POWER ADVISORY

Solar and Battery End of Life Considerations

Prepared for CT Green Bank

July 22, 2024

Contents

1. Study Overview

Introduction to the Study

On November 1, 2023, the Connecticut Public Utilities Regulatory Authority ("PURA") issued a final Decision in Docket No. 23-08-02, the Annual Residential Renewable Energy Solutions ("RRES") Program Review – Year 3. In this decision, PURA determined that a proactive approach is needed to resolve the potential issue of solar panel and battery waste. PURA requested that the Connecticut Green Bank convene and lead a working group of relevant stakeholders, including the Connecticut Department of Energy and Environmental Protection ("CT DEEP") and the Electric Distribution Companies ("EDCs"), to develop by August 1, 2024, recommendations to resolve the potential issue of solar panel and battery recycling and waste for clean energy projects in Connecticut. Among other things, the Decision asked that the End-of-Life Working Group:

- Identify environmental effects of solar panel and battery waste
- Research the success or failure of approaches used in other jurisdictions
- Generate recommendations including:
  - Pros and cons of each approach
  - Implementation timeline and cost of each approach

This decision was replicated on November 29, 2023, in PURA Docket No. 23-08-05, the Annual Energy Storage Solutions ("ESS") Program Review – Year 3

In March 2024, following an RFP process, Green Bank engaged management consulting firm Power Advisory to support this effort

This report was prepared by Power Advisory on the Green Bank's behalf

Guiding Principles

The recommendations in this report were developed with the following guiding principals in mind:

- Consistency with other existing Connecticut programs
- Stakeholder buy-in
- Lessons learned from other jurisdictions
- Minimization of environmental impacts
- Avoidance of policies that discriminate
- Cost and timeline to implement
- Feasibility of getting the recommended frameworks / policies approved in Connecticut

Working Group

- The working group consisted of the organizations on the following page. Additionally, RSIP and ESS approved contractors and manufacturers were invited to join the working group
- Five monthly meetings were held from March to July 2024, which were also open to the general public
  - Recordings of these meetings can be found at ctgreenbank.com/eol-working-group/
  - Notices of each meeting were posted with the Secretary of State
  - Notice of the working group was posted in the RRES docket

POWER ADVISORY

Working Group Members

Category	Organizations	
Connecticut Agencies	• Department of Energy and Environmental Protection (DEEP) • Connecticut Innovations (CI) • Office of Consumer Council (OCC)	
Electric Distribution Companies (EDCs) (Utilities)	• Eversource • United Illuminating/Avangrid	
OEMs / Developers	• Tesla • Sunrun • Enphase	• Sunnova
State Contractors	• PosiGen • Skyview Ventures • Harness the Sun	• Earthlight Technologies • RWE Clean Energy, LLC (formerly ConEdison Solutions)
Waste	• Battery Council International • Solar Panel Recycling • Ontility • Bluewater Battery	• Comstock Metals Corp • Redwood Materials • PRBA - The Rechargeable Battery Association
Other	• Yale University • SEIA	

POWER ADVISORY

Working Group Meeting Agendas

March 27: Introduction and Objectives Overview

- Overview of working group objectives and review of the Public Utilities Regulatory Authority's (PURA) specific objectives
- Review of end-of-life technologies and practices in other jurisdictions

April 29: Needs Assessment and Policy Landscape

- Current and future needs:
  - Introduction to factors impacting size of solar and battery end-of-life markets
  - Analysis of current demand for solar and battery recycling and end-of-life management services
  - Future market growth opportunities
- Policy and regulatory landscape and business model:
  - End of life management regulatory frameworks
  - Current decommissioning plans and recycling plans
  - Business model and issues to discuss for CT policy

May 28: Indicative Economics and Funding Options

- Presentation of Indicative Economics for solar panels and batteries
- Exploration of potential funding sources for recycling frameworks
- Discussion of options

June 26: Development of Recommendations

- Review and finalize recommendations
- Outline steps for the preparation of the final report to PURA

July 17: Finalization and Report Preparation

- Discuss next steps, including further research areas and/or legislation
- Formal closure of the working group sessions with an action plan

Interviews

- During the course of this study, Power Advisory, together with the Connecticut Green Bank, conducted sixteen one-on-one interviews with various organizations including:
  - Industry stakeholders
    - 3 OEMs (manufacturers)
    - 4 developers / Independent Power Producers (IPPs)
    - 2 trade associations
    - 1 solar panel recycler
    - 1 battery recycler
    - 1 academic institution
  - Government stakeholders
    - 3 state agencies
    - 1 federal agency
- We asked the industry stakeholders a series of questions related to current and future plans to address end of life panels and batteries, indicative economics, market readiness, environmental impacts, implications of different policy options, and their recommendations on policy
- We asked the state agencies about their experience with stakeholder groups, existing policies, policies under development, and lessons learned related to those policies

Scope of Study – Solar

Out of scope

Scope of this study

Panel

Types of panels:
- Crystalline silicon (~80% of market)
- Thin Film (CdTe) (15%)
- Advanced technology (5%)

Can be recycled as E-waste

Microinverter

String Inverter

Can be re-utilized with newer technology or readily recycled like other metals

Roof mount rack

Ground mount rack

Electrical Wiring

POWER ADVISORY

Scope of Study – Stationary Batteries

Scope of this study

Battery

Out of scope

Backup Switch

Backup Hardware

Detects grid outages and manages the system's transition to/from backup

Interconnection, Conduits, and Wiring

Scope of Study – Project Size

This study covers all project sizes

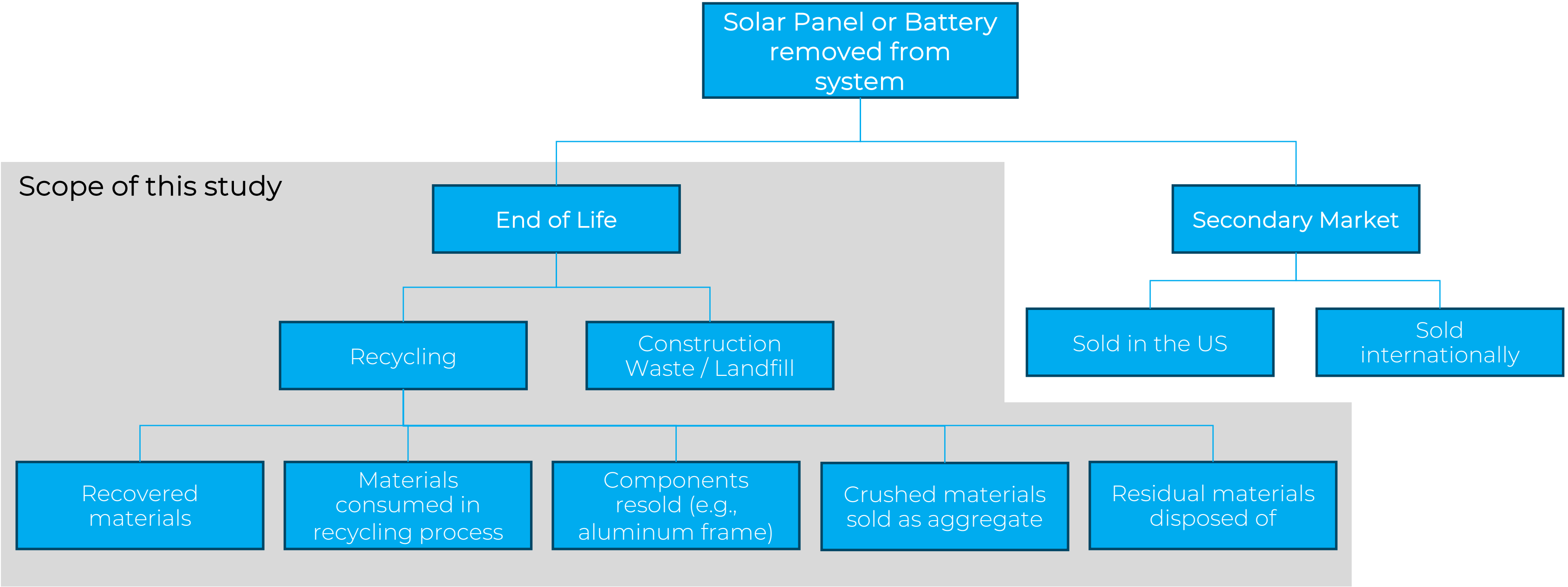
Residential	Commercial & Industrial	Utility Scale
		
		

LI-ION

POWER ADVISORY

End of Life vs. Secondary Market

- The scope of this study is end of life solar panels and batteries. If the equipment is not at the end of life, then there is a secondary market it can be sold into. Equipment can also be refurbished and sold into the secondary market
- While we haven't looked at the secondary market, given stakeholder interest we recommend that Connecticut do so (see Recommendation 5g later in this report)



POWER ADVISORY

Connecticut Solar Programs

The policy recommendations in this study were designed to cover all historical and current solar installed in Connecticut. This includes all State-administered funding programs shown below and any other solar projects (residential, commercial and industrial, and utility scale)

State-Administered Solar Programs				
Program	1st Yr of Program	Program Size	MW_{AC} deployed as of early 2023*	Approximate # of Panels**
Residential Solar Investment Program (RSIP)	2011	• 330 MW_{AC} in total	330	1,430,000
Residential Renewable Energy Solutions (RRES) Program	2022	• Target of 50-60 MW_{AC}/year	161	634,000
Low Emission / Zero Emission Renewable Energy Credit Program (LREC/ZREC)	2012	• 349 MW_{AC} of solar thus far	349	1,376,000
Virtual Net Metering Program (VNM)	2014	• 77 MW_{AC} of solar thus far	77	305,000
Shared Community Energy Facilities (SCEF) Program	Pilot 2017 Permanent 2020	• Max procurement of 25 MW_{AC}/year	3	12,000
Non-Residential Renewable Energy Solutions (NRES) Program	2022	• 6 year program x 60 MW_{AC}/year	2	6,000
		Total	922	3,763,000

* Data is from CT PURA 2023 Clean & Renewable Energy Report

** Assumes 330 W_{DC} per panel (except RSIP which is 300 W_{DC}) and a DC:AC ratio of 1.3

LI-ION

Connecticut Storage Programs

The policy recommendations in this study were designed to cover all historical and current energy storage installed in Connecticut. This includes all State-administered funding programs shown below and any other battery projects (residential, commercial and industrial, and utility scale)

State-Administered Energy Storage Programs		
Program	1st Yr of Program	Program Size
Energy Storage Solutions (Residential & Commercial)	2022	• 1 GW of energy storage by the end of 2030 (includes utility scale) • Interim targets of 300 MW of storage by the end of 2024 and 650 MW by the end of 2027.
ConnectedSolutions Demand Response (Residential & Commercial)	2020	• 11,041 kW total enrolled residential capacity • 950 kW total enrolled C&I capacity

POWER ADVISORY

2. Current Practice in Connecticut and Other States

Common End-of-Life Management Frameworks

Type	Decommissioning Bonds	Extended Producer Responsibility (EPR)	Advanced Fee Administration (AFA)
Description	• End-of-life management decisions for utility-scale PV modules made and financed by the owners of the modules, normally with decommissioning bonds (which are required by some jurisdictions). If modules are not being reused or refurbished, owners are responsible for determining whether a PV module is a hazardous waste and can make EOL management decisions accordingly.	• The program requires a manufacturer (or other identified party, such as a distributor) manage the takeback and recycling of PV modules or batteries. Costs (or profits) are typically identified in Stewardship plans required at program outset, and ultimately borne by the manufacturer at EOL.	• States and/or independent third parties manage dedicated revenues which can be funded through a variety of programs such as advanced recycling fees charged at the time of sale, utility bill fees, or taxes. The funds would be disbursed to manage recycling programs or to reimburse contractors who administer private programs.
Responsible Party	• Asset Owner	• Original Equipment Manufacturer (OEM)	• One of, or some combination of: asset owner, OEM, developer, distributor, installer, ratepayer, taxpayer
Timing of Costs	• Owner puts in place a decommissioning bond at time of COD, and funds are used at end of life	• Costs to recycle materials are borne when services are needed, but there are various methods for ensuring that requirements are met such as financial assurance during project planning.	• Costs are typically borne by asset owners through a fee at the time of purchase. Because PV module lifetimes are longer than other recycled products, this can cause a mismatch between revenue and expenses for management programs that may need to be addressed.
Examples	• Status quo across the US today • NC Utility Scale Solar Management Program / SC Decommissioning Requirements (Proposed)	• Washington's PV Stewardship & Takeback Program (OEM plans are due 2025) • New Jersey's Electric and Hybrid Vehicle Battery Management Act (passed Jan 2024, plans due likely in 2027)	• California's E-Waste Advanced Fee Administration (Proposed)

Introduction

Current industry standard for end-of-life panels and batteries – commercial systems

- At present, in both Connecticut and across the country, few installations of solar panels or batteries have a plan for recycling the equipment at end of life. Rather, in the case of larger commercial systems, there is typically a decommissioning plan that calls for a construction waste company to remove the system, but with no requirement – or budget – to recycle the panels or batteries. These decommissioning plans are driven by the investor and/or lender of a given project. Unless the installed array is located on an otherwise regulated facility or location, there is generally no regulatory or legal mandate. See next page for more information

- As more and more recycling companies emerge in this relatively nascent industry, announcements are being made of partnerships between recyclers and both manufacturers and asset owners. Publicly traded companies in particular are moving in the direction of recycling, in part because of ESG reporting requirements they have

Current industry standard for end-of-life panels and batteries – residential systems

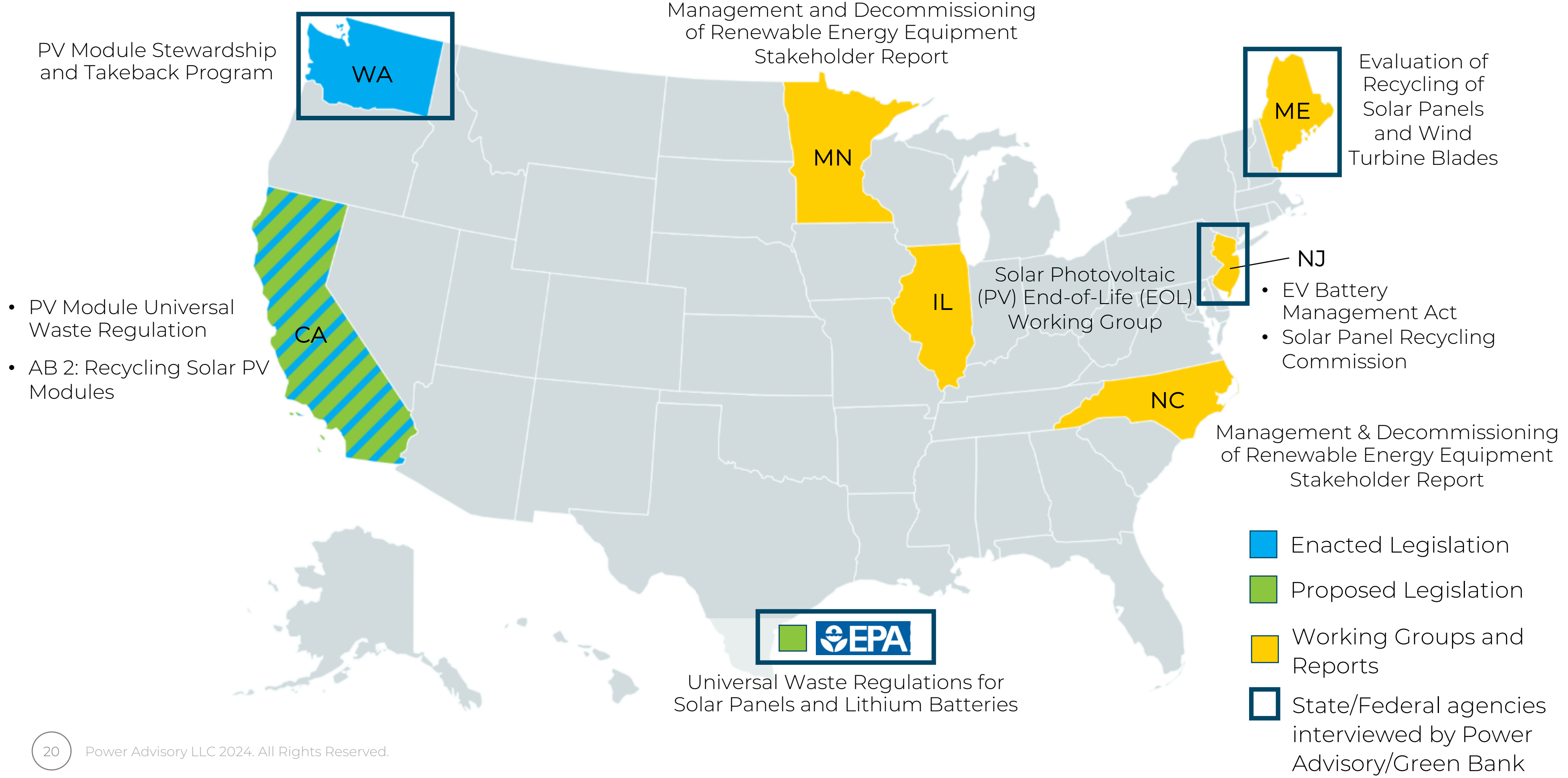
- Similar to commercial systems, few residential solar panel or battery systems have a plan for recycling at end of life
  - For third party owned systems, the asset owner typically expects that the panels will last about 35 years. Some asset owners are working with recyclers and developing plans for end of life, while others are not. At present, the volumes are small and recycling options are only just emerging
  - For host-owned systems, we found no mechanism currently in place whereby the host owner could have their panel or battery collected and recycled

Introduction (continued)

