Progress in Zinc Manganese Dioxide Battery Installations for Stationary Energy Storage Applications

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Objective

Deploy and evaluate performance of systems powered by zinc manganese dioxide cells for stationary energy storage applications.

Main Topics

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

02 Zinc-manganese dioxide chemistry: Proton Insertion (Gen 1 battery) and Conversion Reactions (Gen 2 battery)

03 From concept to product: The development roadmap for Generation 1 and Generation 2 batteries

04 Progress in deploying and evaluating stationary energy storage applications

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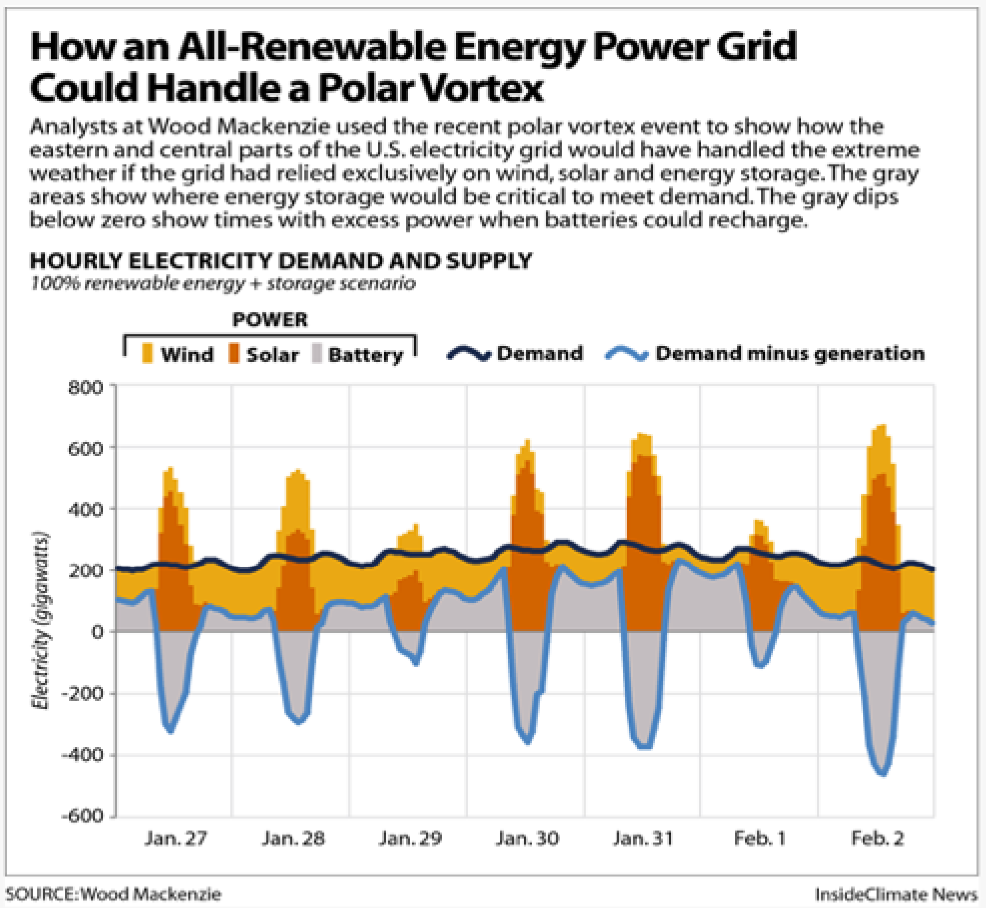
Energy storage for a renewables-based decarbonized grid: an example

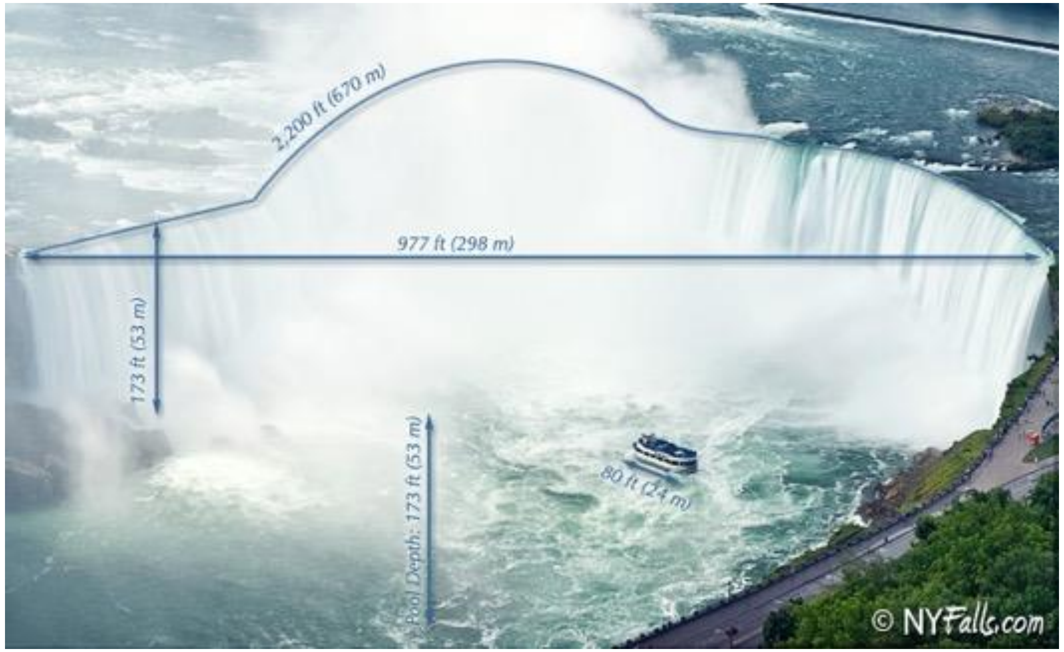
- Peak energy generation does not necessarily align with peak energy consumption on a renewable powered grid.
- Estimating about 30% of renewable energy generated needs to be stored for a renewable powered electricity grid.
- The US will need 4 quads/year (~900 TWh/year) of energy storage to meet 2050 GHG emissions targets.



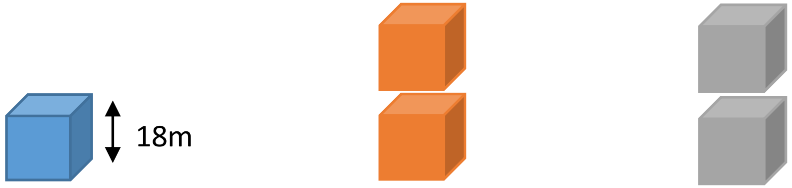
Why Zinc Batteries?

How much material is theoretically needed to store electricity produced by Niagara Falls in a day?

Niagara Falls: 60,000 MWh/day



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



Zinc Lithium Lead

(*) Based on the anode theoretical capacity against a hypothetical air cathode

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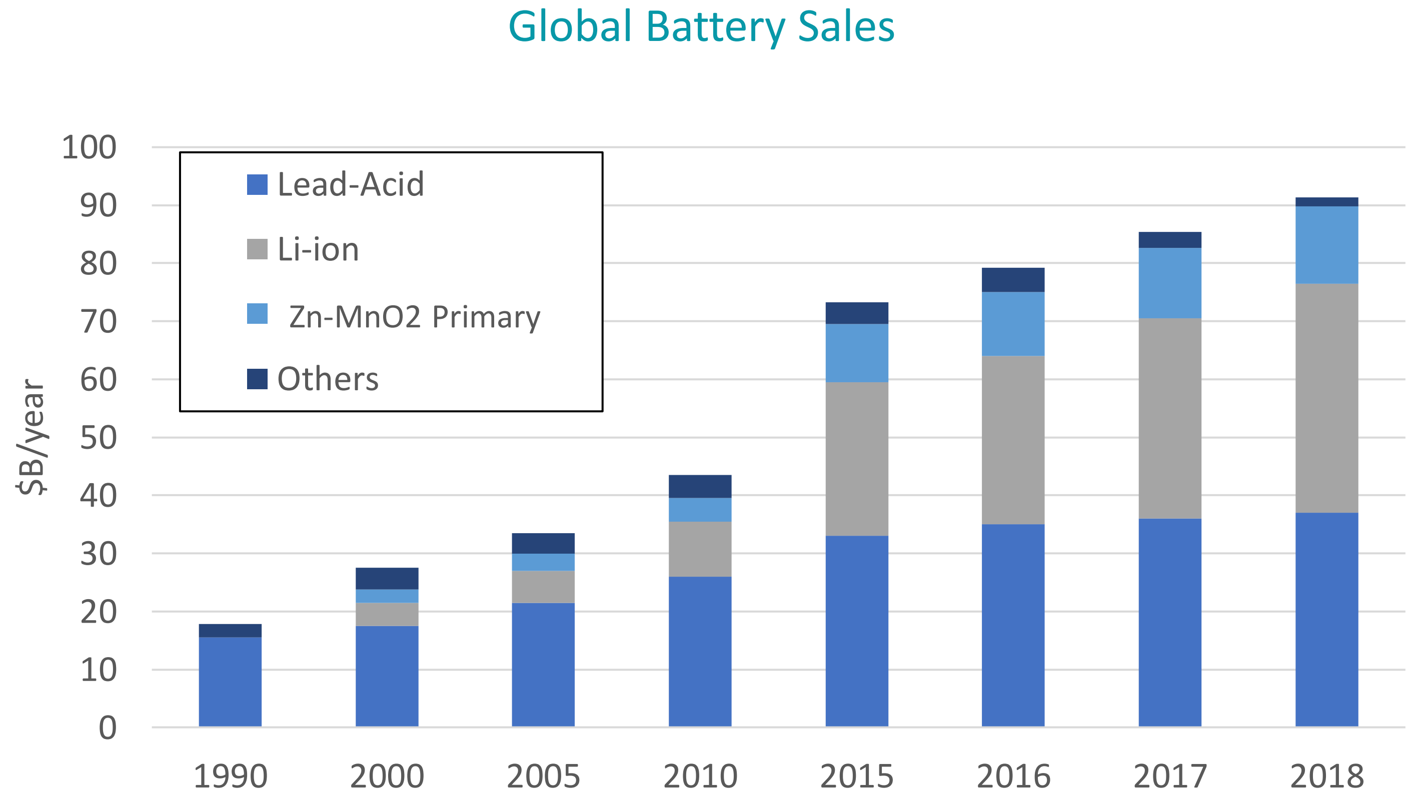
Robust Existing Zinc Battery Supply Chain



