SANDIA REPORT

SAND2015-5242
Unlimited Release
Printed June 2015

ARRA Energy Storage Demonstration Projects: Lessons Learned and Recommendations

Donald Bender, Raymond Byrne, and Daniel Borneo

A Study for the DOE Energy Storage Systems Program

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@adonis.osti.gov
Online ordering:	http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd
Springfield, VA 22161

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.fedworld.gov
Online ordering:	http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2015-5242
Unlimited Release
Printed June 2015

ARRA Energy Storage Demonstration Projects: Lessons Learned and Recommendations

Donald Bender, Raymond Byrne, and Daniel Borneo

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0576

Abstract

The American Recovery and Reinvestment Act (ARRA) of 2009 (Recovery Act) provided funding for 16 energy storage demonstration projects. The projects ranged in scope from feasibility studies and technology demonstrations to full-scale, operational energy storage plants. This investment had a significant positive impact on the grid-connected energy storage industry. The goal of this report is to summarize the lessons learned from the ARRA projects, and to make recommendations for future Department of Energy (DOE) investments. Information for this report primarily came from three sources: a questionnaire and interview with each project team; DOE energy storage program peer review presentations; and DOE reports required as part of the ARRA project. Some lessons learned were common to many projects. Development of standards, codes and protocols specific to energy storage systems will mitigate uncertainty over code compliance, streamline permitting, and should be a priority (especially related to safety). Removal of regulatory barriers that preclude optimal operation of an energy storage system with multiple applications would immediately enable further deployment (e.g., FERC standards preclude the marketing department from reliability activities). Maturity of the approach to monetization varies substantially between applications with frequency regulation as an ancillary service leading other applications. Finally, developers focused on ramp mitigation and time shifting envision a reference plant. This reference plant would scale up from the current demonstration systems and would lead to the deployment of 50 MW-scale peaker plants.

Acknowledgments

This research was sponsored by the American Recovery and Reinvestment Act (ARRA) of 2009 with oversight from the Office of Energy Delivery and Energy Reliability's Energy Storage Program at the U.S. Department of Energy. The authors would like to thank Dr. Imre Gyuk and his colleagues at the Energy Storage Program at the U.S. Department of Energy for their guidance in executing this effort. We also thank Susan Zamora Gorman for carefully reviewing the final draft. Ronald Staubly and Kim Nuhfer provided up-to-date project documents and contact information for the various demonstration projects. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

The authors are grateful for the feedback received from the ARRA energy storage demonstration projects. Contributors who provided information for this report are listed below.

Project	**Contributors**
Amber Kinetics	Ed Chiao, Seth Sanders
Aquion Energy	Ted Wiley
Beacon Power	Jim Arseneaux, Barry Britt
City of Painesville	Jeff McHugh
Detroit Edison	Haukur Asgeirsson
East Penn Manufacturing	Jeff Seasholtz, Jason Hoffman, Ralph Fegely
Enervault	Ron Mosso, Thomas Jahn, Craig Horne
Notrees Battery Storage Project	Matthew Johnson, Stuart Gibson
Premium Power	Doug Alderton
Primus Power	Andrew Marshall, Richard Brody, Charlene Lee
Pacific Gas & Electric	Michael Medeiros
PNM Prosperity	Jon Hawkins, Steve Willard
Seeo	Hany Eitouni, Ulrik Grape, Hal Zarem
SustainX	Ben Bollinger
Tehachapi Wind Energy Storage	Jay Rollo, Blake Chalson, Loic Gaïllac

Contents

List of Figures

List of Tables

Nomenclature

AC	alternating current
AES	AES corporation
AGC	Automatic Generation Control
AGM	Absorbed Glass Matt
Ah	Ampere-hour
AIT	Air Injection Test
ARRA	American Reinvestment and Recovery Act of 2009
ASME	American Society of Mechanical Engineers
BATT	Batteries for Advanced Transportation Technology
Bcf	Billion cubic feet
BESS	Battery Energy Storage System
BMS	Battery Management System
CAES	Compressed Air Energy Storage
CAISO	California Independent System Operator
CEQA	California Environmental Quality Assessment
CES	Community Energy Storage
COTS	Commercial Off-the-Shelf
CTC	Concurrent Technologies Corporation
DC	direct current
DNP	Distributed Network Protocol
DOD	Depth of Discharge
DOE	Department of Energy
DR	Demand Response
DRMS	Distributed Resource Management System
DTE	DTE Energy Company
EISA	Energy Independence and Security Act of 2007
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EV	Electric Vehicle
FEMA	Failure Modes and Effects Analysis

FERC	Federal Energy Regulatory Commission
FRRS	Fast-Responding Regulation Service
GC	General Contractor
HV	High Voltage
IR	Interconnection Request
ISO	International Organization for Standardization
ISO	Independent System Operator
kg	kilogram
kV	kilovolt
kW	kilowatt
kWh	kilowatt-hour
LCOE	Levelized Cost of Energy
LLC	Limited Liability Corporation
LMP	Locational Marginal Price
MBDC	McDonough Braungart Design Chemistry
mD	millidarcys
MID	Modesto Irrigation District
MW	megawatt
MWh	megawatt-hour
NEC	National Electrical Code
NETL	National Energy Technology Laboratory
NPDA	National Pollutant Discharge System
OAQDA	Ohio Air Quality Development Authority
OE	Office of Electricity Delivery and Energy Reliability
OEM	Original Equipment Manufacturer
O&M	Operation and Maintenance
OSHA	Occupational Safety and Health Administration
PCR	Power Control Room
PCS	Power Conversion System or Power Conditioning System
PG&E	Pacific Gas and Electric Company
PJM	PJM Interconnection is a regional transmission organization in 13 states.

PNM	Public Service Company of New Mexico
psi	pounds per square inch
PUC	Public Utilities Commission
PV	photovoltaic
R&D	Research and Development
RFO	Request for Offers
RFP	Request for Proposals
RMS	root mean square
RPM	revolutions per minute
SCE	Southern California Edison
SGDP	Smart Grid Demonstration Program
SGIG	Smart Grid Investment Grant
SMUD	Sacramento Municipal Utility District
SNL	Sandia National Laboratories
SOC	State of Charge
SOW	Statement of Work
TCO	Total Cost of Ownership
T&D	Transmission and Distribution
MW	megawatt
MWh	megawatt-hour
UL	Underwriters Laboratories
UPS	Uninterruptible Power Supply, also Uninterruptible Power Source
USABC	United States Advanced Battery Consortium
UTC	United Technologies Corporation
VAC	Volts alternating-current
var	volt-ampere reactive
VC	Venture Capital
VDC	Volts direct-current
VRFB	Vanadium Redox Flow Battery
VRFS	Vanadium Redox Flow Storage

This page intentionally blank.

1 Introduction

The American Recovery and Reinvestment Act (ARRA) of 2009 (Recovery Act) provided the U.S. Department of Energy (DOE) with approximately $4.5 billion to modernize the electric power grid. The two largest initiatives resulting from this funding are the Smart Grid Investment Grant (SGIG) program and the Smart Grid Demonstration program (SGDP). These programs were originally authorized by Title XIII of the Energy Independence and Security Act of 2007 (EISA), and later modified by the Recovery Act. DOE's Office of Electricity Delivery and Energy Reliability (OE) is responsible for implementing and managing these five-year programs.

The SGDP is authorized by the EISA Section 1304 as amended by the Recovery Act to demonstrate how a suite of existing and emerging smart grid technologies can be innovatively applied and integrated to prove technical, operational, and business-model feasibility. The aim is to demonstrate new and more cost-effective smart grid technologies, tools, techniques, and system configurations that significantly improve on those commonly used today. SGDP projects were selected through a merit-based solicitation in which DOE provides financial assistance of up to one-half of the project's cost. SGDP projects are cooperative agreements while SGIG projects are grants.

The SGDP effort consists of 32 projects. Of these, 16 projects are focused on regional smart grid demonstrations and 16 are focused on energy storage demonstrations (see Table 2). The total value of SGDP projects is approximately $1.6 billion. The federal portion is near $600 million. The Smart Grid Energy Storage Demonstration Projects are being managed by the National Energy Technology Laboratory (NETL) for the DOE Office of Electricity Delivery and Energy Reliability. A list of the energy storage demonstration projects appears in Table 2.

The goal of this document is to provide a summary of the accomplishments for each of the ARRA energy storage demonstration projects, as well as recommendations for future efforts. The information in this report comes largely from three sources: interviews with the project team; interim and final technical reports provided to DOE; and DOE peer review presentations. The authors are extremely grateful for the feedback received from the project team members listed in the acknowledgements section.

The report is organized as follows. A brief overview of each project is followed by lessons learned for that project. An overall lessons learned section then summarizes common themes, and makes recommendations for future investments in energy storage to help facilitate wider adoption of grid connected energy storage systems.

Table 2: Summary of ARRA storage demonstration project goals.

	44 Tech Inc. (Aquion Energy)*	Amber Kinetics*	Beacon Power	City of Painesville	Duke Energy Business Services, LLC	East Penn Manufacturing Co.	Enervault/Ktech	New York State Electric & Gas Corporation	Pacific Gas & Electric Company	Premium Power Corporation	Primus Power Corporation	Public Service Company of New Mexico	Seeo, Inc.*	Southern California Edison Company	SustainX, Inc.*	The Detroit Edison Company
TECHNOLOGY	Na-ion (New)	Flywheel (New)	Flywheel (Beacon)	Flow (New)	Advanced Lead Acid (Xtreme)	Advanced Lead Acid (East Penn)	Flow (New)	CAES	CAES	Flow (Premium)	Flow (Primus)	Advanced Lead Acid (East Penn)	Li-ion (New)	Li-ion (A123)	CAES	Li-ion (A123)
Electric Energy Time Shift	NO	YES	NO	YES	YES	NO	YES	YES	YES	YES	YES	YES	NO	YES	NO	YES
Electric Supply Capacity	NO	NO	NO	YES	NO	NO	NO	YES	YES	NO	NO	NO	NO	NO	NO	NO
Load Following	NO	YES	YES	YES	NO	YES	NO	YES	YES	NO	NO	NO	NO	NO	NO	YES
Area Regulation	NO	YES	YES	NO	YES	YES	NO	YES	YES	NO	NO	NO	NO	NO	NO	YES
Electric Supply Reserve Capacity	NO	NO	NO	YES	NO	NO	NO	YES	YES	NO	NO	NO	NO	NO	NO	NO
Voltage Support	NO	NO	YES	NO	NO	NO	NO	YES	YES	NO	NO	YES	NO	NO	NO	YES
Transmission Support	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	NO	NO	NO	YES	NO	NO
Transmission Congestion Relief	NO	NO	NO	YES	NO	NO	NO	YES	YES	YES	NO	NO	NO	YES	NO	NO
T&D Upgrade Deferral	NO	YES	NO	NO	NO	NO	NO	YES	YES	NO	NO	YES	NO	YES	NO	NO
Substation Onsite Power	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Time-of-Use Energy Cost Management	NO	NO	NO	NO	NO	NO	YES	NO	NO	YES	NO	NO	NO	NO	NO	NO
Demand Charge Management	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO
Electric Service Reliability	NO	NO	NO	YES	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	YES
Electric Service Power Quality	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES
Renewables Energy Time Shift	NO	NO	NO	NO	YES	NO	YES	YES	YES	YES	YES	YES	NO	YES	NO	YES
Renewables Capacity Firming	NO	NO	YES	NO	YES	NO	NO	YES	YES	NO	YES	YES	NO	YES	NO	YES
Wind Generation, Grid Integration, Short Duration (= 15 min)	NO	NO	YES	NO	YES	NO	NO	YES	YES	NO	YES	NO	NO	YES	NO	NO
Wind Generation, Grid Integration, Long Duration (> 15 min)	NO	NO	NO	NO	YES	NO	NO	YES	YES	NO	YES	NO	NO	YES	NO	NO

* No Grid connected demo

2 Beacon Power

The following section provides an overview of the Beacon Power flywheel energy storage project.

2.1 Beacon Power Project Overview

Beacon Power LLC is a privately held firm located in Tyngsboro, MA. Beacon produces flywheel energy storage systems for frequency regulation and other stationary applications. The Beacon facility at Hazle Township, Pennsylvania was developed, built, and commissioned through the DOE Smart Grid Demonstration Program. It comprises 200 flywheels that can source or sink 20 MW for 15 minutes. The facility, owned and operated by Hazle Spindle LLC (a subsidiary of Rockland Power Partners, LP), sells frequency regulation services to PJM. It is the second plant of its kind, with the first being the 20 MW flywheel energy storage plant in Stephentown, NY.

The Beacon flywheel module deployed at both the Stephentown and Hazle sites uses a carbon fiber flywheel weighing approximately one ton spinning at up to 16,000 RPM in a vacuum around a vertical axis. Energy is stored or retrieved via an integral motor with a nominal rating of 100 kW. The extractable energy of each module is 25 kWh and the design life is greater than 100,000 cycles. Each flywheel is installed below grade. Sets of 10 flywheels share a containerized electronics module.

Figure 1: Beacon plant at Hazle Township [1].

System design for the Hazle plant involved evaluating data from Stephentown and applying design changes as appropriate to the Hazle project. The objective was to maintain high availability and performance from Stephentown, but reduce Operation and Maintenance (O&M) costs. Design changes were implemented when there was low risk and high value.