Policy development

- In the US, policies around end-of-life solar panels and batteries are in an early formative stage
  - Solar panels
    - Only one state has enacted a policy that addresses solar panel recycling: Washington State. That law, based on the Extended Producer Responsibility (EPR) framework, was passed in 2018, and requires manufacturers to submit plans by July 2024 with implementation beginning July 2025; there is no definitive track record on implementation to date, but preliminary indications are discouraging, with manufacturers opting to not submit plans
    - California passed a law that classifies solar panels as "Universal Waste" which means they can be legally disposed in conventional landfills but only after verifying that the panels do not contain hazardous materials. California has proposed a recycling law, based on the Advanced Fee Administration (AFA) framework, but it is still in the regulatory process
  - Stationary Batteries
    - The first ever law related to Electric Vehicle (EV) battery management was passed by New Jersey in January 2024, based on the EPR framework, however, it does not cover stationary batteries
  - A limited number of other states have introduced proposed legislation, and several have formed working groups to consider this topic
- Appendix A contains a summary of policy developments and working groups on a state-by-state basis

End-of-Life Related Activities Reviewed



Current Decommissioning Plans and Recycling Plans (1/3)

- **Today, decommissioning plans, which are typically a requirement of the asset owner and/or lender and not necessarily a regulatory or legal mandate, are high level.** A typical plan may state the following:
  - The site must be restored to a useful, nonhazardous condition, including removal of equipment, structures, and foundations. Deviations from such a requirement can be tailored to future use needs
  - A budget showing the cost of implementing the plan is required to be certified by the project engineer and to be approved by the local municipality or other regulating entity
  - A performance (or decommissioning) bond, or other financial assurance, equal to the budgeted amount, plus 10%, must be provided
  - These plans typically call for a construction waste company to take the equipment away. Power Advisory's understanding is that these companies are typically either selling the panels into the secondary market or disposing of them in landfills. The asset owner may or may not know how the panels are being disposed of
- **In terms of how the solar panels are dealt with specifically, the typical language is equally high level.** Typical language includes the following:
  - "The modules should be recycled and sold as salvageable items"
  - "All modules will be removed from the site via semi-trucks"
  - "The owner or future owner-operator will establish policies and procedures to maximize recycling and reuse"
  - "The owner or future owner-operator will be responsible for the logistics of collecting and recycling the PV modules and to minimize the potential for modules to be discarded in the municipal waste stream"

Current Decommissioning Plans and Recycling Plans (2/3)

- An industry standard has yet to emerge in Connecticut or the US. That includes both at the Commercial Operation Date (COD) stage and End of Life (decommissioning) stage.
  - With no policy, mandates or standards in place at present, the sense that end of life is far off in the future, and recyclers just emerging, there has been little urgency for companies to address this issue. In the meantime,
    - SEIA has plans to develop an ANSI standard for solar decommissioning plans that may address some of these issues
    - Some companies have a waste handler that takes broken equipment. At present, most of the waste handlers sell panels into the secondary market or send them to landfills
    - Some solar farms have solar panels that don't work, but keep them on their property simply because they haven't decided how to dispose of them. However, this is just a very small number of panels

Current Decommissioning Plans and Recycling Plans (3/3)

- CT DEEP does regulate some solar farms on landfills in Connecticut (14 operating farms totaling 28 MW and eight construction-ready farms totaling 13 MW)
  - DEEP's approvals for the installation of solar on landfills are licenses and such approvals may dictate ultimate disposition of the decommissioned arrays. These licenses require the development of decommissioning plans that address the reuse, recycling and/or disposal of the solar installations. The requirement is that the plan be submitted at least 60 days prior to deconstruction for DEEP's review and approval. DEEP's plan is to look for standardization of end of life approaches that should include adherence to the solid waste management hierarchy (reuse, recycle, dispose, in that order)
    - The specific language is: "The Licensee shall provide written notification to Department staff, in accordance with condition no. 21, at least sixty (60) days prior to the decommissioning and removal of the ground mounted solar photovoltaic (PV) panels and ancillary equipment and detail the proposed disposition of the materials (e.g., re-use of PV panels, recycling of plastic components, appropriate disposal of any hazardous materials, etc.)"
  - In accordance with CGS Section 22a-228(a) DEEP developed the state-wide Solid Waste Management Plan that was required to incorporate the Solid Waste Management Hierarchy (as provided by CGS Section 22a-228(b)). CGS Section 22a-229 requires that any person or facility regulated under the solid waste section of the statutes is required to act in a manner consistent with the solid waste management plan which incorporates said hierarchy. Hence DEEP has the authority at such regulated facilities or locations to be specific about Best Management Practices (BMPs) regarding EOL management. CGS Sec 22a-228(b) requires that the state develop the state-wide solid waste management plan (SWMP) that shall incorporate the solid waste management hierarchy

Industry Considerations in Recycling

- Although there is no clear consensus that is emerging for recycling, there are some interesting practices that individual manufacturers and developers have adopted

- When solar panels reach their end of life, they are reused, recycled, or disposed. The recycling involves a combination of reselling, landfilling, or materials recovery

- There seems to be an increase in voluntary industry commitments to recycling solar panels and batteries. Several companies have started to explicitly tie their recycling of solar and batteries to ESG metrics. This has likely been accelerated by the SEC's ruling in March 2024 that most publicly traded companies must report ESG metrics in their annual reports beginning in 2025
    - The Sunnova Sustainability Report provides a breakdown of end-of-life materials by how they were recovered, resold or recycled
    - Some manufacturers such as Tesla in the battery space support the development of a "reverse logistics chain" which aims to facilitate product takeback at customer's request
    - There is also an emerging ecosystem of manufacturers, developers, and recyclers who are investing in the circular economy

- Recent research and advancements in solar panel technology have focused on improving the durability of solar panels against adverse weather impacts (e.g., hail, hurricanes). However, hardened panels, which often feature thicker glass and reinforced frames, present unique challenges and considerations for recycling

Case Study: Sunrun Solar Panel Recycling

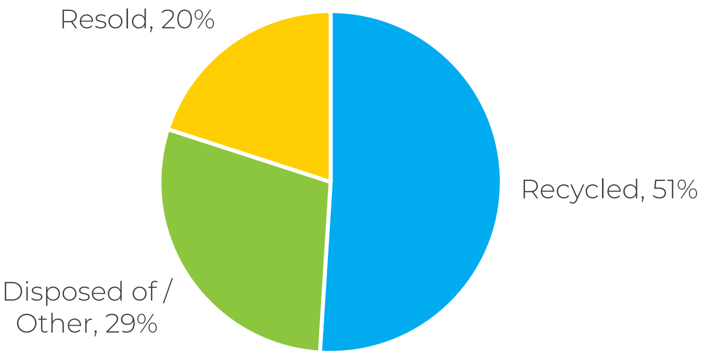
- Sunrun has put processes in place to sustainably dispose of modules, batteries, inverters, and other electronic equipment used in installations through partnerships with third-party recycling and refurbishment vendors
    - The vendors include SolarCycle, Recycle PV Solar, Echo Environmental, and other groups associated with the Solar Industry Energy Association's (SEIA) National PV Recycling Program
    - These vendors are certified under Responsible Recyclers R2:2013, OHSAS 1800:2007, and ISO 14001:2007 standards. They also work with third-party vendors to redeploy or resell modules to support a reduced environmental impact overall
- Sunrun uses monocrystalline and multicrystalline PV modules, thereby avoiding the growing concerns about hazardous materials present in alternative chemistries such as thin-film modules
- In 2023, Sunrun stated in their Impact Report that they redeployed or recycled 100% of solar panels, batteries, and inverters with manufacturers and qualified recycling providers
- Sunrun is the largest installer/owner of residential solar projects in Connecticut

Source: Sunrun 2022 and 2023 Impact Reports

Case Study: Sunnova Solar Panel Recycling

- Sunnova works with specialized recyclers to disassemble panels, recycle or reuse components, and provide a breakdown of how materials are processed
- This includes the percentage of materials recycled, resold, and disposed of. Some vendors buy broken panels to repair and resell them, emphasizing the value of certain components like frames
- This is hinting at the emergence of a recycling ecosystem where a menu of options are made available based on efficiency and cost considerations

Sunnova's End of Life Materials, 2023
*224 tons**



* Were the 224 tons to all be solar panels, that would equate to about 4 MW of panels

Source: Sunnova 2023 Sustainability Report

Implications of Hardened Solar Panels

- Hardened solar panels, which often feature thicker glass and reinforced frames, can present unique challenges and considerations for recycling processes
    - Recycling efficiency
        - Resilience features, such as thicker glass and more robust frames, can make the mechanical separation of materials more difficult. For instance, the processes designed for conventional panels might not be as effective or efficient
    - Economic and Environmental Impact
        - Hail-resistant panels can reduce damage and extend the lifespan of solar panels; they may also lead to increased recycling costs. Specialized equipment may be needed to handle the thicker and more durable materials

Case Study: Tesla Battery Recycling Operations and Strategy

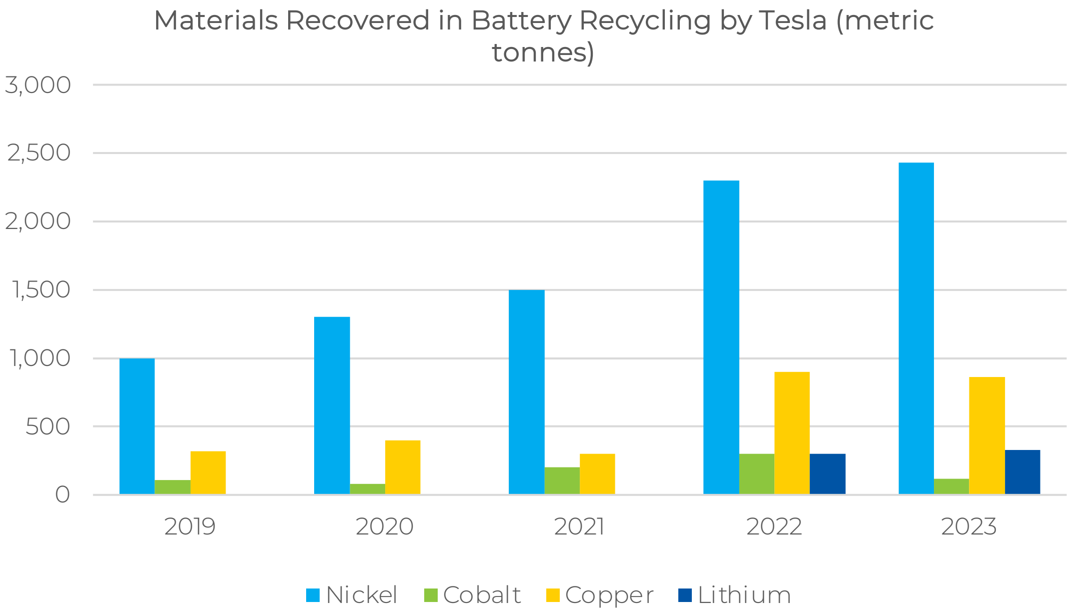
- Although clear decommissioning plans have not emerged, Tesla has actively focused on recycling their products. They support the development of a “reverse logistics chain” which aims to facilitate product takeback at customer’s request
- There is no contractual obligation for customers to return equipment. However, there are numerous competing collectors for used EV batteries, and Tesla anticipates that the market and competition for Battery Energy Storage Systems (BESS) will grow
- In-House Recycling Capacity
    - Tesla has in-house recycling facilities at two sites, focusing on materials processing and recycling manufacturing scrap. The company's long-term goal is to establish recycling facilities at each site
- Role of Third-Party Recyclers
    - Tesla has contracts with third-party recyclers that predate its development of in-house capacity. These contracts supplement Tesla’s in-house recycling operations
    - In 2023, Tesla processed 650MWh of battery materials at their shredding facility, compared to 3GWh of battery materials sent to their recycling partners*

Tesla continues to make strides in recycling batteries and reclaim battery metals

* Source: Tesla 2023 Impact Report

LI-ION

Tesla's Reclamation of Battery Metals (all products)

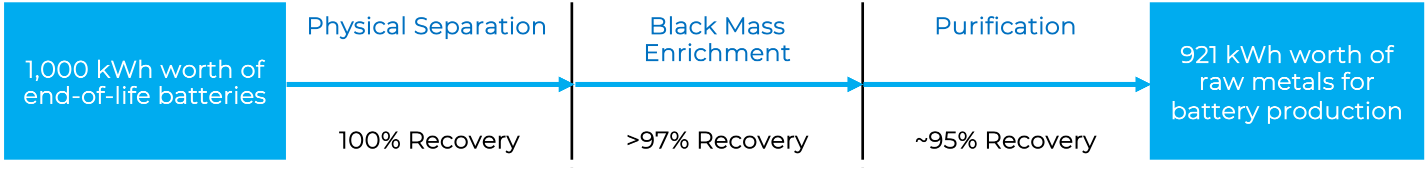


Source: Tesla Impact Reports, 2019-2023

- Since 2019, Tesla has been reporting on materials recovered in the annual Impact Report
- Tesla began reporting lithium recovery in 2022
- The recovery of lithium shows an increase, especially in the last two years, reflecting its crucial role in battery technology and Tesla's efforts to reclaim this valuable resource
- The majority of recovered materials are from the recycling of EV batteries; at present, stationary batteries represent a very small amount

POWER ADVISORY

Tesla's Efficiency of Reclamation of Battery Metals (all products)



- While Tesla has been making strides with increases in overall raw metal recovery, they have also had high rates of raw metal recovery
- In 2021, Tesla reported an overall 92% rate of recovery for 1,000kWh of batteries (921/1,000). Their 2023 Impact Report did not provide detailed breakdowns, however, reported an overall rate of recovery for their batteries at over 90%
- This relatively high sustained recovery rate is illustrative that at least some manufacturers are committed to a closed-loop recycling process and shows the potential to become more optimized and more broadly adopted over time

Source: Tesla Impact Reports, 2021, 2023

LI-ION

Case Study: Redwood Materials' Sustainable and Scalable Recycling

- Redwood offers large-scale sources of domestic anode and cathode materials produced from an increasing number of recycled batteries that directly go back to U.S. cell manufacturers
- They currently process more than 20 GWh of lithium-ion batteries annually, successfully reclaiming 95% of lithium from scrap battery materials
- The company's recycling technology purports to achieve lower emissions in recovery of materials. The graph below illustrates how Redwood reduces environmental impacts:

Analysis of Redwood's recycling process per kilogram of finished battery material

	Energy Used (MJ)	CO2 Emissions (kg)	Water (Liters)
Refining	194.0	14.5	77.3
Typical Battery Recycling	146.0	10.7	22.8
Redwood live-battery Recycling	44.0	6.9	20.0
Redwood factory-scrap recycling	22.0	2.9	9.0

Source: Redwood Materials

POWER ADVISORY

Case Study: Redwood Materials' Sustainable and Scalable Recycling

- Redwood is also an example of how technology can localize and sustainably scale battery materials in the US:
  - Their hydrometallurgy facility recycles battery manufacturing scrap into raw nickel and cobalt but also stands as the only commercial-scale source of lithium supply to come online in the U.S. in decades
  - Redwood also operates reductive calciner facility for battery recycling in North America. The facility is crucial for processing all types of live battery feedstocks efficiently
  - This thermal pre-process allows Redwood to handle live battery cells, consumer electronics, and electric vehicle modules – and can process over 40,000 metric tons (about 15-20 GWh) annually

3. Environmental Impact

Environmental Impacts Overview – Solar and Batteries

There are critical aspects and considerations for the end-of-life management of solar panels and lithium-ion batteries, focusing on environmental impacts, recycling processes, and policy implications

- Solar Panels
  - Environmental Impacts: Landfilling causes resource waste, increased carbon footprint, and soil/water contamination from arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver (known collectively as the RCRA 8 metals)
  - Recycling Processes: Methods include smelting and crush-and-shred; managing by-products like slag is crucial
  - Policy and Standards: A TCLP (Toxicity Characteristic Leaching Procedure) test determines hazardous waste; RCRA (Resource Conservation and Recovery Act) compliance ensures safe disposal and transportation
- Lithium-Ion Batteries
  - Environmental Impacts: Landfilling leads to contamination, fire risks, and material loss
  - Recycling Processes: Modern recycling processes are taking off and there are tradeoffs for many processes. Hydrometallurgy is efficient and eco-friendly; pyrometallurgy is robust but less efficient for lithium; emerging technologies like WPI offer better solutions
  - Policy and Standards: Modular designs, better material use, and advanced recycling tech are key; policies should support sustainable practices from production to disposal. TCLP is also an option to determine hazardous waste

Summary of Impacts of Solar Panels

- Landfilling solar panels can lead to resource waste and increased carbon footprint, and in some cases, environmental contamination and health risks:
  - May waste valuable recyclable materials, contributes to landfill space issues, and increases the carbon footprint due to inefficient resource use
  - Depending on the type of panel, exposure to the RCRA 8 metals can lead to serious health issues such as cancer, nervous system disorders, and reproductive problems. Additionally, they can harm the environment by contaminating soil and water
- While recycling decreases the overall environmental impact of end-of-life solar panels, the by-products of recycling sub-processes can have adverse environmental impact that fall into common categories
  - Many recycling sub-processes' and by-products' impacts include energy consumption, dust and particulate, and air emissions, material loss, and waste generation
- It is important to evaluate specific sub-processes, but also where the by-products end up to understand environmental impacts
  - For instance, solar panels recycled through smelting, or 'crush and shred' approaches have different by-products
  - The smelting approach creates slag or 'black blob'. If this is used for industrial applications, it has a lower environmental impact. Conversely if it is landfilled, the impact is much higher

Note: Additional details can be found in Appendix C: Environmental Impact

Implications for Standards or Policy for Solar Panels (1/2)

Considerations	Implications for standards or policy
Tendency for Landfill. Since the cost of recycling is less than the monetary benefit, solar panels can end up in landfills, with materials that can impact the environment.	• Toxicity tests such as TCLP or more evolved landfill infrastructure and standards (such as bans) can be considered. • Consider implementing a policy that mandates/incentivizes manufacturers to provide PV module labels with concentrations of hazardous material. Labeling modules can eliminate the need to conduct toxicity tests, introduce transparency, and reduce regulatory and legal liabilities for recyclers, making it more competitive with disposal.
Evaluating sub-processes matter when looking at impact to the environment. More than 85% percent of a solar photovoltaic (PV) module by weight is made of materials that industry already know how to recycle, like aluminum and glass.	• Leverage SEIA Working Committees and EPA to communicate specific issues for the State of Connecticut. • Public campaigns, educational programs coupled with list of approved recyclers can help educate PV system owners, installers, and other stakeholders about the importance of responsible disposal and recycling practices.
The management of by-products can be as important as the sub-process or process itself. For instance, both "crush and separate" and smelting are viable processes. However, if the 'black blob' or slag ends up in landfill then the smelting would have more of a negative environmental impact.	• Keeping up with emerging processes, especially to evaluate how by-products are managed can help to reduce impact and make an informed policy decision.