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

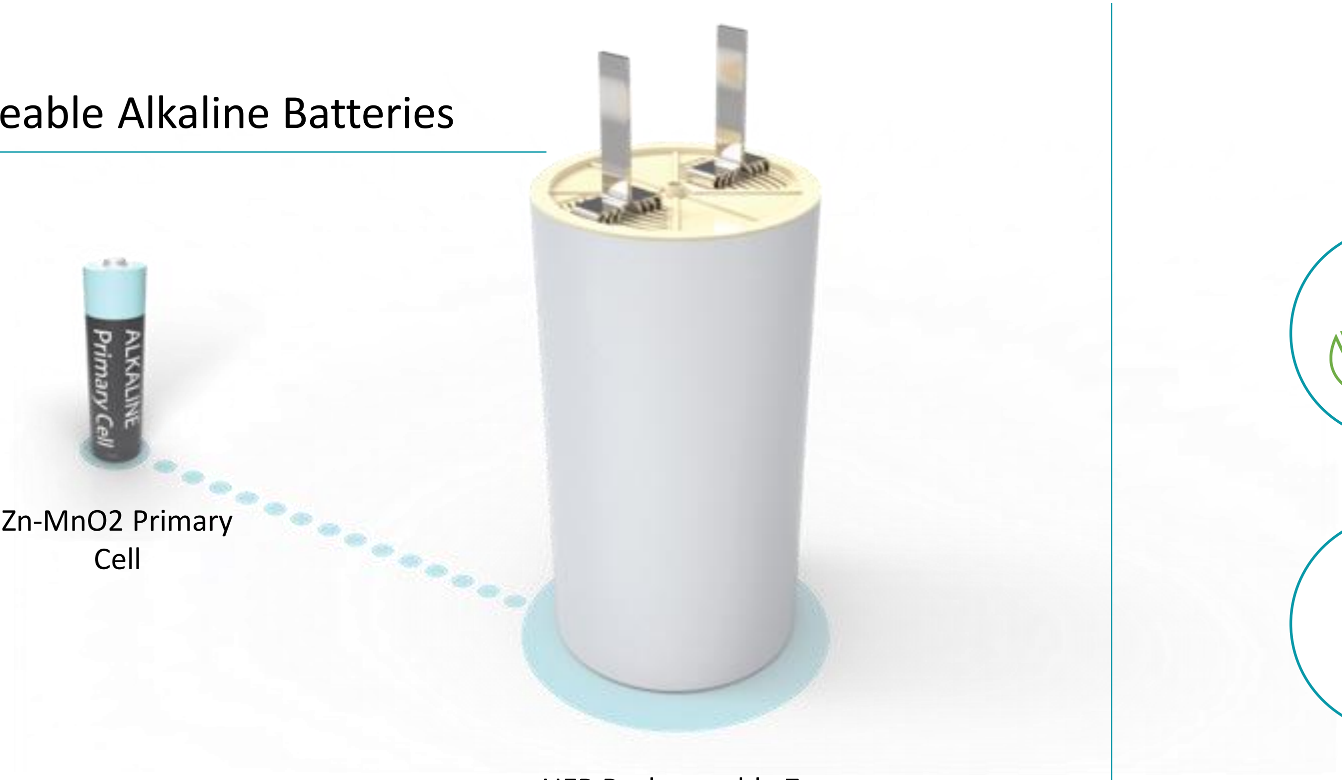
Where are we today?

- Li-ion sales ~$40B/yr growing
- Lead-Acid sales~$38B/yr stable
- Zn-MnO2 primary cell sales ~ $13B/yr growing
- Other battery sales (NiCd, NiMH, Flow batteries, NAS, …) ~$1.5B/yr decreasing

An Evolution in Zn-MnO2 Alkaline Cells:

From Primary to Rechargeable

Rechargeable Alkaline Batteries



UEP Rechargeable Zn-MnO2 Cell

- The CUNY Energy Institute and it's 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

($Zn\text{-}MnO_2$)

Alkaline batteries are recyclable and non-toxic.

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

Modular solution utilized from residential to grid.

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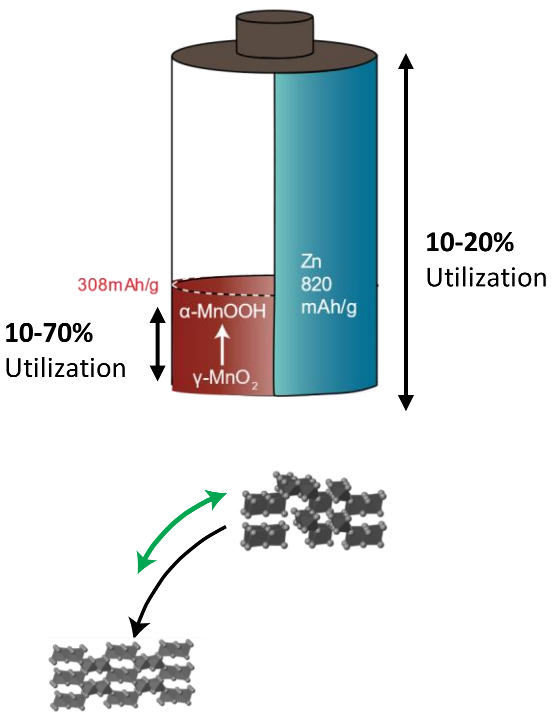
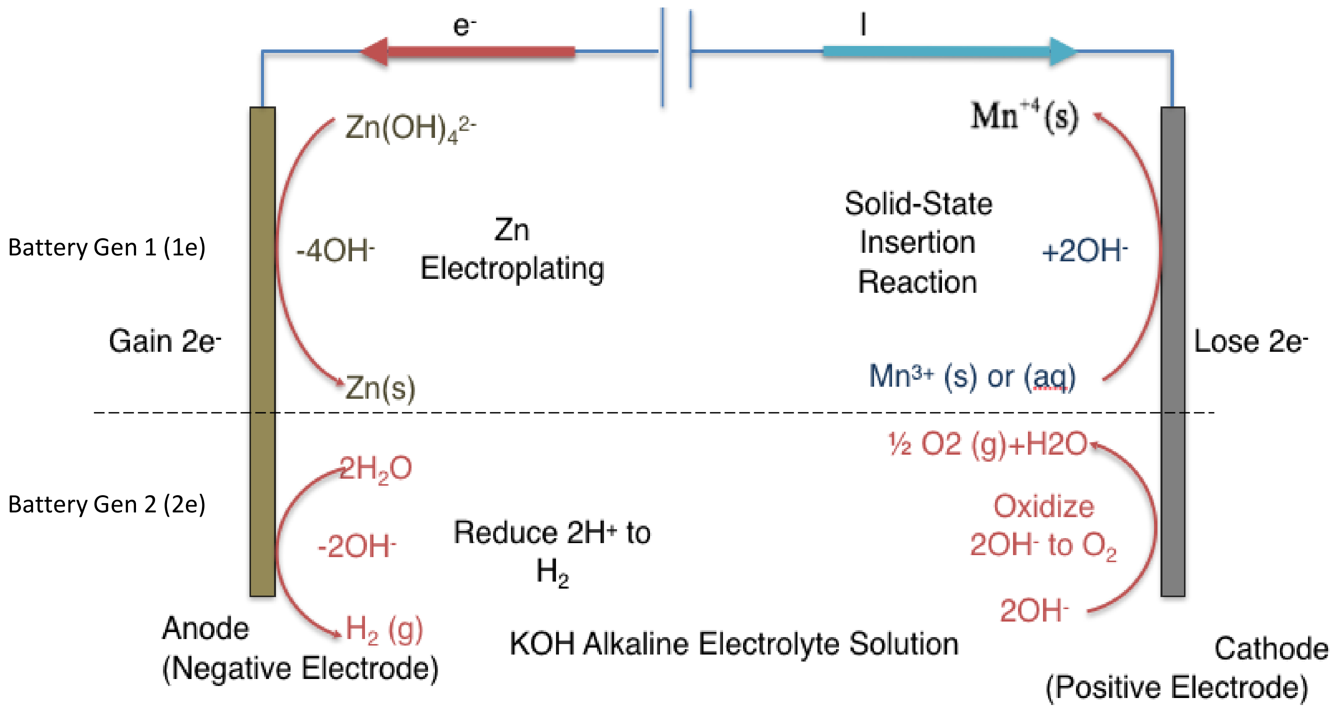
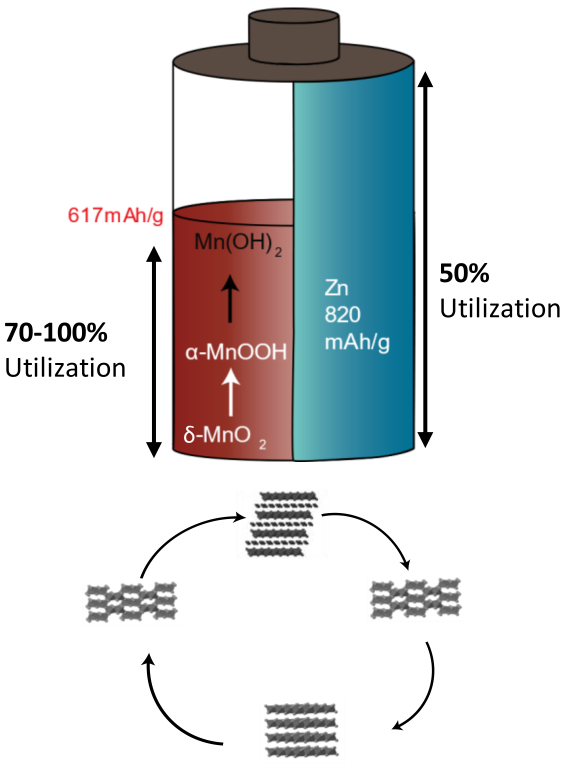
Rechargeable Zinc-Manganese Dioxide Battery Chemistry: A Review

Gen 1
Proton Insertion Battery





Gen 2
Conversion Battery



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

- 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.

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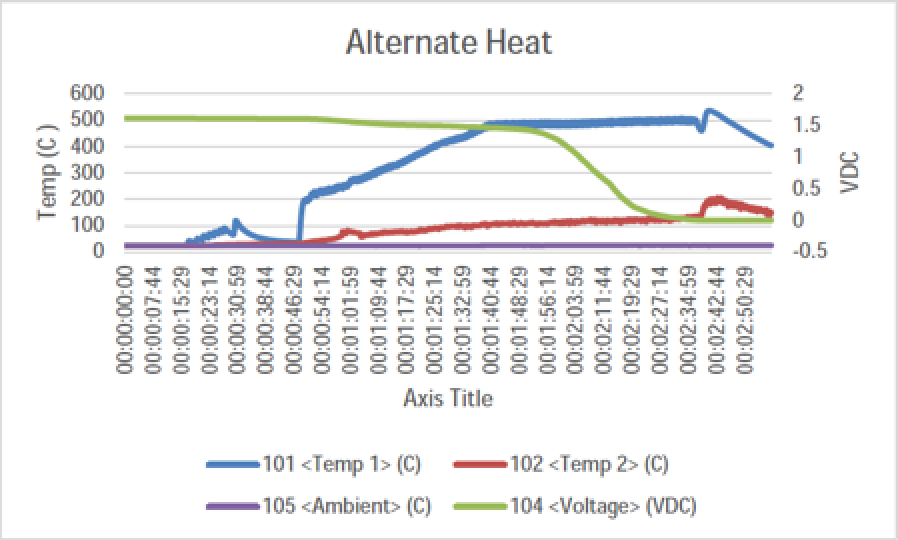
Safety Certifications of Zinc-Manganese Batteries

- 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

UEP Zn-MnO2 batteries after 9540A testing (above) and temperature data captured during the test (below).



