SAND2018-1855C

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Sandia National Laboratories

EMERGING ENERGY STORAGE TECHNOLOGIES, INTEGRATION, SAFETY AND STANDARDS

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SAND No:

Power & Energy Society®

Emerging Energy Storage Technologies

Among the emerging technologies, Zn based alkaline batteries are the most promising

- Rechargeable Zn-MnO_2 has most compelling attributes for low cost grid storage applications
  - Low cost materials and manufacturing
  - Safe and benign aqeous chemistry
  - Large manufacturing supply chain from primary dry cell market

Zn-MnO_2 Batteries

- Zn/MnO_2 alkaline batteries
- Traditionally primary batteries
- Lowest bill of materials cost, lowest manufacturing capital expenses
- Established supply chain for high volume manufacturing
- Readily be produced in larger form factors for grid applications
- Do not have the temperature limitations of Li-ion/Pb-acid
- Are inherently safer, e.g. are EPA certified for landfill disposal.
- Until recently reversibility of Zn/MnO2 has been challenging

History of Rechargeable Zn-MnO2 Batteries

- Long history of research on making $Zn\text{-}MnO_2$ rechargeable.
  - Several commercial products based on cylindrical formats (Rayovac, BTI).
  - All focused on cylindrical designs for consumer markets.

Cylindrical cells

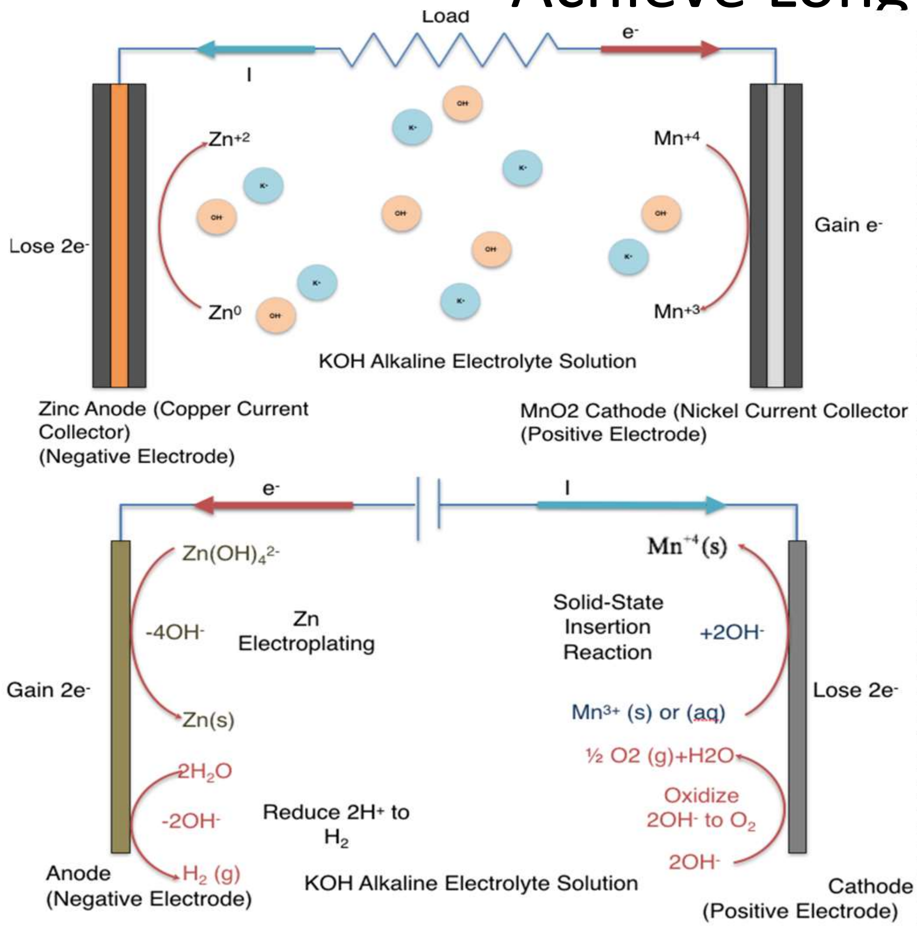
No flexibility to change criticalparameters.

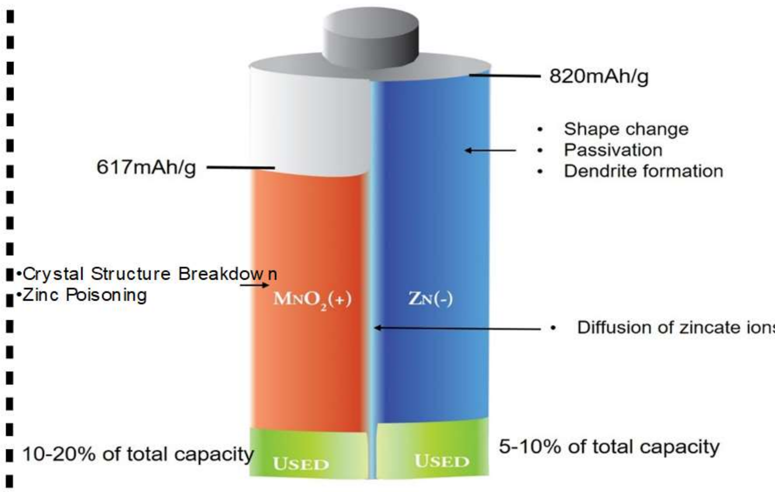
Year	Event
1882	Probably first description of an alkaline MnO_2 cell in German patent 24552 of G. Leuchs
1903	Description of another "wet alkaline cell" in US Patent 746,227 of S. Yai
1912	First alkaline "dry cells" described in German patent 261,319 of E. Aschenbach
1952	W.S. Herbert introduced first commercial alkaline MnO2 "crown" cell for low drain
1960	US patent 2,960,558 of K. Kordesch, P. Marsal and L. Urry describes the invention of the "modern" alkaline cell w/ sleeve type pelletized cathode on the outside in contact w/ the can
1962	US patent 3,024,297 of L. Urry describes a method of forming a cathode depolarizer mix for a rechargeable alkaline cell
~1970	First commercial rechargeable alkaline cells introduced by Union Carbide Corp. and Mallory Corp., but soon withdrawn.
~1980	Research on rechargeable alkaline manganese chemistry was intensified at the TU Graz under the leadership of Prof. Dr. K. Kordesch
1981	Kordesch et al studied the rechargeability of 12 International Common Samples
1983	US patent 4,384,029 of K. Kordesch and J. Gsellman describes a new cell design w/ the cathode constrained by a metal cage.
1985	Titanium doped electrolytic manganese dioxide for improved cycle life described in German patent 3,337,568 of K. Kordesch and J. Gsellman
1986	Battery Technologies Inc. (BTI) founded w/ the mission to commercialize rechargeable alkaline manganese (RAM™) technology
1990	US patent 4,925,747 of K. Kordesch and K. Tomantschger describes the internal pressure management of sealed cells via hydrogen recombination by catalytic means
1991	Ph.D. Thesis of J. Daniel-Ivad on Rechargeable Alkaline Manganese Cells focusing on mercury-free designs
1992	US patent 5,108,852 of K. Tomantschger and C. Michalowski describes a basic rechargeable alkaline cell w/o constraining the cathode
1993	US patent 5,108,852 of R. Flack describes an improved separator bottom seal
1993	Rayovac Corporation launched BTI licensed RAM™ cells manufactured and sold under their trademark RENEWAL™ in the United States

Year	Event
1994	US patent 5,281,497 of K. Kordesch, J. Daniel-Ivad and R. Flack describes a mercury-free rechargeable cell w/ an anode having gas release properties and a hydrogen recombination system to limit in-cell gas pressure
1994	Pure Energy Battery Corporation launched BTI licensed RAM™ cells manufactured under their trademark PURE ENERGY™ in Canada. Cells are mercury-free.
1995	US patent 5,424,145 of J. Daniel-Ivad, J. Book and K. Tomantschger describes a basic rechargeable cell w/ specific anode to cathode Ah-balance to achieve satisfactory performance in consumer use/misuse.
1995	Rayovac's RENEWAL™ cells become mercury-free
1996	US patent 5,626,988 of K. Tomantschger, J. Book and J. Daniel-Ivad describes a mercury-free rechargeable cell w/ a special anode process for reliable performance
1996	Young Poong Corporation launched BTI licensed RAM™ cells manufactured under their trademark ALCAVA™ in South Korea
1997	AccuCell started to sell BTI licensed RAM™ cells in Germany.
1998	Grand Batteries Technologies launched BTI licensed RAM™ cells manufactured under their trademark GRANDCELL™ in Malaysia
1998	Single-use alkaline cell producers introduce cells capable of higher drain rates
1999	BTI released 1st Generation High-Rate RAM™ cell specifications for production
1999	Endurance cycling breakthrough of RAM™ cells in Cordless Phone test: 6500 cycles for 5 minute call, then recharge in cradle
2000	"Marathon" RAM™ cell research to extend the deep discharge stability from 25 to 50 cycles initiated
2000	US patent 6,099,987 of J. Daniel-Ivad, J. Book and E. Daniel-Ivad describes a cylindrical cell w/ a cup seal for improved cumulative performance
2001	BTI acquired the Dema Group, a Swedish distribution company, and launched Demacell™ RAM™ cells in an effort to promote a European expansion of the technology.