Extensive revenue modeling was performed over a period of years to evaluate the financial risk under numerous scenarios of PJM's pay for performance model, considering variables such as projected natural gas prices, and market risk and trends. In 2012, the Hazle project obtained initial permits required to proceed, but the PJM regulation market had just been redesigned and pricing was uncertain. In March 2012, the assets of Beacon Power Corporation were acquired by Beacon Power, LLC a subsidiary of Rockland Power Partners, LP (a private equity fund managed by Rockland Capital, LLC). The PJM Pay of Performance market started operating in October 2012. Additional revenue models were generated and the project was then fully funded based on updated projections early in 2013. The technical details of the project did not change significantly over this period.

Because the design of the plant was based on the existing Stephentown plant, Beacon had an established Statement of Work (SOW) on which the General Contractor (GC) could bid. Beacon, through a design subcontractor, updated the construction prints and the SOW. Beacon then competitively bid several GCs and selected one GC for the main project and one for the substation. Construction was procured through a fixed price contract. Cost and prior experience were key selection criteria.

A similar competitive bid process was used for owner supplied equipment (cooling system, trailers, switchgear, etc.). Each component had a specification including an envelope and was competitively bid. Suppliers were chosen on the basis of prior experience and price. Many of the suppliers who had performed well on the Stephentown project were selected. In some cases, Beacon changed suppliers due to less than expected performance on the first project.

Flywheels were manufactured by Beacon Power LLC in Tyngsboro, MA. All components in the flywheel are Beacon designed and qualified. Key suppliers were selected and qualified using established supplier management procedures. All other components were competitively bid and monitored through the Beacon Quality Control procedures. The electronics were designed by Beacon and manufactured under an approved contract manufacturing agreement. Beacon supplied requirements via drawings for contractor supplied equipment (mostly cables, construction material, conduit, etc.). Beacon had an onsite representative to audit the GC, primarily to verify the materials and specifications.

Three unique challenges were encountered during permitting and construction:

1. Storm water requirements – certain characteristics were requested by the town.
2. Blasting and leveling the site was more expensive than had been anticipated.
3. Delivery of the Power Control Room (PCR) paced getting power to the facility.

There were no significant challenges regarding code compliance. The storm water and blasting challenges were typical of any substation construction and were primarily related to the nature of the terrain. Beacon was aware going into the project that the land would require substantial work, but based on the benefit of the grant from the state of PA, it was still determined to be the best selection.

With the exception of the flywheel itself, the facility is largely covered by codes normally applied in the construction of a substation. Beacon used industry practices and contractors familiar with substation codes and practices. Code compliance issues requiring the greatest attention were related to the substation connection and protection equipment. These were carefully vetted in the interconnection process.

Few codes apply to the flywheel itself other than those pertaining to high voltage equipment. However, it was logical for Beacon to apply safety practices generally used in high speed rotating equipment. This entails detailed Failure Modes and Effects Analysis (FEMA). Beyond typical electrical safety practices, the most important criteria are to assure that the worst case failure modes of the flywheel are contained. The flywheel is designed and validated thru testing so that any failure is contained within the flywheel vacuum housing. As an additional pre-caution, the flywheels are installed in underground cement foundations to provide further protection against any possible containment issues. In addition, the plant design is extremely modular so that failure of any component is isolated and cannot lead to a cascading event.

The application for the construction permit was submitted in July of 2012 and was approved in November of 2012. There had been extensive pre-work with the town and the Pennsylvania Public Utilities Commission (PUC) in 2011 prior to Rockland Capital's acquisition of the assets of Beacon Power Corporation and its formation of Hazle Spindle LLC (a subsidiary of Rockland Power Partners, LP) in March of 2012.

The only noteworthy hurdle in the permitting process was the request by the town to modify the plant design to add a National Pollutant Discharge System (NPDA) to address storm water drainage. This was accomplished by working with the help of civil engineering consultants, who worked with the town and the Environmental Protection Agency (EPA) to modify the original plant accordingly.

No hazardous or flammable materials are used in the plant so there were no unique environmental or safety issues. Typical Occupational Safety and Health Administration (OSHA) training and monitoring was employed to assure safety during construction and operation. Safety practices for electrical equipment, use of cranes, forklifts and confined space were implemented and monitored. Material handling was again reflective of a substation where the most common issues were handling transformer oil and glycol/water mixtures for the cooling system.

The plant was brought online in September, 2013 with a capacity of 4 MW. The capacity was increased to 20 MW in increments of 2 MW. Beacon has its own commissioning plan that verifies correct operation for each 1 MW set of ten flywheels prior to being added online. This typically takes one to two days once all of the equipment is installed.

The main qualification requirement relevant to the outside world was to assure that the protection equipment was set up and performs per the agreed-to interconnection requirements. This was done by third party contractors who did the testing and issued a report. This activity took two to three days once all equipment was installed and power was available from the substation to commission a set of flywheels.

In addition, for each increase in capacity PJM required a test to assure that the system was following their signal with acceptable accuracy. The test procedure was defined by PJM and takes 40 minutes to execute. The system successfully complied with this requirement at each phase.

Manpower committed to this construction was supplied by the contractor and was not tracked by Beacon. Beacon had one person on-site to manage the installation process and one additional person to train the GC on the commissioning process. The commissioning process for the flywheel modules is specific to the Beacon modules and is proprietary to Beacon. Validation of the substation and protection equipment was done by a third party and witnessed by the host utility. Beacon encountered no safety events or issues during the construction, commissioning and operation of this plant. Beacon continues to improve internal documentation of its commissioning process in order for outside personnel to complete the commissioning without Beacon assistance.

This plant is online 24/7 providing fast response frequency regulation in the PJM regulation market. The plant reduces the overall need for regulation, improves system efficiency (no fuel used) and frees up generators to run at more optimum energy output. Frequency regulation is currently the only value stream provided by the plant.

Operation of the plant has gone as expected. Availability of the plant has been greater than 98%. Maintenance costs are as projected. Several unplanned transmission outages and some intermittent communication issues outside of Beacon control have had more effect on availability than performance of the Beacon supplied equipment.

Turbo-pump bearing reliability is an ongoing maintenance item. A new design pump was incorporated for the last 10 flywheels and these have had no issues. Earlier turbo-pumps have a higher replacement rate. Because there is system redundancy, any turbo-pump failures have had negligible effect on overall performance. No flywheels, electronics, or major components have been

Table 3: Key metrics for plant performance

Parameter	Metric
Availability	> 98 %
Accuracy	> 97%
Round trip AC-AC efficiency	85%
Standby loss	0.02-0.03 MWh/MW/hr depending on the cycle
Throughput since commissioning	$> 25,000$ MWh

replaced since commencing operations.

A built-in data historian collects information on numerous flywheel parameters, as well as overall plant output and performance. Data is collected between two to four seconds for some parameters and longer duration for other parameters. Data is collected locally and periodically automatically moved to a central offsite server for trending and analysis. In addition, Beacon has several high speed data acquisition systems to monitor power quality output on an as needed basis. This data is primarily used for post event analysis of any grid disturbances that cause a system to go offline. The data systems have proven to provide all of the information Beacon needs to monitor and analyze events that have occurred.

With extractable energy of 5,000 kWh this is tantamount to a non-dimensional throughput of 5,000 or 5,000 100% Depth of Discharge (DOD) cycles. As expected for flywheels, there has been no fade in capacity.

The next section reviews lessons learned from the Beacon project.

2.2 Beacon Power Lessons Learned

Overall, the project has been successful and Beacon would execute future projects similarly anticipating further improvements in cost, performance, and reliability. Beacon will continue to work with Independent System Operators (ISOs) to optimize signal and revenue.

The benefits of the system are well understood. They include high cyclic life, high performance scores and accuracy, redundancy and high availability. DOE support has been essential in achieving these goals.

Technical objectives and performance requirements were well established, achievable, and not modified over the course of the project. PJM regulation signal and requirements were well established. This resulted in an efficient, effective execution of the project.

System design drew extensively from the prior project in Stephentown. This reduced programmatic risk.

Beacon realized a significant cost reduction between the Stephentown and Hazle plants. Areas for further substantial cost reduction have been identified.

Codes relating to specific energy storage technologies are being developed and will be considered for future projects. Codes for high voltage substation equipment do not specifically address energy storage. Adding code related to energy storage needs to be done carefully as energy storage plants may have different issues and requirements depending on the technology used. For example, codes developed around batteries would not be suitable for flywheels.

During validation of substation equipment, it is important to assure that experienced personnel are performing this operation and follow industry standards for substations.

3 Public Service Company of New Mexico Project

The following section provides an overview of the Public Service Company of New Mexico (PNM) Prosperity energy storage project.

3.1 PNM Project Overview

The PNM Prosperity project was primarily funded by DOE and PNM, with support from the following partners: Sandia National Laboratories, the University of New Mexico, Ecoult/East Penn Manufacturing, Northern New Mexico College, and the Electric Power Research Institute (EPRI). The goals of the PNM Prosperity project were to:

- Demonstrate that intermittent, renewables-based, distributed generation and storage can mitigate voltage-level fluctuations and enable peak shifting
- Quantify and refine performance requirements, operating practices, and costs associated with the use of advanced storage technologies
- Achieve 15 percent or greater peak-load reduction through a combination of substation-sited photovoltaics (PV) and storage

These goals were accomplished by installing two battery systems (one power and one energy) collocated with a 500 kW solar PV plant to create a dispatchable distributed generation resource. The energy battery employs the Ecoult/East Penn – Advanced Lead Acid Battery system for shifting and is rated at 250 kW for four hours (1 MWh). The power battery employs the Ecoult/East Penn – UltraBattery system for smoothing and is rated at 500 kW for 40 minutes (333.33 kWh). The site is located at a substation southeast of Albuquerque, New Mexico, and is shown in Figure 2. The PNM project was the first of the 16 ARRA energy storage demonstration projects to go on line, with operation starting in September of 2011.

Figure 2: PNM Prosperity project [2].

The next section reviews lessons learned from the PNM Prosperity project.

3.2 PNM Lessons Learned

The major challenges in the initial system design were related to integration of the energy storage system into the PNM grid. First, the utility operators and back office teams were unfamiliar with the functionality and benefits of energy storage. Second, it was difficult to obtain or develop the back office software necessary to control a distribution level energy storage resource. PNM could not find a system integrator (no one responded to the Request for Proposals (RFP) for the data acquisition and control system) and ended up internally developing a custom energy storage management system. Another barrier was that the Federal Energy Regulatory Commission (FERC) standards preclude the marketing department from participating in reliability related functions. Therefore, communications related to potential uses for distribution level energy storage are forced to be segregated, which makes it more difficult to optimize the control of the energy storage asset.

The greatest challenge in the RFP and contracting for site construction was the lack of standards and specifications for behind the meter energy storage systems. Another challenge was that the first battery vendor did not meet early milestones, so PNM was forced to change vendors, ultimately selecting Ecoult/East Penn. A fixed price plus liquidated damages contracting strategy was employed. East Penn was the prime and carried the risk. The line extension to the site was performed by PNM.

During the permitting and construction process, the permitting risk was significantly underestimated. The project was one vote away from being denied by the county zoning department. In order to be compliant, a fire hydrant had to be extended to the site and handicap parking had to be installed. The local zoning, planning, and building department also tried to force compliance with the National Electrical Code (NEC), which actually do not apply to a utility. For the most part, applicable codes do not yet exist for battery energy storage systems (National Electrical Safety Code covers energy storage systems, but does not address batteries). PNM defaulted to "accepted good practices". The adoption of existing codes and standards for the project are summarized in the DOE/EPRI 2013 Electricity Storage Handbook [16]. The permitting process took approximately six months.

Another construction lesson learned was related to the transport of the energy storage system to New Mexico from the manufacturer. The trucks were categorized as oversized and overweight. The weight of containers is tracked by the Homeland Security Department, and regulations do not permit travel at night for oversized and overweight loads.

Fire protection was not required for lead acid batteries, but a berm was constructed as a safety barrier for containment if a fire should occur.

Initial startup and commissioning went extremely well and lasted approximately one week. The commissioning plan was developed by Sandia National Laboratories. The initial startup occurred on a Friday, the ribbon cutting ceremony was on Saturday, and the photovoltaic (PV) smoothing was also tested on Saturday. Commissioning was performed by Ecoult and witnessed by PNM.

4 East Penn Manufacturing Project

The following section provides an overview of the East Penn Manufacturing energy storage project.

4.1 East Penn Project Overview

East Penn Manufacturing is a privately held company based in Berks County, PA. Covering 530 acres, East Penn operates the largest single-site, lead-acid battery manufacturing facility in the world. The UltraBattery® is a hybrid device produced by East Penn. It uses a single positive electrode with a dual carbon and lead negative electrode. The UltraBattery® is reported to provide life at partial state of charge far exceeding that of other lead-acid batteries, making it particularly well suited for the frequency regulation application.

Under the DOE Smart Grid Demonstration Program, East Penn constructed a 3 megawatt (MW) energy storage facility on-site at their main plant near Lyon Station, PA. The facility is in commercial operation providing frequency regulation services to the PJM Interconnection. In addition to frequency regulation, the plant is sized to provide 1 MW of demand management.

The motivation for the project has been and remains to provide ancillary services in competitive markets at lower cost than generators or other energy storage technologies. Building on the success of the operational system, East Penn has been developing new battery formats (e.g., optimized packaging) that can increase the service provided at the same price while continuing to reduce balance of plant costs. Performance targets were driven by the objective of providing cost effective frequency regulation service while satisfying PJM requirements.

Figure 3: East Penn UltraBattery installation [3].

