SAND2017-6587PE

Exceptional service in the national interest

Sandia National Laboratories

Sandia Grid Energy Storage

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June 27, 2017

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Why Do We Need Energy Storage?

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- Major reasons for installing energy storage:
  - Renewable integration
  - Transmission and Distribution upgrade deferral
  - Power quality, e.g., UPS application, microgrids, etc.
  - Improved efficiency of nonrenewable sources (e.g., coal, nuclear)
  - Off-grid applications (not the topic of this presentation)

Energy Storage in the Grid Today

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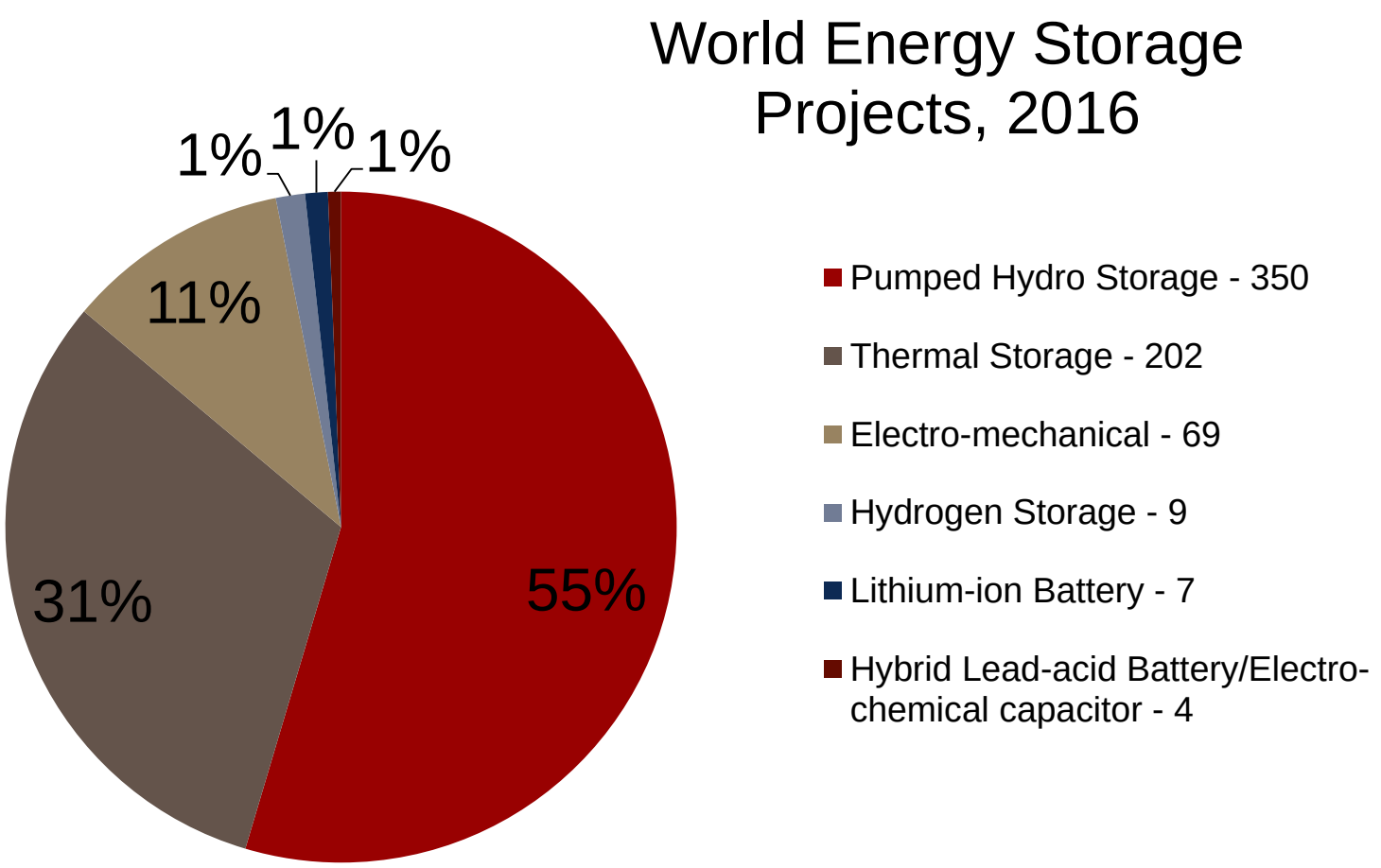
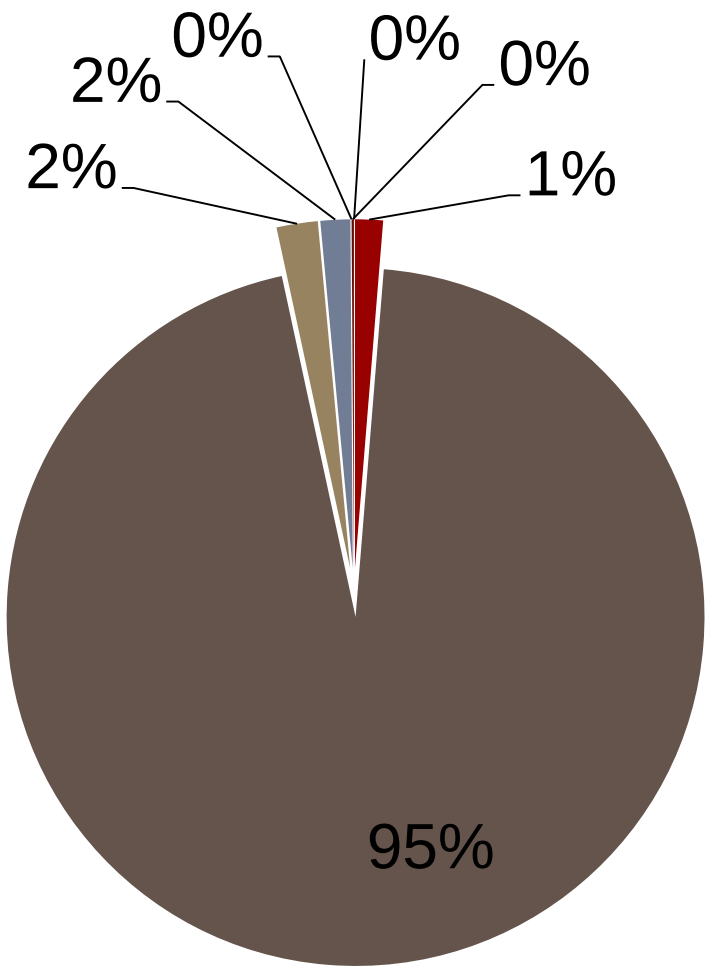