J. Daniel-Ivad and K. Kordesch, "Rechargeable Alkaline Manganese Technology: Past-Present-Future," ECS Annual Meeting, May 12-17, 2002

Limiting the Depth of Discharge to Achieve Long Cycle Life



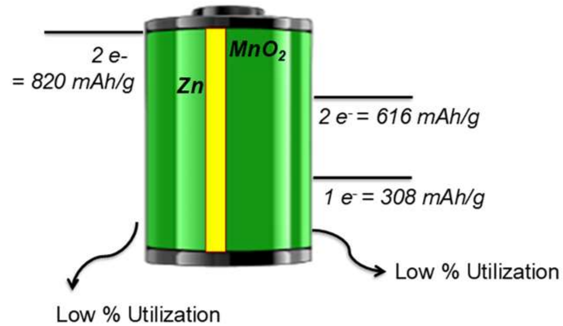


Source: CUNY Energy Institute

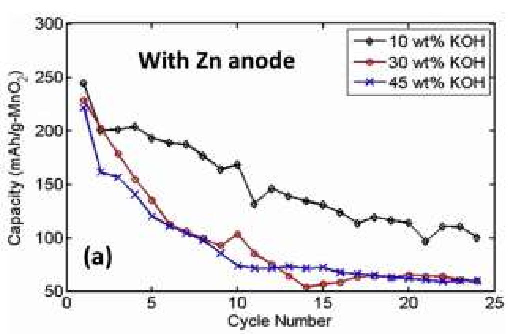
URBAN ELECTRIC POWER

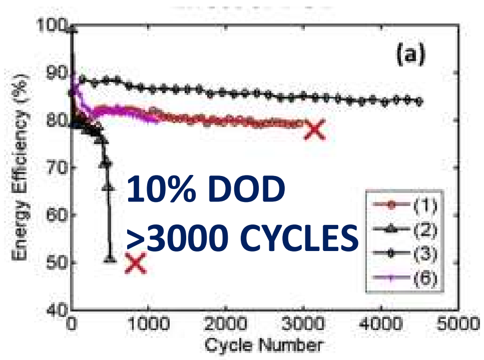
Low DOD discharge makes for a highly viable technology

Single-use Alkaline Battery $23/kWh

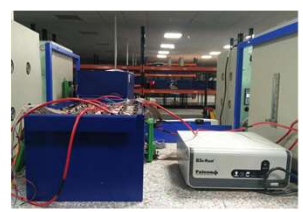


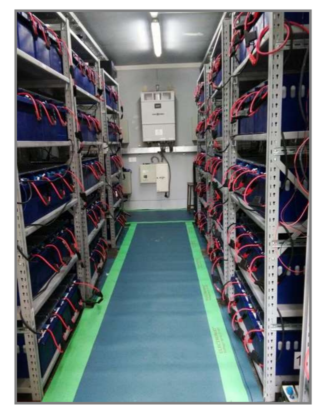
Gen 1 Alkaline Battery
Projected cost: $100/kWh in volume





