



Zinc & Lead Batteries*

*(Zn, Pb, Fe, Al multi-valent-based batteries)

PRESENTED BY

Timothy N. Lambert

DOE-OE Peer Review, Bellevue, Washington, August 7, 2024.

SAND2024-XXXXX PE



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Session OVERVIEW – Zinc & Lead Batteries (Multi-valent)*



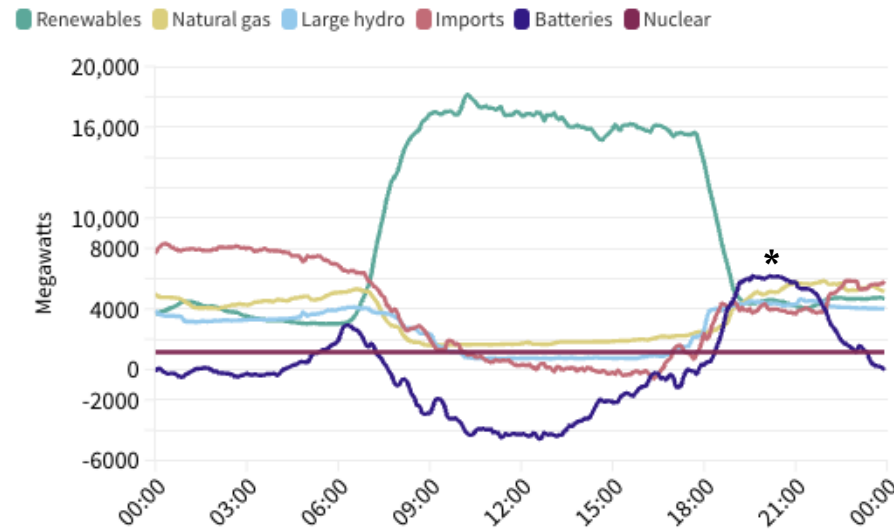
*OE supports RESEARCH&DEVELOPMENT needs of battery chemistries that can impact
Grid Storage: Reliable and resilient electricity system*

10:05 - 10:20 AM	Program Overview / Zinc & Lead Batteries	Timothy Lambert, SNL
10:20 - 10:35 AM	Material Design to Enable Pb Acid Batteries for Long Duration Energy Storage	Tim Fister, ANL
10:35 - 10:50 AM	Latest Developments in Mild Acidic Zinc Battery at PNNL	Matt Fayette, PNNL
10:50 - 11:05 AM	Earth Abundant Multi-valent Materials for Energy Storage	Stephen Percival, SNL
11:05 - 11:20 AM	Molecular Modeling of Gas and Ion Transport in Alkaline Battery Electrolytes	Amalie Frischknecht, SNL
11:20 - 11:35 AM	Progress with Manufacturing and Deploying Zn MnO ₂ Batteries for Grid-Scale Applications	Gautam Yadav, Urban Electric Power

Battery-based Grid Storage

“Battery storage in the power sector was the fastest-growing commercial energy technology on the planet in 2023”

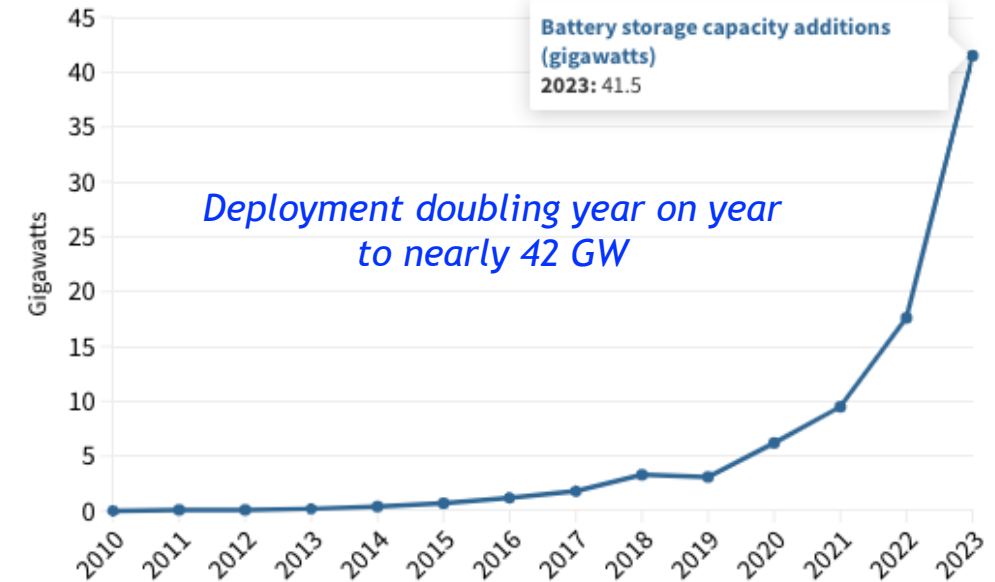
Electricity supply on CAISO, April 19, 2024



Source: California Independent System Operator
Chart by Casey Crownhart, MIT Technology Review

International Energy Agency report calls batteries a “master key”

Global battery storage capacity additions, 2010-2023



“Batteries are starting to show exactly how they'll play a crucial role on the grid”

* On April 16, (2024) for the first time, batteries were the single greatest power source on the grid in California during part of the early evening, just as solar fell off for the day.

