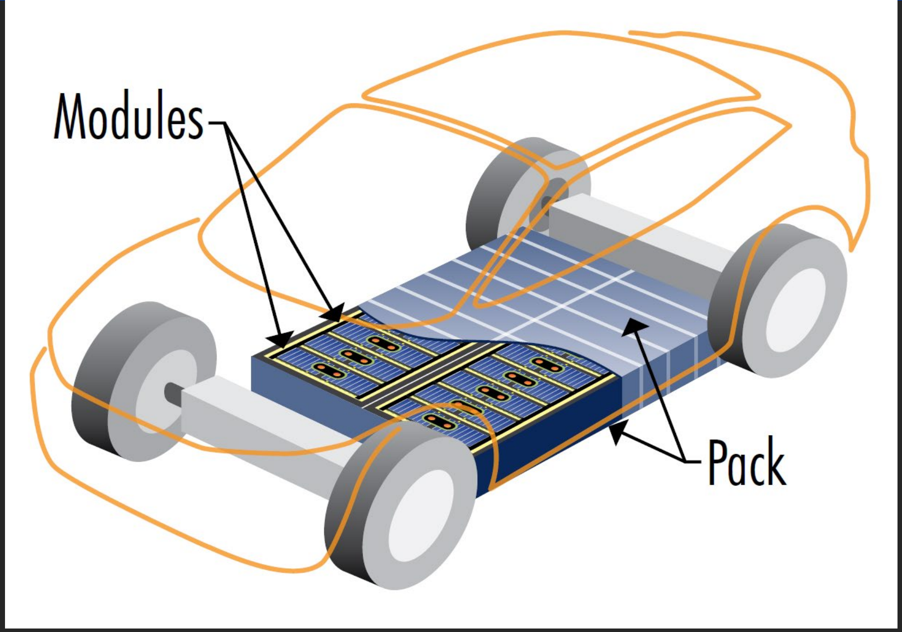
End-of-Life Management for Battery Energy Storage Systems

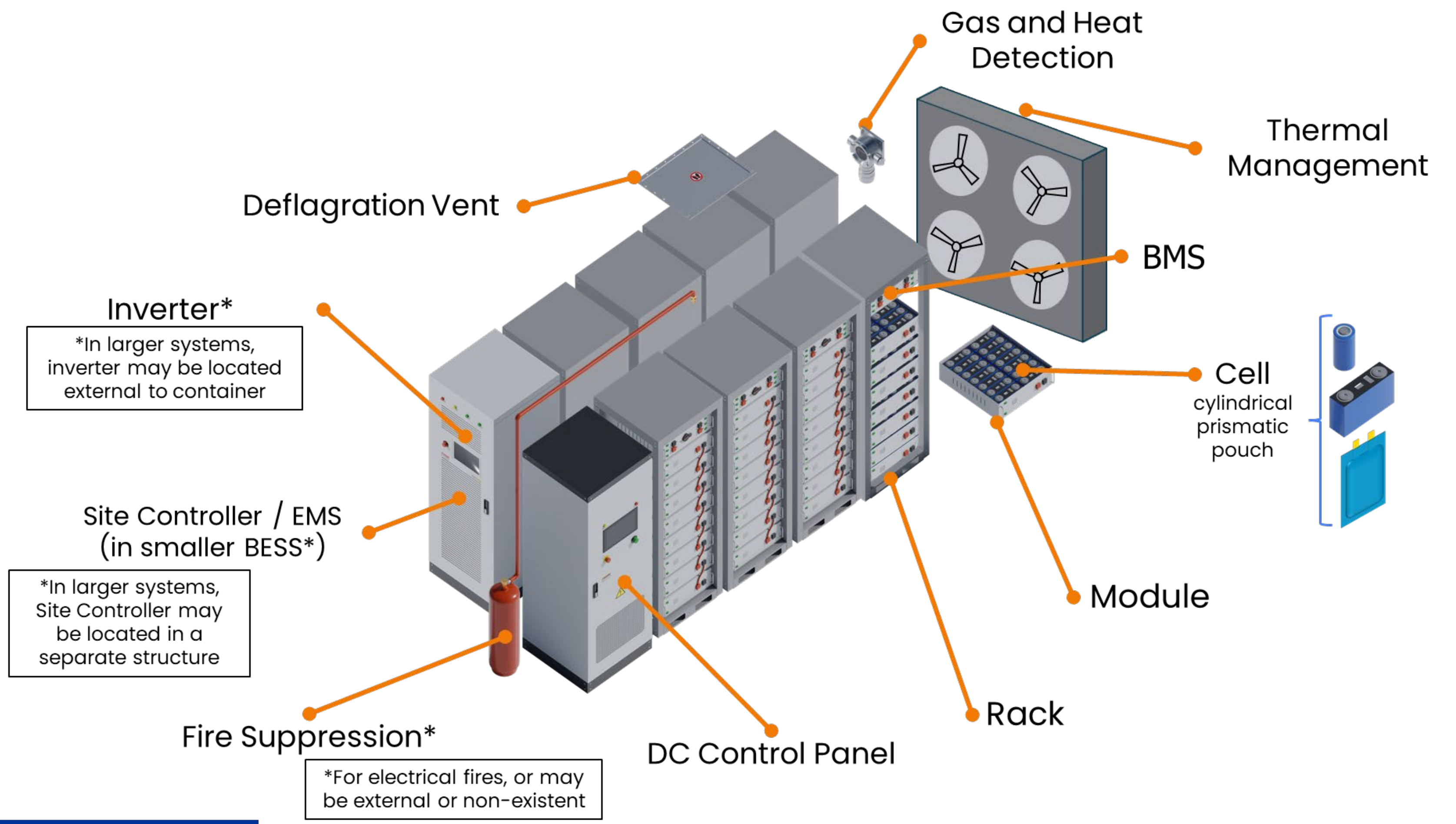


Stephanie L. Shaw, Ph.D., EPRI
Taylor Kelly, Ph.D., EPRI

USWAG Decommissioning Workshop
May 21, 2025

Battery Energy Storage System (BESS)

