Battery Decommissioning, Recycling, and Reuse

September 20, 2023

A Presentation of the Energy Storage Technology Advancement Partnership (ESTAP)

Webinar Logistics

Use the orange arrow to open and close your control panel

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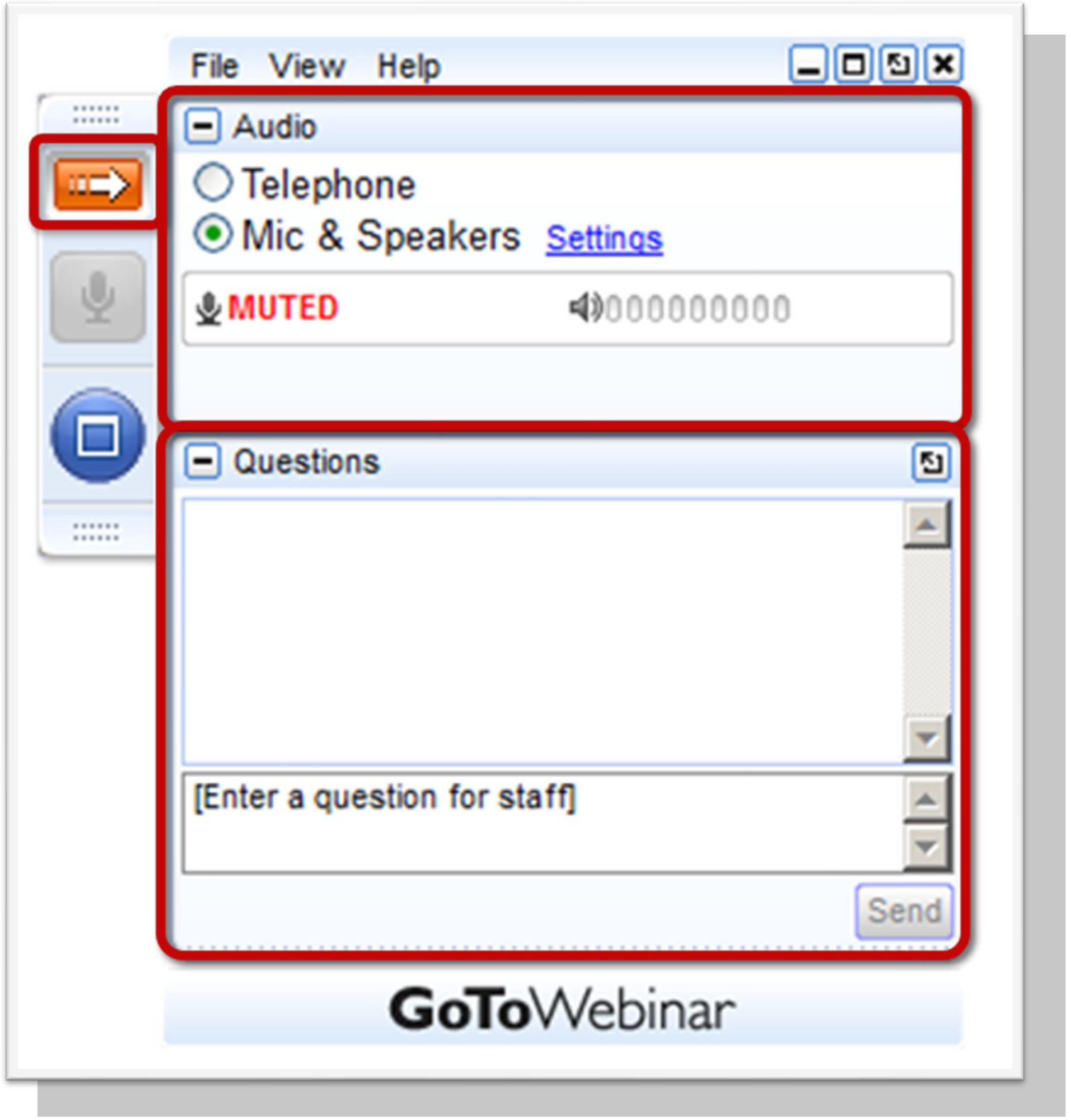

Celebrating 20 Years of State Leadership

20 Clean Energy States Alliance

The Clean Energy States Alliance (CESA) is a national, nonprofit coalition of public agencies and organizations working together to advance clean energy.

CESA members—mostly state agencies—include many of the most innovative, successful, and influential public funders of clean energy initiatives in the country.

www.cesa.org

CleanEnergy States Alliance

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State of California Energy Commission

Connecticut Green Bank

Department of Energy & Environment

Energy Trust of Oregon

IPA Illinois Power Agency

Governor's Energy Office (Maine)

State of New Hampshire Department of Energy

Massachusetts Clean Energy Center

Maryland Energy Administration

EGLE Michigan Department of Environment, Great Lakes, and Energy

BPU New Jersey Board of Public Utilities

New Jersey's cleanenergy program
njcleanenergy.com

New Mexico emnrd
Energy, Minerals and Natural Resources Department

New York State NYSERDA

mn Commerce Department

SMUD
Powering forward. Together.

State of Rhode Island Office of Energy Resources

Vermont Department of Public Service
Clean Energy Development Fund

Virginia Energy

Rhode Island Commerce Corporation

Commissioner Stephanie Garcia Richard New Mexico State Land Office

Illinois Commerce Commission ICC

OEI Wisconsin Office of Energy Innovation

Prairie Island Indian Community in the State of Minnesota

Washington State Department of Commerce

Connecticut Energy Environment

DOER Massachusetts Department of Energy Resources

Oregon Department of Energy

Colorado Energy Office CEO

Inclusive Prosperity Capital

MassDEP

OPC-DC Office of the People's Counsel
Advocacy | Education | Protection

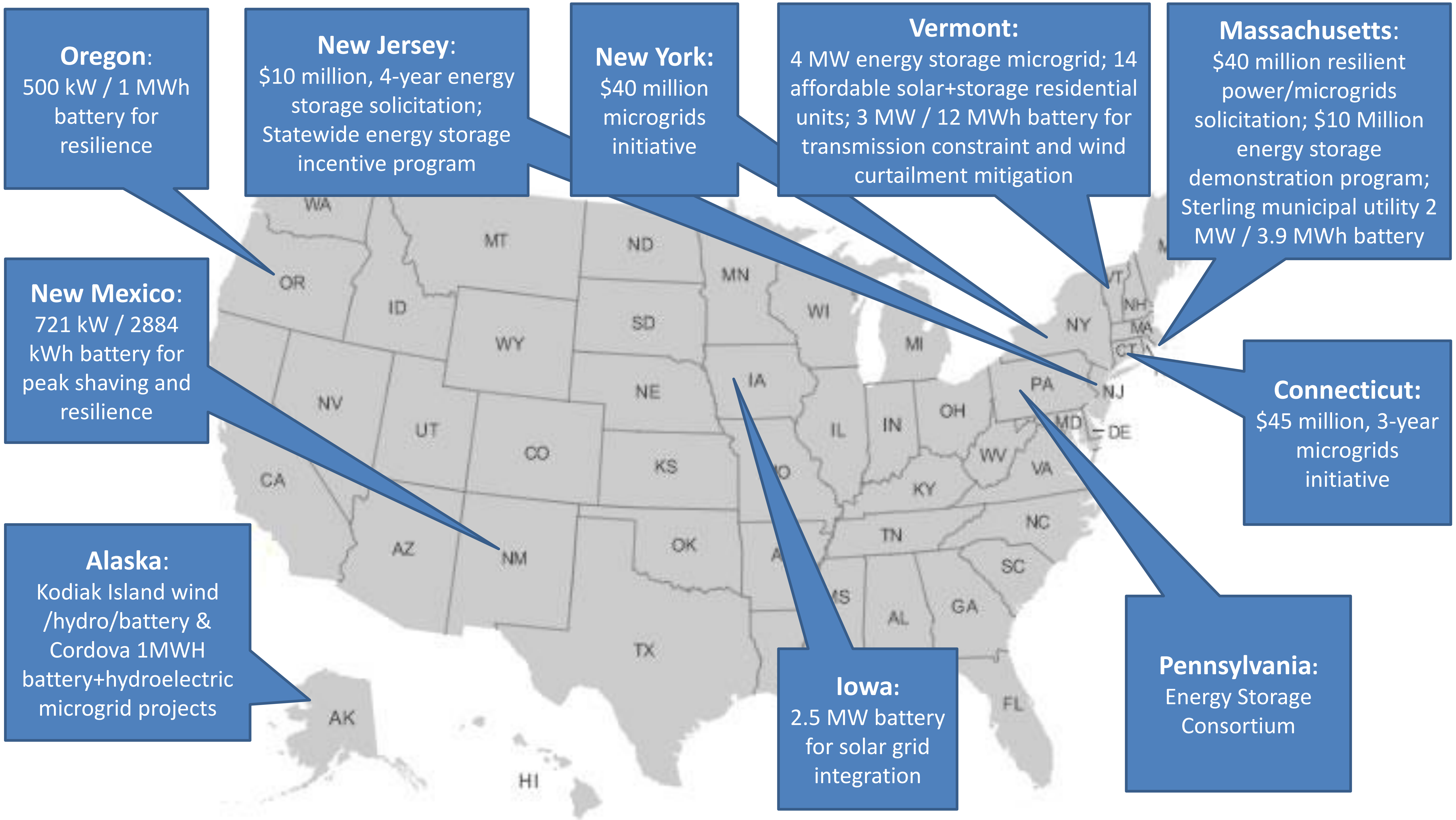
Energy Storage Technology Advancement Partnership (ESTAP)

Conducted under contract with Sandia National Laboratories, with funding from US DOE Office of Electricity.

- Facilitate public/private partnerships to support joint federal/state energy storage demonstration project deployment
- Support state energy storage efforts with technical, policy and program assistance
- Disseminate information to stakeholders through webinars, reports, case studies and conference presentations

www.cesa.org/ESTAP

Technical & Policy Support for Energy Storage Across the Nation



Thank You!