10 GW in CA

*Playing a part in balancing the grid
(2019 – 1.9 GW on entire grid, ~ 1.1% total)*

Battery-based Grid Storage

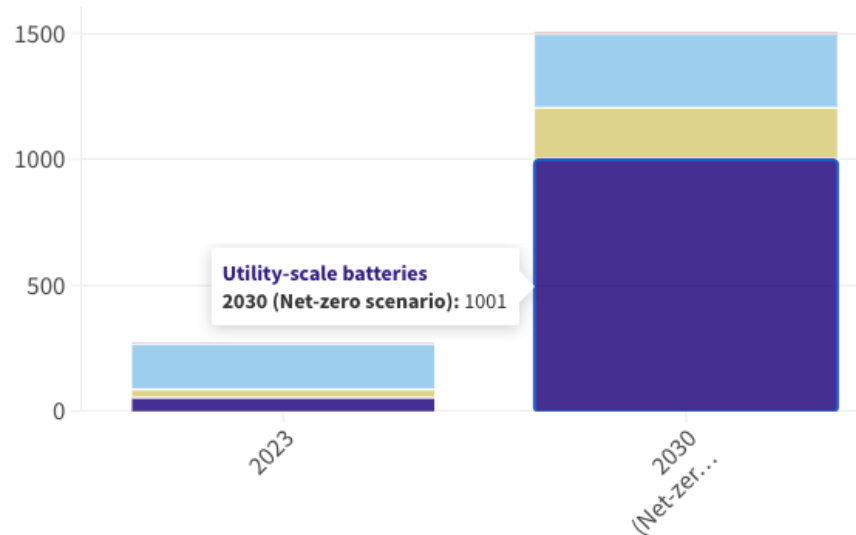
“We need to build a lot more storage”

Global installed energy storage capacity

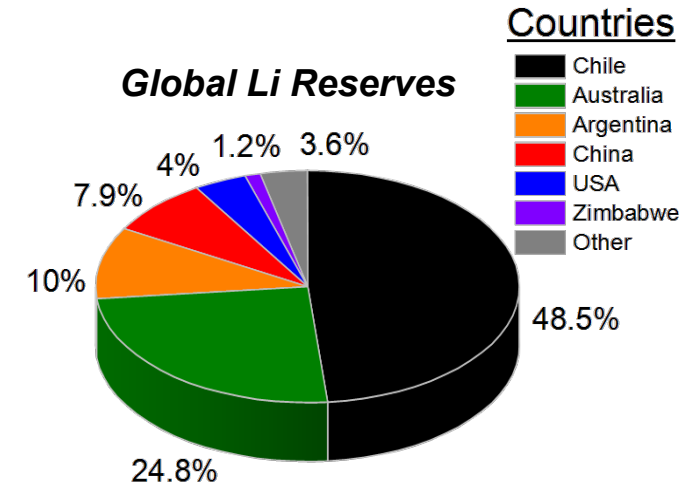
Projected energy storage required to reach net-zero emissions by midcentury

Utility-scale batteries Behind-the-meter batteries Pumped hydro Other storage

Gigawatts



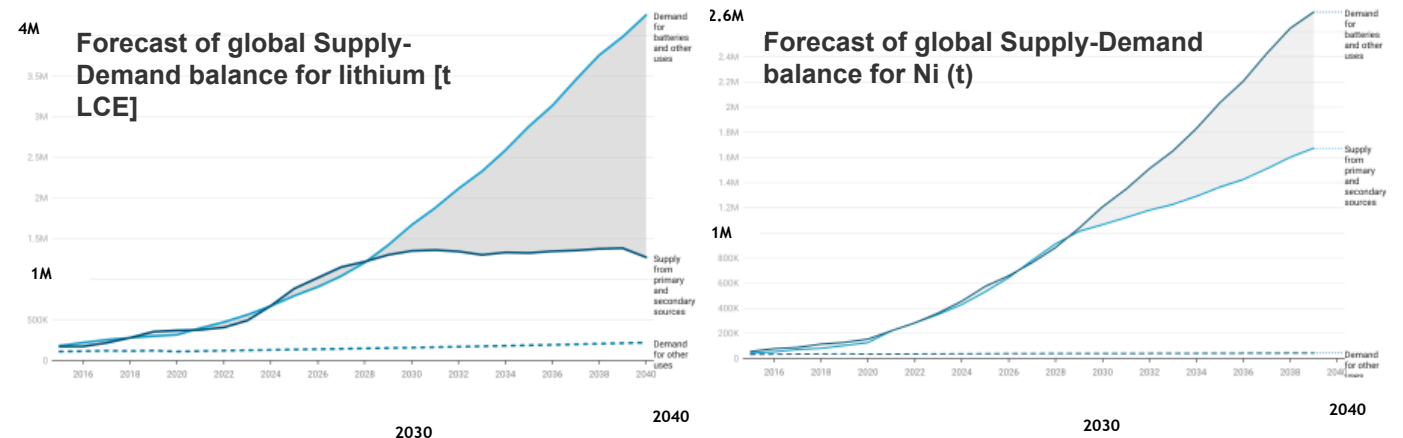
Source: International Energy Agency • Chart by Casey Crownhart, MIT Technology Review



Source: BP Statistical Review of World Energy, 2021

Lithium supply chain issues by ~ 2030 ?

<https://rmis.jrc.ec.europa.eu/analysis-of-supply-chain-challenges-49b749>



<https://www.technologyreview.com> from May 2, 2024

<https://www.iea.org/reports/batteries-and-secure-energy-transitions>

Electrochemical Grid Storage 'Requirements'



- Low cost: < \$100/kWh,
- LDES: Levelized Cost of Storage by 2030: ~ \$0.05/kWh (> 10 h discharge)
- Low-risk components: earth-abundant, minimally processed, available supply chain (in US?)
- Easy to manufacture - roll to roll manufacturing
- Long cycle life: Tens of years of operation
- Safe
- High energy density **

