End-of-Life Management for Stationary Battery Energy Storage Systems

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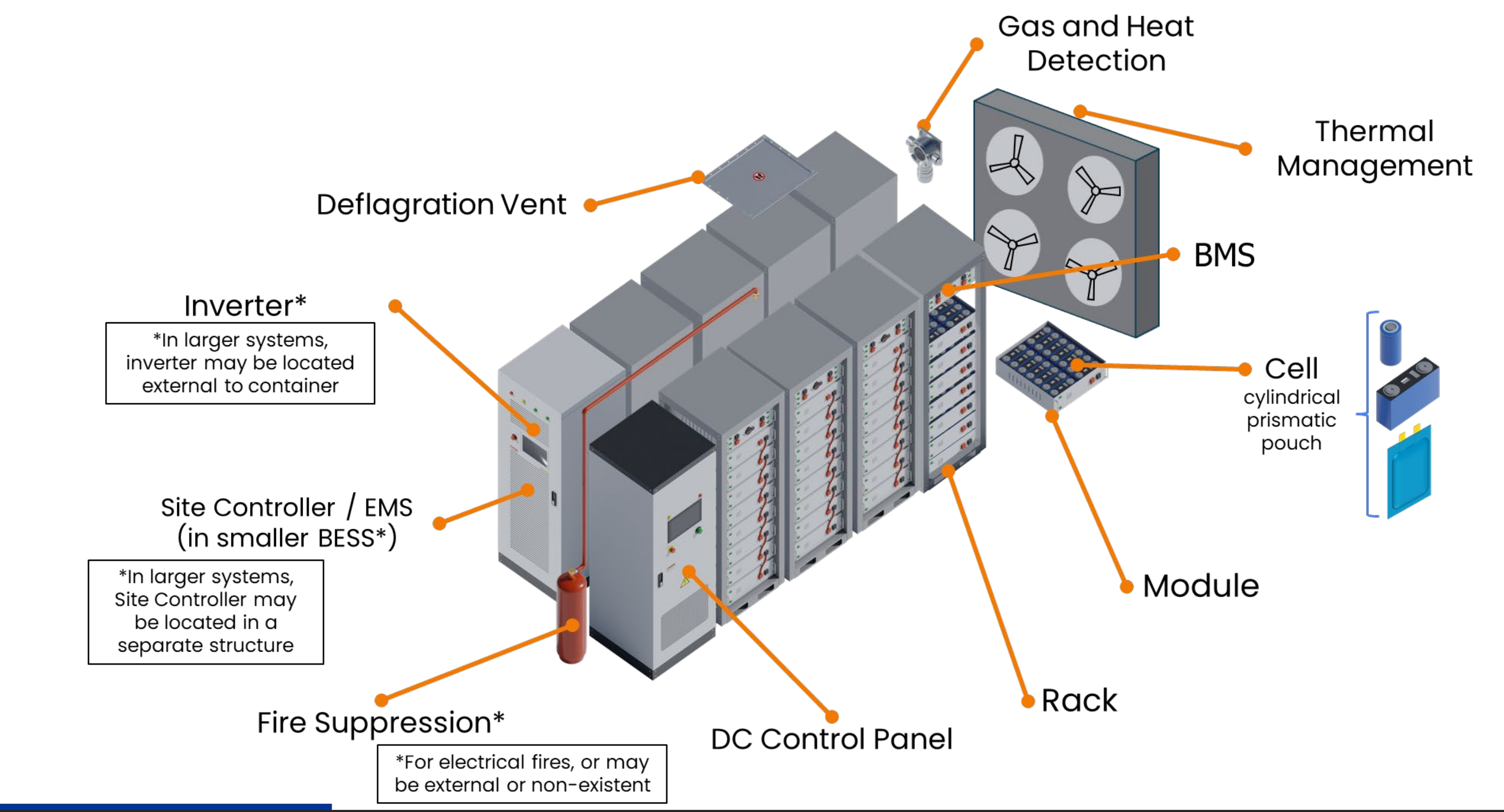
Battery Energy Storage System (BESS)