Inside the Cabinet



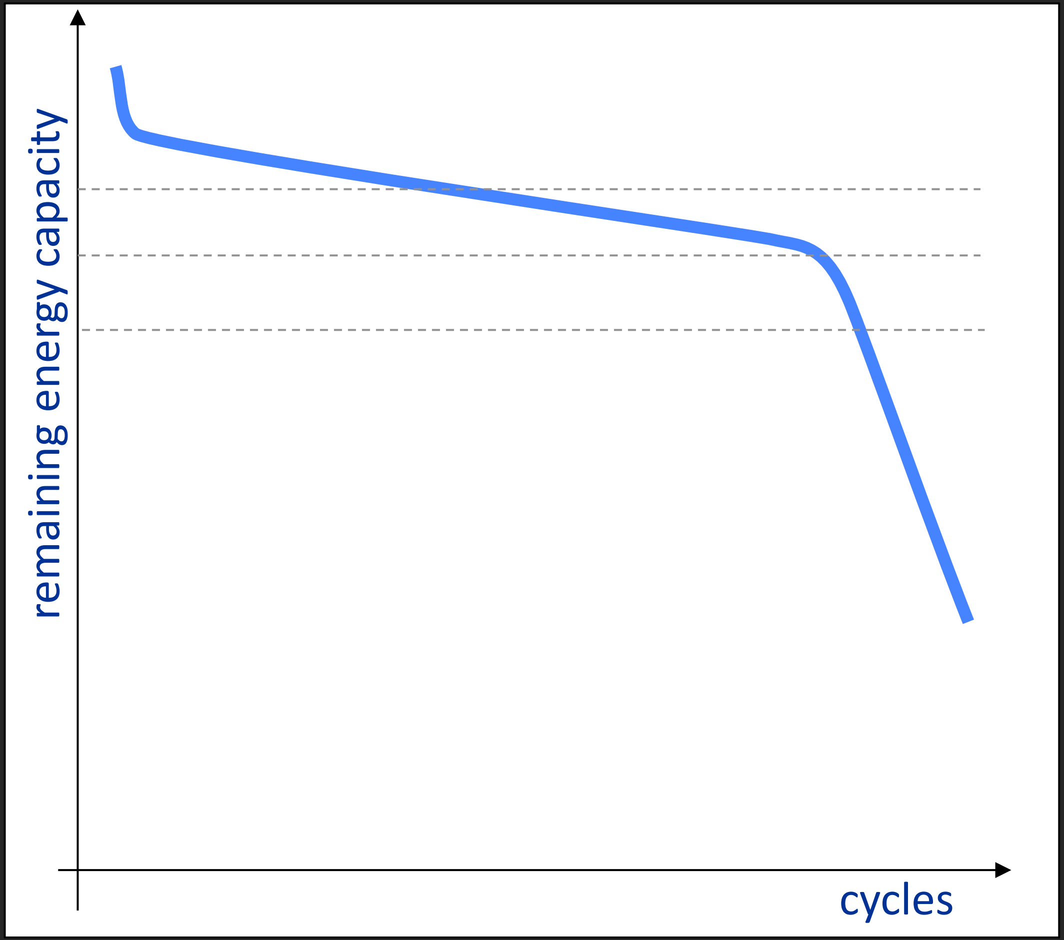
Source: Duke Energy

Site Layout

EPRI

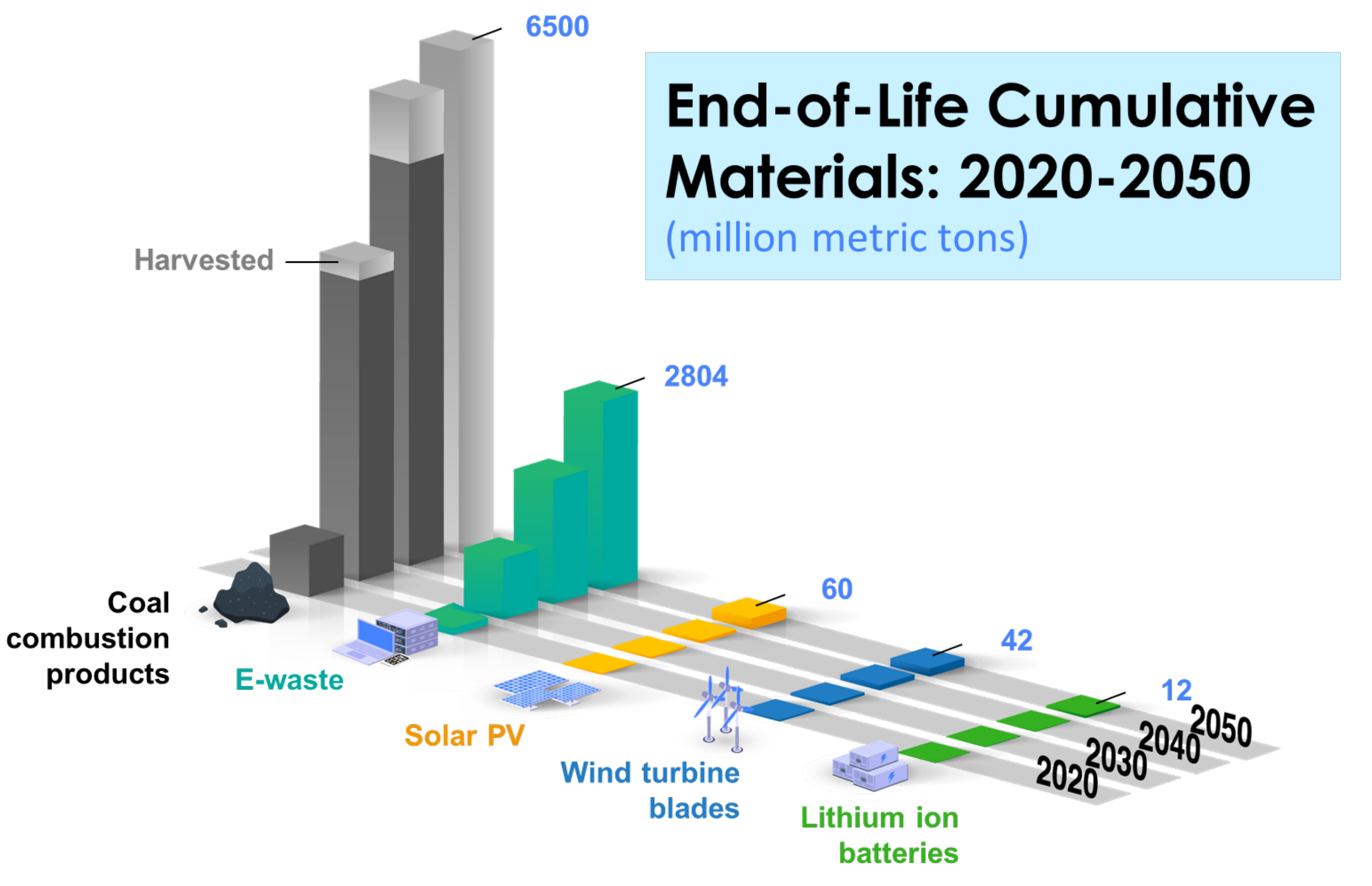
When has a battery reached its end of life?

- If the remaining energy capacity falls below what is needed for its application
- If the remaining energy capacity falls below 80%
- If the battery is out of warranty
- If the battery experiences a failure (fire, short circuit, etc.)



Batteries may still hold 70-80% initial energy capacity at EOL

Putting End-of-Life Materials Streams in Perspective



ITU & UNITAR, 2024; World Economic Forum, 2019; WWCCPN 2024; Liu et al. 2017; IEA 2021; IRENA & IEA-PVPS 2016; EPRI

Scale

- PV, wind, and battery waste streams are projected to remain much smaller than common wastes
- Volume may be an important factor for landfilled material, such as wind turbine blades

Disposition

- Increasing beneficial use can harvest the full CCP waste stream by 2050
- Wind turbine blades are non-hazardous, and recycling pathways are emerging
- PV modules may contain trace amounts of hazardous material, but are generally non-hazardous and recyclable
- Batteries are a recyclable universal or hazardous waste due to flammability, which can be controlled

While they are relatively material-intensive, renewable energy and storage end-of-life waste streams demonstrate many benefits vs. fuel intensive technologies

End-of-Life Management of Lithium Ion Batteries

Planning for decommissioning stationary energy storage or co-located sites is a necessity

- Increasingly required for permitting
- Costs can be unexpectedly high
- Logistics are confusing

3002021775 ; 3002020006; 3002006911; 3002020594
3002023651; 3002022301; 3002027944; 3002031225

Recycling, reuse, associated costs, and regulations are evolving rapidly

- Recent investments are driving market development
- Options for large-format modules are increasing
- Costs vacillating

3002023651; 3002022301; View Presentation; 3002028618;
3002023958; 3002029553; 3002031206 ; 3002029517

Increasing focus on circularity provides environmental and financial benefits

- Recycling reduces raw critical material demand
- Utilities can enhance battery circularity
- Evolving end-of-use management includes site repurposing

3002020568; 3002023085; 3002025849; Schichtel et al., 2022
JAWMA ; 3002028421; 3002029101 ; 3002029483

