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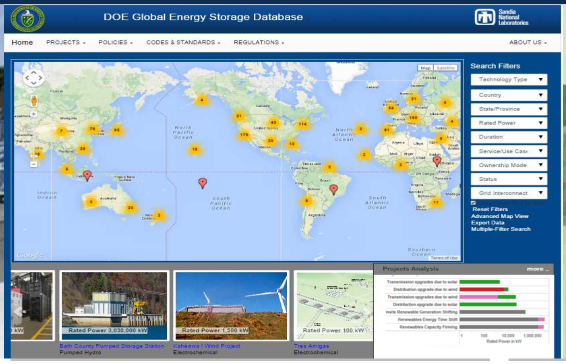


# Grid Energy Storage

Babu Chalamala

May 6, 2016

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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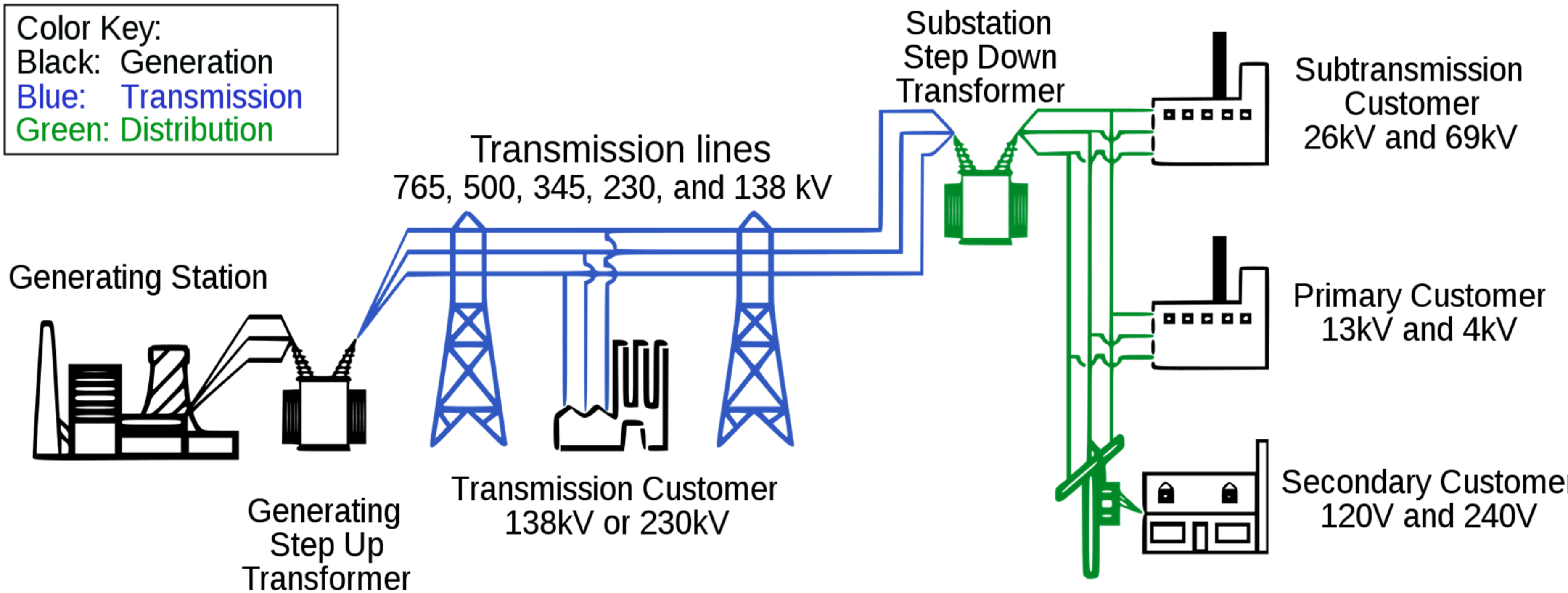
# The Electric Grid




DOE/EPRI Energy Storage Handbook
Sandia, 2013

**The grid is neither smart nor flexible**

# Evolution of the Electric Grid

**Grid 1.0**

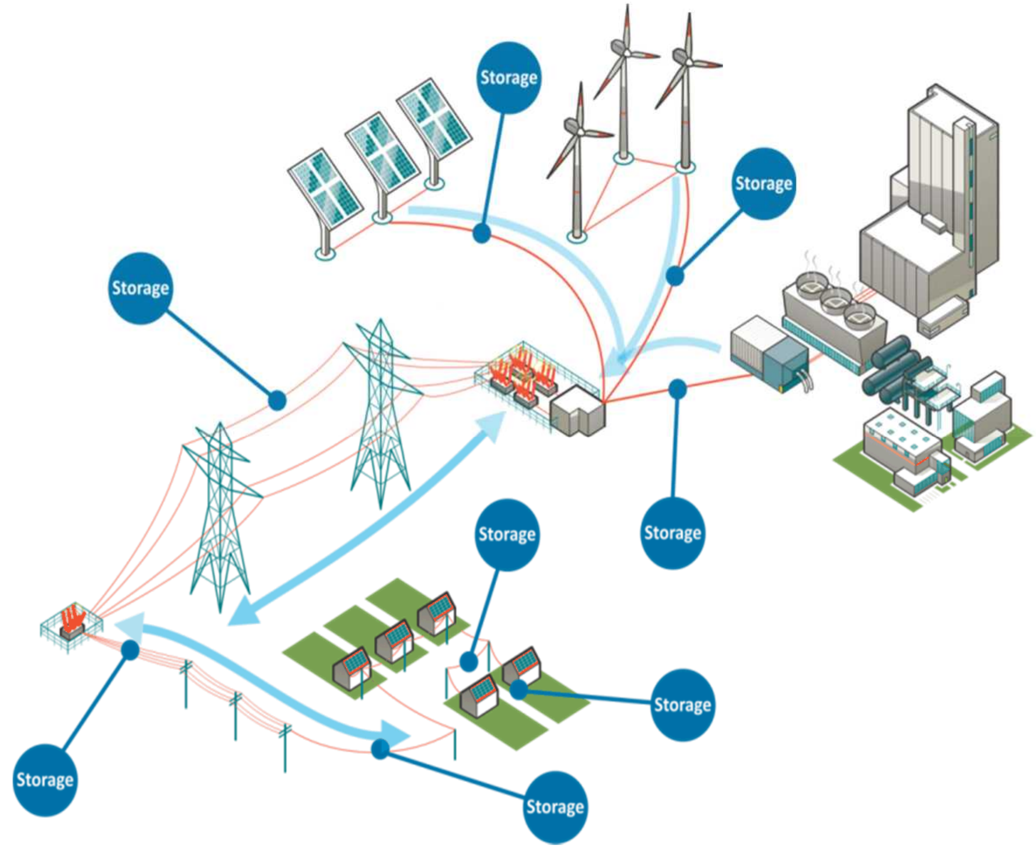
- One way energy flow
- Little/no renewable energy

