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Sandia National Laboratories

Sandia Energy Storage Research

PRESENTED BY

Dr. Ray Byrne

Electric Power Systems Research Department

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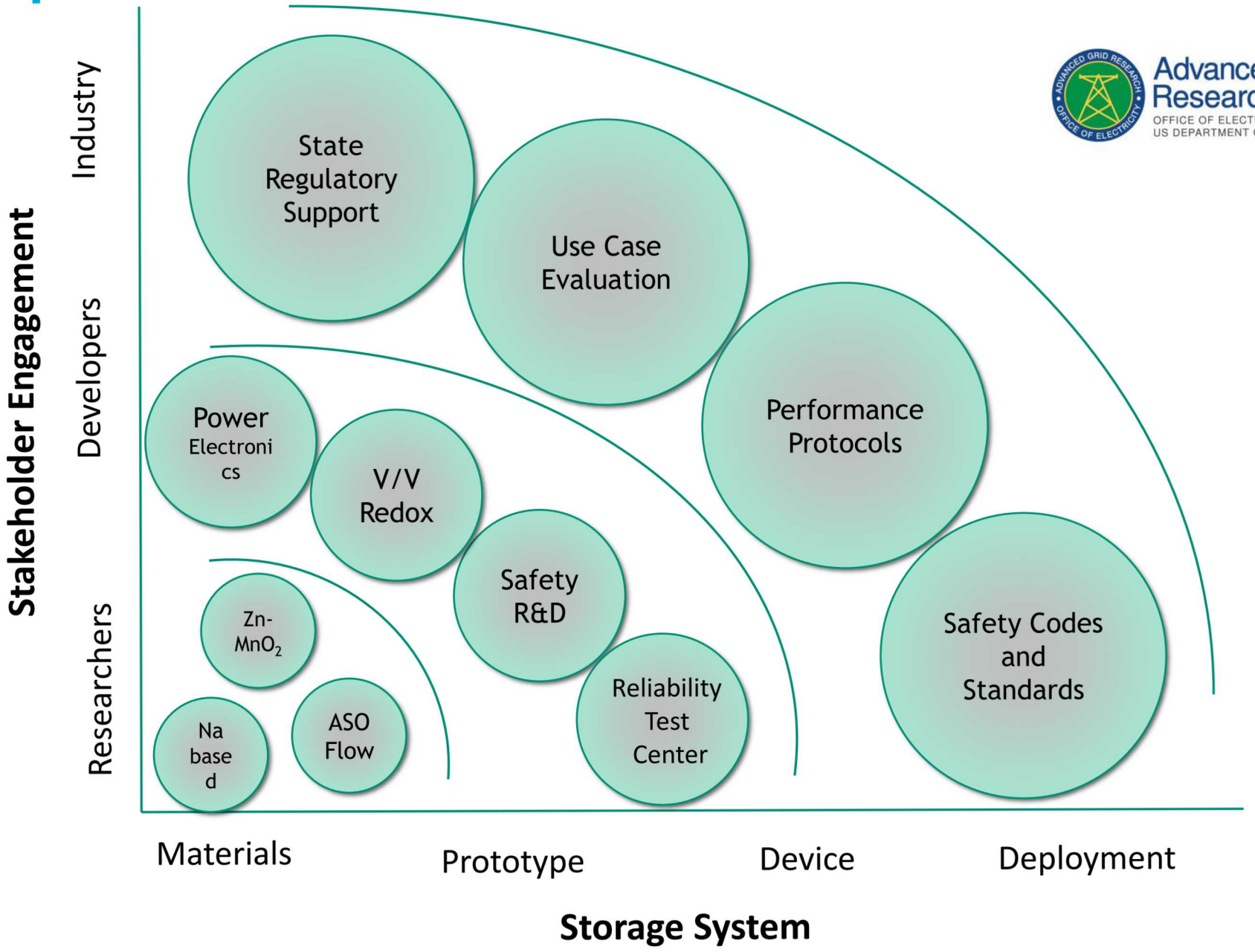
DOE Office of Electricity Priorities

- Puerto Rico and U.S. Virgin Islands
  Restoration and Resiliency Efforts
- North American Energy Systems Resiliency Model
- Mega-Watt Scale Grid Storage
- Revolutionize Sensing Technology Utilization
- Operational Strategy for Cyber and Physical Threats

DOE Energy Storage Program



Advanced Grid Research
OFFICE OF ELECTRICITY
US DEPARTMENT OF ENERGY

Applied Research: Materials, Devices, Systems

Sandia, Pacific NW, Oak Ridge National Laboratories
And University, Industry Partners

FY18: Published. 34; Accepted. 11; Submitted. 30

Patents Granted: 12, submitted: 14

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233 Articles, 106 Patents, 9 R&D 100 Awards!

PNNL

OAK RIDGE National Laboratory

2017 R&D 100 WINNER

University Partners

Harvard University – MA
Case Western Reserve – OH
West Virginia University – WV
Penn State – PA
UW – WA
Davidson College – NC
City University – NY
Northeastern Univ – MA
New Mexico State University
Montana Tech - MT
Stony Brook – NY
Univ. Kentucky – KY
UC -Irvine -CA
Southern Methodist – TX
Univ. of Alaska Fairbanks – AK
Univ. of Houston – TX
Univ. Texas- Austin- TX
Ohio State University – OH
Univ of Texas – Arlington – TX
New Mexico Tech – NM
Univ. New Mexico – NM
Washington Univ – MO
Michigan State University – MI
Univ. of Utah – UT
South Dakota State – SD
Clemson – SC.
Univ. of Tennessee – TN

Sandia Major R&D Thrust Areas

Materials and Systems Development

- Development of next-generation technologies
- Improving current technology (flow batteries, flywheels, membranes, etc.)

Power Electronics

- Development of power electronics and power conversion systems.

Energy Storage Systems Safety and Reliability

- Fundamental Safety R&D of utility class storage systems
- Laboratory testing and analysis from individual cells to 1MW systems

ES Systems Demonstrations and Testing

- Field deployments; State-Initiated Demonstration Project Development

Grid Analytics and Policy

- Providing assessments of the impact of storage placement

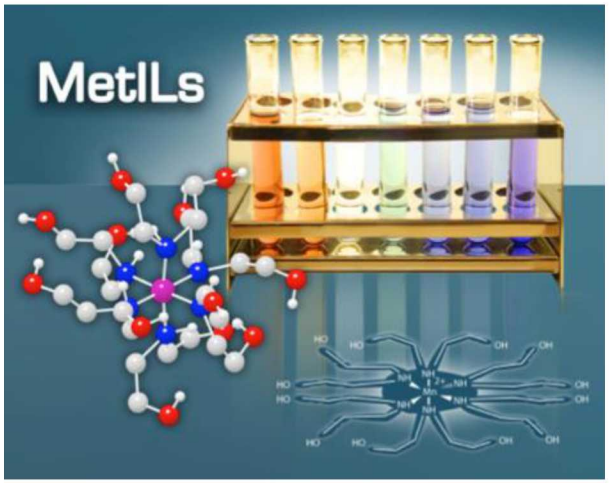
Outreach - publications and meetings to help educate the Grid Energy community