Inside the Cabinet

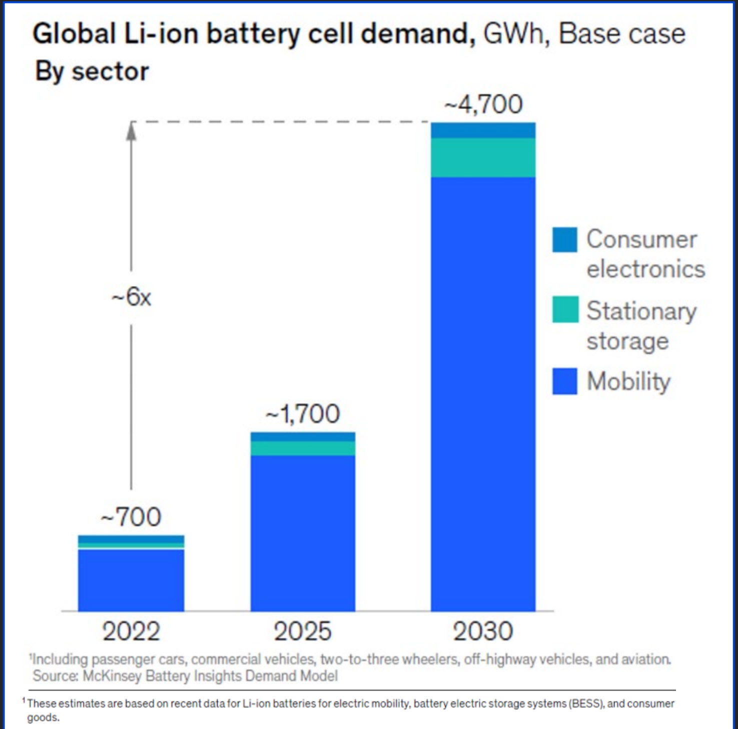


Source: Duke Energy

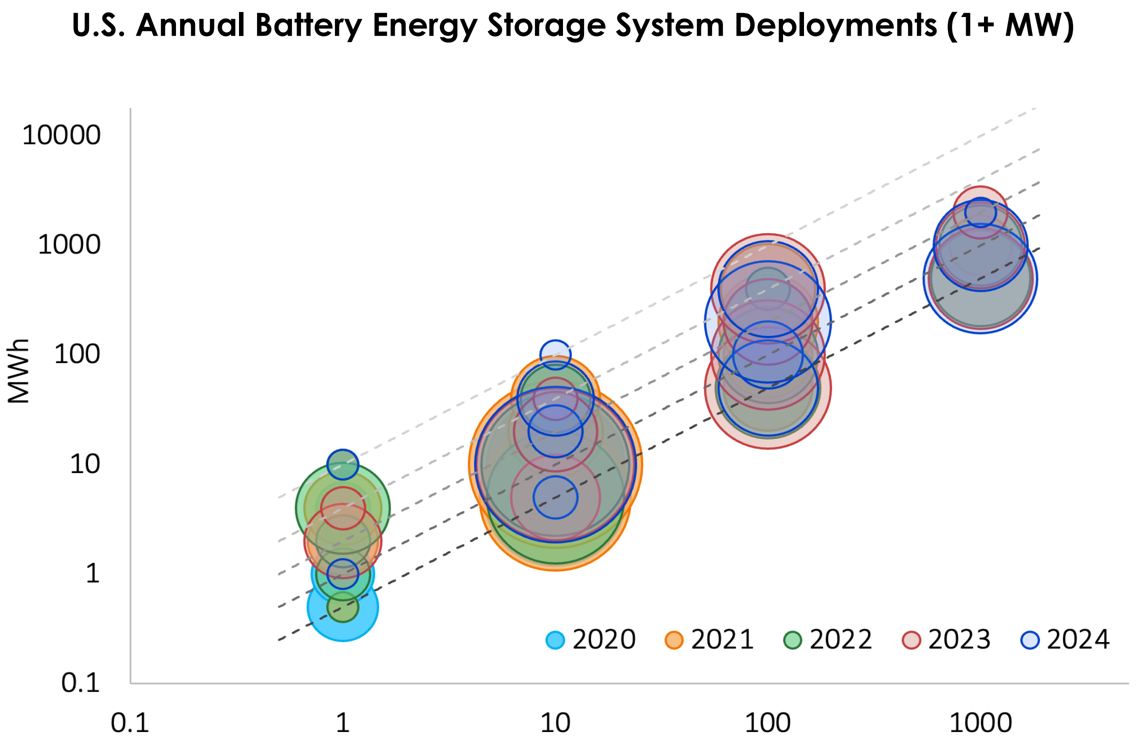
Site Layout

Lithium Ion Battery End-of-Life (EOL) Materials Streams

Expected LIB demand growth driven by the mobility sector, but stationary storage is growing rapidly and provides large and consistent module batches.