**Grid 2.0**

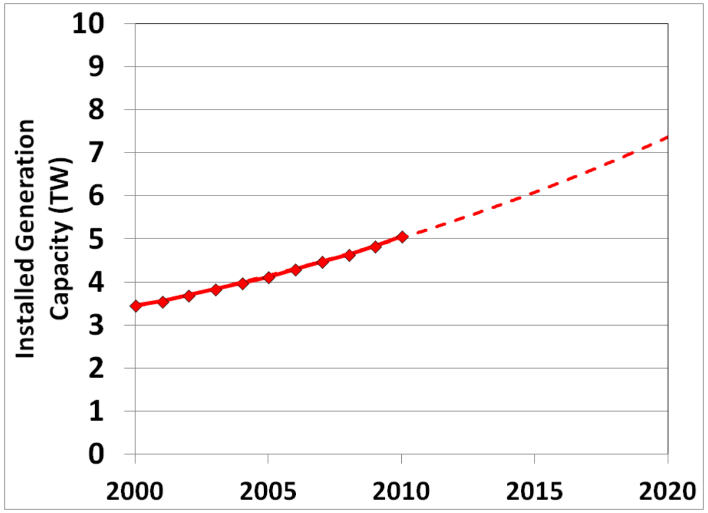
- Integration of renewables and distributed generation beginning to take off
- Minimal tools to manage grid instabilities

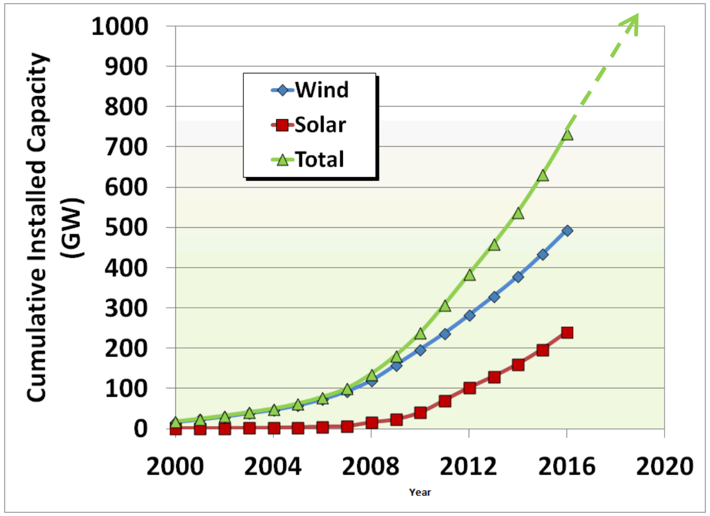
**Future Grid**

- Distributed generation and two-way energy flows
- Energy Storage is key for grid stability and large scale renewable integration



# Growth of Renewables is the Big Story



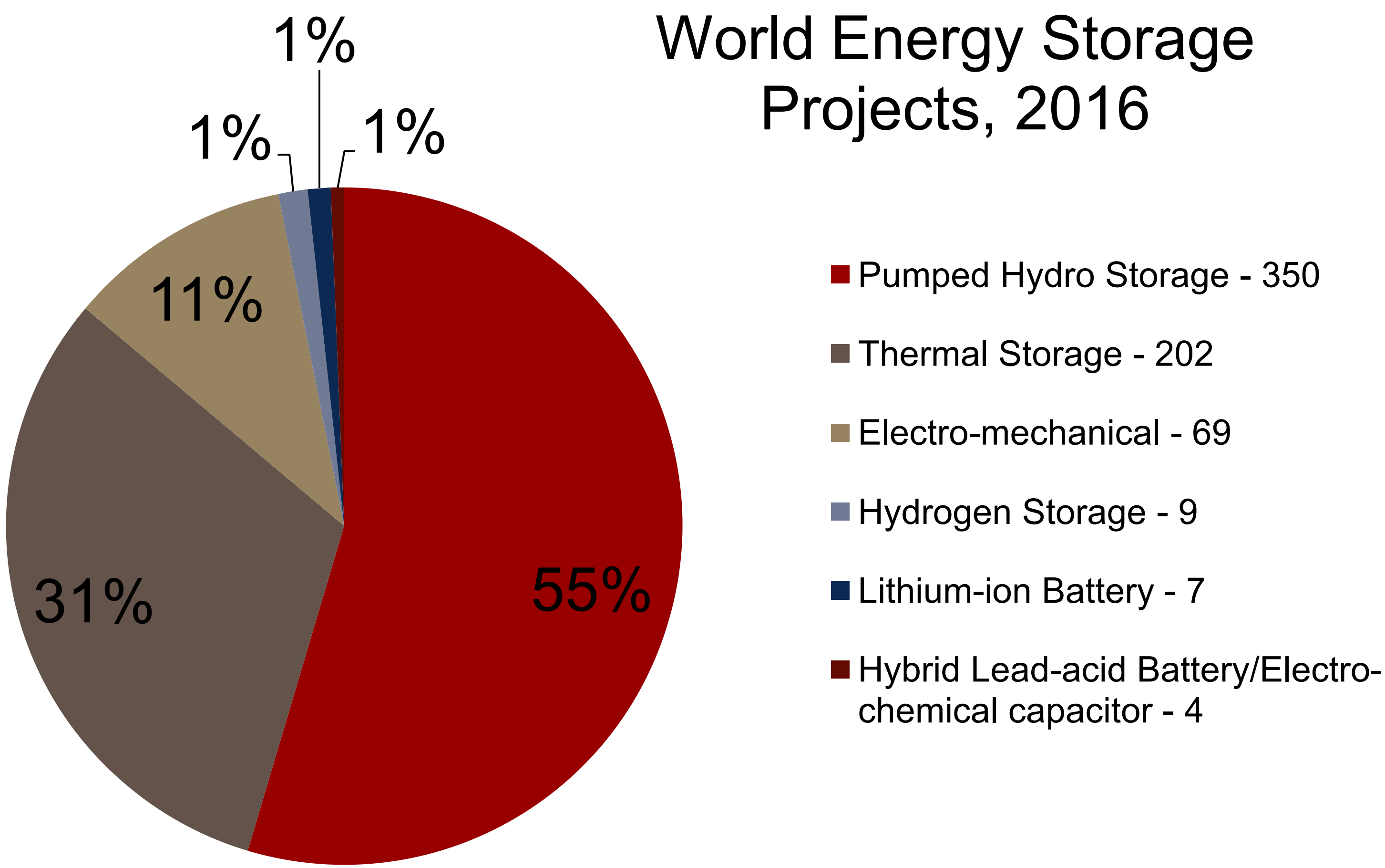

- Of the 6 TW of worldwide generation capacity, wind and solar are reaching the 5-10% range in many areas.
- By 2020, worldwide installed renewables capacity will be over 1 TW, penetration levels may approach 30-40% in some markets.

Data Sources: IEA, EPIA, Global Wind Energy Council, Earth Policy Institute, 2013