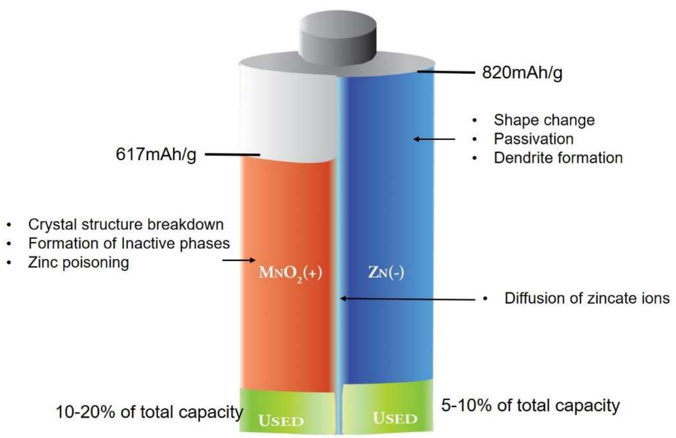
RAPID CELL DEATH >30% DOD

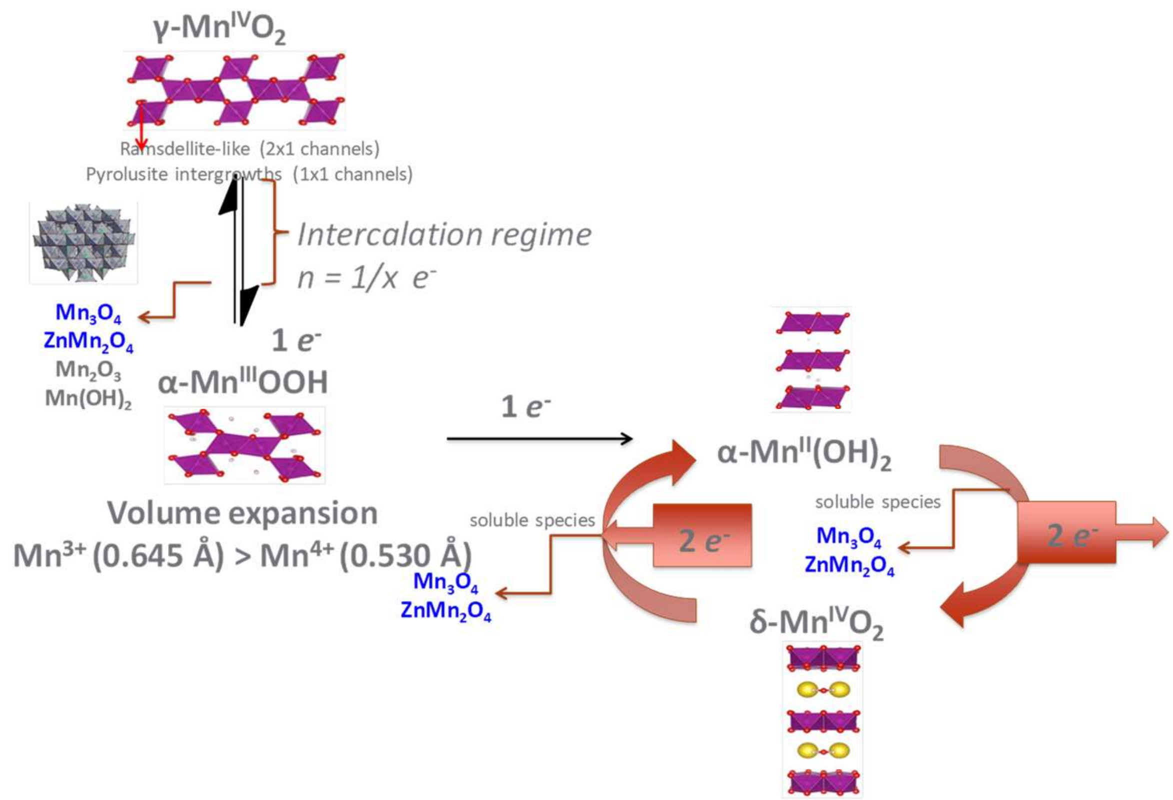




http://www.urbanelectricpower.com

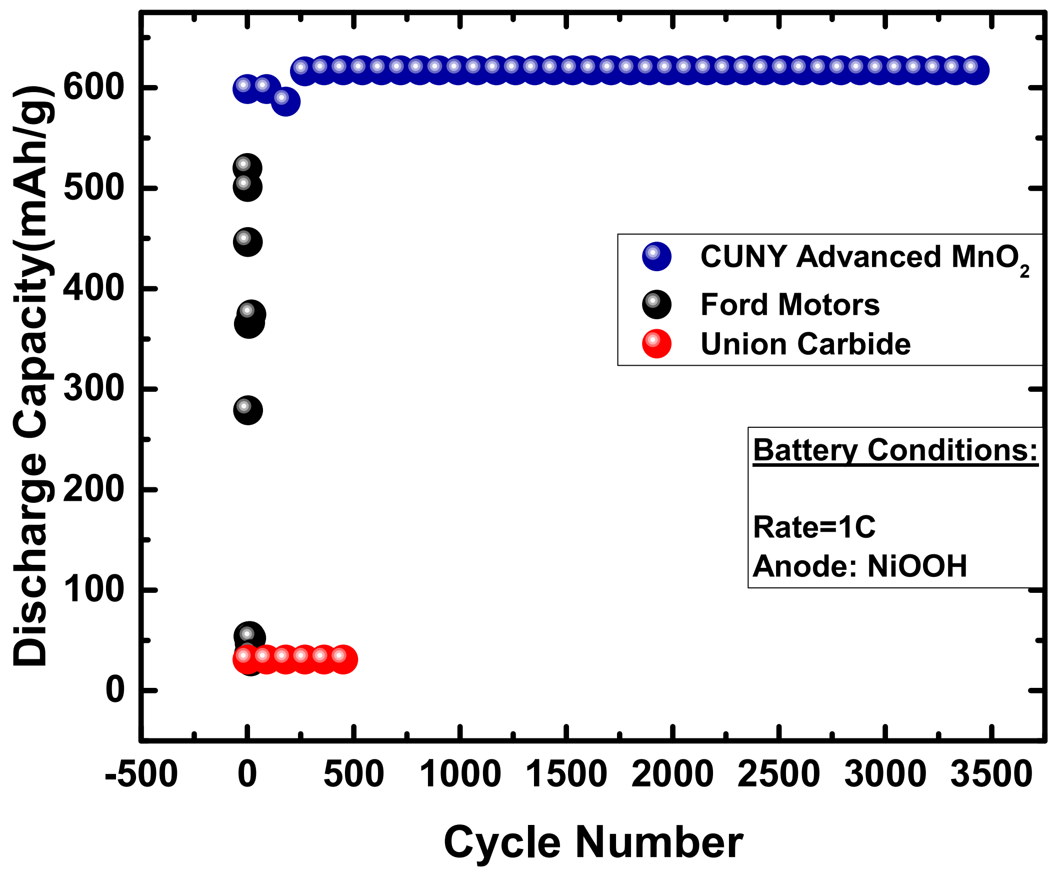
Utilization of 2e in MnO_2
Enabling Zn-MnO_2 to Reach Li-ion in Energy Density





Source: CUNY Energy Institute
G.G. Yadav, J.W. Gallaway, D.E. Turney, M. Nyce, J. Huang, X. Wei and S. Banerjee, Nature Communications, vol. 8, Article number: 14424 (2017). doi:10.1038/ncomms14424

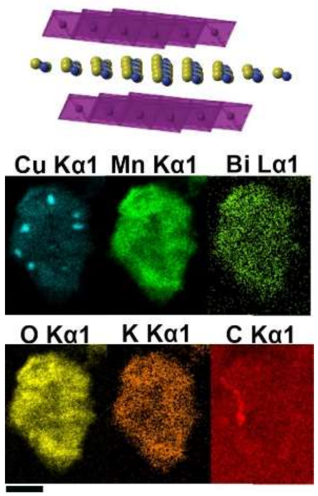
CUNY Breakthrough Advancement

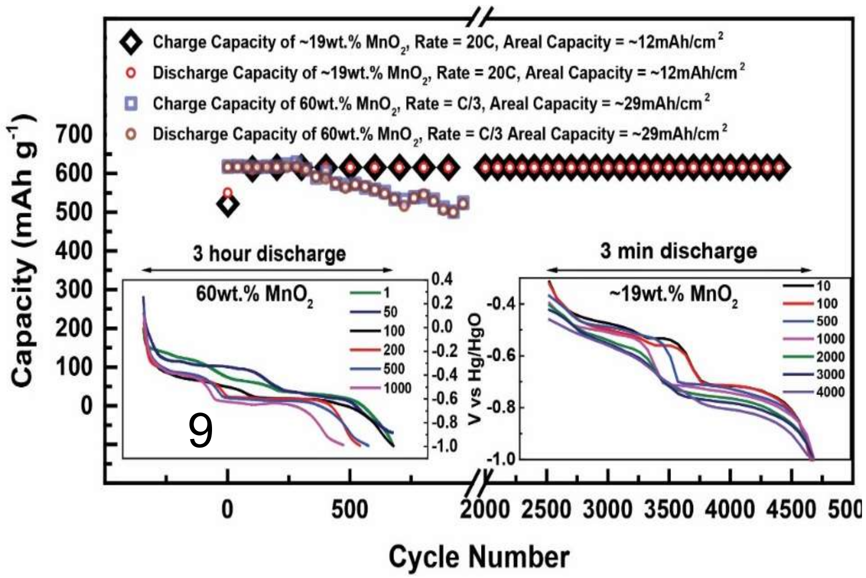


- With full utilization of 2e in MnO_2, we have the possibility of safe, ~$50/KWh rechargeable batteries

Source: S. Banerjee, CCNY

MATERIALS ENGINEERING OF MnO_2 FOR ACCESSING 100% DOD





Source: CUNY Energy Institute

URBAN ELECTRIC POWER

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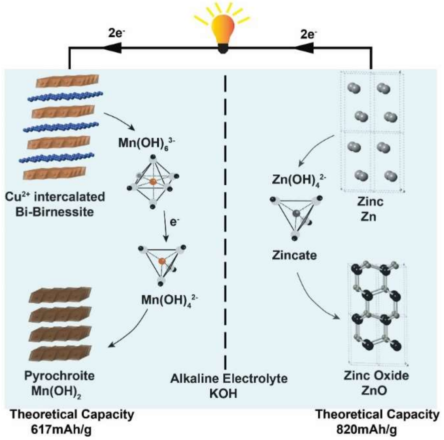
HIGHLY ENERGY DENSE BIRNESSITE/Zn BATTERY

