Progress in the Development and Deployment of Zinc Manganese Dioxide Batteries

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Objective and Topics

Discuss developments and deployments of energy storage systems powered by zinc manganese dioxide batteries and lessons learned

Main Topics

01 Rechargeable zinc manganese batteries as a low-cost option for decarbonizing the grid

02 Zinc-manganese dioxide developments —
   • Improving active materials utilization for proton insertion (Gen 1) cells
   • Cost reductions related to “conversion reaction” two-electron (Gen 2) cells

03 Manufacturing, supply chain and path to scale up.

04 Deployment of Zn-MnO₂ stationary energy storage systems: lessons learned
Energy storage for a renewables based decarbonized grid: an example

- Peak energy generation does not necessarily align with peak energy consumption on a renewable powered grid.
- Estimating about 30% of renewable energy generated needs to be stored for a renewable powered electricity grid.
- The US will need 4 quads/year (~900 TWh/year) of energy storage to meet 2050 GHG emissions targets.
Why Zinc Batteries?
How much material is theoretically needed to store electricity produced by Niagara Falls in a day?

Niagara Falls: 60,000 MWh/day

<table>
<thead>
<tr>
<th></th>
<th>Anode (*)</th>
<th>Cost $M</th>
<th>GHG Produced Mt CO₂</th>
<th>Volume (m³)</th>
<th>Mass (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>93</td>
<td>1.5</td>
<td>6,200</td>
<td>44,000</td>
<td></td>
</tr>
<tr>
<td>Lithium</td>
<td>370</td>
<td>6</td>
<td>10,200</td>
<td>5,300</td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>230</td>
<td>4</td>
<td>12,000</td>
<td>120,000</td>
<td></td>
</tr>
</tbody>
</table>

(*) Based on the anode theoretical capacity against a hypothetical air cathode
### Robust Existing Zinc Battery Supply Chain

**Zinc Production**

<table>
<thead>
<tr>
<th>Location</th>
<th>Mine</th>
<th>Thousand Tons/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tlemcen, Algeria</td>
<td>Ghazaouet Mine</td>
<td>869</td>
</tr>
<tr>
<td>Alaska, United States</td>
<td>Red Dog Mine</td>
<td>491</td>
</tr>
<tr>
<td>Rajasthan, India</td>
<td>Rampura Agucha Mine</td>
<td>369</td>
</tr>
</tbody>
</table>

**Manganese Production**

<table>
<thead>
<tr>
<th>Location</th>
<th>Metric Tons/Year Manganese</th>
<th>Reserves MT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mexico</td>
<td>225.7 thousand</td>
<td>1.5 million</td>
</tr>
<tr>
<td>Canada</td>
<td>2 thousand</td>
<td>9 million</td>
</tr>
<tr>
<td>India</td>
<td>2.8 million</td>
<td>52 million</td>
</tr>
<tr>
<td>South Africa</td>
<td>5.2 million</td>
<td>360 million</td>
</tr>
<tr>
<td>Australia</td>
<td>3.3 million</td>
<td>91 million</td>
</tr>
<tr>
<td>Gabon</td>
<td>2.8 million</td>
<td>250 million</td>
</tr>
</tbody>
</table>

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**Global Battery Sales**

Zinc and manganese dioxide have established supply chains to meet demands of $13Bn/year of Zn0MnO2 alkaline (primary) cells.

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[Links]
- [Zinc Production](https://www.statista.com/statistics/751255/mexico-manganese-production/#:~:text=Mexico's%20manganese%20mine%20production%20amounted%2C%20236%20thousand%20metric%20tons%20produced)
- [Manganese Production](https://novascotia.ca/natr/meb/data/pubs/74egs01/74egs01_Chapter01.pdf)
Rechargeable Zinc-Manganese Dioxide Battery Chemistry:

### Gen 1: Proton Insertion Battery

- **Anode (Negative Electrode):** Zn
- **Cathode (Positive Electrode):** Mn
- **KOH Alkaline Electrolyte Solution**
- **Utilization:** 10-20%

- Analogous to the Li-ion intercalation chemistry.
- Rechargeable utilization till 70% of proton insertion chemistry.
- Inactive spinel formation beyond 70% utilizations.

### Gen 2: Conversion Battery

- **Anode (Negative Electrode):** Zn
- **Cathode (Positive Electrode):** Mn
- **Utilization:** 70-100%

- Analogous to the Li-ion’s Silicon conversion anodes that promise higher energy density.
- UEP’s conversion battery can access energy densities comparable to Li-ion.
An Evolution in Zn-MnO2 Alkaline Cells:
From Primary to UEP’s Rechargeable Cell

- The CUNY Energy Institute and its spinout, Urban Electric Power (UEP), develop rechargeable Zn-MnO2 alkaline cells.