Dr. Imre Gyuk
Director, Energy Storage Research,
U.S. Department of Energy

Waylon Clark
Energy Storage Program Demonstration Team Lead,
Sandia National Laboratories

Webinar Speakers

Imre Gyuk
US Department of Energy Office of Electricity

Dan Borneo
Borneo Engineering (formerly of Sandia National Laboratories)

Jeffrey Spangenberger
Argonne National Laboratory

Jonathan Harter
Oak Ridge National Laboratory

Todd Olinsky-Paul
Clean Energy States Alliance

U.S. DEPARTMENT OF ENERGY

Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

CleanEnergy States Alliance

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www.cesa.org/ESTAP

Upcoming Webinars

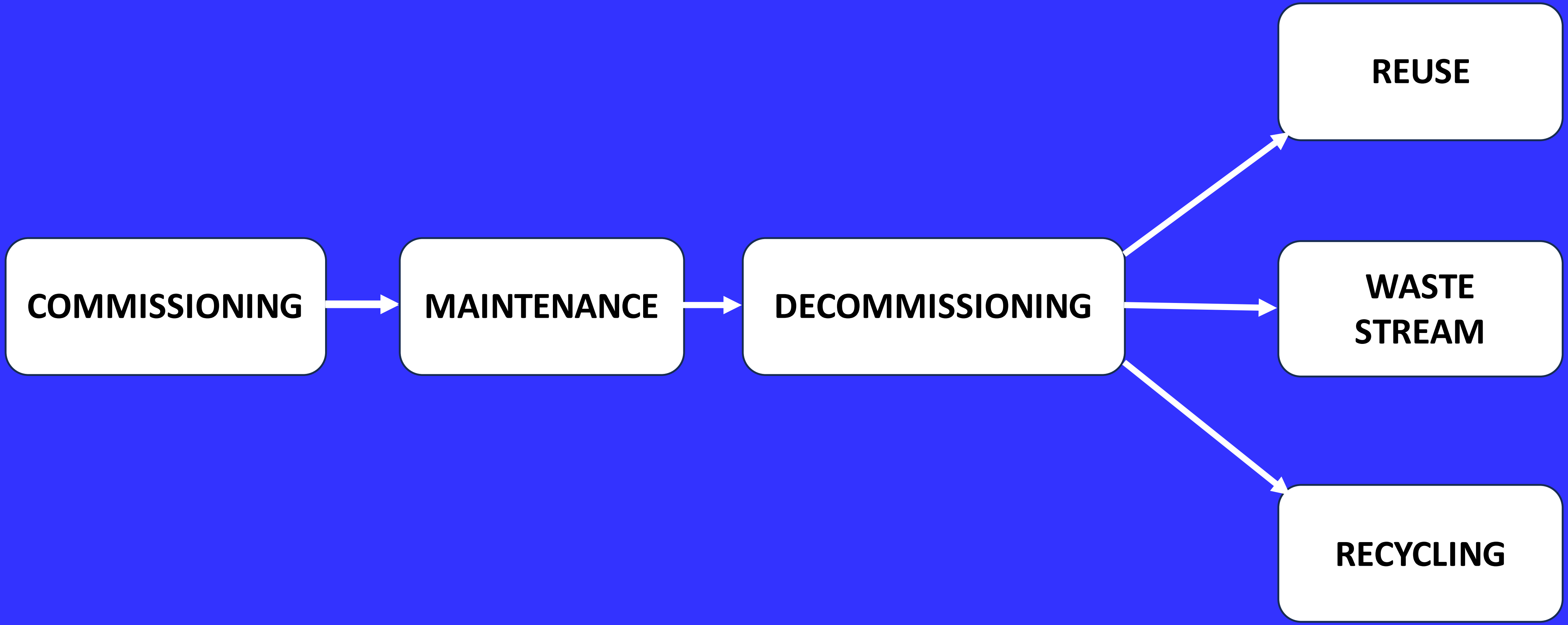
Energy Storage for Peak Demand Reduction: A New Incentive Program by Efficiency Maine (9/28)

NYSERDA's State Energy Financing Fund and DOE's Loan Programs Office: Financing Clean Energy at the State Level (10/3)

Read more and register at
www.cesa.org/webinars

In the Beginning was the Supply Chain

IMRE GYUK, CHIEF SCIENTIST
ENERGY STORAGE RESEARCH, DOE-OE


COMMISSIONING
MAINTENANCE
DECOMMISSIONING
REUSE
WASTE STREAM
RECYCLING

SUPPLY CHAIN AND WASTE STREAM MUST BE PART OF THE DESIGN!

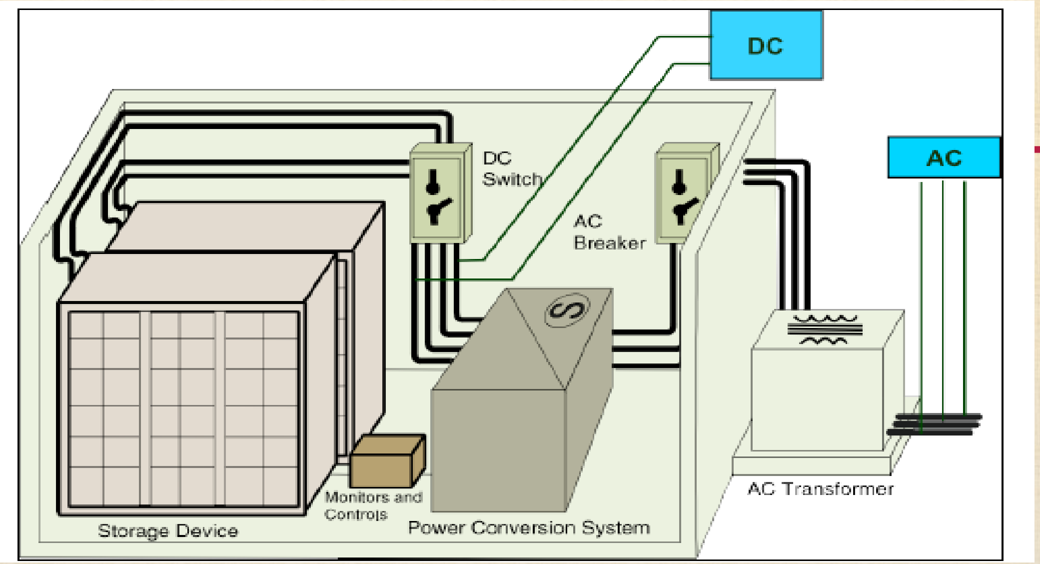
BATTERY ENERGY STORAGE DECOMMISSIONING

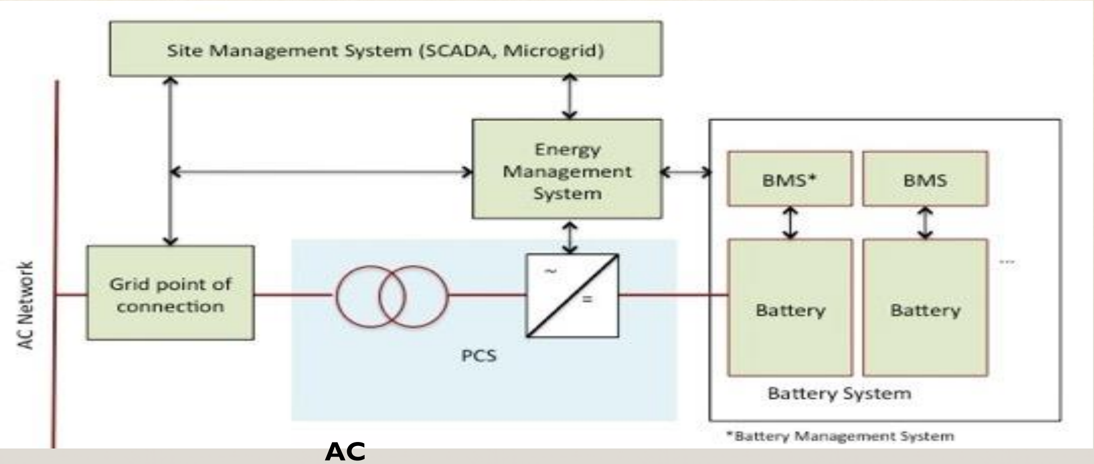
ESTAP Webinar
September 20, 2023

DAN BORNEO

DANIEL.BORNEO@BORNEOENGR.COM

BATTERY ENERGY STORAGE SYSTEM (BESS)

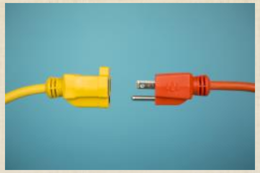




AC Transformer

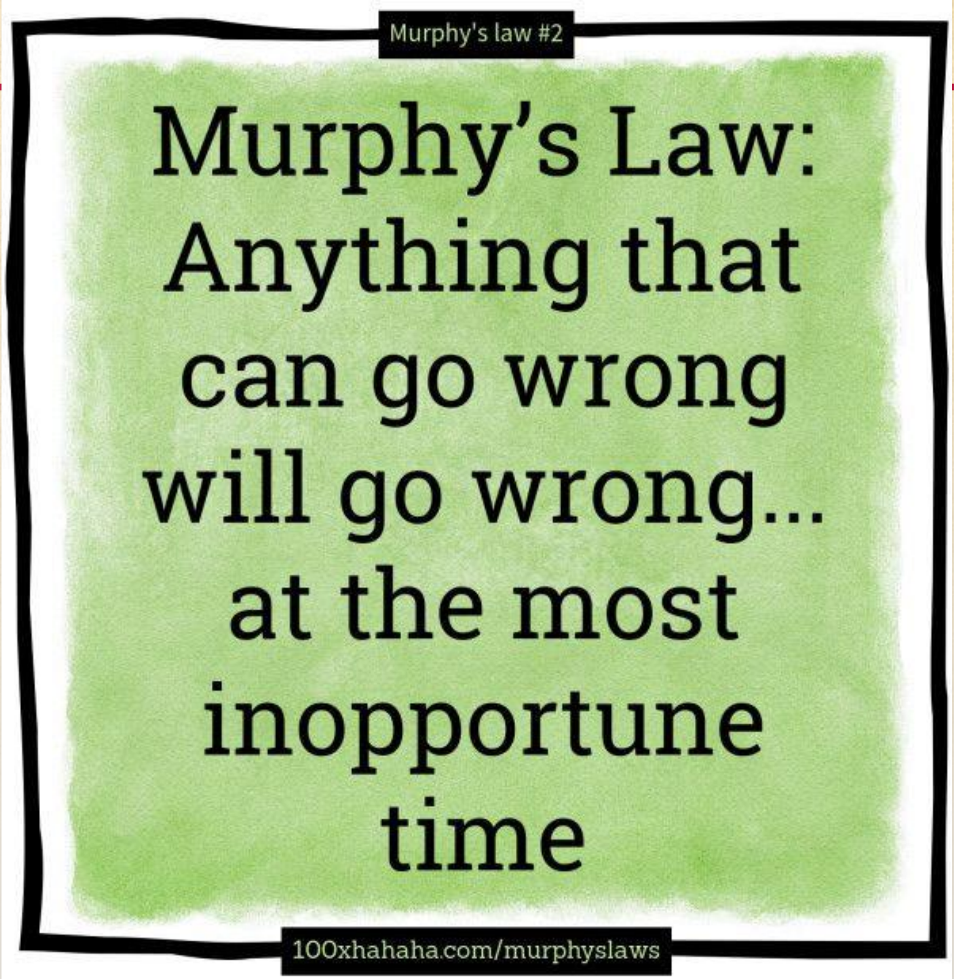
STEPS TO DECOMMISSIONING A BATTERY ENERGY STORAGE SYSTEM (BESS)