Implications for Standards or Policy for Solar Panels (2/2)

Considerations	Implications for standards or policy
While there are a myriad of environmental impacts, many of them cluster around several key categories. Energy consumption, dust and particulate emissions, material loss, waste generation, and impact on soil and water.	• Evaluating standards for mitigating these impacts can be a more efficient way to address environmental effects. • Hold technical conferences on key concerns or lingering issues to enable industry progress.

To make a larger impact on reducing waste and other environmental impacts from solar technologies, actions need to be taken before a module is even made.	• Policy frameworks can evaluate how advancements in each area can decrease overall impact to the environment:
	    • Modular panel design – potentially make panels easier to separate.
	    • Use of materials – decrease the use of expensive, rare, or harmful materials.
	    • Extend panel lifespans
	    • Improve recycling processes, including development of sub-processes to identify improvements for specific materials

Toxicity Characteristic Leaching Procedure (TCLP)

- Discarded solar panels, which is considered solid waste, may be regulated under RCRA Subtitle C as hazardous waste if it is determined to be hazardous
    - Landfills are regulated under RCRA Subtitle D (solid waste) and Subtitle C (hazardous waste) or under the Toxic Substances Control Act (TSCA)
    - The U.S. Department of Transportation (DOT) has specific regulations for the transportation of hazardous materials, outlined in the Hazardous Materials Regulations (HMR; 49 CFR Parts 171-180)
- The most common reason that solar panels would be determined to be hazardous waste would be by meeting the characteristic of toxicity
    - Heavy metals like lead and cadmium may be leachable at such concentrations that waste panels would fail the toxicity characteristic leaching procedure (TCLP), a test required under RCRA to determine if materials are hazardous waste
- Crystalline silicon panels are generally non-hazardous; however, CdTe in thin-film solar panels may be toxic due to the cadmium. Tests can assess whether they need to be managed as hazardous waste

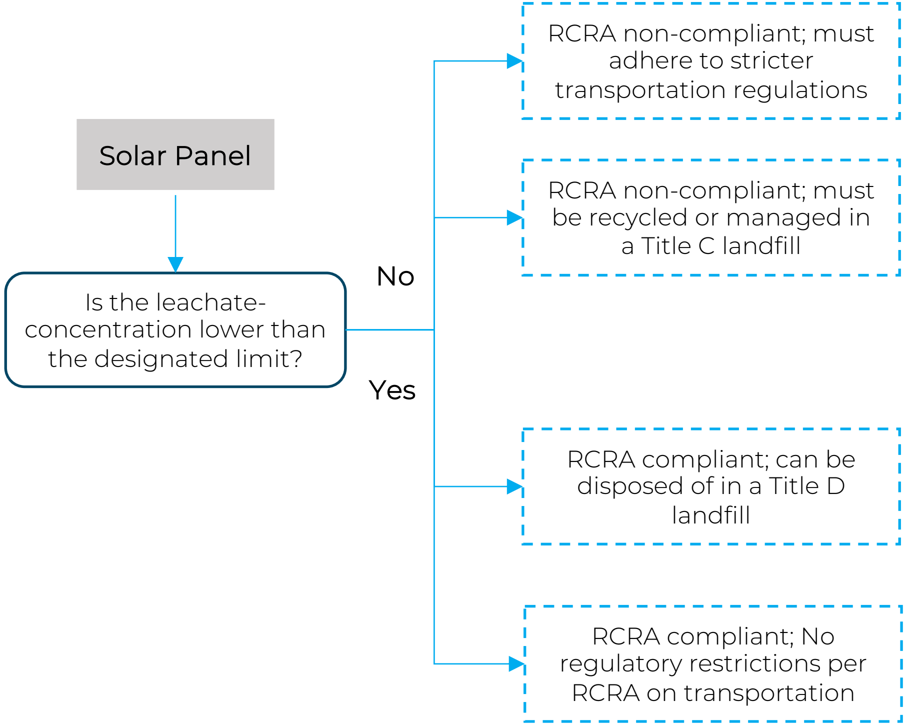
Regulatory Limits of Metal Concentration in leachates mg/L

Metal	Limit (mg/L)
Arsenic (As)	5
Barium (Ba)	100
Cadmium (Cd)	1
Chromium (Cr)	5
Lead (Pb)	5
Mercury (Hg)	0.2
Selenium (Se)	1
Silver (Ag)	5
Copper (Cu)	-
Zinc (Zn)	-
Nickel (Ni)	-
Molybdenum (Mo)	-

POWER ADVISORY

Implications for RCRA Compliance of Solar Panels

Implications of Results of TCLP Test for RCRA Compliance



Requirements for packaging, labeling, documentation, and training for handlers.

Subtitle C establishes a federal program to manage hazardous wastes from cradle to grave. Subtitle C regulations for the generation, transportation and treatment, storage or disposal of hazardous wastes.

Subtitle D focuses on state and local governments as the primary planning, regulating and implementing entities for the management of nonhazardous solid waste, such as household garbage and nonhazardous industrial solid waste.

While no RCRA restrictions apply for transport here, States may have additional regulations to implement RCRA guidelines or impose stricter standards for non-RCRA waste management including transport.

TCLP Test Process

The TLCP test for solar panels evaluates the potential for hazardous substances to leach from the panels into the environment, ensuring compliance with regulatory standards

Size Reduction → Extraction → Simulation of Leaching → Evaluating RCRA Compliance

Size Reduction

Sample pieces with particle size not to exceed the allowed size limit of EPA 1311 standard which is 9.5 mm.

The particle size used in the analysis is consistent with the median particle size expected in landfill disposal.

Extraction

Testing for eight (8) distinct metals – mercury (by Method 7470A), arsenic, barium, cadmium, chromium, lead, selenium and silver (by Method 6010C) as well as the analysis and interpretation of the test results on a module level.

Simulation of Leaching

Materials are placed in a solution to simulate the leaching action of water seeping through waste in the landfill.

The liquid waste is then separated from the solid waste through a fiber glass filter. The solid material is discarded, and the liquid components are then assessed.

Evaluating RCRA Compliance

Source: [SW-846 Test Method 1311: Toxicity Characteristic Leaching Procedure | US EPA]

Summary of Impacts of Lithium-Ion Batteries

- Landfilling or improperly recycling batteries can lead to environmental contamination and health risks, risk of fires, and resource waste and increased carbon footprint
  - When landfilled or improperly recycled, these metals in batteries such as cobalt, nickel, and manganese. can leach into the soil and groundwater
  - Prone to thermal runaway, a process where they overheat and potentially catch fire
  - Landfilling prevents the recovery and reuse of valuable materials
- Like solar panels, while recycling decreases the overall environmental impact of end-of-life batteries, the by-products of recycling sub-processes can have adverse environmental impact that fall into common categories
  - Many recycling sub-processes' and by-products' impacts include energy consumption, dust and particulate, and air emissions, material loss, spent chemicals, residues, and waste generation
- Battery recycling sub-processes have varied advantages and disadvantages
  - Hydrometallurgical methods are more environmentally friendly and efficient for comprehensive recovery of valuable elements, including lithium, but require careful chemical waste management
  - In contrast, pyrometallurgical methods are robust for certain metals but less efficient for lithium recovery and have a higher environmental impact due to greater energy use and emissions
  - For instance, the newly developed Worcester Polytechnic Institute (WPI) process differs from traditional recycling methods in several key aspects, making it more efficient and economically viable

Note: Additional details can be found in Appendix C: Environmental Impact

Implications for Standards or Policy for Batteries

Considerations	Implications for standards or policy
Lithium-ion batteries are prone to thermal runaway, a process where they overheat and potentially catch fire. Fires at landfill sites can release harmful pollutants into the air and cause long-lasting environmental damage.	• Developing standards such as landfill bans, and transportation standards. • Establish policy driven mandates for end-of-life recycling, ensuring there is ownership of the end-of-life management for batteries.
Lithium-ion batteries end up in landfills, they release environmental contaminants, including toxic heavy metals like Cobalt, Nickel or Manganese.	
Recovery and reuse of metals and important in conservation and to meet the raw materials from mined sources.	
There are emerging processes for battery recycling as well as technological progress for existing ones. Innovative recycling process such as the WPI process can decrease recycling costs and reduce environmental impact.	• Keep up with emerging processes, especially to evaluate how by-products are managed can help to reduce impact and make an informed policy decision.
While there are a myriad of environmental impacts, many of them cluster around several key categories. Energy consumption, dust and particulate, and air emissions, material loss, spent chemicals, residues, and waste generation.	• Evaluate standards for mitigating these impacts can be a more efficient way to address environmental effects. • Hold technical conferences on key concerns or lingering issues to enable industry progress.

RCRA Compliance for Lithium-Ion Batteries

- EPA states that Li-ion batteries may meet the definition of hazardous waste under the Resource Conservation and Recovery Act (RCRA) if they exhibit characteristics of hazardous waste such as ignitability, reactivity, or toxicity when disposed. This is determined through testing, including TCLP as an option. For businesses, the EPA recommends managing Li-ion batteries that qualify as hazardous according to federal Universal Waste regulations (40 CFR part 273)

- EPA also states the household hazardous waste exemption under RCRA applies to lithium-ion batteries that are generated in the home. In Connecticut, Household Hazardous Waste (HHW) is residentially generated hazardous waste. HHW should be managed as such and not as routine residential trash

- There are clear risks to the environment and health from the improper treatment of end-of-life batteries, illegal disposal, and traffic accidents. If batteries are decomposed or digested by various processes without proper treatment, hazardous and toxic chemicals will be released into the air, water, and soil, leading to harm to human health

- Different chemical compositions of lithium-ion batteries for different applications, depending on the manufacturer's alternative. The typical chemical composition of LIBs mainly includes graphite, copper (Cu), aluminum (Al), cobalt (Co), nickel (Ni), manganese (Mn), iron (Fe), lithium (Li), organic carbonates, and plastic compositions

Ecotoxicological Effects of Lithium-Ion Batteries

Current contaminants found in batteries and their ecotoxicological effects

Contaminant	Ecotoxicological effects
Lithium	• Alterations in the development of invertebrates. • Interference with nucleic acids synthesis. • Accumulation in soil causes severe phytotoxicity.
Nickel	• High oxidative stress in mammalian and terrestrial plant systems, and disruption of ion homeostasis.
Copper	• Intake by ingestion of contaminated crops, leading to liver damage, gastric-related problems, and neurological issues.
Cobalt	• Adverse effects on biomass and on physiological activity in crops.
Manganese	• Used in some cathodes, manganese can be neurotoxic if inhaled over prolonged periods.
Graphite	• High concentrations of graphite flakes affect mechanisms of the respiratory systems, and a minor risk of physical-mechanical damage to unprotected skin and eyes also exists, with human carcinogenic toxicity.
Electrolyte	• Electrolytes of LIBs usually include both organic solvents and inorganic solutions, can cause corrosive skin burns, eye damage, and produce hazardous gas, leading to respiratory systems • If disposed of with municipal waste, they could lead to water pollution.
Aluminum	• Can be toxic to aquatic organisms, where it becomes more soluble and causes gill and respiratory issues. • Aluminum can inhibit plant root growth, reduces nutrient uptake, and interferes with plant metabolism.
Iron	• Can form hydroxides that smother habitats and reduce oxygen levels, causing respiratory issues and death in fish. • Excessive amounts in soil can lead to chlorosis and impaired growth.

Regulations for Lithium-Ion Batteries (1/3)

- EPA is working on a proposal to add hazardous waste solar panels to the universal waste regulations found at Title 40 of the Code of Federal Regulations Part 273 and to establish a new, distinct category of universal waste specifically tailored to lithium batteries
- On May 24, 2023, the Environmental Protection Agency (EPA) released a memo and related FAQs addressing the status of lithium-ion batteries under the Resource Conservation and Recovery Act (RCRA)
  - In this guidance, EPA did not break new ground but did explain how it interprets current hazardous waste rules to regulate lithium-ion batteries
  - EPA concludes that "most lithium-ion batteries are likely hazardous waste at end of life and that they can be managed under the … universal waste" standards until they reach a destination facility

LI-ION

Regulations for Lithium-Ion Batteries (2/3)

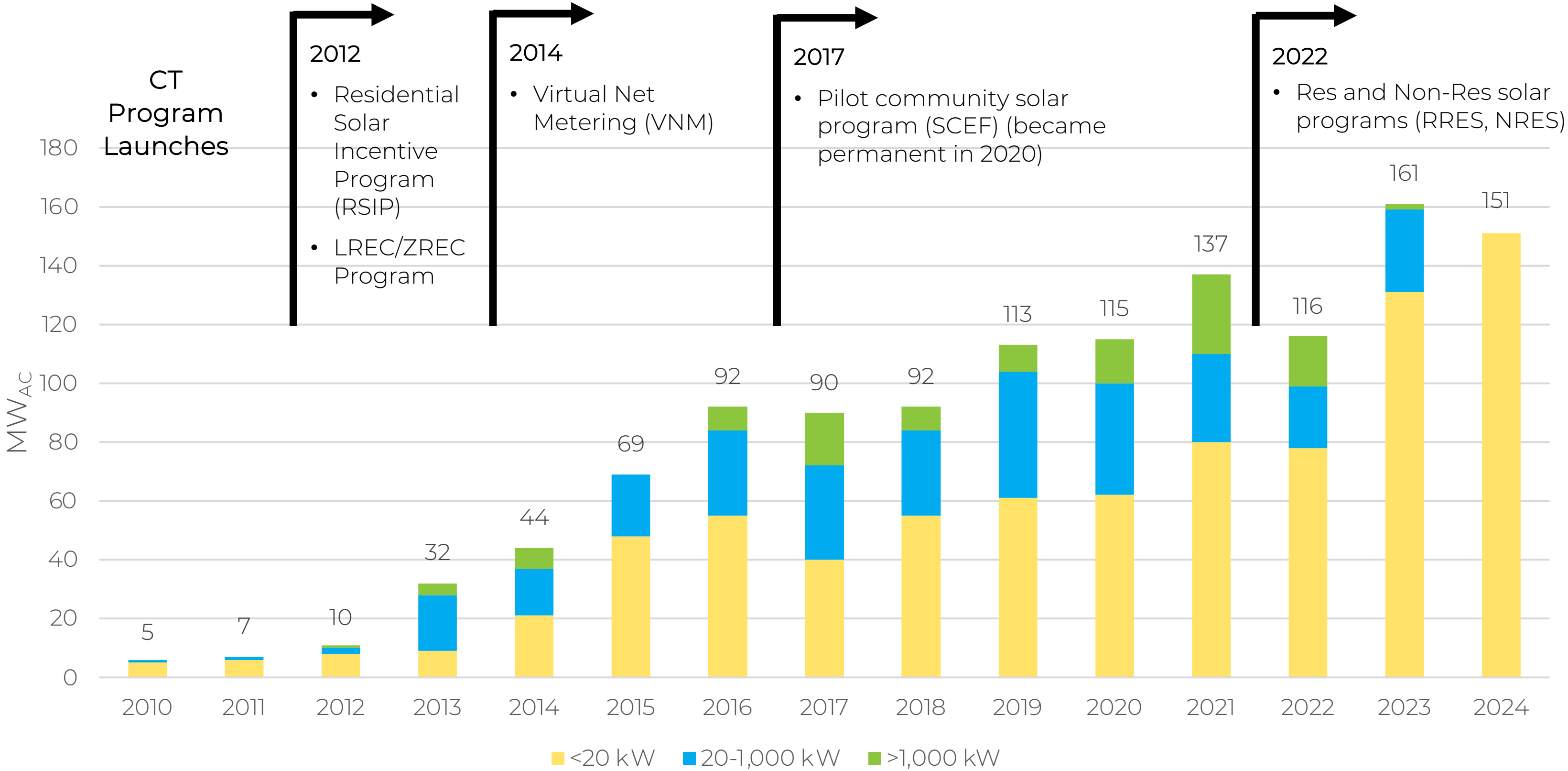
- The main takeaways from the EPA action include:
  - Evaluate whether the handling of lithium-ion batteries has made it a regulated waste
    - Under RCRA, a material is not a waste if it is legitimately being reused, repaired for reuse, or evaluated for reuse; the key is whether there is a "reasonable expectation of reuse"
    - EPA advises, when evaluating whether a lithium-ion battery can be repaired and put back into a device of the same design as its first application, or repurposed for a different application, that battery is not a waste. But if the intention is to destroy a battery to reclaim its critical minerals, it is a waste
  - Generators are ultimately responsible for determining whether end-of-life lithium-ion batteries are a hazardous waste
    - EPA only states that lithium-ion batteries are "likely" a characteristic hazardous waste when they reach end of life
    - According to EPA, at that point "most lithium-ion batteries on the market today" would demonstrate a hazardous characteristic of either "ignitability" or "reactivity"
    - Under RCRA it is the waste generator who makes that determination in the first instance — and that determination could potentially vary depending on the chemistry and charge that remains at the end of life