A CONVERSION BATTERY CHEMISTRY

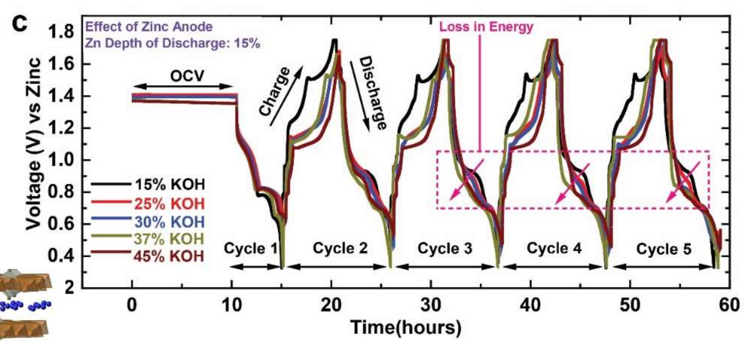


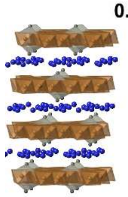
NYSERDA GOALS

- >160Wh/l
- 500 CYCLES

NEED TO HAVE >15% Zn DOD TO HIT TARGETS

Zn POISONING OF THE BIRNESSITE



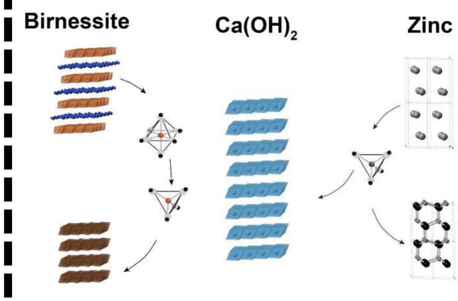


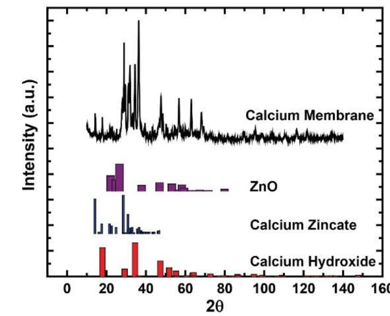
Chalcophanite $ZnMn_3O_7.3H_2O$

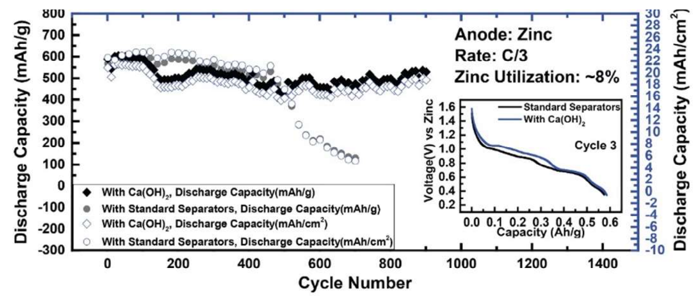
Zn AFFECTS ENERGY

Zn- BIRNESSITE IS RESISTIVE

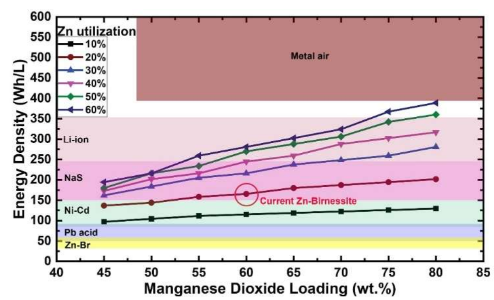
SEQUESTER Zn THROUGH COMPLEXATION





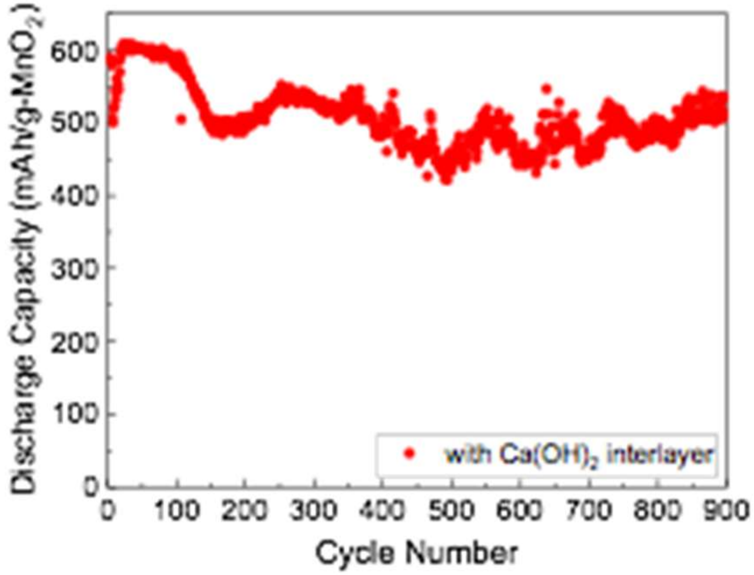


HIGHEST CYCLE LIFE REPORTED IN LITERATURE



CURRENT CELLS GET 160Wh/L
BUILDING & TESTING LARGE CELLS

Utilization of 2e in MnO_2



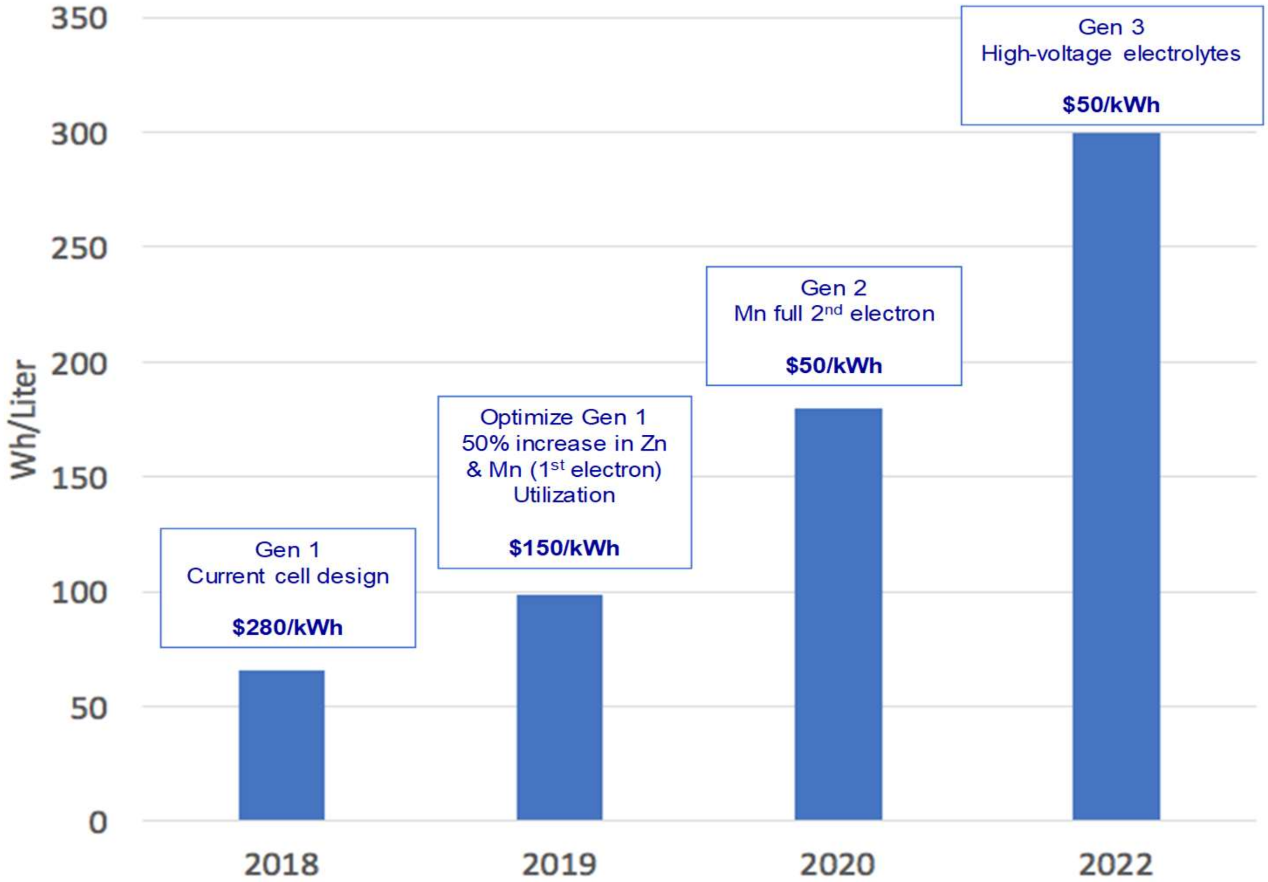
- Current CUNY testing results
- Highest cyclone recorded in literature to date


Large format cells under test

Current university research targets:

- 180Wh/L
- 500 Cycles
- 40% Fade
- <$50/kWH
- Disrupt Li-FePO 4

CUNY Roadmap for $Zn\text{-}MnO_2$



Source: CUNY Energy Institute

Energy Storage Systems

- System and engineering aspects represent a significant cost and component, and system-level integration continues to present significant opportunities for further research.

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Battery to ES System

Battery
- $/kWh
- Efficiency (%)
  Self Discharge
- Cycle life (#)

PCS/BOS
- Power Electronics
  $/kW
- BOS (Container, Safety, Thermal Management)

Softcosts
- Interconnection
- Permits
- O&M

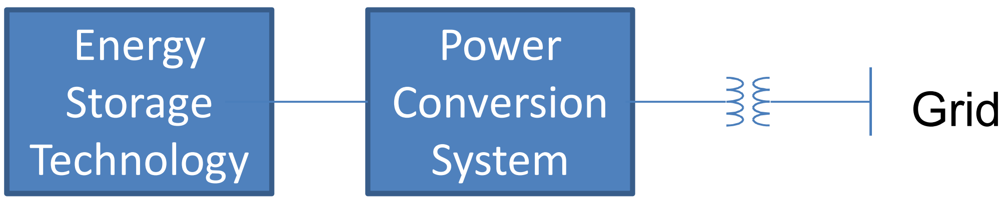
Battery to a Storage System: doubling in cost,
$250/kWh battery ⇨ $500-$700/kWh Storage System

We need cost reductions across all areas, not just batteries

Power Electronics and Systems Integration

- Unlike batteries, cost reductions in power electronics and power conversion systems has been slow to come.
  - Bringing in WBG devices can make format factor smaller, reduces thermal management issues
  - New magnetics and temperature capacitor can make the systems more compact

