SAND2014-17682PE

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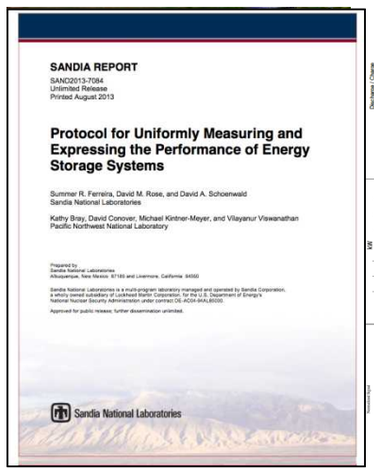

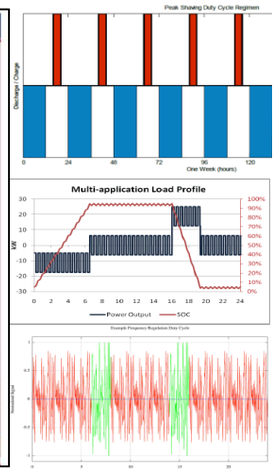

Energy Storage Systems Analysis Laboratory – Cell, Module, and Integrated Systems

9/10/2014 David Rosewater, Summer Ferreira, Ben Schenkman, Josh Lamb, Roy Lopez, Victor Chavez, Wes Baca, Tieshia Francis

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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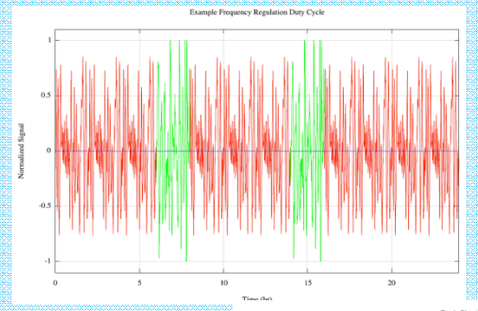
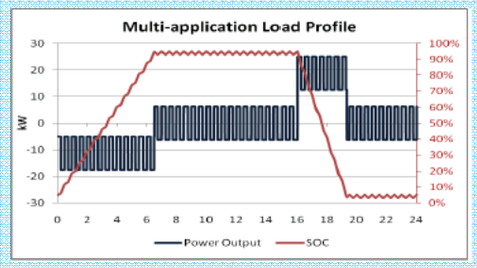
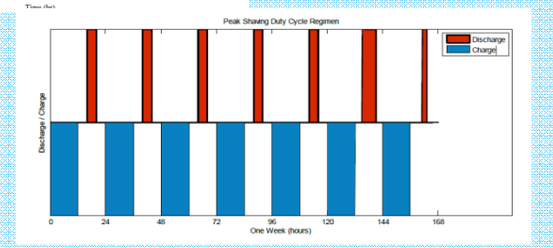
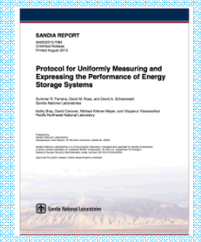
Project Overview:

Development and Application of New Protocols and Analysis Methods









Protocol Development

Cell / Module Analysis

System Analysis

Project Overview: Infrastructure

The Energy Storage Systems Analysis Laboratory (ESSAL)

Providing reliable, independent, third party analysis and verification of advanced energy technologies for cell to MW systems

Cells and Modules

72V 1000A Bitrode (2 Channels)

Cell, Battery and Module Analysis

- **14 channels from 36 V, 25 A to 72 V, 1000 A for battery to module performance analysis**
- **Over 125 channels; 0 V to 10 V, 3 A to 100+ A for cell performance analysis**
- **Potentiostat/galvanostats for spectral impedance**
- **Multimeters, shunts and power supply for high precision testing**
- **Temperature chambers**

Fully Integrated Systems

Lab Analysis

Energy Storage Test Pad (ESTP)

- **Scalable from 5 KW to 1 MW, 480 VAC, 3 phase**
- **1 MW/1 MVAR load bank for either parallel microgrid, or series UPS operations**
- **Subcycle metering in feeder breakers for system identification and transient analysis**
- **Thermal imaging**
- **System Safety Analysis (new)**

Field Analysis (new)

Remote Data Acquisition System (RDAS)

- **Portable, Modular, Remotely Reconfigurable, and outdoor-ready**
- **Subcycle metering**
- **Tractable calibration**
- **Command Signal Ready for Grid Operator Simulation**
- **No control over grid conditions**

Project Overview: Scope (**Jet Analogy**)

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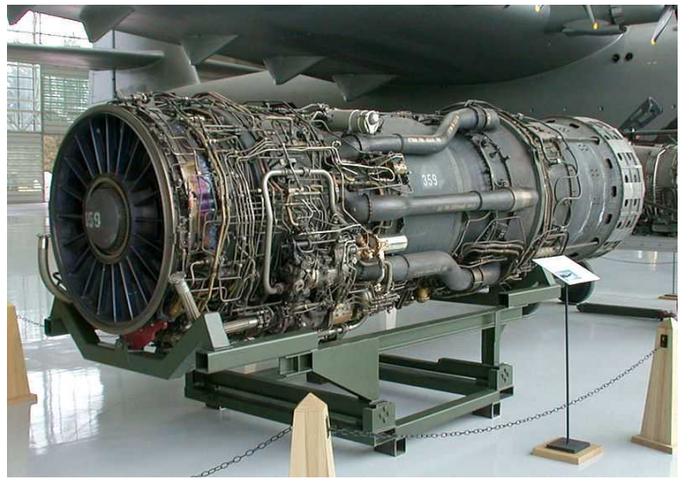
Activity

Analogy

Cells and Module Analysis



By Greg Goebel [CC-BY-SA-2.0 (http://creativecommons.org/licenses/by-sa/2.0)], via Wikimedia Commons

System Laboratory Analysis

By Judson Brohmer/USAF [Public domain], via Wikimedia Commons

Demonstration and Field Analysis

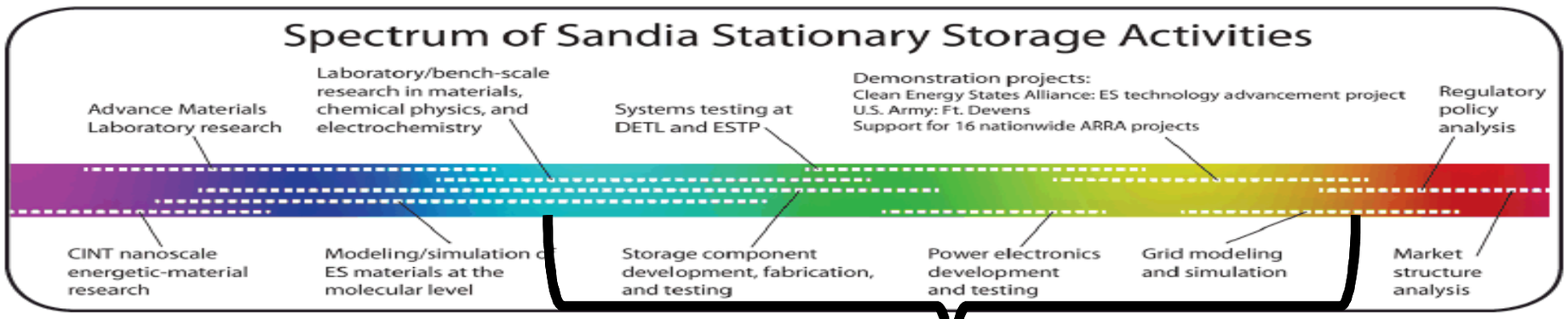
By Aero Icarus from Zürich, Switzerland [CC-BY-SA-2.0 (http://creativecommons.org/licenses/by-sa/2.0)], via Wikimedia Commons