Source: Battery 2030: Resilient, sustainable, and circular", January 2023, McKinsey & Company, www.mckinsey.com. Copyright ©2023 McKinsey & Company. All rights reserved. Reprinted with permission.



Bubble diameter indicates the number of projects that fall within the power and duration bins in the table below. Larger bubbles indicate more projects within a specified system capacity and duration range.

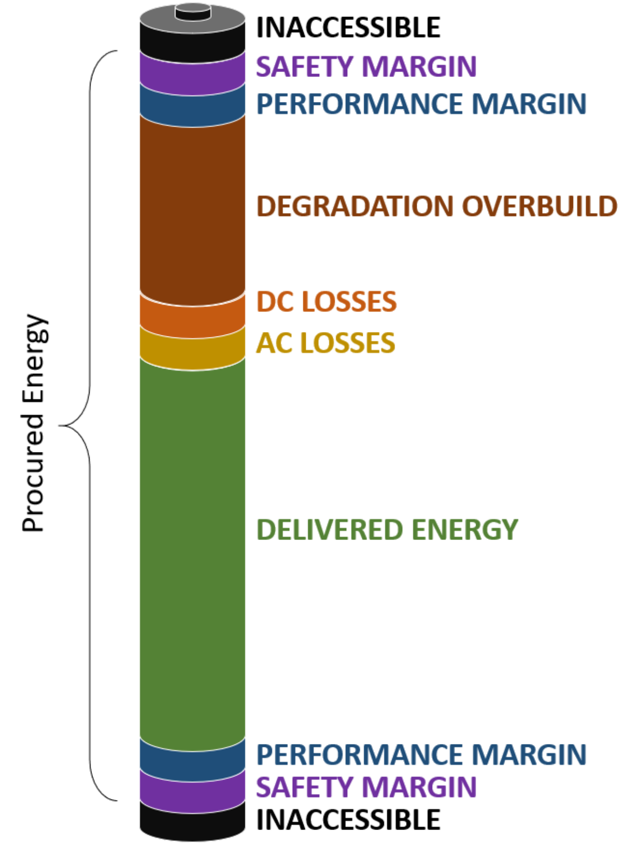
Source: Energy Storage – 2024: A Year in Review. EPRI, Palo Alto, CA: 2024. 3002029645.

Preferred chemistries are similar, but sheer difference in capacity requires a unique approach to decommissioning.

2024 Average Capacity per vehicle/facility (kWh)	
EV	71.4
US facility	188, 500

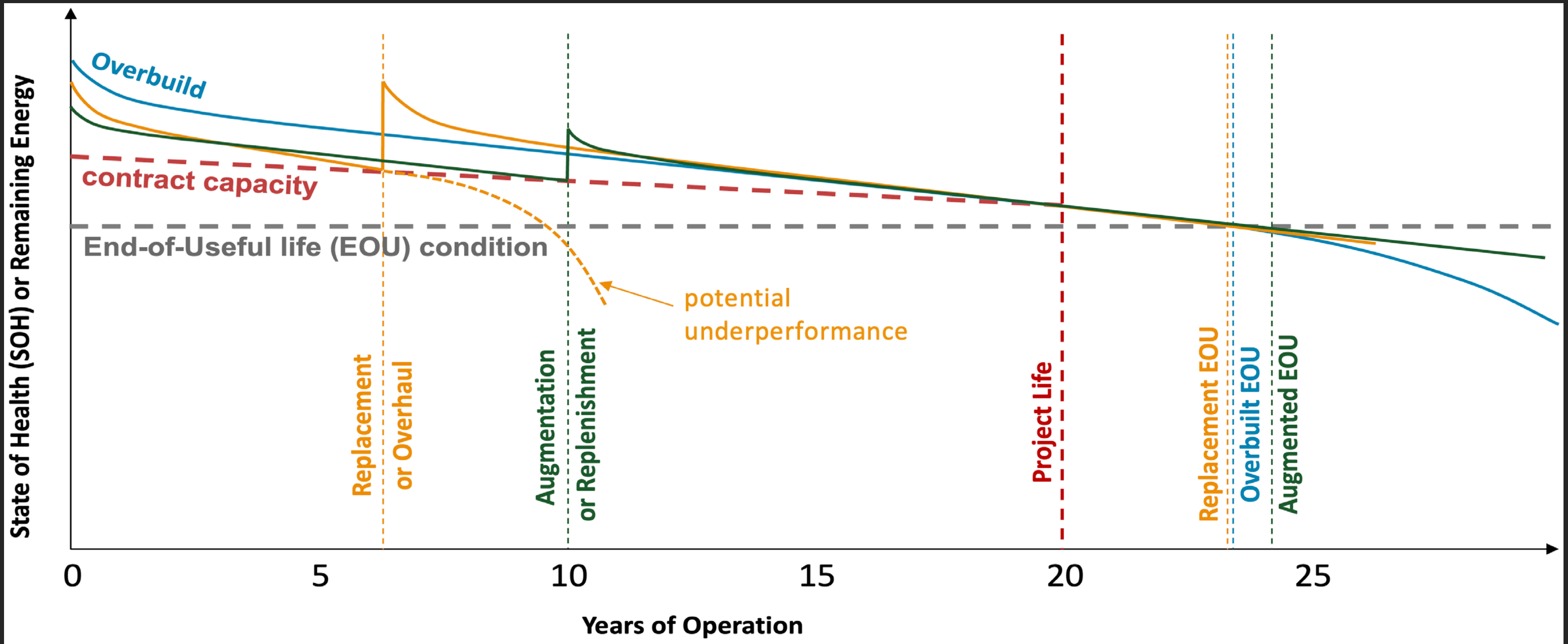
When is EOL for Stationary Energy Storage?