Power Conversion System & Integration

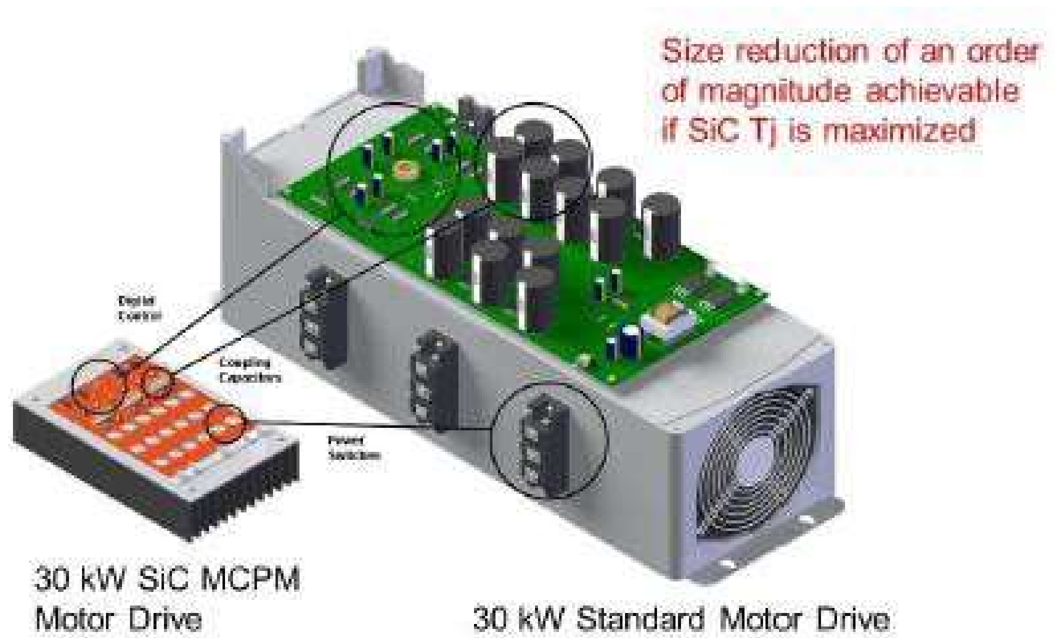


Energy Storage Technologies	PCS interconnect	R&D Opportunity	R&D Opportunity
Flow Batteries	High Current/Low Voltage	Wide band gap electronics - GaN	Energy Density & Controlability
Li-ion	Low Current/High Voltage	High Efficiency - SiC	Safety, Reliability & Controlability
Zinc Manganese Oxide	Low Current/High Voltage	High Efficiency – SiC	Safety, Reliability & Controlability
Sodium Sulfur	Low Current/High Voltage	High Efficiency - SiC	Safety, Reliability & Controlability

- **Flow batteries require higher current and lower cell voltages for optimal energy conversion. This is a challenge for the PCS and high efficiency semiconductors will be critical such as GaN**
- **Li-ion, Zinc Manganese Oxide and Sodium Sulfur have similar cell voltage and current requirements and the charge and discharge characteristics when interfacing with the PCS are similar.**

Example Benefit of Using SiC Switches

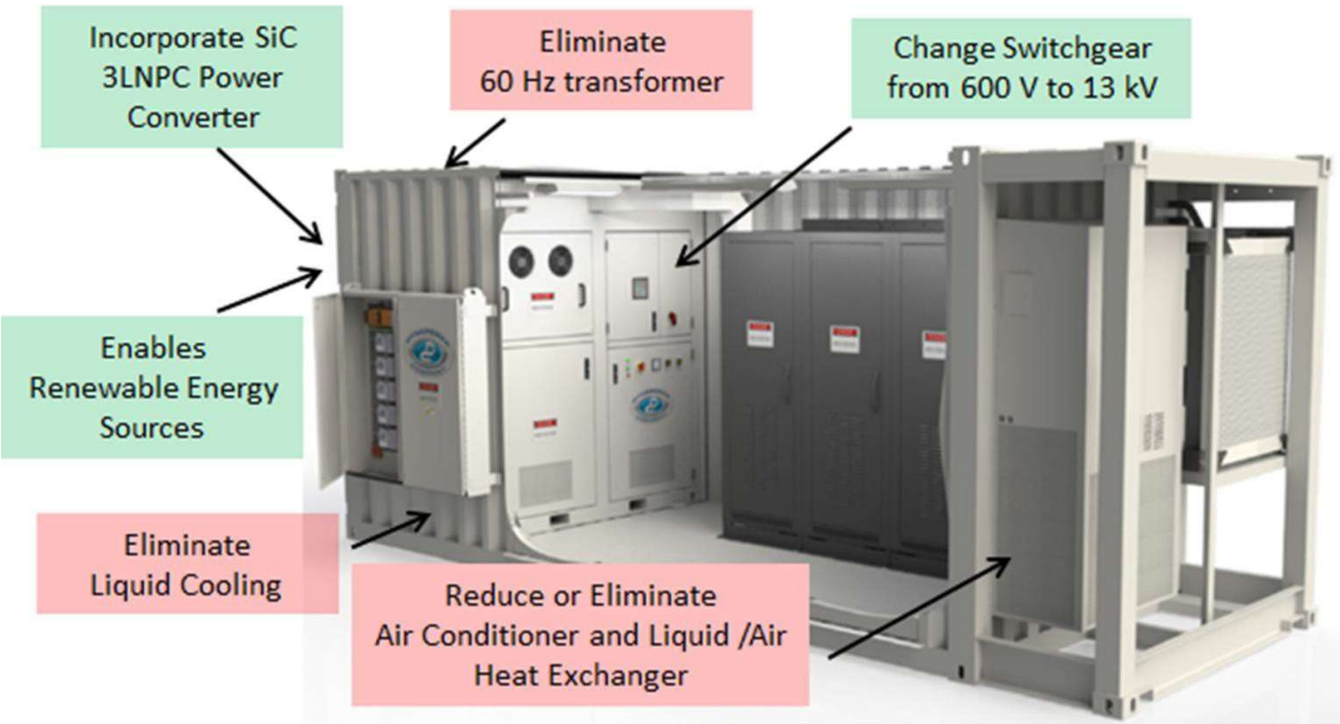
- Miniaturize power electronics systems by employing WBG power devices in high temperature and high efficiency design
- Passive cooling
- Higher switching frequency