Source: DOE Energy Storage Database, 2016

Energy Storage in the Grid Today



World Energy Storage MW, 2016

- Electro-chemical - 2,446 MW
- Pumped Hydro Storage - 180,627 MW
- Thermal Storage - 3,615 MW
- Electro-mechanical - 2,611 MW
- Hydrogen Storage - 6 MW
- Lithium-ion Battery - 196 MW
- Hybrid Lead-acid Battery/Electro-chemical capacitor - 0 MW

Source: DOE Energy Storage Database, 2016

Elements of Energy Storage System

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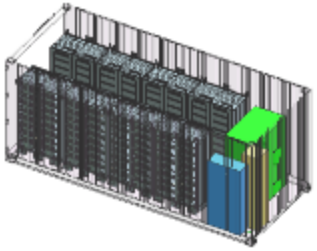
Storage	Integration	PCS	EMS
• Cell • Battery Management & Protection • Racking	• Container / Housing • Wiring • Climate control	• Bi-directional Inverter • Switchgear • Transformer • Skid	• Charge / Discharge • Load Management • Ramp rate control • Grid Stability



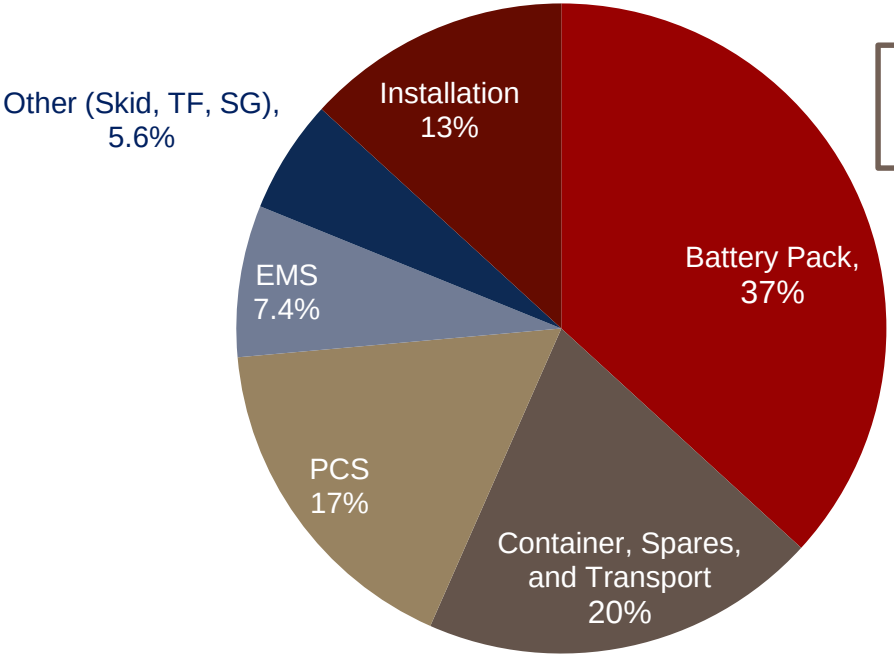
Cost Structure of Storage System

Storage
Racks+BMS

Product
Integration

Power
Conditioning
(PCS)

Field EPC
Grid Integration



1MW/1MWh
LIB ESS

Projected cost line items for a 1MW/1MWh Li-ion energy storage system ($600/kWh and above depending on the system configuration)

Almost 60% of storage system cost is outside the Battery Pack

Data: 2016 Multiple industry sources

Energy Storage at Sandia

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Hydrogen Storage

Hydrogen and Fuel Cells program is developing technologies to accelerate large-scale deployment of hydrogen storage.

Thermal Storage

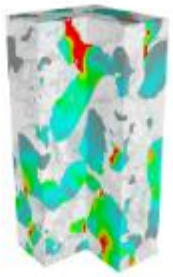
Sandia's Concentrating Solar Power (CSP) program is developing molten salt thermal storage systems for grid-scale energy storage.

Battery Materials

Sandia has a large portfolio of R&D projects related to advanced materials to support the development of lower cost energy storage technologies including new battery chemistries, electrolyte materials, and membranes.

Systems Modeling

Sandia is performing research in a number of areas on the reliability and safety of energy storage systems including simulation, modeling, and analysis, from cell components to fully integrated systems.



Systems Analysis

Sandia has extensive infrastructure to evaluate megawatt-hour class energy storage systems in a grid-tied environment to enable industry acceptance of new energy storage technologies.

Cell & Module Level Safety

Sandia has exceptional capabilities to evaluate fundamental safety mechanisms from cell to module level for applications ranging from electric vehicles to military systems.

Power Conversion Systems

Leveraging exceptional strengths in power electronics, Sandia has unique capabilities to characterize the reliability of power electronics and power conversion systems.

Grid Analytics

Analytical and multi-physics models to understand risk and safety of complex systems, optimization, and efficient utilization of energy storage systems in the field.