- Discharge battery
- Turn off
- Disconnect and Remove from site



Boom…Done…Next

ONLY ONE THING:



REALITY

- Installing something today and worrying about what's going to happen in 10-20 years
  - Will you be around
  - Will the vendor be around
  - Will you be able to track down the contract – What will it say
  - What will the recycling landscape be like
  - How much are you willing to spend today for a known unknown tomorrow

START WITH THE END IN MIND

- Who will decommission the system
  - **Owner (If not end user)**
  - **End user - in-house technicians?**
  - **End user - Contractors?**
  - Vendor
- What can we do during the contracting phase?
  - Contracting strategies
    - **PPA – Power Purchase agreement**
      - Least control, least responsibility, Least Risk
    - PPA with option to buy
    - **EPC – Engineer, Procure and Construct**
      - Most control, most responsibility
      - You will be required to manage decommissioning

HOW TO MAKE YOUR LIFE EASIER

Any contracting strategy should consider the following:

- Operational parameters to HELP predict End-of-Life (EoL)
  - Limits to how the battery can be used
    - ✓ Pro – can measure and track life, i.e degradation over time
    - ❖ Con – may limit use cases
  - Performance parameters:
    - Capacity loss per year
    - End of life projections
- Maintenance program

Contract could include:

- Warranty/Periodic Maintenance
  - What items can internal workforce be trained to do
  - What items should be contracted
- Add plan for decommissioning/removal

  Pro

  ✓Set price, time and scope

  Cons

  ❖What doe the future hold
  ❖Will company be around
  ❖Will the owner remember its there
  ❖Cost can be high given risk

SUMMARY (WHAT TO KNOW, DO, AND WATCH OUT FOR)

- Know what the predicted EoL is - based on performance and operational parameters
- Will installer be around to decommission
- Will your company rep who placed the contract be around to enforce decommissioning.
- Periodic maintenance agreement could include decommissioning
- What can you do with used batteries?
  - Safety concerns may limit any future use of batteries – No reconditioning
- Discharging may be a challenge if removal due to failure

THANK YOU

Dan Borneo

Daniel.Borneo@Borneoengr.com

A CLOSER LOOK AT THE STEPS

- Discharge battery and turn off:
  - If removal is **not** due to an anomaly
    - Operate system as you would otherwise – Discharge into load and then shut down
  - If removal **is** due to an anomaly, you may need to do any one or more of the following:
    - Shut down system
    - Isolate battery strings, and or modules
    - Provide load bank and discharge each module
    - Problematic modules may need to be placed into a saltwater tank

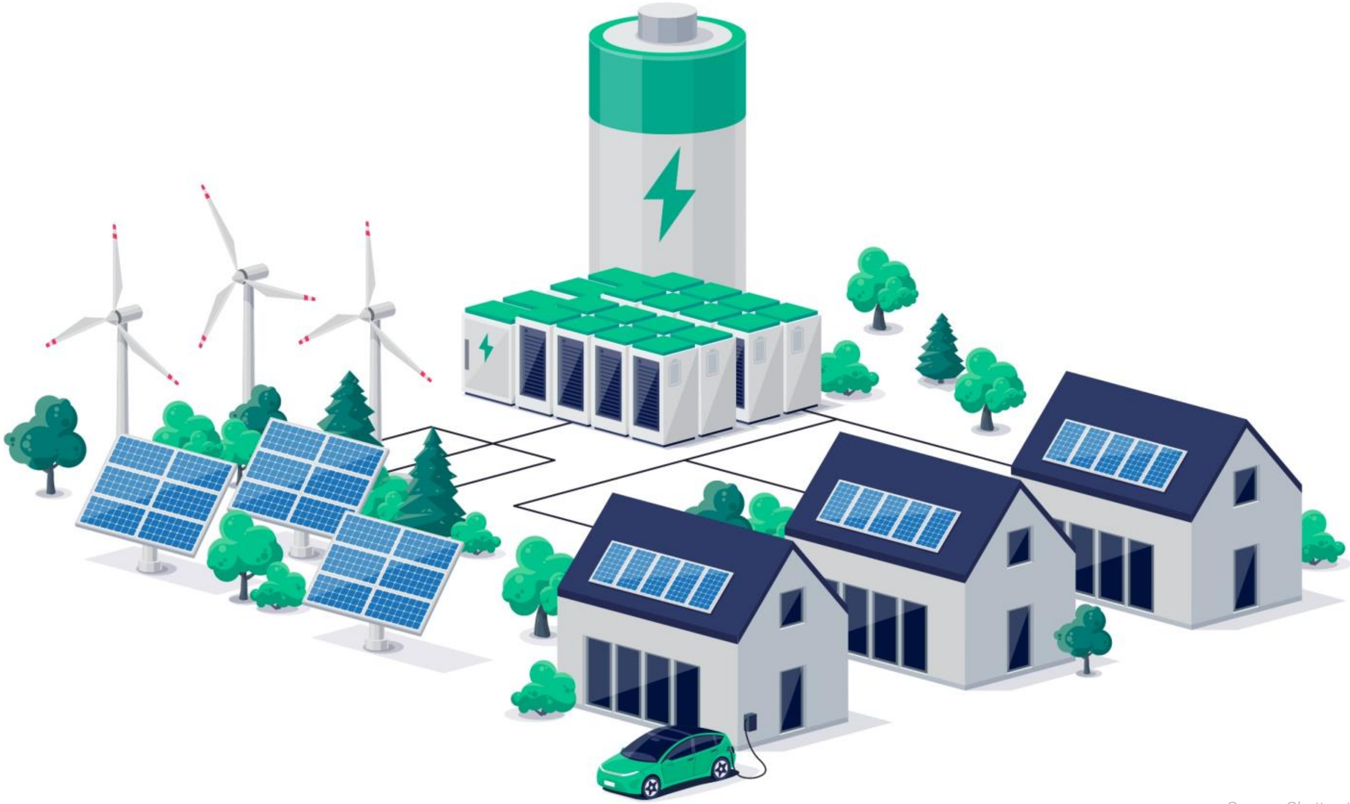
A CLOSER LOOK AT THE STEPS (CONT.)

- Disconnect and remove from site
    - **SAFETY FIRST:**
        - **System should be locked out/ tagged out**
        - **Ensure Batteries discharged**
    - Once batteries are discharged to manufacturing recommendation, battery modules can be disassembled following electrical hot work procedures and shipped out.
    - Once batteries are safely removed, removal of electrical gear and container should follow standard electrical distribution removal procedures.

RECELL: WORKING TO ADVANCE BATTERY RECYCLING

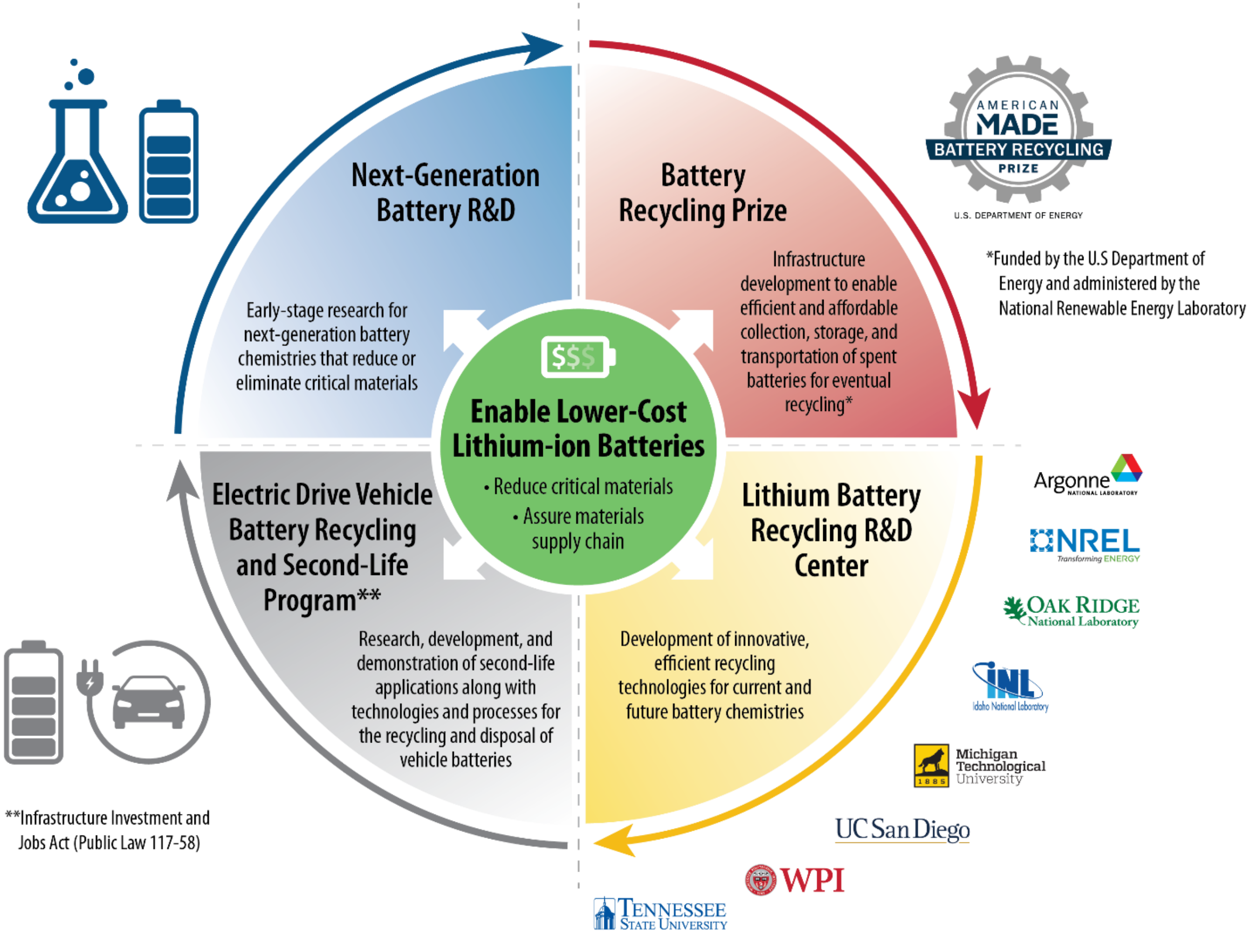
JEFF SPANGENBERGER
Argonne National Laboratory
Group Lead, Materials Recycling R&D
Director, ReCell