Source: Wolfspeed

Example: 500kW PCS using SiC

Key: Eliminate Add

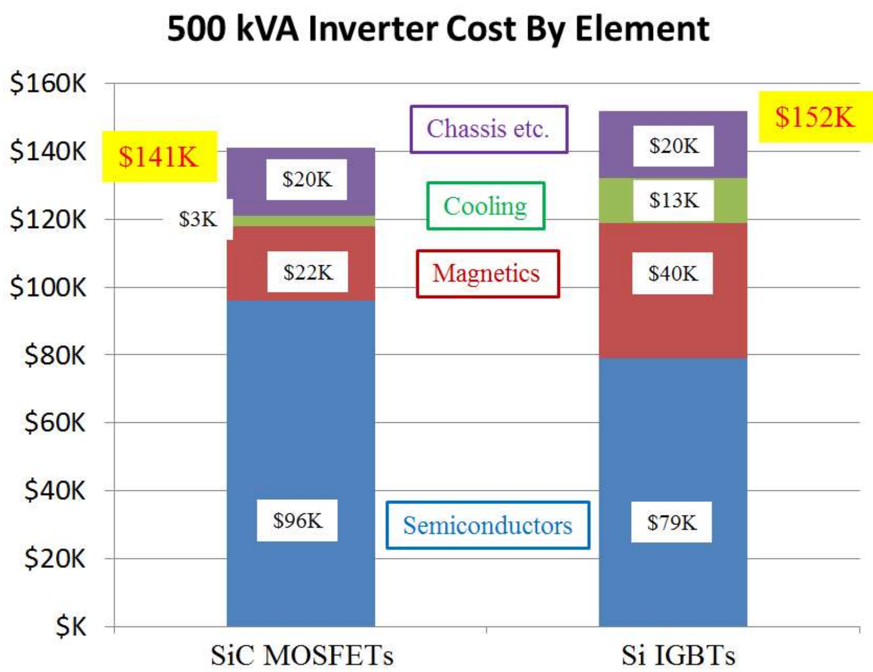


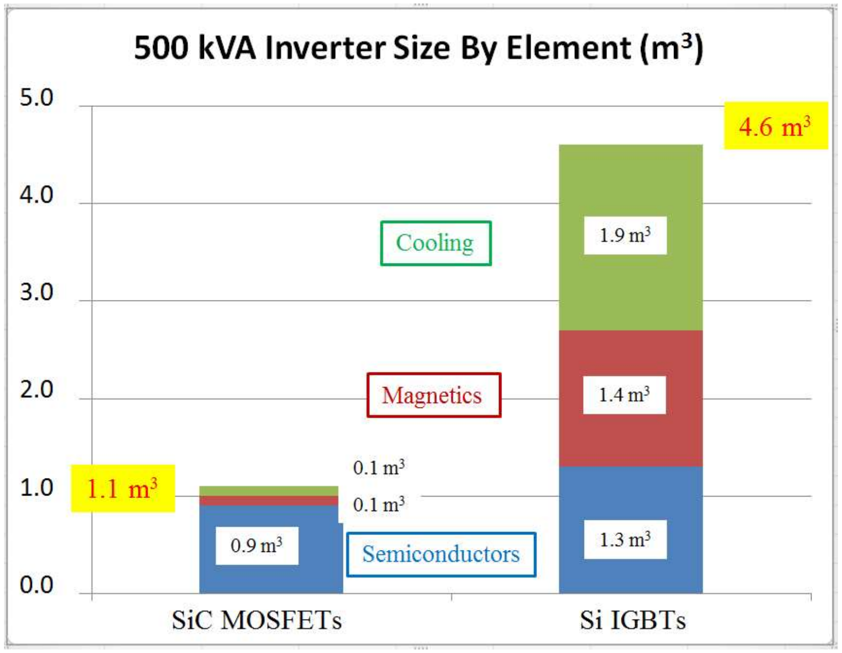
Existing 500 kVA Grid Tied Energy Storage Container

Nominal Existing Generation System
• 500 kW, 250 kW-hr
• 23 x 8 x 10 ft.
• Includes AC & DC switchgear
• Optional: solar recombiner (600 – 1000 V PV arrays)
• Optional: 4 x 2 x 4 ft. 480:480 transformer
• 3 x 7 x 10 ft. 250 kW-hr Li-ion battery
• Ramp rate control, frequency regulation, VAR support
• Seamless dynamic transfer

Courtesy: Creare, LLC

Cost and Size Comparison: SiC vs Si





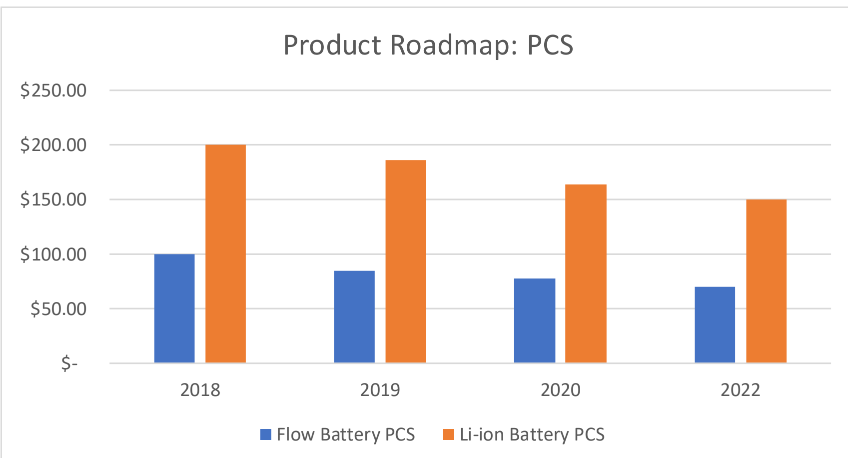
Per unit material costs are comparable ($141K vs. $152K). New design: SiC costs are higher, but magnetics and cooling costs are lower. **SiC costs are likely to reduce.**

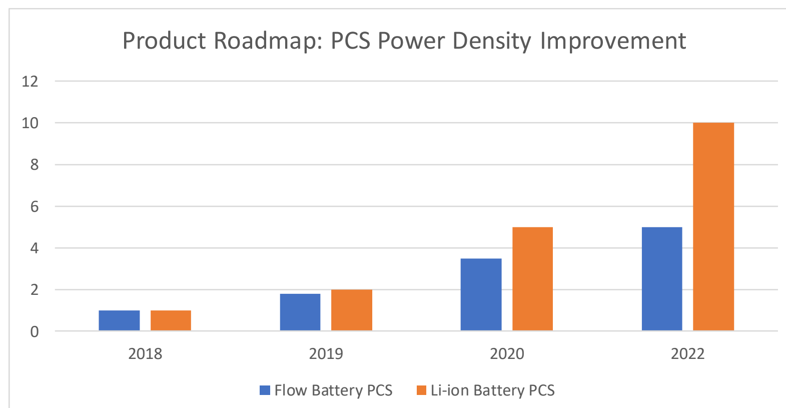
Size of the inverter which uses SiC MOSFETs is much smaller, with 4.3X power density.

Courtesy: Creare, LLC

WBG Power Converters

- WBG power converts present opportunity for improving power density and also reduce system complexity





Safety and Reliability

- Unlike batteries for consumer electronics and battery packs for electric vehicles, the scale and complexity of large stationary applications in the electric grid impose a complex set of requirements on the safety and reliability of grid-scale energy storage systems.
- Safety aspects of grid energy storage and how this safety is connected to the electrochemistry of materials, cell-level interactions, packaging and thermal management at the cell and system level, and the overall engineering and control architecture of large-scale energy storage systems.

Improving Storage Safety

Development of Inherently Safe Cells →

- Safer cell chemistries
- Non-flammable electrolytes
- Shutdown separators
- Non-toxic battery materials
- Inherent overcharge protection

Safety Devices and Systems →

- Cell-based safety devices
  - current interrupt devices
  - positive T coefficient
  - Protection circuit module
- Battery management system
- Charging systems designed

Effective Response to Off-Normal Events →

- Suppressants
- Containment
- Advanced monitoring and controls

Materials R&D for Energy Storage System Safety

- Major research areas
  - Materials origin of safety and reliability
  - Device level failures
  - Cascading failures
- Advanced simulation and modeling of energy storage systems
  - Further
    - Software's role as a critical safety system
    - Better control of cell behavior through power electronics

Safety through Codes and Standards

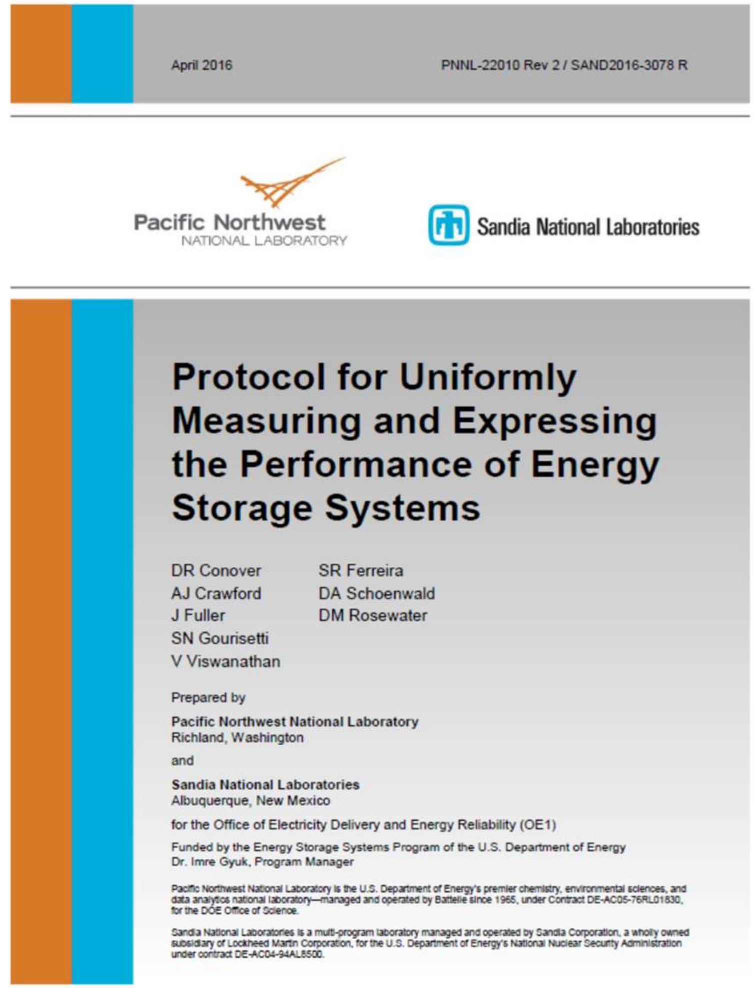
- Many ESS safety related issues are identical or similar to those associated with other technologies
- Some safety issues are unique to energy storage in general and others only to a particular energy storage technology
- Current codes and standards provide a basis for documenting and validating system safety
  - prescriptively
  - through alternative methods and materials criteria
- Codes and standards are being updated and new ones developed to address gaps between ESS technology/applications and criteria needed to foster initial and ongoing safety

