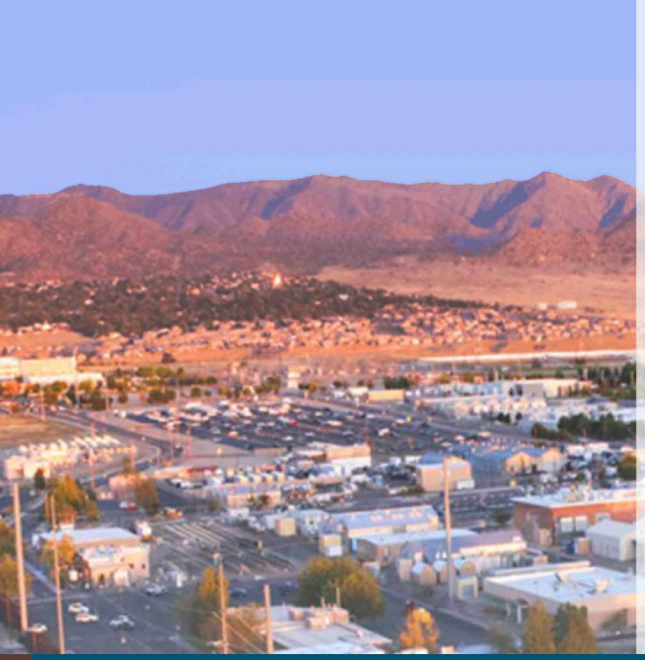


SAND2019-5453PE

DOE Office of Electricity Roadmap—Sandia Grid Energy Storage Program

Presented by Dr. Summer Ferreira—

OE Safety Thrust Lead

On Behalf of Energy Storage Technology and Systems

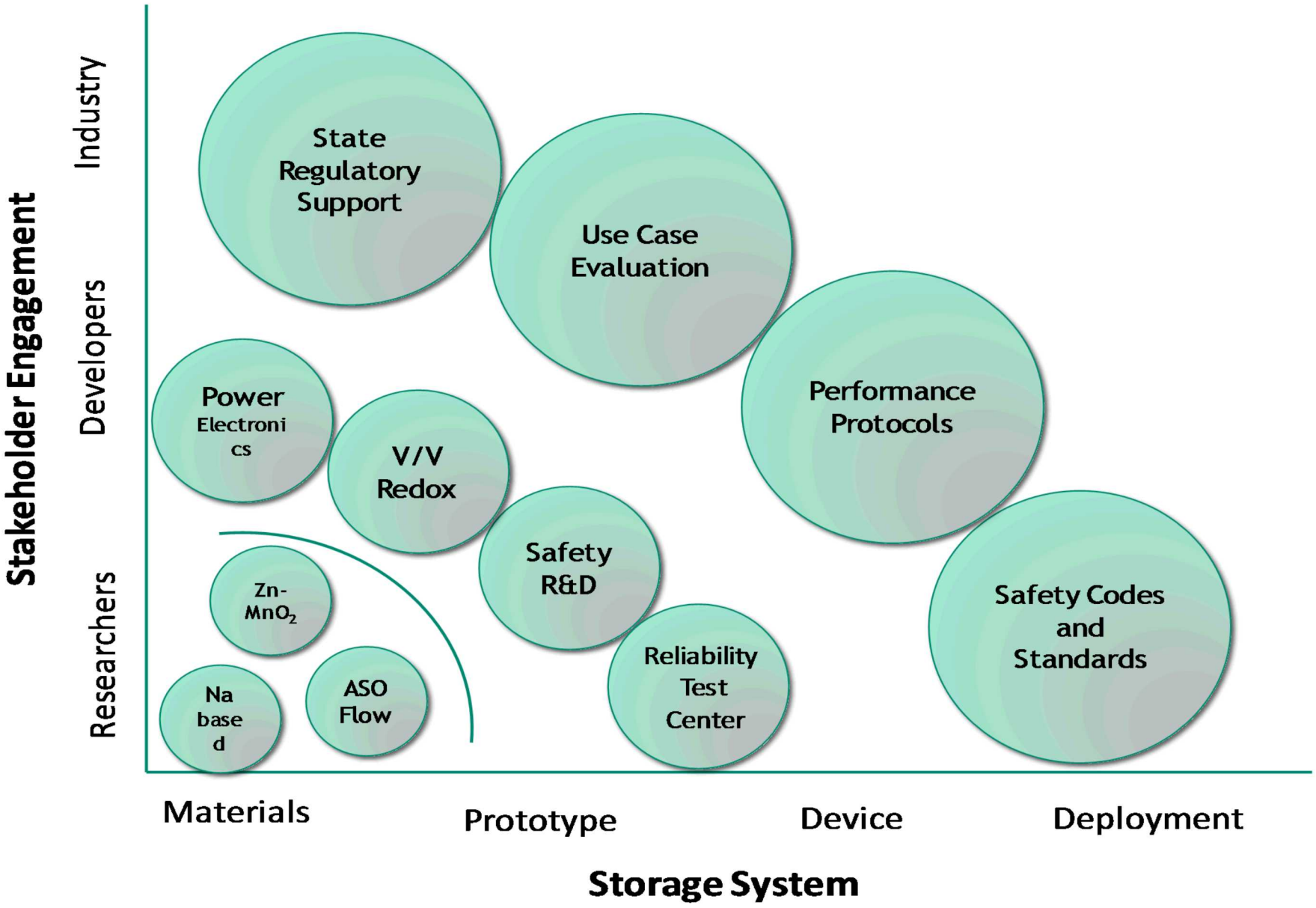
DOE Office of Electricity Priorities

- 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

Energy Storage Program Objectives

Program Areas	Goals	Objective
 Cost Competitive Technology	Capability and cost to meet industry requirements.	• Materials and chemistry • Systems and manufacturing • Cost reduction • Expanded applications
 Reliability & Safety	Increase user confidence	• Lab testing • Codes and standards • Guidebooks • R&D Improvements
 Regulatory Environment	Barriers and requirements equal or comparable to other grid resources	• Policy analysis • Valuation methods • Resolution of benefits
 Industry Acceptance through Demonstrations	Develop locational value and technical use cases	• Stakeholder engagement • Proving success • Seamless integration • Consumer benefits

DOE Grid Energy Storage Program



Energy Storage R&D at Sandia

Energy Storage is a major Crosscut at the lab.

Wide ranging R&D covering energy storage technologies with applications in the grid, transportation, and stationary storage

20+ staff, 10+ post docs, 22 University partners, close industry collaboration

Active University Collaborations










CUNY Energy Institute

Davidson College

Northeastern University

Stony Brook University

University of Kentucky

University of Washington

UC Irvine

University of Alaska Fairbanks

University Texas at Austin

New Mexico State University

Ohio State University

University Texas Arlington

New Mexico Tech

University New Mexico

Washington University at S. L.