Capability

- **Adjustable Environmental Conditions**
- **Control Signals and**
- **Components need to perform reliably**

- **Adjustable Grid Conditions**
- **Simulated Control Signals**
- **Components need to perform reliably**

- **Real World Grid and Environmental Conditions**
- **Real World Control Signals**
- **Interconnection Requirements**
- **Maintenance**



Range of the ESSAL

Grid Energy Storage System Analysis

- Cell Performance Analysis
  - Altairnano, EnCell
- Pack and String Analysis
  - Aquion, EastPenn
- On-Site System Analysis
  - TransPower, EPC Power, Raytheon
- In-Field System Analysis
  - UniEnergy Technologies (UET)
- Wide Area Control of ESS
  - SunSpec Alliance, MESA, Ideal Power
- Safety Protocol Development
- Stacked Services Degradation Analysis
  - DNV-GL
- DOE Performance Protocol Review

Sandia National Laboratories

Research Partners

altairnano

ENCELL technology

AQUION ENERGY

EASTPENN

TransPower

epcpower excellence in power conversion

UET

Raytheon

IDEAL POWER CONVERTERS

SUNSPEC ALLIANCE

MESA Open Standards for Energy Storage

DNV·GL

Cell Performance Analysis:

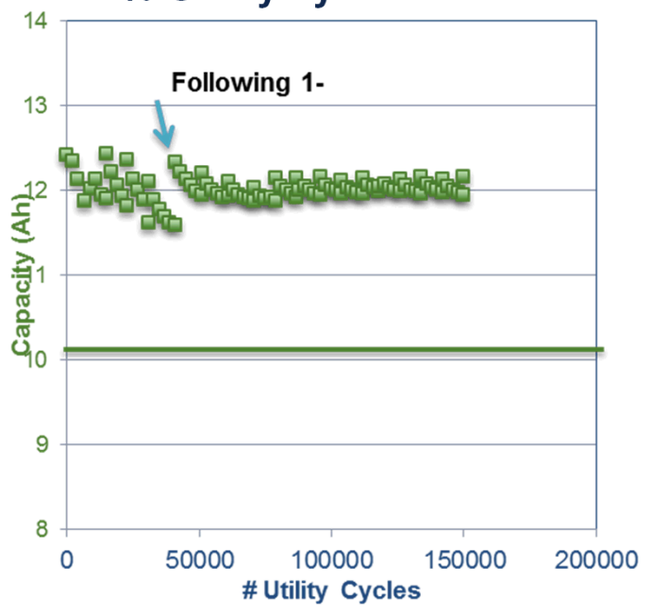
Sandia National Laboratories

Partners: Altairnano, EnCell

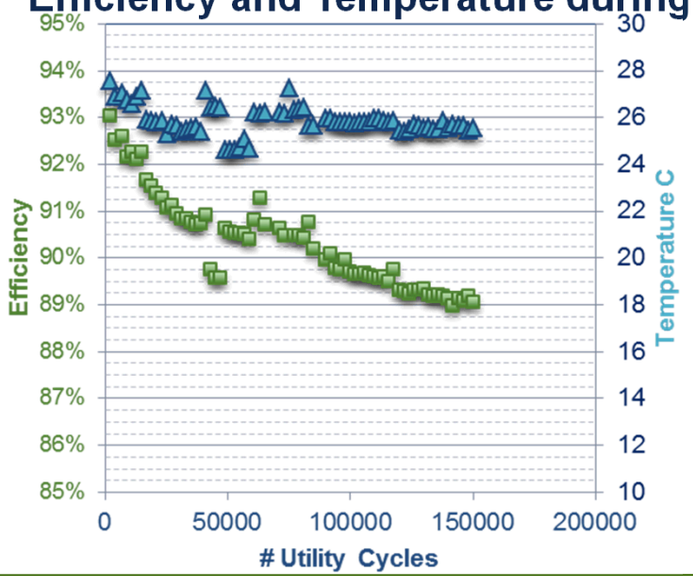
Cycle Life Analysis
11 Ah Altairnano Lithium titanate pouch cell

- 150K+ cycles
- 2% capacity loss
- 5% energy efficiency drop

2C 10% Utility cycles without rests



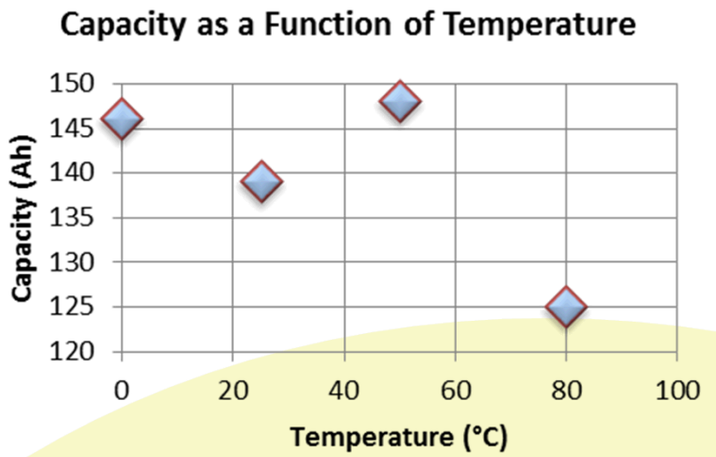
Efficiency and Temperature during Cycling



Encell Alpha Cell Characterization (OE Funded)

Evaluated Alpha design of an Encell rechargeable nickel alkaline battery

- Average capacity of 133 Ah at ambient temperature
- 20% self discharge after 28 days



Manufacturer Funded WFO

Evaluated Beta design of an Encell rechargeable nickel alkaline battery

- Average capacity of 139 Ah at ambient temperature
- 10% self discharge after 28 days
- FY ‘14 beta testing to begin for life cycle testing

Office of Electricity support

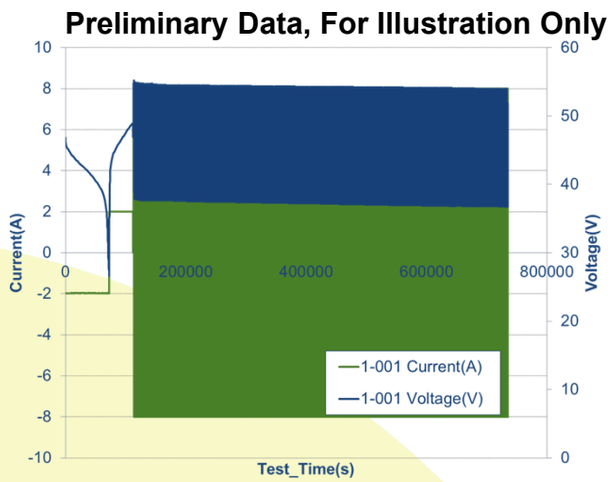
Applied for testing of Beta design cells

Longevity and reliability of cell chemistries identified through dedicated lab capabilities can inform resource allocation at the larger scale, especially in established markets such as Li-ion