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

Major R&D Thrust Areas

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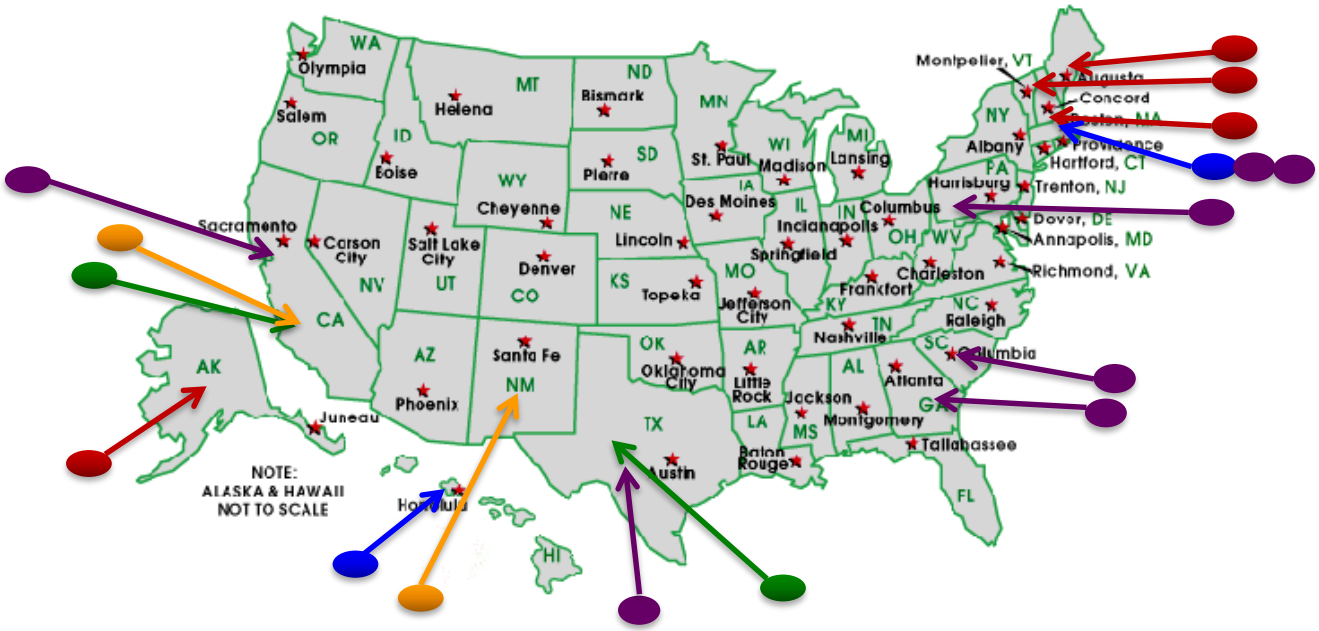
- Materials and Systems Development
  - Development of next-generation technologies
  - Improving current technology (flow batteries, flywheels, membranes, etc.)
- Power Electronics
  - Development of power electronics and power conversion systems.
- Energy Storage Systems Safety and Reliability
  - 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
- Microgrid design

Field Demonstrations

To assistance regulators and utilities in determining how to utilize storage systems to maximize return on investment (ROI). Field demonstrations and pilot projects help to ensure ROI and facilitate adoption via improving confidence in safety, reliability, performance and cost effectiveness.



Legend:

DoD

Commercial End User

State

Academia

Industry

DOE-OE Industry Acceptance and ESS Demonstration Program: Ongoing Projects

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State Projects (CESA):

- Alaska – Cordova Electric Co-Op
- Connecticut DEEP
- Massachusetts DOER/CEC – Sterling Power, Cape and Vineyard, Holyoke
- NYSERDA
- Oregon Dept. of Energy/Eugene Water & Electric Board
- Vermont – GMP, Burlington Electric
- New Mexico – EMNRD, PNM

California/Hawaii:

- California CEC
- HECO
- HELCO
- NELHA
- Sunpower
- UCSD

Other Projects:

- DCICON (DoD)
- Group Nire, TX
- Los Alamos County

Industry Support

- GS Yuasa
- Helix
- Primus Power
- UET
- Transpower
- East Penn/ECOULT
- Aquion Energy
- MegaAmp (S. Africa)

International support:

- Pacific Rim
- WEICan (Canada)

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Energy Storage Analytics

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- 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

Estimating Value – Vertically Integrated Utility

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- Sandia has performed studies for the following
  - Nevada Energy [1]
  - Southern Company [2]
  - Maui Electric Company [3]
- A study is currently under way for the Hawaiian Electric Company
- Typical cost savings come from being able to turn off expensive “must run” units (spinning reserve, regulation) and replace with energy storage

[1] J. F. Ellison, D. Bhatnagar, N. Saaman *et al.*, *NV Energy Electricity Storage Valuation,* SAND2013-4902, Sandia National Laboratories, Albuquerque, NM 87185, 2013.