For interconnection purposes, the project was installed behind East Penn's meter as a Demand Response (DR) resource. As a DR resource, the system can provide frequency regulation to PJM and demand management to the local utility. A DR resource cannot export power to the grid. Therefore, the battery output cannot exceed the load behind the meter for this project. However, the DR resource is a much less complicated option requiring less capital and, more importantly, very little time to implement. Under the initial agreement with the local utility, the project was built to provide demand management when requested, however, the utility never requested this service.

The UltraBattery cells were owner provided. The remaining primary capital items were manufactured to specifications defined by Ecoult, an East Penn energy storage solutions subsidiary. The manufactured items were sourced to third parties and are now part of Ecoult's standard product set.

A number of points worth noting arose during permitting. The local code officer was unfamiliar with the Absorbent Glass Mat (AGM) battery product; he initially assumed that the batteries contained free flowing acid. The inspector was provided with information indicating that this was not the case. The building permit was completed in two weeks. The application for interconnection was submitted on October, 2010, the study was completed on June, 2011, and agreement was finalized on February 2012. The IEEE1547 interconnection standard for a high power custom inverter was achieved through acceptance testing using approximate impedances in place of a transformer.

Commissioning was conducted over two months followed by a startup phase lasting three months. This was East Penn's first 1200 VDC system (center grounded). They used a five winding transformer (one primary, four secondary windings) for each string to reduce cost. While effective, East Penn noted ripple as a result of capacitive coupling between windings and needed to implement corrective circuitry. This took several weeks to resolve.

Initial testing and grid operation required about 270 hours of East Penn manpower along with additional manpower provided by Ecoult. Ecoult managed the commissioning process and provided commissioning documentation specifying system safety checks and tests.

During commissioning, East Penn learned that the smoke detectors were not suitable for use in battery rooms and produced a number of false alarms. Replacing them with suitable alarms solved the problem.

Approximately 20 man-hours per week are allocated to this project during routine operation for scheduling, reporting and maintenance.

Cell temperature management has been a challenge throughout the project. The significant throughput that the batteries experience following the frequency regulation command results in variations in cell temperature within a string. There were also challenges with the Power Conversion System (PCS) cooling system including leaks and pump failures which were resolved.

East Penn proactively removes cells identified by the Battery Management System (BMS) as poor performers for analysis. In the lab, the few cells removed have been recovered through routine cycling.

Data logging is done using Ecoult's BMS plus input from the Dynapower PCS. This data has been very valuable in gaining operational knowledge about the UltraBattery and the PJM frequency regulation market.

In a capacity test conducted in December 2014, the measured capacity of the system was 80% of the initial capacity. However, the majority of the perceived capacity loss can be attributed to cell imbalance within strings. Equalization is expected to increase capacity substantially. In the future, a step will be added to ensure all batteries in the system are equalized prior to beginning operation.

The system availability has been approximately 90% during scheduled operation times. As of January 1, 2015 the total throughput since commissioning was 6,150 MWh. In terms of throughput, the system experiences the equivalent of two 100% Depth of Discharge (DOD) cycles every day when operating at 2 MW. When operating at 3 MW, the system experiences the equivalent of three 100% DOD cycles every day.

The AC-AC efficiency of the system is approximately 82%. When auxiliary loads are counted against efficiency, the resulting value is 75%. Round trip AC-AC efficiency was slightly less than expected by 1% to 2%. Due to the nature of the PJM signal, root mean square (RMS) power of the system is typically below 50% of rated power. PCS efficiency is lower at half power than at full power which accounts for the lower than expected AC-AC efficiency.

The next section reviews lessons learned from the East Penn project.

4.2 East Penn Lessons Learned

The system has provided dynamic frequency regulation to PJM as intended. Cycling of the batteries has been more extensive than anticipated due to the PJM signal becoming more aggressive.

The major strength of the system is that it has successfully demonstrated the ability of an UltraBattery® to reliably follow a continuous, aggressive, high rate frequency regulation signal in an operational scenario.

The principal challenge was that the initial approach to temperature management was not adequate for this type of application. At the outset, East Penn used standard racking associated with also Uninterruptible Power Supply (UPS) batteries for this system which resulted in a variation of temperature of 6° C – 8° C between the top row and the bottom row. Longevity is improved by maintaining a tighter range. East Penn has worked to reduce temperature variation.

Going forward with subsequent projects, East Penn and Ecoult will utilize the newly designed UltraRax for improved thermal management. A new battery format better suited for high power applications is under development and will be employed in future applications.

East Penn has evaluated existing market opportunities for frequency regulation and found PJM leading the way when it comes to integrating fast responding resources into the regulation market. Over the course of the project, PJM modified their dynamic frequency regulation signal and adjusted their payment structure to compensate resources based on how accurately they follow the regulation signal.

Beyond the ARRA energy storage demonstration project, East Penn believes that frequency regulation plants can be financed and built using private funds. For future projects they are open to partnering with an integrator who would build and operate the plant so that East Penn could provide the batteries and service for the batteries.

While existing codes and standards were suitable for this project, East Penn looks forward to a Underwriters Laboratories (UL) code for stationary energy storage. This will result in an equitable environment for the implementation and operation of energy storage systems.

5 Southern California Edison Tehachapi Wind Energy Storage

The following section provides an overview of the Tehachapi Wind Energy Storage project.

5.1 Tehachapi Project Overview

The original motivation for the project was curtailment and voltage problems in the Eastern Kern Wind Resource Area (approximately 100 miles north of Los Angeles, CA). Limited transmission capacity on two transmission lines resulted in wind curtailment [15]. The voltage problems were the result of a lack of reactive power support. Both of these issues can be addressed by energy storage. Transmission studies of the Antelope-Bailey area identified an 8 MW, 32 MWh Battery Energy Storage System (BESS) as an option to mitigate the identified reactive power problem and line overloading. Therefore, the main objective of the project was to demonstrate utility scale lithium-ion battery technology in improving grid performance and integrating intermittent wind generation.

The DOE awarded ARRA funding in early 2010 and project work began in October of that year. The project was jointly funded by DOE and Southern California Edison (SCE). The initial design, specification and procurement of the BESS were disrupted by financial issues of the original BESS supplier. Subsequently, a revised project plan was developed to select a new BESS provider and continue with the project. Installation and commissioning of the BESS was completed in July 2014.

The project is installed in the Monolith substation (Tehachapi, CA at the corner of Williamson Road and East Tehachapi Boulevard) where it is connected to the 66 kV bus and will be tested under various load and wind power generation conditions. An areal photograph of the storage facility and substation is shown in Figure 4. The testing planned for the Tehachapi system is summarized in Table 4. There are thirteen proposed operational uses, which can be broken into three categories: transmission, system, and Independent System Operator (ISO) market. Eight tests are planned to evaluate performance for each of the proposed operational uses.

Figure 4: Tehachapi Wind Energy Storage plant, Tehachapi, CA [4].

The next section provides a summary of lessons learned from the Tehachapi project.

Table 4: Tehachapi operational uses and tests [15].

Operational Use			Test 1	2	3	4	5	6	7	8
Transmission	voltage support	1	X	X						
	decreased losses	2			X					
	diminished congestion	3			X					
	increased system reliability	4				X				
	deferred transmission investment	5			X		X			
	optimized renewable-related transmission	6			X		X			
System	system capacity/resource adequacy	7				X		X		
	renewable integration (firming & shaping)	8					X			
	output shifting	9				X				
ISO Market	frequency regulation	10						X		
	spin/non-spin reserves	11							X	
	deliver ramp rate	12						X	X	
	energy price arbitrage	13								X

5.2 Tehachapi Lessons Learned

Financial difficulties with the first BESS vendor required a redesign and switch to LG Chem as the battery supplier. While this caused some difficulties, such as the building had already been designed so the footprint was constrained, it also provided an opportunity to update the system design. The initial approach put all of the control logic in the SCE Supervisory Control and Data Acquisition (SCADA) system. For the final design, more of the system control software was developed by the system integrator (ABB Group) and battery vendor (LG Chem). A competitive source selection was used to select the battery vendor and a fixed price contract was employed.

The permitting and construction process was greatly simplified because of the remote location and the Monolith substation was already owned by SCE. This enabled leveraging of SCE substation standards and eliminated the need for the typical permitting process employed within big city limits or otherwise densely populated areas. The dimensions of the site did put constraints on the building shape, which resulted in an L-shaped building (see Figure 4). Because existing fire codes and standards lack guidance for lithium ion battery energy storage facilities, SCE applied best practices and guidance from the BESS supplier and a professional consultant, along with actual destructive testing of battery system components in a lab setting. In order to streamline the permitting process and address existing conditions within the substation, the interconnection was classified as temporary. A permanent connection would have required a substation extension, which would have involved a more lengthy ISO approval, expansion of the substation footprint, and an environmental impact assessment.

A significant plus for the project was the development of a mini-system at the SCE Pomona test facility prior to full-scale deployment. The mini-system is shown in Figure 5. The mini-system enabled subscale testing in the lab before full-scale operation of the BESS at Monolith Substation. This included safety performance of the battery system, operational verification of the battery and power conversion system controls, as well as the interface to SCE network. Many safety and operational issues were resolved with the mini system over a period of nine months, which ultimately enabled the successful completion of full system acceptance testing on-site without any significant delays. A comparison of the mini-system to the full system appears in Table 5.

Figure 5: SCE Tehachapi mini-system, Pomona, CA [4].

One of the main challenges during startup and commissioning was scheduling an outage at the point of interconnection. The substation supported loads that could not be shifted to another substation. Two factors created this situation. First, upgrades to the Eastern Kern Wind Resource Area were completed ahead of schedule. Then, the energy storage system schedule slipped. Several months were spent developing a method of interconnection without an outage.

The commissioning process involved test plans for the battery and Power Conversion System (PCS), as well as an overall system test plan. Validation testing for the PCS was performed at the factory. Some battery testing was performed at LG Chem, primarily thermal modeling, thermal performance, and fire testing. Full system acceptance testing was completed successfully including charging and discharging at full power between maximum and minimum state of charge.

Another important lesson learned was the significant time and resources required for interconnection. The California Independent System Operator (CAISO) Interconnection Request (IR) required significant lead time to allow for processing in Queue Cluster (typically 18 months)[15]. There is also a limited time window to submit an IR. As part of the IR process, a Power System Load Flow Model (PSLF) must be submitted. Ideally, the system vendor can provide this model. There are significant costs associated with system upgrades, and an up front security deposits is required to stay in the IR queue. The interconnection agreement can stipulate operating restric-

Table 5: Mini-system compared to the Tehachapi full system [4].

	Mini-System	**Full System**
Footprint	77 ft^2	6300 ft^2 building
Power	30 kW	8 MW
Energy	116 kWh	32 MWh
Power Conversion System	One Mini-Cabinet	Two 40-foot containers
Sections	1	4
Banks	1	32
Racks	2	604
Modules	36	10,872
Cells	2,016	608,832

tions or limitations on BESS due to system topology and/or reliability requirements. Another consideration is the time required for environmental impact studies for the property.

Overall, the project has progressed largely as planned. Good process was a strength of the project. A well specified, Commercial Off-the-Shelf (COTS) approach allowed for a quick recovery when the battery vendor had to be changed. The original metrics and benefits reporting plan was so well written, that it has not required any updates over the course of the project. In the coming months, SCE will be executing the planned tests for the 13 operational uses.

For future systems, sizing will be evaluated differently. At the 12kV distribution level, a larger number of smaller storage sites will be used in partial fulfillment of SCE's commitment to own and operate 290 MW of storage in their service territory under AB2514 [17]. The 8 MW deployed in this project counts towards that total. Future deployments will be precise and targeted. The experience gained in this project is already proving highly valuable in determining how to approach the 290 MW deployment.

SCE has interest in continuing to operate the battery at the conclusion of the two year study. They are evaluating a number of alternatives including permanent interconnection at the substation or relocating the battery.

6 Duke Energy Notrees Wind Storage

The following section provides an overview of the Duke Energy Notrees energy storage project.

6.1 Duke Energy Project Overview

Duke Energy Renewables owns and operates the Notrees Wind Farm in west Texas's Ector and Winkler counties. The wind farm was commissioned in April, 2009 and has a total capacity of 152.6 MW. The objective of the Notrees Wind Storage Demonstration Project is to demonstrate that energy storage increases the value and practical application of intermittent wind generation and is commercially viable at utility scale. The Notrees Wind Storage Demonstration Project delivers 36 MW at peak power and has a capacity of 24 MWh.

Figure 6: PowerCell Modules at the Duke NoTrees Wind Storage Project [5].

The major objectives of the project are as follows:

- Integrate with intermittent renewable energy production.
- Improve the use of power-producing assets by storing energy during non-peak generation periods.
- Demonstrate the benefits of using fast-response energy storage to provide ancillary services for grid management.
- Confirm that an energy storage solution can dispatch according to market price signals or pre-determined schedules utilizing ramp control.
- Verify that an energy storage solution can operate within the market protocols of the Electric Reliability Council of Texas (ERCOT).

In November 2009, DOE awarded Duke Energy a $21.8 million cost-shared grant for the Notrees Wind Storage Demonstration Project, funded through the American Recovery and Reinvestment Act (ARRA) of 2009. The Electric Power Research Institute (EPRI) was a sub-recipient of the grant. In January 2011, DOE and Duke Energy agreed to the terms and conditions of the grant. EPRI assisted with the request for proposal (RFP) resulting in Xtreme Power's selection as the BESS provider. An economic viability model developed by Integral Analytics helped Duke Energy conduct an economic viability analysis, which was completed in June, 2011. Project construction was completed in October, 2012. Performance testing was completed in December, 2012. Commercial operation testing was completed in February, 2013. In March, 2013, the Notrees Wind Storage Demonstration Project began providing frequency regulation services to ERCOT as part of a Fast-Responding Regulation Service (FRRS) pilot program.