- Procured and delivered energy are not the same. Owners and operators may not know the procured energy capacity.
- Contractually allowable degradation may be based on delivered energy and terms could differ from project to project.



Note: *Figure is illustrative, not to scale.*

- Different strategies are used to maintain an allowable energy capacity over the project life, defined in years.



Does the 60? 70? 80% rule apply?

Case Studies

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

- 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

2023 Decommissioning collaboration with Redwood Materials (Report: 3002027944)

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**	

**Recycling and packing materials not included*

Cedartown Recycling vs. Reuse Valuation

- **Disassembly 50 minutes per module, considered in cost to recycle**
  - Individual aqua regia digestion with heat >30 min until no visible reaction
  - ICP-OES for metal content

- **Metal content is the biggest variable in determining total recycling value**
  - High Mn content (low value) as compared to Ni, Li, Co which recently exceeded $1.50/kg
  - Cathode was not pure NMC as documented, but mix of NMC and LMO
  - Net recycling value: $0 / kg

- **Resale of modules likely to bring greater financial return**
  - SOH used capacity of “least healthy” cell of 42 tested; close to average
  - Resale market: $300-$500 per module per ebay.com and evwest.com

Consolidated to Total Mass Distribution

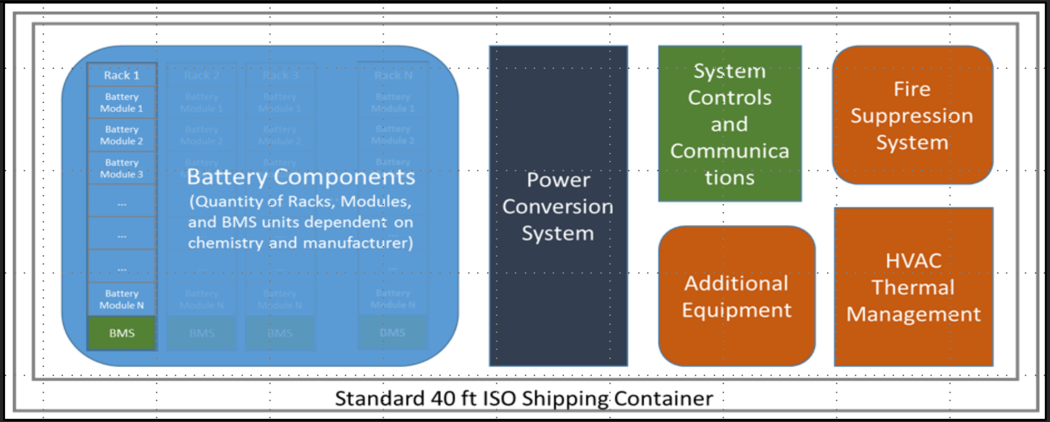
Sample ID	Unit	Al	Ca	Co	Cu	Fe	Li	Mg	Mn	Na	Ni
LG BESS Cell	%	7.75	0.00	4.38	11.22	0.04	2.39	0.00	9.26	0.27	4.24