# Why Do We Need Energy Storage?

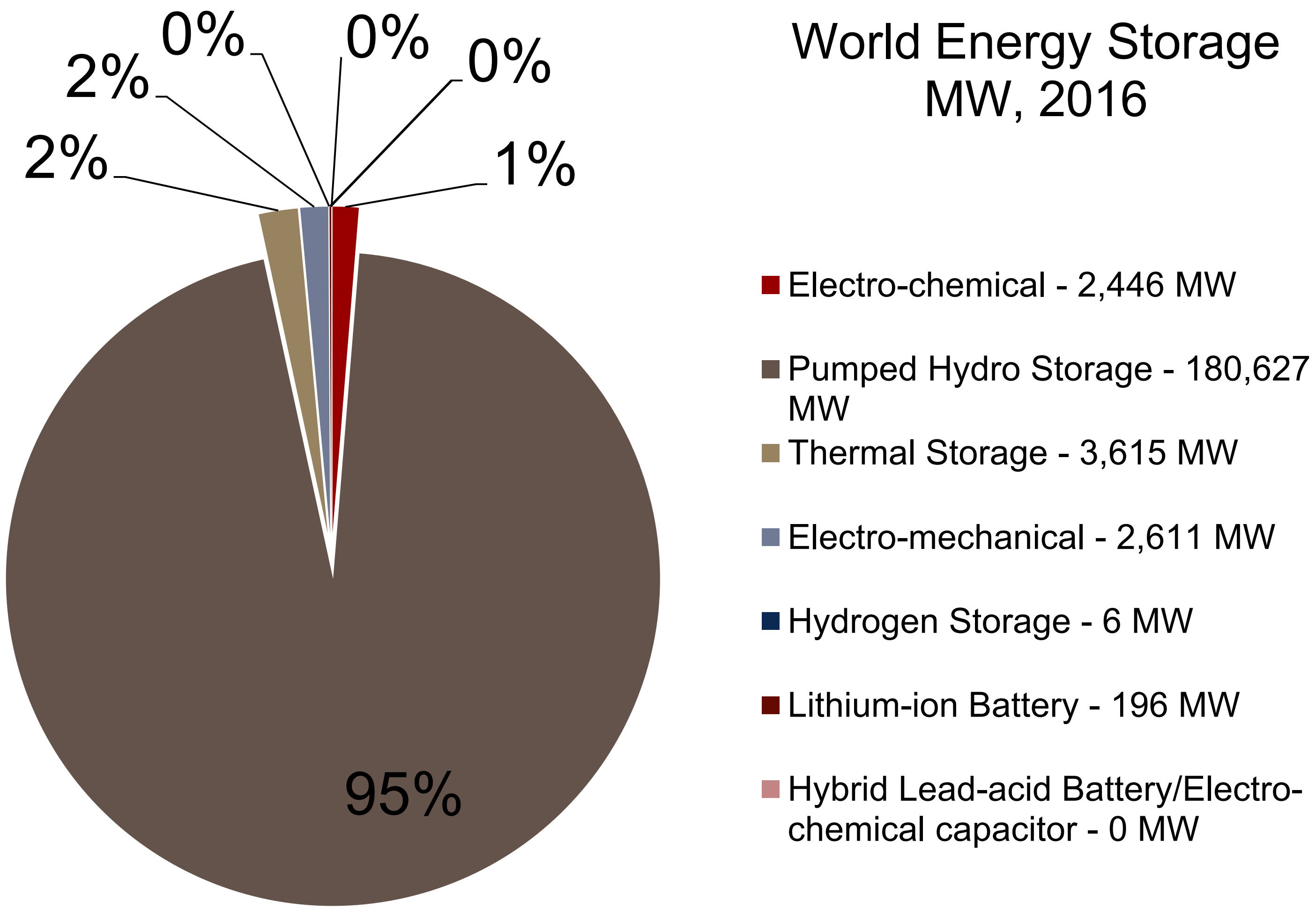
- Major reasons for installing energy storage:
  - Renewable integration
  - Transmission and Distribution upgrade deferral
  - Power quality, e.g., UPS application, microgrids, etc.
  - Improved efficiency of nonrenewable sources (e.g., coal, nuclear)
  - Off-grid applications (not the topic of this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

# Energy Storage in the Grid Today




**Source:** DOE Energy Storage Database, 2016

# Energy Storage in the Grid Today



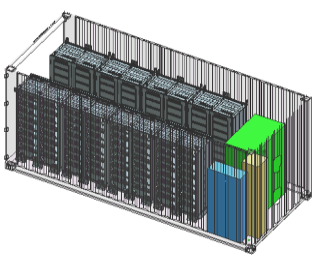

**Source:** DOE Energy Storage Database, 2016

# Elements of Energy Storage System

Sandia National Laboratories

## Storage

- Cell
- Battery Management & Protection
- Racking

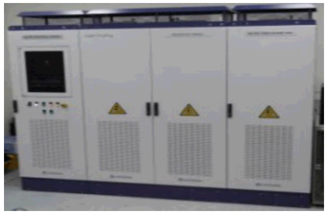


## Integration

- Container / Housing
- Wiring
- Climate control

## PCS

- Bi-directional Inverter
- Switchgear
- Transformer
- Skid

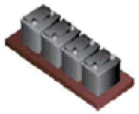


## EMS

- Charge / Discharge
- Load Management
- Ramp rate control
- Grid Stability

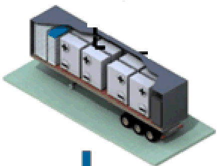
# Cost Structure of Storage System 2016

Sandia National Laboratories



Storage Racks+BMS

+



Product Integration

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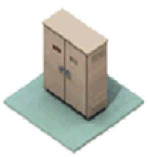
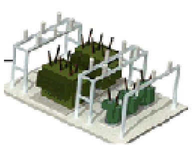
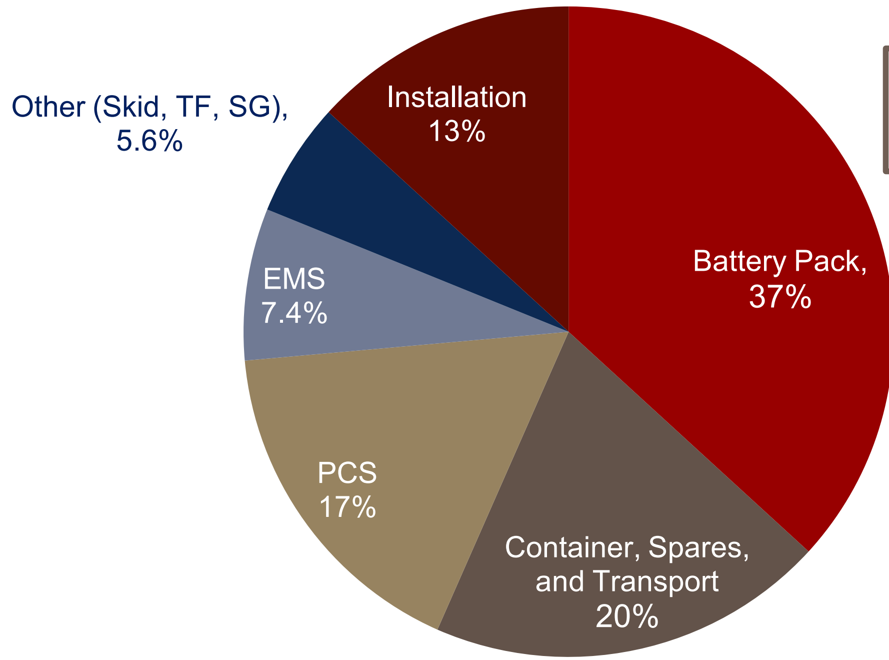


Power Conditioning (PCS)