[2] J. Ellison, D. Bhatnagar, C. Black *et al.*, *Southern Company Energy Storage Study: A Study for the DOE Energy Storage Systems Program,* SAND2013-2251, Sandia National Laboratories, Albuquerque, NM 87185, 2013.

[3] J. Ellison, D. Bhatnagar, and B. Karlson, *Maui Energy Storage Study,* SAND2012-10314, Albuquerque, NM 87185, 2012.

Maximizing Revenue – Market Area

- Recent case studies:
  - CAISO [1] (included sensitivity analysis to parameters)
  - ERCOT [2,3]
  - PJM [4]
  - ISO-NE (in progress – 2017 IEEE PES GM)
  - Singapore (in progress)
  - MISO (in progress – 2017 IEEE PES GM)

[1] R. H. Byrne, and C. A. Silva-Monroy, *Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation,* SAND2012-3863, Sandia National Laboratories, Albuquerque, NM 87185, 2012.

[2] R. H. Byrne, and C. A. Silva-Monroy, "Potential Revenue from Electrical Energy Storage in the Electricity Reliability Council of Texas (ERCOT)," in IEEE Power and Energy Society (PES) General Meeting, Washington, DC, 2014.

[3] R. H. Byrne and C. A. Silva-Monroy, Potential revenue from electrical energy storage in ERCOT: The impact of location and recent trends," in Proceedings of the 2015 IEEE Power and Energy Society (PES) General Meeting, Denver, CO, July 2015, pp. 1-5.

[4] R. H. Byrne, R. Concepcion, and C. A. Silva-Monroy, \Estimating potential revenue from electrical energy storage in PJM," Proceedings of the 2016 IEEE Power and Energy Society (PES) General Meeting, Boston, MA, July 2016, pp.1-5.

Reports available at: http://www.sandia.gov/ess/

Standards Development

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- Working with PNNL to develop performance protocols for the energy storage industry
  - Micro-grids (completed)
  - Frequency regulation (completed)
  - Peak shaving (completed)
  - PV smoothing (in progress)
- Working to generate a U.S. standard based on the protocols
  - ANSI
  - NEMA
  - IEC
- Industry user group is test driving the protocols