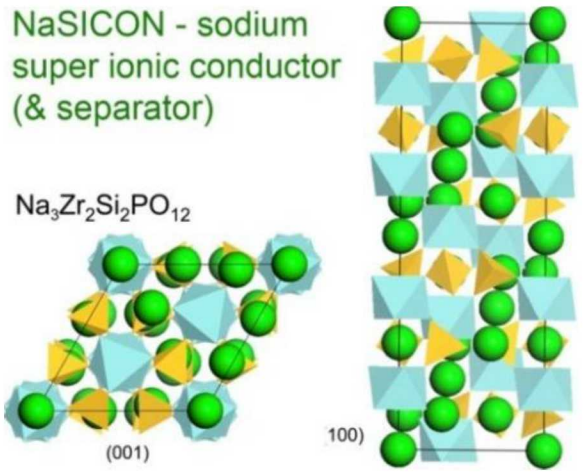
- EESAT and DOE Energy Storage peer review
- US DOE Global Energy Storage Database

Energy Storage Materials R&D

Materials R&D capabilities covers battery chemistry and component technologies

- Low Cost Membranes for Flow Batteries
- Sodium Based Batteries
- Advanced Materials for Ionic Liquid Flow Batteries
- High Voltage Capacitors
- Soft Magnetics
- Lightweight Composites for Flywheels
- Wide Bandgap Materials and Devices for Power Electronics





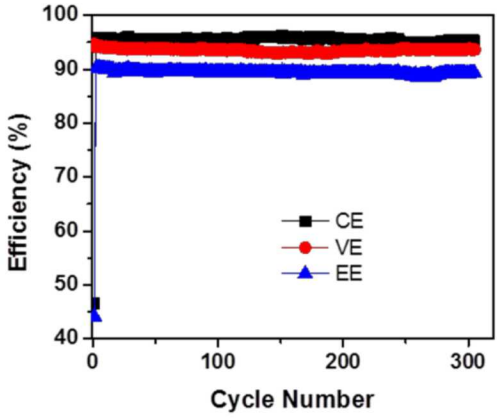
Advanced Membranes for Flow Batteries

Collaboration with PNNL and ORNL

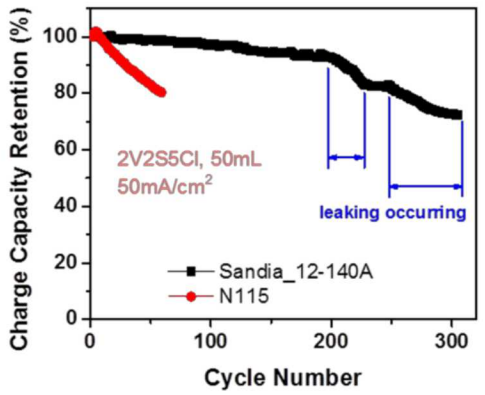
Project Goals: Develop and commercialize a new class of polymeric membranes that are superior to commercial membranes like Nafion in cost (10x lower) and performance.

Present Status:. Developed membranes with enhanced ion selectivity and durability. Testing has shown improved performance over current state of the art.

Commercialization: Secured patent protection for materials synthesis and membrane application in flow batteries, fuel cells and electrolyzers. 1 issued patent and 4 pending applications. Commercialization through spin off.



New membranes are stable (300 cycles, 4 months), higher energy efficiency (90%) compared to state of the art (80%).



New membranes retains higher energy capacity for over 200 cycles. Longer term testing is in progress.

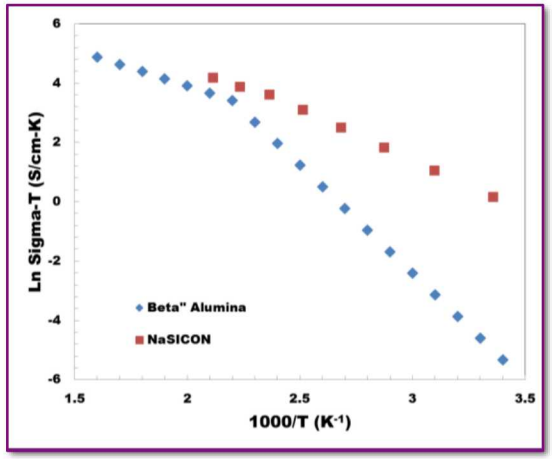
Sodium Ion Battery Development

Collaboration with Ceramatec (CoorsTek)

Project Goals: Develop and demonstrate low cost sodium batteries operating at lower temperature (< 200°C) than state of the art NaS batteries. Technology based material innovations in NaSICON ceramic membranes (collaboration with Ceramatec/CoorsTek).

Present Status: Successfully demonstrated cells using Na-Ni(Fe)Cl2 as well as novel Na-I battery chemistries. 100 Ah cells demonstrated stable performance during 1+ year of operation. 250 Ah cells under test.

Working towards the Demonstration of a 10 kWh battery module in a grid application.



NaSICON is 10 × more conductive than β"-Al_2O_3 @ room temperature

Prototype Na-ion cells

CERAMATEC TOMORROW'S CERAMIC SYSTEMS

CoorsTek Amazing Solutions

Power Electronics - Leveraging world class capabilities in Wide Bandgap Materials

2015 R&D100 Winner

2003

WORLD' S FIRST FIBER OPTIC ELECTRICAL TRANSDUCER TO PASS MILITARY VIBRATION AND SHOCK CERTIFICATION
Exceeds 30Mhz
Capable of Operating up to 34.5kV without additional Insulation, Isolation, or Cooling

2004

WORLD' S FIRST VOLTAGE CONTROLLED 4500V/400A TURN-OFF THYRISTOR
4500V and 400A rated
Integrated Si MOSFET and GTO Embedded Current Sensing Capability

2005

WORLD' S FIRST HIGH TEMPERATURE SIC SINGLE-PHASE INVERTER
3 kW (1200 V/150 A peak)
250 ° C Junction Temperature
Integrated Gate Driver

2006

2007

2008

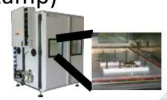
2009

WORLD' S FIRST HIGH TEMPERATURE SIC POWER MODULE
50 kW (1200 V/150 A peak)
250 ° C Junction Temperature
Integrated HTSOI Gate Driver

2010

WORLD' S FIRST COMMERICALLY AVAILABLE ULTRA-HIGH-VOLTAGE SIC THYRISTOR
Rating exceed 6.5kV, 200kHz, 80A
> 200° C junction temperature

WORLD' S FIRST HIGHLY ACCELERATED LIFETIME TESTING (HALT) OF HIGH VOLTAGE SIC MODULES
Dramatically Accelerates Design Cycle
-100 ° C to 250 ° C (1.7 ° C/s Ramp)
48 in × 48 in Table Size
6 axis 75 gRMS Vibration