+



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)**

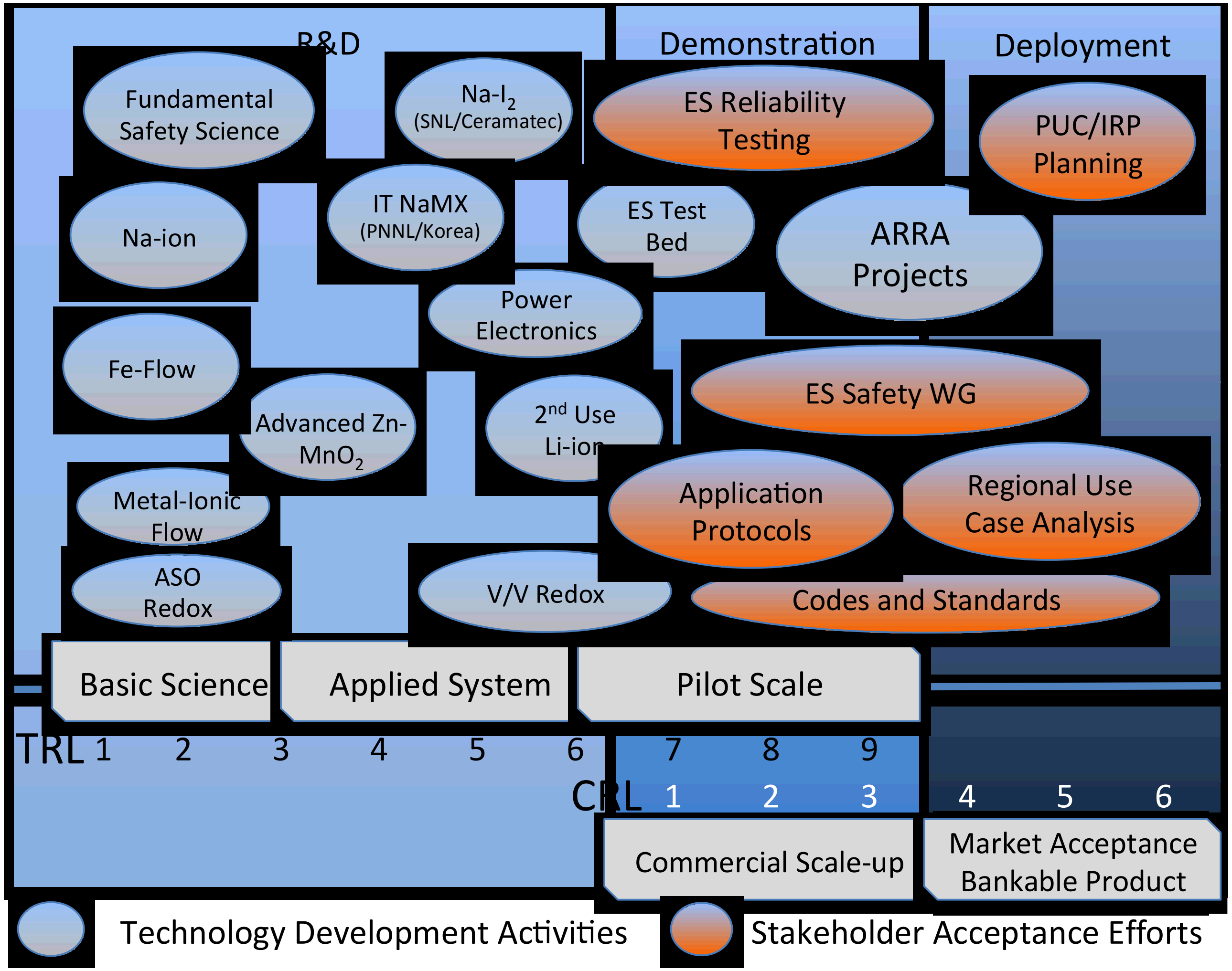
**Almost 60% of storage system cost is outside the Battery Pack**

Data: Multiple industry sources

# Making Energy Storage Cost Competitive

- Critical challenges for energy storage are high system cost and cycle life
  - Existing storage solutions are too expensive
  - Deep discharge and longer cycle life
  - Safe and reliable chemistry
  - Scalable technology to cover all markets
- To make storage cost competitive, we need advances across all major areas:
  - Batteries, power electronics, PCS
  - BOS and Integration
  - Engineered safety of large systems
  - Codes and Standards
  - Optimal use of storage resources across the entire electricity infrastructure

# DOE Grid Energy Storage Program




**Grid Energy Storage program covers the entire technology development cycle, in partnership with universities, other labs, and companies**

# Energy Storage at Sandia

### Hydrogen Storage

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

### Thermal Storage

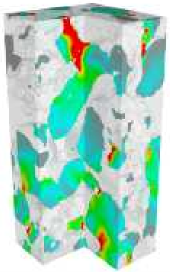
Sandia's Concentrating Solar Power (CSP) program is developing molten salt thermal storage systems for grid-scale energy storage.