Michigan State University

University of Utah

South Dakota State University

Clemson University

Southern Methodist University










$2.2M in funding to universities

Industry and Utility Collaborators

GeneSic Semiconductor

Creare

InnoCit

Mainstream Engineering

Powdermet

Urban Electric Power

Helix Power Corporation

Eugene Water and Electric Board

Cordova Electric Cooperative

Strategen

Mustang Prairie Energy

ANZA Electric

PNM Resources

WattJoule

UniEnergy Technologies

Sterling Municipal Light Department

Public Service of New Mexico

National Rural Electric Cooperative Association

Hawaii Electric Light

Green Mountain Power

Electric Power Board of Chattanooga

Electric Power Research Institute

Ecoult Battery

Demand Energy

Burlington Electric Department

NELHA

Major R&D Thrust Areas at Sandia National Laboratories

Materials and Systems Development

- Development of next-generation technologies
- Improving current technology (flow, sodium, Zn-MnO2 batteries, membranes, etc.)

Power Electronics

- Development of power electronics and power conversion systems.

Energy Storage Systems Safety and Reliability

- Fundamental safety R&D, Advanced Modeling
- Laboratory testing and analysis from individual cells to MW size systems

ES Systems Demonstrations and Testing

- Field deployments; State-Initiated Demonstration Project Development

Grid Analytics and Policy

- Systems optimization, wide area controls, modeling and open access tools

Industry Outreach – publications, webinars and conferences to help educate the Grid Energy community

Energy Storages Materials Research

Improving the performance of Flow Batteries, Sodium batteries, and Zn-MnO_2 through materials research

Key Projects

- Zn-MnO_2 rechargeable batteries (in collaboration with CUNY, Northeastern Univ, New Mexico State, Stony Brook University, Urban Electric Power)
- Low cost membranes and energy dense electrolytes for flow batteries (in collaboration with University of Washington, Davidson College, LANL, WattJoule)
- Sodium batteries (in collaboration with University of Kentucky, Field Upgrading (former Ceramatec))

Power Electronics and Power Converters

Optimization at the interface between power electronics and electrochemistry. Development of power converters using SiC and GaN. Reliability of WBG Power Converters. Improved energy storage safety through power electronics.

- New methods for the optimization and efficient coupling between batteries and power electronics for improved power conversion. Topologies and architectures configured for aqueous batteries including flow batteries, alkaline zinc based batteries
- New topologies at the cell and module level power electronics to improve the performance, safety and reliability of cells
- Synthesis, structure property investigations of soft magnetic materials and the development of magnetic cores for high frequency transformers.

External Projects with Universities

- High-temperature iron-nitride transformer for high frequency converters (with UC Irvine)
- Development of advanced gate oxide for wide band gap devices
- SiC and GaN-based power inverters (in collaboration with GeneSiC, Creare, and Innocit)
- High energy dielectrics for scalable capacitors (in collaboration with SMU/UT Dallas)
- Low voltage and high current bidirectional converters for flow battery systems (with UT Austin)
- Medium-voltage power electronics and reliability of MV power converters (with Ohio State and Univ of Houston)
- Power converter integration with large format batteries and PV panels (New Mexico State and Urban Electric Power)

Energy Storage Safety and Reliability

Cell and module level safety test and analysis. Engineered safety of large systems. Predictive models for ES safety. Storage safety standards and protocols.

Key Projects

- DC Arc flash analysis of energy storage systems (with Univ Texas Arlington)
- Analysis of Li-battery failure mechanisms through spectroscopy (with New Mexico Tech)
- Energy storage safety collaborative
- Energy storage materials safety
- Fire suppressant analysis and failure mitigation analysis
- Electrochemical abuse testing and electrochemical safety modeling
- Improved safety through integration of power electronics

Program Areas	Goals	Objective
Reliability & Safety	Increase user confidence	• Lab testing • Codes and standards • Guidebooks • R&D Improvements

Mission:

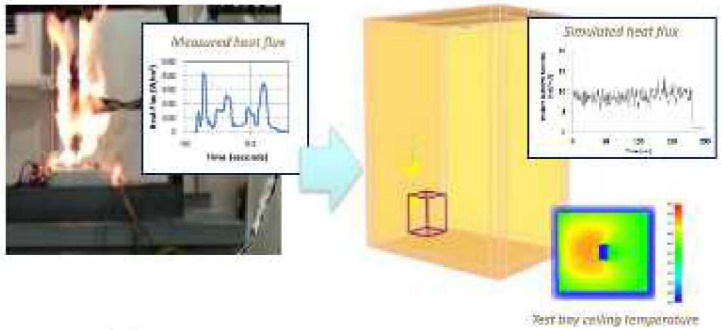
Validate and improve the safety and reliability of energy storage systems to decrease human and financial risk while accelerating acceptance of new storage:

Current Efforts:

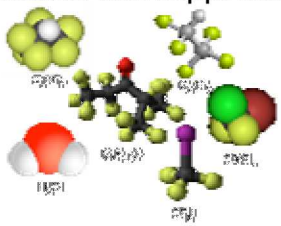
Energy Storage Safety Working Group (ESSWG) with industry stakeholders
Energy Storage Reliability Workshop.
Safety Codes and Standards Documentation.
Development of safer materials.

Greater Commercial and Societal Acceptance of Energy Storage requires significant advance in Safety and Reliability R&D and the field validation of system performance.

Thermal runaway experiment and modeling



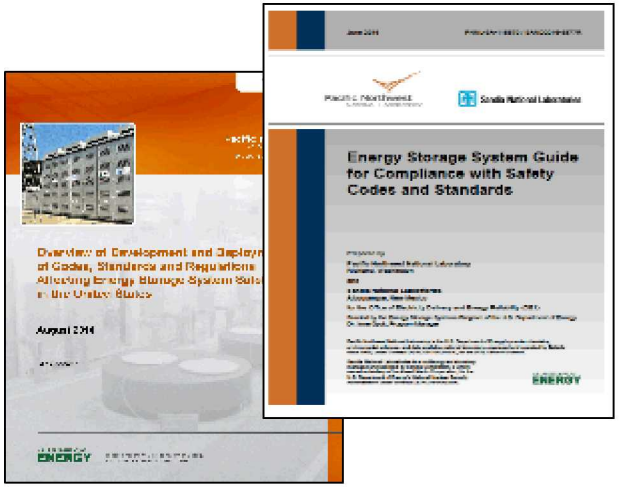
Commercial suppressants



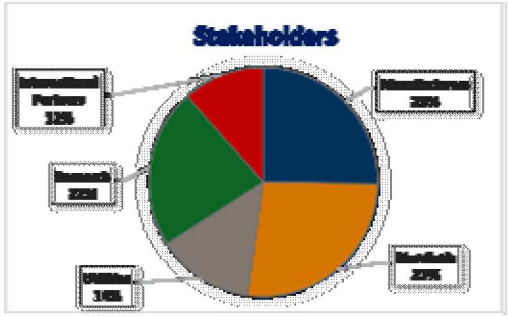
Objective: ESS safety R&D dictated by industry priorities solicited through our diverse working group.