2011

WORLD' S FIRST MONOLITHICALLY INTEGRATED SINGLE CHIP TRANSISTOR
Integrated SJT/Diode Chip at 1200V

2012

WORLD' S FIRST HIGH VOLTAGE, HIGH TEMPERATURE, REWORKABLE SIC HALF-BRIDGE POWER MODULE
> 15 kV / 100 A, > 200 ° C
Reworkable
Wire Bond Free, Low Parasitic Design
Device Neutral
HV Isolated Gate Driver

2013

2014

WORLD' S FIRST HIGH FREQUENCY, HIGH TEMPERATURE, SIC HALF-BRIDGE POWER MODULE
15 kV/100 A, 20 kHz, 200C
Reworkable
Low Parasitic Design
Device Neutral
HV Isolated Gate Driver

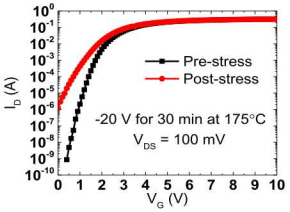
2015

WORLD' S HIGHEST VOLTAGE NORMALLY OFF SIC JFET
6.5 kV, 20kHz, 60A
200° C Junction Temperature

Power Electronics – Current Projects

WBG Reliability Characterization

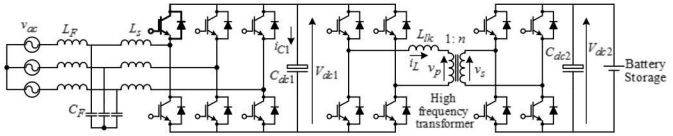
- Static and dynamic reliability characterization of SiC and GaN semiconductor devices under stress conditions
- 10 kV/50A/600C wafer-level device measurement capability
- 3kV/50A package-level device measurement capability
- Double-pulse switching testing capability
- Impedance spectroscopy



Advanced Magnetics

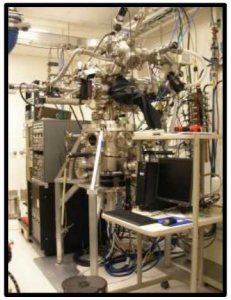
- Electron microscope for raw magnetic powder characterization
- Quantum design magnetic property measurement system

γ'-Fe_4N toroidal inductive cores



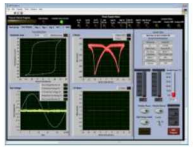
Advanced Gate Oxide for WBG Devices

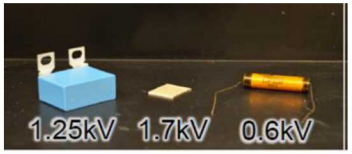
- Unique oxide molecular-beam eptiaxy instrument (1 of ~30 such instruments in the US)
- Grows MgO, CaO, La_2O_3, and Gd_2O_3 gate and passivation dielectrics on GaN, AlGaN, and SiC power semiconductors
- Comprehensive dielectric characterization tools
- 5 Hz to 26 GHz, -100C to 300C capabilities



Advanced Capacitors

- Test voltages as high as +/-10kV, with kA transients with HV diagnostics from mHz-MHz capability
- Impedance bridges and polarization-hysteresis looper allows full dielectric characterization
- Temperature dependent insulation resistance characterization capability





Energy Storage Safety and Reliability - Outreach

Focus on developing a fundamental understanding of safety and reliability through R&D in four areas:

- Materials origin of safety and reliability
- Device level failures
- Mechanisms of Cascading failures
- Software's role as a critical safety system

Extensive laboratory infrastructure at Energy Storage Test Pad (ESTP), BATlab, Thermal Test Complex

Advanced simulation and modeling of energy storage systems


Energy Storage Test Pad (ESTP)


Cell Lab


Battery Abuse Testing Laboratory

Predictive Modeling of Energy Storage Systems

Materials chemistry for engineered safety of batteries – New electrolyte materials

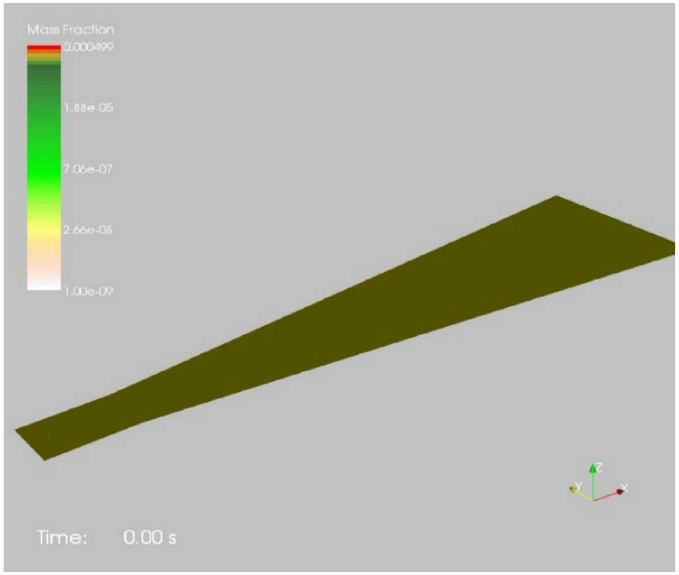
Modeling & simulation tools that predict thermal environments and the response of an object to that environment. (Advanced Scientific Computing (ASC) Program)

- We can predict: Turbulent fluid mechanics (buoyant plumes); Participating Media Radiation (PMR); Reacting flow (hydrocarbon, particles, solids); Conjugate Heat Transfer (CHT)

Adaption of ASC modeling framework to battery system to establish its' safety basis

- We have demonstrated proof of concept

Image Source: WindPower Monthly
http://www.windpowermonthly.com/article/1284038/analysis-first-wind-project-avoids-storage-30m-fire



Predictive Simulation of Smoke Plume from Abnormal Event. The colors correspond to concentration of chemical species

Energy Storage Safety Protocols

As an increasing number of energy storage systems are deployed, the risk of safety incidents increases.

Damage to Facilities

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm (15 MW, 10 MWh)

- There were two fires in a year at the Kahuku Wind Farm
- There was significant damage to the facility
- Capacitors in the power electronics are reported to be associated with the failure.