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

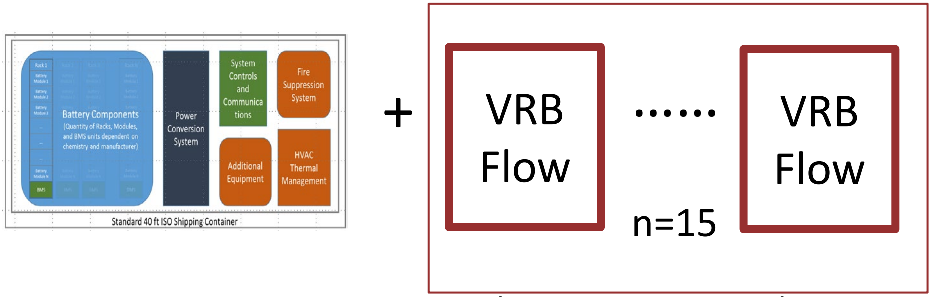
Cost Breakdown Framework: Flow Batteries at LADWP

2017: Framework for 1MWh LIB Container



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



2021: LIB 20MW/ 10MWh. $1.2M in 2023$

30% Disassemble/Package - 25% Transport - 45% Recycle

2021: Mixed VRFB (100kW/400kWh) + LIB (100kW/ 400kWh) System

Reports: 3002023651 and 3002023958

Mixed Flow Battery + LIB BESS Cost Estimate (400kWh+400kWh)