Case Studies

- Commissioned 2015
- Research collaboration with EPRI and Southern Company
- 1 MW/2MWh Li-Ion. LG-Chem (battery), ABB system controls
- Planned applications: Renewable Integration, Peak Shaving & Voltage Support

Equipment :

- Battery container with 39 Battery Racks
- ABB Power Converter
- 1500kVA Transformer
- CT/PT Cabinet (current transformer/ potential transformer)
- Aux Power Panel

Free Public Report: 3002027944

Stationary Storage Decommissioning Process

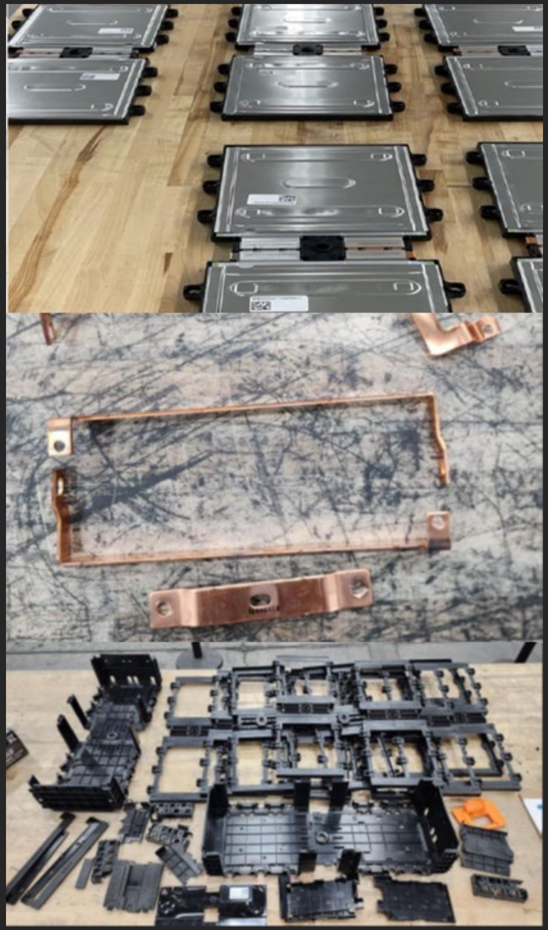
- Collect System Information
- De-energize & Disconnect
- Module Removal & Packaging
- Loading for Transport (Crane/Forklift Rental)
- Transportation and Shipping
- Non-Battery Components Recycling and Reuse
  - Scrap Metal and Electronics Recovery
- Specialized Battery Recycling or Sorting Facility
  - Stored until ready to process
  - Module Disassembly
  - Cell Recycling & Material Recovery

Lessons Learned

- **Over-prepare.**
  - Sitewalk
  - Project plan
  - Ship supplies ahead of time
- **Find local off-takers**
- **Right-size use of expensive equipment**
- **Bring all paperwork.** No office on site!
  - Project plans
  - JHA forms
  - BOLs
  - Packing lists
  - DOT Hazmat Labels – bring rolls. Store extra rolls in your project kit.
- **Minimize time onsite**
- **Integrators and owners: Save the paperwork!**

Cedartown Decommissioning Overall Cost*

Spend Category		Cost
Logistics	**$58,300**	
Extra-long flatbed lowboy w/pilot car		$42,400
Tractor-trailer truck (53’ trailer) (2)		$11,000
Box truck (25’ trailer)		$ 4,900
Equipment Rented	**$22,313**	
Crane, 2.5 days		$20,283
Forklift		$1,530
Generator		$500
Travel, Lodging, Food, etc.	**$12,838**	
Labor	**$12,240**	
Tools & Materials Purchased	**$2,457**	
Grand Total	**$108,147**	

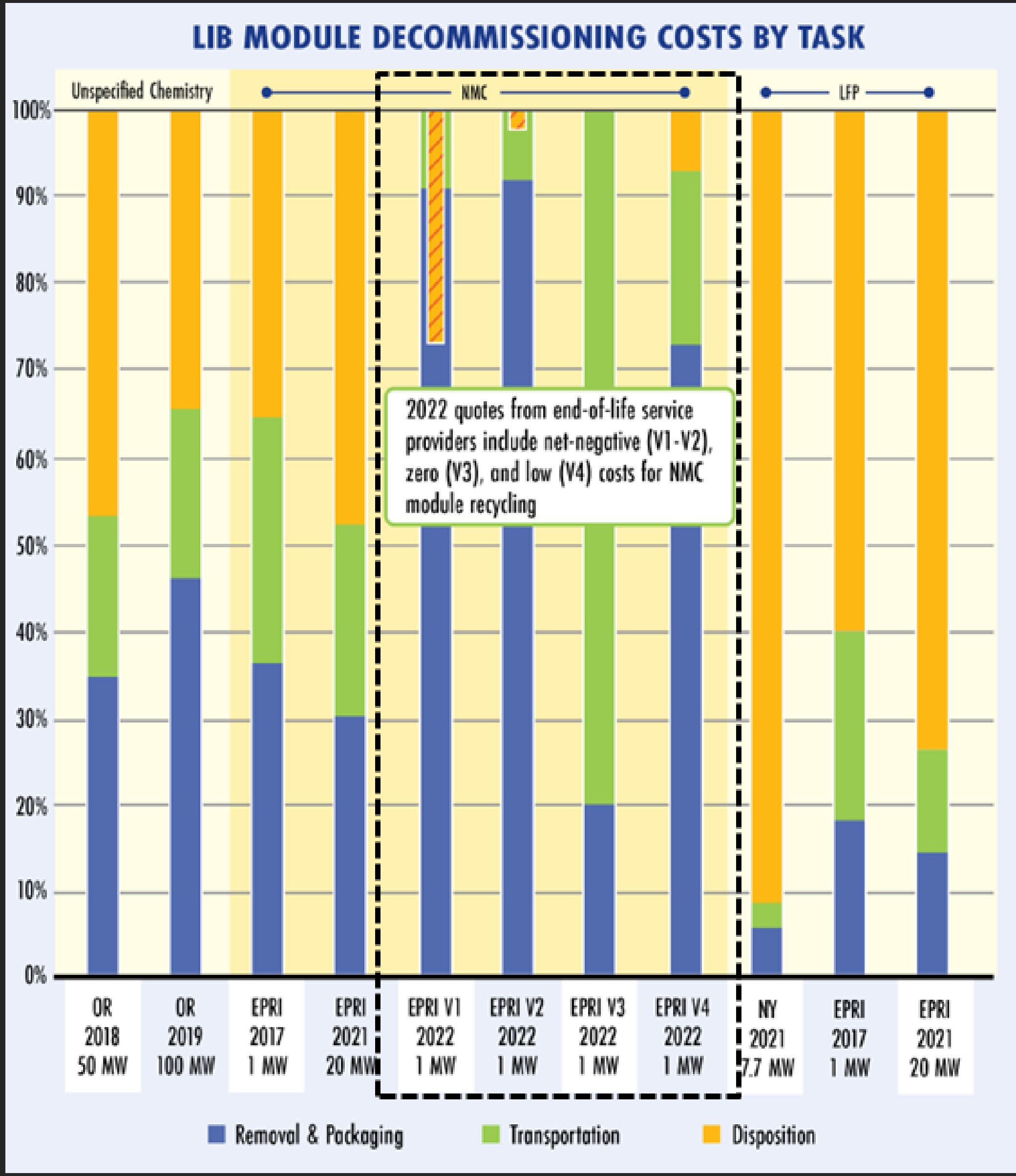


- Metal content is the biggest variable in determining total recycling value
- Documentation (NMC) vs reality (LMO + NMC)
- Resale of modules to bring greater financial return