- **Fire Suppression testing** and analysis
- **Thermal runaway** research
- **System scale burn test**
- **Commodity classification** development
- **Fire and vent gas modeling** and analysis

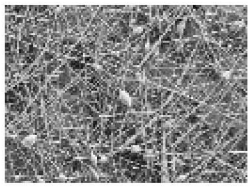
Objective: Distill codes and regulations, providing common sense feedback to code bodies while identifying gaps to facilitate safe and efficient adoption.



Objective: Provide awareness to first responders and authorities with jurisdiction; metering perception of risks with reality.



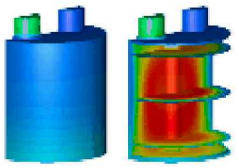
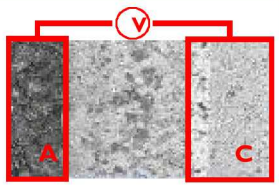
ESS Safety: R&D for Making Systems Safe and Reliabl




Materials R&D to date:
- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials

Materials R&D needs:
- Viable flow batteries
- Aqueous electrolyte batteries
- High specific heat suppressants
- Vent gas composition

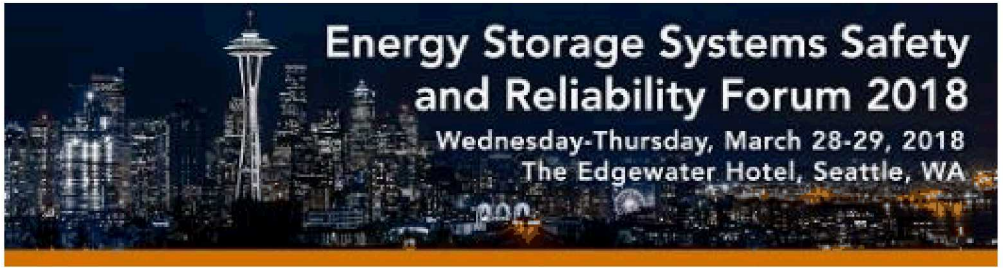

Testing
- Electrical, thermal, mechanical abuse testing
- Failure propagation testing on batteries/systems
- Suppressants and delivery with systems and environments
- Large scale thermal and fire testing (TTC)

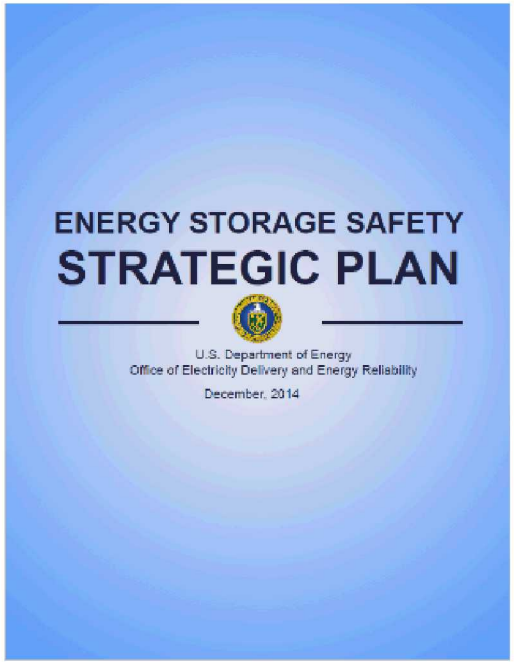



Simulations and Modeling
- Multi-scale models for understanding thermal runaway
- Validating failure propagation models
- Fire Dynamic Simulations (FDS) to predict the size, scope, and consequences of battery fires

Procedures, Policy, and Regulation
- UL 1973-13 Batteries for Use in Stationary Applications
- ANSI/UL 9540-P (ESS Safety)
- UL 1974 (Repurposing)
- IEEE 1635-12 (Ventilation and thermal management)

Energy Storage Safety and Reliability





ESS Safety WORKING GROUP

Research & Development
- Research & Development Overview
- Safety Research Priorities
- Finding Research Collaborators
- Collaborative Research Publications

Codes & Standards
- Overview of Codes and Standards
- Status of Codes and Standards
- Adoption of Codes and Standards
- Documenting and Verifying Compliance

Task Forces
- Large Scale ESS Fire Performance Testing Protocol

Publications

External Resources

For more information on the Energy Storage Safety Working Group (ESSWG) visit our website

The goal of the energy storage safety working group is to ***"Foster confidence in the safety and reliability of energy storage systems."***

http://www.sandia.gov/energystoragesafety/

Pacific Northwest NATIONAL LABORATORY

Sandia National Laboratories

DOE OE Energy Storage Systems Safety Roadmap

U.S. DEPARTMENT OF ENERGY | Office of Electricity Delivery & Energy Reliability

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

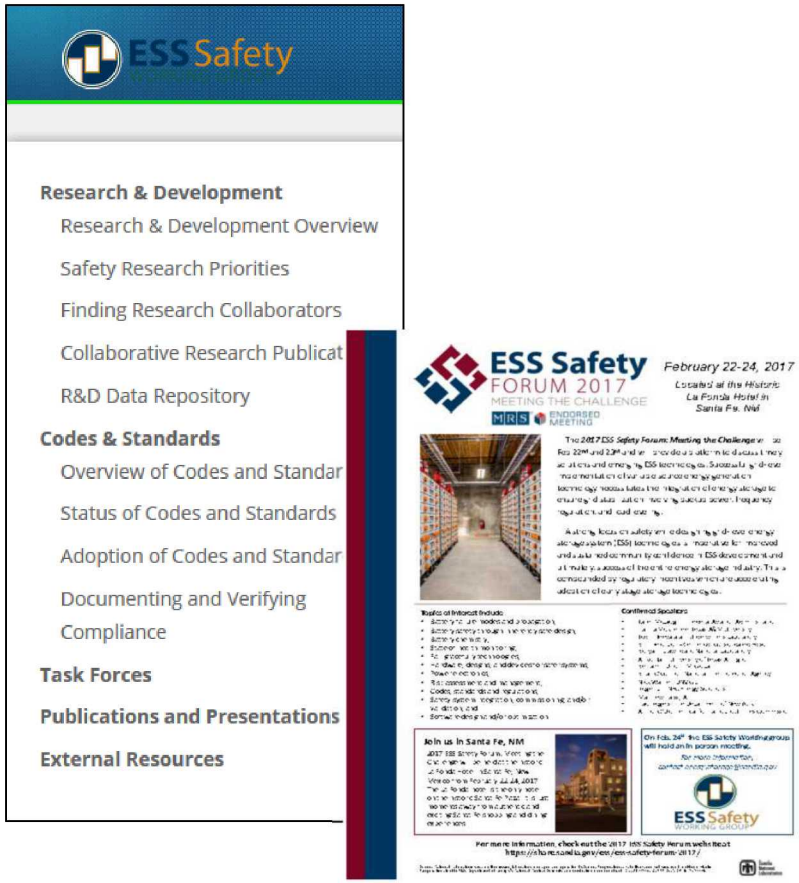

Energy Storage Test Pad (ESTP)