Xtreme Power was a vertically integrated provider of turnkey energy storage systems. As of April 2014, their assets were acquired by Younicos. Their PowerCell^{TM} is an enhanced version of the Electrosource Horizon battery. It is a starved electrolyte, lead acid, dry cell battery rated at 12 V and 1 kWh for a 3-hour discharge. Each PowerCell is 30 x 5 x 5 inches (76 x 13 x 13 cm) in size and weighs 54.6 pounds (24.8 kg). A PowerCell Pack uses 1200 PowerCells in a matrix of 15 parallel stacks. A PowerCell Module comprises a PowerCell Pack with a capacity of 1.0 MWh and a 1.5-MVA power conditioning system (PCS) manufactured by Dynapower Corp. The Notrees project Dynamic Power Resource^{TM} (DPR) energy storage system comprises 24 PowerCell Modules. The project is installed in a single 6,000 square foot building near the wind farm.

Commissioning of the Notrees Energy Storage Facility was performed in accordance with a Startup Testing & Commissioning Plan to ensure that all modules and ancillary equipment were properly installed and undamaged. This included visual, mechanical and electrical checks to assess the condition of the equipment and identify any deficiencies that needed correction. Each of the 24 inverters was brought up one at a time. Commissioning concluded with functional and operational tests to demonstrate that the system's electric output characteristics and operation were as expected. Xtreme Power also executed a Commissioning Plan and Testing and Documentation process. Acceptance testing included ramping each module up and down at 1.5 MW/min and 1500 kVA/min. All 24 modules were tested simultaneously. The entire system delivered 14.4 MWh over a 3 hour period (4.8 MW for 3 hours).

In early 2013, participation in the ERCOT FRRS pilot project became the primary activity. The facility began providing FRRS service to ERCOT for a one-year pilot program on February 25, 2013. At the outset, the project was capable of providing 32 MW of FRRS up-regulation and 30 MW of FRRS down-regulation. An additional 1 MW FRRS up and down regulation were provided by other resources beginning in March, 2013. The demand for service varied form month to month. In April 2013, the facility received 1646 MWh and delivered 1287 MWh with a corresponding efficiency of 78%. In November, 2013 the facility received 1179 MWh and delivered 792 MWh with a corresponding efficiency of 67%.

The FRRS pilot program ended in February, 2014. Subsequently, FRRS became a subset of Regulation Services. Notrees BESS continues to offer services into the ERCOT ancillary services market. Revenue is based on regulation market price.

6.2 Duke Lessons Learned

Obtaining land rights and siting in proximity to the collector substation, wind farm O&M building and associated leech field, and wind farm high voltage (HV) radial transmission line were early challenges. Wind easement did not have provisions for installation of this type of facility so the process to amend the lease/easement was lengthy.

Initially, the intended use was not well defined. The financial model forecast that the facility would be used in some combination of arbitrage and ancillary service, but as the project progressed, and ERCOT needs were better understood, the project operation evolved to provide ancillary services exclusively, particularly FRRS – fast responding regulation service. Since ERCOT is a market area, the wind firming would have been provided by engaging in arbitrage.

ERCOT represents a single market. Consequently, the Notrees storage facility may be responding to frequency regulation requirements throughout the ERCOT system, with origins potentially far removed from the Notrees site.

The installed cost was higher than anticipated. With respect to metrics and benefits, the primary economic benefit is due to the sale of frequency regulation as an ancillary service[18, 19]. The clear prominence of frequency regulation as the most valuable service was unexpected [20].

Pilot resources generally followed ERCOT FRRS deployments and responded automatically using local frequency detection techniques. Duke observed less demand for FRRS-down regulation and lower performance for FRRS-down regulation.

ERCOT observed that FRRS improves ERCOT's ability to arrest frequency decay during unit trips. When deployed, FRRS reduces the rate of change of frequency and the amount of regulation provided by conventional resources. ERCOT stated that by the end of the first three months of operation, the pilot had already provided exceedingly valuable information about the degree to which the total Regulation Service can be reduced by FRRS Resources.

While well suited for wind firming, the current battery is challenged by the frequency regulation application. Simultaneous participation in the regulation up and regulation down markets requires the system to operate in a partial state of charge. Initial operations quickly highlighted the detrimental impact on the batteries. Therefore, focus shifted to participation in the regulation up market, with charging between 1AM and 5AM daily. While this mode of operation was significantly better given the cell chemistry, there was still a correlation between the amount of regulation provided and cell failures. In typical operation, about 15 cells per week are replaced out of 28,800 cells in total. The nominal replacement rate to maintain capacity due to cell failure is therefore 2.7% per year. The greatest operational challenge is finding the balance between how much to bid into the market (how aggressively the battery is used) versus the lifespan of the battery. The more the battery is used, the more frequently cells are replaced. Initially, the bid in to the regulation up market was 36 MW. This was reduced to 22 MW to improve battery life, and a reduction to 20 MW is under consideration. The plant has been operational for 28 months so far, out of an expected battery life of 5 years.

The modules are configured with one sensor set per column. When a column has low voltage, the weak cells are identified manually and replaced. In an expansion or future deployment, it would be preferable to instrument at the cell level.

Duke Energy Renewables has entered into an agreement with Younicos to provide design, engineering, construction, software integration, and testing services for the repowering of the facility with Samsung SDI lithium-ion batteries [21]. The new batteries will operate in combination with the advanced lead acid batteries currently in use. The hybrid system will accommodate planned battery replacements over time while maintaining ongoing operations of the system.

Recommendations for future investments include continued research and development of energy storage systems for renewable integration. One barrier is related to the wind energy production tax credit, which states that the electricity produced must be sold to an unrelated party in order to receive the credit. If wind energy is stored, the tax credit is lost, which creates a disincentive for collocated storage for wind firming. Additionally, common rules and standards for battery energy storage systems will speed adoption.

7 Aquion

The following section provides an overview of the Aquion energy storage project.

7.1 Aquion Project Overview

Aquion is a privately held company in Pittsburgh, PA undertaking the development and commercialization of a low cost, ambient temperature, aqueous hybrid ion (AHI^{TM}) battery for time-shifting and renewables firming. Aquion executed an ARRA funded demonstration of aqueous hybrid ion battery technology from July 2010 through September 2012. Subsequent to the completion of the program, Aquion has continued the deployment of AHI battery systems reporting over 90 installations around the world totaling approximately 5 MWh of deployed energy storage. Notable installations include:

1. 80 kWh at an off-grid ranch near Jenner, CA,
2. 1 MWh at the off-grid Bakken Hale Estate on the Kona Coast of Hawaii,
3. 1 MWh system under development for Puerto Rico,
4. Aquion batteries are with key partners such as Siemens, Princeton Power, Ideal Power, SMA, and others.

The prototype 10 kWh (5 hour discharge), 1000 V energy storage demonstration system developed for the ARRA project is shown in Figure 1, alongside the current M-Line battery module which supplies approximately 25 kWh.

Figure 7: Aquion 10 kWh, 1000V ARRA prototype (left), 25 kWh M-Line battery module (right) [6].

Aquion originated as a spin-off out of Carnegie Melon University. The core technology is thick-cell, salt based electrolyte optimized for long duration discharge. At the time that the proposal for ARRA funding was submitted, Aquion comprised two individuals with an investment of $600k. The $5M ARRA award attracted $7M in investment. Consequently, the ARRA project comprised more than 80% of funding through September 2012 and was essential to Aquion's early progress. By the end of the project, Aquion employed more than 50 people. Today Aquion has raised more than $100M by world class investors – privately held, grants, and venture capital funding.

The ARRA project yielded the S10 module which has been succeeded by the S20 and S20P modules. The first generation product design was not scalable and laser welded seals tended to leak. These problems were solved with energy density and rate capability increasing with each generation. Aquion reports improvement in cycle life of 25% - 50% for each generation. Cells under test accumulated cycles at a rate of about one per day. Aquion reports that test cells have reached 1000 cycles and are on target to reach 3000 cycles with 70% capacity at end of life.

Round trip DC-DC efficiency is in the range of 80% - 90% depending on the characteristics of the charge-discharge cycle. The current generation modules are robotically assembled at a 350,000 square foot facility with a projected capacity of over 200 MWh per year. Aquion reports that their batteries are the first batteries in the world that are "Cradle to Cradle CertifiedTM" Bronze for sustainability. Their batteries were evaluated by McDonough Braungart Design Chemistry (MBDC), the creators of the Cradle to Cradle Certified Products Program, and certified by the Cradle to Cradle Products Innovation Institute. Cradle to Cradle Certified™ is an independent, third-party verified certification program that assesses products and materials for safety to human and environmental health, design for future use cycles, and sustainable manufacturing. Cradle to Cradle Certified products are evaluated for material health, material reutilization, renewable energy use, water stewardship, and social fairness.

Aquion purposefully designed their battery to have voltage characteristics matching 12V lead acid batteries. This enabled Aquion to capitalize on the highly evolved network of integrators and distributors serving the lead acid battery market. Aquion works extensively through partners who perform all integration activities.

To date, all projects have been behind the meter. Applications on the utility side of the meter have been found to be far too complex, too lengthy, and too costly to be worth pursuing at this stage.

7.2 Aquion Lessons Learned

The manufacture of dry electrodes was much less problematic than wet electrodes. Therefore, Aquion switched to a dry electrolyte press. The cells were found to balance passively: consequently active cell voltage balancing is not required or implemented. The original design goal was for a 20-30 hour discharge cycle. Based on the market, the real value is provided with a 4-6 hour discharge. Improvements in the rate capability, achieved through thinner electrodes, have helped match the capabilities of the cell technology with the market. Based on the experience gained from the ARRA prototype, significant improvements in sealing were achieved on subsequent designs.

Effective next steps depend on where DOE wants to help – on which side of the meter. Aquion believes that batteries are already commercially viable on the customer side of the meter.

8 EnerVault Project

The following section provides an overview of the EnerVault energy storage project.

8.1 EnerVault Project Overview

EnerVault, located in Sunnyvale, CA, is developing iron-chromium flow batteries for stationary applications. Through the Smart Grid Demonstration Program, EnerVault deployed a 250 kW, 1 MWh (4 hour) flow battery system in Turlock, CA. The purpose of the system is to demonstrate energy time shifting. The battery is grid-connected and collocated with a 150 kW solar power system and a 260 kW irrigation pump.

Figure 8: EnerVault Fe-Cr Redox flow battery, Turlock, [7].

By the time the ARRA solicitation was announced, EnerVault had already completed an analysis of the energy storage market. EnerVault determined that the redox flow battery would be the best approach for grid-scale energy storage. Market analysis also indicated that behind the meter applications would become available first. The market analysis drove technical objectives, and as a result, EnerVault focused on behind the meter applications for this first demonstration to lay the ground work for future grid-scale implementations. The technical objectives and performance requirements were determined at the outset and remained consistent over the course of the ARRA demonstration project.

The relatively nascent state of development at the start of the build phase led EnerVault to use cost plus contracts for system assembly and site construction. Cost plus was fast, but increased procurement costs. EnerVault established a relationship for site construction with the solar provider in the central valley who built the solar plant. EnerVault leased the land and owns the hardware.

EnerVault encountered one surprise during permitting. The Department of Fish and Game required a bird survey which was motivated by concern for nesting raptors. A biological survey and certification were completed. EnerVault worked with public works, fire, building, and planning department staff on permitting. EnerVault went into planning well prepared. The discussions with the Merced fire staff went smoothly, and EnerVault was impressed with the fire department's preparation and knowledge of energy storage systems.

Existing codes and standards for chemical plants were employed over the course of the project. EnerVault engaged competent and recognized engineers for the design and construction effort, and there were no major setbacks. Some of the potentially difficult questions relating to batteries were avoided as the EnerVault system is more like a chemical plant.

There is no thermal runaway mechanism in the EnerVault battery as the electrolyte is comprised mostly of water. Consequently, no fire suppression system is installed. In an unrelated project, there had been a fire in Hawaii due to an inverter which raised concerns. EnerVault worked with the inverter vendor to de-rate the electrolytic capacitors, add sensors to detect over-temperature conditions, and add hardware and software features to prevent fire.

Installation was completed in early February, 2014 and the first test with electrolyte was conducted in mid-May 2014. The commissioning process was developed internally with support from an engineering subcontractor. They developed detailed check lists, procedures, instrument calibration, and limits on inverter noise. Commissioning was done in-house with the support of consultants. Three technicians and three engineers worked on commissioning full time for three months. During commissioning, consideration was given to arc flash hazards and managing clearances. It was helpful that iron and chromium are easy to handle.

The system was built to provide energy time shifting and is operated as intended, accumulating one cycle per day. The system has met availability goals and has experienced no cell or module failures. Test results matched the predicted performance meeting forecast ramp, power, and efficiency targets. The AC-AC round trip cycle efficiency is about 60% which includes power consumed to provide ventilation but not cooling or electrical heating. There has been no degradation in efficiency since commissioning.

Logging detailed data has been very helpful. EnerVault has 6000 cells in their system and the data is used for debugging. Cell voltage is monitored at 1 Hz. Since commissioning, EnerVault has operated the system in campaigns typically consisting of a week of testing, a period of modifications, a week of testing, and so on. A single cycle test involves a 100% DOD and a 7–8 hour charge due to the 60% efficiency.