UL 9540A Tests for Fire Hazard

Test	Test Method	Thermal Runaway Time	Thermal Runaway Time
1	Film Heater	Not observed	N/A
2	Pipe Heater	Not observed	N/A
3	Nail Penetration	Not observed	N/A
4	Overcharge	Not observed	N/A
5	Overdischarge	Not observed	N/A

Zinc – Manganese Battery Stationary Storage Applications

COMMERCIAL & INDUSTRIAL

Applications

- Distributed storage
- Peak shifting
- Critical power backup
- Demand charge reduction

Existing Customers/Partners

SDSC
SAN DIEGO SUPERCOMPUTER CENTER
CUNY
SIEMENS

RENEWABLES

Applications

- Align solar generation with demand
- Reduce solar curtailment
- Grid Support
- Regulate and smooth power quality and quantity

Existing Customers/Partners

NTUA
Sandia National Laboratories

UTILITY

Applications

- Transmission and distribution deferral
- Peaker plant reduction
- Power generation shifting

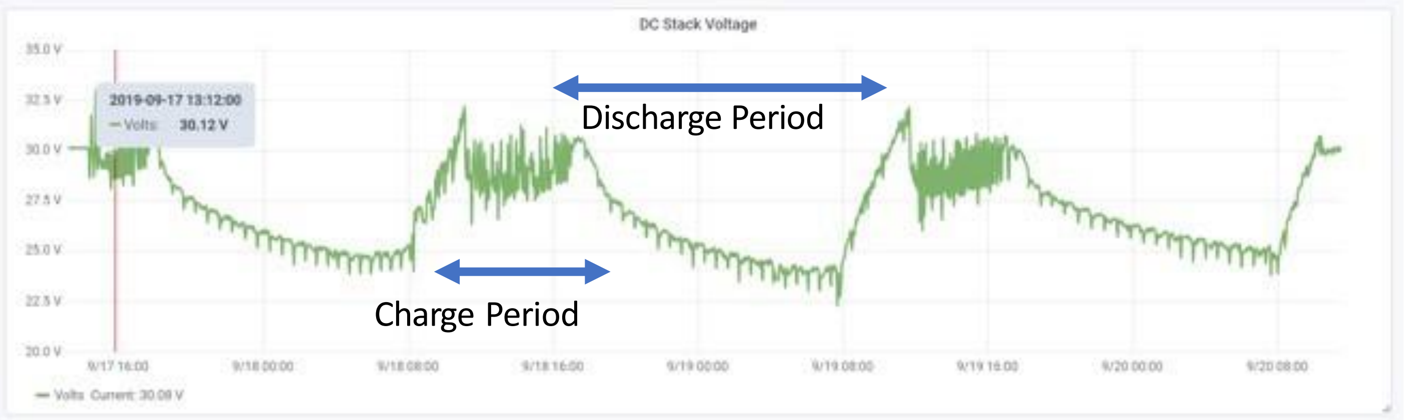
Existing Customers/Partners

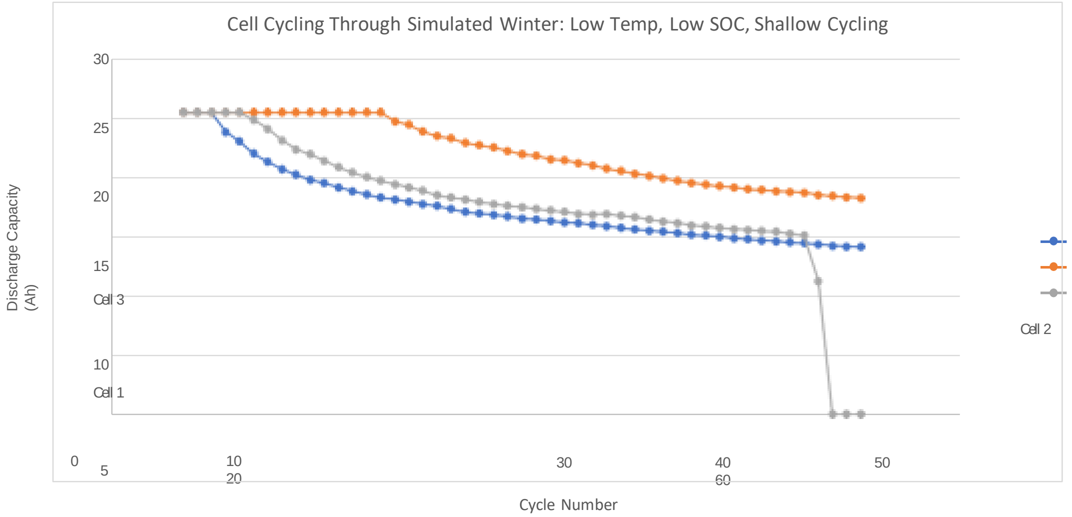
New York Power Authority
EPRI

Ongoing Project Renewables Example:
Navajo Tribal Utility Authority (NTUA) Solar Microgrid

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

- 13 kWh solar microgrid system to be deployed in October 2021
- System uses a standard Outback inverter and seats on a self-contained pod



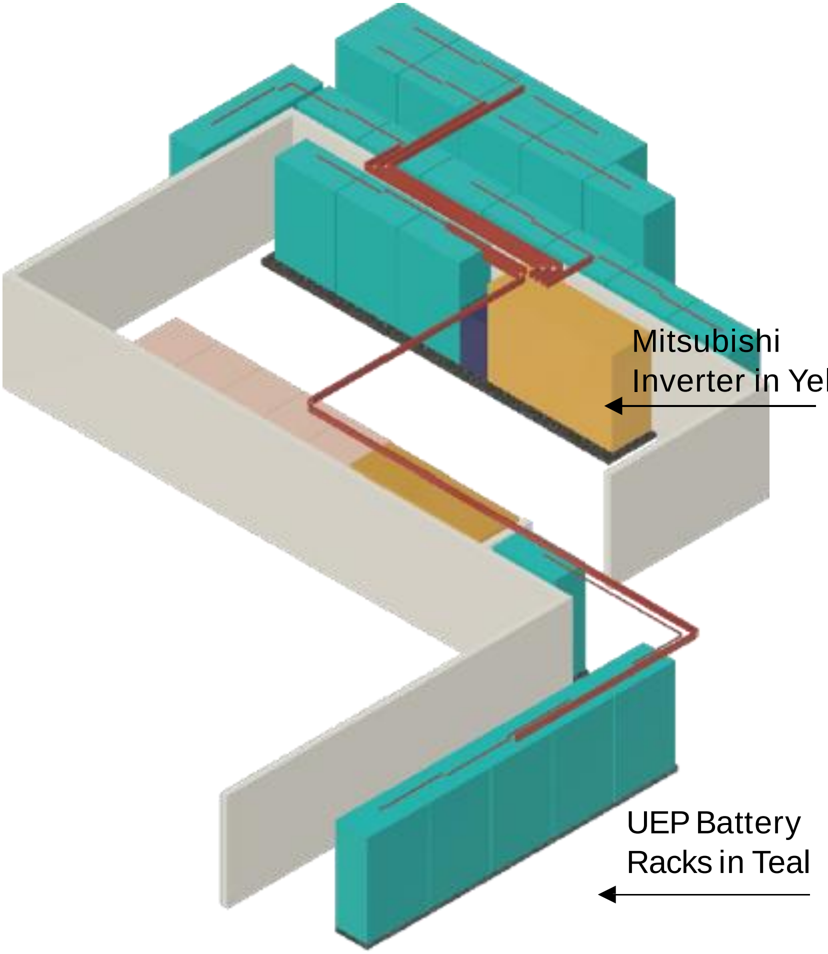


Top: System voltage test for 3 days. The system ran for 3 days paired with solar, charging when the sun was available and discharging during other times

Bottom: Cell testing at low temperature (-4°C) to simulate winter field conditions. Cells ran successfully through the testing period. Indicates value in adjusting charging protocol to compensate for temperature effects.

Ongoing Project Commercial Example:

Backup System for the San Diego Supercomputer Center (SDSC)



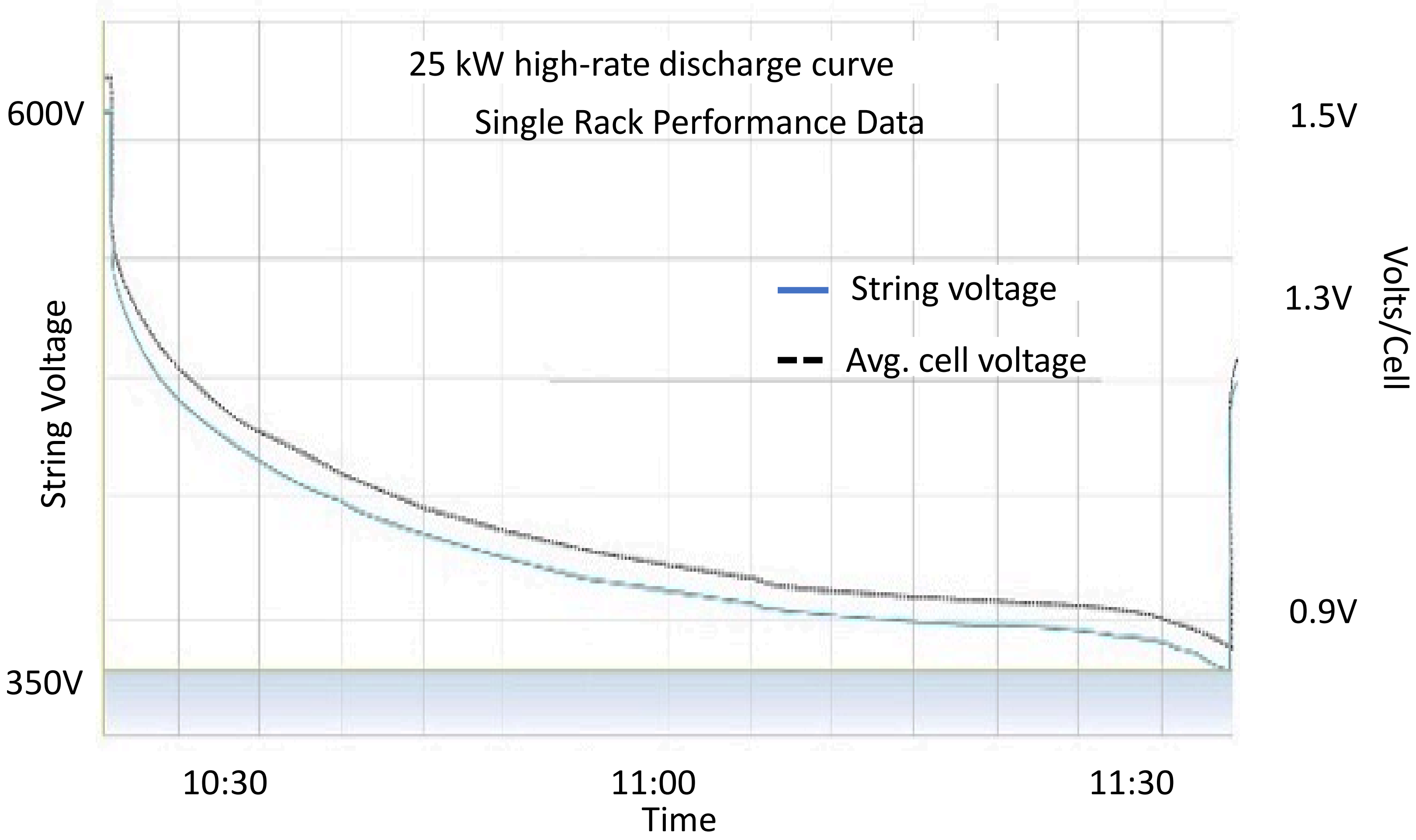
Layout for the San Diego Supercomputer Center 1MW/3MWh Backup System

- UEP received a purchase order for a 1 MW data-center UPS installation at SDSC to provide 3-hour backup
- UEP is proposing 27 standard 4D (BCI) battery racks (see Slide 11) for the installation.
- For comparison, the VRLA lead acid system currently installed would require 60 racks and twice the cost for the same duration as Urban Electric Power.

Ongoing Project Commercial Example:

Power Backup/UPS for the San Diego Supercomputer Center

- Testing of a constituent rack for the SDSC UPS/backup system.
- 26 such racks in parallel will provide 90 minutes of power backup.