- Evolves the familiar alkaline battery (e.g., double AA) into a rechargeable Zn-MnO2 alkaline battery to enable decarbonization goals.

Zinc Manganese Dioxide

(Zn-MnO₂)

- Alkaline batteries are recyclable and non-toxic.

- UL 1973/9540A safety certification confirms no fire risk.

- Modular solution utilized from residential to grid.
Safety

Certifications of UEP’s Rechargeable Zinc-Manganese Batteries

- UL 9540A testing demonstrated UEP batteries do not reach thermal runaway when subjected to abuse tests
- Abuse testing performed by DNV-GL produced similar results and determined that “Unlike lithium-ion batteries, UEP’s cell is essentially nonflammable”
- FDNY Certificate of Approval and CE marking efforts currently in process

<table>
<thead>
<tr>
<th>Test</th>
<th>Test Method</th>
<th>Thermal Runaway Time</th>
<th>Thermal Runaway Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Film Heater</td>
<td>Not observed</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Pipe Heater</td>
<td>Not observed</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>Nail Penetration</td>
<td>Not observed</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>Overcharge</td>
<td>Not observed</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>Overdischarge</td>
<td>Not observed</td>
<td>N/A</td>
</tr>
</tbody>
</table>

UEP Zn-MnO2 batteries after 9540A testing (above) and temperature data captured during the test (below).
Development Stages For Zn-MnO$_2$ Batteries

**Gen 1**  
Battery 1 and 2  
Proton Insertion Battery

- Analogous to the Li-ion intercalation chemistry.
- Rechargeable utilization till 70% of proton insertion chemistry.
- Inactive spinel formation beyond 70% utilizations.

**Gen 2**  
Battery 3  
Conversion Battery

- Analogous to the Li-ion’s Silicon conversion anodes that promise higher energy density.
- UEP’s conversion battery can access energy densities comparable to Li-ion.

**Gen 2+**  
Battery 4  
The Li-ion Competitor  
High Voltage 2.45-2.8V Zn-MnO$_2$

- Breakthrough accessibility in >2.4-2.8V & 100% utilization of 308mAh/g of MnO$_2$ allows higher energy density than Li-ion.
Product Roadmap: UEP Zn-MnO2 Gen 1 Cell Development

**Current Gen 1 Cell**

- **Current Cost**
  - UEP-Pilot Scale: BOM: $150/kWh

- **Intermediate Cost**
  - Indian Plant Scale: BOM: $100/kWh

- **Target Cost**
  - Indian Plant Scale: BOM: $40/kWh

**Trajectory: Gen 1 Cell Cost Reduction and Energy Density Improvement**

- **2022**
  - Current UEP Pilot: $150/kWh, 114 Wh/L
  - Indian Plant Scale: December 2022: $100/kWh, 195 Wh/L

- **December 2022**
  - Intermediate Target 1: March 2023: $70/kWh, Reduced Inactive Materials Cost
  - Intermediate Target 2: July 2023: $60/kWh, Double Active Material Utilization in Anode

- **December 2023**
  - Final target – Indian Plant Scale: December 2023: $40/kWh, Double Active Material Utilization in Cathode

* All costs based on solar microgrid application with 5-year warranty conforming to IEC Solar Standard 61427-1. The standard simulates daily cycling in microgrids under representative varying solar insolation conditions. By ‘Indian Plant Scale’ is meant a plant being built in India for completion by end 2022.
Gen 1 Battery 1: Comparison to Pb acid batteries

Zinc Manganese Dioxide compared to Lead Acid

UEP Cell Self-Discharge Performance
UEP Zn-MnO2 Gen 1 battery 1 tests: Solar Microgrid Protocol

UEP Battery cell 70 Ah nameplate capacity, completed 5 years and still running under IEC 61427-1 testing protocol, defined below, for solar microgrid use case.

Phase A: 3h C/10 charge and 3h C/10 discharge cycling at low state of charge for 50 cycles.
Phase B: 6h charge and 2h C/8 discharge cycling at high state of charge for 100 cycles.
A 9-hour C/10 discharge is done between phases B and A at the end of each year.

UEP Gen 1 shows an energy retention above 80% of its nameplate after 7 years of service life.
Gen 1 Battery 2 Progress

- Developed improved Zn anodes with 20% utilization >600 cycles
- Developed improved MnO2 cathodes with 40% utilization >250 cycles
- Developed cheaper current collectors to reduce overall cost

Performance of improved electrodes manufactured on the line
Scaling up laboratory made improved electrodes to the manufacturing side
Product Roadmap: UEP Zn-MnO₂ Gen 2 Cell Development

**Current Gen 2 Cell**

- **Current Cost**
  - UEP-Pilot Scale: BOM: $190/kWh
- **Intermediate Cost**
  - Indian Plant Scale: BOM: $90/kWh
- **Target Cost**
  - Indian Plant Scale: BOM: $27/kWh

