltage limits being exceeded, which temporarily took the system offline. Part of the issue was the initial alignment of cell SoCs which did not change significantly throughout the project. To prevent this from occurring in future projects, prior to operation, the batteries will be equalized. In addition, development is underway to allow for battery equalization during operation, to tighten up cell SoCs and maintain that tight grouping following equalization.

The 2V cells installed for this project had trouble operating continuously at the high rates demanded by the Dynamic frequency regulation application. The system was able to operate at the rated 3MW, however it was not able to maintain that level of operation continuously without occasionally exceeding individual cell temperature or voltage limits during peak power commands. The design of the batteries was revisited and a new format 12V battery, the 12UB700, was developed specifically for high rate pSoC applications. The US DOE supported EPM's proposal to replace a string of the 2V batteries with a storage block of the 12V technology. The new format 12V batteries will continue to be tested and will be deployed in future frequency regulation and other high rate pSoC applications.

Cell temperatures were observed to have a larger than desired range over a stack while operating in the frequency regulation market. While the maximum temperatures observed were around 100°F, the variation between the lower temperature cells (bottom of the stacks) and the higher temperature cells (middle of the stacks) was measured to be approximately 14°F. Through various trials, East Penn and Ecoult were able to reduce the variation to less than 4°F. The data and experience from these temperature trials was fed into the design of a new racking system for the new format 12V

UltraBattery® and will be implemented in future installations to ensure consistent cell temperatures throughout the system.

Some issues were experienced with incorrect temperature and voltage readings being reported to the battery management system. This caused string faults to occur when there was no real problem present. The cause of these faults was determined to be mechanical stress exerted on sensor wiring and transferred to the connectors to the battery management system. The system design for future installations has been revised to utilize more flexible wiring systems that do not transfer the mechanical stress to the connector and maintain a solid connection with the battery management system.

The project attained all of the project criteria that were set up at commencement, but with the consent of the DOE, EPM was able to travel further on the path to making UltraBattery® energy storage a cost effective, reliable, and standard solution for grid ancillary services by acting on the learning within the project period. This was accomplished by implementing corrections for the performance challenges noted above and installing the second generation 12UB700 device and enhanced racking/monitoring solutions to deliver higher service levels from smaller systems. East Penn Manufacturing is grateful for the assistance of the US Department of Energy which made this project possible and the contribution of all the partner participants.