**Recycling and package materials not included*

Battery Recycling Markets Fluctuating: Availability and Cost

- EPRI receiving quite variable quotes for net recycling value
  - ***Salvage value is a driver:*** NMC battery value ranged from $1 to >$1.50 / kg over previous year
  - ***But recycling capacity and facility operations are now bigger drivers***

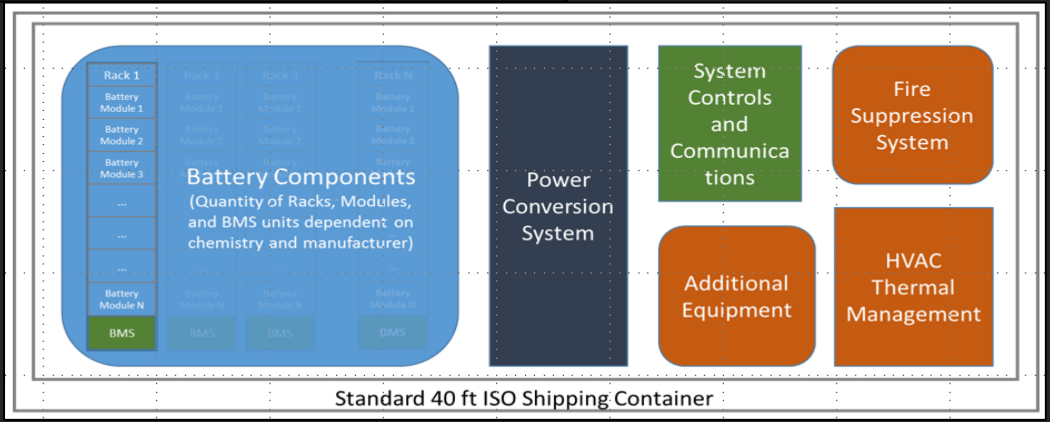


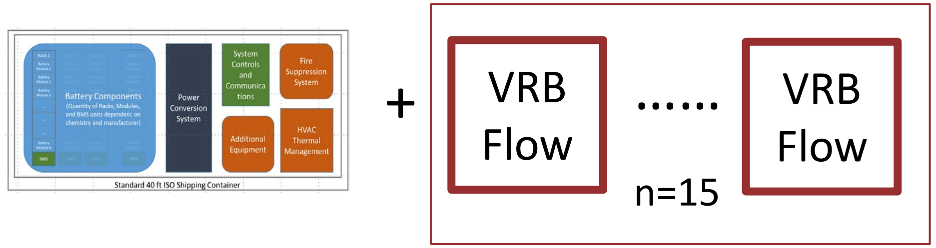
Material Destinations Primarily Reuse

Item Description	Qty	Unit	Reuse / Recycle	Destination	Rationale
BATTERY CONTAINER	1	Ea.	Reuse	Redwood Materials campus, reused to house information technology (IT) equipment	Still useful in current form with minor modifications
- Batteries	772	Modules	Reuse & Recycle		
- Group 1	60	Modules	Reuse	Redwood Materials R&D	Batteries have 86% state of health & remain useful in current form
- Group 2	10	Modules	Reuse	3rd party buyer	Batteries remain useful in current form; selling to test market value
- Group 3	702	Modules	Recycle	Redwood Materials cathode active material production	Redwood's primary business; known value, least-risk disposal option
- Racks	39	Ea.	Recycle	3rd party buyer	Custom-built racks have non-standard dimensions, fewer reuse applications & buyers
- HVAC equipment	1	System	Reuse	Remaining in container (Redwood IT trailer)	Remaining useful life in current form
- Fire Suppression	1	System	Reuse	Remaining in container (Redwood IT trailer)	Remaining useful life in current form
PCS & ASSOCIATED EQUIPMENT	1	Cabinet	Recycle	3rd party buyer	Low market value, high transport cost. Seen by market as obsolete & project-specific
- 3-Phase Distribution Transformer	1	Unit	Reuse	3rd party buyer	Value well understood with large, well-established market & buyer pool
CABLES & WIRING	1083	Kg	Recycle	Redwood Materials battery copper foil production	Non-standard lengths due to previous use; comparatively high commodity value

Breakdown Cost Methodology: Flow Batteries at LADWP

2017: 1MWh Container





2021: 20MW/ 10MWh LIB + Vanadium Redox

LIB 2023 cost of $1.2M (30% Dismantling/Packaging - 25% Transportation - 45% Recycling)

Selected Assumptions:

- **Site Labor** (Electrical, Module Removal, etc): $150/hr, $200 per diem
- **Off-site Labor** (Balance of Plant Dismantling): $60/hr, no per diem
- **Other Costs** (Transportation, cranes): 2.5% inflation rate for 2030 costs

Reports: 3002023651 and 3002023958

Flow Battery + LIB BESS Cost Estimate

Estimated System Cost Components for the Mixed Chemistry Energy Storage System (Costs displayed as positive numbers, end-of-life values are displayed as negative numbers)				
Item (Description)	On-site Dismantling and Packaging for Shipment	Transportation	Equipment Recycling	Subsystem Total
Preparation and Crane Cost				**$66,000.00**
System Disconnection (Initial system disconnection in preparation for disposal.)	$21,600.00	$0.00	$0.00	
Crane for System Removal (Crane for 1 days to remove battery containers.)	$14,400.00	$30,000.00	$0.00	
Vanadium Flow Battery				**$56,350.00**
Flow Battery Containers (15 units) (Based 10 kW, 30 kWh units)	$7,200.00	$15,000.00	$33,150.00	
NEXTracker Network Communications Unit (System communicaiton system.)	$900.00	$0.00	$100.00	
Lithium Ion Battery Unit				**$35,150.00**
Lithium Battery Cabinet with Modules (Standalone outdoor rated unit with 8 racks and 72 modules.)	$3,600.00	$1,200.00	$24,000.00	
Power Conversion System Based on Dynapower MPS250-800)	$3,600.00	$750.00	$2,000.00	
Balance of System				**$7,100.00**
Eaton Switchgear Cabinets (Computer Interface, Switches)	$3,600.00	$1,500.00	$2,000.00	
Post-site Work				**$3,600.00**
Post Removal Site Cleanup (Final site clean up.)	$3,600.00	$0.00	$0.00	
Subtotals	$58,500.00	$48,450.00	$61,250.00	
Total Estimated System Disposal and Recycling Cost				**$168,200.00**

Preparation and Crane Cost Estimate $66,000

Vanadium Flow Battery Cost Estimate $56,350

Lithium Battery Cost Estimate $35,150

Total Cost Estimate $168,200

Plus any site considerations

BESS Decommissioning Plans

- **Project details**: location, size, battery technology, general purpose, and anticipated lifetime
- **Parties and roles**: project owner/assignee, landowner, locality, and authority having jurisdiction (AHJ)
- **Scope of work**: schedules, tasks, and outcomes relating to mobilization, equipment and infrastructure removal and disposition, and site restoration
- **Estimated cost**: labor and other costs for site preparation/restoration and for disassembly, transportation, reuse, recycling, disposal, and restoration tasks
- **Performance guarantee**: contractual/financial commitment to ensure decommissioning in the event of abandonment or at end of life

Decommissioning planning can help mitigate end-of-life risks and cost uncertainties