### 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

- 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

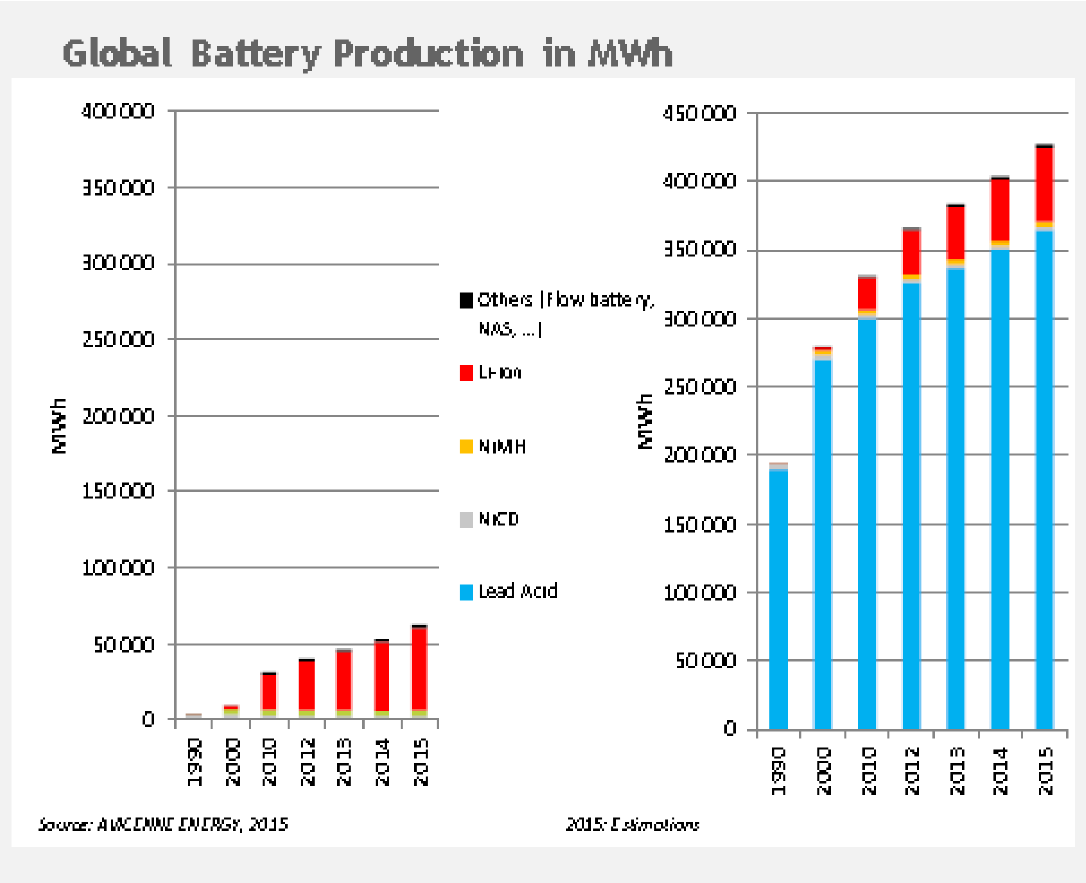
# Battery Technologies

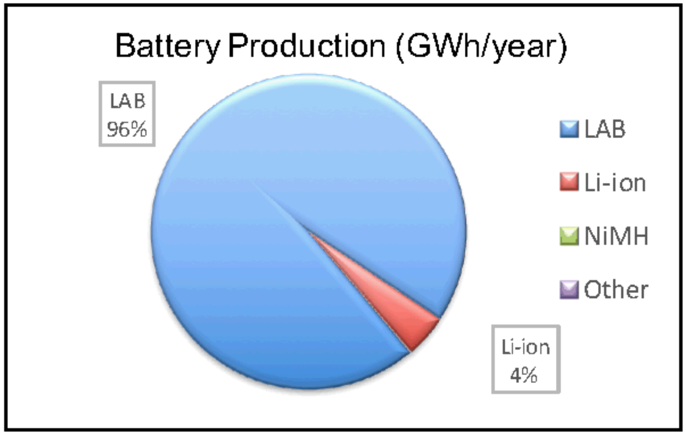
Sandia National Laboratories

| Mature Technologies | | | | |
|---|---|---|---|---|
| | **World Wide Capacity (GWh/y)** | **Cost and Performance Improvements** | **Key Challenges for Energy Storage** | **Major Suppliers** |
| **Lead Acid Batteries (LAB)** | 300 | 2%/year ((30 year data). $150/kWh | Cycle life. Advanced lead acid cycle life on par with EV grade LIB | JCI, GS Yuesa, EastPenn, EnerSys, Exide, Hagen |
| **Lithium Ion Batteries (LIB)** | 50 | 8%/year (20 year data). Cell level price reaching $200/kWh | Cycle life for deep discharge. Safety. Thermal management | Panasonic, Samsung, LG Chem, BYD, GS Yuesa (Nissan, Honda JVS), Lishen, JCI, A123, Toshiba. EV Batteries: Converging to NMC chemistry |
| **Emerging Technologies** | | | | |
| **NaS and NaNiCl** | 300 MWh | No economies of scale | High temperature chemistry. Safely, Cost | NGK, GE |
| **Flow Batteries** | <100 MWh | Not fully mature. Potential for lower cost. $400/kWh. Reach $270/kWh | Not mature. Has not reached manufacturing scale. | Sumitomo, UET, Rongke Power, ZBB, Imergy, Gildenmeister. Only Sumitomo provides 18 yr. warranty |
| **Alkaline chemistries (Na, Zn-MnO2,..)** | <100 MWh | Not fully mature. Lowest cost BOM | Has not reached manufacturing scale. | Aquion (Na), UEP (Zn-MnO2), Fluidic Energy (Zn-air) |

**Lead acid and Lithium ion**: Only two battery technologies with manufacturing capacity and scale to serve MWh - GWh ES markets

# Global Production Volumes



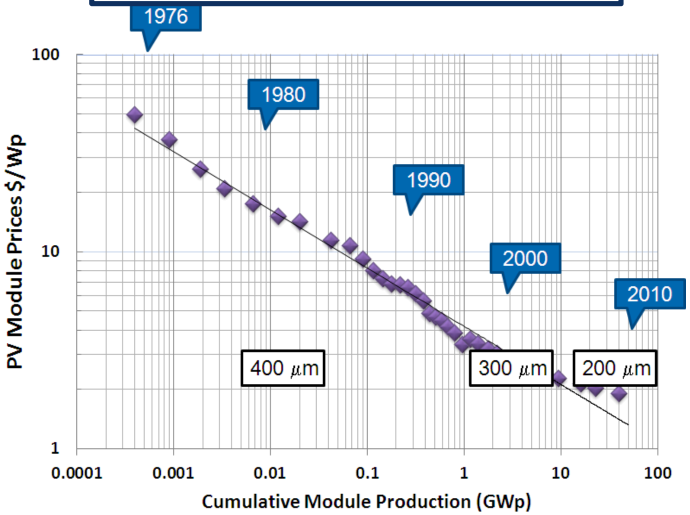




Source: Avicenne (2015), DOE

Lead Acid Battery business continues to be highly profitable
Li-ion struggling with low factory utilization rates of ~10-20%

# Manufacturing and Scale

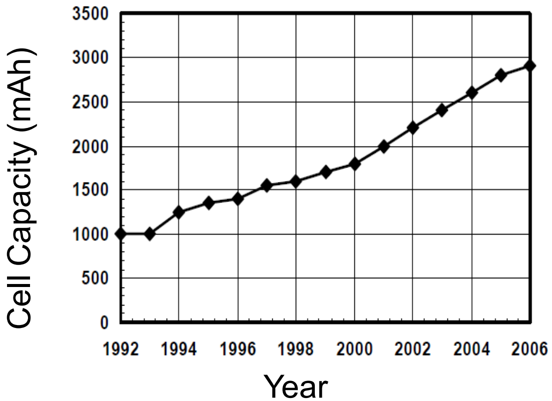
## PV Learning Curve




Source: Fisher, Proc IEEE, May 2012

- Rapid growth in PV deployment driven by10X drop in $/kW and 50% increase in cell efficiency for c-Si in 20 years
- Cost reduction is the stronger driver
- 2015 PV production capacity: 60 GW

## Li-ion Learning Curve



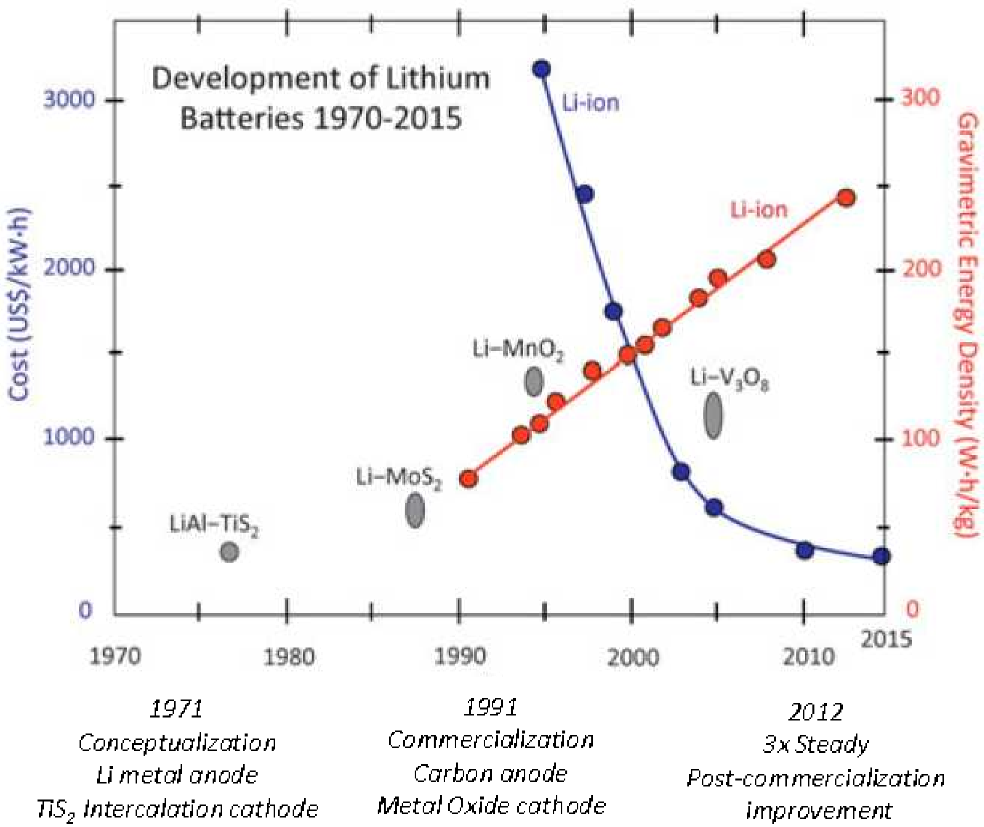

18650 cell capacity improvement of 8% per year

- In batteries capacity improvements are incremental
  - 2% for Lead acid, 8% for LIB (1992-2007)
- 2015 LIB manufacturing capacity: 40 GWh
- 2015 LAB manufacturing capacity: 300 GWh