Outreach and Industry Tools

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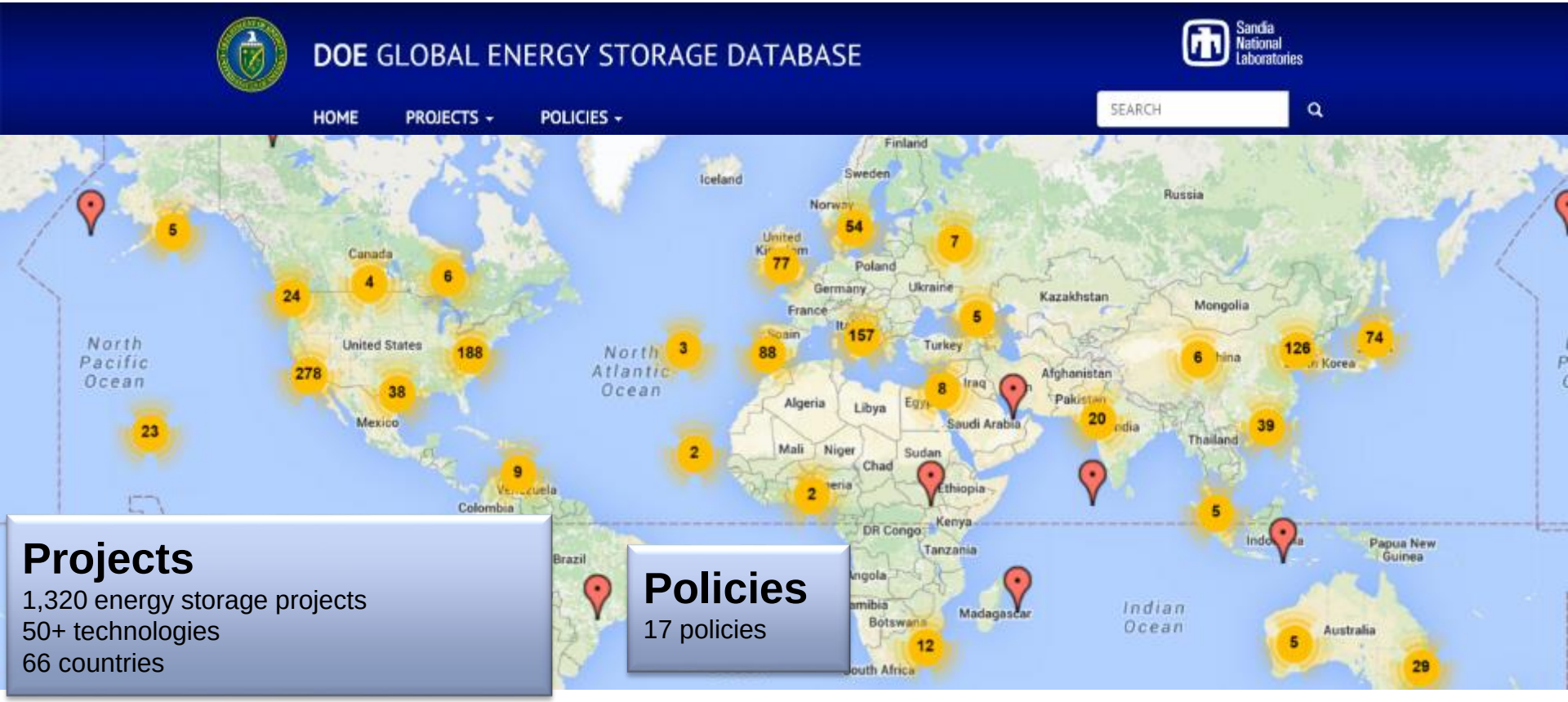
- ***DOE/EPRI Electricity Storage Handbook*** is a how-to guide for utility and rural cooperative engineers, planners, and decision makers to plan and implement energy storage projects safety in communities
- ***DOE Global Energy Storage Database*** provides free, up-to-date information on grid-connected energy storage projects and relevant state and federal policies.
- ***DOE Performance Protocol*** focuses on developing uniform methods of measuring ESS performance for specific applications.

Grid Storage – Installed Capacity

Sandia maintains a comprehensive online resource of energy storage projects and policies.



Li batteries in storage: 900 projects, 2400 MWh

Compare that to 60GWh of PV that got installed in 2015 alone

Capabilities and Benefits of Microgrids

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- Emergency Power
- Power Quality
- Enhanced renewable, storage and CHP integration
- More efficient and cost effective than diesel standby
- Peak Shaving
- Demand Response
- Load Shedding

NYC After Tropical Storm Sandy -
Local microgrids provided energy reliability, security, and mission assurance

Sandia Advanced Microgrid Analysis, Modeling and Testing Capabilities

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- Energy Surety Design Methodology
  - initiated in 2001 to provide performance-based, risk informed designs for energy infrastructures
  - Applied to electric power, energy pipeline, marine and railroad energy transport, and energy refineries
  - Used since 2006 for microgrid designs
- Distributed Energy Technology Laboratory
  - Operational 500 kW microgrid test facility with diesel, PV, microturbine, and energy storage resources to test power and load management and control approaches
- Scalable-Secure Microgrid Testbed
  - Laboratory testbed focused on control and integration of multiple microgrids
  - Agent-based and Hamiltonian DC and AC control research and cyber security protection
- Microgrid Design Toolkit
  - Series of user friendly energy reliability, consequence, risk, cost, and optimization models developed for DOE to support universal microgrid analysis and design