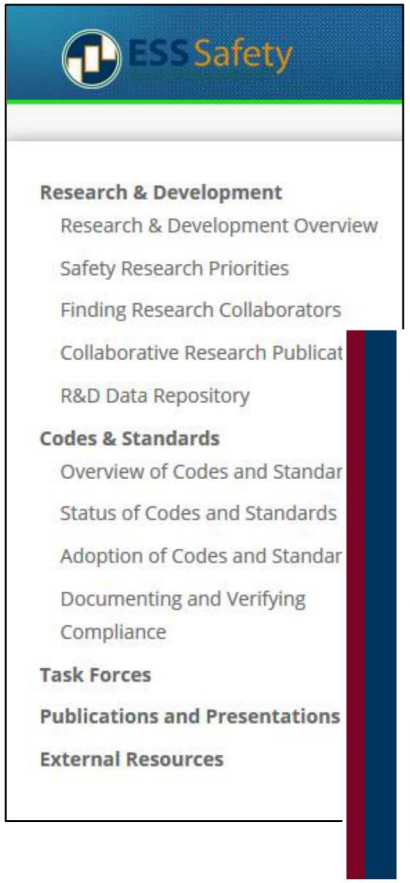
Impact to First Responders

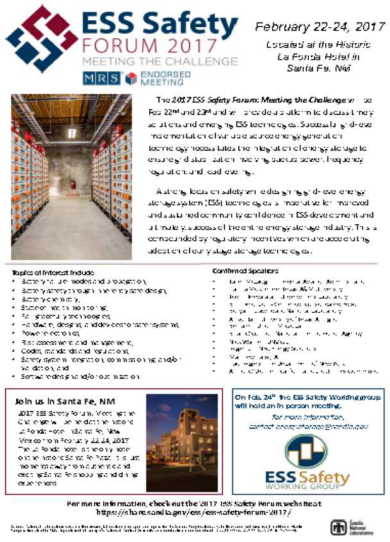
2013 Storage Battery Fire, The Landing Mall, Port Angeles WA (75kW, 50kWh)

- First responders were not aware of the best way to extinguish the fire,
- It reignited a week after it was thought to be extinguished.

Outreach in Energy Storage Safety

- **Website**: http://www.sandia.gov/energystoragesafety/ provides a common platform for safety researchers to find collaborators, share data, and post publications. This site is a widely accessed repository of resources for all stakeholders on energy storage safety.
- Annual **Energy Storage Safety and Reliability Forum** – brings 150 stakeholders annually to review storage safety and reliability aspects
- Monthly reports on the **status of safety related codes and standards** with biannual webinars
- Engagement with NFPA. EPPI, and ESA on **safety education**, outreach, protocols and standards
- Support for energy storage safety **standards development** working in collaboration with IEEE, IEC, UL, NFPA, ICC
- Regular **stakeholder surveys** to collect feedback and maximize impact

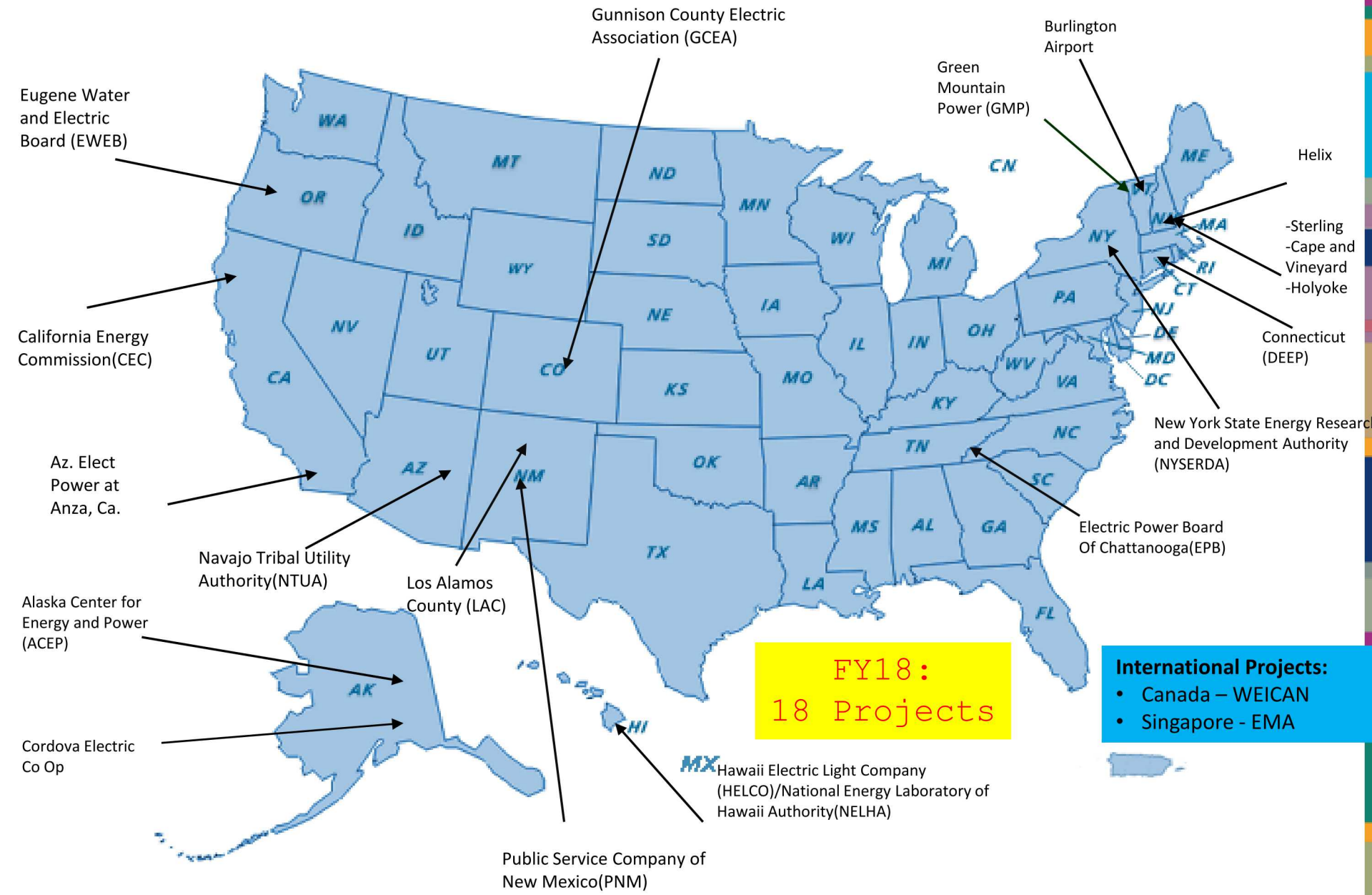




Technical Contributions to Ongoing Standards Development

- **IEEE 1635-12, IEEE 1547.9, IEEE 946, IEEE 1375**
- **UL 1973-13 Batteries for Use in Stationary Applications**
- **ANSI/UL 9540-P (ESS Safety)**
- **UL 1974 (Repurposing)**

Energy Storage Demonstration Projects



FY18:
18 Projects

International Projects:
- Canada – WEICAN
- Singapore - EMA

Energy Storage Analytics

Estimating the value of energy storage

- Production cost modeling (vertically integrated utility)
- LP Optimization (market area)
- Stochastic unit commitment/planning studies (vertically integrated utility)

Control strategies for energy storage

- Wide area damping control
- Control and architectures for MWh-GWh storage plants

Model development (e.g. for dynamic simulation)