The 400 cell strings in each rack behave similarly to single cells in their discharge characteristics.

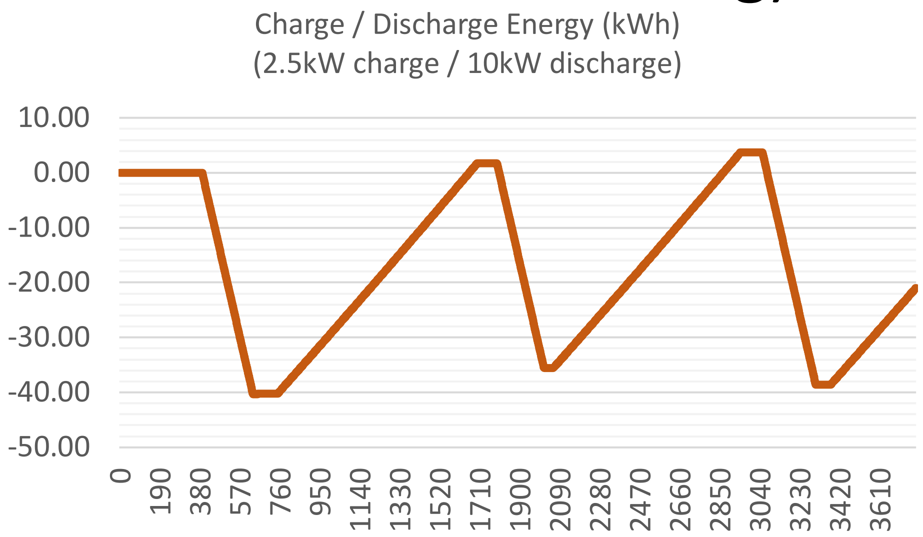
Ongoing Project Utility Scale:

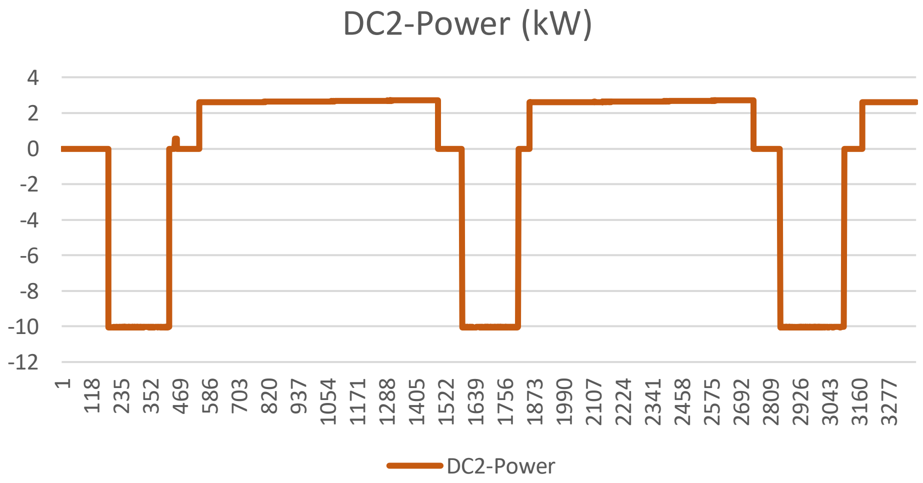
Electrical Power Research Institute

EPRI Test System Specifications –

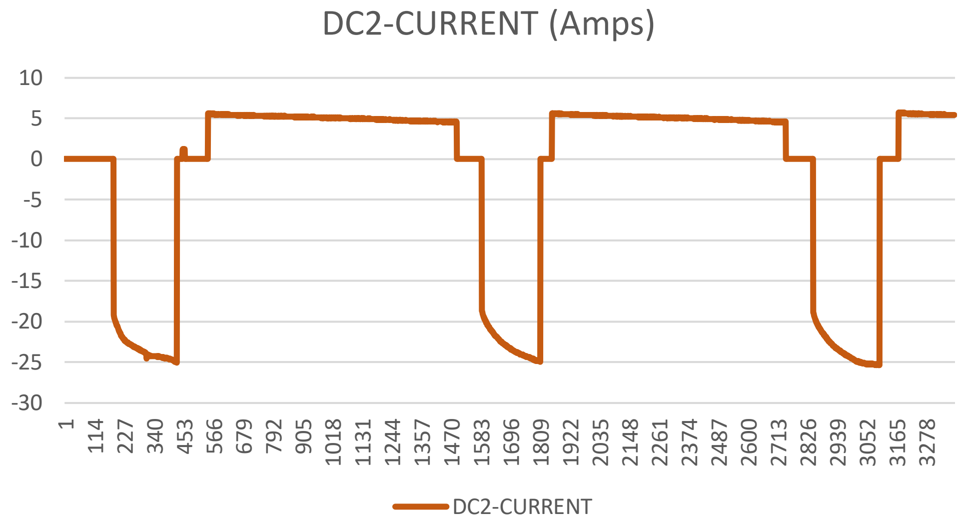
- 40kWh Energy capacity
- 10kW Nominal Power
- 600V – 350V DC Range
- 4D standard battery format
- 35 4D battery modules are populated
- Max available rack capacity is 40 battery modules

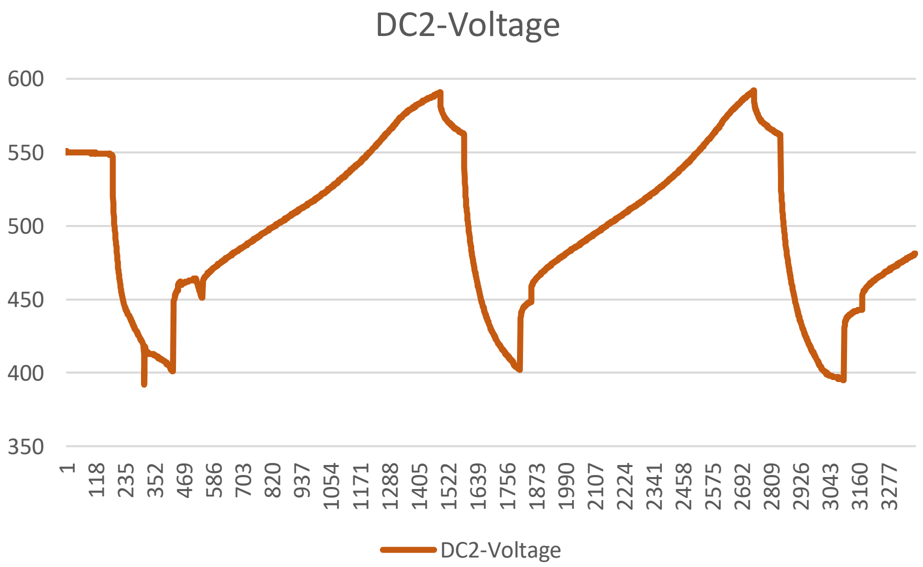
EPRI Test Results
(40 12V batteries in a 480V string)





D(1-3) – 10kW ~ 40kWh discharge
C(1-3) – 2.5KW ~40kWh Charge





The dip in the first discharge in panel 4, indicates a lower voltage module, which was switched out to retain system performance.

Conclusions

1. Cells are performing in all the tests consistent with their lab scale data, Gen 1 battery appears to be robust under a variety of applications ranging from power back up through solar microgrids to demand response.
2. Results from evaluations of installed battery storage systems indicate the need to optimize charging protocols according to applications, for example by developing energy management systems that control charge rate and operating voltages to extend system life.
3. Evaluations of battery storage system performance also indicate value in monitoring battery state of health and switching out weaker batteries in large strings to augment overall performance.
4. System evaluations are continuing with several projects coming online in 2022.

SUPPLEMENTARY MATERIAL

Timeline of $Zn\text{-}MnO_2$ Development

1866
Primary
Low Power
$Zn\text{-}MnO_2$ primary "Leclanché" cell

Georges Leclanché

1950-1970
Primary/Low Capacity Rechargeable
Alkaline $Zn\text{-}MnO_2$ battery primary / 5% rechargeable

Lewis Urry

Karl V. Kordesch

1980
Low Cycle Life Rechargeable
Alkaline $Zn\text{-}MnO_2$ battery 60-80% rechargeable with low cycle life

Ford

Halina Wroblowa

2010-2016
Stabilized Full-Cycle MnO_2
Alkaline $Zn\text{-}MnO_2$ battery shallow cycle to full-cycle of MnO_2 with high cycle life

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2019
Li-Ion Competitor
High voltage (2.4-2.8V) dual electrolyte Zn-Mn cell

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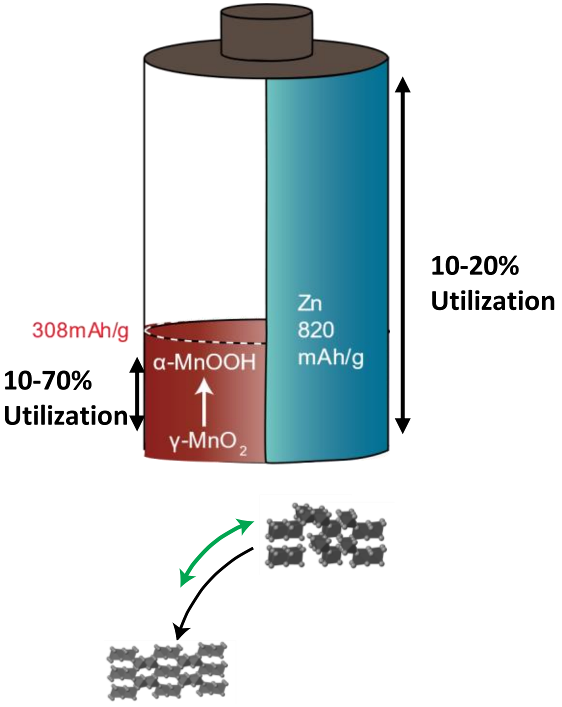
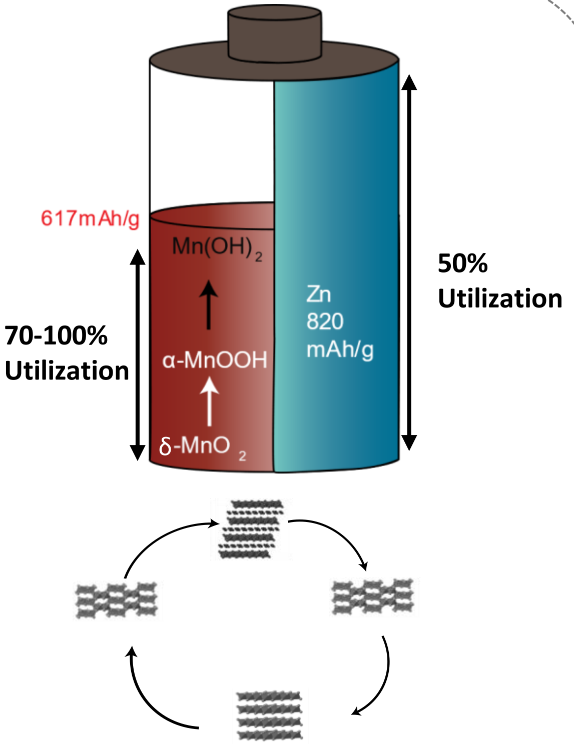
Development Stages For Zn-MNo$_2$ Batteries

Gen 1
Battery 1 and 2
Proton Insertion Battery



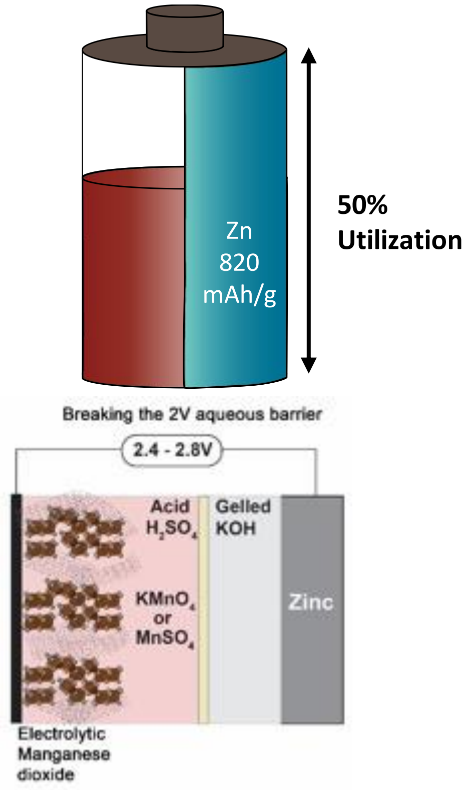
- Analogous to the Li-ion intercalation chemistry.
- Rechargeable utilization till 70% of proton insertion chemistry.
- Inactive spinel formation beyond 70% utilizations.