Regulations for Lithium-Ion Batteries (3/3)

- Lithium-ion batteries initially can be managed as a universal waste
  - EPA recommends that businesses manage lithium-ion batteries under RCRA's "universal waste" regulations. These rules are more streamlined than RCRA's full hazardous waste rules. Thus, batteries can be transported and collected by "handlers" under reduced requirements. Primarily, the handlers store universal waste, subject to regulatory requirements on labeling and accumulation times, among others, although a handler can do more than just store the batteries: it can disassemble battery packs, sort batteries, or discharge batteries, so long as the cells remain closed and intact
  - To take the next step in the recycling process and shred a battery to collect its critical minerals, a facility must be RCRA permitted. Once a battery enters this stream it is a hazardous waste, not a universal waste
  - For instance , recycling a battery by shredding it to create the mix of valuable material known as "black mass" must be done at a RCRA-defined "destination facility." A destination facility for these purposes may be either a hazardous waste recycler (which does not accumulate the material before recycling) or a RCRA-permitted treatment, storage, and disposal facility

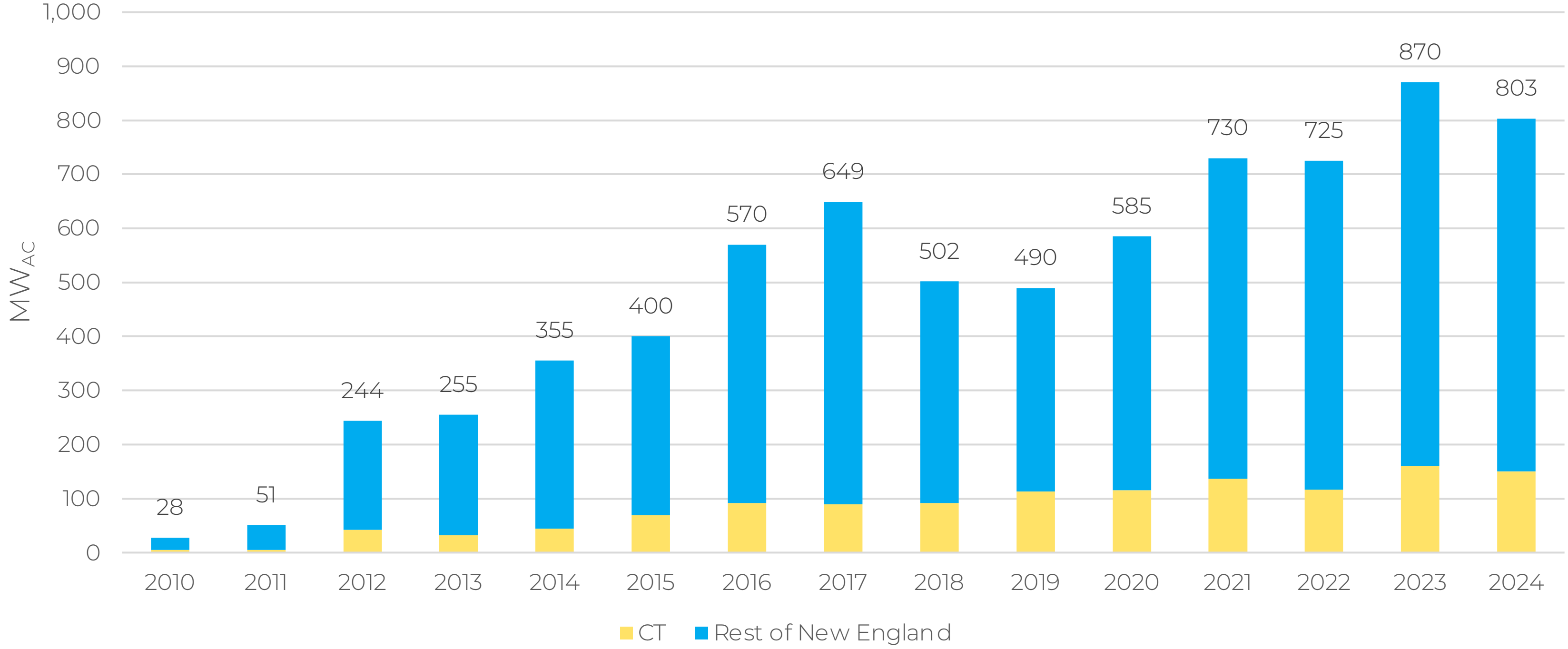
4. Needs Assessment and Market Readiness

Solar Installations in CT, 2010-2024 (MW_{AC})



Note: As of July 2024, installed storage projects totaled 1.8 MW of residential and 0.4 MW of commercial.
Source: ISO-New England 2024 Final PV Forecast, Eversource

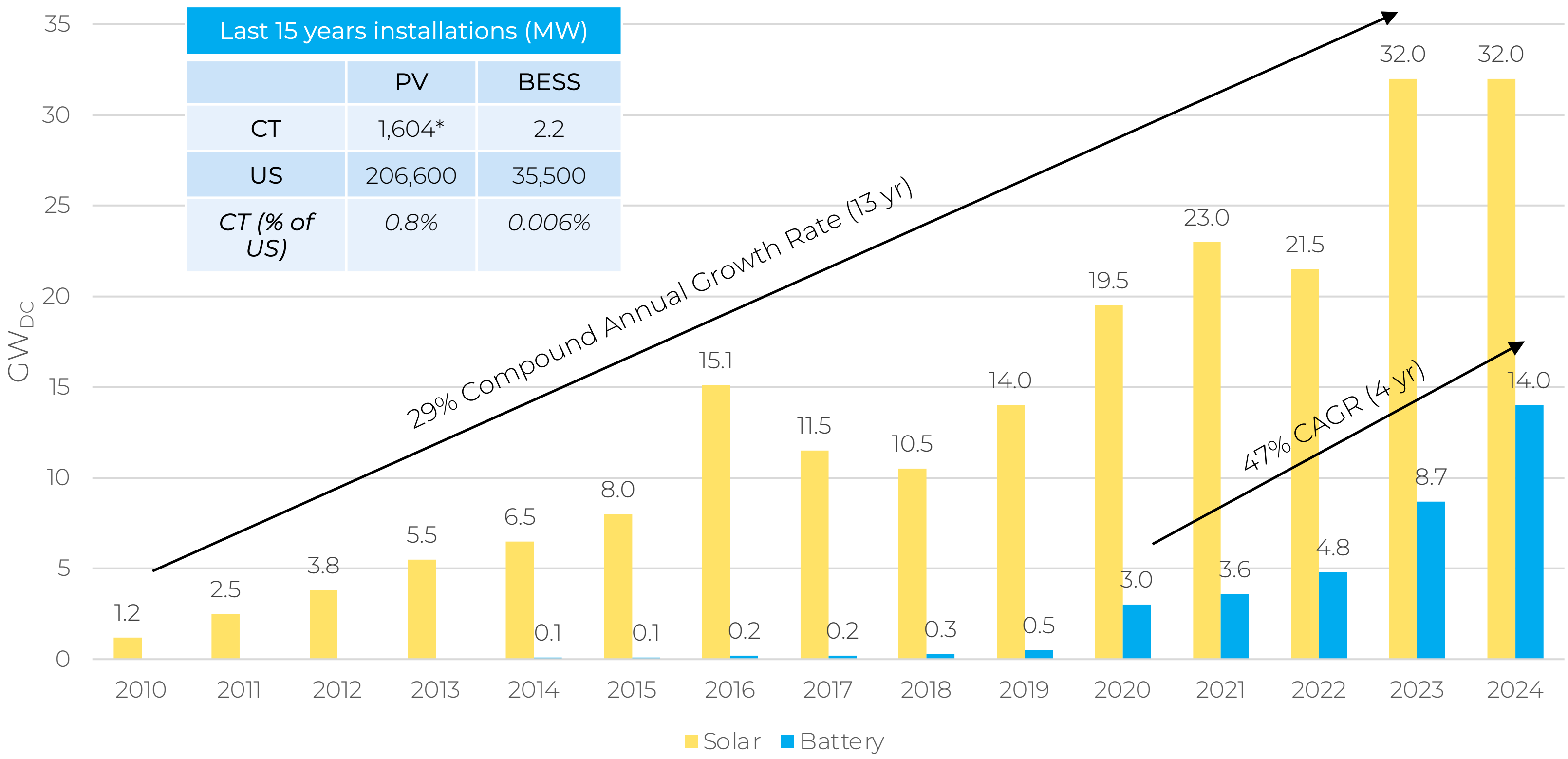
Solar Installations in New England, 2010-2024 (MW_{AC})



Source: ISO-New England 2024 Final PV Forecast

Solar/battery Installations in the US, 2010-2024 (GW_{DC})

Last 15 years installations (MW)		
	PV	BESS
CT	1,604*	2.2
US	206,600	35,500
CT (% of US)	*0.8%*	*0.006%*

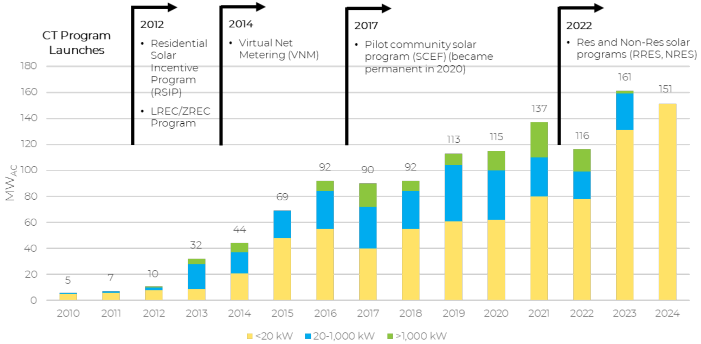


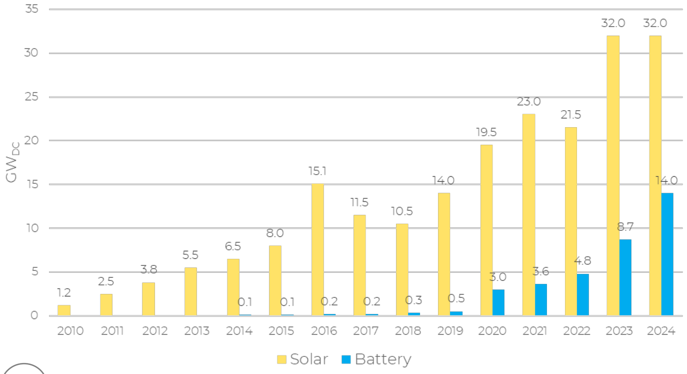
*Assumes a DC:AC ratio of 1.3

Source: Wood Mackenzie, American Clean Power, Power Advisory estimates

Determining the Waste Stream (metric tons per year)

Take actual and forecasted annual installations…





…Make assumptions that convert installations into the metric tons of waste generated over time…

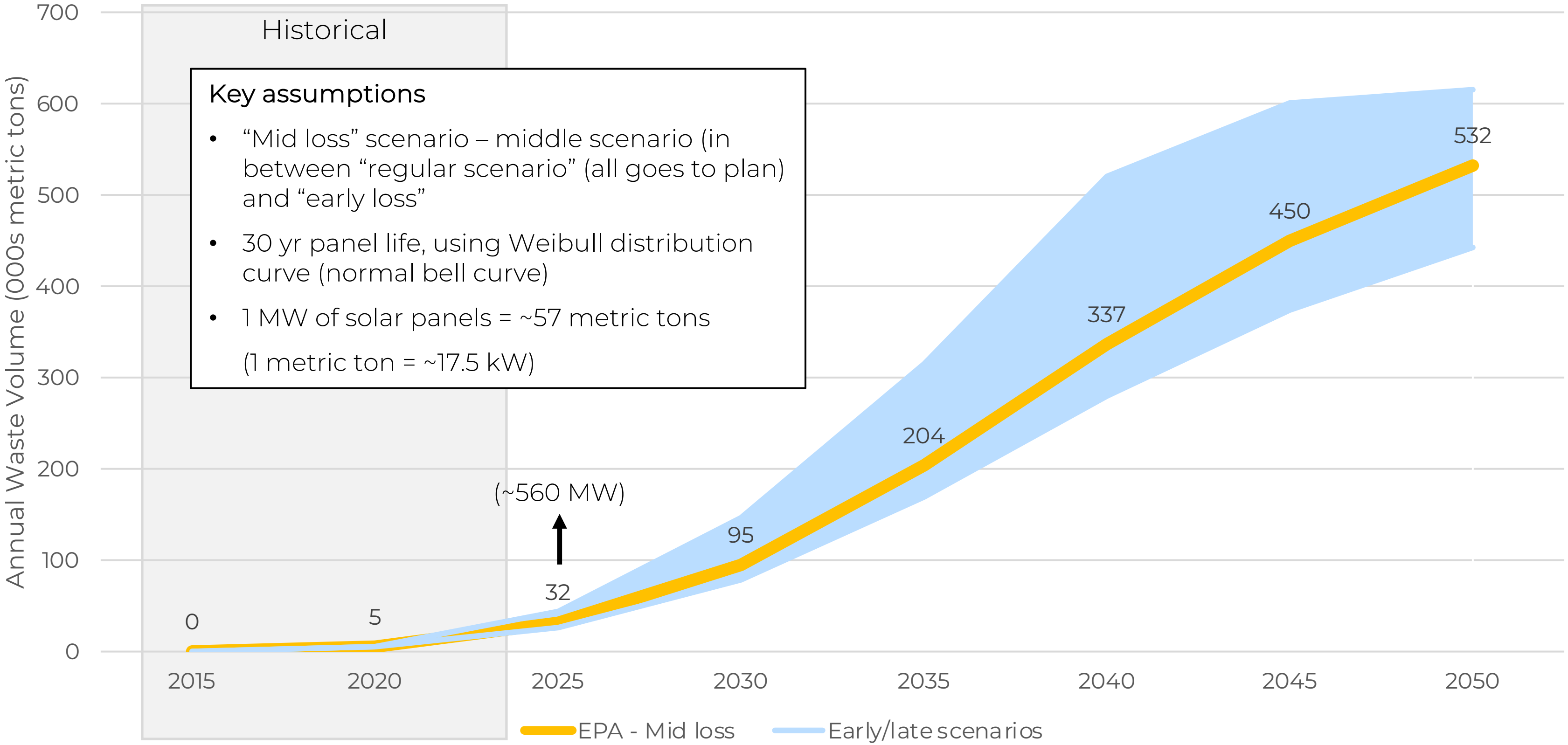
- Panel/battery life
  - Equipment life in years, and dispersions around the mean
  - Equipment broken during manufacturing, transport to the site, and construction
  - Extreme weather, fires and other events that damage or destroy equipment
  - Repowering trends
    - Cost and conversion efficiency of new panels
    - Investor decisions
- Metric tons/panel, metric tons/battery
  - Product mix (e.g., residential vs. commercial vs. utility scale)
  - Equipment design leading to lighter / heavier equipment
    - Number of hours of storage
    - Solar panel conversion efficiency improvements

…To yield waste per year

Metric tons of waste per year

POWER ADVISORY

US Annual PV Waste Volume Forecast



Source: US EPA, 2023, "early/late" scenarios are Power Advisory rough estimates

Factors Affecting Expected Solar Panel Life

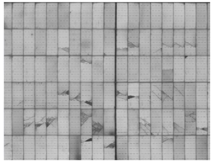
Repowering

- To date, repowering in the solar industry is rare, however, in certain cases may be justified economically. This differs somewhat with wind, where technology improvements (rotor size and turbine height) and the fact that many components tend to wear out at the same time, make the economics for repowering favorable in more cases
- The decision to repower solar after 10-15 years, for example, is driven mainly by the need to replace the inverters. At that time, an asset owner may decide that it's worthwhile to replace other equipment concurrently including the panels and/or wiring, depending on technology cost and performance at the time. New inverters may not be a 1:1 replacement for the original inverters, thus necessitating panel replacement. Adding batteries is another consideration
- Today, it's much more likely that panels would be either sold into the secondary market, or disposed of in landfills. But that may change if and when recycling costs decline to more economic levels and/or landfilling is banned

Extreme Weather Events

- Extreme weather events have damaged solar panels including:
  - Damage from hail storms (although hail storms are most prevalent in the Midwest and South, and rare in Connecticut)
  - Microcracking from freeze/thaw conditions

Solar panels damaged by hail in March 2024 in Needville, TX at a 350 MW solar farm



Microcracking

Select Solar Panel Recycling Factories (1/2)