Industrial lead acid: $150/KWh (high volume)

Large format LIB: cell level cost reaching the $200/kWh range

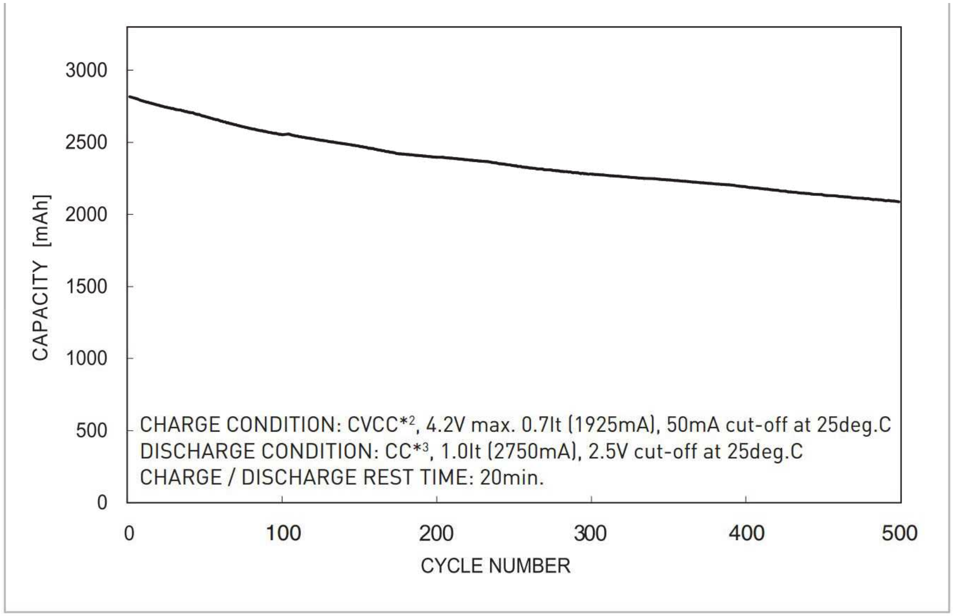
# There is no Moore's law in Storage

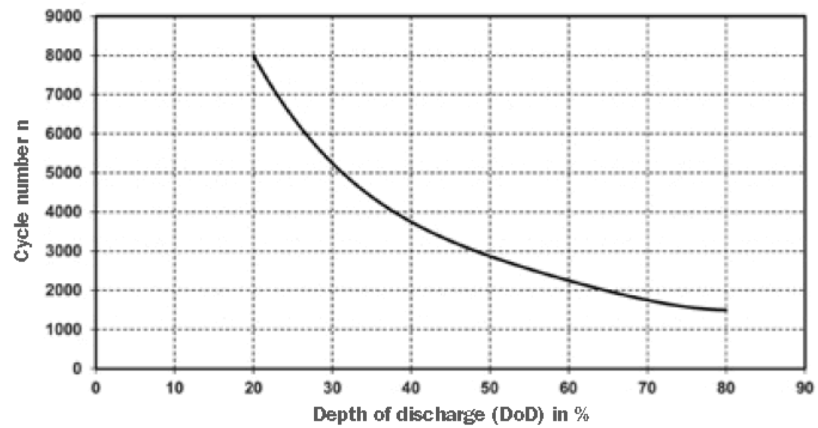


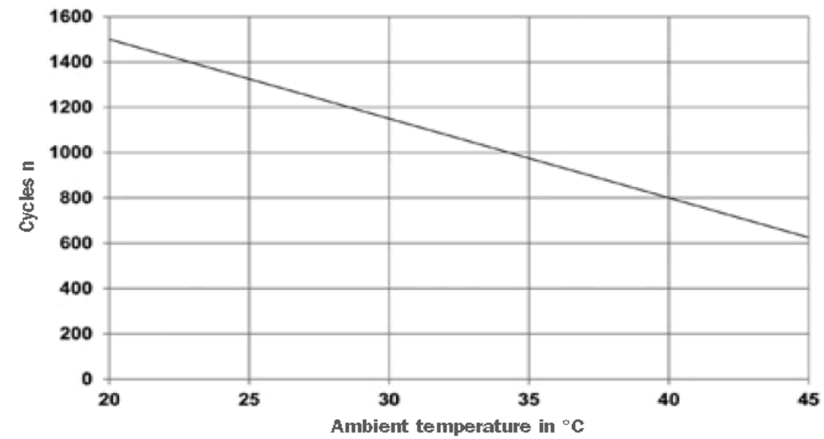

Source: Crabtree, Kocs, Trahey, MRS Bulletin, Dec 2015

- There is no equivalent of Moore's law in battery technology. Microelectronics scaling laws don't apply. Storage is based on volumetric material properties.
- Major improvements will be based on increased cycle life, reliability, and safety of batteries.

# Deep Discharge Cycle Life Needs Major Improvements



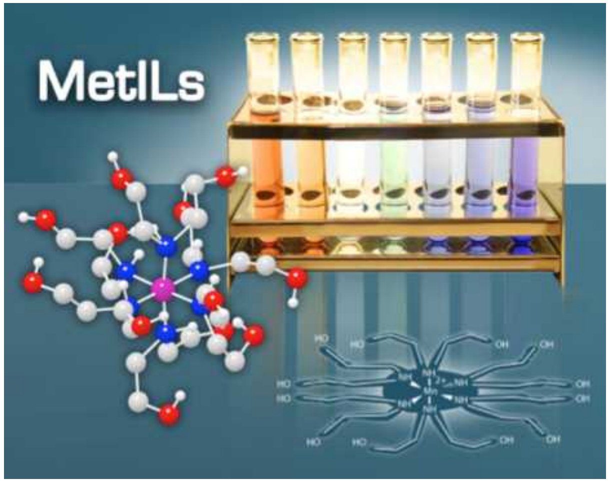

Panasonic NCR18650 cell – cycle life

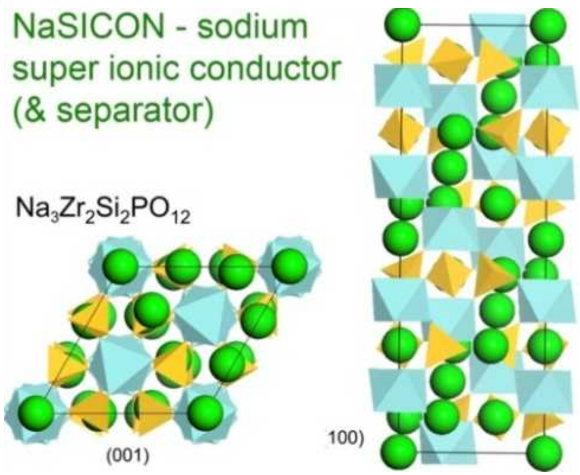
Hoppecke Lead Acid Batteries
Cycle life with DOD and Temperature