The system comprises 120 cells in a stage, six stages in a cascade, and nine cascades in a system. Cell pair voltage is measured. Any type of cell anomaly will impact the cell pair voltage.

A major strength of the flow battery system architecture is that power and energy are decoupled. Longer duration requires a larger tank. Electrolyte is inexpensive in the iron-chromium system. For extremely long discharge time, system price asymptotically approaches electrolyte price. There is no upper limit on capacity: 100MW for 50 hours is possible.

Constant power can be provided for the full duration of the discharge. The electrolyte is safe. The design is robust – there is no plating and therefore no dendrite formation that degrades performance and reduces life. Self-discharge is approximately 2% over a few months. One downside is that the machine is large, which results in a low energy density. Therefore, this type of system is not recommended for space-constrained applications.

The next section reviews lessons learned from the EnerVault project.

8.2 EnerVault Lessons Learned

EnerVault had completed an analysis of the energy storage market prior to the ARRA solicitation. Their design was based on this assessment. A market analysis drove technical objectives, and as a result, they focused on behind the meter applications for initial deployment. The technical objectives and performance requirements were determined at the outset and remained consistent over the course of the project.

EnerVault's management believes that the ARRA energy storage demonstration projects were insightful, well timed, and had a profound impact in moving iron-chromium redox technology forward and getting it on the grid. Replicating the ARRA solicitation again would now provide another big boost to energy storage.

EnerVault initiated the interconnection process as a distributed generator one year prior to planned commissioning. Unfortunately, one year did not allow enough time for the Rule 21 interconnection process to be completed. The front end design (the electrical interface) could have been completed and the interconnection process started earlier. In retrospect, EnerVault should have started the interconnect process a year earlier.

At the proposal stage of the project, there were minimal connections to the line selected for the energy storage system. Currently, several MW of solar have been added. Therefore, voltage regulation is a problem. When the collocated 260 kW irrigation pump turns on, the site secondary line voltage drops from 480 VAC to 350 VAC for a few seconds, causing inverter anti-islanding trip outs. The Pacific Gas and Electric Company (PG&E) is required to net meter solar but PG&E is not required to allow a battery to perform arbitrage. EnerVault was caught by surprise due to the way FERC Rule 21 for expedited interconnect was applied. Initially the PG&E project manager indicated that because EnerVault was sourcing less than 1MW, there would be no problem. Later, the PG&E project manager realized that 3MW of solar were added to the line with no additional voltage regulation. This problem, combined with the non-arbitrage limitation, led to the conclusion that EnerVault would not be allowed to put power back on the grid. Fixing the line with voltage regulation to enable fully functional grid-connected operation of the Enervault system might be an appropriate project for California Electric Program Investment Charge (EPIC) funding.

Construction of the initial terms of the ARRA contract and the inability to communicate directly with DOE were major obstacles for EnerVault. At the time the application was submitted, EnerVault had four employees and was operating with limited funding. Feeling that they were too small at the time to execute the ARRA project, they partnered with Ktech Corporation.

One challenge arose from a delay in placing the ARRA contract. Initially slated to start around Thanksgiving 2009 the contract was not signed until 11 months later in October 2010. Ktech would not execute the contract with EnerVault until the contract with DOE was signed. Consequently, EnerVault had to make difficult decisions regarding maintaining the original timeline and had to reforecast every month. When the DOE and Ktech contracts were signed, EnerVault was allowed to charge back to December 2009 which was very helpful.

The concept at the outset was that Enervault would provide the stacks and cascades and that Ktech would provide the balance of plant. Raytheon acquired Ktech in early 2011 precipitating a number of challenges. Following the acquisition, Raytheon divested the division with flow process expertise. From this point onward, Raytheon was unable to deliver much of the agreed upon services. In the end, EnerVault partnered with another engineering firm to design and build the entire system. The DOE share was \$4.8M with an equal cost share borne exclusively by EnerVault. The actual EnerVault share was much greater due to additional development requirements. If EnerVault were able to go back and start over, they would do so as the prime contractor.

The structure of the ARRA contract barred EnerVault from communicating directly with NETL and DOE lacked the flexibility to re-examine the contract following the Raytheon acquisition. EnerVault would have liked to deal directly with NETL throughout the project and especially when funding was exhausted.

The state of California provides a mechanism for exempting federal funding from the state sales tax. EnerVault explored this option, but additional help from DOE would have been beneficial in identifying and completing the required application for sales tax exemption. This would have increased the federal funds available for the demonstration project.

Venture Capital (VC) funding today gets drawn primarily into software developments, where the disposition of a company is determined after 18 months (e.g., the company either succeeds or fails). Energy storage development takes place over a much longer timeframe, and it is difficult to find VC investor money for this kind of demonstration.

EnerVault has spent about \$35M to date. The project cannot yet be used for collateral for a loan until the DOE project is closed out. Project funds were exhausted in 2013 but the project is not closed out. DOE had offered to release or transfer the plant to EnerVault before closeout if the value were written off down to zero. Unfortunately, reducing the value of the plant to zero also limits the amount of collateral the plant can provide (to zero).

For Enervault, the ideal next project would have been peaker plant size (25 MW, 100+ MWh). This would have required at least $50M in capital, so there would likely have to have been an intermediate size demonstration. An intermediate project could have been a 1 MW - 2 MW, 4 hour plant for $5M - $10M. In June 2015, Enervault initiated a process to wind down the company and liquidate assets [22].

9 Pacific Gas and Electric Company (PG&E) Compressed Air Energy Storage (CAES)

The following section provides an overview of the PG&E CAES feasibility study project.

9.1 PG&E Project Overview

The goal of the PG&E ARRA energy storage project was to determine the feasibility of a 300 MW Compressed Air Energy Storage (CAES) facility in a porous rock reservoir, with up to 10 hours of storage. The project was co-funded by the DOE, the California Energy Commission (CEC), and the California Public Utilities Commission (CPUC). The PG&E CAES effort plans to utilize a porous rock formation like a depleted gas reservoir for air storage. Potential abandoned or depleted gas reservoirs in northern California are shown in Figure 9. The two utility scale CAES systems currently operating in the world employ a salt dome for the storage reservoir, so this project will be the first using porous rock. The goals of the feasibility study, which began in February 2011, are:

1. Identification, evaluation and testing of a reservoir.
2. Preliminary engineering, environmental studies, and economic analysis.

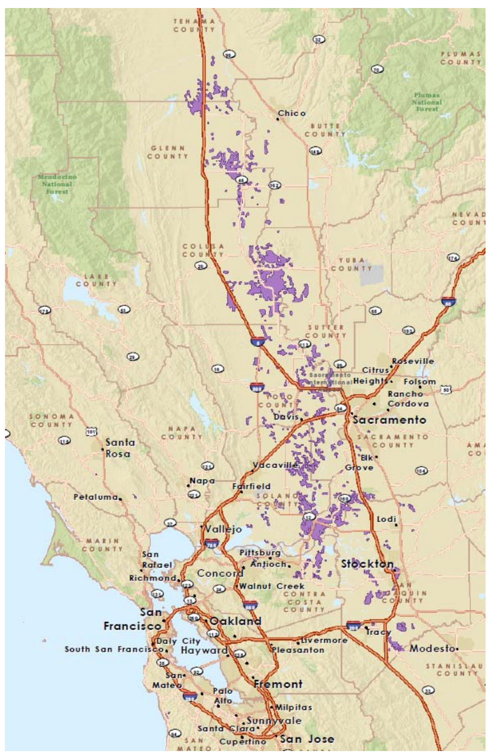

Figure 9: Abandoned or idle gas reservoirs in northern California [8].

The achievements to date include screening of over 100 reservoirs for technical feasibility, as well as core drilling at two sites. The core results show excellent permeability, porosity, and other geologic characteristics suitable for CAES. The top site has been selected for an Air Injection Test (AIT), and the engineering, procurement, and site preparation are complete for the AIT. A reservoir model has also been constructed based on three-dimensional seismic data [23].

Two factors are critical in reservoir selection: permeability and porosity. Permeability refers to the flow rate of air through the porous rock medium. Porosity is a measure of the proportion of void space available for air storage in a given sandstone. Core samples from both sites had permeability in the range of 800-2800 millidarcys (mD) and porosity of 30-32%, which are suitable for a CAES system. The next steps include an air injection test to build an air bubble that is approximately 6% of what is required for a full scale development, injection/withdrawal tests, and analysis of methane concentrations in the withdrawn stream. A Go/No-Go decision is expected to be made in 2016 after the analysis phase and Request for Offers (RFO) process is completed. If a Go decision is made, phase 2 consisting of permitting, engineering, and construction is expected to be completed in 2021 [23].

The next section provides a summary of the lessons learned from the PG&E CAES project.

9.2 PG&E Lessons Learned

To date, lessons learned can be categorized into two categories: reservoir selection and site control.

Reservoir Selection
There are many depleted or nearly depleted natural gas reservoirs that may be candidates for "re-use" to support a CAES facility. For this feasibility study which is investigating a 300 MW facility with 10 hours of storage, ten geological factors were taken into account in determining the suitability of the site for CAES:

1. Reservoir Size: Reservoirs with an air storage capacity as small as 4 billion cubic feet (Bcf) could be used though at that size, it may not be able to support the project objective of 300 MW and 10 hours. A 10 Bcf air storage capacity is more suitable; an upper limit of 20 Bcf was established to limit the time necessary to build an adequate air bubble. In regards to the aerial size, qualitatively smaller footprints are more desirable, requiring smaller development footprints.
2. Porosity: The field should have a minimum porosity of 15%.
3. Permeability: The field should have a minimum permeability of 400 mD.
4. Depth and Pressure
5. Reservoir Thickness: The minimum average reservoir thickness should be 20 feet. Reservoirs thinner than 20 feet are difficult to develop for high withdrawal capacity necessary for a storage project like CAES.
6. Remaining Reserves: The lower the volume of residual gas remaining, the better for a CAES facility in order to limit the interaction of native gas over time with the injected/withdrawn air.
7. Trapping Mechanism: Simple structures such as anticlines or fault traps are easier and less costly to develop and operate than more complex structures.
8. Number of Producing Horizons: Ideally the reservoir has a single producing formation; if not, then have having well-defined formations lend some certainty to the reservoir size and ease of development.
9. Drive Mechanism: Due to the very short injection/withdrawal cycles expected for the CAES facility, either a depletion drive or water drive mechanism will work although a weak water drives would be preferable to strong water drives simply due to the difference in gas recovery factor and the potential impact of that on the air storage operations.

10. Geological Complexity: Simpler reservoir geology is better; increased complexity leads to potential development risk and increased cost, as well as potential performance issues during the operational phase.

Site Control

Ownership complexity, as it relates to all of the rights necessary to develop and operate a CAES facility, have a direct correlation to the probability of success. Were the mineral rights retained by the surface owner or severed? If the mineral rights were severed, were the mineral rights retained as a whole or were they also severed and owned by multiple entities? What were the economic and commercial terms required by the owners of the various rights? To the extent there are/were more than one owner, the owners would all have different perspectives of the value of their rights as well as specific commercial and/or non-commercial terms that were important to them.

10 DTE Energy

The following section provides an overview of the DTE energy community energy storage demonstration project.

10.1 DTE Project Overview

The goal of the DTE ARRA project was to demonstrate the value of distributed energy storage that is often referred to as Community Energy Storage (CES). In addition, the project includes the deployment of secondary use Electric Vehicle (EV) batteries, as well as another 500 kW battery system for PV integration [9]. Eighteen CES units were installed with the following characteristics. Seventeen of the units are on one distribution circuit fed from a substation named Trinity. One

Table 6: DTE CES parameters [9].

Paramerer	**Value**
Power	25 kW
Energy	50 kWh
Voltage	240/120 VAC
Battery	Li-Ion

system was installed in a training yard. The eighteen units were installed in 2013 with the battery located in a below ground vault. The inverter was mounted on the vault cover next to a distribution pad-mount transformer, as shown in Figure 10.

The 500 kW, 250 kWh battery system is collocated with a 500 kW of PV generation as shown in Figure 11. The system is located on the same circuit as the 17 CES units and can be included as part of the aggregated fleet of energy storage on one circuit. The 500 kW system was commissioned in September 2014.

The following grid functions will be evaluated by the DTE project [9]:

- Voltage/VAR support
- Islanding during outages
- Frequency regulation, e.g., response to an AGC signal
- Renewable energy time shift
- Renewable generation smoothing
- Circuit peak shaving
- Energy arbitrage, e.g., discharge during high LMP price
- Circuit model commands

The project also created a DNP3 (Distributed Network Protocol) master in the Distributed Resource Management System (DRMS) to communicate to individual energy storage systems and to aggregate all system as a fleet.

The two re-purposed EV batteries are demonstrating the use of used automotive EV batteries for grid applications. The re-purposed (or secondary use) batteries are from six Fiat 500e vehicles that had reached end of life. The two battery systems are configured as 25 kW with one at 47 kWh and the other at 94 kWh. Prior to installation, one of the battery systems will be tested at DNV GL.

Figure 10: DTE CES system installation. In the bottom right photo, the CES is located to the left and the transformer is located on the right [9].

Figure 11: DTE 500 kW system collocated with a 500 kW PV [9].

The test plan for the project is listed in Table 7. Each CES can be addressed individually or in the aggregate fleet mode. The DEW Service mode is a model-centric operating mode that uses the electrical circuit model to make recommended setting to the CESs.

The next section provides a summary of the lessons learned from the DTE project.

10.2 DTE Lessons Learned

As expected in a new technology demonstration project, there are many challenges that surface as the project progresses. This section provides highlights of the lessons learned. Additional details

Table 7: DTE CES test plan.