$$\text{Energy} = \text{Voltage (V)} \times \text{Capacity (mAh/cm}^2\text{)}$$

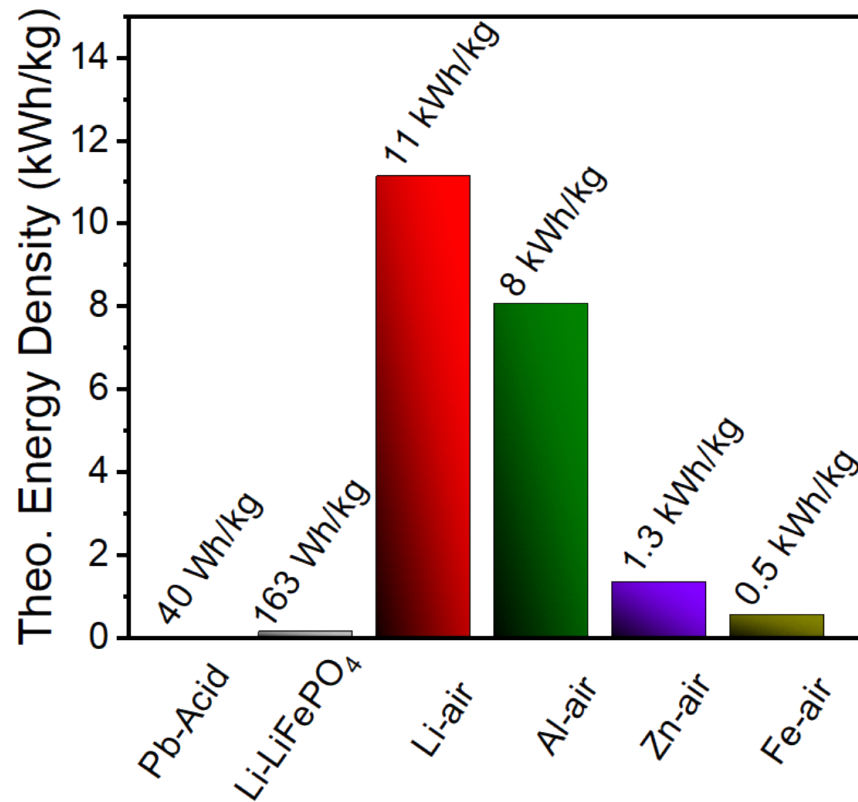
Lower Voltage Systems Require will higher Capacities to be Competitive

Zn/MnO₂ : 15 mAh/cm² to achieve similar energy density to a lithium cobalt oxide (LCO) battery with 1-5 mAh/cm² active loading

A case for multi-valent Zn, Pb, Fe, Al-based batteries



These Materials have a lot of energy



1^0 - Zn/MnO₂
(400 Wh/L ~ \$20/kWh)