Pack and String Analysis

Aquion single stack

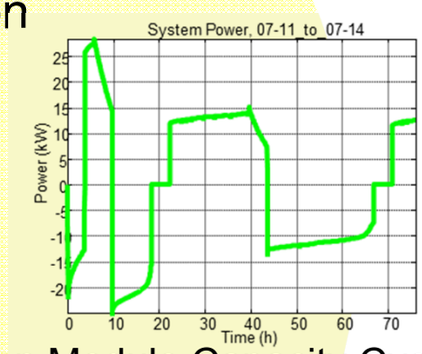
Cycling at Sandia



Aquion Stack PSOC Cycling Data

Supporting analysis of 11 modules

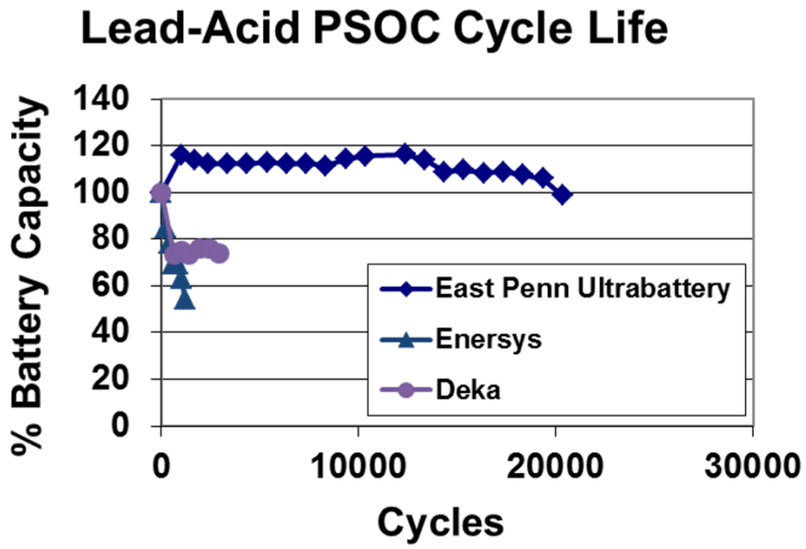
(132 Stacks total) Cycling at Aquion



Aquion Module Capacity Cycling Data

Long term cycling of Aquion begun at Sandia while Aquion designs and tests larger scale systems at their headquarters. Data shared-cycling data can inform design of limits for long term longevity of systems and can inform DOE OE of possible use-cases.

Dramatically longer life in Ultrabattery® Pb-acid compared to more traditional Pb-acid batteries



After a two years of operation in the field we can now compare the laboratory data for power cycling to the demonstration power cycling for this design

Demonstration of the technology through the PNM Prosperity site 0.5 MW/0.35 MWh power smoothing Ultrabatteries

Figure 1: PNM Prosperity energy-storage project.

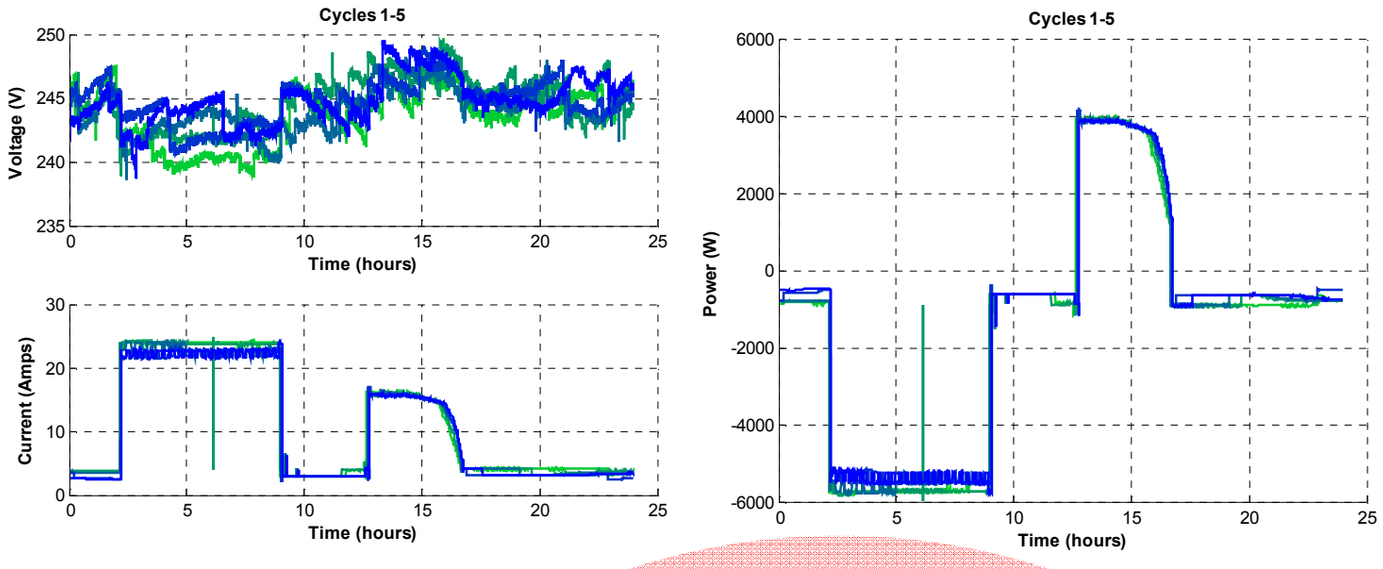
On-Site System Analysis

Partner: Raytheon

5kW, 20kWh, Zinc-Bromide Flow Battery System

Installation of the Raytheon RK10 at ESSAL

Preliminary Data, For Illustration Only



Performance Analysis

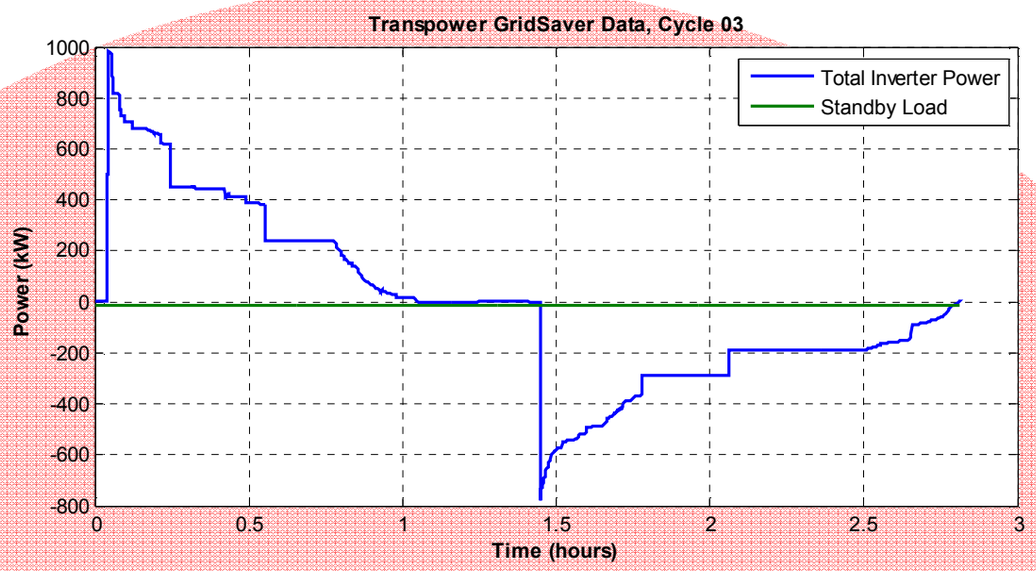
- Capacity (per DOE protocol)
- Peak Shaving (per DOE protocol)
- Power Quality

Project Status

- Accepted Proposal, February 2014
- System Installed, August 2014
- Started Data Collection August 2014
- Data processing in progress

On-Site System Analysis

TransPower: 1MW, 500kWh Lithium-Ion Energy Storage System



Preliminary Data, For Illustration Only

Performance Analysis

- Capacity (per DOE protocol)
- Regulation (per DOE protocol, 2hr)
- Response Rate (per DOE protocol)
- Power Quality