Clean Energy States Alliance
September 20, 2023



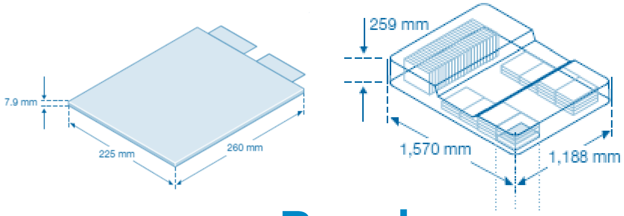
Source: Shutterstock

BATTERIES DECARBONIZE OUR WORLD

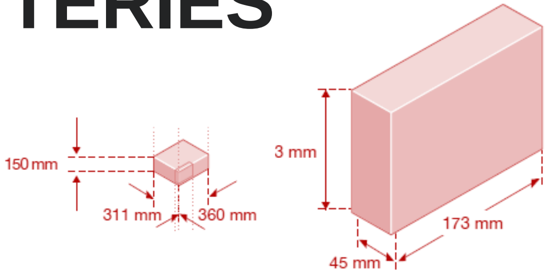


Next-Generation Battery R&D
Early-stage research for next-generation battery chemistries that reduce or eliminate critical materials
Battery Recycling Prize
Infrastructure development to enable efficient and affordable collection, storage, and transportation of spent batteries for eventual recycling*
AMERICAN MADE BATTERY RECYCLING PRIZE
U.S. DEPARTMENT OF ENERGY
*Funded by the U.S Department of Energy and administered by the National Renewable Energy Laboratory
$$$
Enable Lower-Cost Lithium-ion Batteries
• Reduce critical materials
• Assure materials supply chain
Electric Drive Vehicle Battery Recycling and Second-Life Program**
Research, development, and demonstration of second-life applications along with technologies and processes for the recycling and disposal of vehicle batteries
Lithium Battery Recycling R&D Center
Development of innovative, efficient recycling technologies for current and future battery chemistries
Argonne NATIONAL LABORATORY
NREL Transforming ENERGY
OAK RIDGE National Laboratory
INL Idaho National Laboratory
Michigan Technological University
UC San Diego
WPI
TENNESSEE STATE UNIVERSITY
**Infrastructure Investment and Jobs Act (Public Law 117-58)

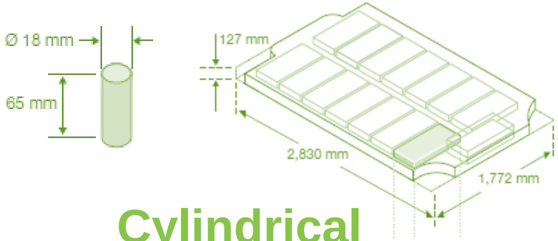
LITHIUM-ION BATTERIES



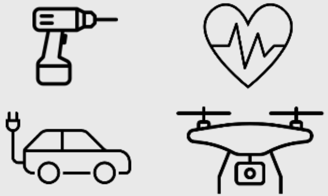
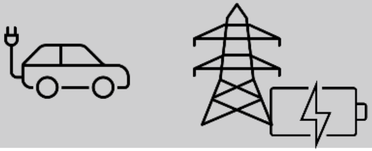
Pouch

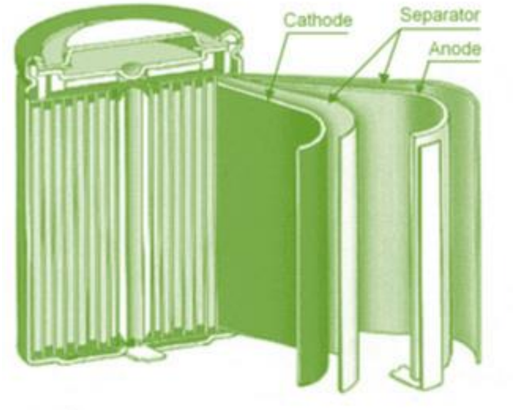


Prismatic



Cylindrical

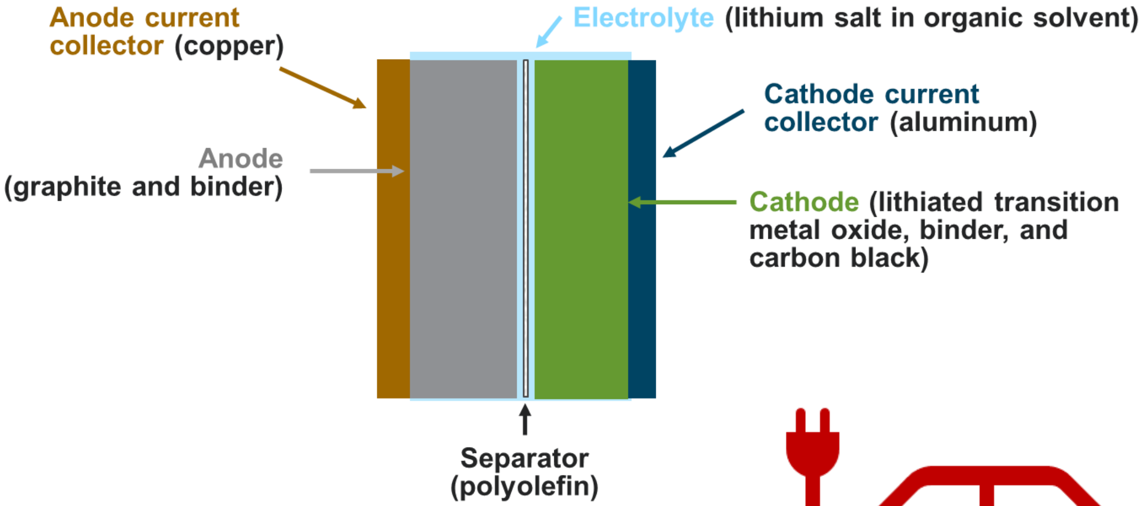
Cathode Materials	Abbreviation	Applications
Lithium Cobalt Oxide	LCO	
Lithium Manganese Oxide	LMO	
Lithium Iron Phosphate	LFP	
Lithium Nickel Manganese Cobalt Oxide	NMC	
Lithium Nickel Cobalt Aluminum Oxide	NCA	
Lithium Titanate	LTO	



Top images: https://doi.org/10.1038/s41586-019-1682-5; Right image: https://www.ntmdt-si.com/resources/applications/afm-raman-characterization-of-li-ion-batteries

WHAT'S IN A BATTERY?

Lithium-Ion Battery Cross Section



Anode	
Graphite	189 lbs.
Copper Foil	43 lbs.

Cathode (NMC622)	
Lithium	23 lbs.
Nickel	115 lbs.
Cobalt	38 lbs.
Manganese	36 lbs.
Aluminum Foil	19 lbs.

Remaining Components	
Electrolyte	79 lbs.
Separator	6 lbs.
Other	554 lbs.

EV Battery Pack (100 kWh)	
Total Materials Weight	1102 lbs.

WE NEED TO MINE A LOT OF MATERIAL

RECYCLING REDUCES HOW DEEP AND HOW MANY PLACES WE DIG

	Li	Ni	Co
For global adoption (kt)[1,2]	10,500	52,000	17,400
US reserve (kt)[3]	750	340	69
World reserve (kt)[3]	22,000	95,000	7,600

1. *Based on 100kWh NMC622 battery from BatPaC 5.0 8March2022*
2. *Assuming 1 billion electric vehicles worldwide*
3. *USGS Mineral Commodity Summaries 2022*

WE CAN RECYCLE TODAY!