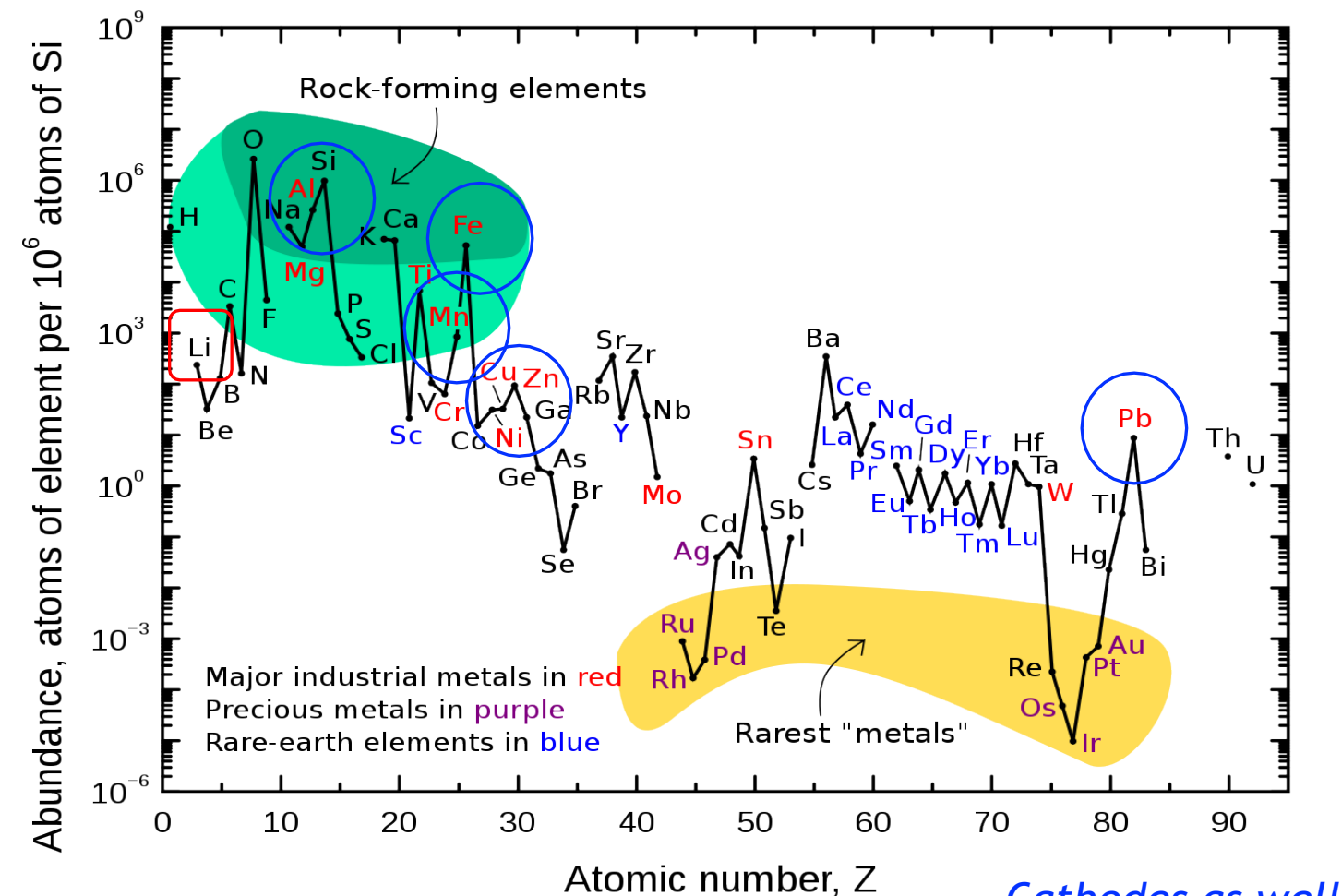
Wikipedia, user Aney, 2005



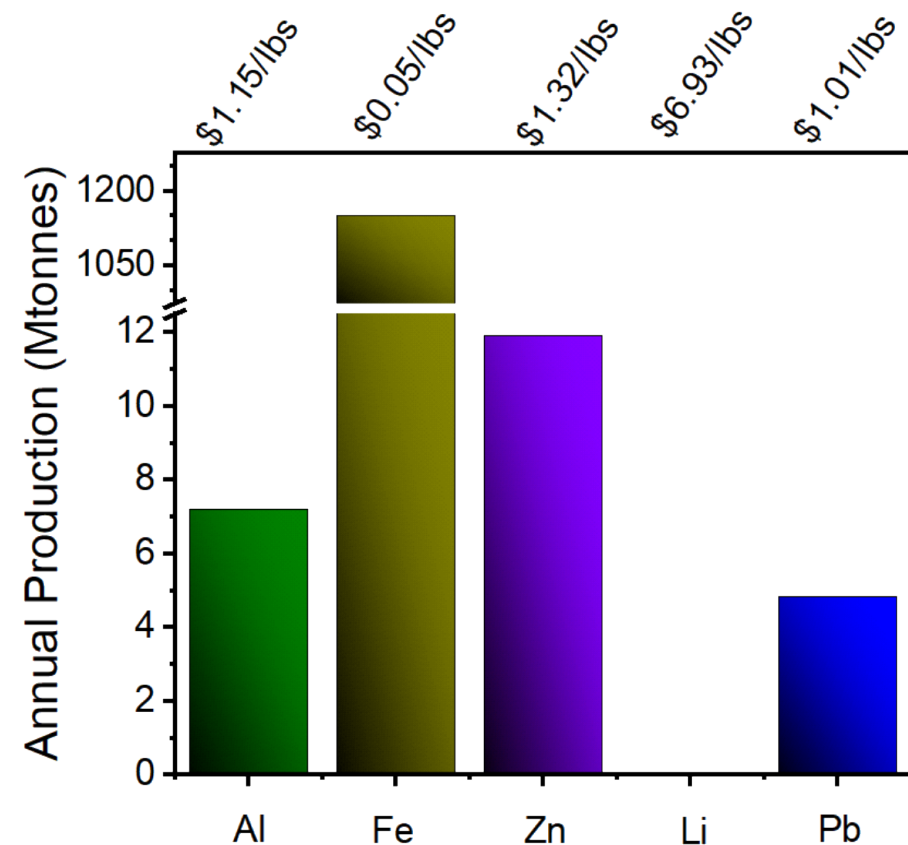
Anode (*)	Cost \$M	GHG Produced (Mt CO ₂)	Volume (m ³)	Mass (tonnes)
Zinc	93	1.5	6,200	44,000
Lithium	370	6	10,200	5,300
Lead	230	4	12,000	120,000

A case for multi-valent Zn, Pb, Fe, Al-based batteries

Low Risk Materials that are readily available at low cost



Cathodes as well



Rechargeable Zn-based Batteries



- Low-cost, high energy density, safety, and global availability have made Zn-based batteries attractive for more than 220 years!
- *Diverse* Zn-batteries offer a range of properties to meet growing demand across varied applications:
 - ✓ Renewables integration (including microgrids)
 - ✓ Backup power (assurance for data centers, telecom, etc.)
 - ✓ Grid stability and resilience
 - ✓ Behind-the-meter applications for residential and commercial applications (Lower energy cost, power quality, etc.)

Zn-MnO₂



ZELOS

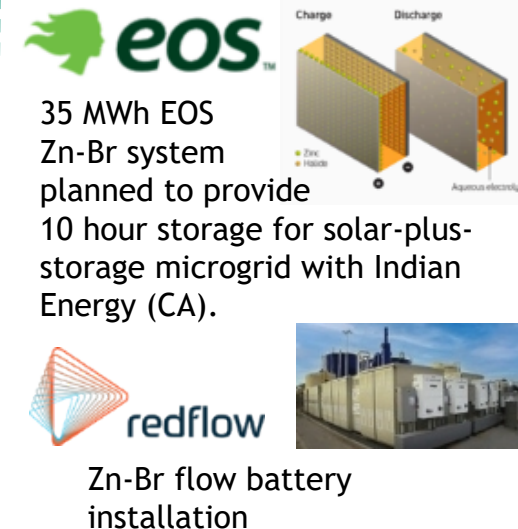
Zn-Ni



Zn-Air



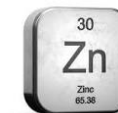
Zn-Br



Zn-ion

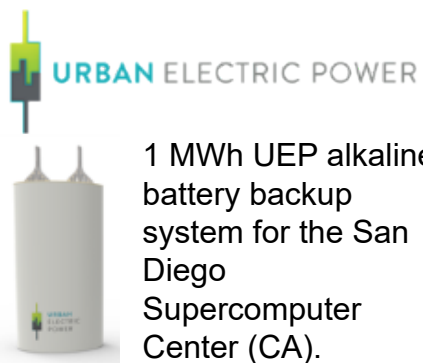


Rechargeable Zn-based Batteries



- Low-cost, high energy density, safety, and global availability have made Zn-based batteries attractive for more than 220 years!