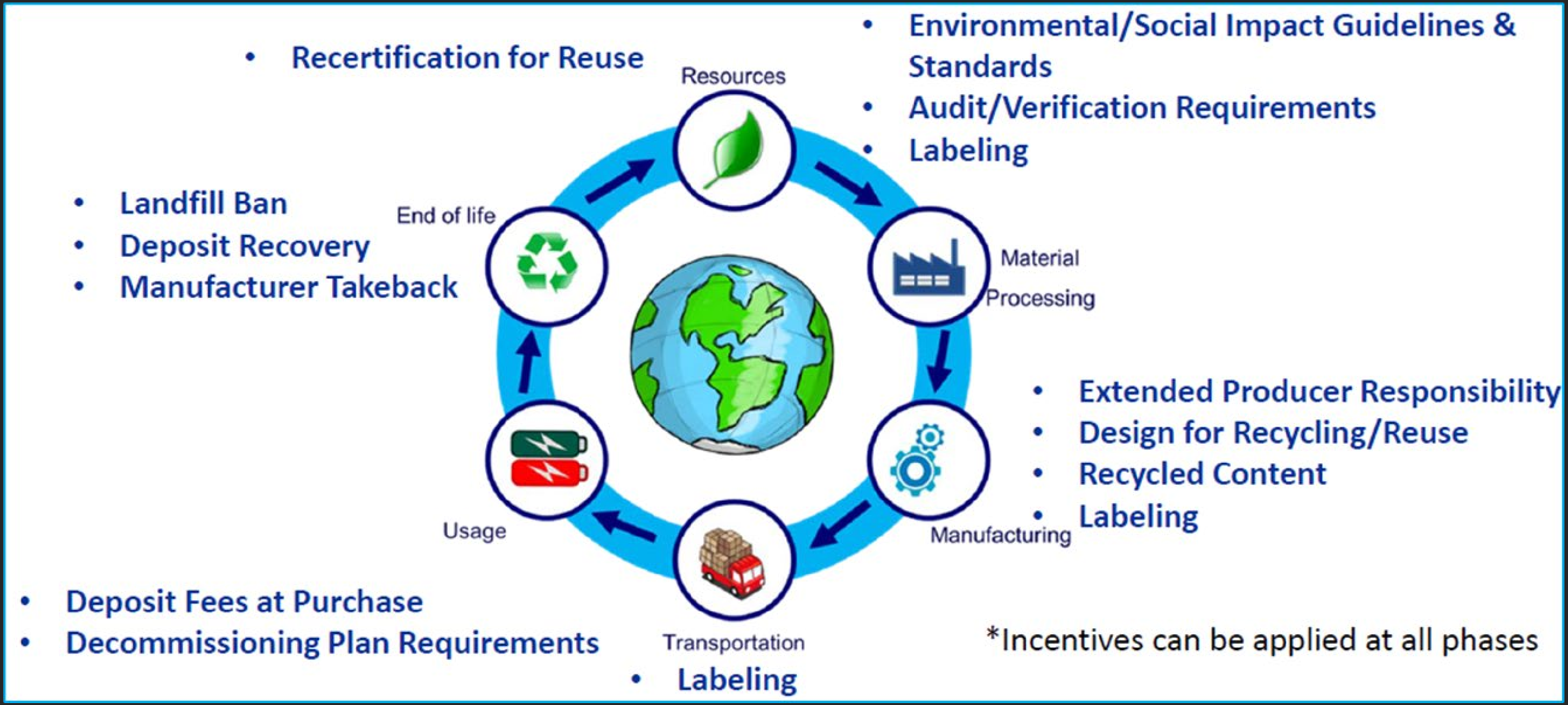
Roles and Responsibility Assignment Matrices

EPRI has created step-by-step guidance throughout the BESS lifecycle

Utility Stakeholder Group	Summary of Decommissioning/Disposal Involvement
Project Management	Integrate input from all other functions/stakeholders into overall decommissioning plan and execution. Ensure cross-coordination among all functions and parties.
Engineering	Undertake electrical disconnection and site disassembly or supervise external contractors undertaking this work. The site and/or land owner(s) must determine if removal of all site structures and any environmental remediation of the site is desired and necessary.
Safety	Engage closely on electrical disconnection, termination of conduits, and disassembly site works.
Operations	De-register BESS from asset pool and update operational plans accordingly.
Legal	Ensure clarity of responsibility/liability for asset and hazards at each stage of decommissioning and site disassembly. Review needs for compliance with relevant environmental and transportation regulations.
IT/OT/Cybersecurity	Ensure proper termination of external communication access as needed.
Corporate Sustainability	Partner with Project Management to ensure that disposal plan in accordance with ESG policy to the fullest extent possible.
Asset Recovery / Asset Management	Track the final disposition and associated costs or profit of key equipment.
Environmental Compliance	Advise on jurisdictional regulations relating hazardous materials retention and disposal that are applicable to the BESS. Prepare any required regulatory documentation of compliance.
Site Manager	Review plans, coordinate onsite activities, and interface with third parties during decommissioning. May own & update decommissioning plan.

Regulations and Policy

Selection of Regulatory Options for LIB Recycling



More mature markets are developing recycling infrastructure, supported by policy mandates