Public policy: identifying and mitigating barriers

Standards development and DOE Protocols

Project evaluation

- Technical performance
- Financial performance

Open source tools for energy storage valuation - QuEST

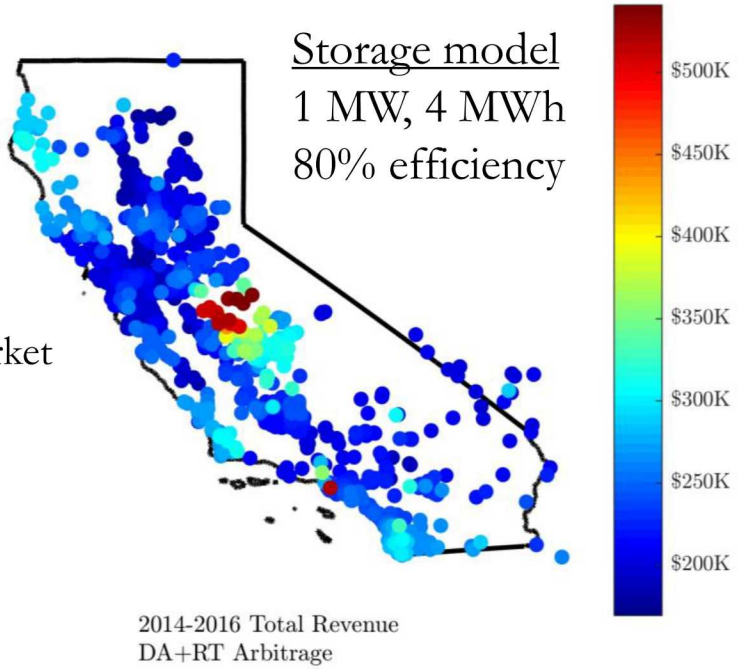
Estimating the Value of Energy Storage – CAISO Example

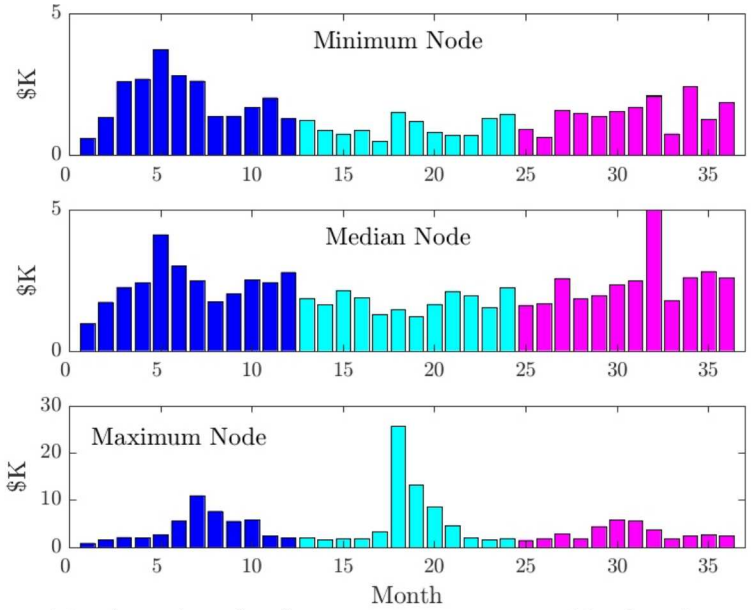
Analyzed ~2200 LMP nodes in CAISO

- Day ahead market arbitrage
- Day ahead and real time market arbitrage

Key takeaways

- Revenue opportunity is highly location specific
- Significantly more potential revenue if the real time market is included





Monthly day-ahead arbitrage revenue profile for the minimum node, the median node, and the maximum node 2014-2016.

In addition to the strong dependence on location, there was also a significant temporal variation in revenue (e.g., some months are much better than others)

R. H. Byrne, T. A. Nguyen, D. A. Copp, R. J. Concepcion, B. R. Chalamala, I. Gyuk, "Opportunities for Energy Storage in CAISO: Day-Ahead and Real-Time Market Arbitrage," proceedings of IEEE Speedam Symposium, June 2018, pp. 1-6.

Sterling Municipal Light Department Resilience Example

Sterling Potential value streams:

- Energy arbitrage
- Reduction in monthly network load (based on monthly peak hour)
- Reduction in capacity payments (based on annual peak hour)
- Grid resilience
- Frequency Regulation

Grid Resilience was the primary goal – other applications help pay for the system

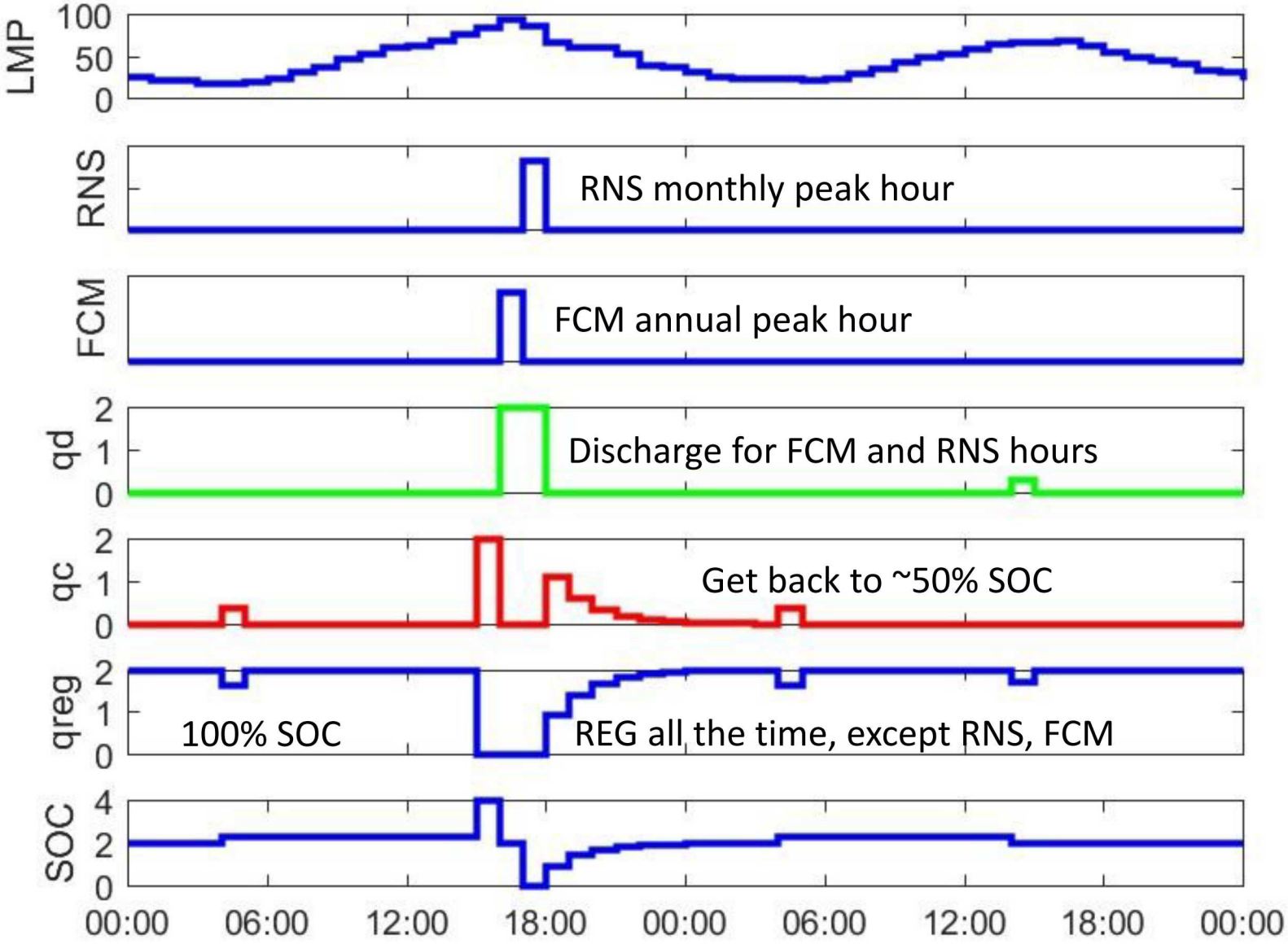
Several potential value streams (1MW, 1MWh 2017-18 data)