Energy Surety Microgrid Efforts

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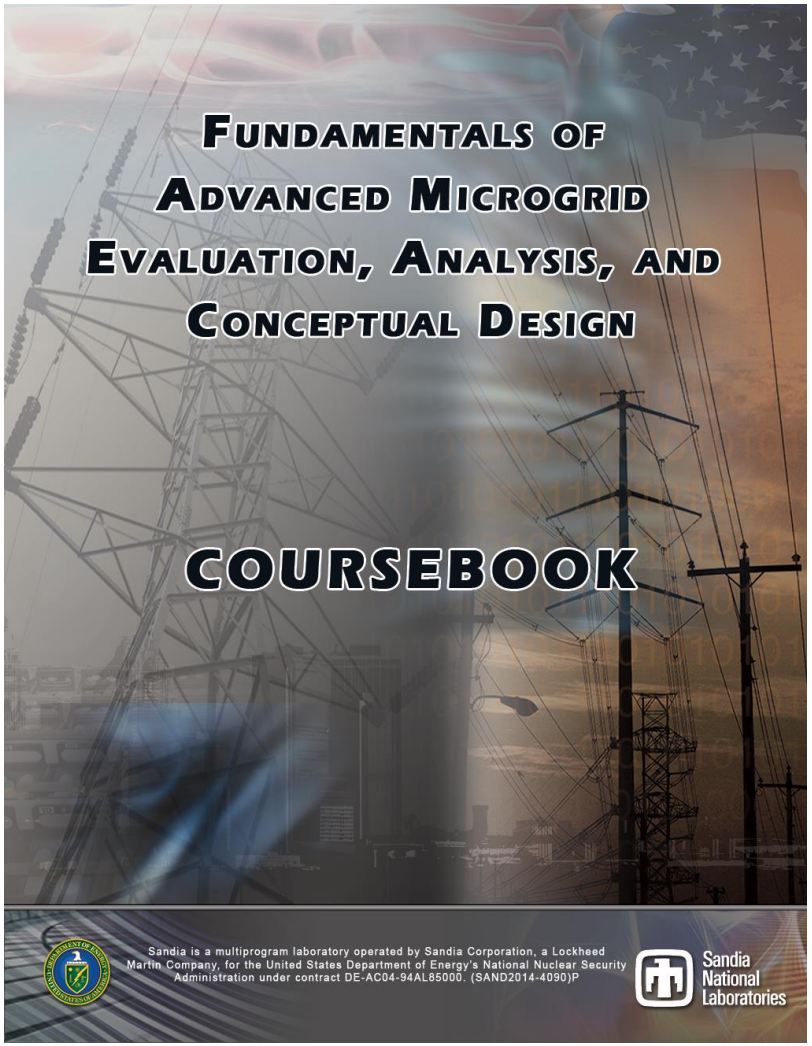
Conceptual Designs/Assessments	Small Scale Microgrid Demos	Large Scale Microgrid Demos	Operational Prototypes

• Creech AFB – FY12 DoD
• Soto Cano – FY12 DoD
• West Point FY12, DoD/DOE
• Osan AFB, FY 12, DoD
• Philadelphia Navy Yard – FY11, DOE OE/PIDC
• Camp Smith – FY10, DOE FEMP
• Indian Head NWC – FY09, DOE OE/DoD
• Ft. Sill – FY08, Sandia LDRD
• Ft. Bliss – FY10, DOE FEMP
• Ft. Carson – FY10, DOE FEMP
• Ft. Devens (99th ANG) – FY09, DOE OE/DoD
• Ft. Belvoir – FY09 DOE OE/FEMP
• Cannon AFB – FY11, DOE OE/DoD
• Vandenberg AFB – FY11, DOE FEMP
• Kirtland AFB – FY10, DOE OE/DoD
• Maxwell AFB – FY09, DoD/DOE
• Alaska Villages– FY12, DOE
• Bagram – FY13, DoD
• Kuwait – FY15, DoD
• 29 Palms – FY14, DoD
• Korea Naval Academy – FY16, DoD
• Kaui – FY15, DOE
• Northhampton, MA – FY14, DOE
• New Orleans – FY17, DOE
• UPS in KY – FY17, DOE
	• Maxwell AFB – FY09, DoD
	• Ft. Sill – FY09, DoD w/ SNL serving as advisor
		• SPIDERS JCTD – FY11, DOE/DoD
		  • Camp Smith
		  • Ft Carson
		  • Hickam AFB
			• H.R. 5136 National Defense Authorization Act