Cell Lab


Battery Abuse Testing Laboratory

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)**

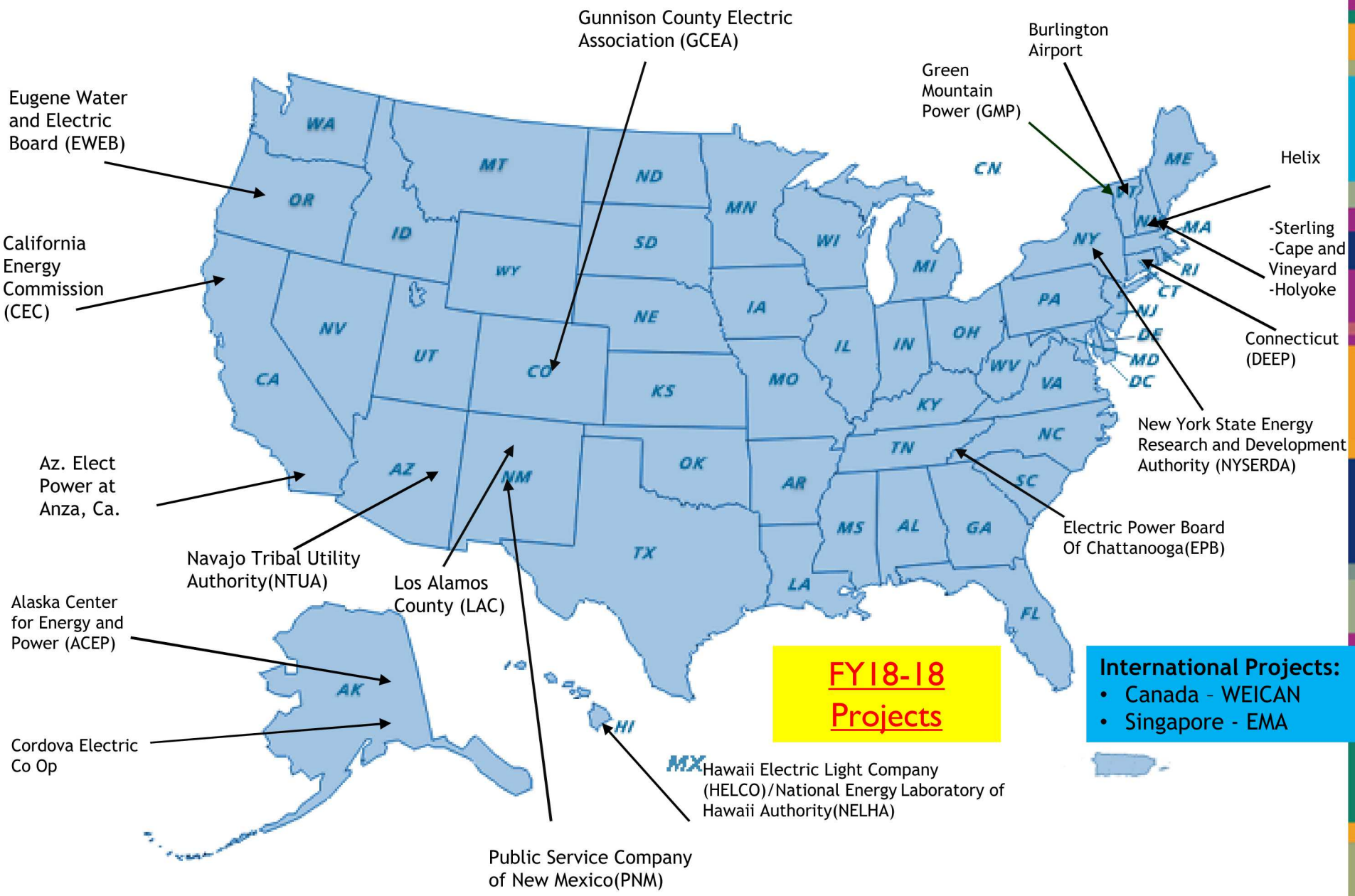
Energy Storage Demonstration Projects

Enable confident development, deployment and operation of energy storage through controlled testing of prototype commercial storage technologies

Key Projects

- Energy storage projects with states (with CESA)
- Energy storage state projects focused on rural resiliency (with NRECA)
- SW Regional demonstration projects in NM, AZ and CO
- Industry support for energy storage engineering and commissioning
- International collaborations (EMA Singapore)
- California/Hawaii projects and technical support
- Flywheel energy storage demonstration project (with Helix Power)

Energy Storage Demonstration Projects



Sterling, MA: Microgrid/Storage Project

$1.5M Grant from MA Community Clean Energy Resiliency Initiative
Additional DOE-OE Funding, Sandia National Laboratories Analytics

Sterling, MA
October 2016
NEC, Li-Ion

December 2016
2 MWh /3 MW

December 2016 - November 201

Actual Savings

- Arbitrage $11,731
- Monthly Peaks $143,447
- Annual Peak $240,660

Total $395,839

2017 GTM Grid Edge Award!

Visitors: Germany, Denmark, England, Japan, Malaysia, Taiwan

2018 Heat Wave: $250K realized in avoided payments!!

Recent Grid Scale Projects

Alabama

Southern Company/Southern Research – Birmingham, AL – 100kW/400kWh

Alaska

Cordova Electric Co-Op – Cordova AK – 1 MW / 1 MWh
Alaska Energy Authority – AK

Arizona

Navajo Tribal Utility Authority – Dikon, AZ - 6 KW / 12 KWh Zinc Manganese Oxide

California

ANZA Electric Co-Op – Anza, CA. est. 2 MW / 2MWh BESS.

Colorado

Gunnison Electric – Gunnison, CO

Recent Grid Scale Projects

Massachusetts

Sterling Municipal Light Department – Sterling MA. - 2 MW/3.9 MWh Lithium-ion.
City of Northampton – Northampton, MA
National Grid – Nantucket Island, MA - 6 MW / 48 MWh lithium-ion system.
National Grid – Worcester, MA – 500kW/3MWh V/V flow battery
Boston Medical – Boston, Ma – Est 1-2MW / 1- 4MWh battery system.

Hawaii

Natural Energy Lab of Hawaiian Authority – Kona Hi – 100 KW / 400 KWh

New Mexico

Public Service of New Mexico – Albuquerque, NM – Est 5-20 MW / 10- 40 MWh
Sandia National Laboratories – Albuquerque, NM – 250 KW / 1 MWh.
Santa Fe Community College – Santa Fe, NM – Est. 2 MW / 2 MWh
Albuquerque Public Schools -Albuquerque, NM – Est. 500 KW / 1 MWh.

New York

City College of New York – New York, NY – 50 KW / 160 KWh zinc manganese oxide

Energy Storage Analytics and Controls

Developing analytics and controls for integration of utility class storage systems. Software tools for optimal use of energy storage across the electricity infrastructure. Standards development. Engineering analysis for demo projects.