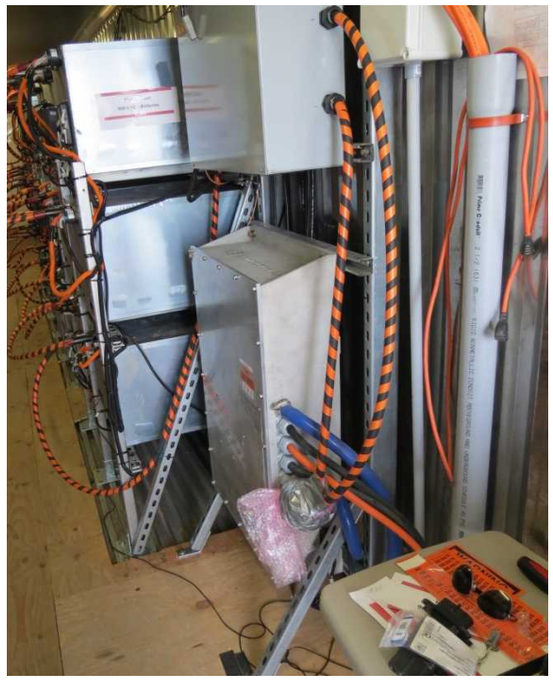
System Safety Analysis

- Initial Safety Review

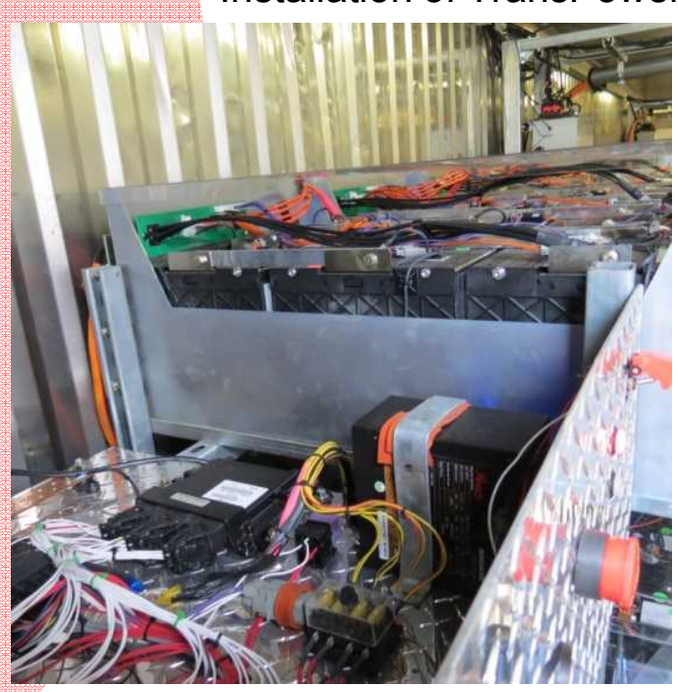
Project Status

- Accepted Proposal, February 2014
- System Installed, June 2014
- Initial safety review completed, July 2014
- Started Data Collection August 2014
- Data processing and analysis in progress

Installation of TransPower Grid Saver at ESSAL



String E (top) and
D (bottom) in GridSaver



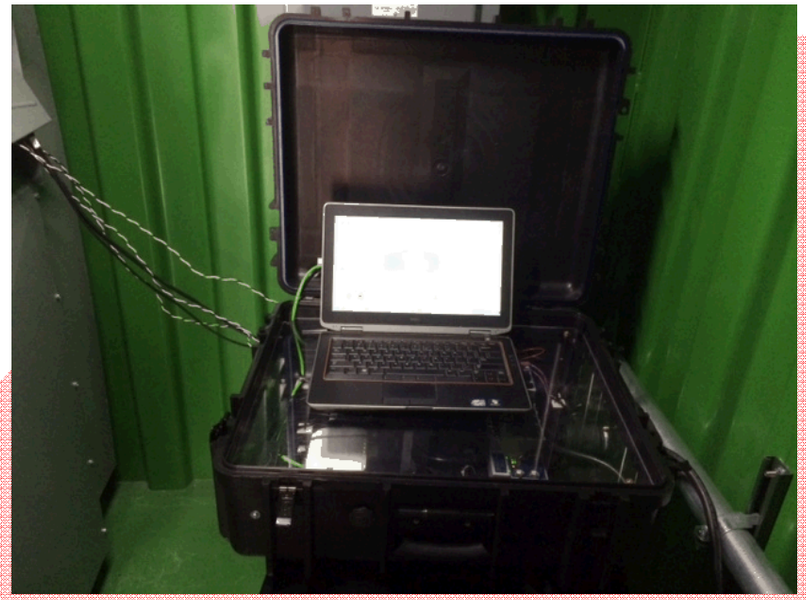
String F in GridSaver

In-Field System Analysis

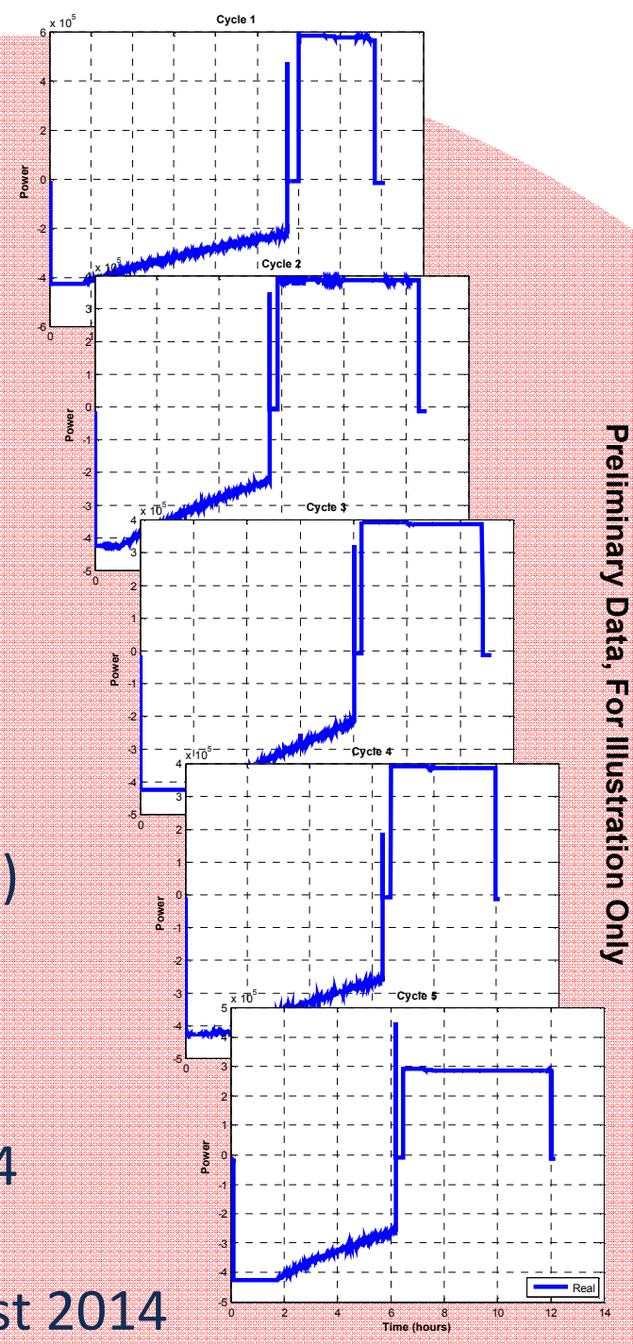
Partner: UniEnergy Technologies (UET)

600kW, 2.2MWh, Vanadium-Redox Flow Battery System

UET system in Washington



RDAS In-Place, Acquiring Data



Preliminary Data, For Illustration Only

Rick Winter (left), David Rosewater (right)

Performance Analysis

- Capacity (per DOE protocol)
- Regulation (per DOE protocol)
- Peak Shaving (sinewave)
- Power Quality