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.

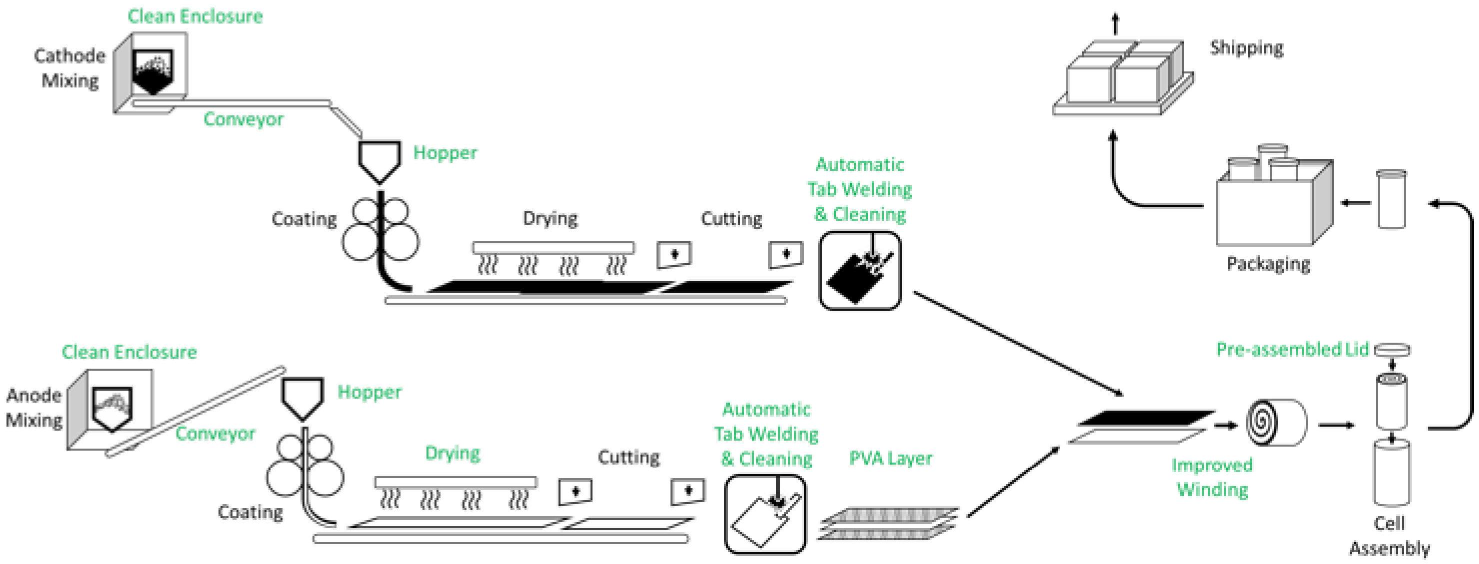
Gen 2+
Battery 4
The Li-ion Competitor
High Voltage 2.45-2.8V Zn-MnO$_2$



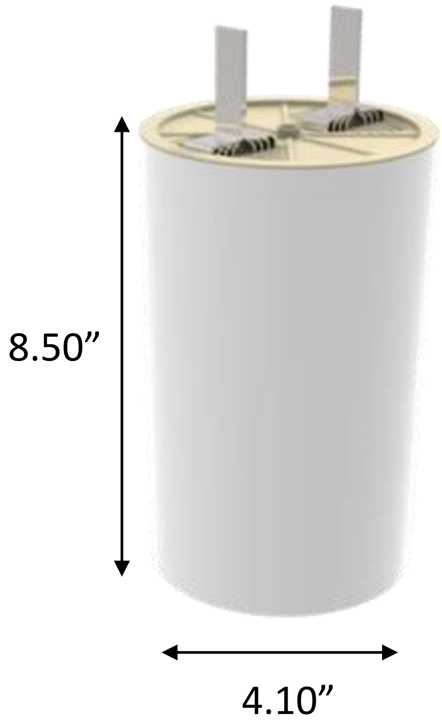
- Breakthrough accessibility in >2.4-2.8V & 100% utilization of 308mAh/g of MnO$_2$ allows higher energy density than Li-ion.

Urban Electric Power (UEP)

Zn-MnO2 Battery Manufacturing Process: Concept to Product



Product: UEP Zn-MnO2 Gen 1 Cell Development Roadmap



Current Gen 1 Cell

2021

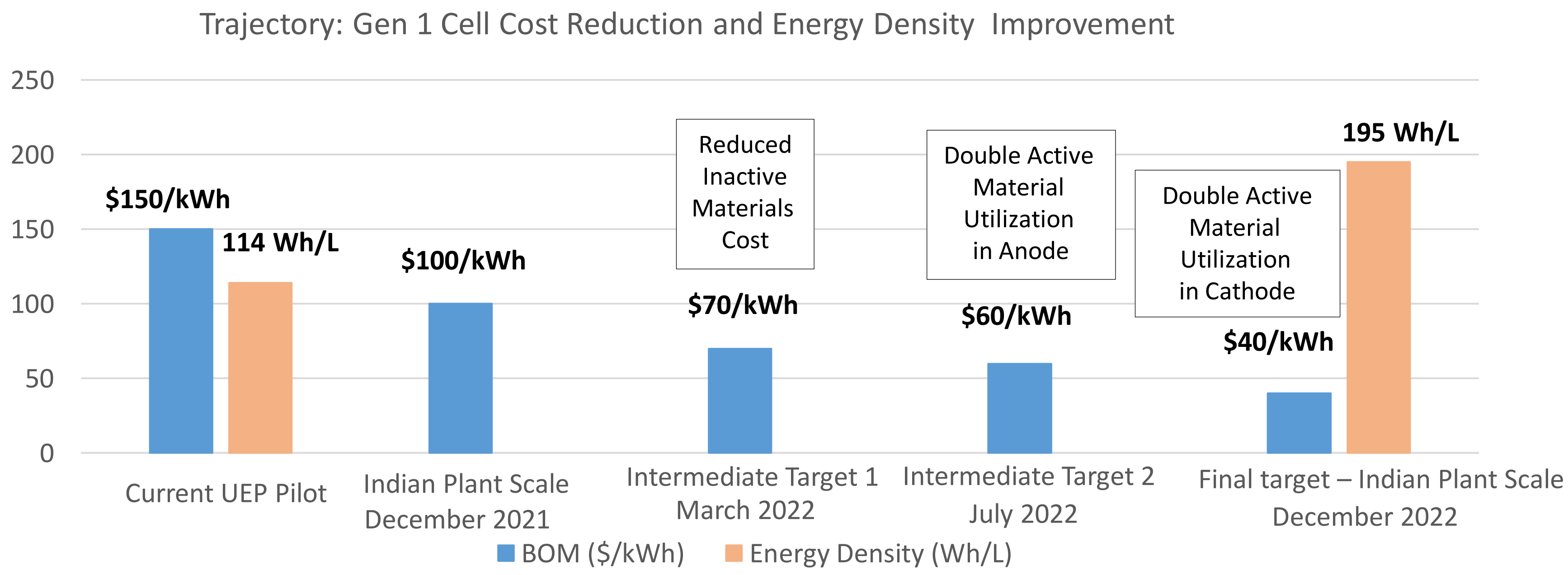
Current Cost
UEP-Pilot Scale:
BOM: $150/kWh

December 2021

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

December 2022

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

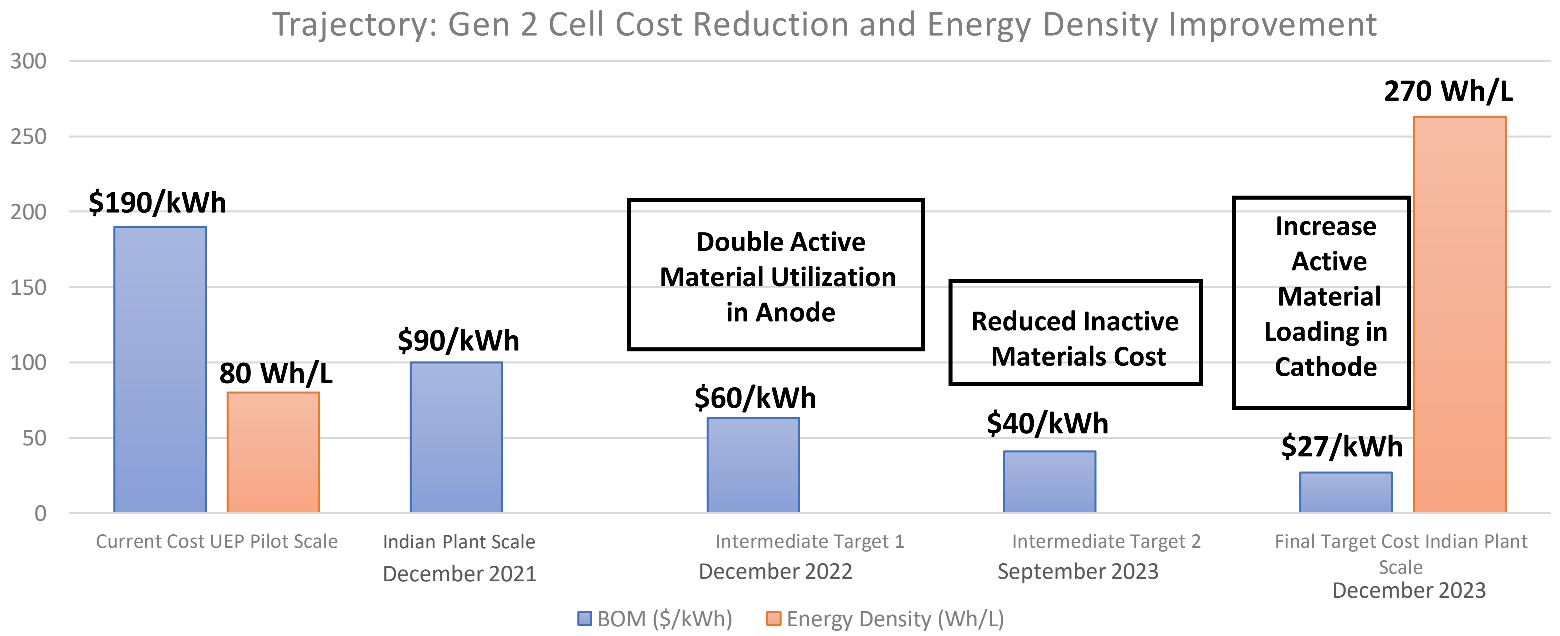


** All costs based on solar microgrid application with 5-year warranty conforming to IEC Solar Standard 61427-1. The standard simulates daily cycling in microgrids under representative varying solar insolation conditions. By ‘Indian Plant Scale’ is meant a plant being built in India for completion by end 2021*