Zn-MnO₂



ZĒLOS

Zn-Ni



$\text{Zn} + 2\text{NiOOH} + 2\text{H}_2\text{O} \rightarrow \text{Zn}(\text{OH})_2 + \text{Ni}(\text{OH})_2$
 OCV per cell = 1.73V; Operating V = 1.2-1.6V
 Practical Specific Energy Density
 ~ 70 – 150 Wh/kg
 200 – 450 Wh/L

$\text{Zn} + 2\text{MnO}_2 + 2\text{H}_2\text{O} \rightarrow \text{ZnO} + 2\text{MnOOH}$
 OCV = 1.61 V per cell; Operating V = 1 – 1.5V
 Practical Specific Energy Density
 ~ 90 – 150 Wh/kg
 135 – 450 Wh/L

Zn-Air



$\text{Zn} + 1/2\text{O}_2 \rightarrow \text{ZnO}$
 OCV = 1.65 V per cell; Operating V = 0.9 – 1.4V
 Practical Specific Energy Density
 ~ 100 – 400 Wh/kg
 135 – 1000 Wh/L

*High utilization of capacity
 Bidirectional oxygen electrocatalysis remain challenging*

Zn-Br



35 MWh EOS Zn-Br system planned to provide 10 hour storage for solar-plus-storage microgrid with Indian Energy (CA).

Zn-Br flow battery installation

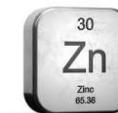
$\text{Zn} + \text{Br}_2 \rightarrow \text{ZnBr}_2$
 OCV = 1.85 V per cell; Operating V = 1 – 1.8V
 Practical Specific Energy Density
 ~ 65 – 75 Wh/kg
 60 – 70 Wh/L

$\text{Zn} + \text{MO}_x \rightarrow \text{ZnMO}_x$
 OCV = 1.60 V per cell; Operating V = 1 – 1.5V
 Practical Specific Energy Density
 ~ 80 – 150 Wh/kg
 200 – 450 Wh/L

Zn-ion



Rechargeable Zn-based Batteries



- Low-cost, high energy density, safety, and global availability have made Zn-based batteries attractive for more than 220 years!

Zn-MnO₂



ZĒLOS

Zn-Ni



Zn-Air



Zn-Br



Zn-ion



Matt Fayette, *PNNL*

Latest Developments in Mild Acidic Zinc Battery at PNNL

Amalie Frischknecht, *SNL*

Molecular Modeling of Gas and Ion Transport in Alkaline Battery Electrolytes

Gautam Yadav, *Urban Electric Power*

Progress with Manufacturing and Deploying Zn|MnO₂ Batteries for Grid-Scale Applications

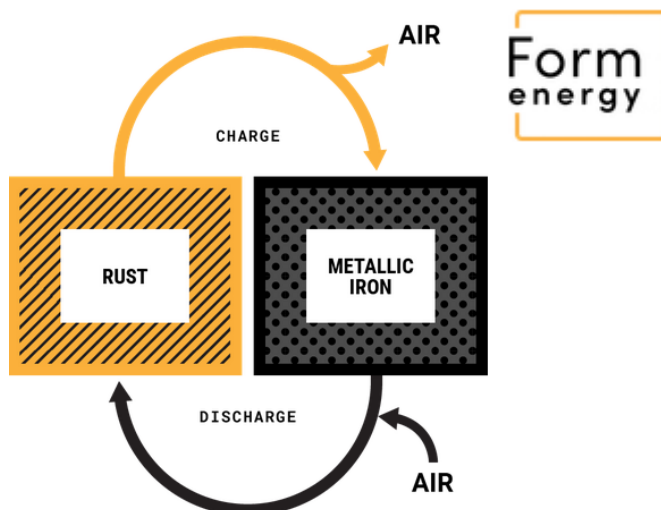
Rechargeable Fe or Al-based Batteries



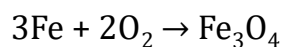
- Commercialization of Fe and Al batteries
- Long Duration Energy Storage Applications - economical with earth abundant materials

Fe-air

(The 100 h battery)



Forms Rust, Electrochemical 'un-rusting'
utilizing excess PV/Wind



Theo V = 1.28 V per cell

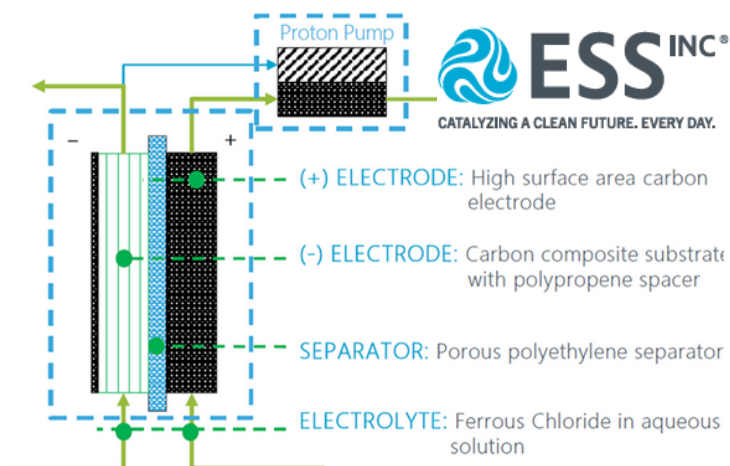
Practical Specific Energy Density
~ 50-75 Wh/kg

HER upon charge, poor discharge rate due to
 $\text{Fe}(\text{OH})_2$, air cathode ?

<https://doi.org/10.1002/cplu.201402238>

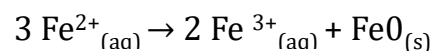
<https://formenergy.com/technology/battery-technology/>

Fe Flow



The ESS iron flow battery uses the same electrolyte on both positive and negative sides. And the proton pump maintains the state of charge and battery health.

Based on Ferrous and Ferric chloride
"ESS iron flow chemistry delivers 25
years or more with no capacity fade or
degradation."