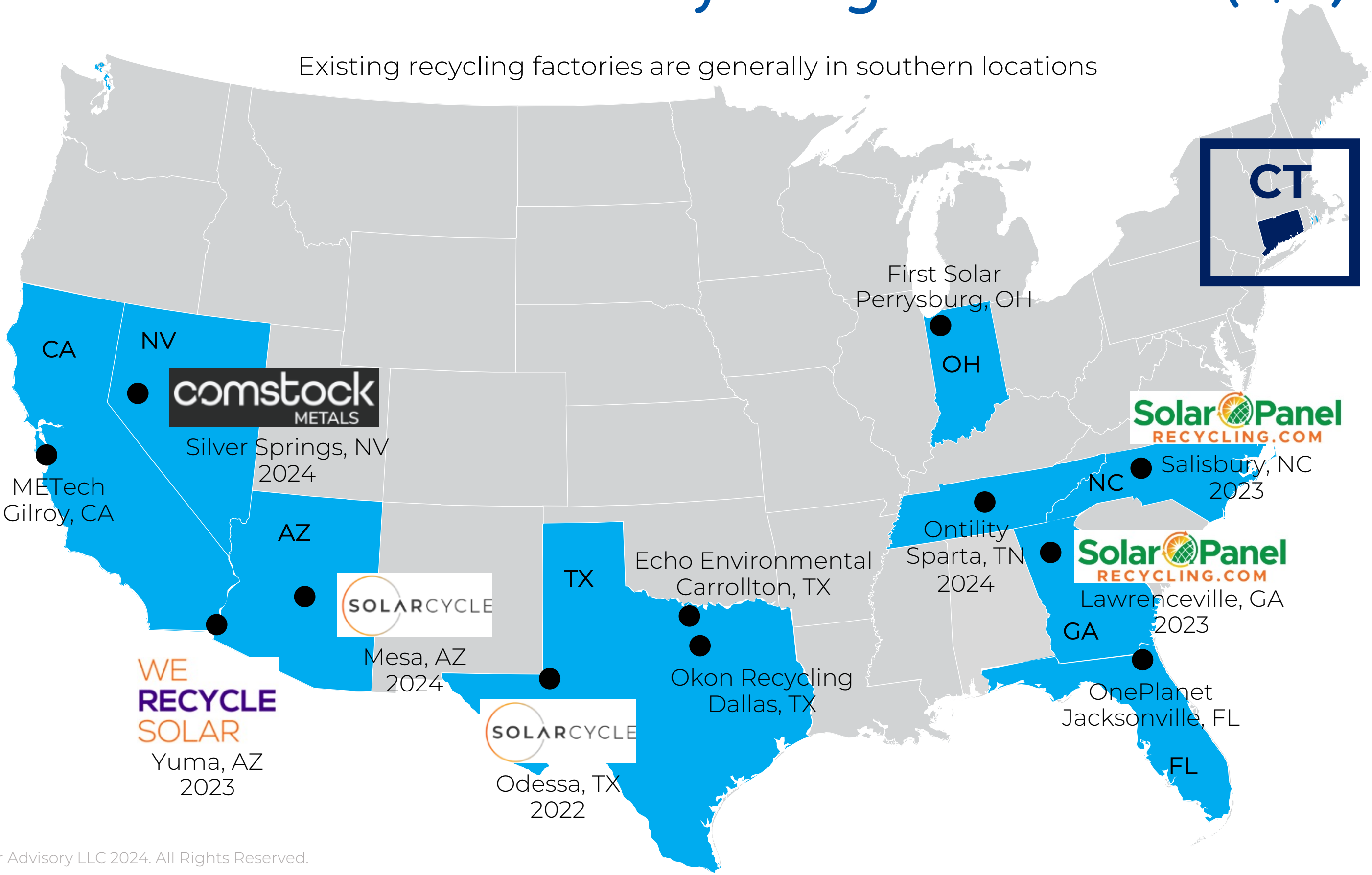
The factories below are ones that are Recycling Partners of SEIA + Comstock Metals*

	Company	Ownership	Solar Panel Recycling Factory Location	Year Commissioned	Recycling Type
1	SolarCycle	Fifth Wall, various other VCs	Odessa, TX	2022	Crush and separate
			Mesa, AZ	2024	Crush and separate
			Cedartown, GA	2025E	Glass manufacturing using recycled materials
2	We Recycle Solar	Management, others	Yuma, AZ	2023	Smelting; crush and separate
3	Solarpanelrecycling.com	PowerHouse Recycling	Salisbury, NC	2023	Crush and separate
			Lawrenceville, GA	2023	Crush and separate
4	Comstock Metals	Comstock Inc. ("LODE")	Silver Springs, NV	2024	Smelting; crush and separate
5	Echo Environmental	Envela Corp.	Carrollton, TX	Not known	Crush and separate
6	METech Recycling	First America Mgmt Group	Gilroy, CA	Not known	Not known
7	First Solar	"FSLR"	Perrysburg, OH	~2008	Crush and separate (CdTe)
8	Ontility / Terrepower	BBB Industries	Sparta, TN	2024	Not known
9	OnePlanet Solar Recycling	Management	Jacksonville, FL	Company founded in 2023	Not known
10	Okon Recycling	Management, others	Dallas, TX	Not known	Not known
11	ERI	Closed Loop Partners, others	Various	Various	Smelting; crush and separate

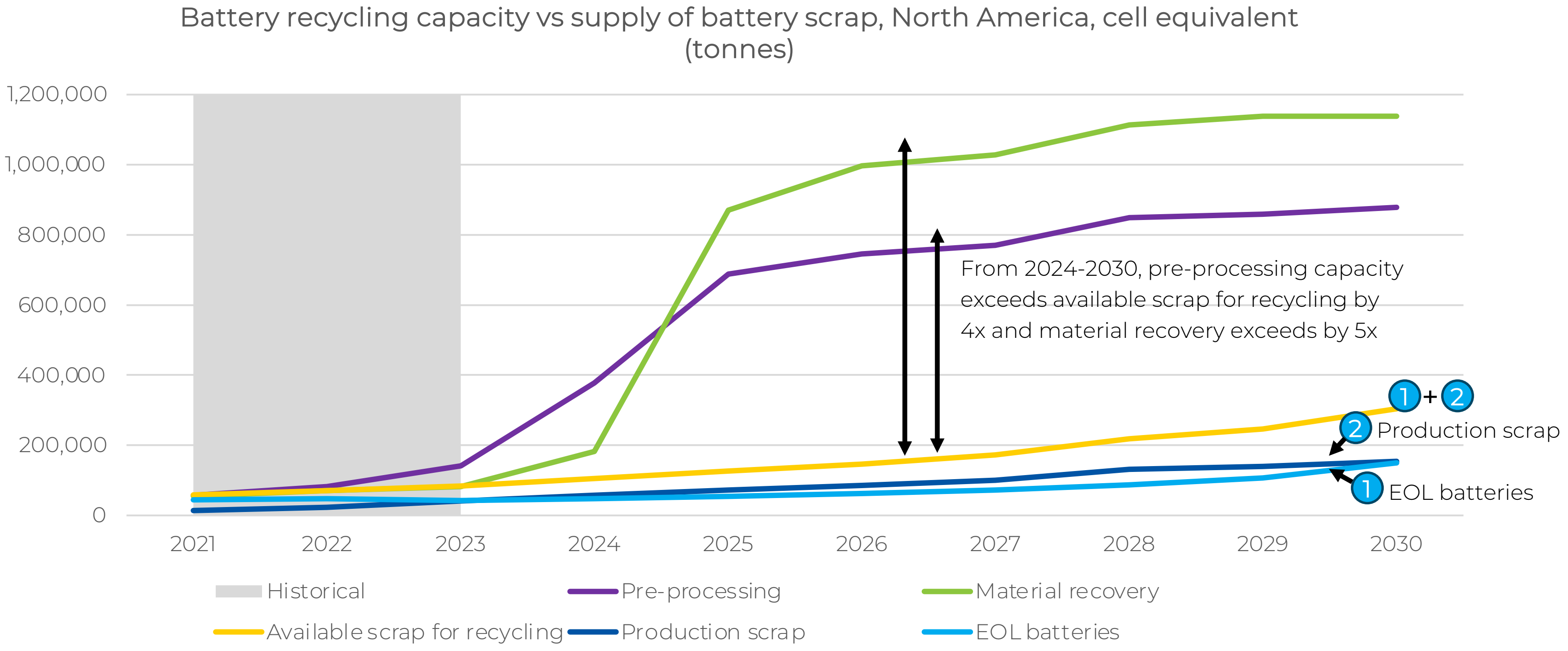
* SEIA has a process to approve partners, which includes a factory audit. FabTech and Revive PV are also partners of SEIA but are refurbishers, not recyclers

Select Solar Panel Recycling Factories (2/2)

Existing recycling factories are generally in southern locations

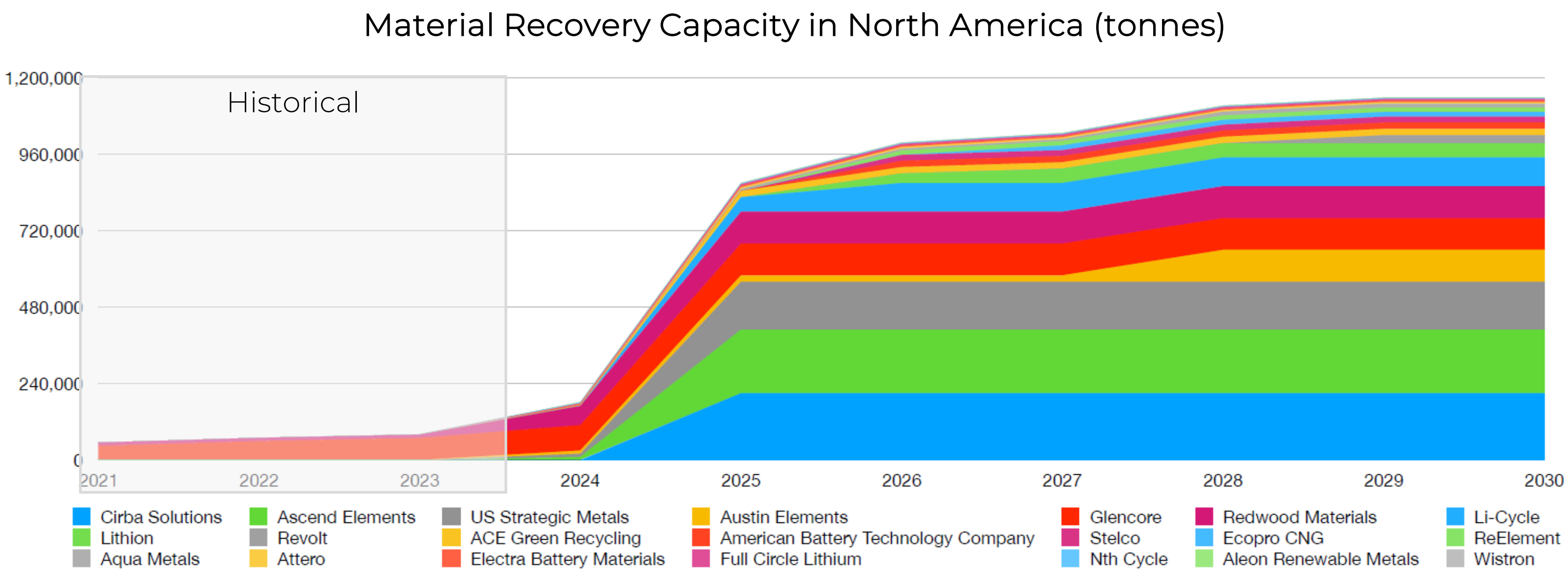


Li-Ion Battery Recycling vs. Supply of Battery Scrap



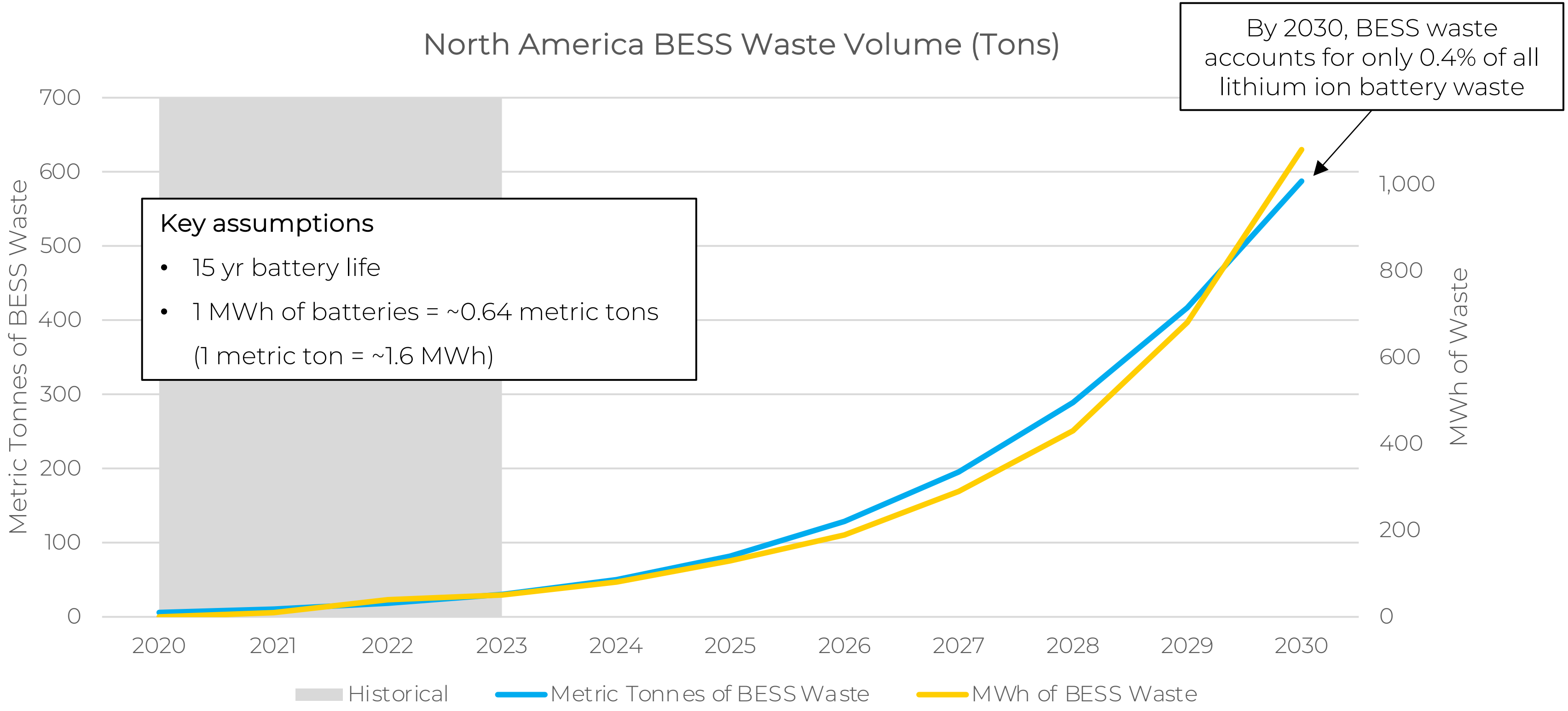
Source: Circular Energy Storage, May 2024

Li-Ion Material Recovery Capacity, 2021-2030



Source: Circular Energy Storage, May 2024

US Annual BESS Waste Volume (metric tons)

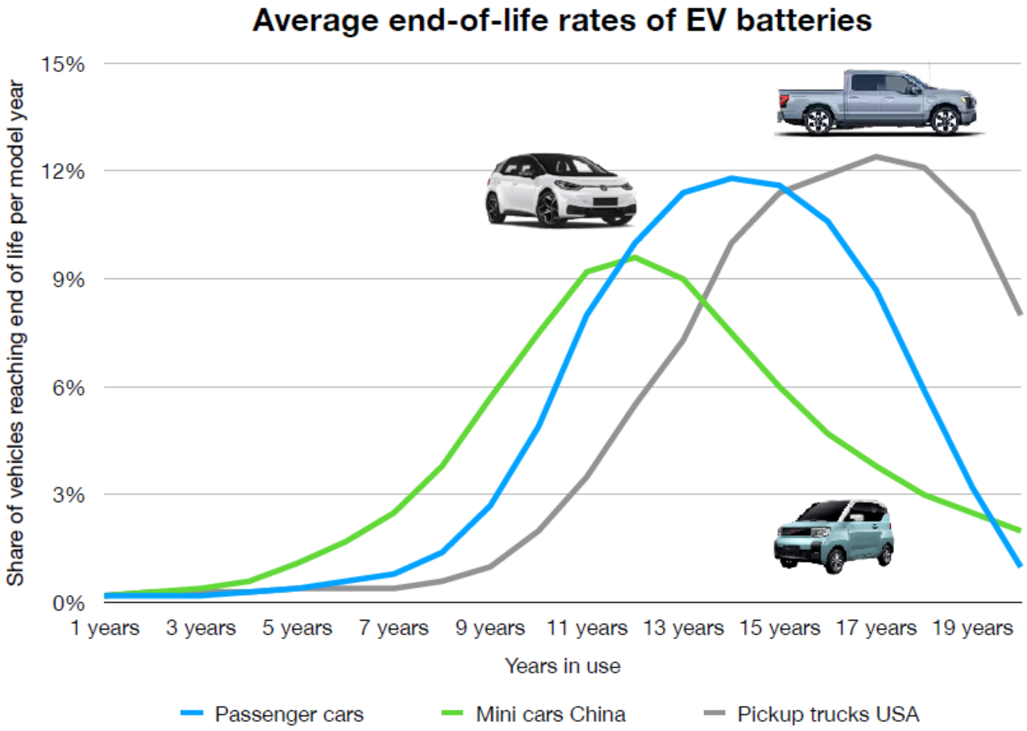


Key assumptions

- 15 yr battery life
- 1 MWh of batteries = ~0.64 metric tons
  (1 metric ton = ~1.6 MWh)

Source: Circular Energy Storage, May 2024

Expected EV Battery Life
(proxy for Stationary Battery life)



Source: Circular Energy Storage, May 2024

Key points:

- Expected battery lives for EVs act as a proxy for stationary batteries, though there is virtually no track record to go on at the moment
- The average end of life rates for different EV vehicles shown at left are from Circular Energy Storage, and are based on a variety of published statistics and discussions with OEMs
- Most batteries last about 15 years

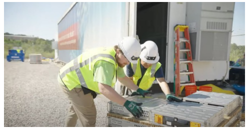
Sample Battery Recycling To Date

Anahola Solar Project, Kauai, Hawaii

- **Project name**: Anahola Solar Project, which consists of a 12 MW solar array, substation, and the storage component
- **Storage project size and vendor**: 6 MW x 0.75 hours = 4.6 MWh. Saft batteries
- **Ownership and Project life**: The project was owned by Kauai Island Utility Cooperative (KIUC) and was installed in 2015. It was decommissioned in 2023 after 8 years of operation
- **Reason for recycling**: KIUC said "The Anahola Saft batteries from 2015 were our first major battery storage system. They are still operable and have capacity, but the costs to KIUC to maintain the system outweigh the current benefit. Since they were installed we have added Tesla and AES battery systems which are significantly larger and are maintained by those vendors. The Saft batteries served their purpose but are no longer needed."
- **Recycler**: Redwood Materials was the recycler, and they dismantled the system and shipped it to their recycling facility in Carson City, NV. The recovered materials were used in new batteries