Product: UEP Zn-MnO2 Gen 2 Cell Development Roadmap

Current Gen 2 Cell

2021	December 2021	December 2023
Current Cost UEP-Pilot Scale: BOM: \$190/kWh	Intermediate Cost Indian Plant Scale: BOM: \$90/kWh	Target Cost Indian Plant Scale: BOM: \$27/kWh

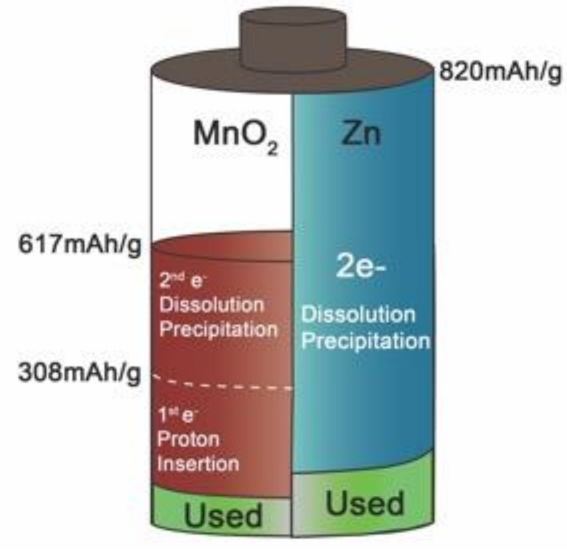


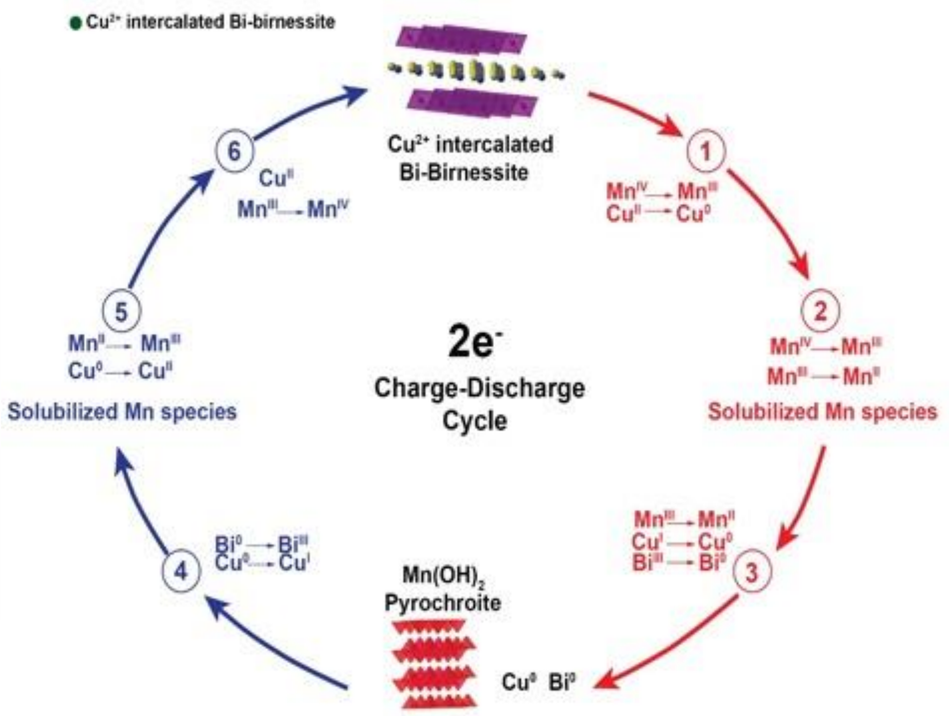
** All costs based on solar microgrid application with 10-year warranty conforming to IEC Solar Standard 61427-1. The standard simulates daily cycling in microgrids under representative varying solar insolation conditions.*

UEP Zn-MnO2 Gen 2 PRODUCT

Accessing 2 electron capacity using the manganese dioxide polymorph, birnessite

Birnessite Cathode Capable of Accessing 100% of 2e





Key Challenges

MnO_2 Cathode
- Crystal structure breakdown
- Formation of Inactive phases
- Susceptibility to zinc poisoning

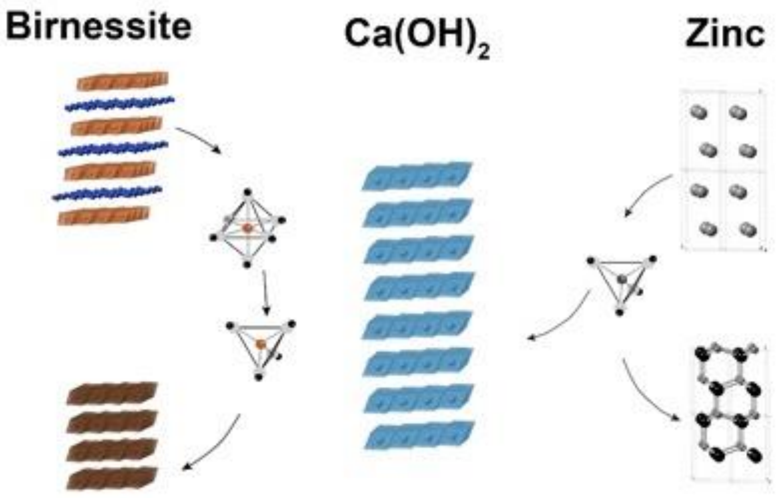
Separator
- Reduce zinc crossover

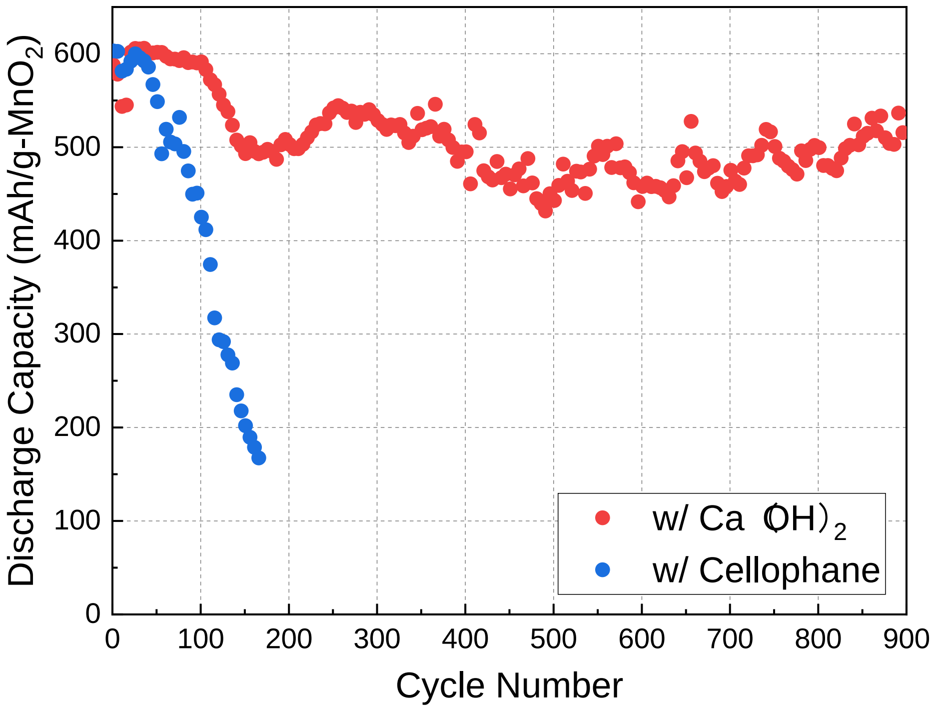
Zn Anode
- Control shape change
- Passivation
- Dendrite formation

Developments in materials utilization, process optimization and engineering larger format cells.

UEP Zn-MnO2 Gen 2 Cell Performance Improvement:

Zinc Crossover Blocking with $Ca(OH)_2$ Interlayers





- The $Ca(OH)_2$ interlayer captures zincate ions by forming an insoluble compound $\mathrm{Ca(OH)_2 \cdot 2Zn(OH)_2 \cdot 2H_2O}$ (calcium zincate) and extends the cell's cycle life with stabilized capacity and energy (80% retention of the full 2-electron capacity).

Yadav, G. G. et al. *J. Mater. Chem. A*, **2017**, 5, 15845

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UEP Zn-MnO2 Gen 1 & Gen 2 Cell Cost By Stationary Storage Application

Note: Accessible capacity depends on the discharge power level as dictated by the application

Use Case	Cell Type	Current UEP Pilot BOM ($/kWh)	Current Indian Plant Scale BOM ($/kWh)	Target* BOM ($/kWh)	Target* Energy Density (Wh/L)	Warranty Period
Solar Micro Grids **	Gen 1	150	100	40	195	5-year warranty
	Gen 2[1,2,3]	190	90	27	270	10-year warranty
Demand Charge Reduction	Gen 1	300	200	70	114	5-year warranty
	Gen 2[1,2,3]	190	90	27	270	10-year warranty
Power Backup (5-hour)	Gen 1	90	60	40	187	5-year warranty
	Gen 2[1,2,3]	190	90	20	328	10-year warranty
Power Backup (24-hour)	Gen 1	80	50	35	228	5-year warranty
	Gen 2[1,2,3]	190	90	20	328	10-year warranty

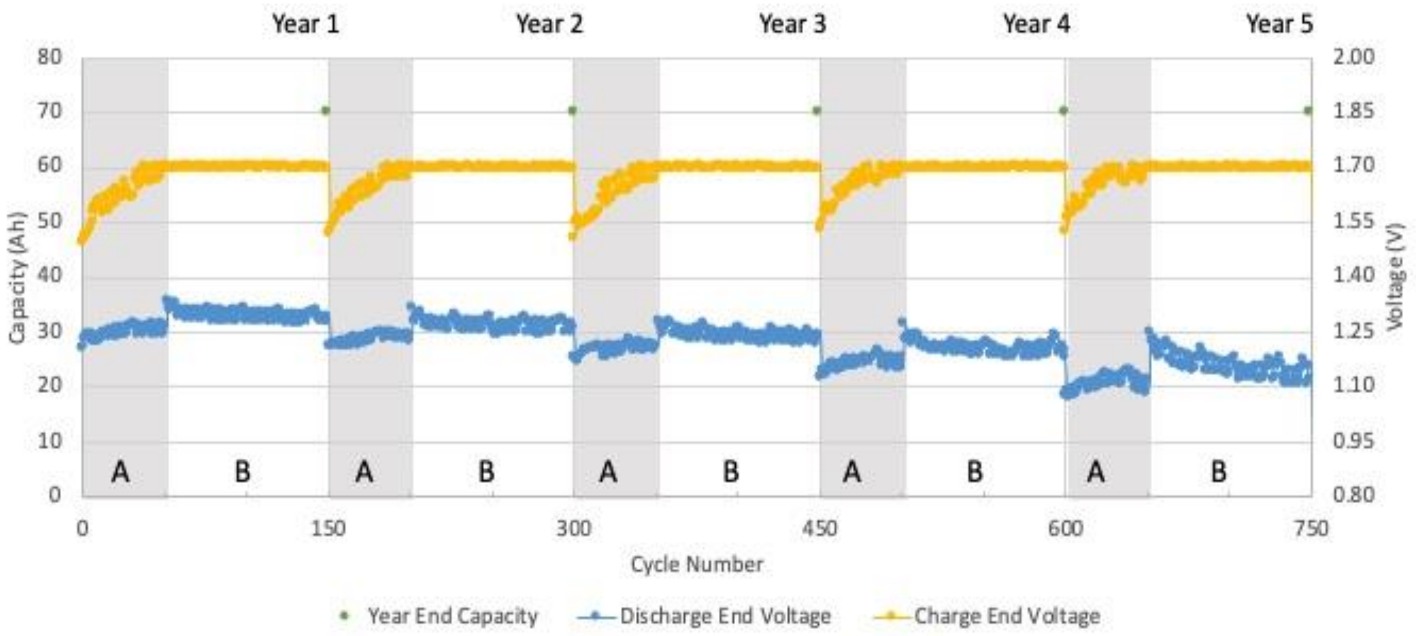
* Gen 1 Target will be achieved by December 2022; Gen 2 Target will be achieved by December 2023