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

Prior BESS Case Studies

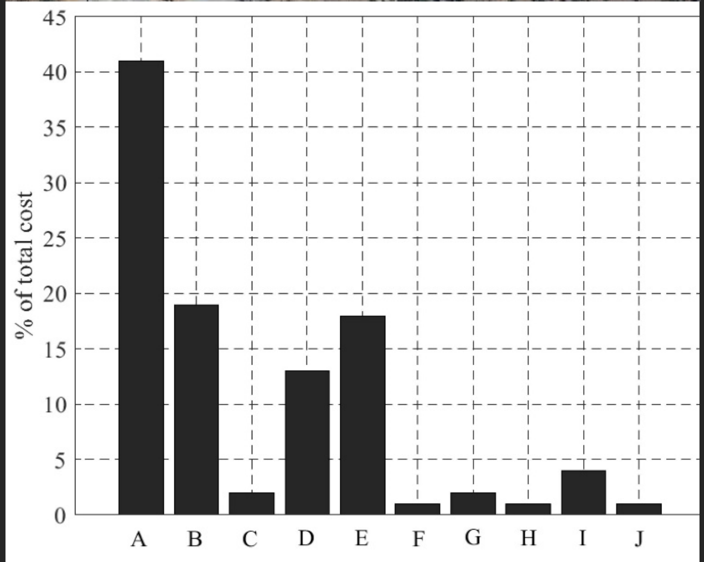


Fig 3. Cost of the decommissioning project

Southern California Edison, Tehachapi

A= BESS dismantling, repairing site

B = PCS dismantling, repairing site

C = Battery packaging

D = Battery transportation

E = Battery recycling

F = Documentation

G = Consumables

H = Temporary facility

I = Project management services

J = Insurance

Report available: IEEE 2023 Green Energy and Systems Conference