**Trajectory: Gen 2 Cell Cost Reduction and Energy Density Improvement**

- **BOM ($/kWh):**
  - $190/kWh
  - $90/kWh
  - $60/kWh
  - $40/kWh
  - $27/kWh
- **Energy Density (Wh/L):**
  - 80 Wh/L
  - 60 Wh/L
  - 40 Wh/L
  - 270 Wh/L

*All costs based on solar microgrid application with 10-year warranty conforming to IEC Solar Standard 61427-1. The standard simulates daily cycling in microgrids under representative varying solar insolation conditions.*
Gen 2 Battery 3 Progress

Prismatic Battery 3 cathodes cross >2000 cycles

Translating Prismatic Performance to Cylindrical Form Factor (6.5Ah)

Scaling Cylindrical Cell to 16Ah
Current Manufacturing: Rechargeable aqueous Zn/MnO2 batteries

UEP has submitted to the US Dept of Energy for $50M in funding for a total $150M investment to scale a GWh scale factory potentially in Houston, Texas.

30 MWh pilot manufacturing plant in Pearl River, New York.

100 MWh manufacturing plant in Mumbai, India.
Manufacturing

UEP’s Rechargeable Zn-MnO2 Battery Manufacturing Process: Concept to Product
UEP is submitting to the US Dept of Energy for $50M in funding for a total $150M investment to scale a GWh scale factory in America. Of the $150M, $75M will be capital equipment expenditures.

- Integrated Electrode Tabs
- High Speed Coating (Pasting)
- High Speed Winding
- 43% reduced water consumption per cell per year
ZAPP Proposed Layout in DAC Facility
Identified potentially in Houston, TX.
## Ongoing and Recently Completed Gen 1 System Deployments

<table>
<thead>
<tr>
<th>Project</th>
<th>Use Case</th>
<th>Timeline</th>
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</thead>
<tbody>
<tr>
<td>Electrical Power Research Institute</td>
<td>40 kWh scalable utility modules for demand response and renewables</td>
<td>2021</td>
</tr>
<tr>
<td>San Diego Supercomputer Center backup</td>
<td>1MW / 2 MWh High-Rate UPS</td>
<td>½ - 2021</td>
</tr>
<tr>
<td>(San Diego, California)</td>
<td></td>
<td>½ - Quarter 4, 2022</td>
</tr>
<tr>
<td>Five Spoke Creamery Power Backup System</td>
<td>200 kWh Long Duration UPS</td>
<td>2021</td>
</tr>
<tr>
<td>(New York)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Navajo Nation Microgrid</td>
<td>Multiple 10 KW Solar Microgrids</td>
<td>2021</td>
</tr>
<tr>
<td>(New Mexico)</td>
<td></td>
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<tr>
<td>CCNY Grid Modernization Center</td>
<td>1 MWh Grid Storage (demand response / demand charge)</td>
<td>Quarter 4, 2022</td>
</tr>
<tr>
<td>(Manhattan, New York)</td>
<td>Solar Microgrid</td>
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</tr>
<tr>
<td></td>
<td>High-Rate UPS</td>
<td></td>
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<tr>
<td>BMCC Energy Storage System</td>
<td>200kWh Grid Storage (demand response / demand charge)</td>
<td>Quarter 2, 2022</td>
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<tr>
<td>(Manhattan, New York)</td>
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</table>
Installation Highlights:
Backup System for the San Diego Supercomputer Center (SDSC)

- At the 15-min cutoff, which is the max backup time that the lead acid batteries can provide, the voltage of the UEP system is about 453 V, well above the 380 V inverter limit.
Navajo Tribal Utility Authority (NTUA) Solar Microgrid

Data on Cycling at -4°C (performed by Sandia)

- 13 kWh solar microgrid system deployed in Q1 2021
- System uses a standard Outback inverter and seats on a self-contained pod
Ongoing Project: CCNY Grid Modernization Center

Mitsubishi: 100kW/400kWh UPS unit
- Short and long duration emergency UPS
- 100 kW of demand response

Vertiv Inverter
- 100 kW of demand response peak shaving

UEP 4D Commercial Battery Rack
- 6 Racks in C11
- 10 Racks in C12

(3) Ideal Power 30 kW
UEP modules were tested under a protocol simulating a real utility-scale 10 MW BESS.

- Each module was tested at 1,000 W nameplate. 10,000 module (100,000 cells) will be needed for a 10MW system.
- Under this protocol, the module has a coulombic efficiency of ~93% and energy efficiency ~82%.
- The voltage of the single cells were monitored throughout testing.
Thank you to Dr. Imre Gyuk, Director of the Energy Storage Program, Office of electricity, Department of Energy.

Thank you to the teams at CCNY, SNL, BNL, LNLL, and UEP.