Description	Total	Percent
Arbitrage	$40,738	16.0%
RNS payment	$98,707	38.7%
FCM obligation*	$115,572	45.3%
Total	$255,017	100%

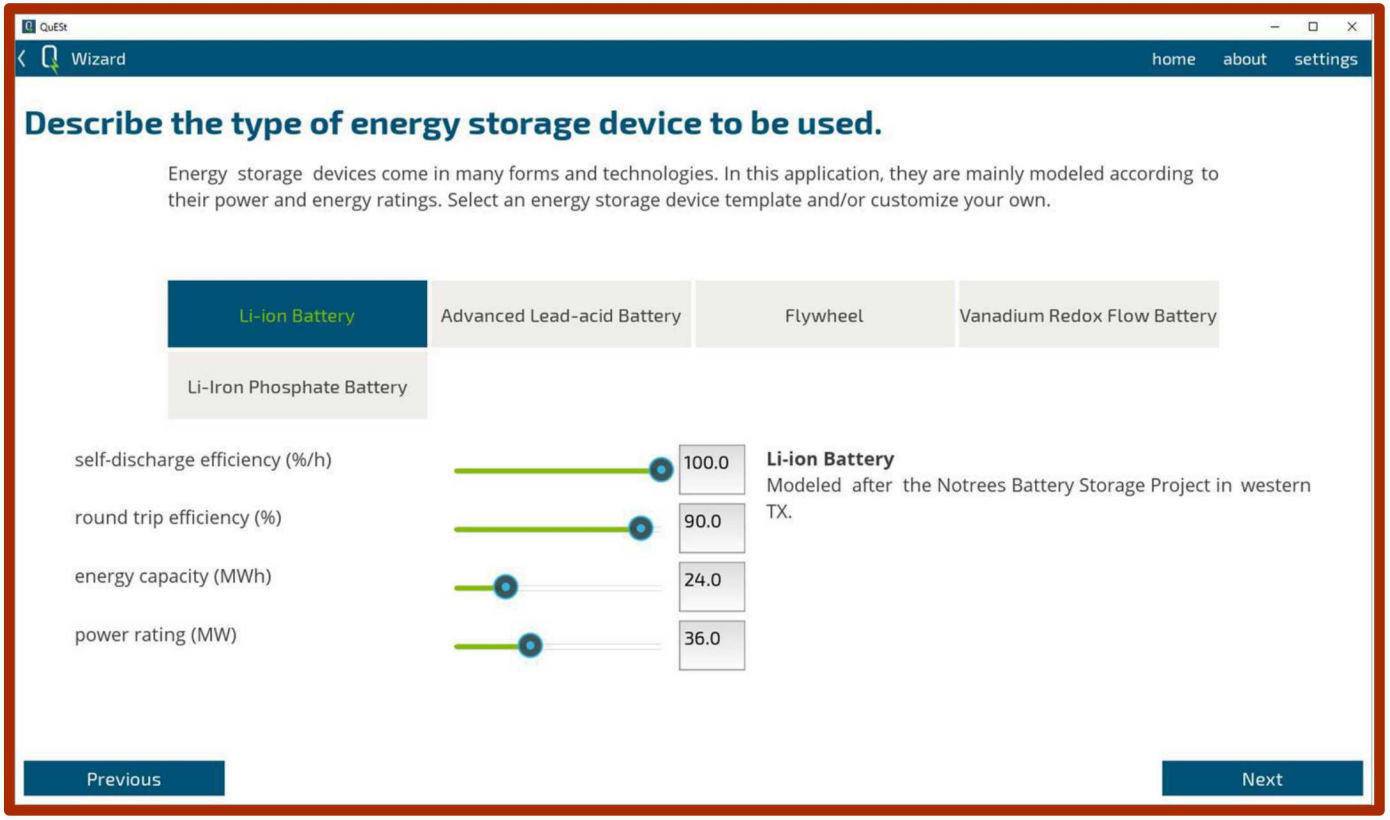
For more information, please refer to:

R. H. Byrne, S. Hamilton, D. R. Borneo, T. Olinsky-Paul, and I. Gyuk, "The value proposition for energy storage at the Sterling Municipal Light Department," proceedings of the 2017 IEEE Power and Energy Society General Meeting, Chicago, IL, July 16-20, 2017, pp. 1-5. DOI: 10.1109/PESGM.2017.8274631