Demo BESS 750kWh

Renewance, IPD, RCI Construction

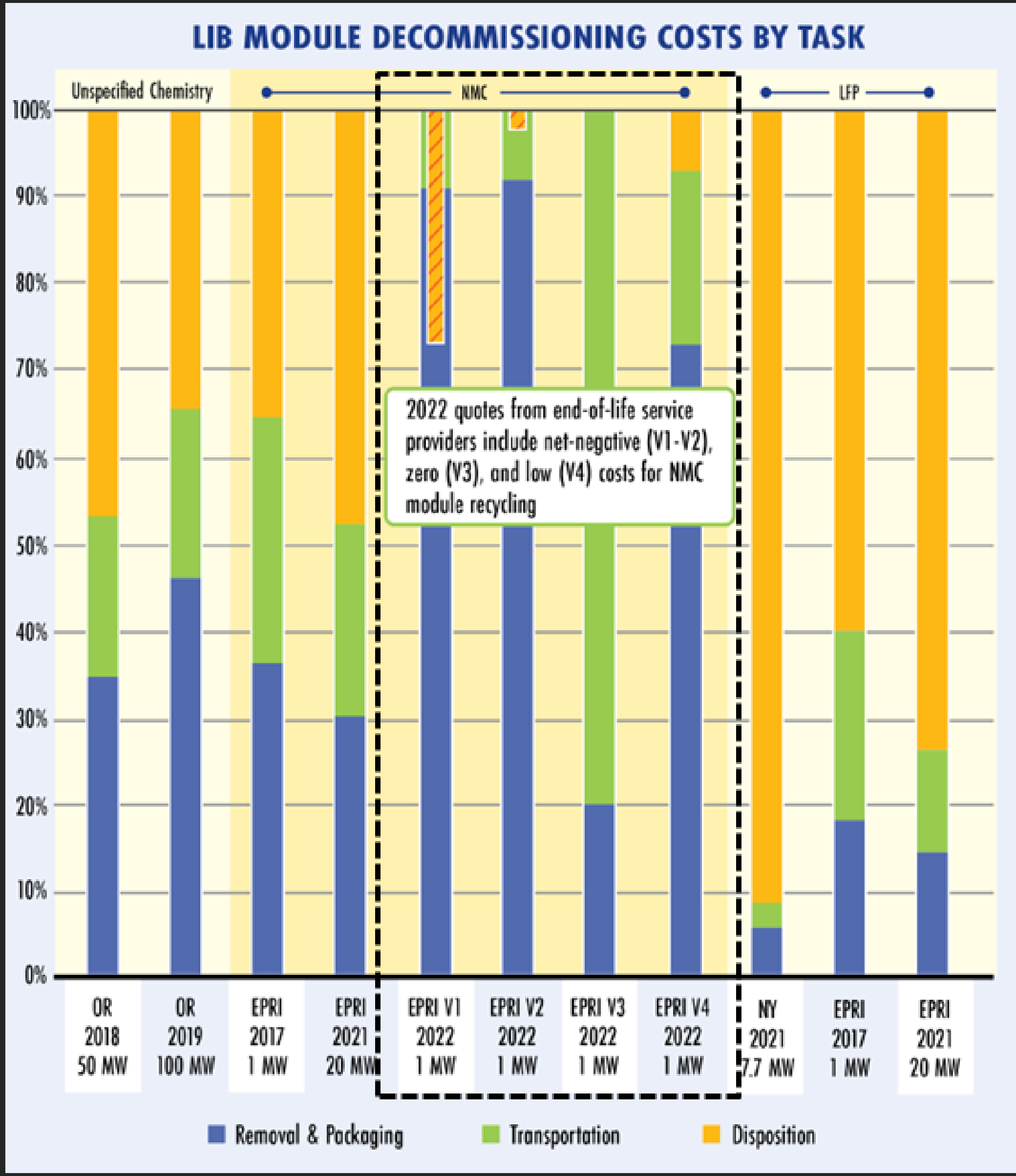
Webinar available: here

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!**

Battery Recycling Markets Fluctuating: Availability and Cost

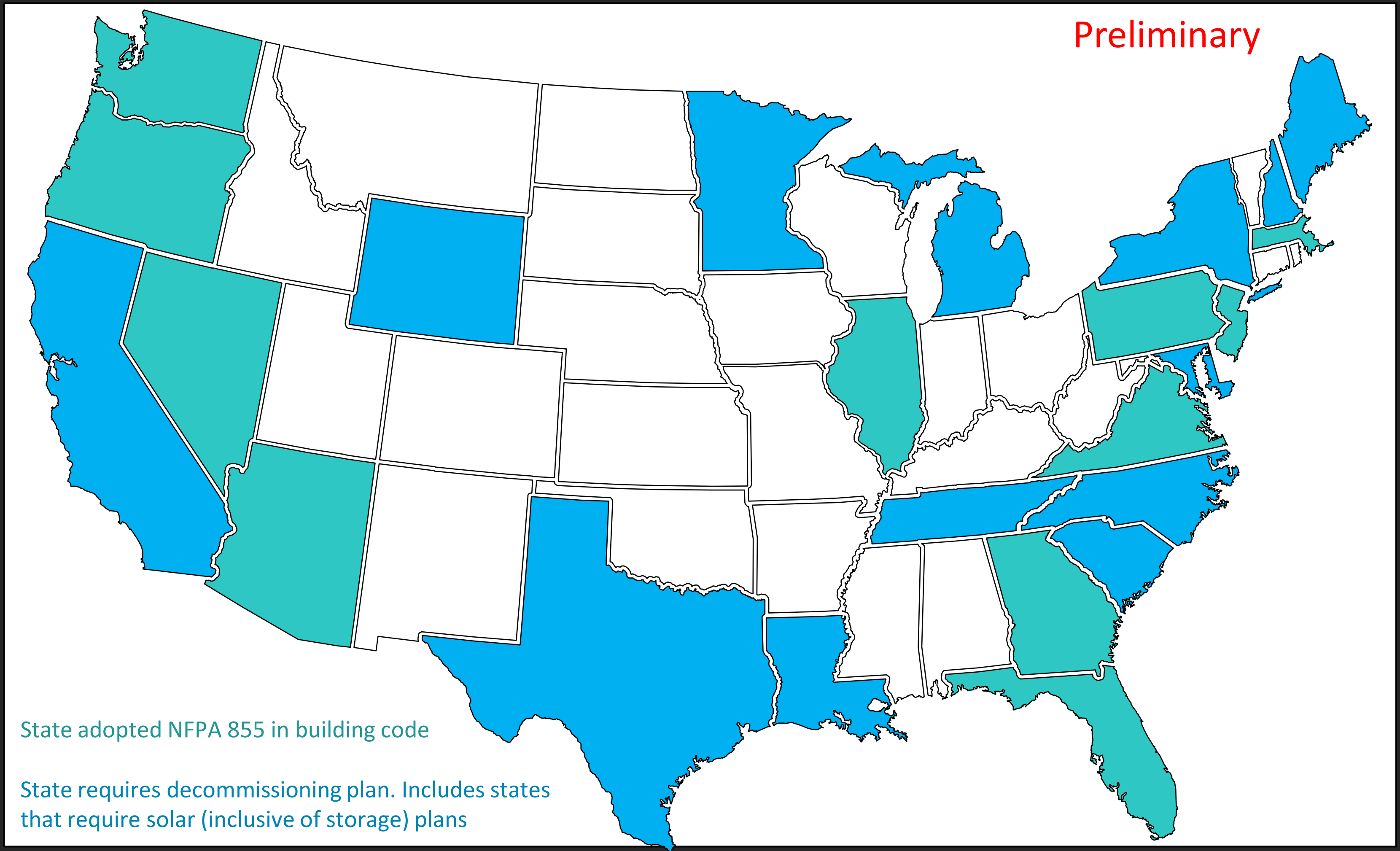
- EPRI receiving quite variable quotes for net recycling value
  - ***Salvage value is a driver:*** NMC battery value ranged from $1 to >$1.50 / kg over previous year
  - ***But recycling capacity and facility operations now appear to be bigger drivers***