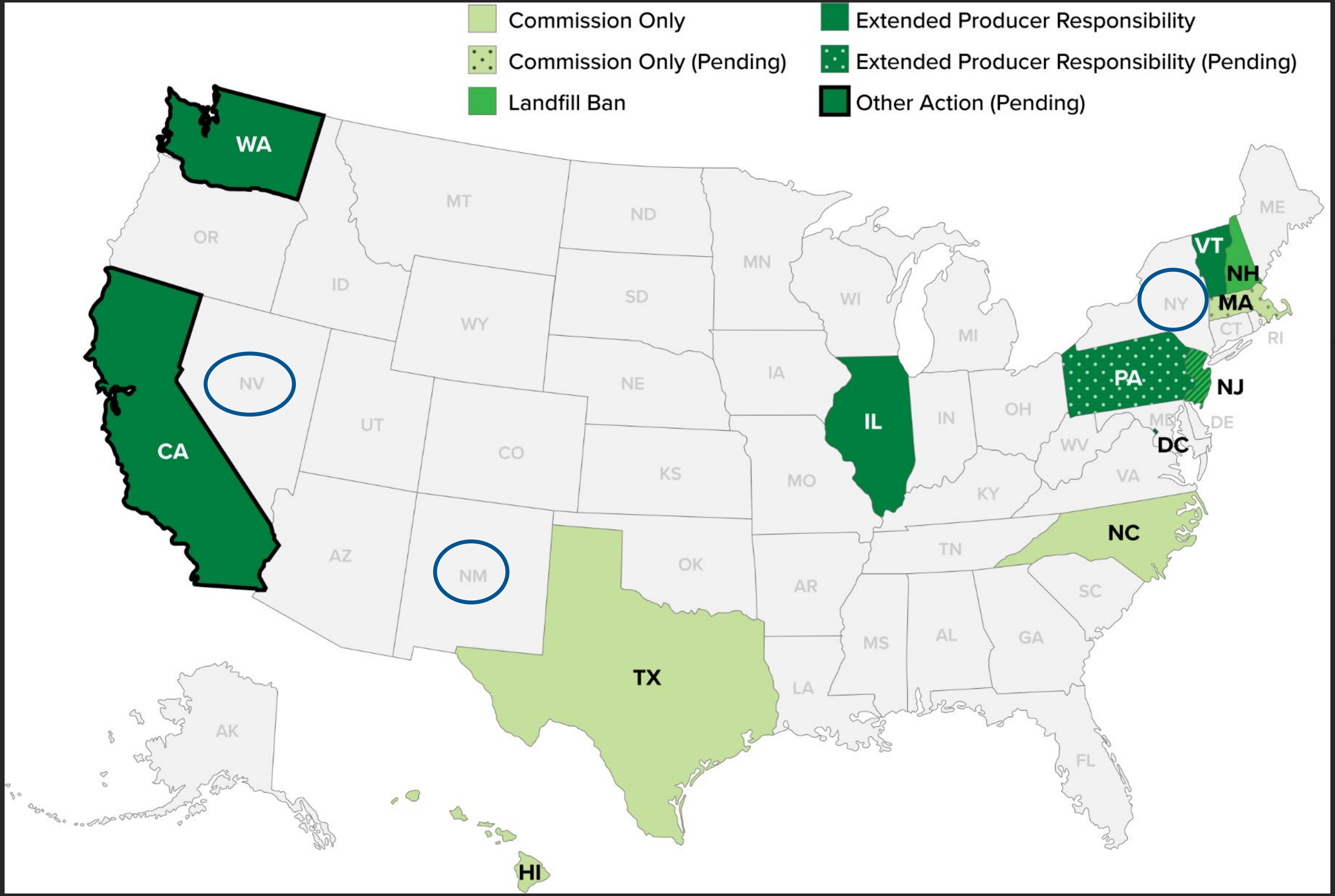
U.S. Federal Policies

- Project owners responsible for decommissioning and disposition. Hazardous due to ignitability/reactivity.
- No US federal policy specifically addresses EOL management of utility-scale LIB projects
- State-level decommissioning requirements exist, usually in the form of a required decommissioning plan
  - Also, where adopted, *NFPA 855 Standard For The Installation Of Stationary Energy Storage Systems* requires decommissioning plans

Recent/Upcoming Updates

- 2023 EPA guidance for owners, transporters, handlers, recyclers to implement ***current*** RCRA hazardous waste regulations for LIB
  - Transfer-based exclusions from “solid waste” definition if going to recycle or “reasonable expectation of reuse” *(40 CFR 261.4(a)(24) and/or 40 CFR 261.4(a)(25), which address domestic and export recycling*). Must apply to states of generation and recycling
  - Black mass is a waste
  - Inconsistent universal waste requirements for damaged, defective and recalled batteries
- EPA proposing new and specific universal waste regulations for LIB and PV in summer 2025 with goal to harmonize with industry best practices

Enacted or Pending U.S. State Regulations for Lithium Ion Battery EOL Management



States may have the authority to set more stringent requirements than federal standards and to define what constitutes solid waste in their own regulations.

States may also delegate regulatory authority to local governments

Research & Development

Second Life Needs for Large-Format Lithium Ion Batteries

01
Performance Assessment

BMS software that can effectively manage operations, even with batteries of varying characteristics or mixes of different manufacturers or models.

Commercialization of quick, accurate, cost-efficient SOH monitoring with standard calculations

02
Market Uncertainty

Economic value for various platforms, applications, capacity sizes, and designs

Include costs of testing, refurbishing and certification procedures

No government incentives

Battery-As-A-Service?

03
Associated Risk

Extensive safety testing (e.g., aging effects and other drivers)

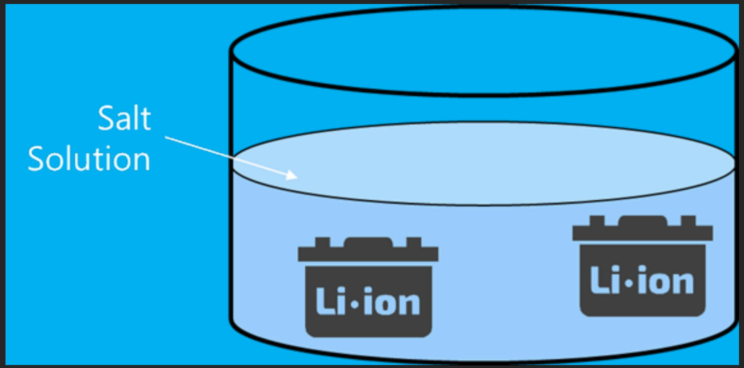
Insufficient data yet to characterizes risk for vendor guarantees and warranties

Feasible contractual and legal terms that clearly address liability

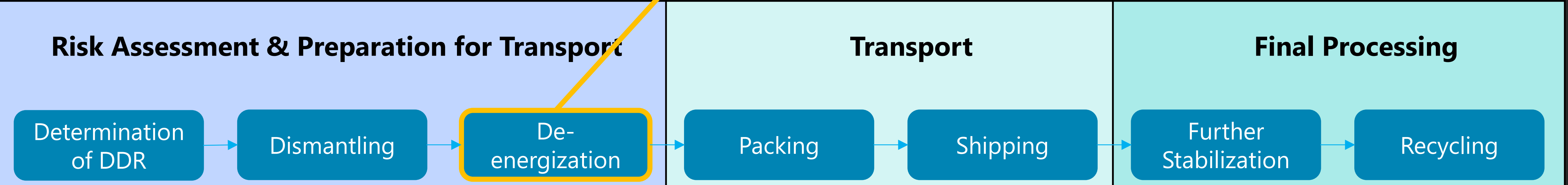
04
Cooperation

Strong cooperation is needed among the original battery supplier, EV manufacturer, and second-life vendor to ensure the transfer of appropriate information needed to develop safe and efficient second-life BESS

R&D Needs for Damaged Battery Decommissioning



- **If de-energizing with a salt solution:**
  - *What salt? What concentration?*
  - *How much per module?*
  - *How long? Cost?*
  - *What post-processing is required for the solution?*
  - *… and so forth.*



Key Research Questions

- How does one accurately identify the condition of the LIB?
- When might I consider de-energizing the LIB for transport?
- What are current methods for de-energizing DDR LIB?

Key Research Questions

- What are leading practices for packaging?
- What are current regulations for transport and shipping?

Key Research Questions

- Once arrived, how should the LIB be handled?
- What implications does DDR have for recycling and final disposition?

Novel Recycling and Pre-Treatment Options

Accessible here: 3002029517

- OnTo Technology and ProteQ demonstrated "stabilization" or "cathode healing" at Marine and Army bases Hawaii, Oct 2024
  - Two packs prepared via discharge and mechanical piercing before exposure to pressurized CO2 in autoclave
  - Eliminated flammable metals and solvents (Sandia Nat. Lab verified non-flammability); yielded an inert item (PHMSA letter states no longer batteries and do not have flammability or toxicity)

- What to watch:
  - Packaging for transport (propagation resistance, PHMSA drums)
  - Direct recycling (Princeton NuEnergy plasma assisted separation)
  - Reduction of by-products
  - Automatic feed management for lower costs and improved sorting and safety

Potentially safer methods in development now; cost unclear

Decommissioning Considerations for Advanced Li and Non-Li Energy Storage at Early Stages

NaS: Identifying U.S. recycler or incinerator challenging. High cost. Petitions for holding time extensions.

Solid-State Li: Conventional recycling not effective to separate active materials and solid electrolyte. Higher energy density may increase thermal runaway hazard. Separation R&D underway.

Sodium Ion: Conventional recycling for low-value chemistries may have limited or negative economic and environmental benefits. Direct recycling could be cost-effective; lab work suggests less energy intensive than LIB direct recycling but requires more water.