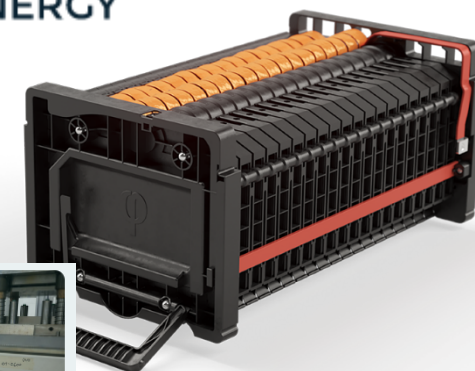
Max V = 1.21 V per cell

Practical Specific Energy Density
~ 20 Wh/L

Crossover, Air oxidation, pH,
plating

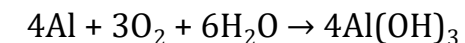
<https://essinc.com/iron-flow-chemistry/>

Al-air (& Zn-air)



Phinergy launches its new automated
production line, capacity will reach up
to 10,000 backup systems per year

Pure Al corroded by Electrolyte,
\$\$ catalyst, recharge ?
Forms Alumina Hydroxide ,
later re-processed



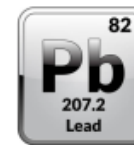
OCV = 1.2 V per cell; ~ 0.7 V in saltwater

Practical Specific Energy Density
~ 1300 Wh/kg

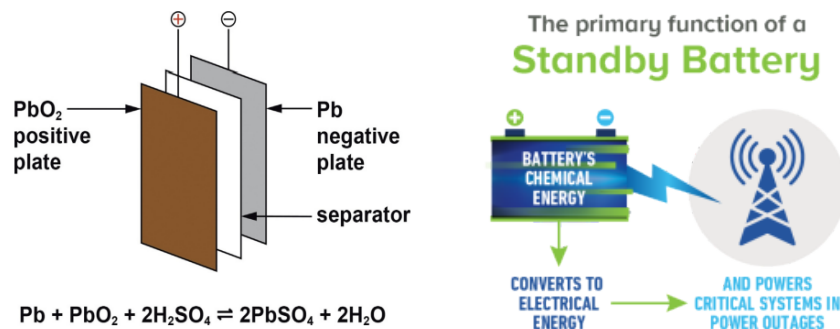
Earth Abundant Multi-valent
Materials for Energy Storage
Stephen Percival, SNL

<https://phinergy.com/>

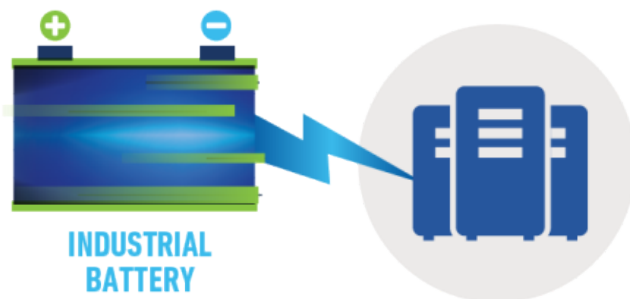
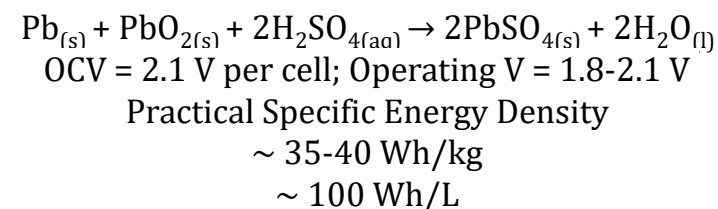
Rechargeable Pb-based Batteries



- First invented in 1859, large industry - (Provide about 45% of the world's rechargeable power)*
\$52.1 billion in 2022
- Large-format lead-acid designs are widely used for storage in backup power supplies in cell phone towers, high-availability emergency power systems like hospitals, and stand-alone power systems



Installed 2012, Lead-based Ultra-battery used for frequency regulation at Lyon Station, Pennsylvania
3.6 MW power capability



*<https://battery council.org/>

Successful recycling program

Improve energy density, low temperature performance, cycle life, charging efficiency, rates

Material Design to Enable Pb Acid Batteries for Long Duration Energy Storage Tim Fister, ANL

Storage Innovations 2030 – Technology Strategy Assessments

Storage Innovations 2030 (SI 2030) goal is a program that helps the Department of Energy to meet Long-Duration Storage Shot targets.

These targets are to achieve 90% cost reductions by 2030 for technologies that provide 10 hours or longer of energy storage.

On July 19, 2023, DOE released a series of technical reports summarizing and analyzing the results from the SI 2030 stakeholder engagement process, including SI Flight Paths and SI Framework, as detailed in the Methodology report. These reports are opportunities to explore promising RD&D pathways to substantially lower the costs of long-duration energy storage.

Released July 19, 2023, DOE

- [Methodology Report](#)
- [Lithium-ion Batteries Technology Strategy Assessment](#)
- [Lead-acid Batteries Technology Strategy Assessment](#)
- [Flow Batteries Technology Strategy Assessment](#)
- [Zinc Batteries Technology Strategy Assessment](#)
- [Sodium Batteries Technology Strategy Assessment](#)
- [Pumped Storage Hydropower Technology Strategy Assessment](#)
- [Compressed-Air Energy Storage Technology Strategy Assessment](#)
- [Thermal Energy Storage Technology Strategy Assessment](#)
- [Supercapacitors Technology Strategy Assessment](#)
- [Hydrogen Storage Technology Strategy Assessment](#)



Precompetitive Energy Storage Technology Liftoff

FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT



Department of Energy (DOE)
Office of Electricity (OE)

STORAGE INNOVATIONS 2030: TECHNOLOGY LIFTOFF
Funding Opportunity Announcement (FOA) Number: DE-FOA-0003020
FOA Type: Initial
Assistance Listing Number: 81.122 Electricity Research Development and Analysis

FOA Issue Date:	July 25, 2023
Submission Deadline for Concept Papers:	September 15, 2023 8PM ET*
Submission Deadline for Full Applications:	December 4, 2023 8PM ET*
Expected Date for Concept Paper Notifications:	October 06, 2023
Expected Date for Selection Notifications:	January 31, 2024
Expected Date for Award:	April 05, 2024

*Applicants who do not submit a concept paper cannot submit a Full Application.