- Most feed material is currently manufacturing scrap and consumer batteries
- The products are metal salts that can be used to make new batteries

Hydrometallurgical

Pyrometallurgical

THE RECELL CENTER

Purpose

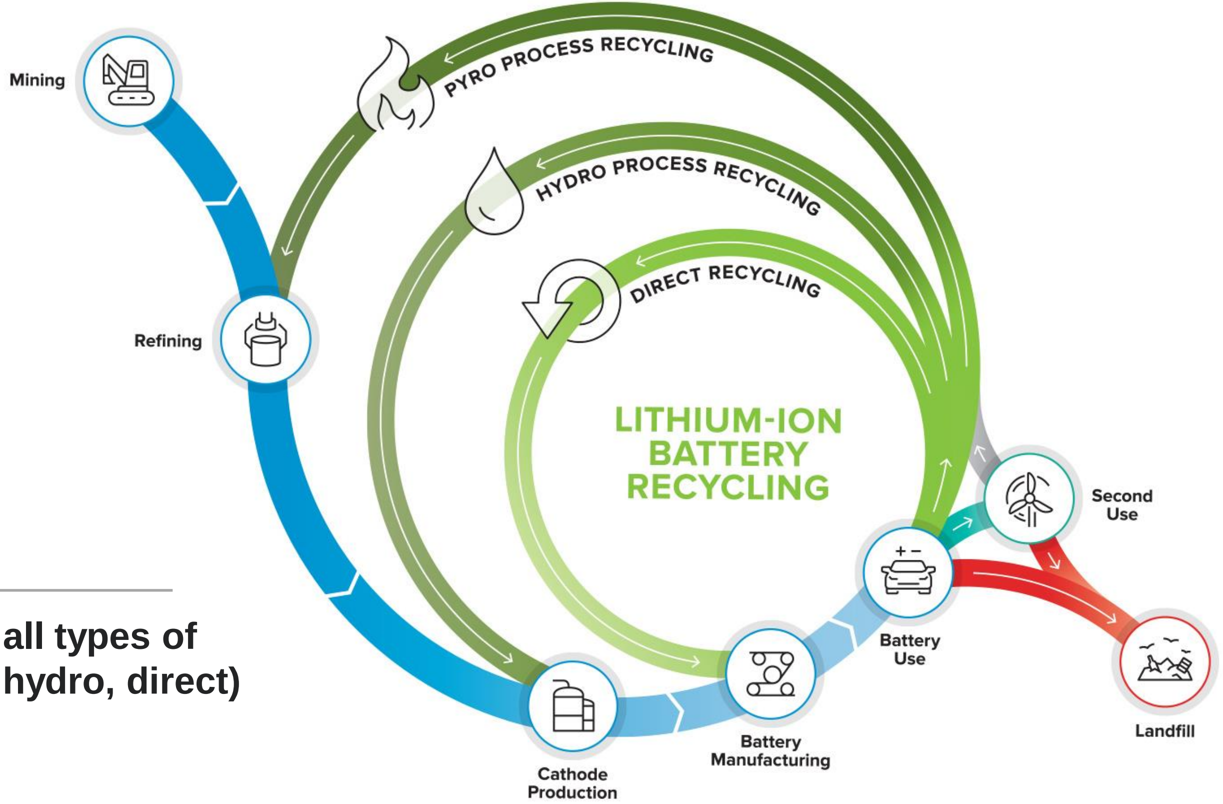
- Foster the continued improvement of cost-effective, environmentally sound processes to recycle lithium-ion batteries
- Research and develop direct cathode recycling
- Bring together experts from all battery recycling areas and bridge the gaps as a team to efficiently address the challenges that we face

Outcome

- Minimize use of the earth's limited resources, reduce energy consumption and increase our national security
- Provide stability to the battery supply chain
- Drive battery pack costs down to DOE's $80/kWh usable energy goal in about 10 years (currently $135/kWh)

LITHIUM-ION BATTERY LIFECYCLE

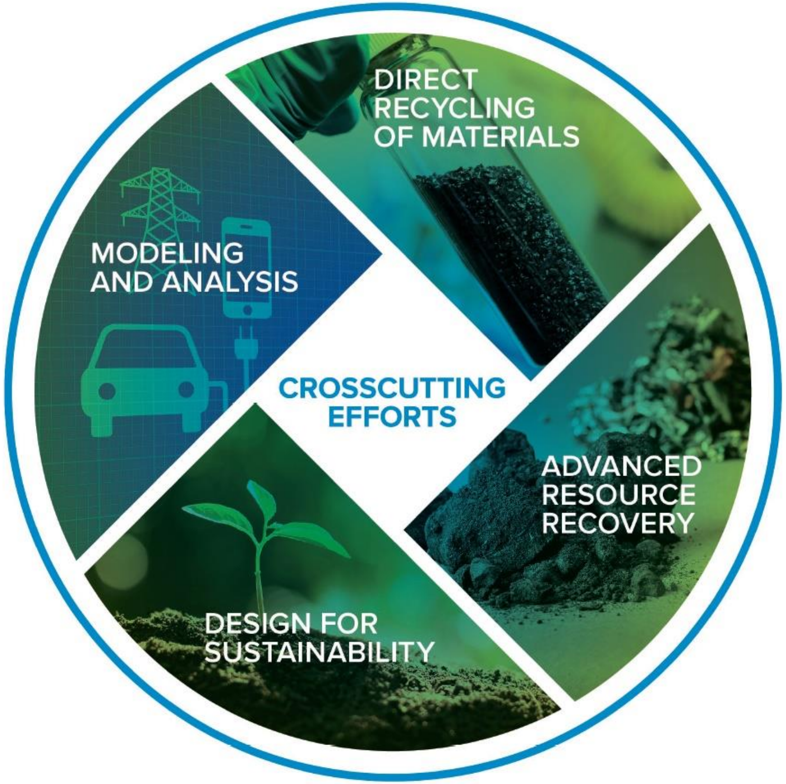
Different Recycling Pathways



ReCell includes all types of recycling (pyro, hydro, direct) and second life

THE RECELL CENTER'S FOCUS AREAS

Addressing Recycling Challenges



Direct Recycling

26 projects

Advanced Resource Recovery

13 projects

Design for Sustainability

8 projects

Modeling and Analysis

11 projects

MAIN OBJECTIVES OF RECELL 2019-2022

- Assemble the collaboration
- Get the word out and engage with industry
- Focus on addressing:
  - Direct Recycling
  - Recovery of Non-cathode Materials
  - Design for Recycling
  - Modeling and Analysis
  - ➢ Crosscutting Projects
- Mostly bench scale testing of new ideas
- Reviewing the projects in EverBatt
- Scaling up the most promising technologies years two and three
- Demonstrate that direct recycling cathode from end of life batteries can be done

ReCell ADVANCED BATTERY RECYCLING

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
VEHICLE TECHNOLOGIES OFFICE

Courtesy Argonne

ACCOMPLISHMENTS FROM RECELL 2019-2022

- Over 20 inventions and 40 publications
- Demonstrating that direct recycling works
  - A simple direct cathode recycling demonstration from 80% capacity material produced a 622 NMC that performed at 175 mA/g
- Demonstrating that direct recycling is a great opportunity for manufacturing scrap
  - Not only is it a great opportunity for cathode, it is a great opportunity for anode

Courtesy Argonne

ReCell ADVANCED BATTERY RECYCLING

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
VEHICLE TECHNOLOGIES OFFICE

MAIN OBJECTIVES OF RECELL IN 2023…

- Grow the collaboration
- Continue to engage industry
- Focus on addressing:
  - Direct Recycling of Materials
  - Advanced Resource Recovery
  - Design for Sustainability
  - Modeling and Analysis
  - ➢ Crosscutting Projects
- Prepare more research space (adding 12,000 sf)
- Construction of a versatile pilot scale plant capable of processing kg quantities of material for evaluation
- Continued review of projects in EverBatt
- Large scale demonstration of direct recycling for manufacturing scrap

RECELL INDUSTRY COLLABORATION MEETING

April 2023

Provided an opportunity for ReCell and industry stakeholders to exchange challenges and ideas.

The meeting included stakeholders from every corner of the vehicle battery value chain

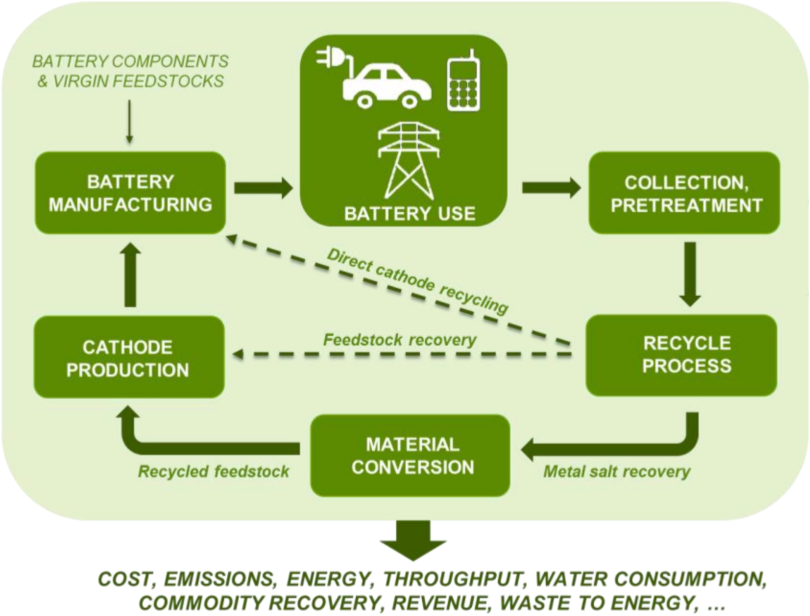
Courtesy Argonne

EverBatt: A Battery Lifecycle Stage Cost and Environmental Impact Tool

The model is a tool that helps compare end of life cost and environmental impacts within, and among, each of the lifecycle stages of a battery and can be used to make better decisions

Example functions:

- Process flow optimization
- Pinpoint process and supply chain hotspots
- Design for reuse, remanufacture, and recycle
- Identify opportunities for improvement
- Identify barriers to commercialization
- Provide a holistic picture of battery sustainability over the life cycle



Available for download at:
https://www.anl.gov/egs/everbatt

ReCell
ADVANCED
BATTERY RECYCLING

www.recellcenter.org

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

VEHICLE TECHNOLOGIES OFFICE

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EV Battery Recycling & Reuse

Jonathan Harter- Electrical Engineer, Oak Ridge National Laboratory- Electrification and Energy Infrastructure Division

Email: harterjj@ornl.gov

Clean Energy States Alliance Webinar
9/20/2023

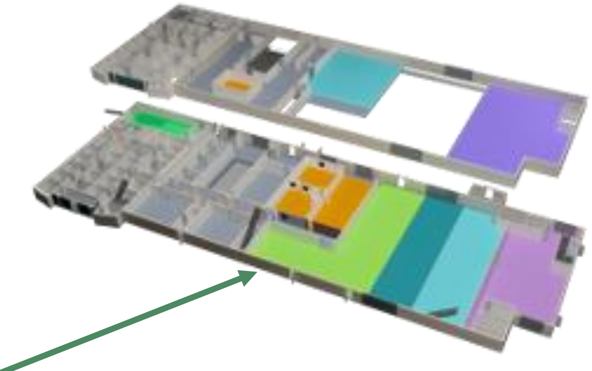
ORNL is managed by UT-Battelle LLC for the US Department of Energy