*** All costs based on solar microgrid application with 5-year or 10-year warranty conforming to IEC Solar Standard 61427-1. The standard simulates daily cycling in microgrids under representative varying solar insolation conditions.*

1. *Yadav, G. G. et al., Nat. Commun., 2017, 8, 14424*
2. *Yadav, G. G. et al., J. Mater. Chem. A, 2017, 5, 15845-15854*
3. *Yadav, G. G. et al., ACS Energy Letters, 2019, 4 (9), 2144-2146*

UEP Zn-MnO2 Gen 1 Cell Performance: 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.

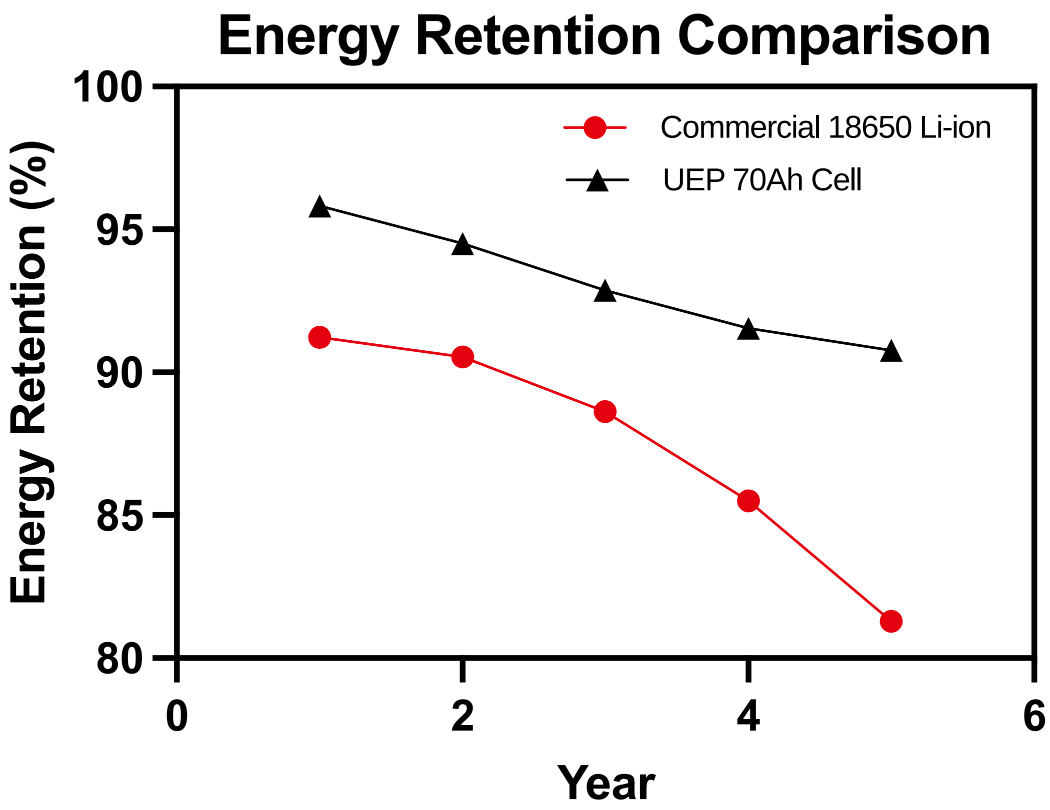


Phase A: 3h C/10 charge and 3h C/10 discharge cycling at low state of charge for 50 cycles.

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.

Energy Retention Comparison Between Commercial 18650 and UEP Zn-MnO2 70Ah Cell



UEP's Zn-MnO2 Cell has a nameplate capacity of 70Ah

Commercial Panasonic 18650 cell has a nameplate of 3.2Ah

Completed UEP Zn-MnO2 Gen 1 System Deployments

Project	Use Case	Completed
Godrej and Boyce Grid – Tied System (Mumbai, India)	Demand Response	2016
New Mexico State University	Grid – Tied Solar Demand response	2020
Pearl River, NY	Solar Micro-grid System	2019
US Navy	Backup System	2018

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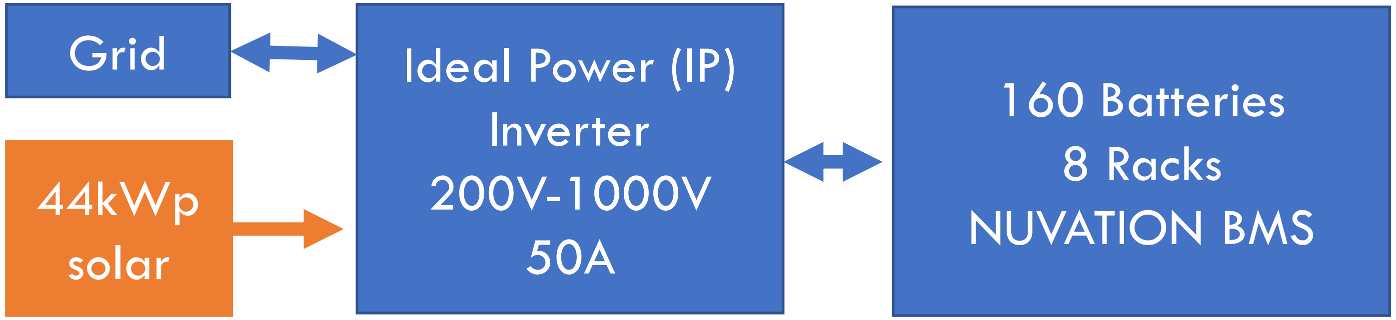
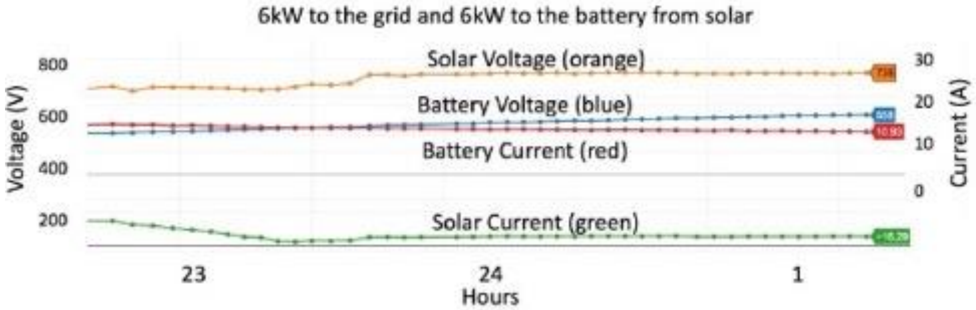
Completed Projects:

Gen 1 Containerized Grid-Tied Solar Demand Response System in India

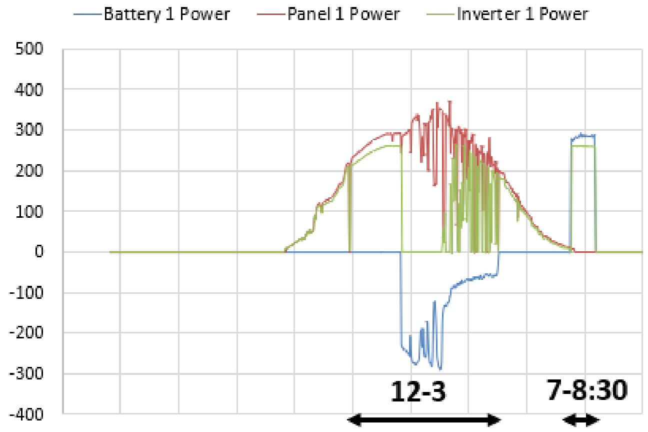




- System built in 2016 with G&B
- Use standard off-the-shelf BMS from NUVATION and Ideal Power grid-tied inverters
- Operates between 400V and 800V DC
- 30kW inverter with 44 kWp of solar

Completed Projects:
Gen 1 Grid-Tied Solar Demand Response System In New Mexico

Data from one week of operation of two systems in New Mexico



Detailed Daily Profile

The blue curve is the battery power (negative is charging and positive is discharging).
The Green curve is the Inverter Power (standard Enphase IQ7+). The Red curve is the solar power.
The solar is used to charge the batteries between 12PM and 3PM and the batteries provide power to the Enphase Inverter between 7 PM and 8:30 PM.

Solar integrated batteries

- Direct pairing of batteries and solar panels on the DC side with low-cost (<$50) electronics
- Batteries are also used to hold the panels down
- Product made possible by the ability of the $ZnMnO_2$ batteries to charge in 4-6 hours with a wide range of constant current/power values and to work at high temperature
- Future step is to add the battery electrodes flat under the panels to make 24-7 solar panels