Advanced Microgrid Evaluation & Design Course

- Developed as a 3-day course
- 200 page course book
  - Background info, vugraphs, appendices of detailed data
- 50 page work book
  - Example problems and worksheets
  - Final microgrid design demo of full design and analysis process
- Course book and work book to keep as future reference
- Designed to be used by key stakeholders and technical users
- Organized to directly follow Sandia ESDM process



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Backup Slides

Energy Storage Materials R&D

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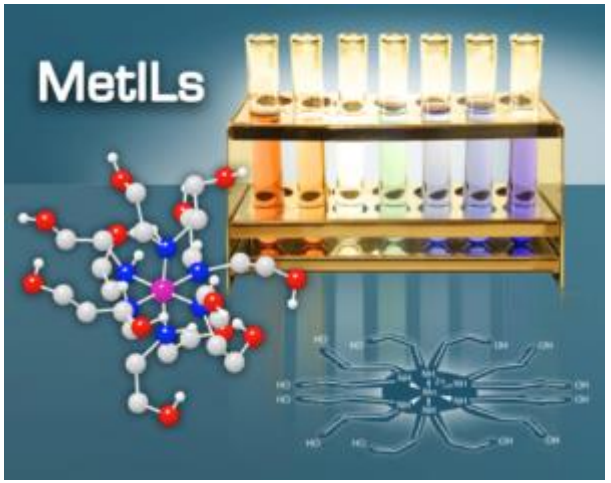
Materials R&D capabilities covers battery chemistry and component technologies

- 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



Leveraging world class capabilities in Wide Bandgap Materials

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R&D 100 53 Years of Invention

2015 R&D100 Winner

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

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

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

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

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

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

2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015

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

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

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

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

Power Electronics – Current Projects

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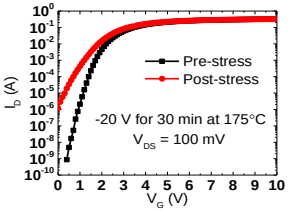
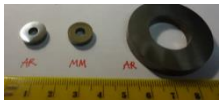
WBG Reliability Characterization

- 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

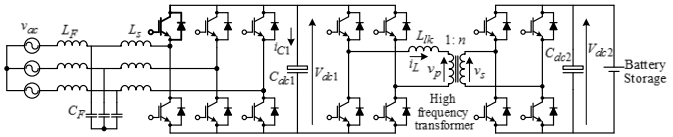


Advanced Magnetics

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



γ'-Fe_4N toroidal inductive cores

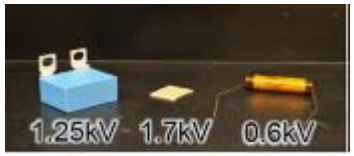


Advanced Gate Oxide for WBG Devices

- 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



Safety and Reliability of Grid Storage

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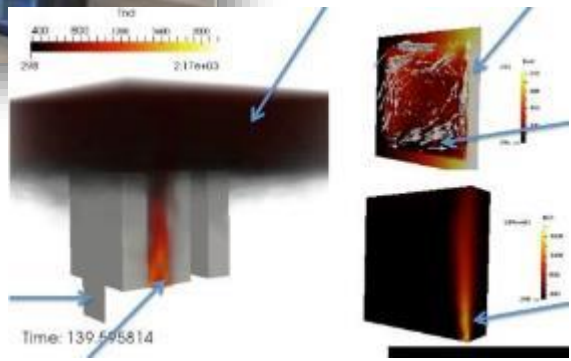
- Focus on developing a fundamental understanding of safety and reliability through R&D in four areas:
  - Materials origin of safety and reliability
  - Device level failures
  - Cascading failures
  - Software's role as a critical safety system
- Extensive laboratory infrastructure at Energy Storage Test Pad (ESTP) and BATlab
- Advanced simulation and modeling of energy storage systems



Predictive Modeling of Energy Storage Systems

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- 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 Evet. The colors correspond to concentration of chemical species

Energy Storage Safety Protocols

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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.

Energy Surety Design Methodology And Use for Advanced Microgrids

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