Discussion Points

- Current ORNL projects
- Technology Gaps
- Technology Thrusts
- Reuse Opportunities and Research
- ORNL Validation Capabilities

ORNL Battery Recycling Research Lab Current Projects

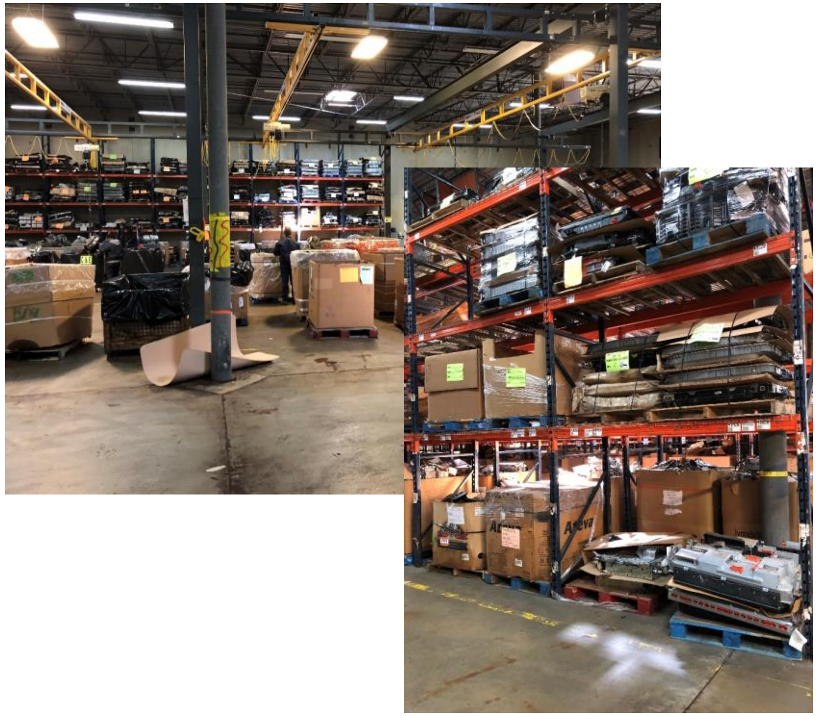
- Precise Cell/Group Diagnostics
- Advanced Fastener Removal
- Partner with Princeton NuEnergy Inc. Bipartisan Infrastructure Law Automated Disassembly Project



Grid Research Integration & Deployment Center at ORNL

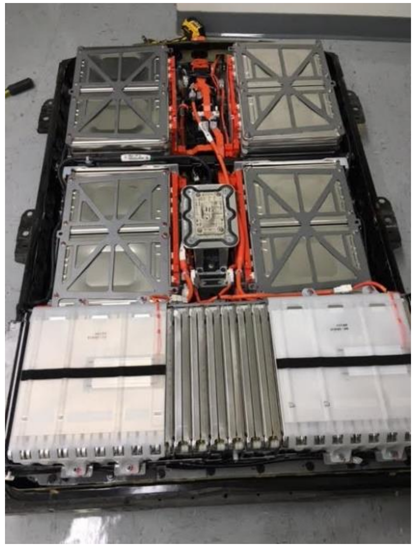
ORNL Battery Recycling Research Lab

Technology Gaps in EV Battery Recycling



2013 Ford Focus

2017 Chevy Volt



2013 Nissan Leaf

Shredded Pouch LIBs

Warehousing due to long battery processing/decommissioning

Manufacturer Diversity

Manual Disassembly and Shredding

Technology Thrusts

Automated Disassembly

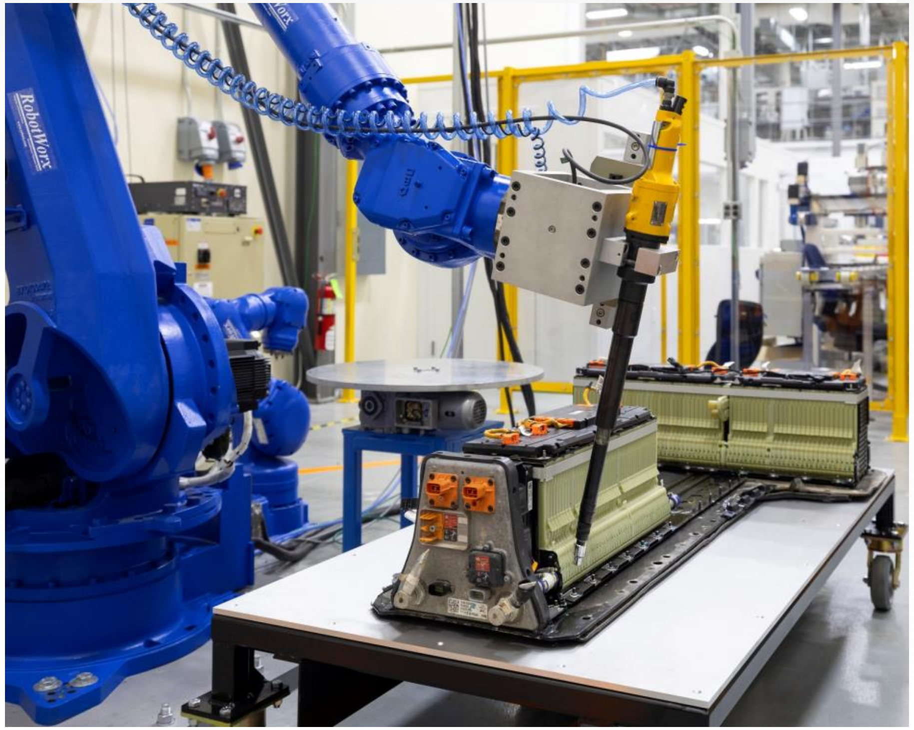
- Fastener extraction
  - Rapid removal
  - Corroded/tampered
  - Diversity
- Machine Vision
  - Large Field of View
  - Precise location/identification
- System Flexibility
  - Old vs. new packs
  - Make/model
  - Multi chemistry
  - SOC/SOH

Advanced Diagnostics

- Cell isolation from pack
- Premature Failure Mechanisms
- SOC/SOH determination

Reuse, Refurb, Recycle

- Multi-chemistry
- Damage free removal
- Power electronics developments



Why Disassembly, Why Automated? Cake example

Disassembly of Cake

1. Pick off round and eyeball sprinkles
2. Remove black icing from top and base
3. Remove purple icing from outside edge
4. Unstack layers of cake, top to bottom

Options:

- Eat the separated cake
- Rebuild the cake
- Rebuild 4 cakes
- Reuse parts to build a new cake

Shredding eliminates direct reuse opportunities!

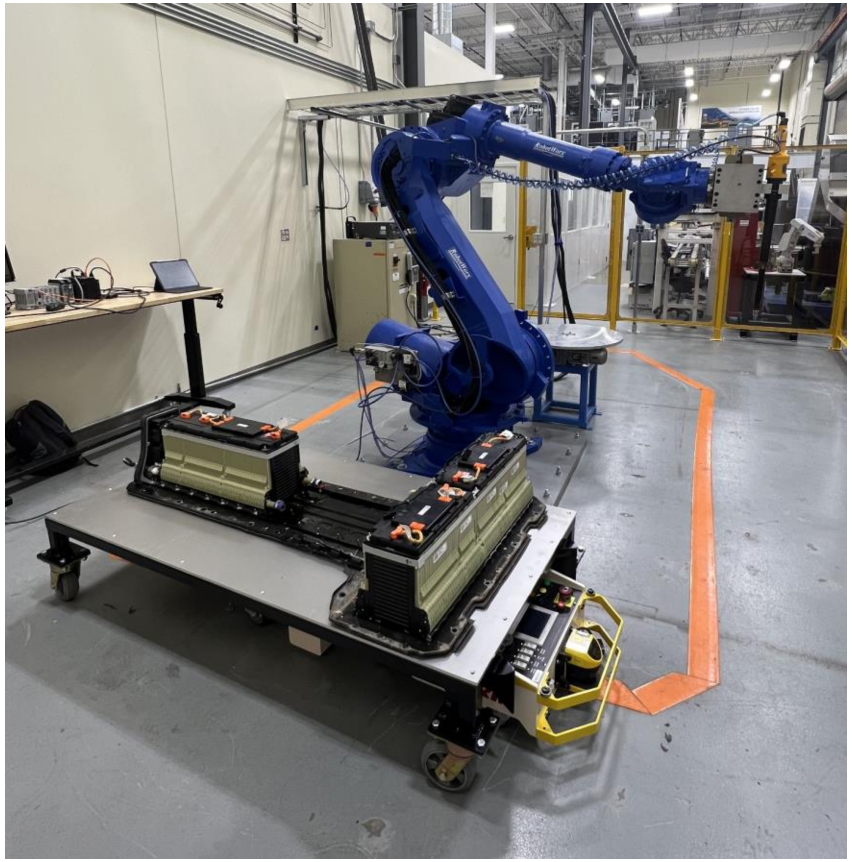
Disassembly Vs. Shredding

Chevy Volt Modules and structural components

Recycled Materials: Aluminum Foils, Copper Foils, NMC622 Cathode, Graphite (Anode)

Shredded Pouch Cells

Why Disassembly, Why Automated?