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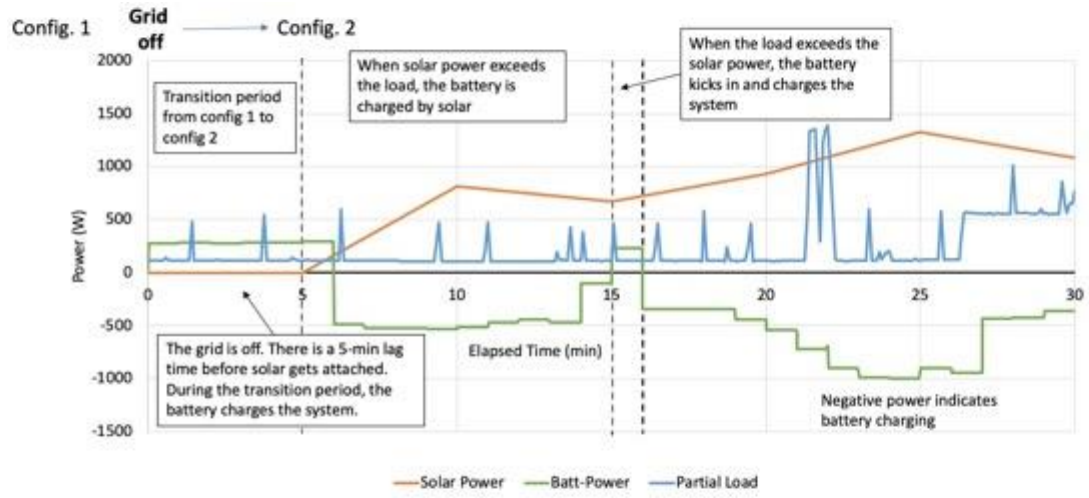
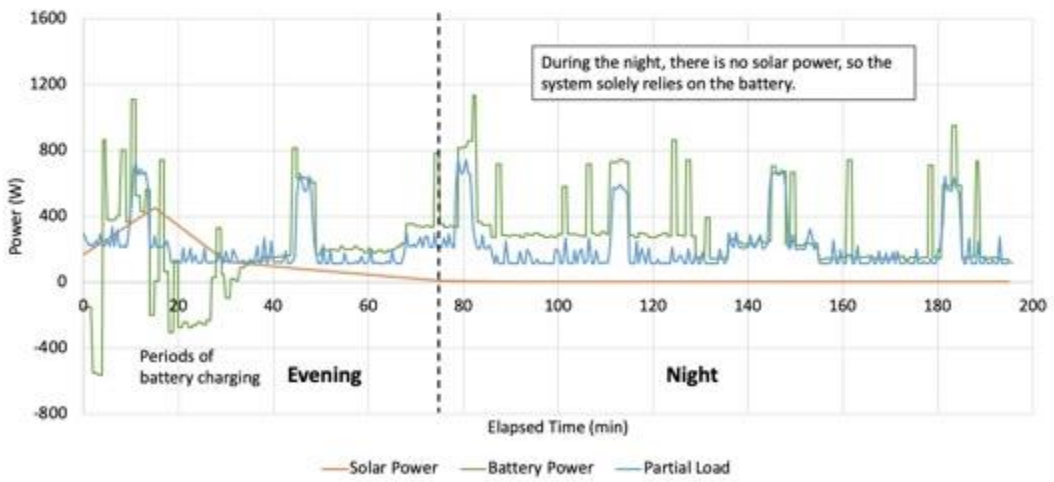
COMPLETED PROJECT:

Gen1 Solar Microgrid System For Long Duration Power Backup



Solar powers the load and battery when the grid is off (transitioning from config 1 to config 2)



Load, solar power and battery power during evening and night

COMPLETED PROJECT:
Backup system test for the US Navy

As part of an SBIR funding award with Motivo Engineering, UEP's first generation batteries underwent testing to simulate the powering of public announcement systems on board DDG-51 Class ships.

Test results (below) demonstrate that UEP batteries outperform the existing lead-acid batteries within the same physical footprint. Additionally, the UEP batteries did not fail when subjected to abuse.

100A System Current Draw	UEP Battery	Lead-Acid Battery	% Improvement over Lead-Acid
Runtime (h)	3.2	2.1	52%
Energy (kWh)	5.5	4.7	17%
Volume, full system (L)	315	360	13%
Energy Density, full system (Wh/L)	17.3	13.0	33%
Mass, full system (kg)	260	258	-1%
Specific Energy, full system (Wh/kg)	21.0	18.2	15%

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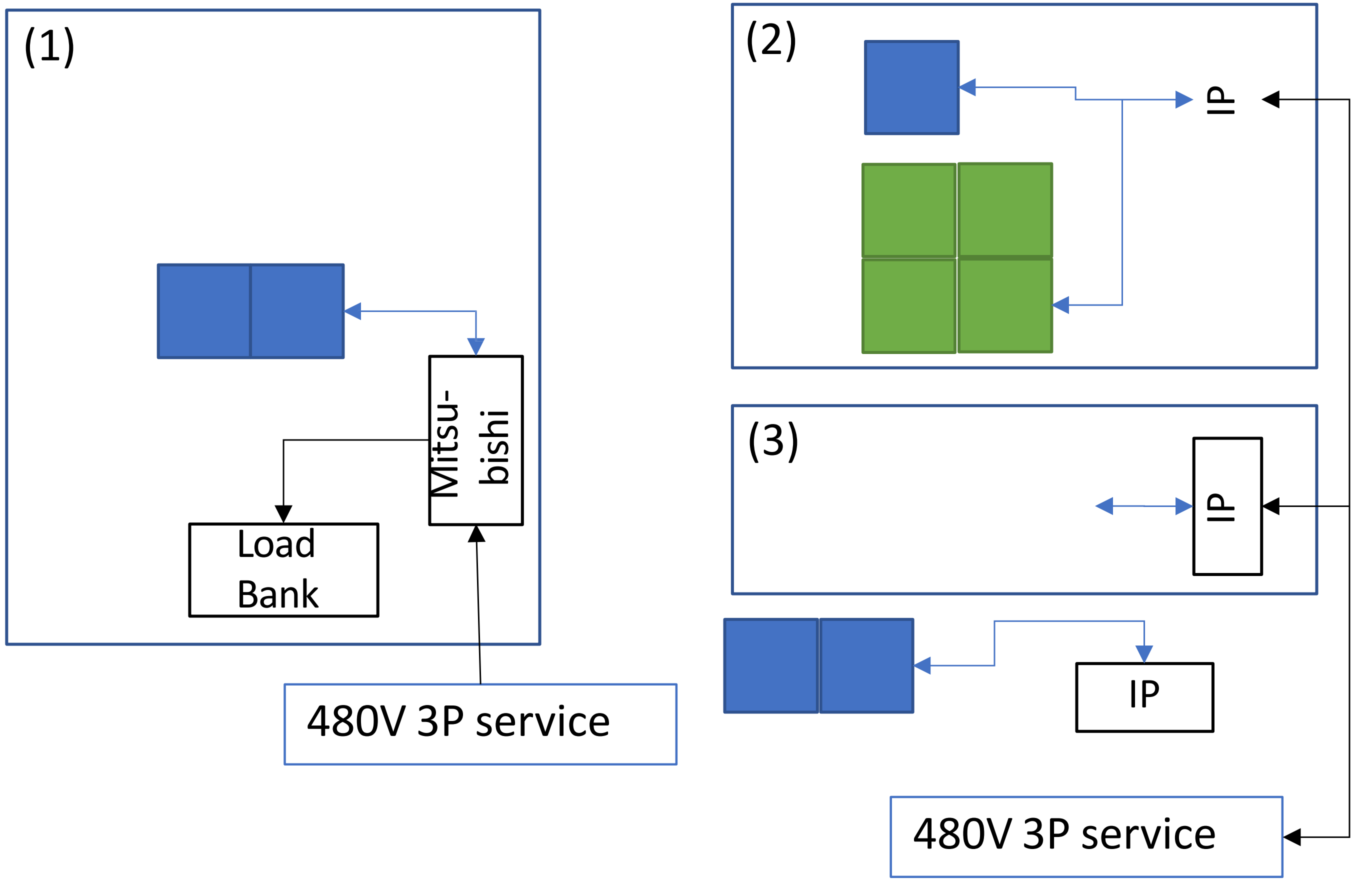
Prototype system tested by a 3rd party lab

Ongoing Gen 1 System Deployments: 2021- 2022

Project	Use Case	Estimated Completion
San Diego Supercomputer Center backup (San Diego, California)	1MW / 2 MWh High-Rate UPS	Quarter 4, 2021
CCNY Grid Modernization Center (Manhattan, New York)	1 MWh Grid Storage (demand response/ demand charge) Solar Microgrid High-Rate UPS	Quarter 1, 2022
BMCC Energy Storage System (Manhattan, New York)	200kWh Grid Storage (demand response / demand charge)	Quarter 2, 2022
Five Spoke Creamery Power Backup System (New York)	200 kWh Long Duration UPS	Quarter 4, 2021
Navajo Nation Microgrid (New Mexico)	Multiple 10 KW Solar Microgrids	Quarter 4, 2021
Electrical Power Research Institute	40 kWh scalable utility modules for demand response and renewables	Quarter 4, 2021

Ongoing Project:
CCNY Grid Modernization Center



1000V DC lines for all the racks

480V 3p AC 1-way lines (for UPS and Load Bank) 480V

3p AC 2-ways lines (For IP converters)

Ideal Power (IP): Three 30kW/120kWh

- 100 kW of demand response
- Peak shaving
- Support hybrid battery packs connected on the AC and DC side

Mitsubishi: 100kW/400kWh UPS unit

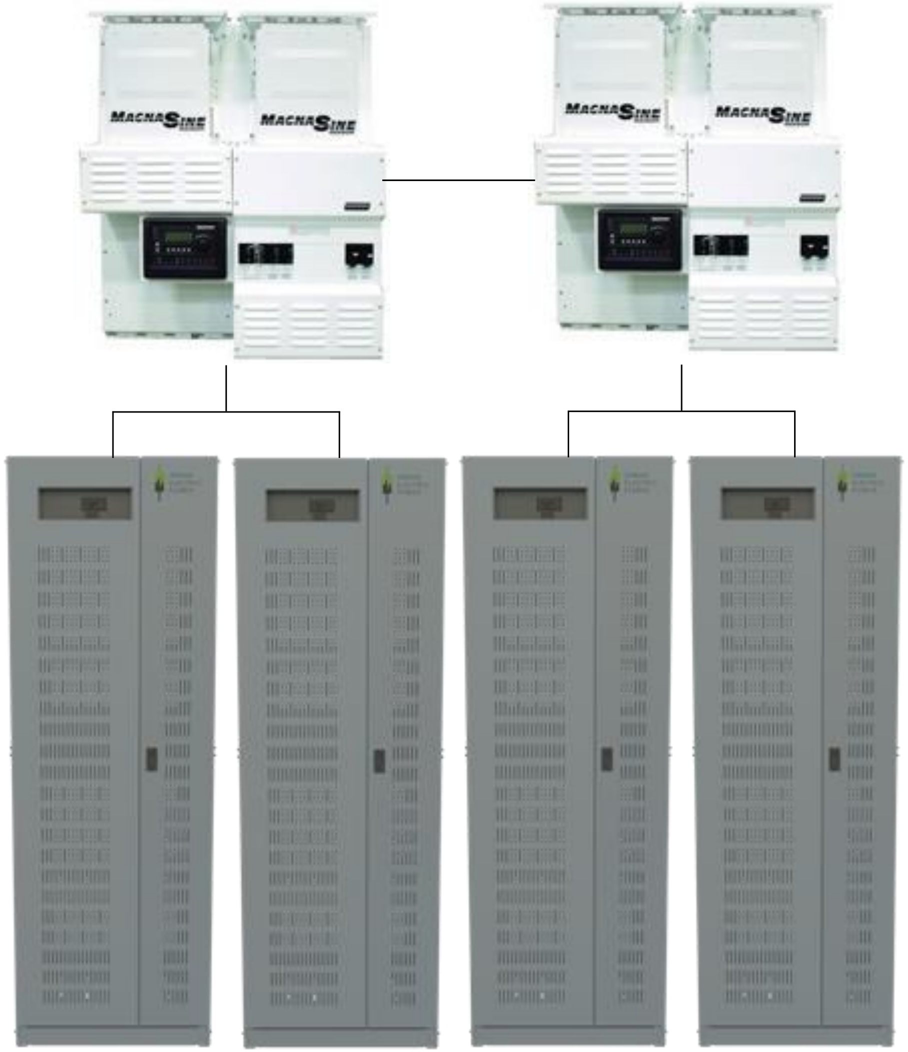
- Short and long duration emergency UPS
- 100 kW of demand response

Load bank

- 50kW resistive in increments of 5kW
- 480V 3p AC

Ongoing Projects:

Agricultural Energy Storage at Five Spoke Creamery



- 12kW/120 kWh energy storage system based on the power assurance system building block.
- System will provide long-duration backup power and peak load management as needed.
- Can be paired with solar PV for recharging during extended periods of outage.