Registration Requirements

There are several one-time actions that must be completed before submitting an application in response to this Funding Opportunity Announcement (FOA) (e.g., register with the System for Award Management (SAM), obtain a Unique Entity Identifier (UEI) number, register with Grants.gov, and register with FedConnect.net to submit questions). It is vital that applicants

Energy Storage Demonstration and Validation

FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT



Department of Energy (DOE)
Office of Electricity (OE)

Energy Storage Demonstration and Validation

Funding Opportunity Announcement (FOA) Number: DE-FOA-0003036
FOA Type: Initial
Assistance Listing Number: 81.122 Electricity Research Development and Analysis

FOA Issue Date:	7/25/2023
Submission Deadline for Concept Papers:	9/15/2023 8PM ET
Submission Deadline for Full Applications:	12/4/2023 8PM ET
Expected Date for Concept Paper Notifications:	10/10/2023
Expected Date for Selection Notifications:	01/20/2024
Expected Date for Award:	02/20/2024

*Applicants who do not submit a concept paper cannot submit a Full Application.

Registration Requirements

There are several one-time actions that must be completed before submitting an application in response to this Funding Opportunity Announcement (FOA) (e.g., register with the System for Award Management (SAM), obtain a Unique Entity Identifier (UEI) number, register with

Technology Liftoff: LDES: Pathways to LCOS of \$0.05/kWh



ESGC: To enable long-duration energy storage technologies through durable research partnerships

Selections Announced April 8, 2024

“Pre-competitive R&D” includes activities that are of interest to multiple or all entities in the partnership. Such activities should propel an entire technology industry forward, and the outputs of this work should provide value to all participating members of the partnership.

DE-FOA-0003020

Storage Innovations 2030: Technology Liftoff FOA Awards

DOE Awards \$15M to Launch Long Duration Energy Storage Innovations

The following projects have been selected:

• **Newlab, LLC**

- Project Title: *Enabling high-capacity **Zinc** utilization through electrode and electrolyte fundamentals*
- Federal share: \$4,992,570

• **Battery Council International**

- Project Title: *Consortium for **Lead** Battery Leadership in LDES*
- Federal share: \$4,972,746

• **Clean Tech Strategies LLC**

- Project title: *Pre-Competitive Research & Development to Accelerate the Maturation of **Flow Battery Technologies** into Cost-Effective Long Duration Energy Storage*
- Federal share: \$5,000,000

POSTERS – Zinc & Lead Batteries



*OE supports RESEARCH&DEVELOPMENT needs of battery chemistries that can impact
Grid Storage: Reliable and resilient electricity system*

Stabilizing Zn Anodes by Molecular Interface Engineering with Amphiphilic Triblock Copolymer

Xingbo Li, WVU

Mapping electrode and acid speciation in lead batteries using powder X-ray diffraction

Tiffany Kinnibrugh, ANL

Interrogation of Pb-acid battery performance using ultrasonic techniques

Tim Officer, UC

Investigation of Calcium Zincate ($\text{Ca}[\text{Zn}(\text{OH})_3]_2 \cdot 2\text{H}_2\text{O}$) Cycling Performance
for Rechargeable Alkaline Zinc Batteries

Patrick Yang, CCNY

Sr-doped barites for enhanced nucleation in lead-acid batteries

Colin Campbell, PNNL

Zn-Air Batteries for Long-Duration Energy Storage

Ruhul Amin, ORNL

Inhibiting the Formation of Zinc Hydroxy Sulfate for High-Performance Aqueous Zn Batteries
by stabilizing the pH of electrolyte

Wonkwang Lim, PNNL

Flowing Zinc-Air Batteries Enabled by Nickel Sulfoselenide Oxygen Electrocatalysts

Bryan Wygant, SNL

Electrochemical Cycling of Zinc in Mildly Acidic, Acetate-Based Electrolytes for Zinc-ion
Batteries

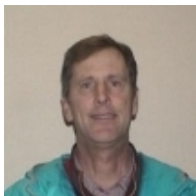
Debayon Dutta, CCNY

PROJECT CONTACTS



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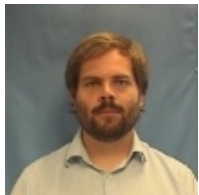
Tim Lambert



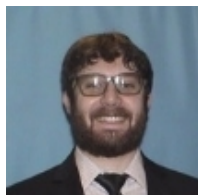
Ray Byrne
rhbyrne@sandia.gov

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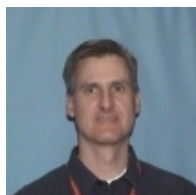
Sandia Team



Bryan Wygant



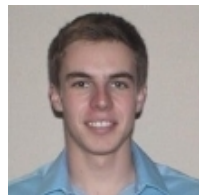
Noah Schorr



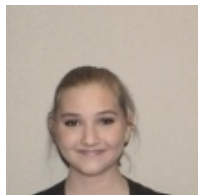
Nelson Bell



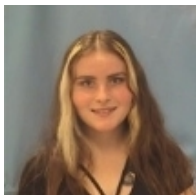
Erik Spoerke



David Arnot



Rachel Habing



Ciara Wright

ACKNOWLEDGEMENTS



This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division



AND
OUR MANY COLLABORATORS!