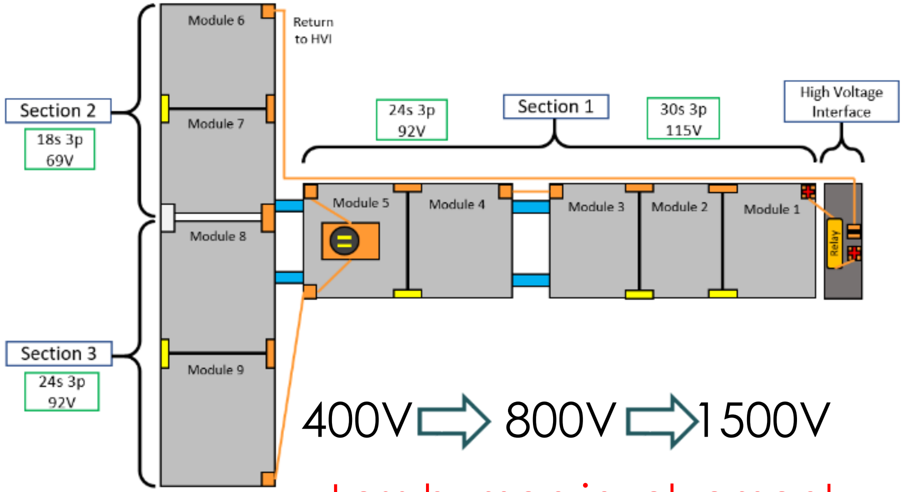
<u>Pack Disassembly</u>

1. Visually inspect battery shipping container for damage if present.
2. Unpackage battery and perform second inspection of the battery.
3. Identify battery, fill out Energized Electrical Work Permit (EEWP), and fill out Hazard Analysis for Electrical Work form.
4. Don properly rated PPE for the nominal voltage rating of the battery.
5. Perform live-dead-live multi-meter test and test for external voltage at battery interface.
6. Remove manual safety disconnect plug (MSDP) and measure battery interface for external voltage.
7. Remove coolant if present and safe to do so.
8. Connect Midtronics battery service system to battery interface to determine voltage and battery health.
9. Discharge battery to desired voltage level.
10. Remove external connectors (High Voltage Interface and Communication Connectors)
11. Extract external cover fasteners.
12. Remove cover and observe battery interior. Specifically look for battery swelling, thermal indications, and mechanical damage.
13. Use rated multi-meter to measure section and module voltage levels.
14. Isolate and reduce high voltage hazards by removing HV bus bars.
15. Disconnect module to module links.
16. Remove modules from container and place on insulated surface.
17. Continue disassembling modules to cell level.
18. Extract cells from modules and place on insulating surface.

Note: Place insulating tape on energized conductors or covers to prevent unintentional contact.

Why Automated Disassembly, continued?

- Safety
  - High Voltage
  - Hazardous Chemicals
  - Thermals
- Manual labor ease
  - Stacks can weigh hundreds to thousands of pounds
- Throughput
  - Millions of battery stacks are being manufactured



Less human involvement at higher voltage

New Hummer EV batteries weigh as much as a small sedan

Chevy Volt battery disassembly at ORNL, dressed in full PPE

OAK RIDGE National Laboratory

Why do we need advanced diagnostics?

- Further enables reuse opportunities
- Could provide premature failure warnings
- More accurate SoC and SoH, better range/fuel gauge
- Prevents premature end of first life or discard
- Saves money, raw materials, time, energy, manufacturing and so on…

Let’s compare to a “doctors' checkup”

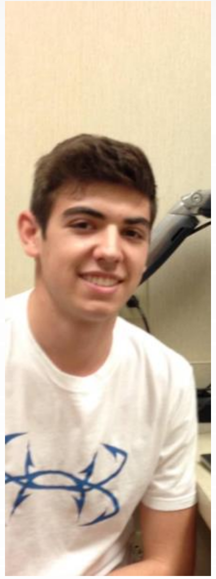
Let's compare a basic and advanced health diagnostic of a human and an electric vehicle battery stack

Basic checkup

- Temperature
- Responsiveness
- Visual
- Verbal

Advanced Diagnostics

- Blood, urine test (chemicals)
- X-Ray, MRI, CT, (machine imagery)
- Electrical Tests



Jonathan Harter appears fine, but further inspection shows a broken clavicle, ski trip 2016

Basic EV Test

- Voltage of battery system, module, **groups** of cells
- Current of system
- Charge/Discharge

Advanced Diagnostics

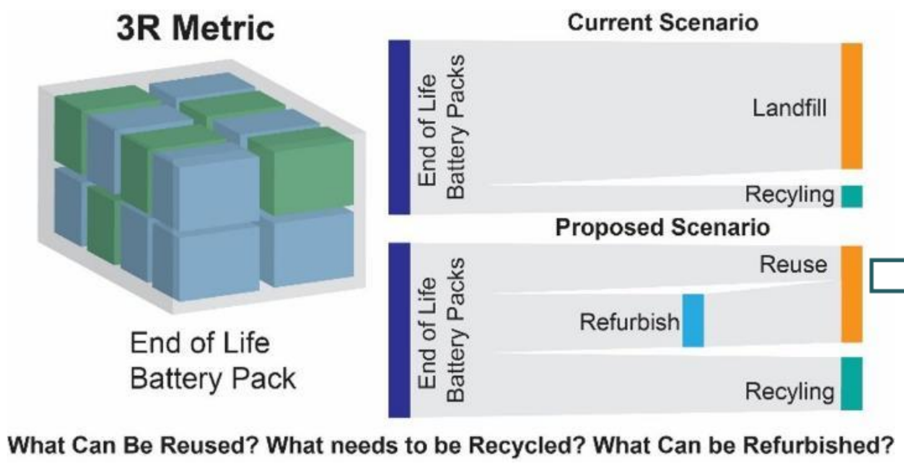
- Non-invasive imaging
- Electrochemical Impedance Spectroscopy
- Ultrasound

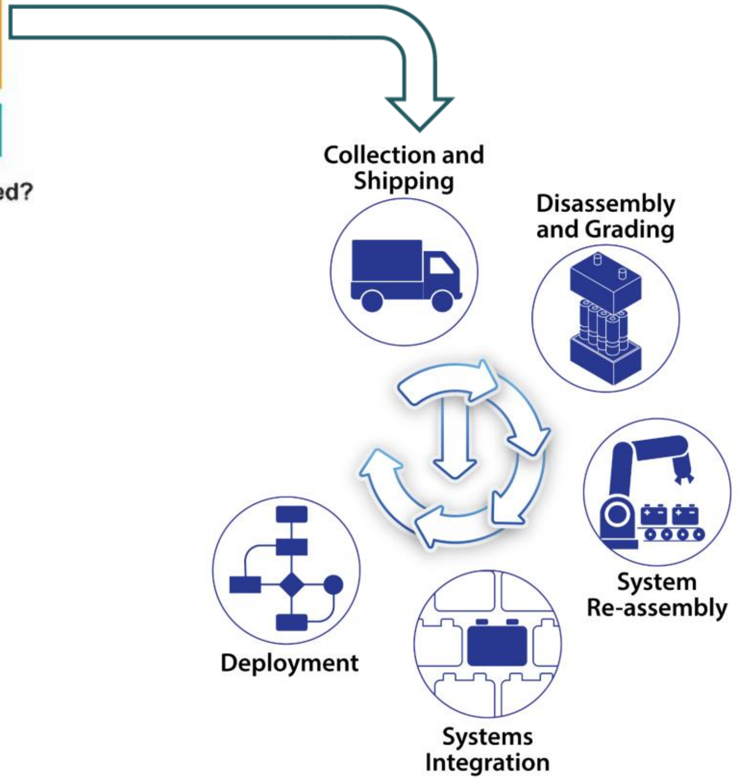
EV battery appears fine, but further inspection shows electrode bending

Reuse, Refurb, Recycle

What kind of data do we need to decide?

- Metrics
  - Capacity
  - Age
  - Cycles
- Support
  - Warranty
  - Charging
  - Part availability
  - Service Technicians
- Secondary Market