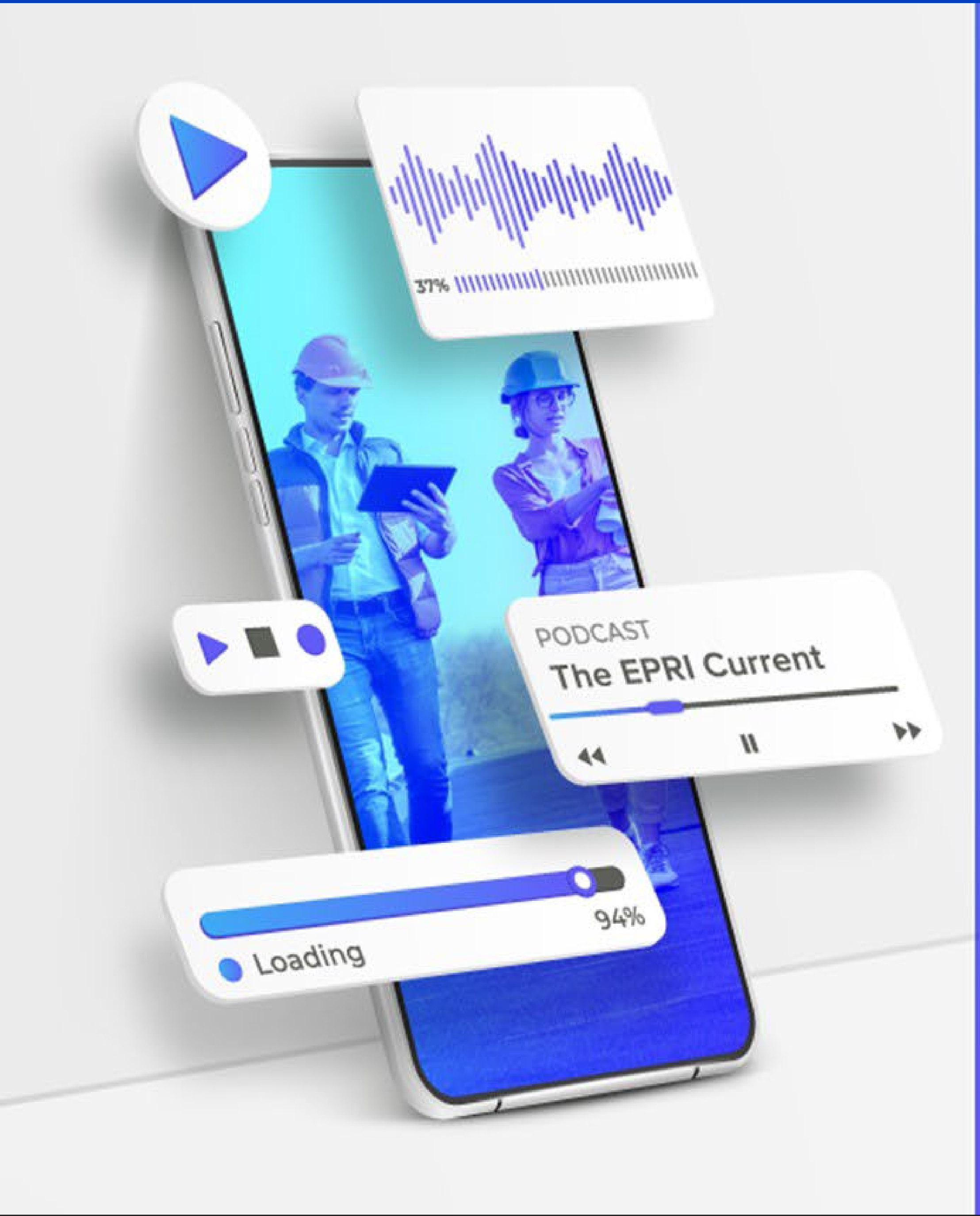
Iron Oxide: Could potentially leverage developing H_2 infrastructure (e.g., electrolyzer and fuel cell recycling) to recover the critical minerals used as air cathode oxygen catalysts.

EOL infrastructure for advanced-Li and non-Li storage lags technology development but is increasingly critical for commercialization success

BESS Decommissioning Summary

- Decommissioning requirements vary widely by jurisdiction, but LIBs are increasingly understood by regulators.
- New solutions are being created to serve both regular decom plans, and those for DDR batteries
- Battery recycling infrastructure expanding, with currently favorable costs. Must updated planning over project lifetime.
- Provider base of experienced decommissioning firms and recyclers is limited, but increasing. Not all recyclers ready to accept modules.

Plan for decommissioning at the point of procurement!



EPRI CURRENT PODCAST

epri.com/epricurrent

EPRISODE 05:

Reduce, Reuse, Recycle — the Circular Economy

FEATURING:

Dr. Stephanie Shaw

Technical Executive,
EPRI

Cara Libby

Principal Technical Leader,
EPRI

Lithium Ion Battery End-of-Life Resource List

EPRI Research Activities on Renewable and Battery End-of-Life Management and Circularity (3002030366)

Solar Photovoltaics, Battery Storage, and Wind Turbine Blade End-of-Life Service Providers (3002020492)

2023 Update: Solar Photovoltaic, Lithium ion Battery, and Wind Turbine Blade End-of-Life Service Providers (3002025769)

Guidelines for Assessing End-of-Life Management Options for Renewable and Battery Energy Storage Technologies (3002020594)

Lithium Ion Battery Energy Storage End-of-Life Management Infographic (3002022203)

End-of-Life Management for Lithium Ion Battery Storage: Issues, Uncertainties, and Opportunities (3002020006)

Recycling and Disposal of Battery-Based Grid Energy Storage Systems: A Preliminary Investigation (3002006911)

Energy Storage Decommissioning Case Study: Lessons Learned from the Energy Storage Implementation Practices Collaborative (3002022301)

Investigation of Battery Energy Storage System Recycling and Disposal: Industry Overview and Cost Estimates (3002023651)

Investigation of Battery Energy Storage System Recycling and Disposal Presentation Summary (3002023958)

Environmental Impacts of Battery Recycling: A Summary of Recent Environmental Life Cycle Assessment Results (3002023723)

Holistic Decommissioning Planning for Lithium Ion Battery Modules and Energy Storage Facilities (3002021775)

EPRI Insights: Current Events, Industry Forecasts, and R&D to Inform Energy Strategy, December 2022 (3002025959)

ESIC Energy Storage Commissioning Guide (3002027455); Includes decommissioning planning

Cedartown Battery Energy Storage System Decommissioning Case Study: Lessons Learned from Decommissioning an Early-Stage Utility-Scale Lithium Ion Project (3002027944)

Architecture and Application of Repurposed Second Life EV Batteries in Stationary Energy Storage (3002029556)

Second Life for Large Format Lithium Ion Batteries (3002028618)

Overview of Second Life for Large-Format Lithium Ion Batteries (3002029553)

End-of-Life Regulatory Actions for LIB Energy Storage: Large-Format EV and Stationary Platforms (3002031206)

Decommissioning Damaged, Defective, and Recalled Lithium Ion Batteries (3002031225)

Novel LIB Deactivation and Recycling Developments (3002029517)