SNL & PNNL Protocol for Evaluation of ES Systems

Companies looking for an accurate method to gauge how well large batteries and other grid-scale energy storage systems work now have a new set of evaluation guidelines, called the Energy Storage Performance Protocol, at their disposal. The guidelines currently evaluate three energy storage performance uses:
Peak shaving, Frequency Regulation, and Islanded Microgrids

Additional Lab Protocols:

- Duty Cycle for ESS Firming
- Duty Cycle for PV Smoothing



April 2016 PNNL-22010 Rev 2 / SAND2016-3078 R

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

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Albuquerque, New Mexico

for the Office of Electricity Delivery and Energy Reliability (OE1)

Funded by the Energy Storage Systems Program of the U.S. Department of Energy
Dr. Imre Gyuk, Program Manager

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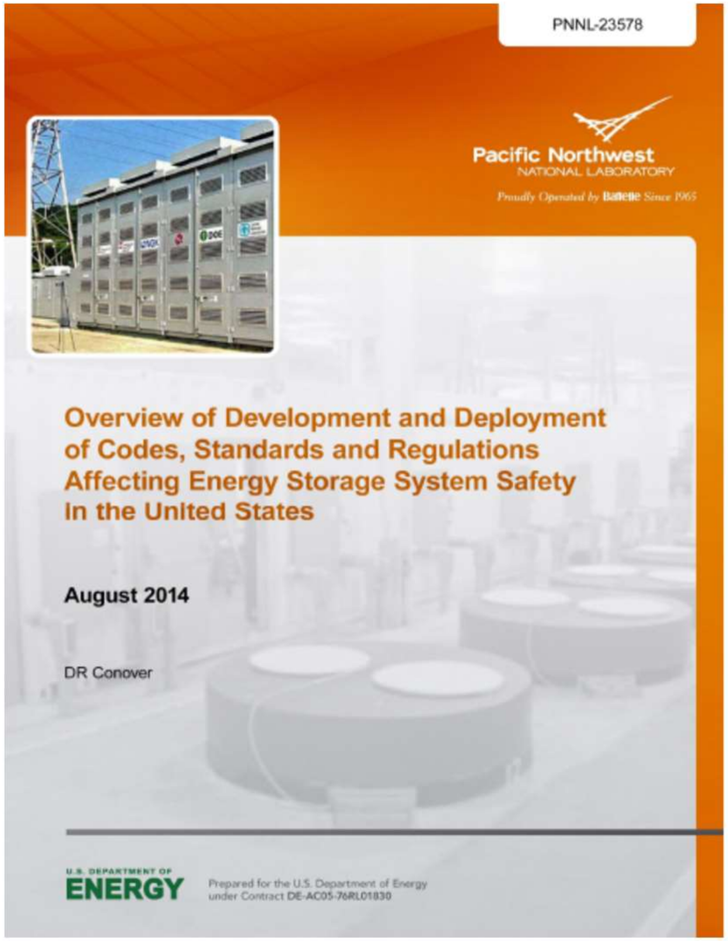

PNNL-23578

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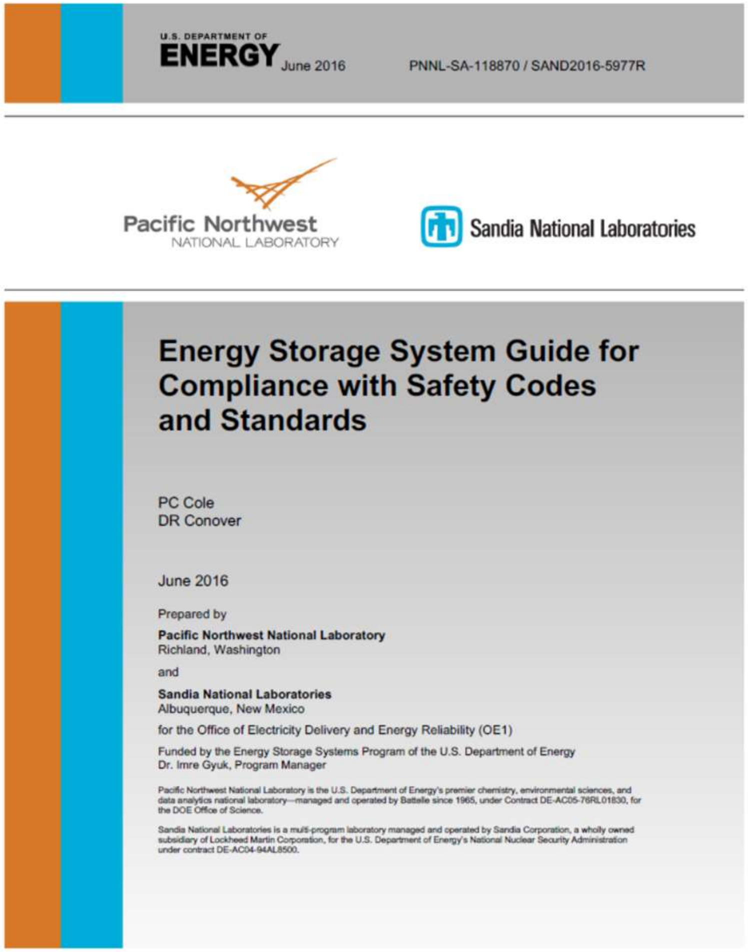
Overview of Development and Deployment of Codes, Standards and Regulations Affecting Energy Storage System Safety in the United States

August 2014

DR Conover

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830



U.S. DEPARTMENT OF ENERGY June 2016 PNNL-SA-118870 / SAND2016-5977R

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Sandia National Laboratories

Energy Storage System Guide for Compliance with Safety Codes and Standards

PC Cole
DR Conover

June 2016

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Albuquerque, New Mexico

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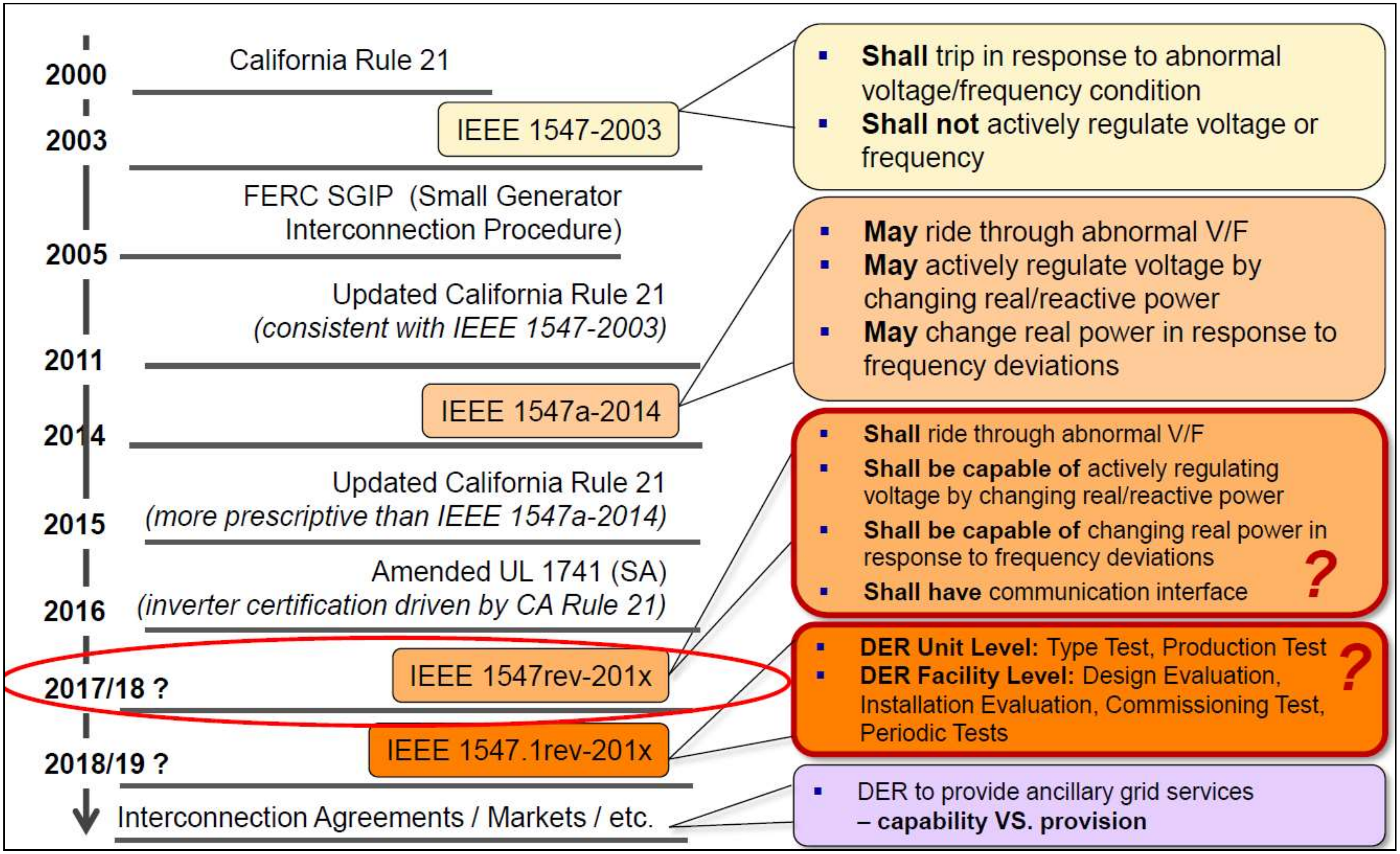
IEEE 1547: Timeline of Major Changes