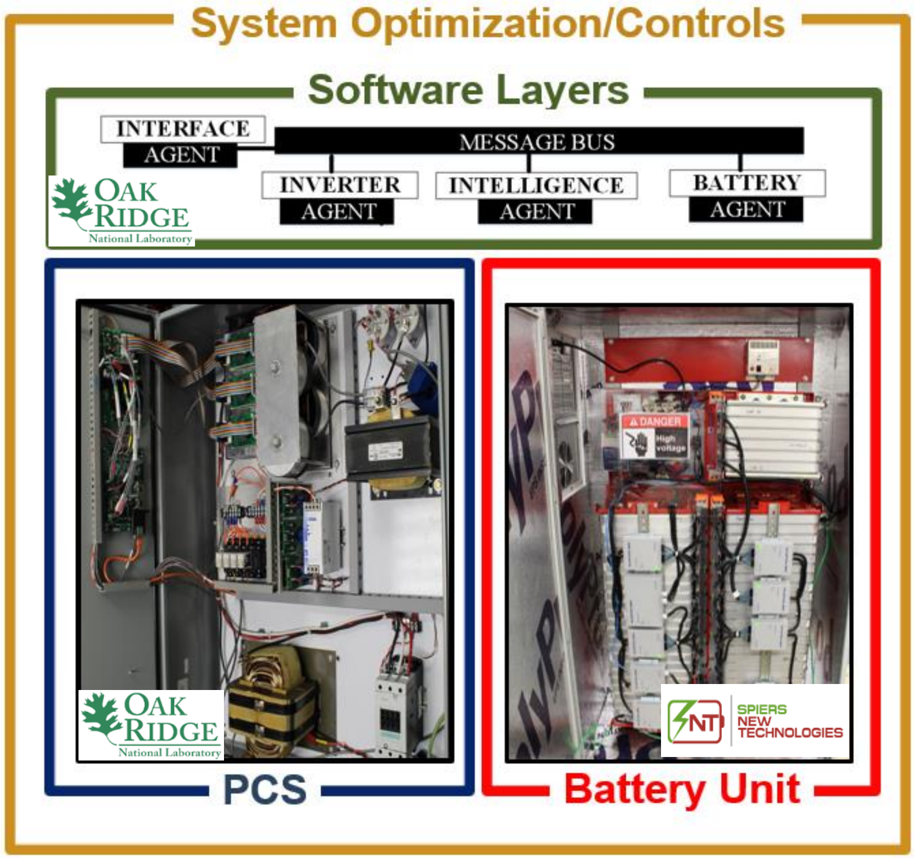
Other thoughts on reassembly

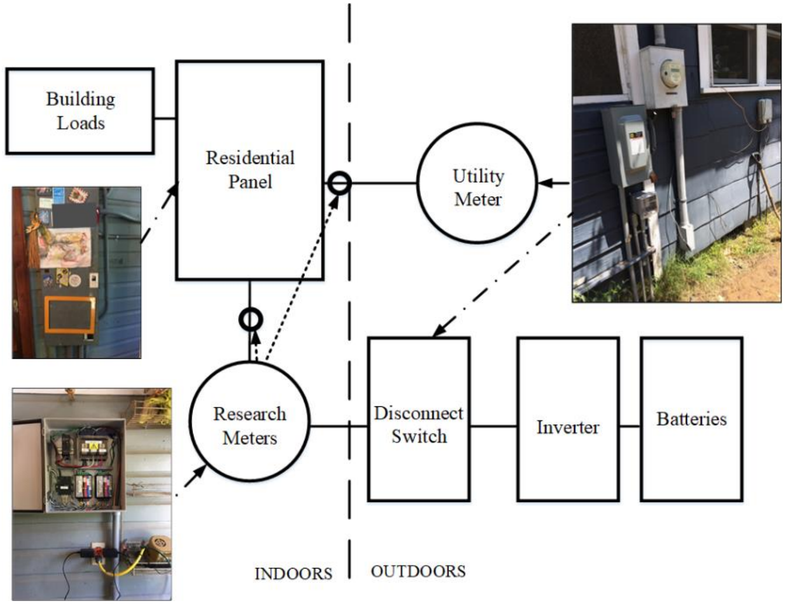
- Many of the battery modules require compression
- Packaging of modules is often in a different form factor than that of the vehicle (standing up)
- Ease of assembly and disassembly in terms of modularity.
- Other auxiliary systems to be included for safety

SNT Watt Tower

Collaborative Demo for Secondary Use and Use Case Validation

- ***Objective*: Develop and deploy a secondary use residential scale system**

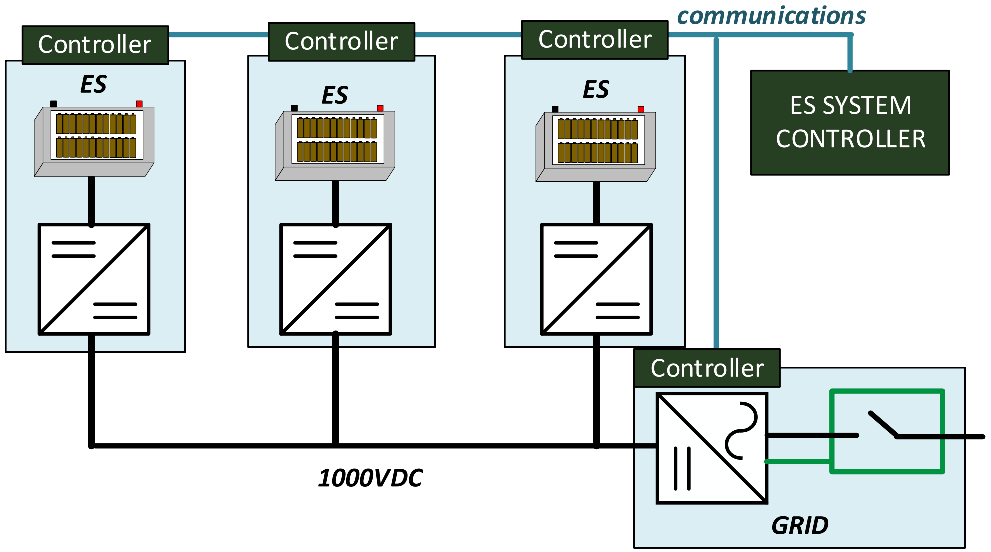




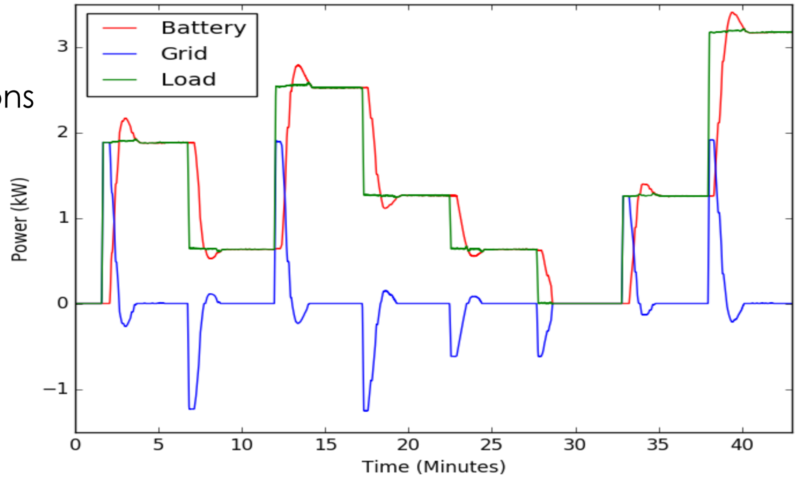
Secondary use system developed with Spiers New Technologies, tested in lab, and deployed.

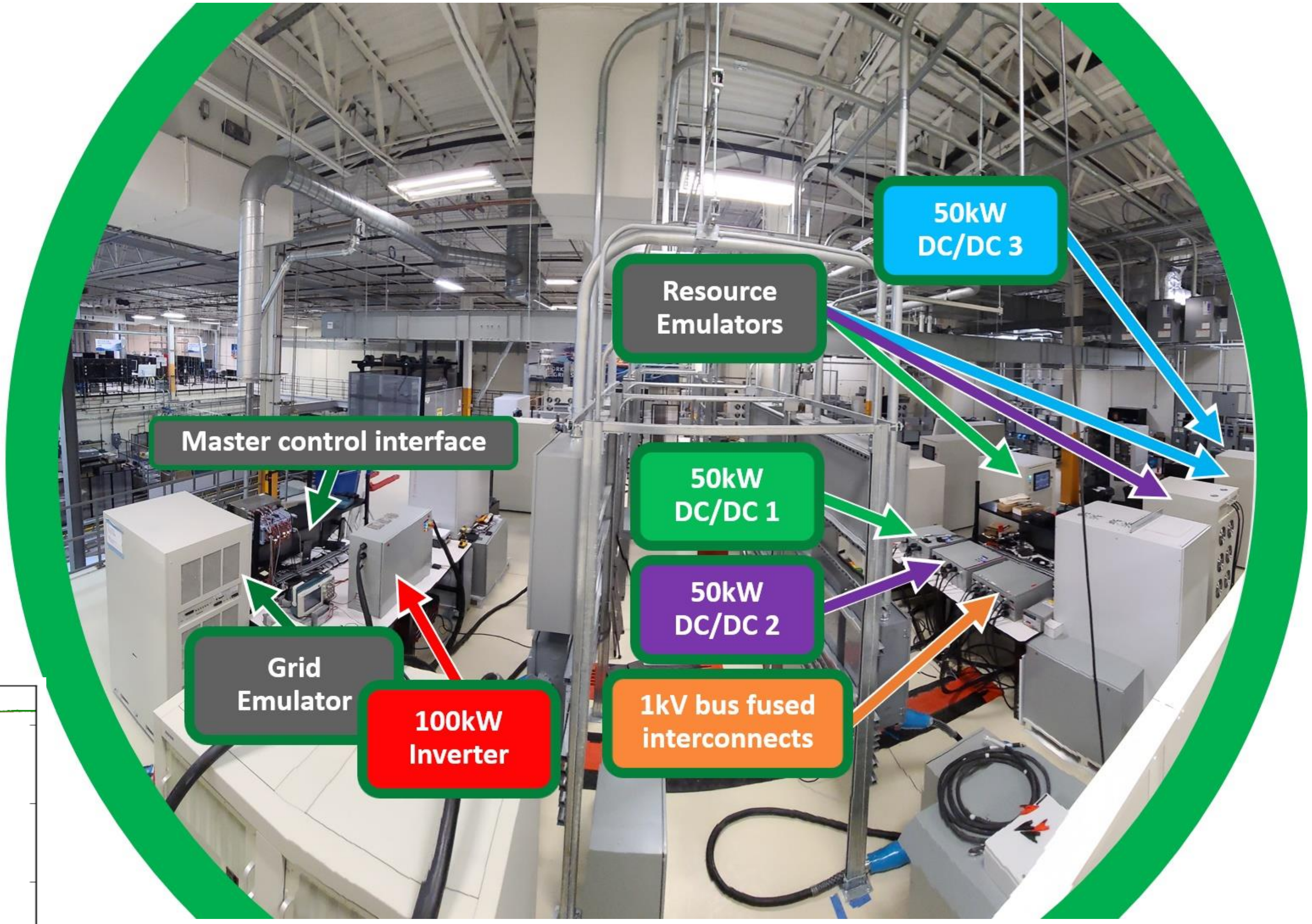
M. Starke et al., "Residential (Secondary-Use) Energy Storage System with Modular Software and Hardware Power Electronic Interfaces," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), 2019, pp. 2445-2451.

Integration of Energy Storage Systems



- Plug and play energy storage integration for different systems.
- Key Considerations:
  - Safety
  - Cost
  - Operations





- *M. Starke et al., "Secondary Use-Plug-and-Play Energy Storage System Composed of Multiple Energy Storage Technologies," 2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2021, pp. 1-5.*
- *M. Starke, S. Campbell, B. Dean and M. Chinthavali, "An Intelligent Power Electronic System for Secondary Use Batteries," 2022 IEEE Electrical Energy Storage Application and Technologies Conference (EESAT), Austin, TX, USA, 2022, pp. 1-5.*

Challenges and food for thought

- Diversity of EV battery stacks, modules, and cells
- Joining technologies: welds, adhesives, one and done connectors- are there other low impedance, easy to separate, safe, and robust methods?
- Volume of End-of-Life batteries
- Original Equipment Manufacturer standardization and design for disassembly
- Reuse/refurb certifications and opportunities
- Are hydrometallurgical and pyrometallurgical separation methods the right investment for the planet?
- Where does disassembly need "help", is there a hybrid approach?

THANKS! Reach out for further discussion and questions.