Together…Shaping the Future of Energy™

Designing LIB for Repair / Reuse / Recycling

Achievable Now

Water or alcohol-soluble binders

Single crystal cathode

Packaging: screws v. bolts, vacuum release v. welding

Labelling and tagging

Next Steps

Anode graphite is a regenerable resource for cost and Li resource

High cost, purity, and F content concerns with electrolyte recycling

Future Vision

Easier disassembly and dissolution

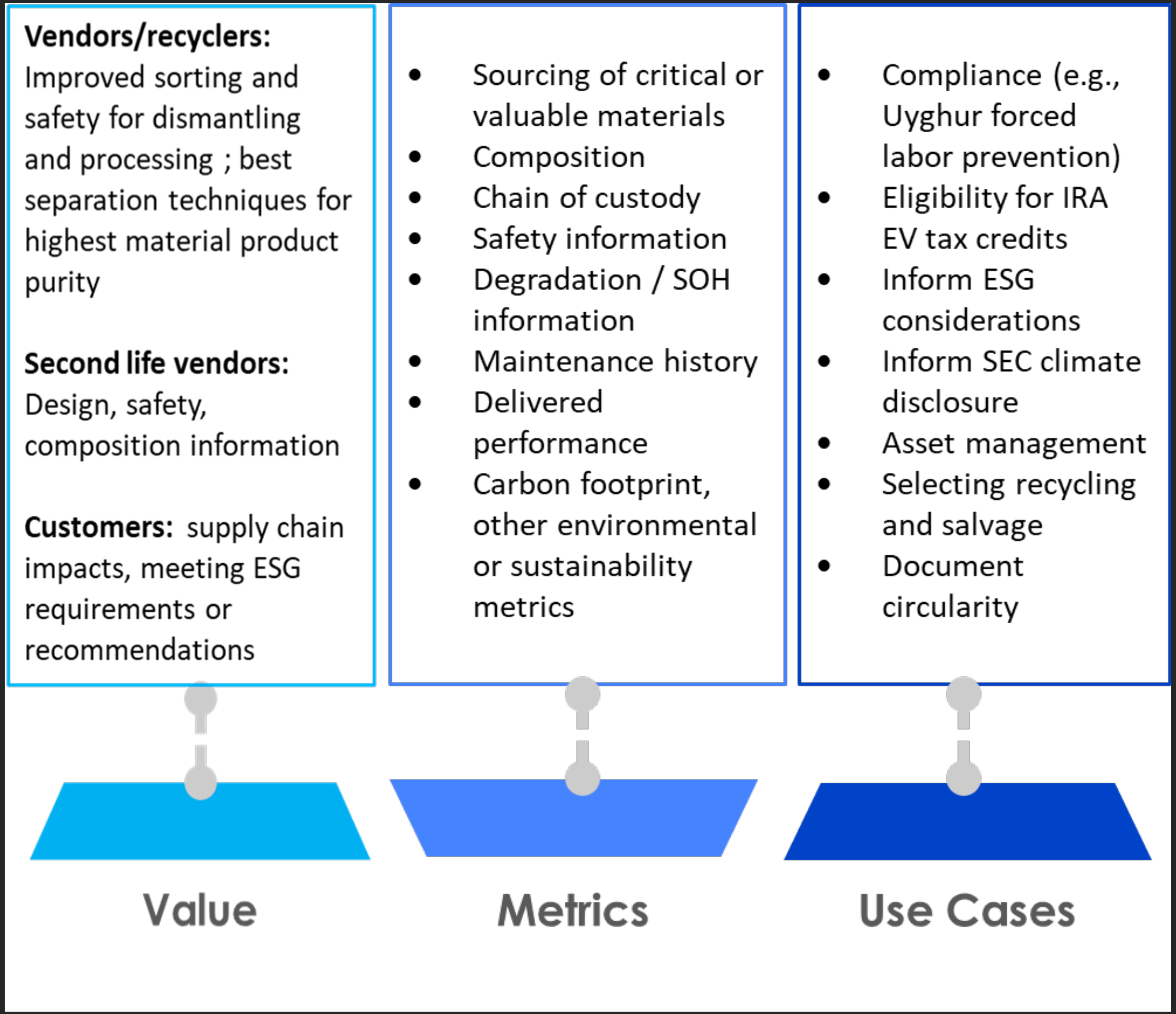
Longer lifetimes

Biodegradable electrodes?

Xu et al., 2021; Norgren et al., 2020

How can customers influence product and service offerings?

Traceability Aggregates Information Cradle-Cradle



Source: EPRI, 2023b

What can be tracked?

- Upstream materials sourcing
- Manufacturer, design, and composition
- Carbon footprint
- Replacement part compatibility
- Maintenance, repairs, use history
- Performance metrics and historical performance
- EoL disposition
- Critical mineral reclamation
- Second life applications
- Materials leakage

NFPA 855 (2023) Requires Decommissioning Plans

8.1.3* The decommissioning plan shall be provided to the AHJ and include the following information:

(1) An overview of the decommissioning process developed specifically for the ESS that is to be decommissioned
(2) Roles and responsibilities for all those involved in the decommissioning of the ESS and their removal from the site
(3) Means and methods in the decommissioning plan submitted during the permitting process to be made available at a point in time corresponding to the decision to decommission the ESS
(4) Plans and specifications necessary to understand the ESS and all associated operational controls and safety systems, as built, operated, and maintained
(5) A detailed description of each activity to be conducted during the decommissioning process and who will perform that activity and at what point in time
(6) Procedures to be used in documenting the ESS and all associated operational controls and safety systems that have been decommissioned
(7) Guidelines and format for a decommissioning checklist and relevant operational testing forms and necessary decommissioning logs and progress reports
(8) A description of how any changes to the surrounding areas and other systems adjacent to the ESS, including, but not limited to, structural elements, building penetrations, means of egress, and required fire detection and suppression systems, will be protected during decommissioning and confirmed as being acceptable after the system is removed

8.2 Decommissioning Process.

8.2.1 The AHJ shall be notified prior to decommissioning an ESS.

8.2.2 The ESS shall be decommissioned by the owner of the ESS or their designated agent(s) in accordance with the decommissioning plan.

8.3 Decommissioning Report. A decommissioning report shall be prepared by the ESS owner or their designated agent and summarize the decommissioning process of the system and associated operational controls and safety systems.

8.3.1 The report shall include the final decommissioning plan and the results of the decommissioning process.

8.3.2 The report shall include any issues identified during decommissioning and the measures taken to resolve them.

8.3.3 The decommissioning report shall be retained by the owner and provided to the AHJ upon request.

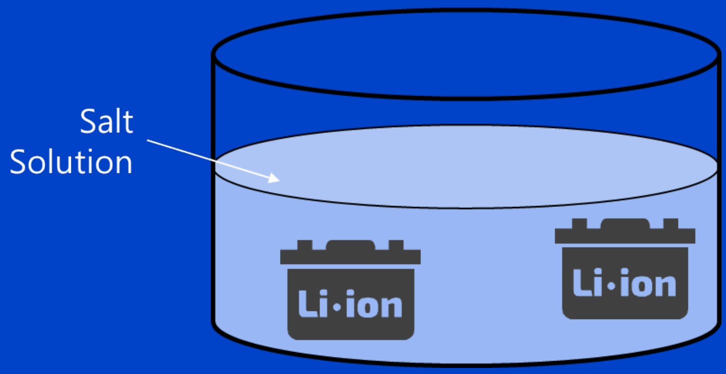
Current De-Energization Practices for Damaged Batteries

Resistive Discharge

- Gradual discharge of stranded energy through **resistive load banks**
- **Pro:** Simple to execute, process on **order of hours**
- **Con:** Relies on integrity of electrical connections inside module.
- Suited to less-damaged or suspect modules

Salt Solution Discharge

- Gradual discharge of stranded energy through conductive salt water
- **Pro:** More likely to discharge cells even when electrical connections are damaged. Liquid provides cooling effect. Can run de-energization of modules in parallel.
- **Con:** Potential to leach toxics from LIBs, may require post-treatment, process on **order of days**
- Suited to highly-damaged or very unstable modules



Crushing

- Excavator removal from pack or BESS. Salt solution discharge, then crushing.
- **Pro:** "Not a battery". Non-hazardous transport and recycling possible.
- **Con:** Arcing and sparking common. Requires voltage assessment. May need breathing apparatus.

EPA Lithium Ion Batteries: Maui Wildfires Case Study