Key Projects

- Open Source Tools for Energy Storage Analytics
- Control of Distributed Energy Storage, Optimal control and dispatch of energy storage
- Modeling for ES Enabled Distribution Grid (NRECA, Univ collaboration)
- Energy Storage in the Transmission System
- Tech Specific Modelling & Optimization (University of Utah)
- Market Survey-Financing-Insurance Energy Storage Financing Roadmap (Mustang Prairie)
- Hydrogen Energy Storage Analytics
- Holistic Optimization Framework for Grid Integrated Energy Storage (Michigan State Univ)
- Integrating Virtual Inertia in Energy Storage Systems and Energy Markets (South Dakota State University)
- Distributed Control Algorithms Wide-Area Power Grids using Energy Storage (Clemson Univ)

Energy Storage Analytics

Estimating the value of energy storage
- Production cost modeling (vertically integrated utility)
- Stochastic unit commitment/planning studies (vertically integrated utility)
- LP Optimization (market area)

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

T&D simulation with energy storage (PSLF, OpenDSS)

Supporting Public policy: identifying and mitigating barriers

Standards development and DOE Protocols

Project evaluation
- Technical performance
- Financial performance

Technical Challenges in Energy Storage Analytics

Energy storage models

- Model selection critical as there are a range of technologies and applications
- Development of technology specific models (energy flow models for chemistries)

Analytical and numerical method development

- Industry currently lacks good analytical tools to optimize storage deployment
- Developing methods to accommodate non-linear, highly accurate models for optimization

Simulation and analysis tools

- Currently, multiple tools must be applied to evaluate storage projects. Developing a unified tool set for energy storage across multiple technologies and markets

Dynamic Simulation PSS®E PSLF	Technical requirements at transmission level	**Production Cost Model** PLEXOS PRESCIENT®	Analysis of potential revenue in market areas
Distribution Simulation DSS GridLAB-D	Technical requirements at distribution level	**Optimization Tools** PYOMO MATLAB	Analysis of system cost savings at from more efficient generation

R. H. Byrne, T.A. Nguyen, D.A. Copp, B. R. Chalamala and I. Gyuk, "Energy Management and Optimization Methods for Grid Energy Storage Systems," in IEEE Access, vol. 6, pp. 13231-13260, 2018.

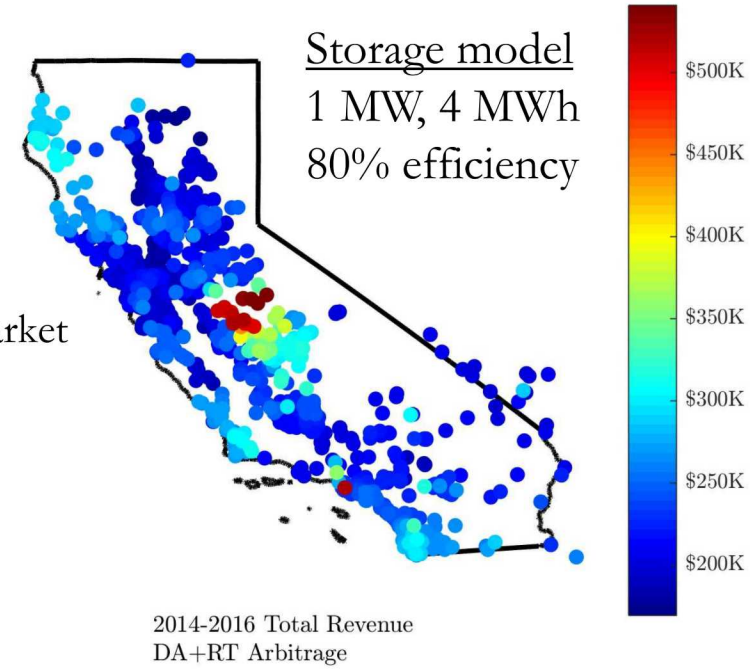
Estimating the Value of Energy Storage – CAISO Example

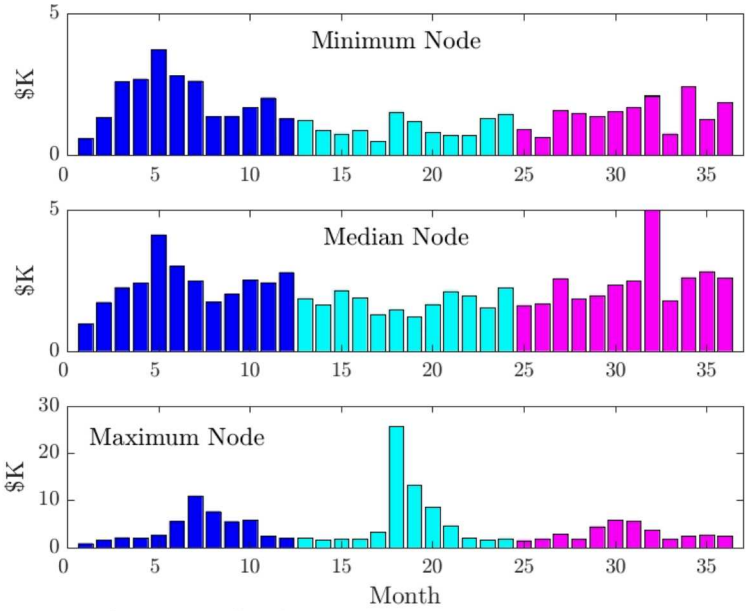
Analyzed ~2200 LMP nodes in CAISO

- 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





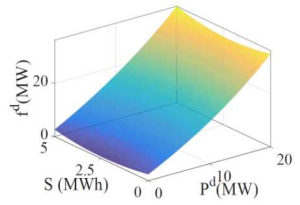
Monthly day-ahead arbitrage revenue profile for the minimum node, the median node, and the maximum node 2014-2016.

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)

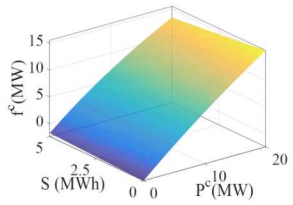
R. H. Byrne, T. A. Nguyen, D. A. Copp, R. J. Concepcion, B. R. Chalamala, I. Gyuk, "Opportunities for Energy Storage in CAISO: Day-Ahead and Real-Time Market Arbitrage," proceedings of IEEE Speedam Symposium, June 2018, pp. 1-6.

Non-linear Energy Storage Models

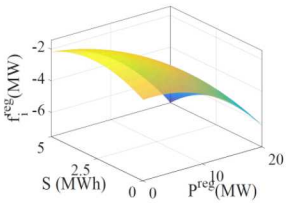
Vanadium Redox Battery



(a) Discharge function f^{d} of the VRFB system

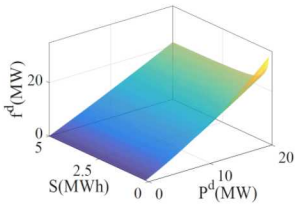


(b) Charge function f^{c} of the VRFB system

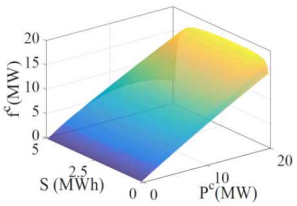


(c) Regulation function f_i^{reg} of the VRFB system during the first hour of June 2017