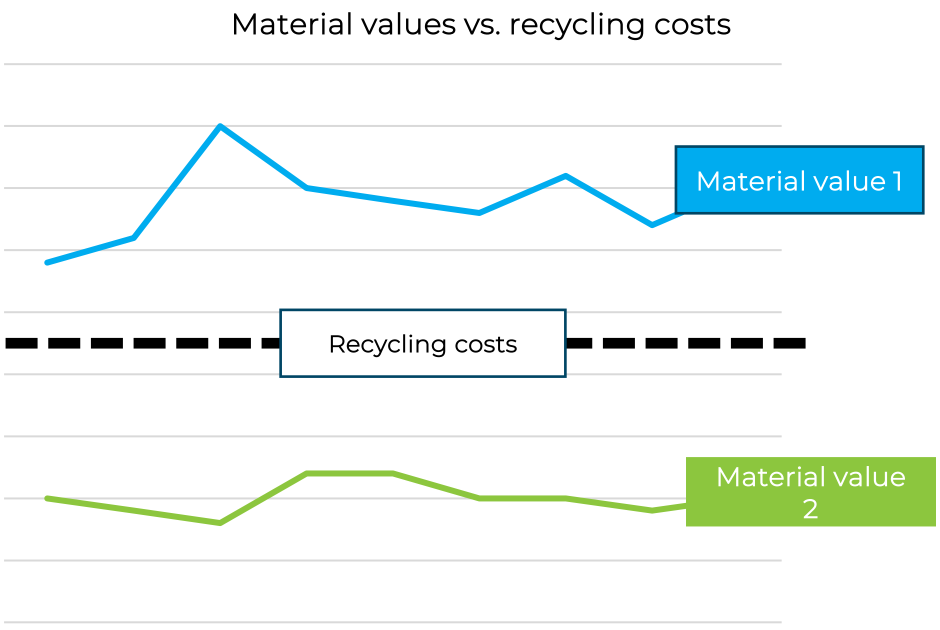
Cedartown Battery Energy Storage Project, Cedartown, GA

- **Project name**: Cedartown Battery Energy Storage Demonstration Project in Cedartown, GA. Co-located with a 1 MW solar farm (owned by WGL Energy)
- **Project size and vendor**: 1.0 MW x 2 hours = 2.0 MWh. LG Chem batteries
- **Ownership and project life and reason for recycling**. The project was owned by Southern Company and was installed in 2015. EPRI was a partner in this demonstration project and federal funds supported it. It was dismantled after 8 years of operation in 2023
- **Recycler:** Redwood Materials was the recycler, and they dismantled the system and shipped it to their recycling facility in Carson City, NV. The recovered materials were used in new batteries



5. Indicative Economics

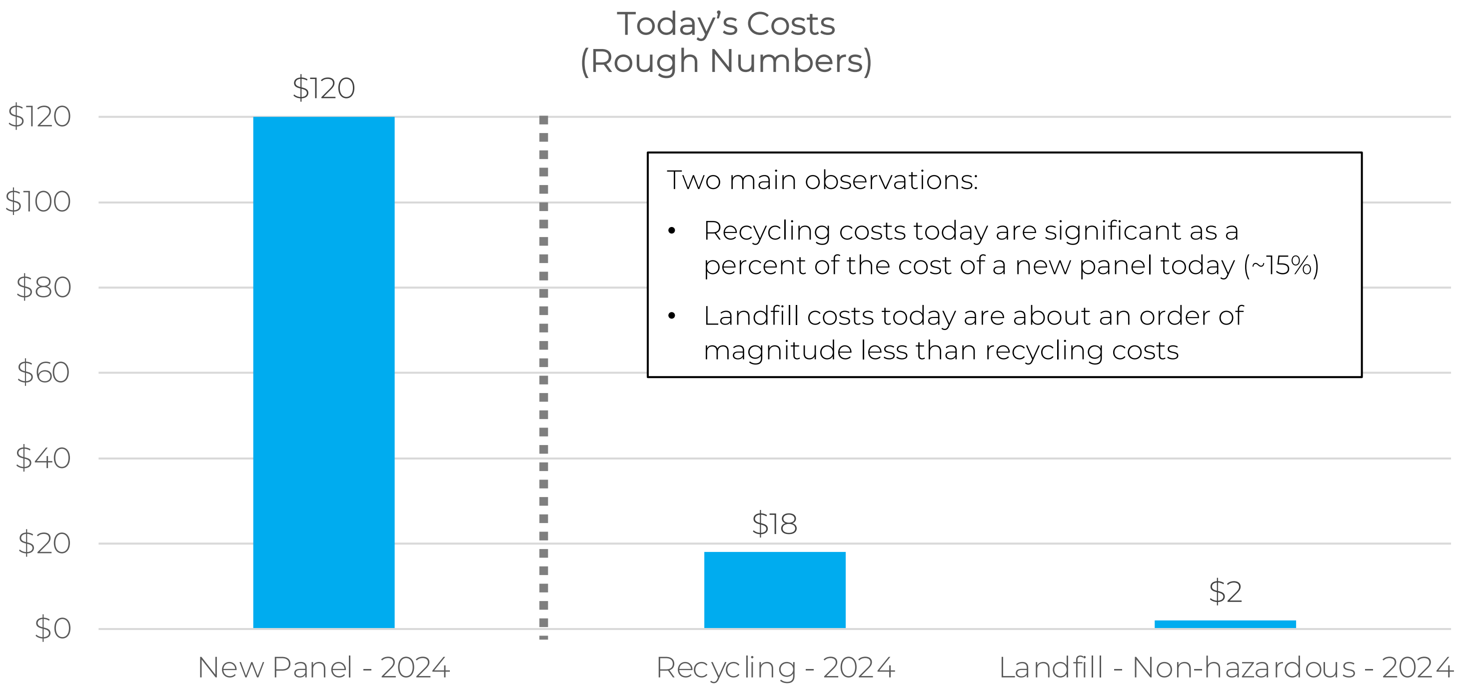
Value-Positive vs. Value-Negative Recycling Markets



- A recycling market is **value positive** if the value of the recovered material a recycler is producing typically is higher than the costs to process the feedstock, sometimes referred to as **"profit center"** (see "Material value 1" at left)
- A recycling market is **value negative** if the value of the recovered material is lower than the processing costs, referred to as a **"cost center"** (see "Material value 2")
- If recycling costs are higher than the value (value negative market) a recycler will charge to accept material (often called processing fee, gate fee or tipping fee)
- If costs are lower than the value (value positive market) the recycler can share the value with the upstream supplier
- In both cases the level of the fee or the share of the value depends on the competition
- The solar panel market is currently value negative while some battery markets are value positive (depending on chemistry and commodity costs)

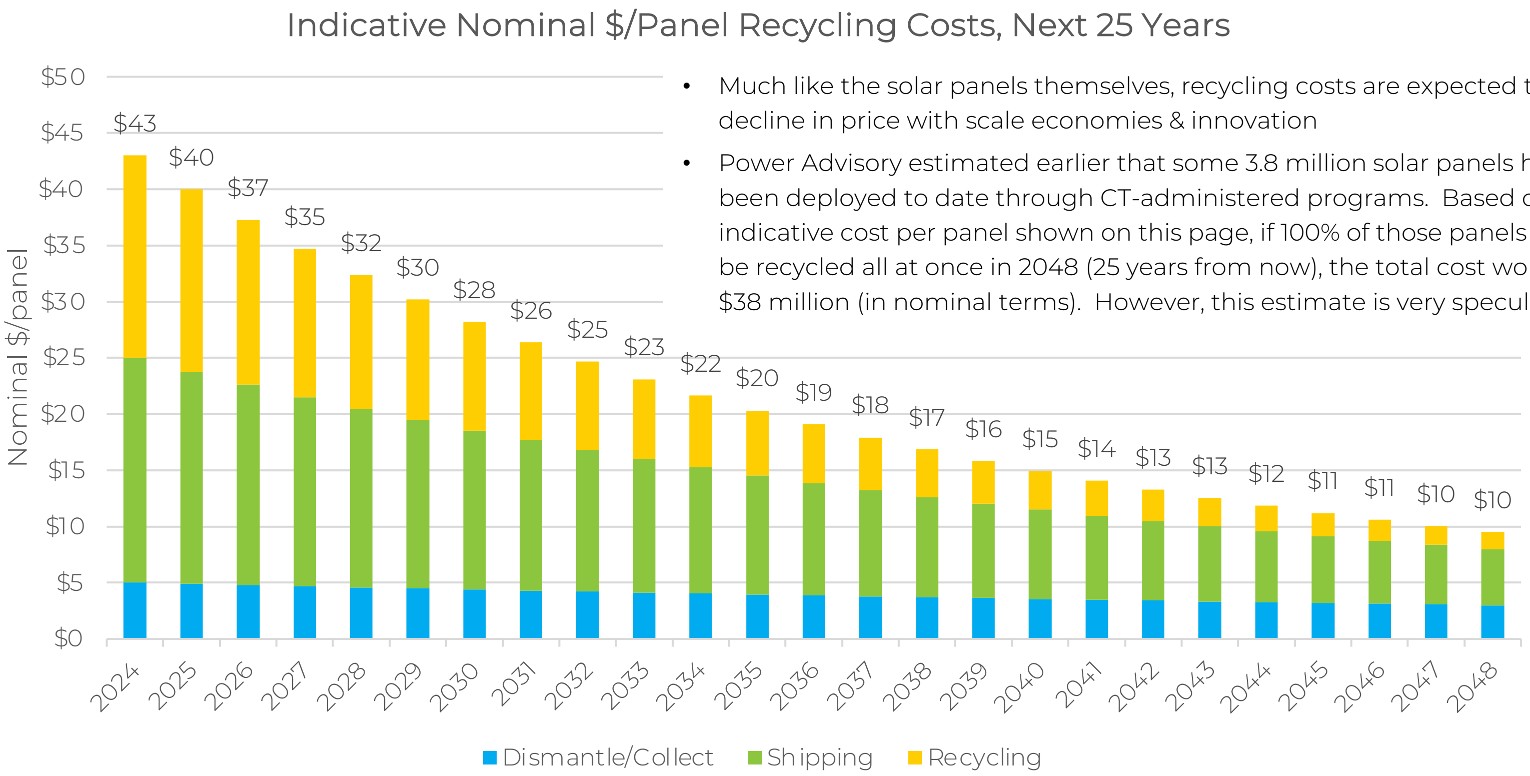
Source: Adapted from Circular Energy Storage

Indicative Pricing – Solar Panels



(Assumes 400 W panel, $0.30/W)

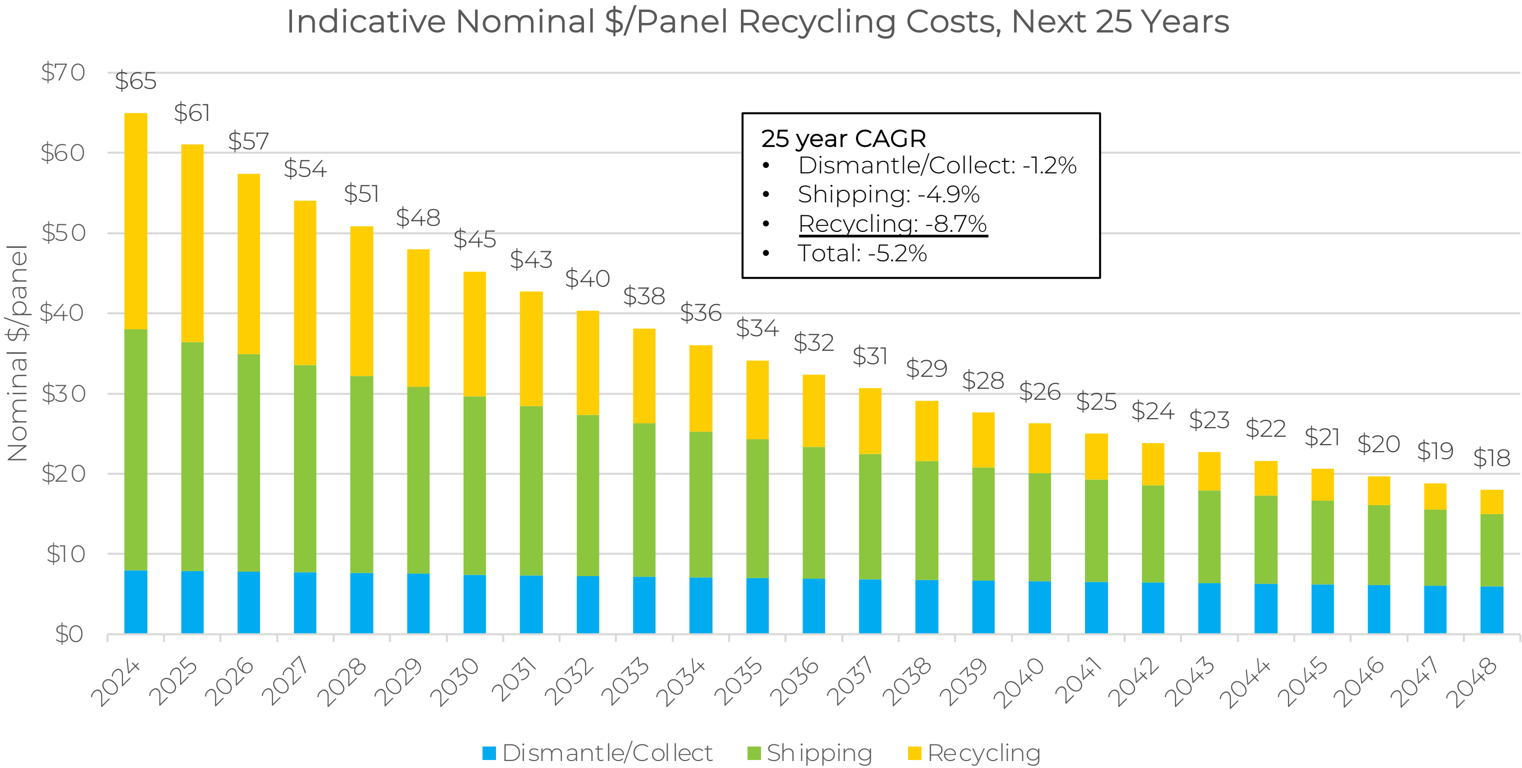
Indicative Pricing – Solar Panels – Commercial



- Much like the solar panels themselves, recycling costs are expected to decline in price with scale economies & innovation
- Power Advisory estimated earlier that some 3.8 million solar panels have been deployed to date through CT-administered programs. Based on the indicative cost per panel shown on this page, if 100% of those panels were to be recycled all at once in 2048 (25 years from now), the total cost would be $38 million (in nominal terms). However, this estimate is very speculative.

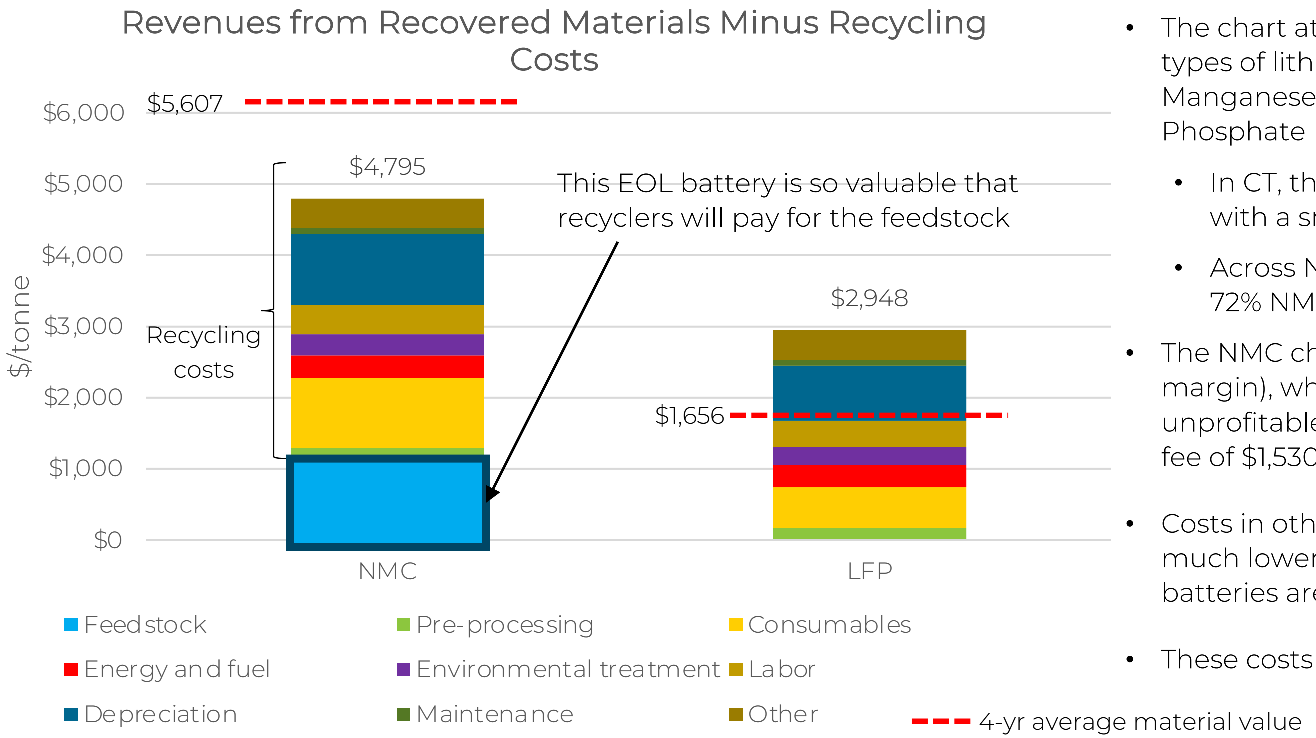
Source: Power Advisory estimates based on stakeholder feedback