Project Status

- Accepted Proposal, April 2014
- Installed RDAS, May 2014
- Started Data Collection August 2014
- Data processing in progress

Wide Area Communication for ESS

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Partners: SunSpec Alliance, Modular Energy Storage Architecture (MESA), Ideal Power Converters 30kW, Bi-Directional Inverter

Performance Analysis

- Communication interface
  - Interoperability
- Conversion Efficiency
- Power Quality

Project Status

- Inverter Installed, February 2014
- Started Data Collection, March 2014
- Hardware issues incurred delays
- Plan for analysis to restart in FY15

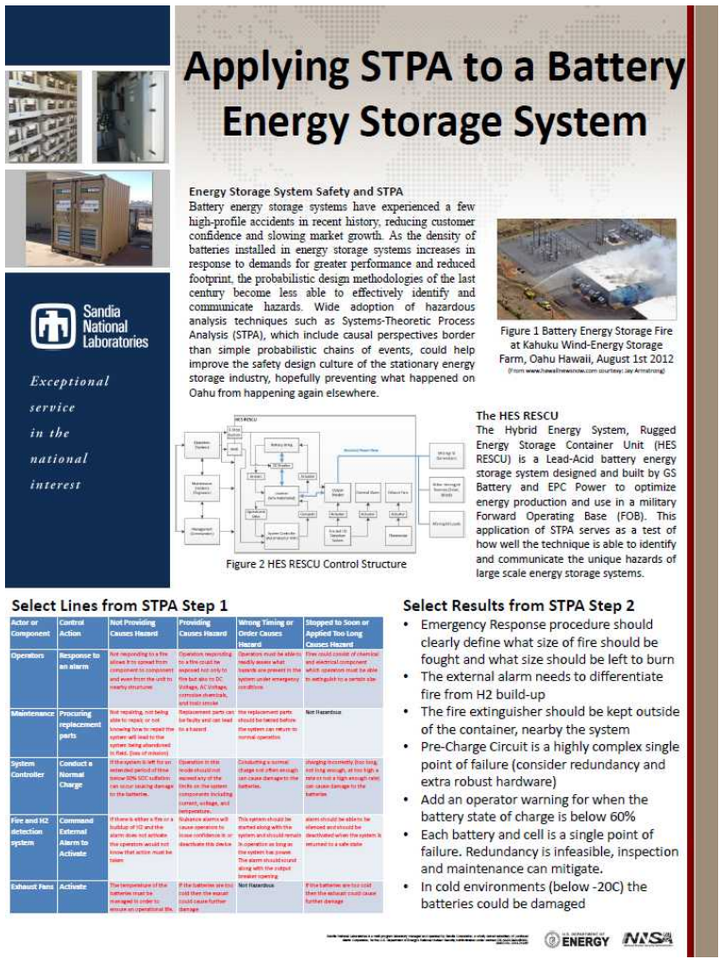
Installation of the IBC-30kW-480 at ESSAL

Safety Protocol Development

Sandia National Laboratories

Safety Engineering Protocols for ESS

- System-Theoretic Accident Model and Processes (STAMP)



Applying STPA to a Battery Energy Storage System

Energy Storage System Safety and STPA

Battery energy storage systems have experienced a few high-profile accidents in recent history, reducing customer confidence and slowing market growth. As the density of batteries installed in energy storage systems increases in response to demands for greater performance and reduced footprint, the probabilistic design methodologies of the last century become less able to effectively identify and communicate hazards. Wide adoption of hazardous analysis techniques such as Systems-Theoretic Process Analysis (STPA), which include causal perspectives border than simple probabilistic chains of events, could help improve the safety design culture of the stationary energy storage industry, hopefully preventing what happened on Oahu from happening again elsewhere.

Figure 1 Battery Energy Storage Fire at Kahuku Wind-Energy Storage Farm, Oahu Hawaii, August 1st 2012

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Figure 2 HES RESCU Control Structure

The HES RESCU

The Hybrid Energy System, Rugged Energy Storage Container Unit (HES RESCU) is a Lead-Acid battery energy storage system designed and built by GS Battery and EPC Power to optimize energy production and use in a military Forward Operating Base (FOB). This application of STPA serves as a test of how well the technique is able to identify and communicate the unique hazards of large scale energy storage systems.

Select Lines from STPA Step 1

Actor or Component	Control Action	Not Providing Causes Hazard	Providing Causes Hazard	Wrong Timing or Order Causes Hazard	Stopped to Soon or Applied Too Long Causes Hazard
Operators	Response to an alarm	Not responding to a fire allows it to spread from component to component and even from the unit to nearby structures	Operators responding to a fire could be exposed not only to fire but also to DC Voltage, AC Voltage, corrosive chemicals, and toxic smoke	Operators must be able to readily assess what hazards are present in the system under emergency conditions	Fires could consist of chemical and electrical components which operators must be able to extinguish to a certain ste
Maintenance	Procuring replacement parts	Not repairing, not being able to repair, or not knowing how to repair the system will lead to the system being abandoned to Fate. (loss of mission)	Replacement parts can be faulty and can lead to a hazard	the replacement parts should be tested before the system can return to normal operation	Not Hazardous
System Controller	Conduct a Normal Charge	If the system is left for an extended period of time below 60% SOC collision can occur causing damage to the batteries.	Operation in this mode should not exceed any of the limits on the system components including current, voltage, and temperature.	Conducting a normal charge not often enough can cause damages to the batteries.	charging incorrectly (too long, not long enough, at too high a rate or not a high enough rate) can cause damage to the batteries
Fire and H2 detection system	Command External Alarm to Activate	If there is either a fire or a build-up of H2 and the alarm does not activate the operators would not know that action must be taken	Nuisance alarms will cause operators to loose confidence in or deactivate this device	This system should be started along with the system and should remain in operation as long as the system has power. The alarm should sound along with the output breaker opening	alarm should be able to be silenced and should be deactivated when the system is returned to a safe state
Exhaust Fans	Activate	The temperature of the batteries must be managed in order to ensure an operational life.	If the batteries are too cold then the exhaust could cause further damage	Not Hazardous	If the batteries are too cold then the exhaust could cause further damage

Select Results from STPA Step 2

- Emergency Response procedure should clearly define what size of fire should be fought and what size should be left to burn
- The external alarm needs to differentiate fire from H2 build-up
- The fire extinguisher should be kept outside of the container, nearby the system
- Pre-Charge Circuit is a highly complex single point of failure (consider redundancy and extra robust hardware)
- Add an operator warning for when the battery state of charge is below 60%
- Each battery and cell is a single point of failure. Redundancy is infeasible, inspection and maintenance can mitigate.
- In cold environments (below -20C) the batteries could be damaged

SAND2014-2146P
Presented March 2014

Application of Safety Codes and Standards

- NFPA 70 , NEC, Article 480 Storage Batteries
- NFPA 70E Article 320 Safety Requirements Related to Batteries and Battery Rooms
- IEEE Stationary Battery Committee Standards
- IEC 60812 Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA)
- IEC 61508 Functional Safety of Electrical /Electronic/ Programmable Electronic Safety-related Systems
- UL and other battery abuse testing standards