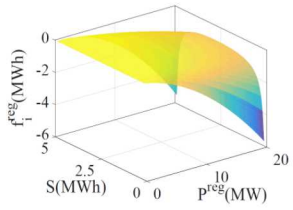
Lithium-ion/lead-acid Battery



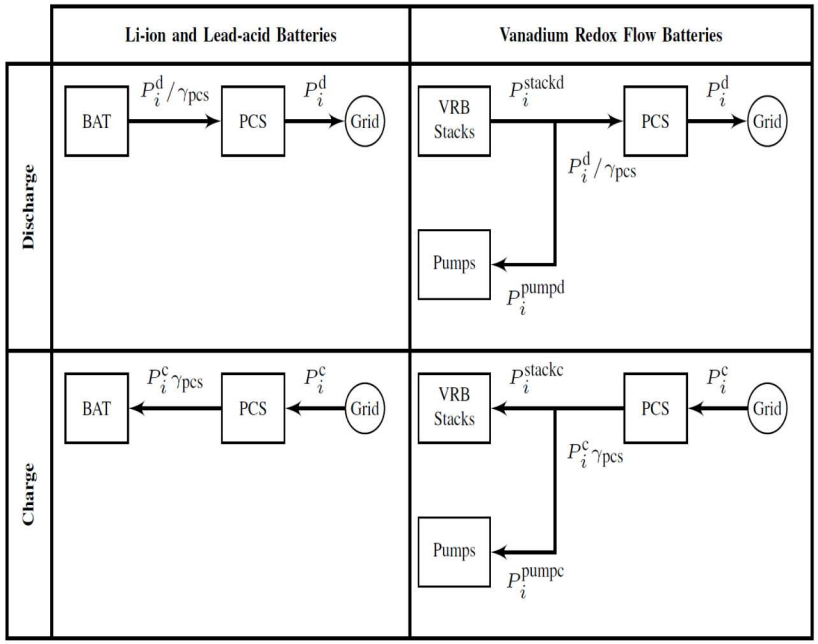
(a) Discharge function f^{d} of the Li-ion battery system



(b) Charge function f^{c} of the Li-ion battery system



(c) Regulation function f_i^{reg} of the Li-ion battery system during the first hour of June 2017



- Charge/discharge characteristics of energy storage devices are highly dependent on SOC, Temp, input/output power
- Efficiencies are not constant. Developing new models to capture technology specific characteristics to improve system performance

T. A. Nguyen, R. H. Byrne, B. R. Chalamala and I. Gyuk, "Maximizing The Revenue of Energy Storage Systems in Market Areas Considering Nonlinear Storage Efficiencies," in the proceedings of the 2018 IEEE SPEEDAM, June 2018, Amalfi, Italy.

Open Access Energy Storage Tools

Sandia plans to release the internal Python-based software tools that have been employed in-house since ~2012 (July 2018 release)

Based on Sandia's Pyomo optimization framework in Python

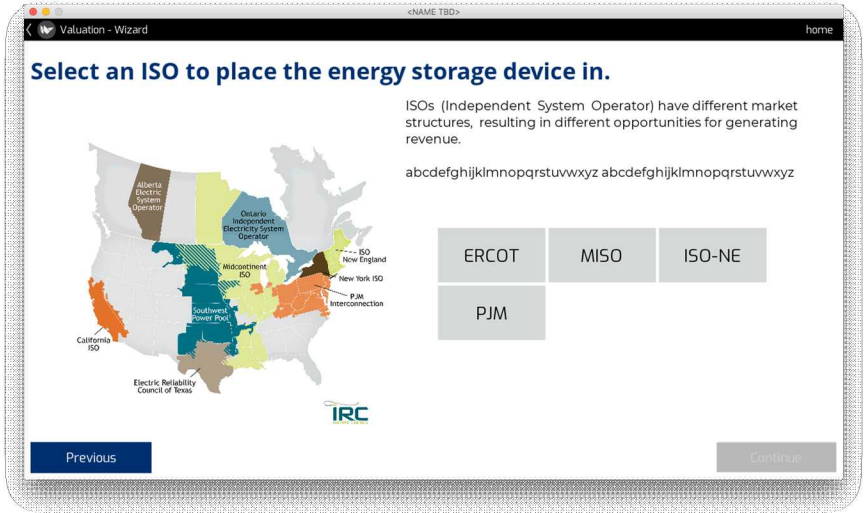
- High level object oriented language for formulating optimization problems
- 2016 R&D 100 award winner
- Open source software package with technical support from Sandia

Initial capabilities

- Revenue optimization in ISO market areas
- Arbitrage and frequency regulation

Planned capabilities for subsequent releases

- Microgrid design and operation
- Storage plus solar and wind
- Technology selection guide
- Total cost of ownership calculations using updated data from the Energy Storage Handbook



Public Policy: Helping to Identify and Mitigate Barriers

Power market design[1]

- Standardized contracts for energy and reserve
- Linked centrally-managed forward markets to support trading of standardized contracts

Inform market and policy barriers[2]

- Regulatory issues at the federal and state level
- Market issues that affect non-ISO/RTO and ISO/RTO markets
- Utility and developer business model issues
- Cross-cutting issues that bridge a number of these categories
- Technology issues that affect the multitude of energy storage technologies

Educational reach out to regulators and policy makers

[1]Leigh S. Tesfatsion, C´esar A. Silva-Monroy, Verne W. Loose, James F. Ellison, Ryan T. Elliott, Raymond H. Byrne, and Ross T. Guttromson, "New Wholesale Power Market Design Using Linked Forward Markets", Sandia National Laboratories, SAND2013-2789, April 2013.
[2]Dhruv Bhatnagar, Aileen Currier, Jacquelynne Hernandez, Ookie Ma and Brendan Kirby, "Market and Policy Barriers to Energy Storage Deployment", Sandia National Laboratories, SAND2013-7606, September 2013.