Indicative Pricing – Solar Panels – Residential



Source: Power Advisory estimates based on stakeholder feedback

Indicative Economics – Batteries

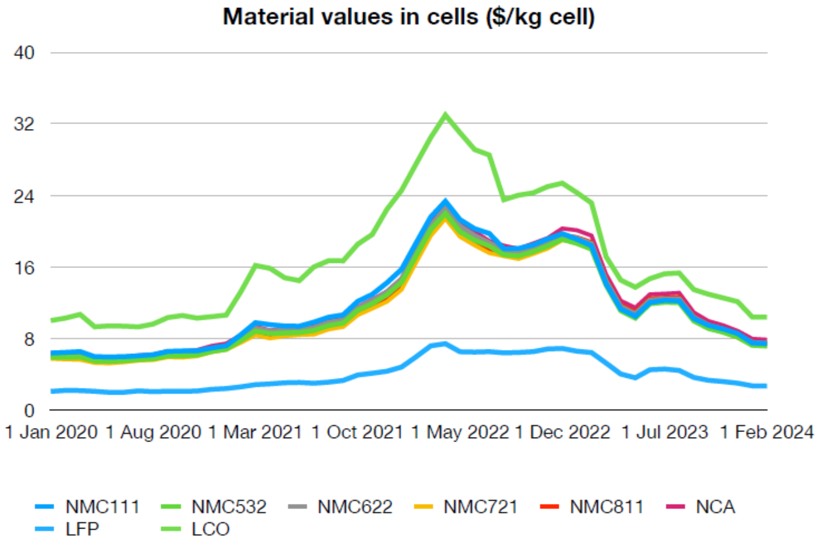


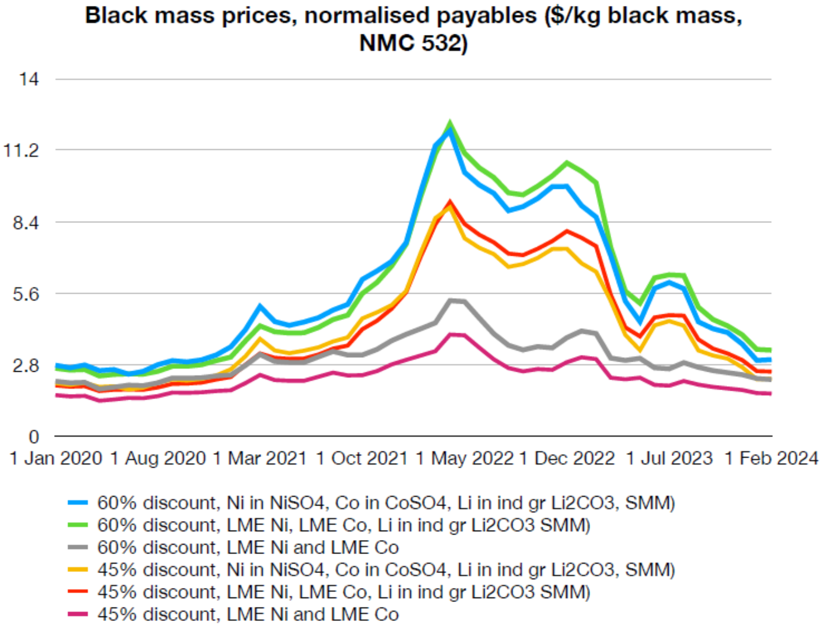
- The chart at left shows the economics for two types of lithium-ion chemistries: Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP)
  - In CT, the split is 87% LFP, 13% NMC, albeit with a small sample size of 2.2 MW
  - Across North America, the split is reversed: 72% NMC, 26% LFP, 2% other
- The NMC chemistry is currently profitable (14% margin), whereas the LFP chemistry is unprofitable and would require a processing fee of $1,530/tonne to make a 14% margin
- Costs in other countries, such as China, are much lower than the US, and thus, many EOL batteries are shipped there
- These costs do not include logistics

NMC – Nickel Manganese Cobalt
LFP – Lithium Iron Phosphate
Source: Circular Energy Storage

Indicative Economics – Batteries – Material Values

Price development for scrap cells and black mass
The last four years have shown that there is no "normal" price for lithium-ion batteries. It also shows how much effect the price development of one single element (lithium) can have on the whole value chain when some recyclers and markets have the capabilities to recover it, while others don't.



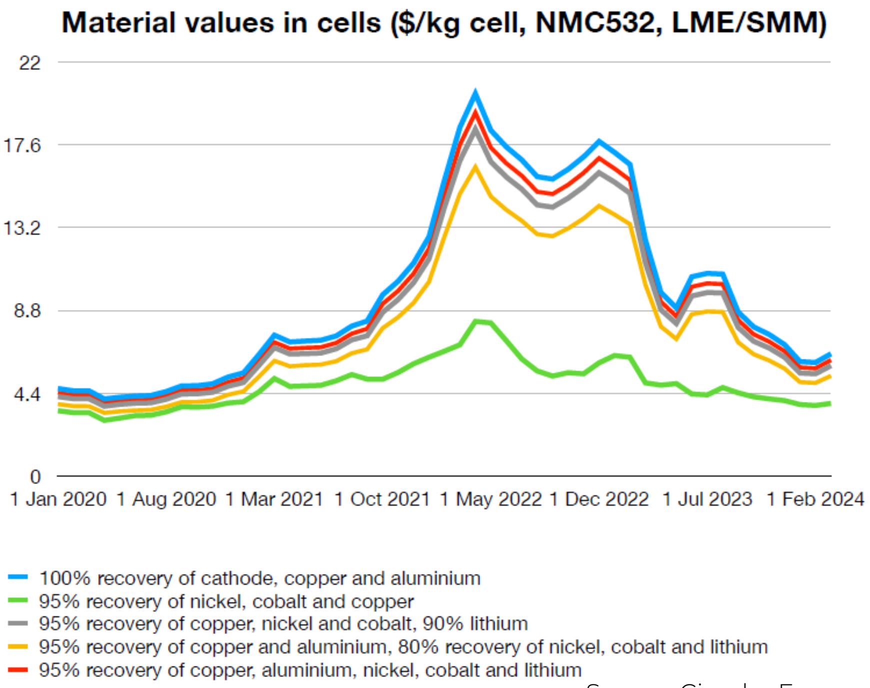


Source: Circular Energy Storage

POWER ADVISORY

Indicative Economics – Batteries – Material Values

Prices for different recovery routes
A combination of better recovery methods and lower battery prices will make the differences between methods like pyrometallurgical and mechanical routes less dramatic. The lower the prices are in general the more other factors such as shipping cost, storage, and payment terms will have importance for where feedstock will end up.



100% recovery of cathode, copper and aluminium – **Reference value**

95% recovery of nickel, cobalt and copper – **Current smelting operations**

95% recovery of copper, nickel and cobalt, 90% lithium – **Modern smelting operations**

95% recovery of copper and aluminium, 80% recovery of nickel, cobalt and lithium – **Mediocre mechanical operations**

95% recovery of copper, aluminium, nickel, cobalt and lithium – **State-of-the art mechanical operations**

Source: Circular Energy Storage

6. Stakeholder Perspectives on End-of-Life Management Options

Funding – An Integral Part of Recommendations

- Questions of funding and economics are closely tied up with the choice of an end-of-life management framework, as different frameworks will entail different costs and therefore would require specific funding mechanisms
- This section of the report presents the feedback on options for end-of-life management frameworks, and therefore implicitly on funding mechanisms, that Power Advisory and the Connecticut Green Bank have heard through their exploration of those different options with:
  - The Working Group
  - DEEP
  - One-on-one interviews with industry stakeholders
  - One-on-one interviews with government departments across the country

Highlights of Feedback

- The following slides present an overview of the feedback and research inputs for the three main end-of-life management frameworks (namely, extended producer responsibility, advanced fee administration, and decommissioning bonds – cf. Section 2 of this report), additional options that do not neatly fall into any of the three main frameworks, and specific lessons learned by departments of the environment in three other states
- Our discussions have yielded such important considerations as:
  - Residual material value of solar panels versus batteries
    - Creates differing incentives for customers to recycle each product, and for manufacturers to recycle product
  - End user: individual homeowners / small business owners vs utility-scale facilities
    - Implies different levels of ability to recycle, and feasibility of regulatory compliance/enforcement
  - Uncertainties around length of life of equipment, and lifespan of manufacturers/suppliers themselves
    - The point in time at which projects/equipment are likely to be decommissioned, and therefore volume of materials available for recycling, is difficult to predict
    - Manufacturers and recyclers have different views on product lifespan, feedstock volumes etc.
  - Implementation requires collaboration between multiple parties
    - Recycling policy that is perceived as unduly onerous can impact industry's willingness to serve a given market
- Additional information on stakeholder perspectives is contained in Appendix B

What We've Heard – Management/Funding Frameworks

Extended Producer Responsibility

- EPR frameworks can entail OEMs: funding and managing recycling; funding recycling but contracting actual processing to a third party; or – possibly – bearing responsibility for managing recycling but having funding provided by a third party.
  - EPR can also be established such that it is administered by a third party
- Fundamentally, manufacturers must be willing to participate in such frameworks, i.e., to bear that responsibility
  - If compliance obligations are perceived as too costly or onerous relative to the profits to be made in-state, there is evidence that some manufacturers will walk away from the state rather than comply
- EPR requires at least some degree of tracking of products sold, such that a manufacturer's funding obligations can be budgeted accordingly
- Cost of EPR compliance is generally buried in total product cost

Advanced Fee Administration

- AFA model generally entails collecting a fee as a one-off from customer at point of sale of equipment; alternative funding sources could include collecting fee from OEM, or collecting funds over time from ratepayers/as part of utility tariff, etc.
  - Funds are pooled by a third party and then disbursed to fund recycling; this entails administrative costs
- Charging customers a recycling fee at the point of sale could deter purchase of solar panels and/or batteries

What We've Heard – Management/Funding Frameworks

<u>Decommissioning Bond</u>

- Financial instruments/assurances that are meant to ensure a site is decommissioned (or equipment is recycled) at end-of-life
- This is essentially the status quo for many larger projects, and may continue to be the most appropriate for some (or some kinds) of facilities
- However, the effectiveness of these bonds in actually ensuring materials get recycled is unclear
    - Power Advisory has attempted to obtain actual decommissioning plans, but few have been made available to us
    - Of those that have been provided, details on recycling are minimal
    - Legal enforceability of recycling commitments made in decommissioning plans is also uncertain
- SEIA has plans to develop an ANSI standard for solar decommissioning plans that may address some of these issues

What We've Heard – Other/Interim Options

<u>Other options to fund recycling</u>

- Costs borne by the customer at the time of recycling, i.e., a fee-for-service or user-pays model
  - This was likened to how, in some jurisdictions, individuals wishing to dispose of bulky items, electronic waste, or waste volumes in excess of certain limits, are responsible for transporting the items to municipal transfer stations and paying to deposit the waste there
    - Note that Connecticut's EPR law for residentially-generated electronic waste requires that drop off at collection points must be free of charge to the residential generator
  - Requiring customers to pay at time of disposal may also inadvertently incentivize some customers to attempt to bypass the recycling process, e.g., by illegal dumping
- State and/or federal governments could subsidize recycling costs for one or more segments
- Revenue from renewable energy credits (RECs) could be leveraged to offset recycling costs
- Until a fully-fledged framework were developed, state or state agency could maintain a list of qualified recyclers in order to facilitate residents' recycling solar panels and batteries

What We've Heard – Other/Interim Options

Other options to fund recycling

- The Federal government provides significant grant funding for battery recycling, battery recycling R&D, etc.
- For example, the Infrastructure Investment and Jobs Act:
  - Provides $200M to expand an existing DOE program for research, development, and demonstration of electric vehicle battery recycling and second-life applications for vehicle batteries in FY2022-26
  - Requires the EPA to develop battery collection best practices and battery labeling guidelines
    - Report on best practices for battery collection to be published in 2024; will include EPA's next steps
    - EV batteries and BESS labelling and collection to be studied in 2024-25
    - Introduces the Advanced Energy Manufacturing and Recycling Grant Program that will provide $750 million to re-equip, expand, or establish facilities to, among other things, recycle solar equipment
- Similarly, the Inflation Reduction Act:
  - Provides incentives for critical mineral sourcing (Section 30D) that supports EV battery production; there could potentially be similar incentives for BESS batteries
  - Provides an Advanced Manufacturing Production Credit for domestic production (Section 45X). This could drive manufacturing in the US of new product using recycled materials.

Lessons Learned in Other States

- Power Advisory conducted one-on-one interviews with the departments of environment in three of the states that have considered solar panel and/or battery recycling policies: Maine, Washington, and New Jersey

- The primary purpose of these interviews was to learn how and why each state chose the recycling policy model that it did; lessons learned from implementation; and ultimately to obtain any relevant advice for Connecticut as it considers these policies

- Three primary thematic findings emerged from these discussions:
    1. Considerable policy variation exists between states: End-of-life management policies for solar panels and stationary batteries are under development by multiple states and the federal government, and there does not appear to be a harmonized approach to either determining the desired management framework nor to the timeframe in which such policies ought to be rolled out
    2. Importance of Department – Legislature coordination: Given the complexity of the policy and economic questions surrounding end-of-life management, better outcomes for both the state and the industry are likelier when the legislature works with the department in both developing and implementing recycling policy
    3. Risks of being an early mover: Early mover states risk enacting policies that either are too onerous for industry (with the potential to drive that industry to a less-onerous state) or not stringent enough (such that they don't actually achieve the state's goals with respect to recycling)

Lessons Learned in Other States – Policy Variation Between States

- From both desktop research and discussions with other states' departments of environment (or equivalent), it is clear that no single end-of-life management framework is dominant with respect to solar panels and batteries
    - This is the case even though the desired outcome (keeping these products out of landfill) is likely common to most if not all states
- In particular, some states have adopted an EPR model while others have gone with AFA for solar panels and/or batteries; some have also opted to not do anything specific at present with respect to recycling these products
    - While different states will have different local circumstances, this divergence suggests that no single option is an overwhelmingly better choice
    - Idiosyncratic local factors (e.g., stakeholder influence, political preferences, government priorities, departmental resourcing levels, vagaries of the legislative process, etc.) also appear to be, at least in part, behind these divergent outcomes
- For Connecticut, this suggests that any policymaking with respect to end-of-life management frameworks be done with a degree of tentativeness and with the understanding that national convergence on the most effective long-term policy framework is still very much underway
    - Furthermore, while best-fit options for Connecticut are presented later in this report, Power Advisory notes the importance of monitoring and evaluating any implemented option with the aim of taking a flexible approach in light of changing market and product characteristics

Lessons Learned in Other States – Importance of Department-Legislature Coordination

- Power Advisory's interviews revealed that the process of developing end-of-life management legislation often took place without substantial engagement with the state's department of the environment (or equivalent)

- As a result, the legislation enacted in various states contains gaps that likely could have been avoided had the department's expertise been engaged during the drafting process. These include things like:
  - Policies that have significant lack of industry/stakeholder support
  - Frameworks whose implementation needed data that the state did not possess, nor had legal authority to obtain
  - Insufficient human and financial resources to effectively administer, enforce, and/or monitor & evaluate the program
  - Legislation being put in place before the department had a firm understanding of the lay of the land in-state, including with respect to waste quantities, cost and availability of recycling, etc.

- This disconnect means that legislation that is enacted may ultimately fail to meet the state's recycling objectives
  - In the most extreme case, manufacturers frustrated with an overly burdensome recycling framework have threatened to pull out of the state altogether, in direct contradiction to the state's green energy objectives
  - On the other hand, a legislative framework that is not fully thought-through can expose the state to risk of capture by industry seeking to advance its own preferences, which may not fully align with the public interest

- For Connecticut, this suggests that strong department-legislature coordination from the inception of, and continuing throughout, policy development would lead to better overall outcomes for the state

Lessons Learned in Other States – Early Mover Risks

- A key theme that emerged from Power Advisory's industry interviews was that no party wants to bear the cost of recycling – neither consumers (for whom added costs could disincentivize installation of solar/batteries) nor industry (for which those costs would erode profit)
- As a result, various parties suggested that recycling costs and/or compliance burdens could cause them to shift business away from Connecticut
  - There is therefore some risk to being an early mover in developing end-of-life management policies for solar panels and batteries, particularly if other states may not address these technologies for many years to come (and therefore may present more attractive markets)
  - While Power Advisory is not in a position to evaluate the actual likelihood of these claims, Connecticut is a small state with a small market (in 2024 Connecticut was about 0.5% of the US market for solar PV by MW deployed)
- Once there is greater convergence among states on a) the need to develop end-of-life management policies for these technologies, and possibly also b) the choice of management model, the risk of defection will presumably be lowered
- Given these risks, and the current low volumes of solar panel and battery waste, some states appear to have decided that it is not unreasonable, at least in the near term, to take a "wait and see" or alternatively an incremental approach rather than making definitive decisions on end-of-life management frameworks
  - This could be coupled with interim measures and a formal framework to help the state determine when it should move from "wait and see" to more concrete action

Current/Contemplated Action in Other States

- The table below provides an overview of recycling policies other states are implementing or considering implementing
- In no state has the legislative framework for solar panel or battery recycling been fully implemented
  - The state closest to full implementation is Washington, whose EPR law requires stewardship plans to have been submitted by July 1, 2024, and enforcement set to begin July 1, 2025
- In Washington, manufacturers were given approximately seven years to prepare for compliance; the California solar panel recycling bill (still before the legislature) proposes to take effect in four to five years

Infrastructure type	End-of-life management framework		
	Extended Producer Responsibility	Advanced Fee Administration	Decommissioning bond
Solar – residential-scale	WA	CA	
Solar – commercial-scale	WA, CA	CA	NC, SC
Battery storage – residential-scale	NJ*		
Battery storage – commercial-scale	NJ*		

* Only covers EV batteries, not stationary batteries

7. Best Fit Solutions for Connecticut

Introduction to Recommendations

- Power Advisory and the Connecticut Green Bank have evaluated various options for end-of-life management frameworks for solar panels and batteries
  - This analysis has been informed by the End-of-life Working Group, both collectively and through feedback from individual participants. These recommendations should not be understood as uniformly representing the views of the working group or specific members, who have nuanced and dissenting viewpoints as discussed in Appendix B of this report
- The recommendations in this report are primarily focused on the best end-of-life option for panels and batteries, rather than setting out a roadmap for implementation
  - This report does not provide detailed program design considerations, but rather high-level guidance to PURA as the basis for further stakeholdering and policy/program development
  - These recommendations should therefore only be understood as laying the groundwork for future policymaking
- A key next step for PURA might be to open a proceeding or issue an order(s) in respect of some or all of the recommendations
  - Recommendations presented here do not include legal analysis of the means to implement them, nor a consideration of the respective statutory authorities of PURA, the Connecticut Green Bank, and/or DEEP
  - Power Advisory acknowledges that PURA may therefore determine that further developing and/or implementing some of the recommendations contained in this report would require legislative amendments

Overview of Recommendations

Infrastructure type	End-of-life management framework		
	Extended Producer Responsibility	Advanced Fee Administration	Decommissioning bond
Solar – residential-scale		X	
Solar – commercial-scale			X
Battery storage – residential-scale	X		
Battery storage – commercial-scale	X		

Recommendation 1: Segmentation

- Recommendation: Distinct solutions should be designed for each of residential-scale solar, commercial-scale solar, and stationary battery energy storage systems.