Cell Failure Propagation Protocol Development

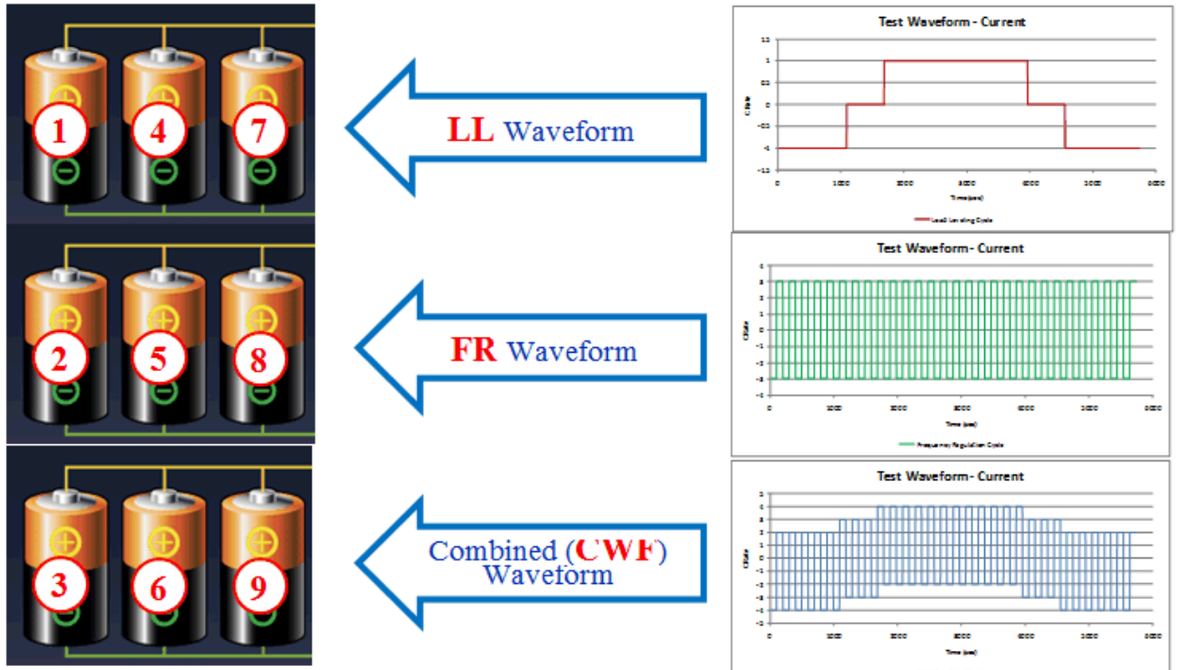
- Developed stationary battery test procedure to determine if single cell failures will propagate to modules

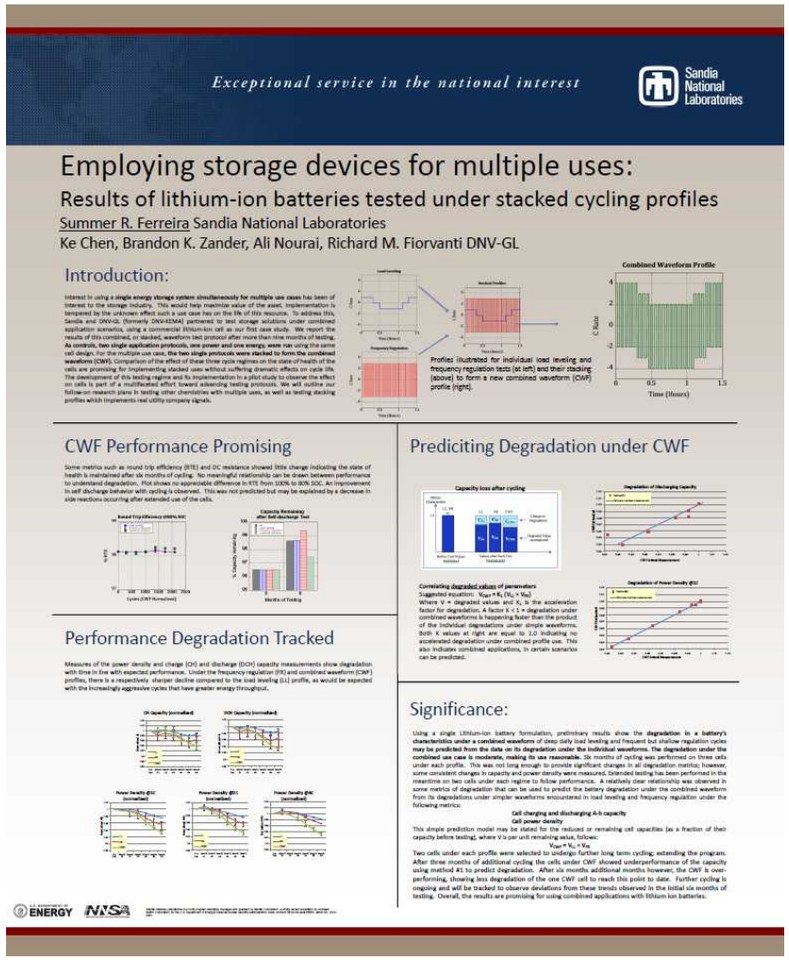
Project Status

- Poster Presented, March 2014
- System Safety Analisys of TransPower GridSaver is in progress
- Waiting on laboratory availability for module abuse procedure validation

Stacked Services Degradation Analysis

Experimental Design

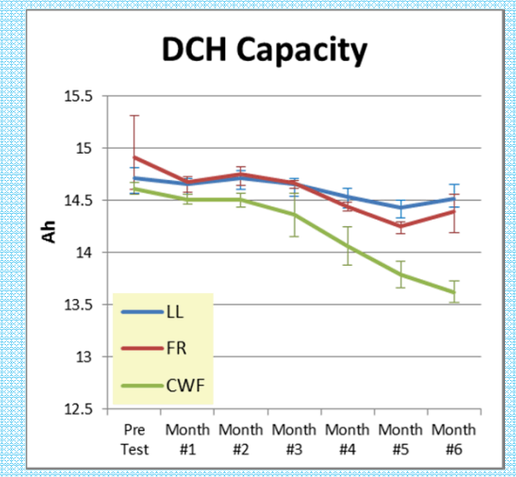


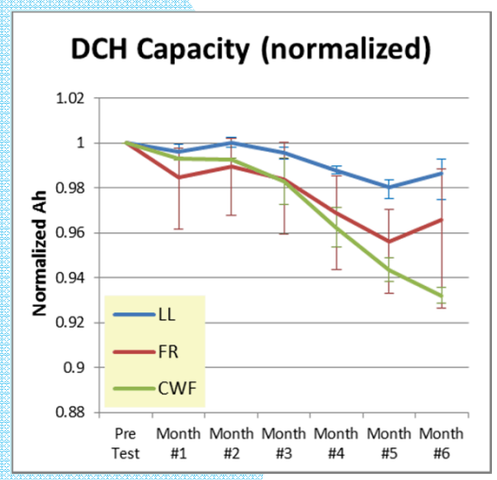


SAND2014-4442P
Presented June 2014

Project Status

- Poster Presented at ESA
- Cells cycling at Sandia
- Planning for implementation on other chemistries and designs
- Planning for implementation of other stacking conventions