EPRI

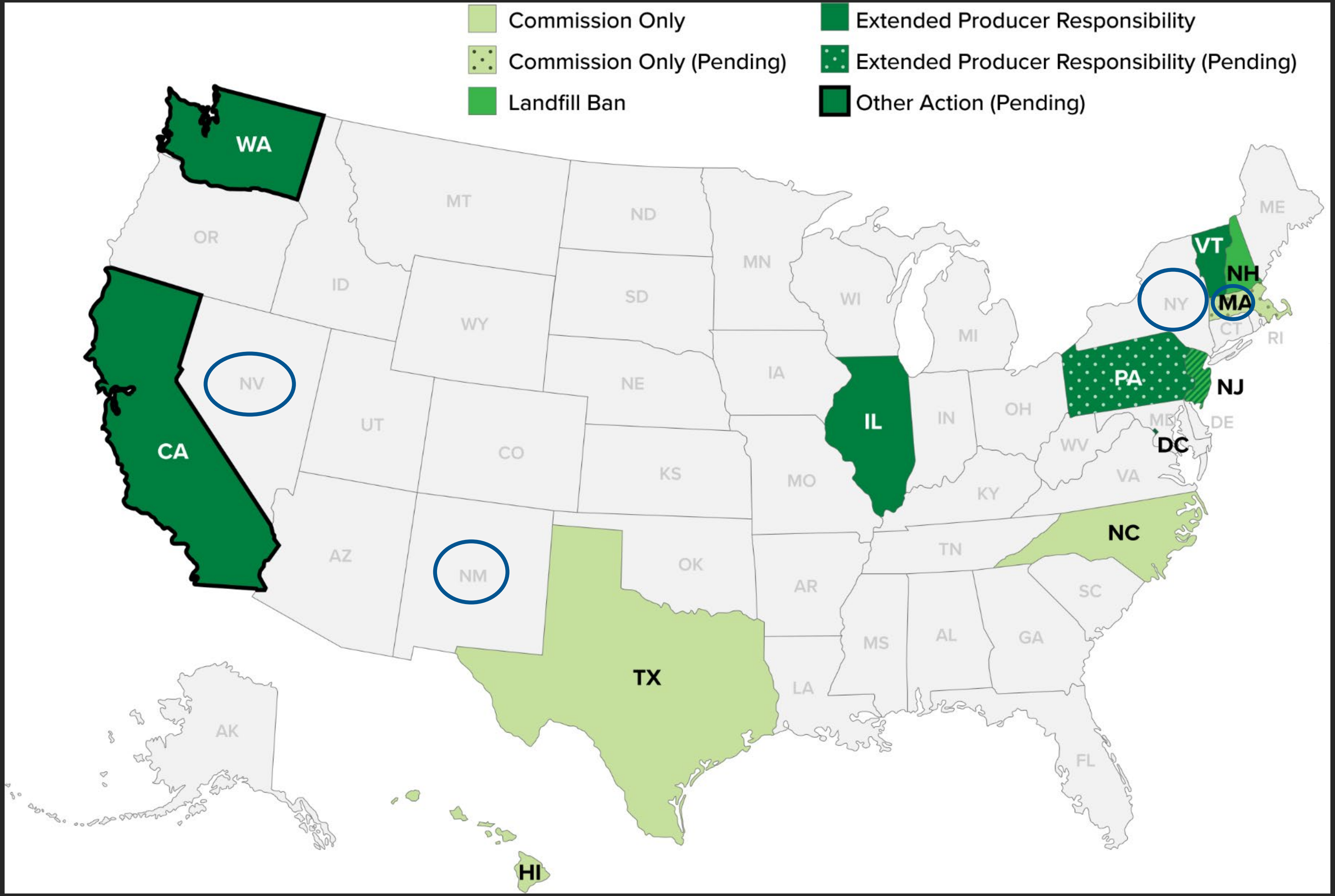
Regulations and Policy

Adoption of BESS Decommissioning Requirements



- Project owners responsible for decommissioning and disposition
- 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 plan
  - Where adopted, *NFPA 855 Standard For The Installation Of Stationary Energy Storage Systems* requires decommissioning plans

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

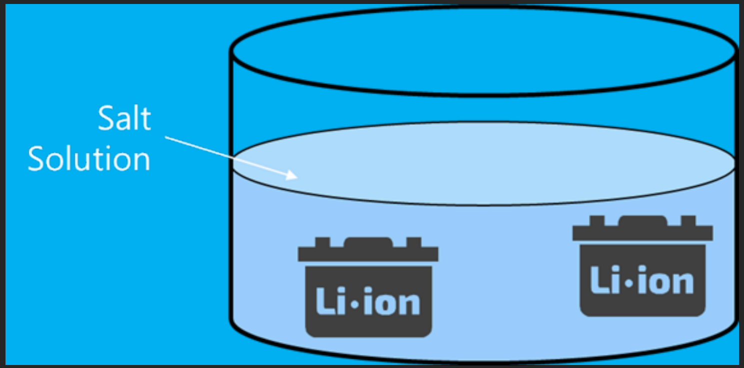
BESS Decommissioning Plans

- **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

Research & Development

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.*

Risk Assessment & Preparation for Transport

Determination of DDR → Dismantling → De-energization

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?

Transport

Packing → Shipping

Key Research Questions

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

Final Processing

Further Stabilization → Recycling

Key Research Questions

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

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.

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.

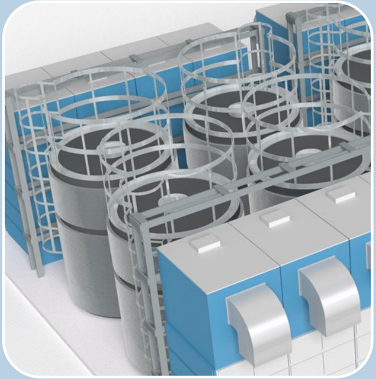
Solid-State Li: Conventional recycling not effective to separate active materials and solid electrolyte. Higher energy density may increase thermal runaway hazard. Separation R&D underway.

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.

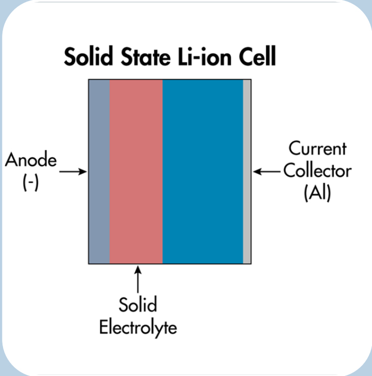
EOL infrastructure for advanced-Li and non-Li storage lags technology development but is increasingly critical for commercialization success

Upcoming Activities

New case study starting for a stilted 4MWh LFP



Overview of flow battery EOL practices



Seeking solid state recycling information

Seeking recycler interviews for processing information

Thought leadership on applying circularity concepts to utility-scale energy facilities

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

Together…Shaping the Future of Energy™

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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.