Session OVERVIEW – Zinc & Lead Batteries



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Grid Storage: Reliable and resilient electricity system*

- | | | |
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| 11:20 - 11:35 AM | Progress with Manufacturing and Deploying Zn MnO ₂ Batteries for Grid-Scale Applications | Gautam Yadav, Urban Electric Power |



Thank. you

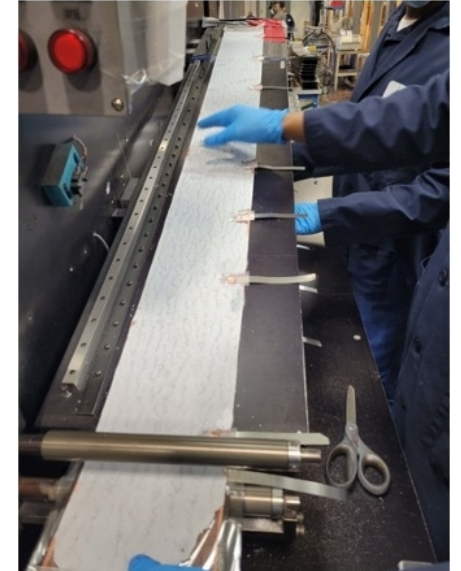
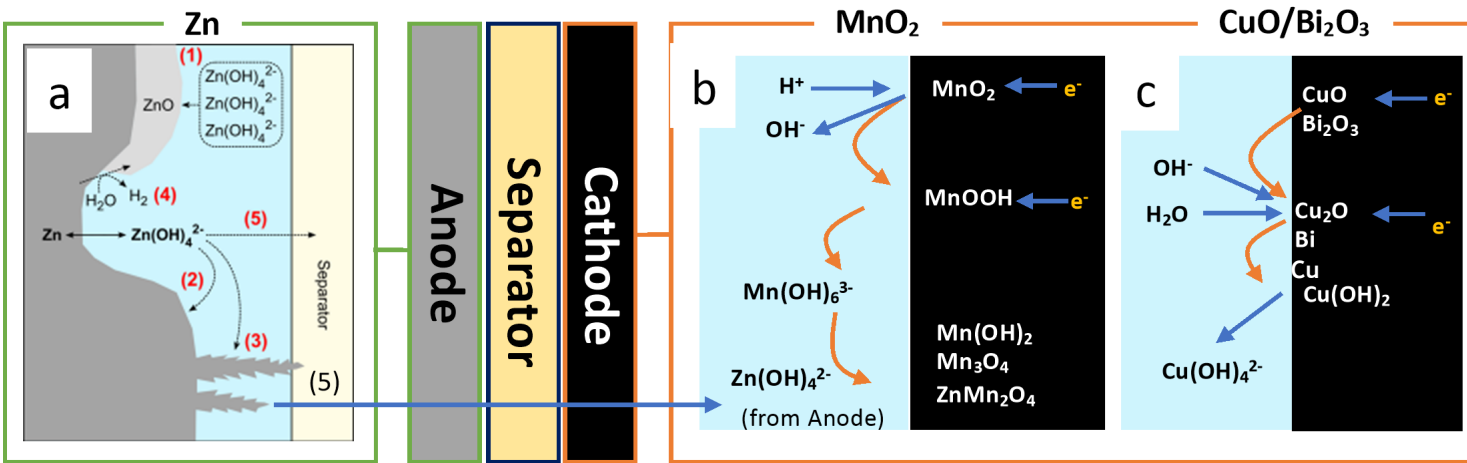
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DOE OE: Low Cost Aqueous Batteries based on Zinc



Program Objective: Develop the understanding, materials, methods, components & technologies to enable low cost Zn-based batteries for grid and long duration energy storage

- Zinc-based batteries offer an energy dense, safe and readily manufacturable technology
- OE Funded Project collaboratively investigates new materials and chemistries while supporting technology maturation and US manufacturing
- Zn/(1e-)MnO₂, Zn/(2e-)Bi,Cu-MnO₂, Zn/(2e-)Bi-CuO, Zn/Ni, Zn/air, Zn-ion.



Adapted from "A Critical Comparison of Mildly Acidic versus Alkaline Zinc Batteries"
Acc. Mater. Res. 2023 4, 4, 299-306.

Photos provided by UEP



Sandia
National
Laboratories



U.S. DEPARTMENT OF
ENERGY

OE program focuses on increased understanding/performance at lower cost and increased safety

Zn Project Team – Sandia National Laboratories and Collaborators



Sandia
National
Laboratories



Timothy Lambert

Alkaline Batteries for Grid Storage



The City
University
of New York



Prof. Sanjoy Banerjee

Energy Institute

Stephen Budy, Matthew Lim, Igor Kolesnichenko, Noah Schorr, David Arnot, Rachel Habing, Logan Ricketts, Elijah Ruiz, Nelson Bell, Ciara Wright, Bryan Wygant

Damon Turney, Michael D'Ambrose, Junsang Cho, Brendan Hawkins, Snehal Kolhekar, Michael Nyce, Xia Wei, Prof. Rob Messinger

Stable Zinc Anodes for High-Energy-Density Rechargeable Aqueous Batteries



Prof. Igor Vasiliev

Birendra A. Magar, Nirajan Paudel

Theoretical Studies of the Electrochemical Behavior of Solid-State Cathode Materials



Prof. Joshua Gallaway

Andrea Bruck, Matthew Kim, Erik Zimmerer, Yogeshwaran Agilan



Prof. Yang-Tse (YT) Cheng

Ryan Hill, Andrew Meyer

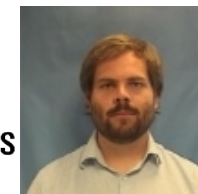


Prof. Nian Liu

Zn-ion Batteries



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Bryan Wygant

Collaborative research to advance solid state ion conductors for emerging batteries [w/Erik Spoerke (SNL)]



Stony Brook
University



Prof. Esther Takeuchi

Amy Marschilok, Ken Takeuchi

Advanced Materials for Next Generation Batteries



Gabe Cowles



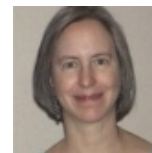
Gautam Yadav

Gabe Cowles, Gautam Yadav, Jinchao Huang, Aditya Upreti, Meir Weiner, Sanjoy Banerjee

Membrane Modeling



Sandia
National
Laboratories



Amalie Frischknecht

Advanced Manufacturing Research



Lawrence Livermore
National Laboratory



Cheng Zhu

3D electrodes for rechargeable Zn-MnO₂ batteries

Tony Van Buuren

Zn-air