In Partnership With

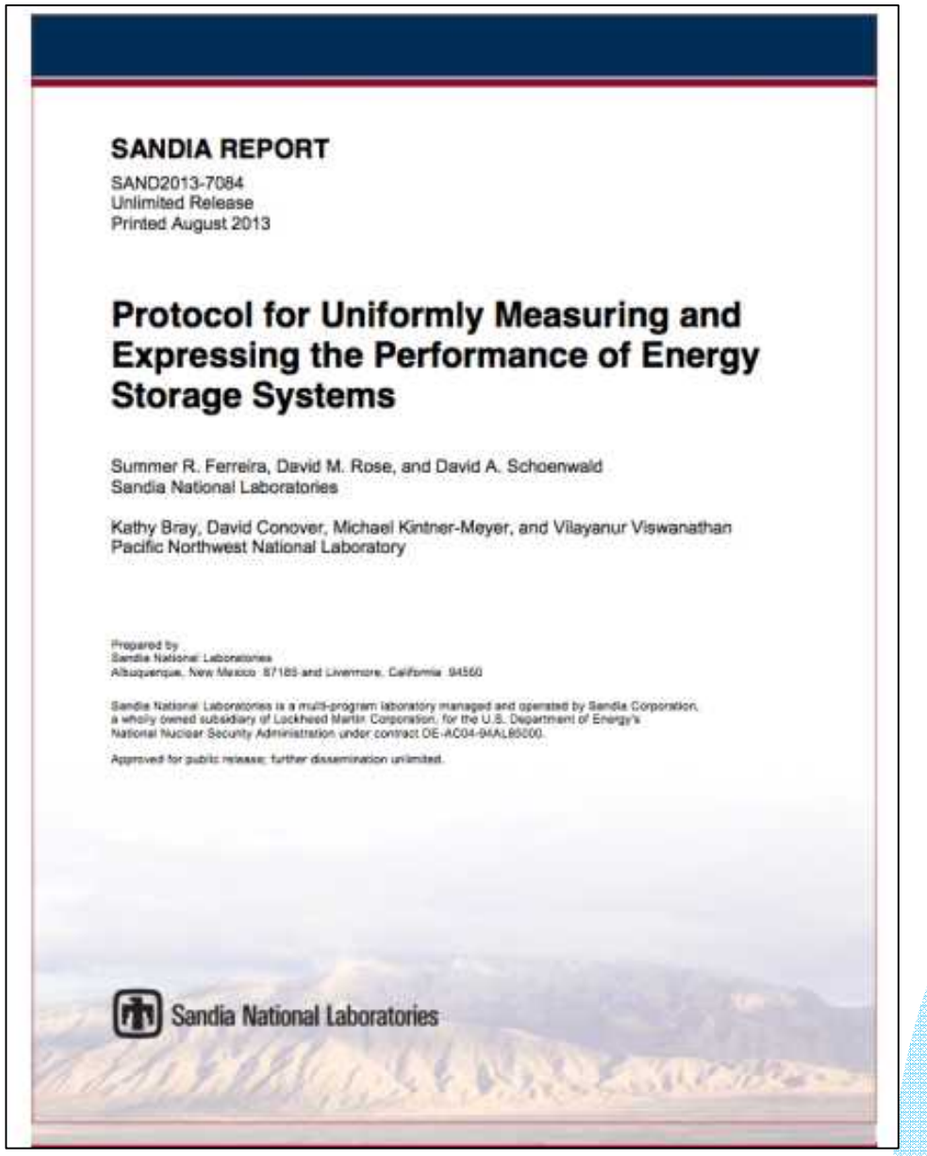
DNV·GL

Summarized Results to Date

Capacity under CWF = (capacity under LL waveform) × (capacity under FR waveform)

DOE Performance Protocol Review

Compulsion of lessons learned from application of DOE performance protocol



SANDIA REPORT

SAND2013-7084
Unlimited Release
Printed August 2013

Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems

Summer R. Ferreira, David M. Rose, and David A. Schoenwald
Sandia National Laboratories

Kathy Bray, David Conover, Michael Kintner-Meyer, and Vilayanur Viswanathan
Pacific Northwest National Laboratory

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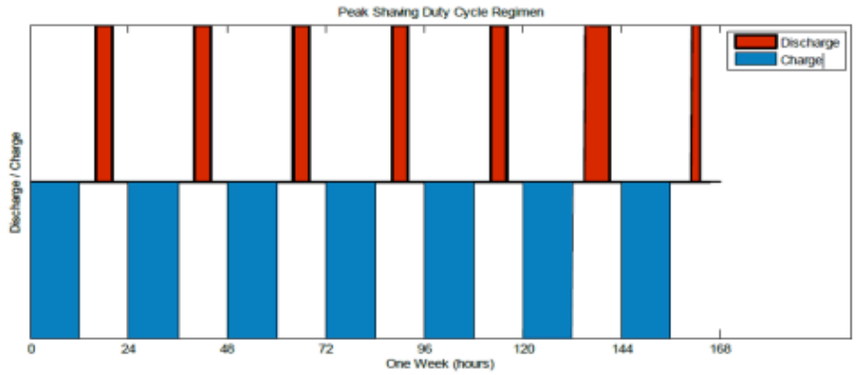
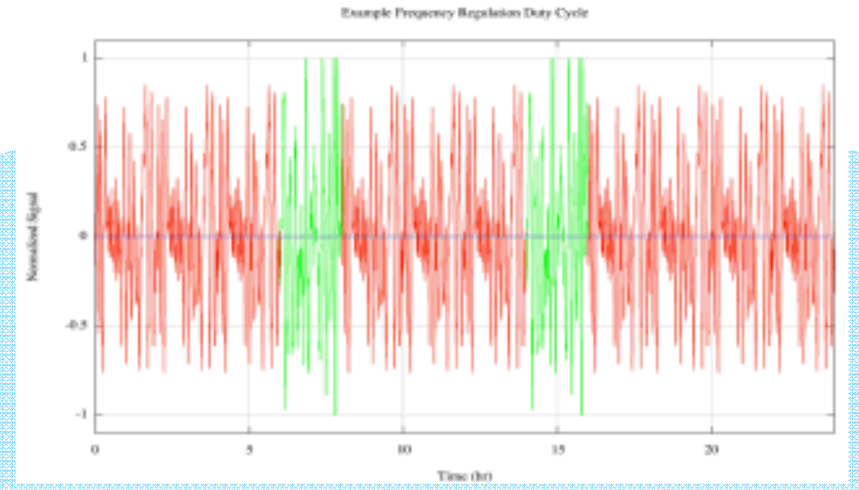




Project Status

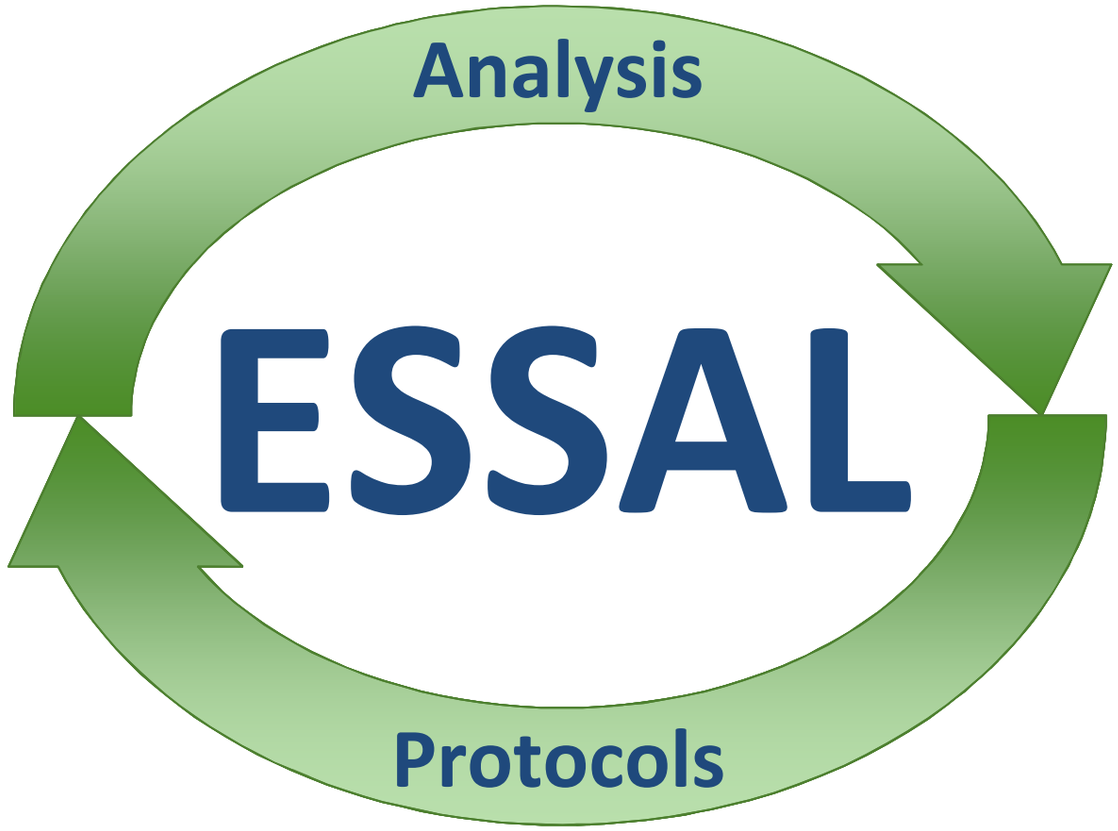
- Data and application notes are being collected
- Working with review committees to add new sections