Requirement	Test Performed	Component Tested	Mode of Operation
DRSOC-CES-001	Data usage test	Cellular communications	Standby/hub command
DRSOC-CES-002	CES maintains minimum reserve margin	CES controller logic	Hub command
DRSOC-CES-003	CES unit will operate safely when unit is at 100% SOC and is given a charge command	CES controller logic	Hub command
DRSOC-CES-004	CES unit will operate safely when kW and kVAR setpoints cause the unit to exceed discharge kVA rating	CES controller logic	Hub command
DRSOC-CES-005	CES unit will operate safely when kW and kVAR setpoints cause the unit to exceed charge kVA rating	CES controller logic	Hub command
DRSOC-CES-006	DRSOC Hub will dispatch a reasonable setpoint when algorithms command a kW setpoint that exceeds unit charge rating	DRSOC Hub	Hub command
DRSOC-CES-007	DRSOC Hub will dispatch a reasonable setpoint when algorithms command a kW setpoint that exceeds unit discharge rating	DRSOC Hub	Hub command
DRSOC-CES-008	DRSOC Hub will distribute fleet kW charge or discharge accross all units based on SOC of each unit	DRSOC Hub	Hub command
DRSOC-CES-009	CES efficiency	CES efficiency	Hub command
DRSOC-CES-010	DRSOC Hub will issue commands per a set schedule to produce renewable energy time shift	DRSOC Hub	Schedule
DRSOC-CES-011	DRSOC Hub will issue commands per a set schedule to produce electric energy time shift	DRSOC Hub	Schedule
DRSOC-CES-012	DRSOC Hub will send commands to CES units based on simulated AGC signal	DRSOC Hub	AGC
DRSOC-CES-013	DRSOC Hub will discharge CES fleet to maintain maximum kW at the circuit feeder	DRSOC Hub	Peak shaving
DRSOC-CES-014	Charge when needed for reserve capacity	DEW Service	DEW
DRSOC-CES-015	Discharge when price is high and unit is not needed	DEW Service	DEW
DRSOC-CES-016	Do not charge when could cause overload	DEW Service	DEW
DRSOC-CES-017	Do not discharge when it would cause overload	DEW Service	DEW
DRSOC-CES-018	Resolve transformer overload by discharging	DEW Service	DEW
DRSOC-CES-019	Resolve low voltage by supplying vars	DEW Service	DEW
DRSOC-CES-020	Resolve high voltage by absorbing vars	DEW Service	DEW
DRSOC-CES-021	Resolve low voltage by discharging	DEW Service	DEW
DRSOC-CES-022	Resolve single-phase primary overload by discharging only batteries on that phase while charging others (low price)	DEW Service	DEW
DRSOC-CES-024	Forecast overload alert	DEW Service	DEW
DRSOC-CES-025	Minimum profit margin test	DEW Service	DEW

will be published in the DTE final technical report.

Financial difficulties of the original battery manufacturer forced DTE to find a new battery supplier. This delayed the installation of the CESs and the 500 kW batteries. The CES integrator, S&C Electric, assisted in identifying an alternative Li-ion battery provider. Other challenges were related to the development and integration of a battery system with complex software that can survive in a harsh environment. Detroit is in a northern latitude (42° N), which potentially exposes the system to immersion in water, extreme temperatures (high and low) and high humidity.

As the project developed, the CES system was sent to a nationally recognized testing laboratory for IEEE 1547 certification. This enabled the electric utility system project engineers to accept this new equipment on the electric grid without requiring detailed system studies for each installation. The first CES was successfully tested at the DNV GL (Kema) battery test facility. Basic functionally was tested, including the uses cases listed below.

- Round trip efficiency
- Peak shaving profile test
- Frequency regulation profile test
- Islanding test
- Harmonic analysis

Over ten trials, the round trip efficiency typically varied between 87% and 90%. The ability of the system to follow a representative frequency regulation signal was also verified. In addition, DNV GL performed cost effectiveness studies on the value of regulation services and peak shaving of the battery system on the Trinity circuit.

The first CES was installed in a training center to verify engineering standards documents, operating procedures and to provide training to the underground field crews who would be installing and maintaining the CESs on the Trinity circuit. Engaging engineering and field crews in a new technology project is very important to gain acceptance. It also allows for them to provide feedback that can be incorporated in future designs and operational improvements.

Community engagement was key to the success of this project. The community was contacted and provided information on the project to gain their approval, even though the CES was installed in the utility easement. Nearby homeowners were also contacted directly to answer questions on the battery installation. Circuit modeling was performed to identify distribution transformer loading. Potential sites were identified that would enable serving customers for at least two hours in the event of an outage. The final site selection was based on accessibility for installation, maintenance and repair (a field visit evaluated each potential site).

Testing of all use cases identified in Table 7 is on-going and will be reported on in the DTE final technical report.

11 SustainX

The following section provides an overview of the SustainX energy storage project.

11.1 SustainX Project Overview

SustainX, located in Seabrook, NH, is developing a Compressed Air Energy Storage (CAES) system. Their technology is based on the isothermal compression of an air-water foam. In 2013, the company completed construction of their first MW-scale CAES system, shown in Figure 12.

The SustainX system is referred to as the S165 and is nominally rated at 1.65 MW. The S165 uses a crankshaft drivetrain (based on a marine diesel engine) coupled to two-stage compression/expansion cylinders to compress a mixture of air, water and a foaming agent. The mass ratio of water to air is 2:1. When compressed to 3,000 psi, the temperature rise of the air-water mixture is 50° C. Energy capacity and charge or discharge time depend on size of the compressed air storage element. At their in-house installation, SustainX uses large ASME pressure vessels. It is also possible to store the same compressed aqueous mixture in lined rock caverns.

Construction started in January 2013 and was complete in August 2013. Full power operation was attained in September 2013. The system can discharge at 1.5 MW and charge at 2.4 MW. For testing purposes, discharge is done into a load. Since the start of testing, round trip AC-AC efficiency increased from 45% to 54%.

The next section provides a summary of the lessons learned from the SustainX project.

11.2 SustainX Lessons Learned

Over the course of their development program, SustainX technology evolved through three stages. A 1 kW system was used as proof of concept. A 40 kW system was the first system developed under DOE funding. It used a lower speed hydraulic drivetrain to drive the air compression/expansion cylinders. Going through these steps influenced the design of the current system.

The evolution of the product was largely driven by potential utility partners who were not interested in storage systems rated less than 1 MW. A revenue model based on Levelized Cost of Energy (LCOE) drove the understanding that capital costs were more important than efficiency. The original target for efficiency was 50% and this has been exceeded.

The SustainX team relied heavily on model-based design principles and software tools from the Mathworks. The models were derived from first principles and automatic code generation was employed for the control loops in the system. This approach enabled hardware-in-the-loop testing and greatly accelerated the system design, implementation, and testing.

Figure 12: SustainX 1.65 MW isothermal CAES.

12 Primus Power

The following section provides an overview of the Primus Power energy storage project.

12.1 Primus Power Project Overview

Primus Power Corporation, based in Hayward, CA, develops zinc flow batteries for stationary applications. The Primus battery module, the EnergyCell, can store 72 kWh of energy with a discharge time of 3.6 hours at its nominal voltage of 20 kW. The EnergyCell can discharge at slower or faster rates (down to 7.2 hours at 10 kW or 2.4 hours at 30 kW). The EnergyPod® comprises 14 EnergyCells housed in an International Organization for Standardization (ISO) shipping container and has a nominal rating of 280 kW DC. Primus Power is preparing to deploy the first EnergyPod® in San Diego at Marine Corps Air Station Miramar in a solar-plus-storage project with Raytheon. That project will be deployed in June 2015. Following that, Primus will deploy a system at a Puget Sound Energy substation on Bainbridge Island near Seattle in a distribution upgrade deferral project and at the Ripon Generating Station in the Modesto Irrigation District (MID) utility area. The system at MID will be controlled from the MID load office and will follow a signal that optimizes gas generation to balance renewables. Primus will also deploy a number of EnergyCells in 2015 in behind-the-meter applications to manage energy and demand charges for commercial and utility customers. The first project will be at a factory near Los Angeles in June.

Figure 13: Primus Power EnergyPod® (left) and EnergyCell (right) [10].

When Primus Power applied for the ARRA grant, it had not yet built the first prototype. ARRA funding was used for stack development. The challenge was to get to a containerized system with low cost (capital and Total Cost of Ownership (TCO)) and high power density. Primus did a market scan at the beginning of the ARRA project and developed cost goals early on from a 2010 Sandia report [24]. Primus is focusing on applications that require frequent, multi-hour deep discharge of the battery – a use profile that is difficult for Li-ion batteries because of their limited deep-discharge cycle life.

The Modesto project is a turnkey project that delivers power to MID at 480 VAC. For this project, Primus had to complete a California Environmental Quality Assessment (CEQA). Installing at a generator site and not changing the boundary simplified permitting. There were no code compliance challenges. Developing the relationship with local fire department and first responders was important. Primus had to produce:

1. a hazardous material plan,

2. a fire suppression plan (lacking codes or standards, they used a CH2MHill plan for natural gas generators), and
3. a spill plan.

Primus intends to offer commissioning as a service. When installed in Ripon, the system will demonstrate peaking capacity, spinning and non-spinning reserve, and balancing solar. For the initial deployment, the Primus energy management system will provide only one grid service at a time, but in the future the software will be upgraded to handle multiple concurrent value streams.

A big challenge is anticipating O&M cost. Maintenance is understood but more running time is required before reliability is understood. Primus measures voltage and many other key indicators at the cell and stack level to manage performance and ensure reliability. Primus is over-instrumenting early systems to provide comprehensive performance data.

The Primus goal is deep cycling with long life – duration without degradation. This leads to lower TCO and other benefits. Within the energy battery space, Primus should have higher power density resulting in fewer cells and lower cost. Primus is working to further reduce the EnergyPod® footprint for increased energy and power density. A major lesson learned was the importance of communicating the development ramp to potential customers. Performance requirements evolved slightly over time. Development started with 3-hour duration. Modesto will get a 2-4 hour system.

The Primus system can quickly switch between charging and discharging. A challenge is that frequent mid-range charge/discharge cycles can lead to dendrite formation. A strip cycle (a process of shorting the battery terminals across a low impedance shunt, while the electrolyte pumps are running, that removes excess zinc from the battery stack) is used to remove any zinc deposits [25]. It is a non-productive discharge that takes 15-30 minutes. Strip cycles have to be done about once a week, so individual modules are strip-cycled while the rest of the system remains on line.

The next section provides a summary of the lessons learned from the Primus project.

12.2 Primus Power Lessons Learned

According to Primus, the ARRA investments categorically kick-started the energy storage industry. There is a large ecosystem that did not exist at the start of the project with companies currently becoming highly advanced. In order to move the energy storage industry forward, Primus believes that the next round of government funded projects should focus on reference projects that get storage to a tipping point. For Primus, the next tier would be a 2 MW reference project. It would also be helpful if the DOE loan guarantee program could encompass projects of this size.

Initially, Primus targeted objectives based on the following metrics: kW rating, kWh rating and cost. After extensive market research, Primus is now also considering end customer revenue models such as a utility build-own.

Primus plans to design for a prefabricated enclosure instead of a container for future systems, especially multi-MW scale. This lowers capital and maintenance costs and can optimize site design.

Utilities are starting to adopt energy storage for a variety of functions. The market will grow as the technology is proven and profitable applications are demonstrated. Primus is focused on high energy applications that are not economical for Li-ion technologies. Primus will provide some ancillary services, but not as its main applications focus. As Primus comes to market, bankability is a significant concern and the company is working with a number of potential partners to bridge this gap.

On the regulated side, Primus believes that Transmission and Distribution (T&D) deferral is a real market and would be appropriate for a reference project. Once storage is installed for T&D deferral, it can be used for other applications. Primus believes that the market for distributed peaking using energy storage is challenged by low natural gas prices. But in some areas, storage is already beating gas turbines for peaking applications. AES is a leader in this area and won an energy storage peaking project competing against natural gas turbines at Southern California Edison.

Oncor in Texas owns assets and addresses T&D deferral. The population of Texas will double over the next 25 years and a significant quantity of photovoltaic and wind generation will be added. These factors will tax distribution systems and create market opportunities for distribution-level storage.

For Primus, the ideal 2 MW reference plant would require a $10M investment and will address one of the following applications:

1. Solar farm in southern California connected to the solar on the DC bus,
2. High penetration feeder - solar at the end of a feeder is a problem that storage can address,
3. Customer sited – behind the meter (large commercial/industrial enterprise).

Primus states that energy storage-specific market structures do not exist at this time but will come in the future. Technology is coming along but markets are structured to generate and deliver power. The markets that currently exist for storage are behind the meter, at generators experiencing ramping challenges, or for T&D deferral.

According to Primus, one of the great successes of the ARRA energy storage demonstration projects is that they are proving that grid-connected energy storage systems can provide value to the ratepayers. There are times that vertically integrated utilities do not make a good case for valuing energy storage.

13 Amber Kinetics

The following section provides an overview of the Amber Kinetics, Inc. energy storage project.

13.1 Amber Kinetics Project Overview

Amber Kinetics, headquartered in Union City, CA, has spent several years researching, developing and testing flywheel energy storage systems for utility grid connected applications. The company's stated ambition is to produce cost-effective, multi-hour flywheel systems at commercial scale.

The company's 1^{st} generation flywheel system stored a total of 5 kWh of energy in a high-strength steel rotor that weighed approximately 750 pounds. The unit was designed, built and tested in California.