Graphics source: EPRI

1547 Revision Includes

- **Performance categories**
  - Gives flexibility to accommodate different DER futures
- **More coordinated operation under normal conditions**
  - Section 5 – many details on reactive power capabilities and voltage/power control requirements (not just allowance)
- **Grid support under abnormal conditions**
  - Maintains distribution grid safety (cease to energize, trip on voltage or frequency when necessary)
  - Maintains bulk power system reliability (rides through voltage and frequency disturbances)
- **New guidance for interoperability**
  - Starts us on the path to more open communications
  - Seeks to strike a balance between varying topologies & needs
- **New guidance for intentional islands**
  - Much needed and immediate relevance
- **Testing requirements completely revised to address new capabilities**
  - Strikes a balance between needs for large and small installs

Other Significant Results from 1547 Revision

Gap for ES Interconnection Standards Identified, and Action Taken

1.1 Project Number: P1547.9
1.2 Type of Document: Guide
1.3 Life Cycle: Full Use

2.1 Title: IEEE 1547.9 Guide for Interconnection of Energy Storage Distributed Energy Resources with Power Systems

5.2 Scope: This Guide provides information on and examples of how to apply the IEEE Std 1547, for the interconnection of Energy Storage Distributed Energy Resources (DER ES). Scope includes DER ES connected to area Electric Power Systems (local EPSs) that are capable of bidirectional real and reactive power flow, and are capable of exporting real power to the EPS. Guidance is also provided for non-exporting DER ES, such as UPS type systems that support onsite loads, or EV chargers, with charging attributes that could have power system impacts, e.g. modulating rate of charge proportionally to system frequency.

Source: Charlie Vartanian

Smart Grid Comm & Controls

P2030.7/Draft D11 - IEEE Draft Standard for the Specification of Microgrid Controllers

1.1 Scope

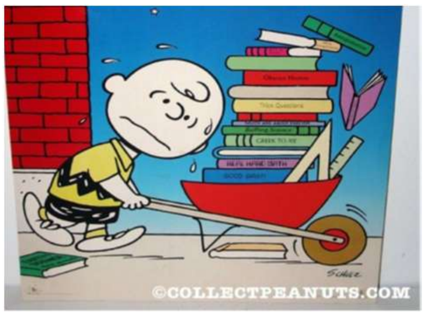
A key element of microgrid operation is the Microgrid Energy Management System (MEMS). It includes the control functions that define the microgrid as a system that can manage itself, and operate autonomously or grid connected, and seamlessly connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services. The scope of this standard is to address the technical issues and challenges associated with the proper operation of the MEMS that are common to all microgrids, regardless of topology, configuration or jurisdiction, and to present the control approaches required from the distribution system operator and the microgrid operator. Testing procedures are addressed. Scenario and/or use cases for testing are identified in this standard for dispatch function and transition function respectively. These cases shall be tested according to IEEE P2030.8.

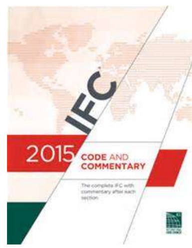
IEEE Std 2030.2-2015 Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure

1.1 Scope

This document provides guidelines for discrete and hybrid energy storage systems (ESSs) that are integrated with the electric power infrastructure, including end-use applications and loads. This guide builds upon IEEE Std 2030™-2011.[1]

Major Fire/Building Codes that Include Stationary Battery Regulations

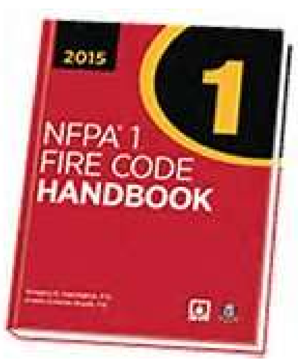




New Battery Section in 2018 Edition

2021 Battery Section Already Drafted! - FCAC

New!
NFPA 855
1st DRAFT DONE
2nd DRAFT



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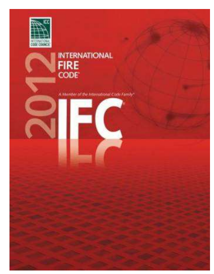

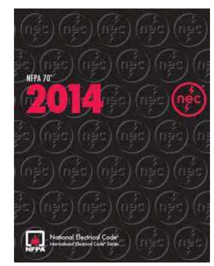

Courtesy: Randy Schubert, Ericsson

Code Meeting Schedule

Code	Title	Current Edition	Next Edition
NFPA-1	Fire Code	2018	2021
IFC	International Fire Code	2018	2021 (2021 input was due 12-January 2018)
NFPA-855	Energy Storage Standard "New "	New	2020 (First Draft Posting April 11, 2018)
NFPA-70	National Electrical Code	2017	2020 (First Draft Posting July 6, 2018)
NFPA-101	Life Safety Code	2015	2021
IBC	International Building Code	2018	2021
IMC	International Mechanical Code	2018	2021
NFPA-110/111	Standard on Stored Electrical Energy Emergency and Standby Power Systems	2016	2019 (Jan 24, 2018 Second Draft Posting, Feb 21, 2018 NITMAM deadline)

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2018 IFC and NFPA-1 Threshold Quantities

Figure 1. Battery Capacity Threshold Covered by Codes	
Technology	Capacity Threshold (kilowatt hours)
Lead Acid (all types)	70 KWh (252 Mega joules)
Nickel Cadmium (Ni-Cd)	70 KWh (252 Mega joules)
Lithium (all types)	20 KWh (72 Mega joules)
Sodium (all types)	20 KWh (72 Mega joules)
Flow Batteries	20 KWh (72 Mega joules)
Other Battery Technologies	10 KWh (36 Mega joules)

NFPA-855 Threshold 1 KWh for Residential Battery !!!

Kilowatt-hours for a single string (array):
rated amp-hours (at an 8-hour rate) multiplied by the battery string voltage and divided by 1000. As an example of a system that is covered by the code, the photograph below shows strings of VLA batteries that are rated at approximately 4000 amp-hours. So even a single string would be subject to the codes. 48V x 4000 amp-hours / 1000 = 192 KWh.

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NFPA-855

- New Technical Committee developing a comprehensive energy storage system standard
- First Meeting Was January 2017
- First Draft Posting April 11, 2018
- Covers all stationary storage applications
  - Fire protection
  - Placement and Siting
  - Thermal Management & Ventilation
  - Interconnection
  - General Battery Requirements

NFPA-111 Standard on Stored Electrical Energy Emergency and Stand-by Power Systems

- Guidelines for safe deployment and operation of stationary battery systems in stand-by applications.
  - The emergency power systems that operate at less than 24 volts and/or less than 500 VA are not subjected to these requirements.
- Not used as basis for existing code enforcement.
- Industry best practices for power sources, controls, converters, transfer equipment, and accessory equipment including:
  - Installation
  - Maintenance
  - Operation
  - Testing
- A sister document NFPA-110 focuses more on generators and associated back-up power.

Summary

- Currently, the entire storage system (batteries to interconnection) is expensive.
- Manufacturing and scale-up needed for new technologies
- PCS costs are not coming as fast
- Advances in several areas will make grid-based storage systems safer, more reliable, and cost-effective.
- Codes and standards need further work