# 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

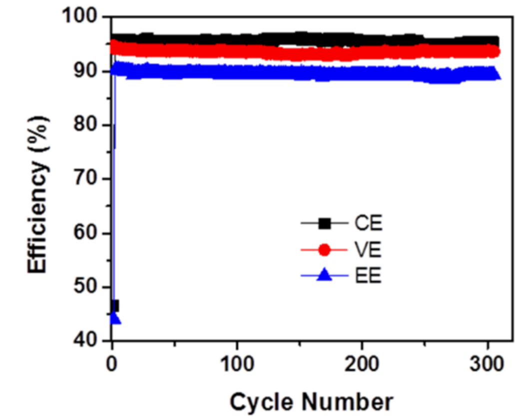


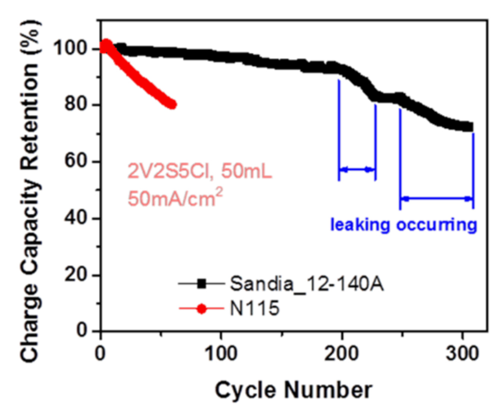
# Advanced Membranes for Flow Batteries

**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.

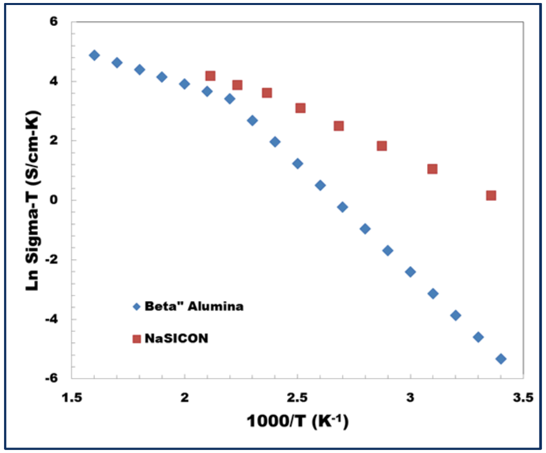
# Sodium Ion Battery Development

Sandia National Laboratories

**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.
- **Project Milestone**: Demonstrate a 10 kWh battery module in a grid application (Q2, FY`18).

CERAMATEC TOMORROW'S CERAMIC SYSTEMS    COORSTEK Amazing Solutions.




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


Prototype Na-ion cells

# Power Electronics - Leveraging world class capabilities in Wide Bandgap Materials

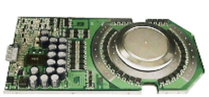
Sandia National Laboratories

2015 R&D100 Winner

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

**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

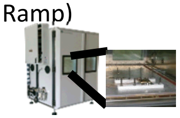
**WORLD' S FIRST VOLTAGE CONTROLLED 4500V/400A TURN-OFF THYRISTOR**
4500V and 400A rated
Integrated Si MOSFET and GTO
Embedded Current Sensing Capability



**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

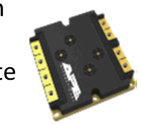
**WORLD' S FIRST HIGHLY ACCELERATED LIFETIME TESTING (HALT) OF HIGH VOLTAGE SIC MODULES**
Dramatically Accelerates Design Cycle
-100 ° C to 250 ° C (1.7 ° C/s Ramp)
48 in × 48 in Table Size
6 axis 75 gRMS Vibration



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

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

**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

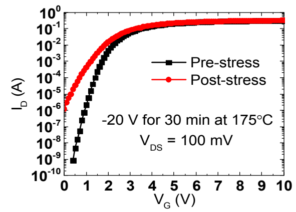


**WORLD' S FIRST HIGH FREQUENCY, HIGH TEMPERATURE, SIC HALF-BRIDGE POWER MODULE**
15 kV/100 A, 20 kHz, 200C
Reworkable
Low Parasitic Design
Device Neutral
HV Isolated Gate Driver

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

# Power Electronics – Current Projects

## WBG Reliability Characterization

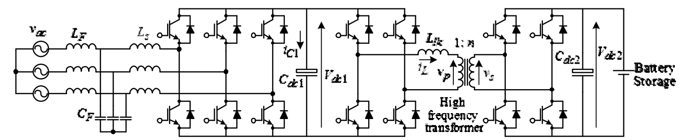



- Static and dynamic reliability characterization of SiC and GaN semiconductor devices under stress conditions
- 10 kV/50A/600C wafer-level device measurement capability
- 3kV/50A package-level device measurement capability
- Double-pulse switching testing capability
- Impedance spectroscopy

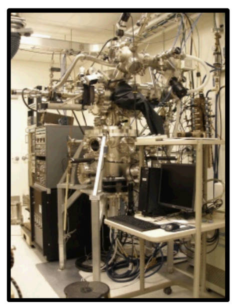
## Advanced Magnetics

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

**$\gamma'$-$Fe_4N$ toroidal inductive cores**

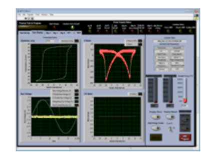


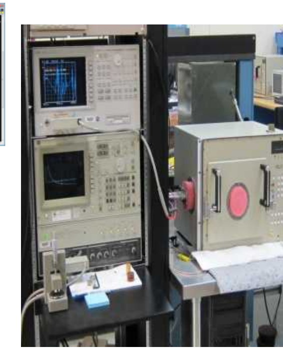

## Advanced Gate Oxide for WBG Devices



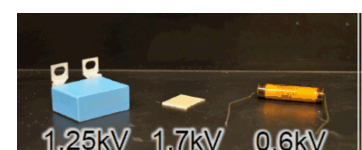
- Unique oxide molecular-beam eptiaxy instrument (1 of ~30 such instruments in the US)
- Grows MgO, CaO, $La_2O_3$, and $Gd_2O_3$ gate and passivation dielectrics on GaN, AlGaN, and SiC power semiconductors
- Comprehensive dielectric characterization tools
- 5 Hz to 26 GHz, -100C to 300C capabilities

## Advanced Capacitors





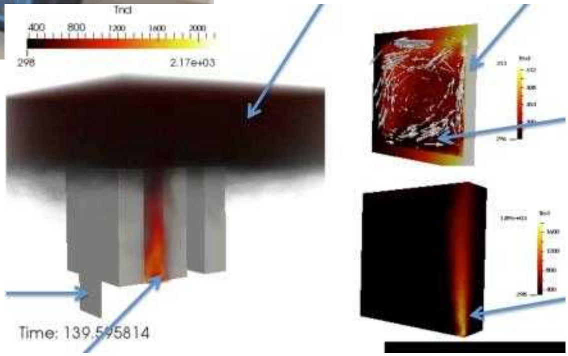
- Test voltages as high as +/-10kV, with kA transients with HV diagnostics from mHz-MHz capability
- Impedance bridges and polarization-hysteresis looper allows full dielectric characterization
- Temperature dependent insulation resistance characterization capability