Figure 14: Amber Kinetics, first generation flywheel system [11].

Spin testing for the 1^{st} generation flywheel rotor was conducted at Test Devices, Inc., in Hudson, MA. The design surface speed at 5 kWh was approximately 375 m/s at 7500 revolutions per minute (RPM). During spin testing, the surface speed attained was 530 m/s at 11,000 RPM. Kinetic energy of the rotor at 11,000 RPM was 10 kWh.

Data gathered on the 1^{st} generation flywheel system, including coasting loss and ancillary power consumption, was collected from 70 tests. Amber submitted a full technology report to the NETL in April 2012 [26].

Amber Kinetics is currently developing a 2^{nd} generation flywheel energy storage system, shown in Figure 15, that is designed to source or sink 25 kWh over a 4-hour charge or discharge time. An alpha prototype of the 2^{nd} generation system has been designed, built and tested at the company's outdoor test facility in Alameda, CA; a beta prototype is presently being prepared for further testing and data gathering.

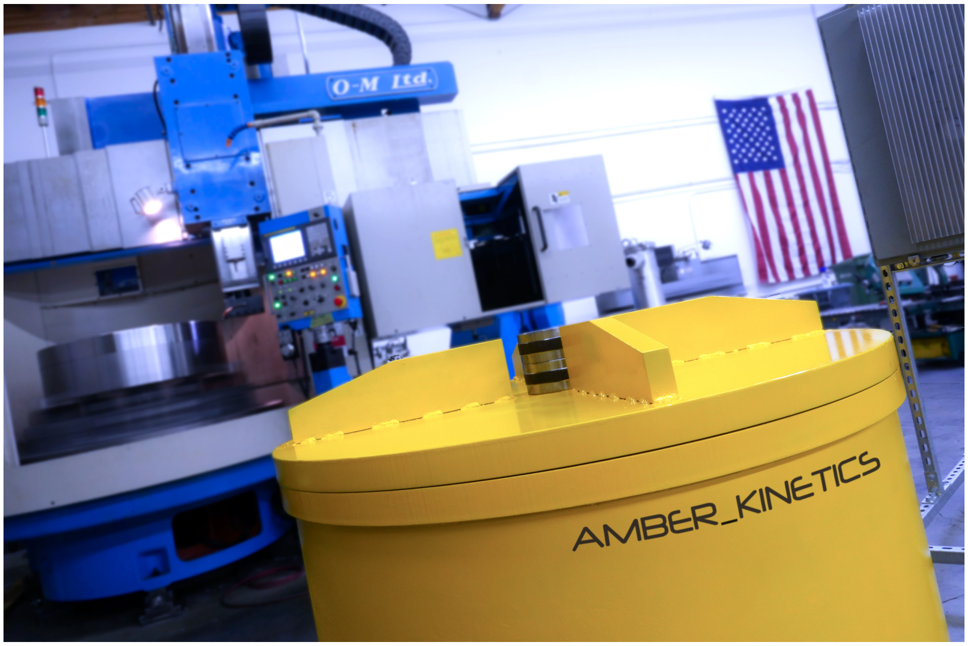

Figure 15: Amber Kinetics, second generation flywheel system [11].

The company has operated on funding provided by a DOE ARRA (NETL) contract, a California Energy Commission (CEC) contract, the Hawaii Energy Excelerator, and private investor funding.

In the 2^{nd} generation flywheel system, the principal energy storage element within the system is a monolithic steel rotor produced using clean steel manufacturing technologies. High speed testing on the 2^{nd} generation system began in the fall of 2014.

The intent of the Amber Kinetics approach is to produce a cost-effective energy storage system capable of continuous cycling with no degradation over a 30 year life before recycling or recertification.

The next section provides a summary of the lessons learned from the Amber Kinetics project.

13.2 Amber Kinetics Lessons Learned

The primary lessons learned from the Amber Kinetics project are listed below.

- The steel flywheel rotor in the 1^{st} generation flywheel design achieved tip speeds which were higher than expected going into the development program; this proof point led the Amber team to conclude that steel, based on a cost to performance ratio, was a very low cost energy storage material.
- The Amber team concluded that cost reduction could be achieved by maximizing the amount of energy stored in a given volume. The 1^{st} generation flywheel used a thin rim rotor design and stored 5 kWh of extractable energy. For the 2^{nd} generation, Amber adopted a monolithic rotor configuration. This reduces cost in two ways. For monolithic and thin rim rotors having the same volume, the monolithic rotor will have much greater mass and therefore store much more energy. In addition, for an isotropic rotor material, the monolithic rotor stores more energy per unit mass than the thin rim. Consequently, the 2^{nd} generation flywheel design occupies a volume similar to that of the 1^{st} generation flywheel but is designed to store 5x the extractable energy (25 kWh).

- Data collected on coasting losses (from bearings, drag losses, and electrical losses) and charge/discharge efficiencies are in line with predictive analytical models.
- In the process of developing and building both the 1^{st} and 2^{nd} generation flywheel systems, Amber worked with material and manufacturing vendors in both the United States and abroad. Based on actual purchase orders and forward-looking quotes, Amber expects that raw material costs of steel are low enough for flywheels to be cost-effective; however, the company points out that manufacturing processes are fragmented and it will require processes to be consolidated under one company to drive down flywheel system costs on a $/kWh basis.

14 Seeo

The following section provides an overview of the Seeo, Inc. energy storage project.

14.1 Seeo Project Overview

Seeo is a growing company located in Hayward, CA that is developing a new type of lithium battery referred to as DryLyte^{TM} [27]. Potential benefits of this technology include increased energy density, longer lifetime, improved safety (relative to other lithium-ion technologies), and reduced cost. Two promising applications are electric vehicles and large-scale renewable energy storage. The Drylyte^{TM} cell is solid state meaning that a nanostructured solid polymer electrolyte functions as a cathode and a separator and lithium metal are used for the anode. The technology originated with nanostructured polymer electrolyte initially developed at the Lawrence Berkeley National Laboratory under funding from the DOE Batteries for Advanced Transportation Technology (BATT) program. Seeo undertook the ARRA project to scale the technology from experimental cells to a 10 kWh prototype battery system. Figure 16 shows a timeline of the program.

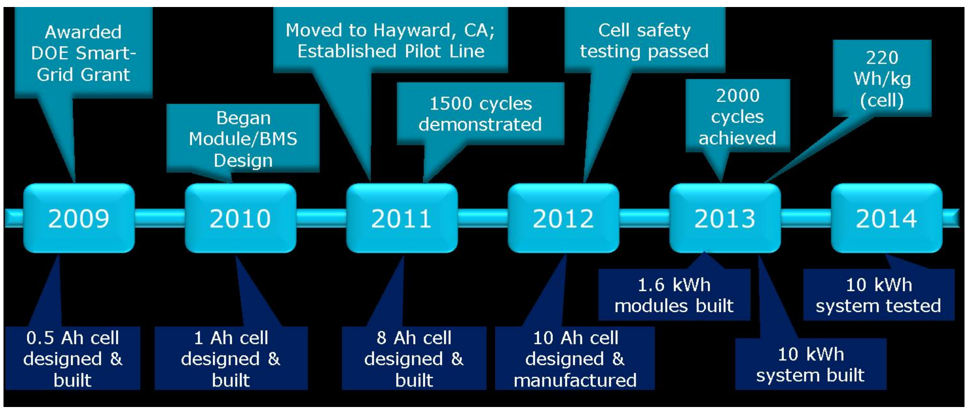

Figure 16: Seeo, Inc. timeline of program and major achievements [12].

The original objective of the ARRA project was to develop a 25 kWh system. During that effort, the design capacity was reduced to 10 kWh. This change was implemented so that the same battery design could be employed for both the ARRA project and a DOE SunShot Program project. The 10 kWh size was better suited for residential or commercial energy storage systems targeted by the SunShot Program. Other than capacity, there is no difference in functionality between the 10 kWh and 25 kWh systems.

Seeo assembled the system, conducted internal testing and an initial field demonstration. During the field demonstration, the battery initially performed as expected accepting charge from the photovoltaic array and discharging to the grid. Unfortunately, after one month the battery system experienced a failure due to an overvoltage condition that resulted in the loss of the system. Additional information about the field testing can be found in [12].

Over the course of the program, Seeo scaled cell area and capacity up 100x from the initial cells to the current large format 10 Amp-hour (Ah) cells. Seeo expanded solid polymer electrolyte manufacturing from laboratory batches to production batches by developing a manufacturing process and Seeo also built a cell pilot fabrication line in-house.

The Seeo manufacturing process is similar to traditional lithium-ion manufacturing with three main differences, all of which simplify the process, reduce cost and improve performance:

1. There is no need for anode coating as the anode is lithium metal.
2. Electrolyte filling is a cumbersome, quality sensitive step in traditional fabrication. Seeo applies the electrolyte to the cathode as a second coating, eliminating the need for electrolyte filling.
3. No formation is required avoiding the process time and manufacturing investment normally required for this step.

The 10 kWh pack uses large format 10 Ah cells. The cells are rated at 0.5° C for continuous discharge and can provide peak power pulses at 3° C for a 30 second discharge. The cells have a voltage range of 2.5 V when discharged and 3.6 V when fully charged. Operating the cells at partial state of charge does not significantly reduce the lifetime of the battery. For the project, the cells were assembled into 1.64 kWh modules weighing approximately 10 kg. The production cells have been tested to 1000 cycles with in excess of 90% of original capacity remaining. Extrapolating from this result, production cells are expected to attain 3000 cycles while retaining 80% of capacity.

The current DryLyte^{TM} battery cell product offering has a specific energy of 220 Wh/kg, which represents an improvement of 40% or more over other existing large format battery cells. Seeo is currently demonstrating Research and Development (R&D) cells that are showing stable performance at specific energy in the range of 300 to 400 Wh/kg.

The next section provides a summary of the lessons learned from the Seeo project.

14.2 Seeo Lessons Learned

The ARRA program was essential in scaling from laboratory size up to large format. The investment in a pilot line has allowed Seeo to start selling to the United States Advanced Battery Consortium (USABC) and others for use in test environments. The achievements under the ARRA project were instrumental in attracting additional investments in the company. Samsung Ventures, along with Khosla Ventures and GSR, invested an additional $17M in Seeo in December, 2014.

Seeo is addressing both stationary and EV markets. Cell chemistry is the same for both markets; the module is similar for both markets, but systems are different for the two markets. Seeo believes that vehicles and stationary applications benefit from higher specific energy density and lower cost. These attributes go together – high energy density means less material and lower cost. Therefore, an appropriate goal for future government R&D projects is continued investment towards increased energy density and lower cost cells.

Original Equipment Manufacturer (OEM) customers expect suppliers to be around for a long time and to have the wherewithal to survive a $100M recall, should the event arise. An investment of a few hundred million dollars does not make a small company a credible supplier to an OEM. Therefore, an effective approach is for a small company to remain focused on technology development and scale up through partnerships. Seeo has been following this business model as it increases the technology readiness level of the DryLyte^{TM} battery.

15 Vionix (formerly Premium Power)

The following section provides an overview of the Vionix energy storage project.

15.1 Vionix Project Overview

Premium Power is in the process of reorganizing into a new entity, Vionx Energy, located in North Reading. In partnership with United Technologies Corporation (UTC), Vionx is developing vanadium redox flow batteries X-FLOW^{TM} technology, based on UTC patent pending Inter-Digitated Flow Field and other Vanadium Redox Flow Battery (VRFB) related advancements.

Figure 17: Vanadum redox flow battery [13].

In the mid 2000s, Premium Power was engaged in the development of Zinc Bromide flow batteries for stationary applications such as a 45kWh and 150 kWh UPS system for cell towers and data centers. At the outset of the ARRA program in 2009, Premium Power was embarking on an effort to commercialize a multi-hour, 500 kW, 480 VAC system based on Zinc Bromide batteries referred to as the TransFlow 2000. The intent of the ARRA project was to demonstrate TransFlows at 3 sites including the Sacramento Municipal Utility District (SMUD), Syracuse, NY and Everett MA. The TransFlow 2000 systems were not deployed.

In late 2013, Premium Power realized an opportunity to work with UTC. In early 2014, they created a new entity, Vionx, to commercialize the UTC stack design and VRFB advancements. Premium Power's systems development team began working on a new flow battery system using the UTC technology. Prior to this pivot, the most difficult challenges were improving performance and longevity of the zinc-bromine stack. While addressing this challenge, Premium Power developed significant experience in stack design and interaction of the stack with the balance of plant. Much of the balance of plant knowledge was directly applicable to the new stack technology.

Vionx accelerated progress transferring UTC VRFB technical knowledge beginning in 2014. Stack level testing is ongoing. In 14 months, they have progressed from the pivot to having accumulated 3,000 hours of run time on the first stack. Currently under testing are a 3 kW, 10 cell stack and a 6 kW, 20 cell stack. The current cell operates at twice the power per unit area compared to competing cells. They operate between 20% State of Charge (SOC) and 80% SOC meaning they use 60% of the Vanadium ions. Vionx forecasts a cycle life greater than 2000 for the first stacks and are targeting a 20 year life for production stacks.

Vionx started a design intent stack design in May, 2014. They worked on seals, flow fields and geometry. This has evolved into a full design intent using high volume production methods and materials. The initial product will have two stacks housed in a customized shipping container with an output of 65 kW for six hours. Vionx plans to use a DC connection to the application up to 500 kW designed to be compatible with most commercially available power conditioning systems (PCS). Systems configured for utility-scale applications are planned to source 500 kW on a 500 VDC to 800 VDC bus.