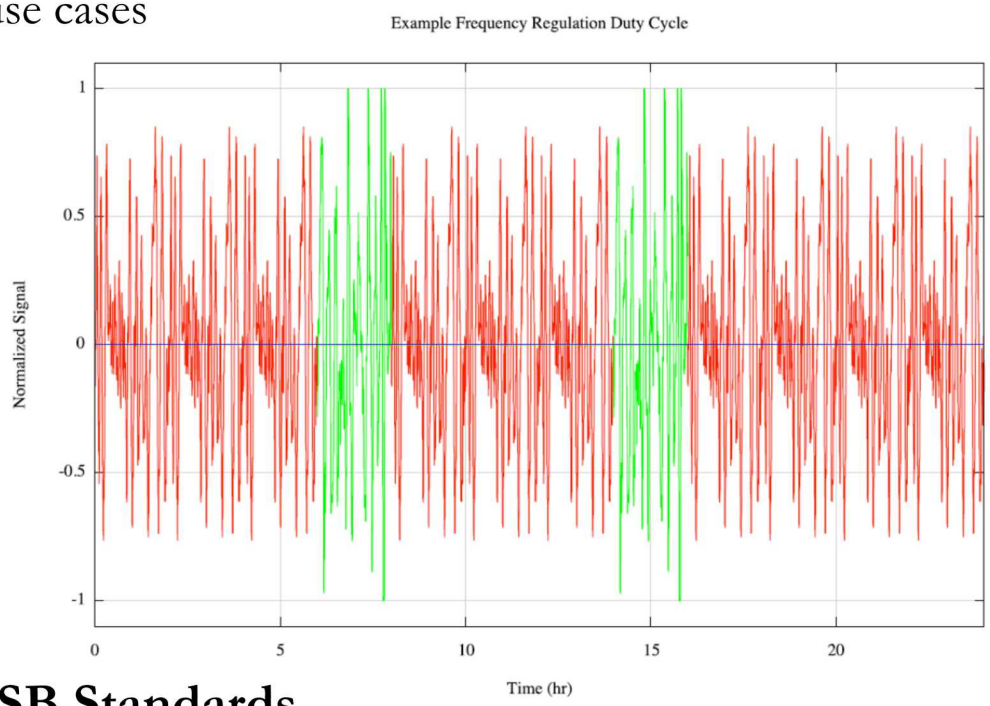
Standards Development

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

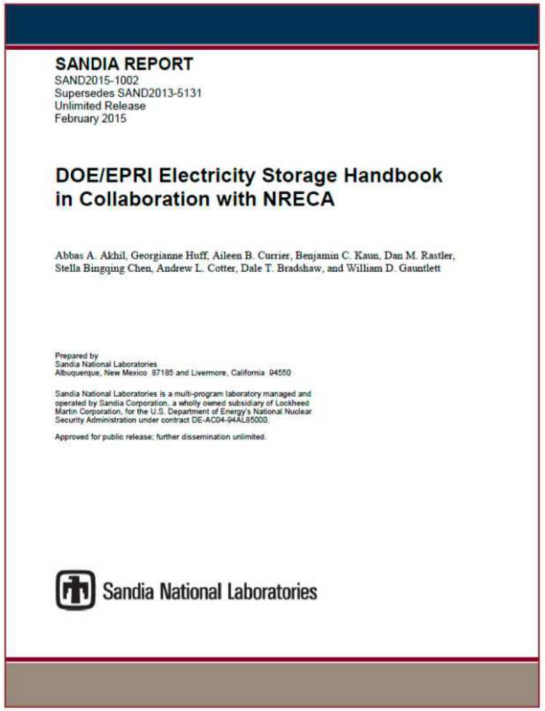
Outreach and Industry Tools

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
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DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA

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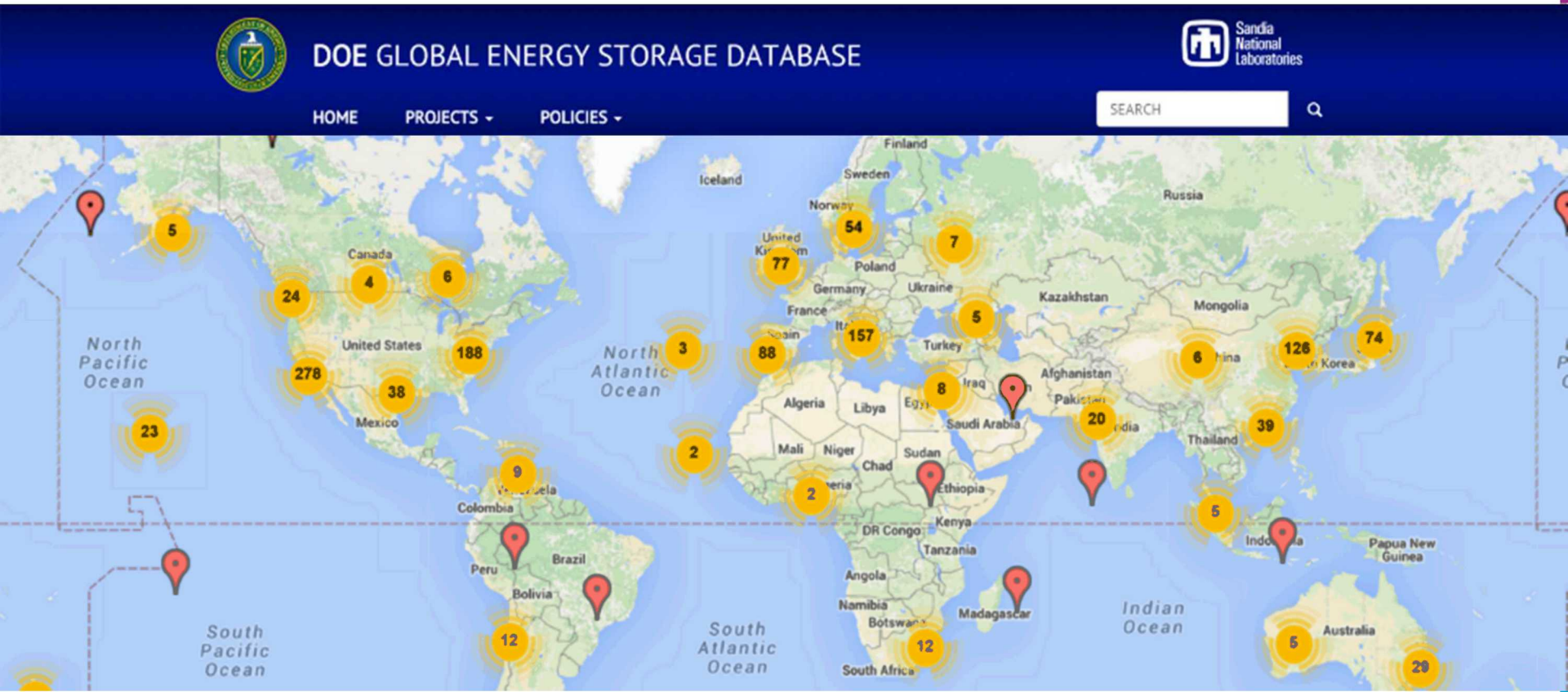
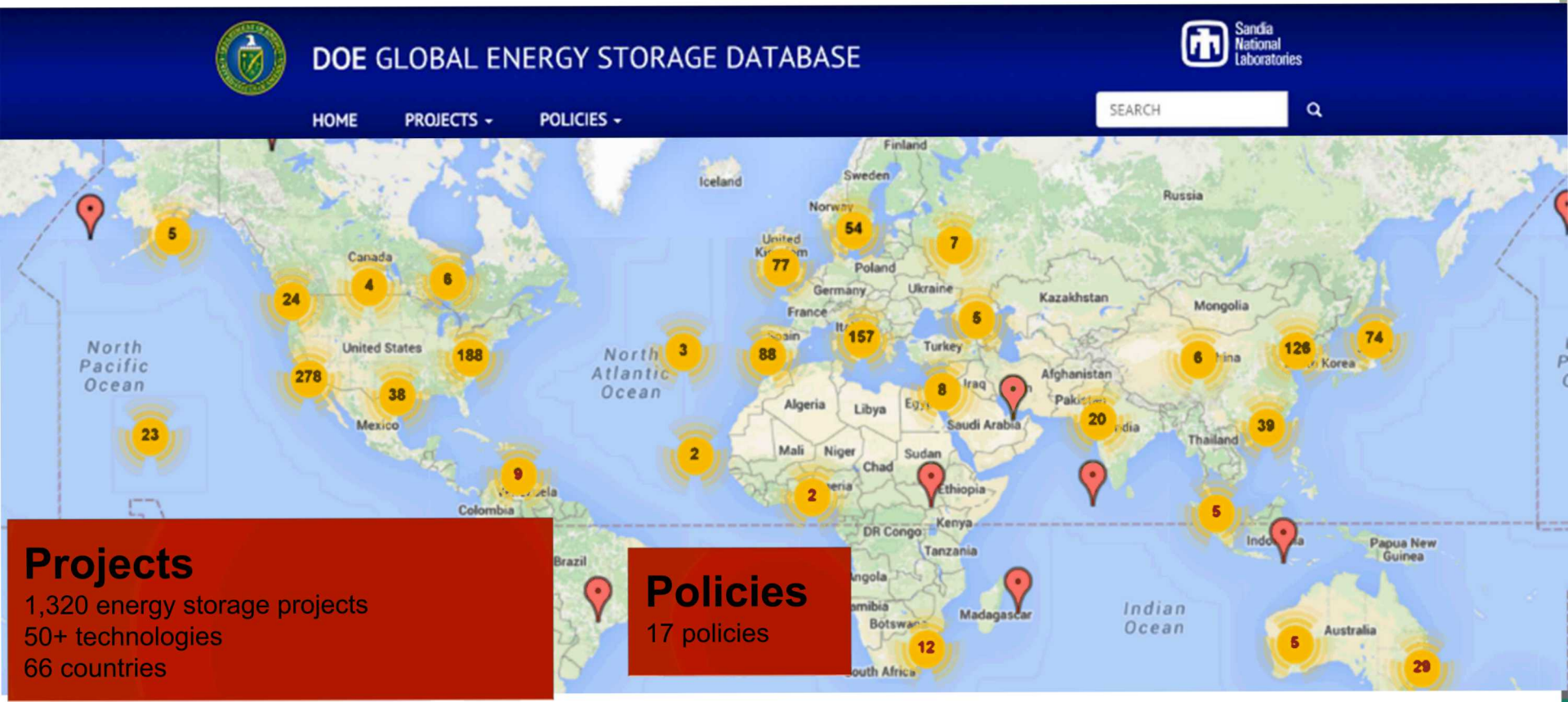
Efforts Under Way