# Safety and Reliability of Grid Storage

- 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





# 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.

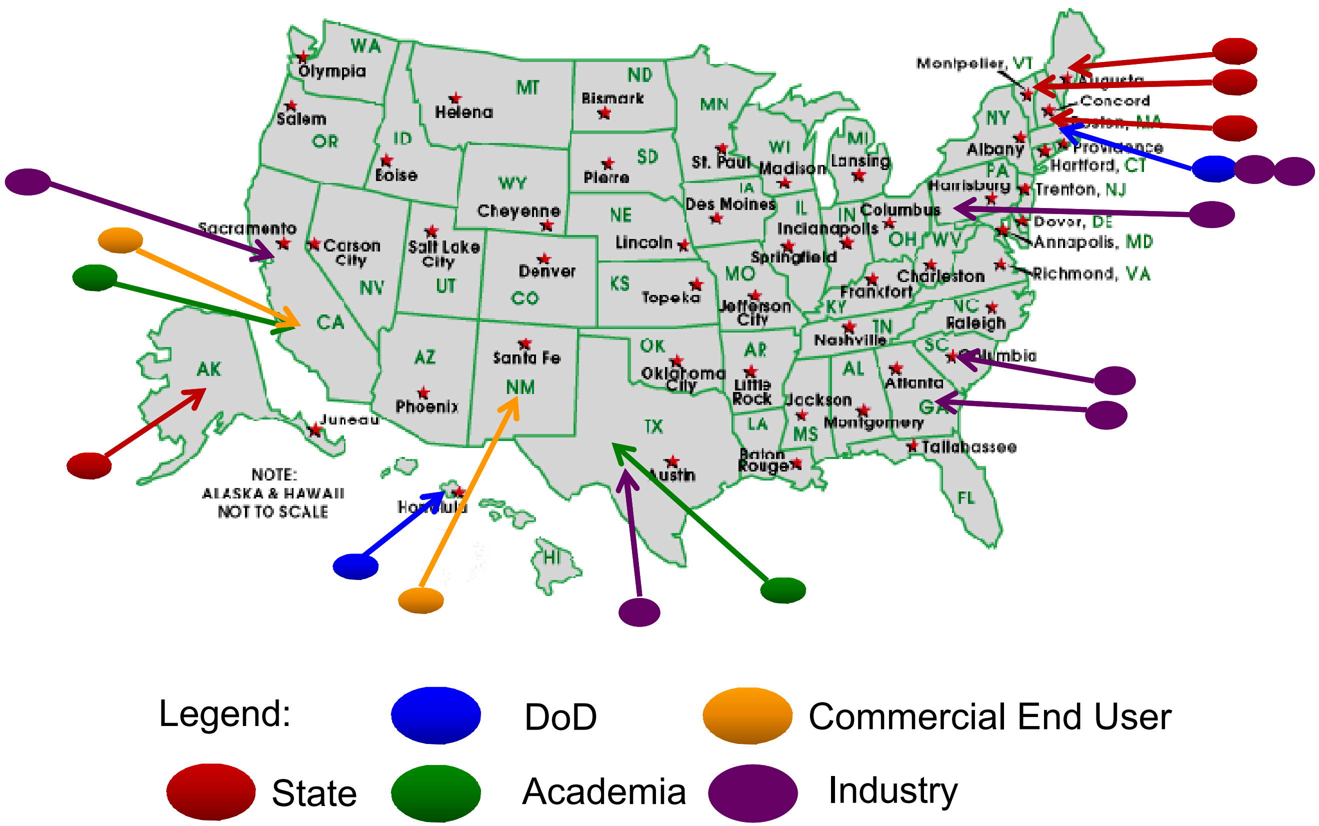
## Impact to First Responders

*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.

# 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.**



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

**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)

# 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

# Standards Development

- 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

# For Energy Storage to Become Ubiquitous


- Got to look beyond bundling multiple benefit streams
- We need a better metric – usable energy capacity in KWh-cycles.
- Pay greater attention to safety

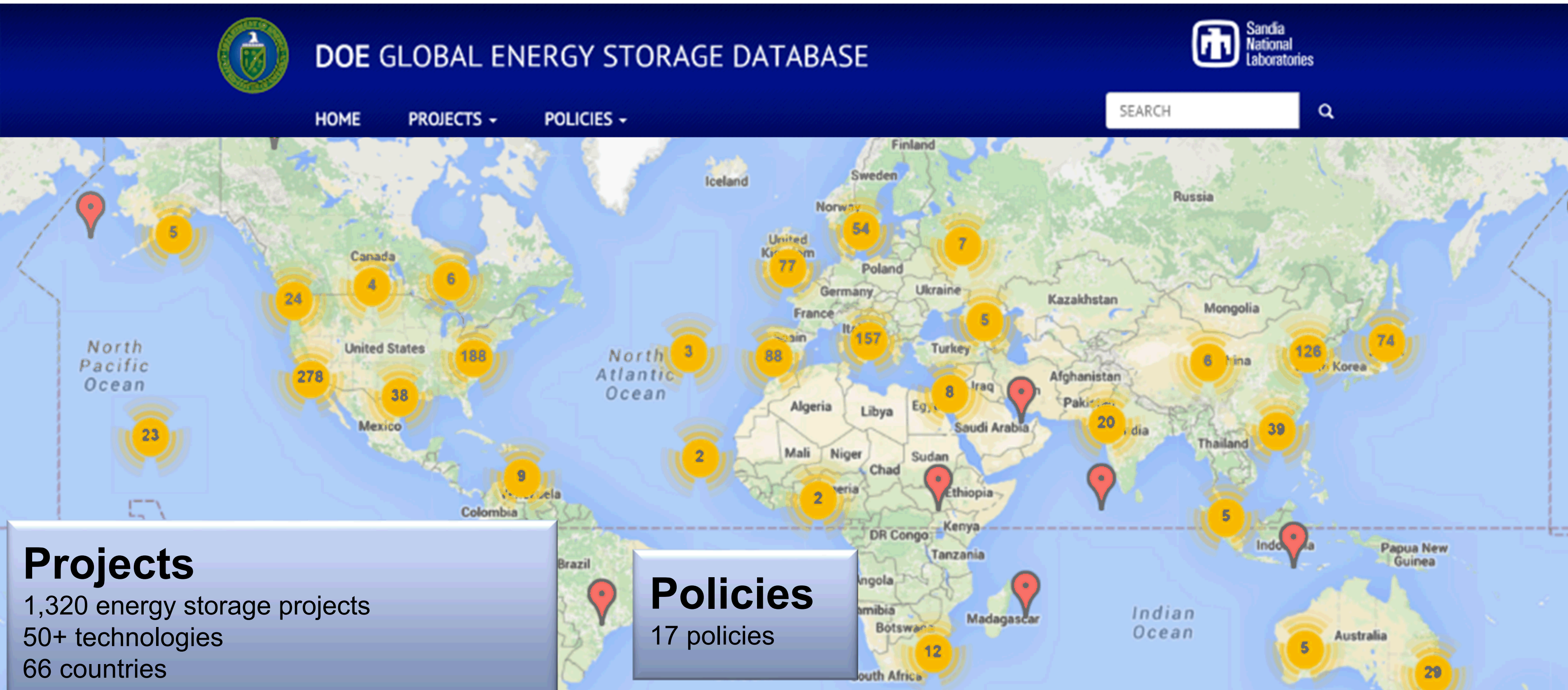
# Outreach and Industry Tools

- ***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 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 National Laboratories

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




## Projects

1,320 energy storage projects
50+ technologies
66 countries

## Policies

17 policies

Li batteries in storage: 900 projects, 2400 MWh
Compare that to 60GWh of PV that got installed in 2015 alone

# THANK YOU

**ADDITIONAL INFO AT:**
**WWW.SANDIA.GOV/ESS/**
**ENERGY.SANDIA.GOV**