Sterling Municipal Light Department Resilience Example



QuEST: An Energy Storage Application Suite



Open source, Python-based energy storage analysis software application suite

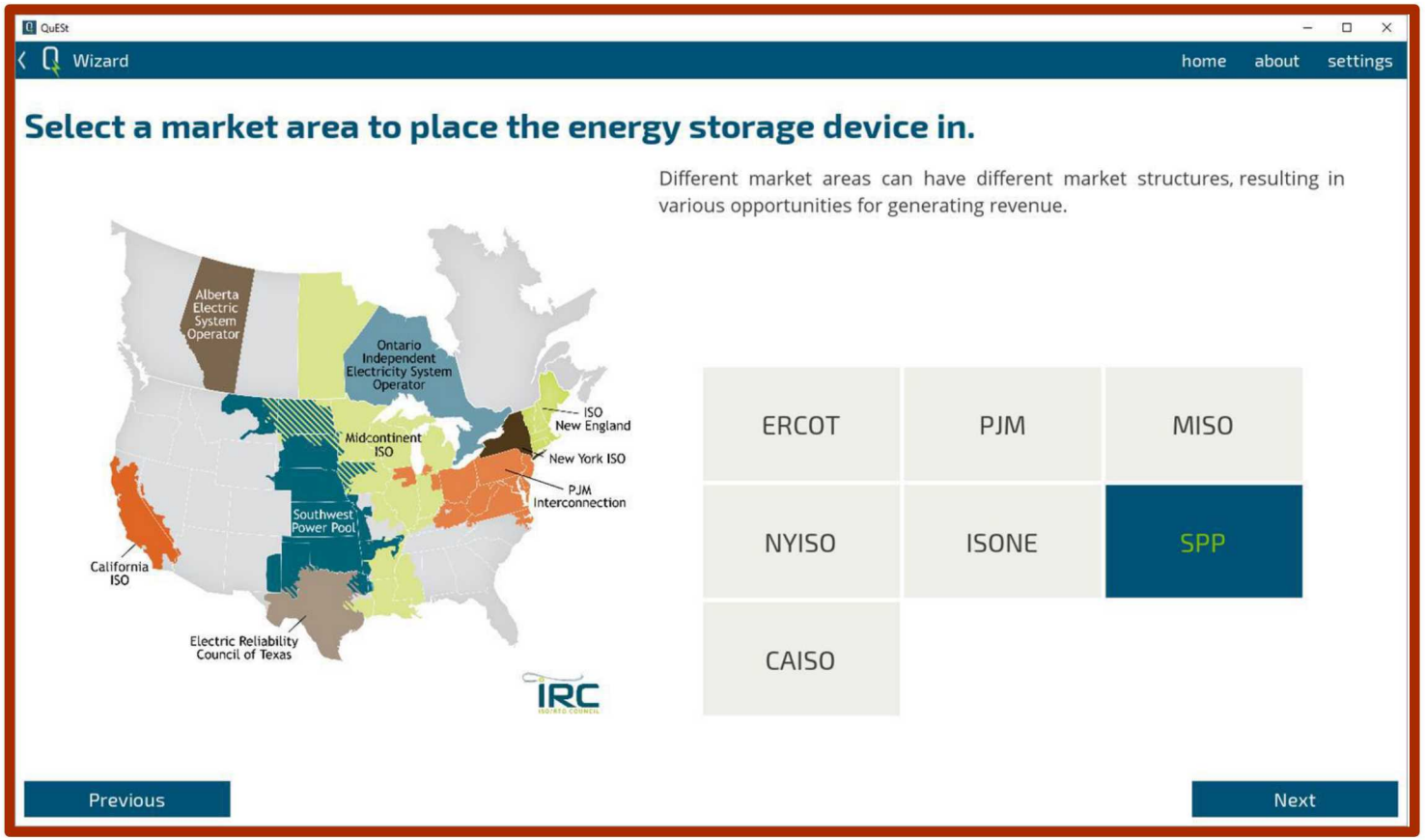
Developed as a graphical user interface for the optimization modeling capabilities of SNL's energy storage analytics group

- Version 1.0 – Analyzes data from market areas
- Version 1.2 – Added capability to analyze behind the meter applications

Now publicly available on GitHub

- github.com/rconcep/snl-quest

QuEST: An Energy Storage Application Suite



Downloads data from each of the North American Independent System Operators (ISOs)

Downloads utility rate structures from the Open EI utility rate database

Downloads simulated building load profiles from the Open EI database

Downloads solar irradiance data from the National Solar Radiation Database for solar+storage analysis

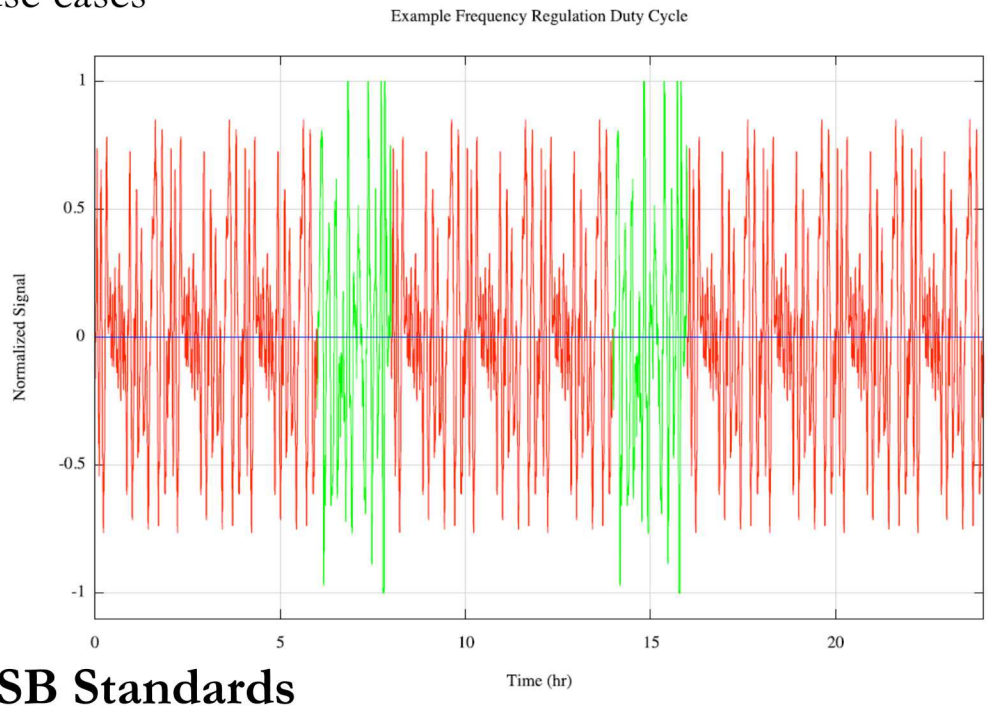
Standards Development

Energy storage protocols

- Pre-standards activity
- Joint effort with PNNL
- Protocols for uniformly measuring the performance of energy storage systems for various use cases

Applications Considered:

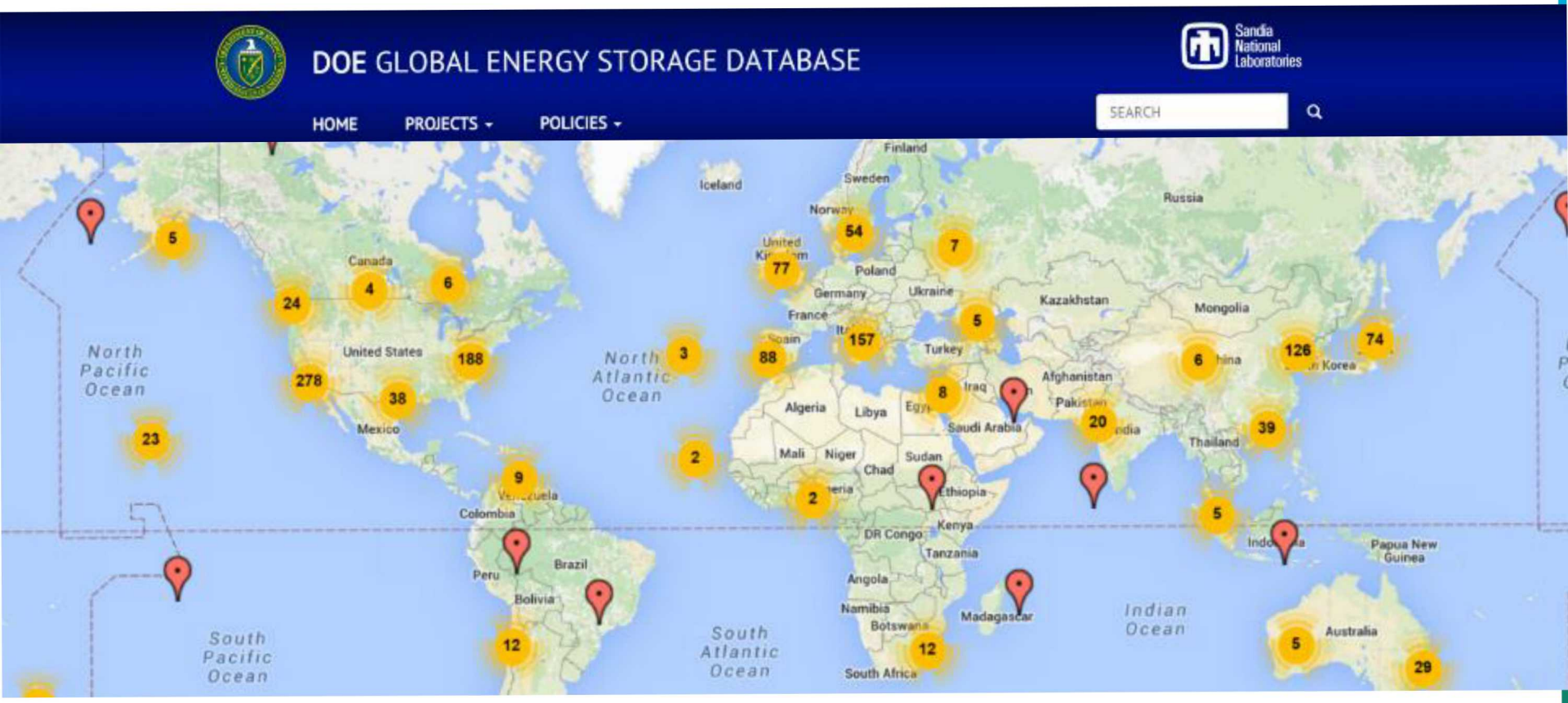
- Peak shaving
- Frequency regulation
- Islanded microgrids
- PV smoothing
- PV firming
- Frequency control
- Volt/var support
- Power quality



Leadership roles with IEEE ESSB Standards Committee

Outreach and Industry Tools

Global Energy Storage Data Base – 1800 entries



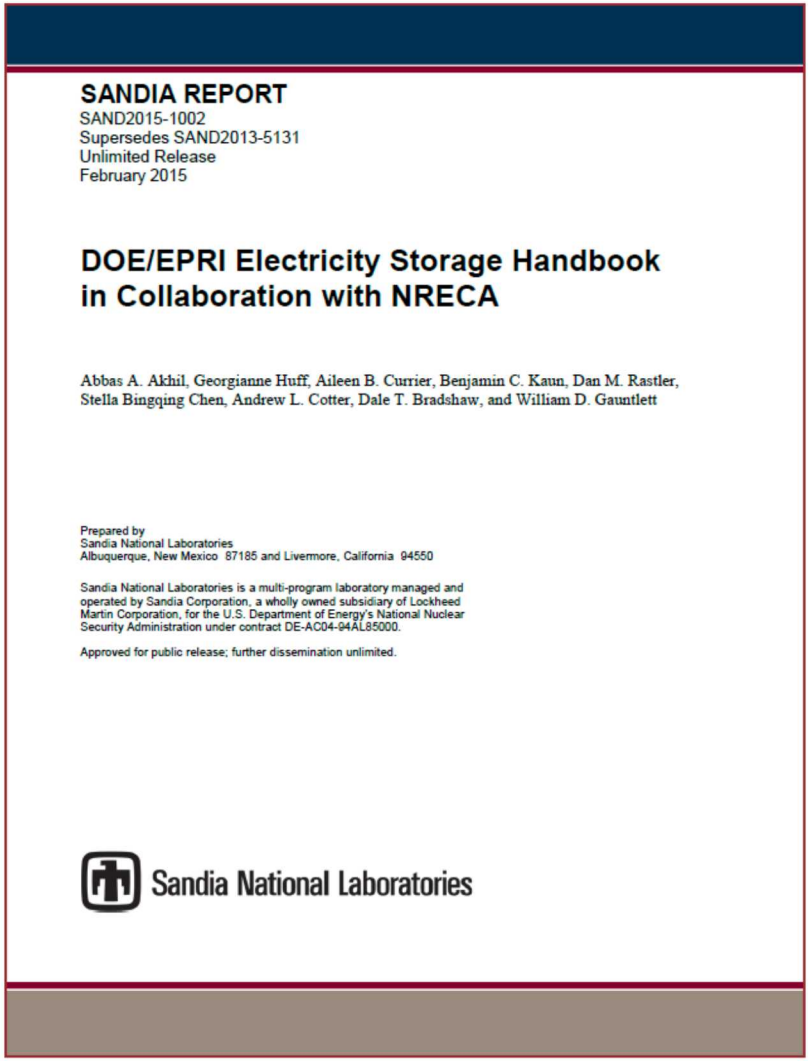
Outreach and Industry Tools

DOE/EPRI Electricity Storage Handbook is a how-to guide for utility and rural cooperative engineers, planners, and decision makers to plan and implement energy storage projects safety in communities

DOE Energy storage program website

- Publications
- Project information
- Archive of DOE Peer Review presentations

www.sandia.gov/ess



SANDIA REPORT
SAND2015-1002
Supersedes SAND2013-5131
Unlimited Release
February 2015

DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA

Abbas A. Akhil, Georgianne Huff, Aileen B. Currier, Benjamin C. Kaun, Dan M. Rastler, Stella Bingqing Chen, Andrew L. Cotter, Dale T. Bradshaw, and William D. Gauntlett

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Sandia National Laboratories

Outreach – Conferences and Workshops

2016 SW Regional PUC Open Forum Information Sharing

Tutorials at major IEEE, MRS, ECS, ESA events

Supporting tutorial program with IEEE Energy Storage and Stationary Battery Committee (tutorial at FERC in Feb, planned tutorial for NARUC)

Summary

The Sandia Energy Storage program focuses on the following thrust areas:

- Materials and Systems Development
- Power Electronics
- Energy Storage Systems Safety and Reliability
- ES Systems Demonstrations and Testing
- Grid Analytics and Policy
- Outreach - publications and meetings to help educate the Grid Energy community

For more information, please refer to: www.sandia.gov/ess

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