- Global Energy Storage Data Base – 1800 entries
- US Energy Storage State Policy Data Base – just issued!
- Valuation Handbook – under development
- ES System Cost Data Base – to be issued soon
- PNNL Reliability Test Center – to be established in FY19

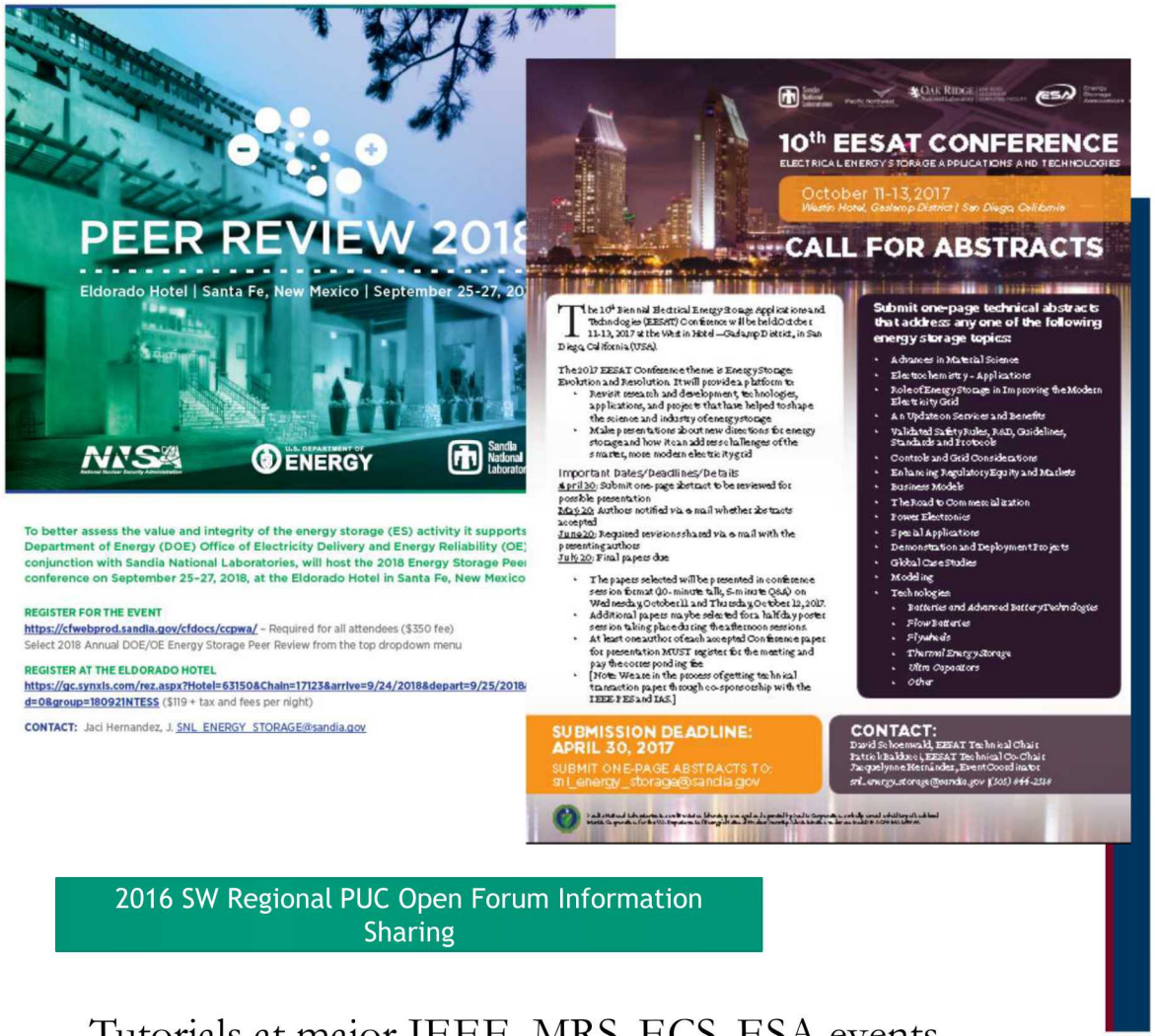


Outreach and Industry Tools

DOE Global Energy Storage Database provides free, up-to-date information on grid-connected energy storage projects and relevant state and federal policies.



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)

Industry Outreach

Disseminate ES information to diverse stakeholders through educational workshops, webinars, technical meetings, and global database

Key Projects

- DOE/OE ESS Website
- DOE SNL Global Energy Storage Database
- DOE/EPRI/SNL/NRECA Electricity Storage Handbook
- Workshops for PUCs and Utilities
- DOE OE Energy Storage Annual Peer Review