Vionix has a contract to build a 160 kW, four hour system to be installed at Fort Devens, MA in 2015. The current ARRA project plan extends to 2018 in order to accumulate 24 months of run time. Vionx is executing a progression from stacks to a 500 kW system.

The next section provides a summary of the lessons learned from the Vionix project.

15.2 Vionix Lessons Learned

Vionx expects that the greatest strength of their technology will be providing long run time at low cost. Applications requiring a 4-10 hour discharge represent the market where flow batteries compete successfully with lithium ion batteries. An additional benefit, common to all flow batteries, is the decoupling of power and energy. Compared to other flow battery technologies, they have twice the power per unit area. Since the stack is an expensive component, this results in a significant cost savings. Their current project is ideal and they are seeking expanded funding for it. Knowledge gained on the balance of plant design from the zinc bromine effort has been relevant to ongoing vanadium redox flow battery development. Their core competency is battery technology: stacks, modules, balance of plant, and software. Vionx prefer to work with a partner for integration, installation and commissioning. Their initial systems are primarily targeted towards distribution level storage. The primary applications are T&D deferral and renewable integration and firming.

16 City of Painesville

The following section provides an overview of the City of Painesville vanadium redox flow battery energy storage project.

16.1 City of Painesville Project Overview

The City of Painesville and Ashlawn Energy, LLC, undertook a project to build a one-megawatt, eight-hour, Vanadium Redox Flow Storage (VRFS) Battery for installation at the Painesville Municipal Power Plant in Painesville, Ohio. The plant is coal fired and rated at 32 MW. The objective of the project was to demonstrate reducing carbon footprint by peak leveling.

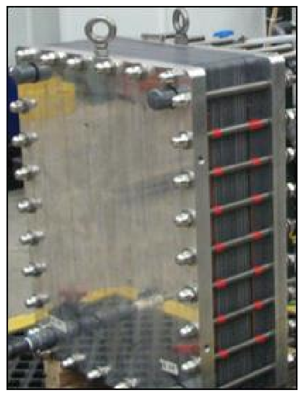

Figure 18: Ashlawn Energy vanadium redox flow battery 10 kW Stack [14].

The City of Painesville contracted with Ashlawn Energy, LLC to manage and build the battery as well as to prepare and provide all reporting to DOE. Ashlawn Energy secured a license for the core battery technology from V-Fuel, New South Wales, Australia. They developed a supplier base comprising InnoVentures LLC, Concurrent Technologies Corporation (CTC), ITEN, MAGNET, and others.

The City of Painesville funded construction of a new 4,900 square foot Butler building to house the battery at the site of its Municipal Power Plant. City funding of the construction represented part of project cost share. Five patent applications were filed for improvements to the VRFB made by Ashlawn Energy engineers.

Painesville assesses that the project is approximately half complete. Technical expertise has been acquired. The building to house the battery has been built and electrical service to the building has been installed. The drawing package for the battery stacks are estimated to be 95% complete and provisions have been made to procure all battery stack components, including molds to mass produce battery frames. The balance of plant plans are complete including selection of a vendor for the inverters. Ten prototype stacks rated from 2.5 kW up to 10 kW have been built. Prototype stacks have been tested and characterized at CTC. Six extant stacks are retained by Ashlawn.

The next section provides a summary of the lessons learned from the City of Painesville project.

16.2 City of Painesville Lessons Learned

The awardees had planned for receiving project matching funds from the state of Ohio under the Ohio Air Quality Development Authority (OAQDA) Advanced Energy forgivable loan program.

After a change in Administration, funding appropriation was withdrawn by the State of Ohio from this program resulting in insufficient funds to complete the project.

17 Summary and Conclusions

In general, the ARRA energy storage demonstration projects were very successful in advancing the energy storage industry. The smaller technology demonstration projects increased the technology readiness level of several different technologies. Aquion Energy successfully demonstrated in a laboratory setting its Aqueous Hybrid Ion (AHI^{TM}) battery based on a saltwater technology. Seeo significantly increased the technology readiness level of their solid state lithium battery, going from laboratory cells to small scale production of a large format cell. The success of the ARRA project was instrumental in attracting an additional $17M in venture capital funding. Amber Kinetics successfully demonstrated a first generation low-cost flywheel and has made significant progress on a second generation device. SustainX developed and demonstrated a 1.65 MW isothermal CAES system that employs an air-water foam solution.

The large-scale grid connected demonstration projects were instrumental in increasing the maturity of the technology and proving revenue models for several different systems. Beacon Power successfully deployed a second generation flywheel plant in Hazle Township. In conjunction with the Stephentown plant, these systems have demonstrated the benefits and commercial viability of flywheel frequency regulation plants. The PNM and East Penn projects successfully established the benefits of the Ecoult UltraBattery® system for frequency regulation and other partial state of charge applications. The SCE Tehachapi project illustrates the potential for utility-scale lithium ion systems. The Duke Notrees system has validated the benefits of energy storage for firming wind generation and providing frequency regulation. Some notable lessons learned and recommendations are listed below:

- Permitting risks are often severely underestimated. For the Beacon system, this included the NPDA discharge system. PNM was one vote away from being denied by the county zoning department with respect to fire hydrants, handicap parking, and code compliance. In the East Penn case, the local code officer was unfamiliar with battery technologies. Both SCE and EnerVault underestimated the CAISO interconnection process. EnerVault was required to complete a biological survey for nesting raptors.

- Transportation of energy storage system components can take longer than expected if the Homeland Security Department classifies them as oversize/overweight. This limits travel to daylight hours and delays delivery.

- Codes for stationary energy storage would decrease the complexity of the permitting and construction process.

- Deployment of a small scale test system can significantly reduce development and integration time. Benefits include:
  - performance testing,
  - environmental testing,
  - safety testing,
  - power conversion controls testing,
  - and utility network interface testing.

- For distribution level energy storage, initial installation in the utility training center enables: verification of engineering standards documents; verification of operating procedures; and training for the underground field crews who will be installing and maintaining the CESs.

- Streamlining the requirements for the DOE loan guarantee program and reducing the minimum loan size would be very beneficial for future energy storage demonstration projects, especially in light of the lack of availability of venture capital funding for longer time horizon demonstrations.

- Additional DOE support for future energy storage demonstration projects will help increase adoption by facilitating validation of the economic viability of energy storage system technologies.

- Several industry participants are focused on T&D deferral and time-shifting markets. These participants have demonstrated < 1 MW installations with the goal of eventually developing 20 MW to 50 MW scale facilities. These participants indicated a need for a subsequent demonstration, loosely referred to as a reference project, on the scale of 1 MW to 5MW as a necessary risk mitigation step before proceeding with > 20 MW installations.

- The industry participants concur that frequency regulation ancillary service currently represents an economically viable market for grid connected energy storage. There is general consensus regarding economic viability of a number of markets on the customer side of the meter. However, there is a range of views regarding economic viability of markets on the utility side of the meter beyond frequency regulation. T&D deferral and time-shifting were cited most frequently as the next likely opportunities.

- Utilities generally, and vertically integrated utilities in particular, have historically found it challenging to identify optimal implementation for energy storage. Utility participants report that the experience gained through the ARRA program will make future installations more targeted and precise.

- A competitive offering for some continued support of the successfully executed large-scale grid connected ARRA energy demonstration projects would be beneficial. This support would be used to continue testing and evaluation of existing systems, further refine the operation to maximize revenue or benefit to the grid, and to disseminate results. Given the large initial investment, a relatively small additional investment would guarantee that the results from the projects are communicated over the expected life of the plant.

- The structure of the ARRA contracts required award recipients to store test data and to insure that the data was adequately saved in perpetuity, but did not call for the data to be shared with the government. In the future, government contracts for energy storage demonstrations should have clauses that allow access to all test data, if requested.

- The majority of the energy storage technology companies have struggled to develop a network of distributors and system integrators, and often have ended up designing, building, and operating plants in order to deploy their own technology. Aquion intentionally designed their battery to emulate the electrical characteristics of a traditional lead acid battery. Because this is an established technology, they were able to quickly build a network of distributors and integrators.

References

[1] J. Areseneaux, “20 MW flywheel energy storage plant,” in *2014 DOE/OE Energy Storage Systems Program Peer Review*, (Washington, DC), September 17-19, 2014.

[2] S. Willard, “PNM’s Prosperity energy storage project,” in *2013 DOE/OE Energy Storage Systems Program Peer Review*, (San Diego, CA), October 24-25, 2013.

[3] Ecoult, “East Penn installation.” www.ecoult.com, March 2015.

[4] L. Gaïllac, “Tehachapi wind energy storage project,” in *2014 DOE/OE Energy Storage Systems Program Peer Review*, (Washington, DC), September 17-19, 2014.

[5] Duke Energy, “Technology performance report: Duke Notrees wind storage demonstration project,” tech. rep., Duke Energy, July 2014.

[6] A. Energy, “Company & technology overview.” slide presentation, 2015.

[7] EnerVault, “Turlock plant photo.” www.enervault.com, March 2015.

[8] A. Narang, “PG&E compressed air energy storage,” in *Proceedings of the 2011 Electrical Energy Storage Applications and Technologies (EESAT) Conference*, (San Diego, CA), Oct 2011.

[9] H. Askeirsson, “DTE Energy large field deployment of community energy storage,” in *Proceedings of the 2014 DOE Energy Storage Program Peer Review*, (Washington, DC), September 2014.

[10] Primus Power, “EnergyPod® and EnergyCell product literature.” www.primuspower.com, March 2015.

[11] S. Sanders. private communication, March 2015.

[12] Seeo, Inc., “Recovery Act – solid state batteries for grid-scale energy storage,” tech. rep., Seeo, Inc., March 2015.

[13] Vionx. www.vionxenergy.com, March 2015.

[14] J. McHugh, “Technology performance report, vanadium redox flow battery project,” tech. rep., City of Painesville, Ohio, February, 1, 2015.

[15] Southern California Edison, “Tehachapi wind energy storage project, technology performance report #1,” tech. rep., Southern California Edison, December 2014.

[16] A. A. Akhil, G. Huff, A. B. Currier, B. C. Kaun, D. M. Rastler, S. B. Chen, A. L. Cotter, D. T. Bradshaw, and W. D. Gauntlett, “DOE/EPRI 2013 electricity storage handbook,” Tech. Rep. SAND2013-5131, Sandia National Laboratories, July 2013.

[17] State of California, “Assembly bill no. 2514, chapter 469.” http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200920100AB2514, 2014.

[18] R. H. Byrne and C. A. Silva-Monroy, “Estimating the maximum potential revenue for grid connected electricity storage: Arbitrage and the regulation market,” Tech. Rep. SAND2012-3863, Sandia National Laboratories, Albuquerque, NM, December 2012.

[19] R. H. Byrne and C. A. Silva-Monroy, "Potential revenue from electrical energy storage in the electricity reliability council of texas (ERCOT)," in *2014 IEEE PES General Meeting*, (Washington, DC), pp. 1–5, July 2014.

[20] J. Gates, "Notrees energy storage project," in *2014 DOE/OE Energy Storage Systems Program Peer Review*, (Washington, DC), September 17-19, 2014.

[21] Younicos, Inc., "Younicos to enhance 36-Megawatt battery storage plant in Texas." www.younicos.com, June 2015.

[22] E. Wesoff, "Flow battery startup enervault files for assignment before creditors." http://www.greentechmedia.com/articles/read/Flow-Battery-Startup-EnerVault-Files-For-Assignment-Before-Creditors, June 16, 2015.

[23] R. Booth, "PG&E compressed air energy storage (CAES) project," in *Proceedings of the 2014 DOE Energy Storage Program Peer Review*, (Washington, DC), September 2014.

[24] J. Eyer and G. Corey, "Energy storage for the electricity grid: Benefits and market potential assessment guide," Tech. Rep. SAND2010-0815, Sandia National Laboratories, Albuquerque, NM, February 2010.

[25] D. M. Rose and S. R. Ferreira, "Performance testing of zinc-bromine flow batteries for remote telecom sites," Tech. Rep. SAND2013-2818C, Sandia National Laboratories, Albuquerque, NM, 2013.

[26] Amber Kinetics, Inc., "Technology performance report, flywheel energy storage demonstration," tech. rep., Amber Kinetics, Inc., April, 16, 2012.

[27] Seeo, Inc., "Drylyte^{TM} stationary energy storage product literature." www.seeo.com, March 2015.

This page intentionally left blank.

DISTRIBUTION:

1	Dr. Imre Gyuk Program Manager, Energy Storage Research Office of Electricity Delivery and Energy Reliability U.S. Dept. of Energy Washington, DC 20585	
1	Dan Ton Program Manager, Smart Grid R&D Office of Electricity Delivery and Energy Reliability U.S. Dept. of Energy Washington, DC 20585	
1	MS 0330	Georgia L. Artery, 0427
1	MS 0576	Raymond H. Byrne, 5521
1	MS 1033	Abraham Ellis, 6112
1	MS 1108	Stanley Atcitty, 6111
1	MS 1108	Daniel R. Borneo, 6111
1	MS 1108	Georgianne Huff, 6111
1	MS 1108	David M. Rosewater, 6111
1	MS 1104	Charles J. Hanley, 6110
1	MS 1140	Ross Guttromson, 6113
1	MS 1315	Sean J. Hearne, 01132
1	MS 9154	Donald A. Bender, 0427
1	MS 0899	Technical Library, 9536 (electronic copy)

Sandia National Laboratories