Summary of FY14 Accomplishments

Sandia National Laboratories

Milestones Reached

1. ESS Safety Analysis Poster Presented
2. Stacked Services Degradation Poster Presented
3. Raytheon RK10 Installed
4. Installed RDAS at UET
5. Multiple Services Poster Presented
6. Aquion Stack on PSOC Cycle
7. TransPower GridSaver Installed



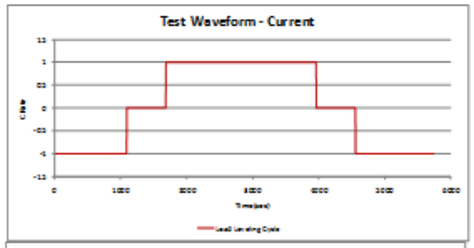
Impact

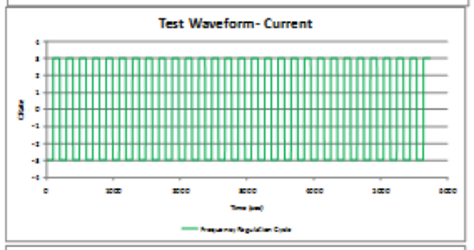
- The next generation of test protocols for energy storage systems will provide better information, at lower cost, then what is now available.
- Data collected and disseminated breaks down the barriers to energy storage acceptance by boosting confidence of customers and regulators
- The technology of research partners can be improved through collaboration
- We are changing how the industry looks at the safety, reliability, and performance of energy storage systems

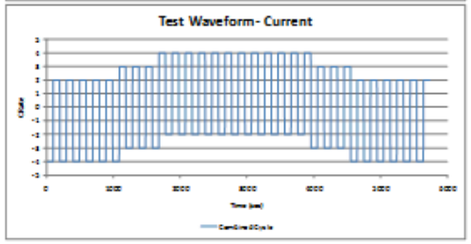
Future Tasks, FY15 and Beyond

Continue to develop new ways of analyzing cell, module, and system performance and safety

- Continue the analysis of UET, TransPower, and Raytheon Systems and expand to other technologies such as flywheels
- Develop robust network of RDAS units and continue to expand safety analysis research
- Expand stacked cell cycle protocol in new next logical dimension
- Develop new safety protocols and analytics



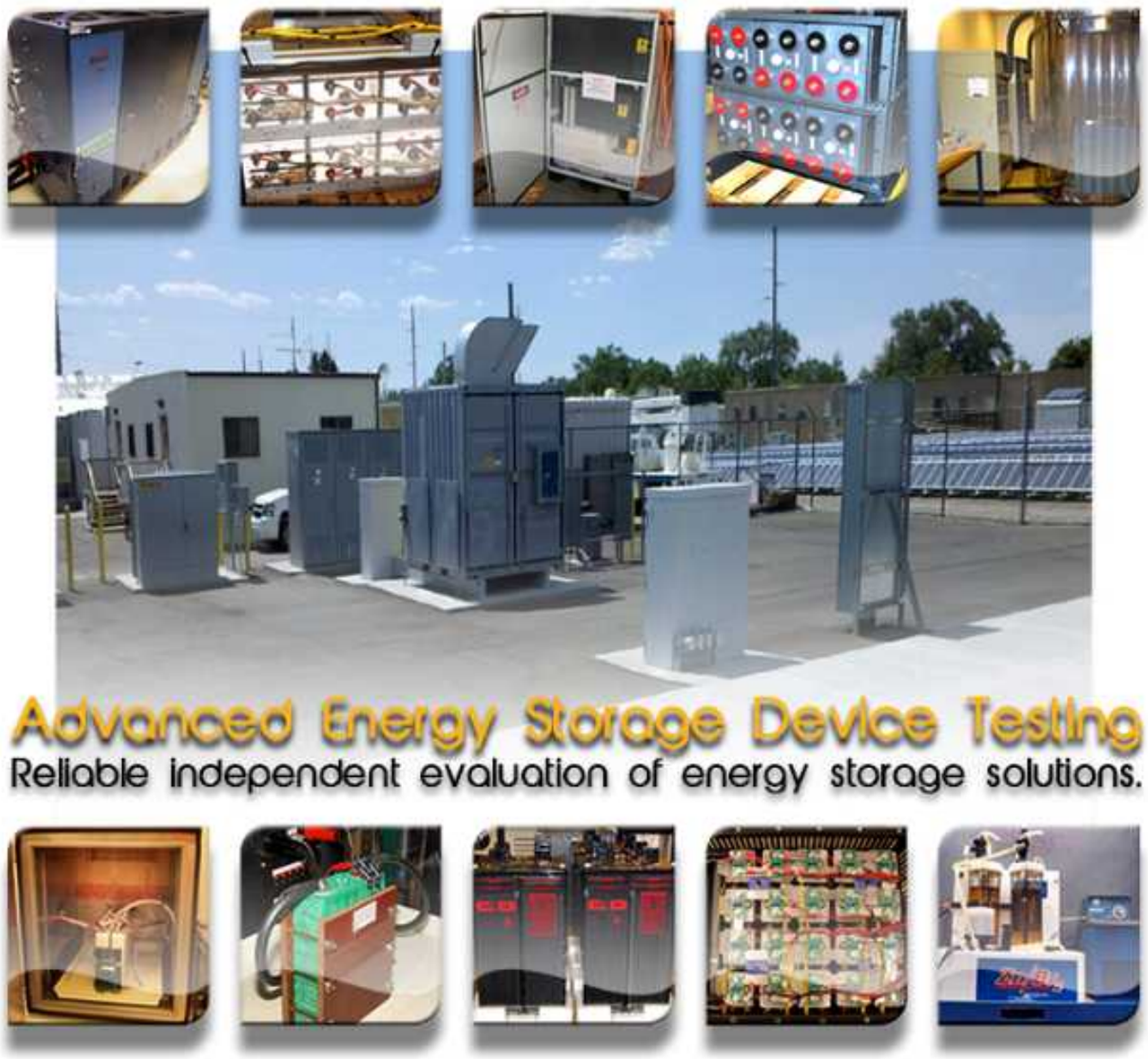




ESSAL Website

www.sandia.gov/batterytesting

The next call for proposals will open soon.



DOE *FAST-Track* Application

Click to get *FAST-Track* Application

DOE Standard Application

Click to get Standard Application
[more than 6 months]

WFO Application

Click to get Application

Download appropriate application,
Fill out,
Save for your records, and
Email a copy to Energystorage@sandia.gov

Thank You to the DOE OE and especially Dr. Gyuk for his dedication and support to the ES industry and Sandia's ES Program.

Questions?

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