- Due to the vastly different economics involved in recycling solar panels compared to recycling batteries, different end-of-life management options are likely necessary for each technology. Our conclusion is based on the following observations:

Observation	Implications
Economic dynamics	• The residual value of solar panels and batteries significantly influences the recycling cost • Recycling cost is the primary determinant of the feasibility and desire to recycle for manufacturers, consumers, and recyclers • The feasibility and desirability of recycling are crucial factors in the success of any end-of-life management framework
Technology-specific considerations	• Different technologies involve distinct economic considerations, leading to different incentives and feasibility issues • Therefore, end-of-life management options should be tailored to specific technologies
Customer segmentation	• Customers' ability to recycle varies, necessitating further segmentation into residential and commercial categories

Recommendation 1: Segmentation – Other Options Considered

Segmentation Option	Potential Benefits	Considerations	Recommendation
Recommended segmentation: residential-scale solar, commercial-scale solar, and BESS	• Addresses substantial economic differences between technologies • Improves recycling outcomes	• Requires more complex program design and legislative processes • May add complexity for contractors/installers	• Recommended as it better addresses economic factors and leads to better recycling outcomes
Less segmentation	• Simplifies program design and legislative processes • Improves customer experience for contractors	• May not adequately address differing economic factors • Potential for poorer recycling outcomes	• Not recommended due to significant economic differences that need addressing
Greater segmentation (e.g., commercial- vs. utility-scale)	• Potential for more tailored solutions	• Adds significant administrative complexity • Limited marginal benefits from additional segmentation	• Not recommended due to increased complexity with limited benefits
No segmentation	• Simplifies program design and legislative processes • Improves customer experience for contractors	• May not adequately address differing economic factors • Potential for poorer recycling outcomes	• Not recommended due to significant economic differences that need addressing

Recommendation 2a: Residential-scale Solar

- Recommendation: Connecticut should adopt an advanced fee administration (AFA) model for residential-scale solar installations

- Assessment:
  - A fee would be assessed to one or more parties (e.g., ratepayers, manufacturers, panel owners) in advance of recycling (e.g., at the time of system installation, purchase, or energization) to cover the cost of recycling, or collection and recycling, of small volumes of solar panels

- Justification:
  - Residential-scale installations, and particularly host-owned panels, present several challenges that can be mitigated by AFA:
    - Volume of panels available for recycling from a single source is, at present, low and sporadic
    - Dispersion of panels across individual properties means higher transportation costs
    - Unwillingness or inability of individual homeowners to pay for disposal/recycling costs at end-of-life

Recommendation 2b: Residential-scale Solar

- Recommendation: Connecticut should require third-party-owners of residential-scale systems to have formal end-of-life protocols

- Two models for residential solar installations have been observed:
  - Host-owned – homeowner owns system; may use installer, who may or may not have responsibility for removal
  - Leased/third-party-owned systems – lessor is responsible for removal of system at end-of-life

- Notwithstanding their deployment at residential sites, third-party-owned residential systems also bear some similarities to larger-scale projects, insofar as the third-party owner:
  - Owns a large number of panels
  - Has an established network of labor/employees for installation, and likely removal, of panels, and may have specialized logistics infrastructure for transportation and storage of panels
  - Deploys panels under contractual arrangements, which may provide a convenient opportunity to introduce requirements for recycling

- While lessors have various obligations to the site host at end-of-life, ensuring panels are actually recycled after they have been removed is not necessarily a contractual or legal obligation

- Formal end-of-life protocols should therefore be developed and introduced for third-party-owned systems, e.g., requiring owners to demonstrate that they have an end-of-life management/recycling plan (e.g., via submission to PURA or DEEP)

Recommendation 2: Residential-scale Solar – Other Options Considered

- As noted in the previous slide, while third-party-owned systems are deployed at residential premises, the aggregate volume of panels under a single owner also lends itself to comparison with utility-scale projects

- On the other hand, third-party-owned systems resemble host-owned systems in that they generally are:
  - Geographically dispersed at individual premises across the state
  - Deployed to host sites at different points in time, meaning the owner's portfolio does not reach end-of-life all at once

- On the whole, for the same reasons as presented in recommendation 1 (particularly added administrative complexity and compliance burden, with limited marginal benefits) we do not recommend greater segmentation of the overall end-of-life management framework for residential-scale installations into host-owned and third-party-owned systems

- Rather, to address the greater volume of panels and the presumed greater ability to recycle on the part of third-party owners, we propose that such systems be subject to a supplementary obligation to prepare formal end-of-life protocols as set out in recommendation 2b
  - Third-party owners subject to such protocols should be entitled to benefit from recycling initiatives funded by the general AFA framework (per Recommendation 2a), if they have paid into it

Recommendation 3: Commercial-scale Solar

- Recommendation: Connecticut should enhance the present model of decommissioning plans and bonds for commercial-scale solar systems by requiring the preparation of decommissioning plans that include details of how panels will be recycled at end-of-life

- Justification:
    - Commercial/utility-scale solar sites have a much larger number of panels and degree of geographic concentration
    - Power Advisory understands that decommissioning plans are often required by lenders or asset owners for such infrastructure, and provide a good framework for end-of-life protocols for the overall site
    - Formalizing this framework in Connecticut would ensure proper management of panels at end-of-life or when facilities are repowered

- Thus far Power Advisory has not observed strong language relating to panel recycling in decommissioning plans, where such plans have even been made available to Power Advisory
    - This seems like a significant shortfall/gap given the potential volume of panels that could be disposed of from commercial-scale facilities

- The Solar Energy Industries Association is developing a decommissioning standard that could ultimately be adopted by one or more states
    - At this time, it is not known whether recycling requirements in the standard will meet the needs of Connecticut

- North Carolina is in the process of introducing requirements around recycling as part of solar farm decommissioning

Recommendation 3: Commercial-scale Solar – Other Options Considered

- An alternative option would be to maintain the status quo in its entirety – i.e., relying on the goodwill of developers and/or assuming that they might have business/economic incentive for the reuse, repurposing, and/or recycling of panels when decommissioning a site

- It is not apparent, at present, how many panels are recycled, rather than landfilled or disposed of in a non-sustainable fashion under this status quo model

- Power Advisory has heard from large solar developers that excessive prescriptiveness – particularly if there are substantial costs associated with requiring recycling within decommissioning plans – would deter the development of commercial-scale solar in Connecticut
  - If this were felt to be a material concern, Connecticut could consider introducing a reporting requirement as an interim measure
  - This would allow the state to determine how much recycling of commercial-scale panels (as opposed to landfilling) is occurring at present and on that basis make longer-term policy decisions (e.g., as to the necessity of requiring that recycling be addressed within decommissioning plans)

Recommendation 4: Batteries

- Recommendation: Connecticut should adopt an extended producer responsibility (EPR) model for stationary batteries
- In addition, this approach should include:
    - Measures to ensure that end-use customers, installers, and contractors can readily access information about where and how to recycle batteries using existing infrastructure
    - An alternate option for producers to submit an end-of-life plan in lieu of participating in EPR and/or in a PRO, as long as this plan meets the 'floor' requirements of the EPR framework
- Justification:
    - This recommendation aims to balance several key aspects of battery recycling and Connecticut state goals:
        - Given the value of battery materials, manufacturers are eager to retrieve and recycle the batteries and expect to make a profit in doing so
        - Some key stakeholders from the battery industry expressed strong preference for an EPR framework
        - Others advocated for minimal government involvement, believing that industry-led recycling programs, or market-based approaches, foster competition and are more efficient and profitable
        - Connecticut would aim to become a leader and create a model that other states can follow

Recommendation 4: Batteries – Other Options Considered

Option	Description	Recommendation
Status quo or 'wait-and-see' approach	Battery materials are expected to have enduring value that will inherently induce recycling. Continue to evaluate divergent opinions within the industry and develop a formal framework in the future.	Not recommended • Connecticut could fall behind on thought leadership in leading regulatory solutions for batteries.
Open market model, with mandatory participation	Manufacturers, retailers, and distributors are mandated to participate in the collection and recycling of lithium-ion batteries. The system leverages market forces to drive the recycling process, with minimal government intervention.	Not recommended, but with caveats • Since there is a preference for battery manufacturers/recyclers for EPR, a regulatory push towards that would be beneficial • To ensure other considerations are heard, the EPR recommendation also includes an option for manufacturers to submit their own decommissioning plans. • Smaller players would have the option to join a collective scheme or handle their recycling independently.
AFA	Involves charging a fee at the point of sale for lithium-ion batteries. This fee is used to fund the recycling and proper disposal of the batteries at the end of their life. The fee can be included in the product price or charged separately to the consumer.	Not recommend • AFA for lithium-ion batteries can increase consumer costs, and administrative burden for a product that already has value in recycling.
Segmentation	Consider different end-of-life management frameworks for residential- vs. commercial-scale battery installations, as with solar	Not necessary • The residential battery storage market is small and nascent, and it is not clear at this time that it would be feasible – either logistically or financially – to set up a separate framework for residential BESS

Recommendation 5: Miscellaneous

- In addition to the end-of-life framework recommendations set out above, a number of other supporting policy recommendations have emerged from our research and interviews

- These recommendations relate to both matters of process and next steps for further developing, and ultimately implementing, the respective end-of-life management frameworks, as well as to ancillary or enabling policies that Connecticut may wish to consider implementing in tandem with the end-of-life management frameworks

Recommendation 5a: The End-of-Life Working Group should be continued and brought under the auspices of PURA or DEEP. The working group has proven to be an excellent source of insight into many of the themes discussed in this report, and as Connecticut moves through the stages of detailed policy development and implementation, we expect that there will be a continuing need for the working group's input

Recommendation 5b: DEEP should launch a process to qualify and publish a roster of state-approved recyclers for batteries and solar panels. This would be an important interim step to allow Connecticut residents and businesses to more readily identify entities that can properly recycle end-of-life batteries and panels, while the formal frameworks set out in the preceding recommendations are being fully developed, enacted, and ultimately implemented

Recommendation 5: Miscellaneous

Recommendation 5c: **DEEP should continue to support federal efforts underway that would allow hazardous waste solar panels to be managed under the universal waste rule**. Solar panels have been classified as universal waste in some states (e.g., California), a change that is also under consideration federally by the EPA. DEEP should support the EPA's rulemaking efforts that, if successful, would add hazardous waste solar panels to the universal waste regulations (40 CFR 273 - Standards for Universal Waste Management)

Recommendation 5d: **Connecticut should consider banning the landfill disposal of solar panels and batteries**. In particular, at present it does not appear that there is any impediment to landfilling solar panels (provided they can be confirmed as non-toxic). Although batteries may be classified as universal waste, a number of states have taken action to specifically ban landfilling them, e.g., due to fire concerns (e.g., New Jersey). Connecticut should consider the merits and downsides of a similar ban for either or both of these technologies

Recommendation 5e: **DEEP should identify intermediate recycling steps or solutions that can be taken at the local level.** Waste collection in Connecticut is the responsibility of local municipalities, but actual recycling of solar panels and batteries will ultimately take place at a small number of centralized facilities. Intermediate steps to, for example, collect, sort, and pre-treat solar panel and battery waste would be expected to make the eventual recycling of this material more efficient

Recommendation 5: Miscellaneous

***Recommendation 5f*: PURA should encourage the replacement of solar PV and/or battery storage systems at end-of-life with new systems, rather than simply removal.** It is likely that many owners and hosts of solar and battery facilities reaching end-of-life would be interested in having their systems replaced, rather than simply being removed and disposed of/recycled. Assisting such owners/hosts in doing so (for example, by tying system removal to replacement) would likely facilitate their continued enrollment in and use of these beneficial technologies

***Recommendation 5g*: Connecticut should investigate opportunities and means of reusing solar panels and batteries, in addition to recycling**. Reuse of this equipment, as opposed to recycling, was not in scope for this study, but there was considerable stakeholder interest in this matter. As a result, we recommend it be formally studied through a separate process, such that equipment that is still useful in some fashion – but which no longer meets the needs of its owner/host – can be repurposed rather than being disassembled and recycled. For example, such investigation might consider if and how second-life equipment could qualify for use in Connecticut programs, and how will second-life equipment would be viewed under whatever end of life management framework is eventually adopted

***Recommendation 5h*: PURA should direct the Green Bank and DEEP to engage with nearby states on developing a regional approach to end-of-life management of solar panels and batteries.** States like New York, New Jersey, and Massachusetts are, like Connecticut, early movers on deployment of solar panels, battery storage systems, and other distributed energy resources. Greater coordination between states on end-of-life policy for these technologies would reduce some of the risks of being an early mover, facilitate regulatory harmonization, and potentially also enable better economies of scale, to the advantage of consumers, manufacturers, and the recycling industry. The Northeast Waste Management Officials' Association (NEWMOA) could be a good forum for this engagement

8. Implementation Considerations

Implementation of Recommendations

- The following slides are a general overview of how the recommendations presented in this report might be further developed and ultimately implemented, as well as items needing further consideration as part of developing an implementation plan

- The proposed recommendations also have interdependencies
  - Certain recommendations can be addressed earlier, which can provide insight and the required data to develop the rest of the recommendations more thoroughly
  - Others would likely require certain recommendations to have already been adopted, and/or further research, stakeholder engagement, legislative amendments, etc.

Indicative Timeline

Year	Key Milestones
End of Year 1: Working Group continuation, stakeholder engagement, and framework development.	• Continue the End-of-Life Working Group to advance policy development and implementation. • Develop a framework for implementation each recommendation, including prioritization. • Initiate advocacy efforts with legislative bodies.
End of Year 2: Pilot programs launched and preliminary regulation drafting.	• Develop and rollout pilot programs. • Incorporate feedback from programs into regulatory frameworks and proposals • Continue legislative advocacy efforts.
End of Year 3: Regulatory approval, early implementation, and program expansion.	• Obtain regulatory approval. • Develop detailed processes, compliance dates based on approved regulation. • Initiate the expansion of the programs. • Develop training, education, and awareness plans for stakeholders
End of Year 4: Full-scale implementation and continuous improvement systems.	• Initiate statewide rollout of programs aligned to compliance dates. • Develop a market monitoring function to evaluate programs. • Implement training, education, and awareness and program support for stakeholders
End of Year 5: Initial compliance filings, comprehensive review, and long-term strategy development.	• Initial compliance filings from manufacturers, installers, and recyclers. • Publish a Market report that includes program reviews, state of compliance, and recommendations.

Matters Needing Further Consideration

To move forward with implementation of the recommendations set out in this report, a number of matters must be resolved; while their resolution is beyond the scope of this report, some of them are provided here for reference and future consideration:

Advanced Fee Administration

- Would the collected fees be tied to the modules being installed or create a fund that could also support legacy modules (e.g. those installed under RSIP)
- Who should administer the funds? e.g., DEEP, PURA, a third-party organization, etc.
- What should the fee be? How would it best be calculated, and who should pay? e.g., customer at point-of-sale, distributor at point of acquisition from manufacturer, etc.?
  - The United Illuminating Company expressed strong opposition to having electric distribution companies assess or manage fees collected under AFA, for reasons including customer impacts, operational considerations, liability concerns, etc.
- How should administrative costs be calculated and charged? Who should calculate and pay them?
- How would the requirements for the end-of-life/recycling protocols for third-party owners be developed?
  - What is an appropriate level of prescriptiveness for these requirements, given how rapidly the solar panel recycling industry is developing?
- Would the end-of-life protocols for third-party owned system be reviewed, or merely filed? With whom would they be filed, and who would review? How would these requirements be enforced?

Matters Needing Further Consideration

Decommissioning

- By what mechanism (e.g., statutory, contractual) would decommissioning plans be made mandatory and enforced?
- How would the requirements for the end-of-life/recycling component of decommissioning plans be developed? Would they be reviewed, or merely filed? With whom would they be filed, and who would review? How would these requirements be enforced?
- How would the decommissioning model apply to legacy modules (e.g. those already installed)

Extended Producer Responsibility

- Who would collect and track manufacturing volumes for the purpose of allocating funding obligations?
- Who would review and, if applicable, approve, manufacturers' stewardship plans?
- How can the program be structured so that the roles and responsibilities of regulation (oversight and audit) and operation of the program are separate?

POWER ADVISORY

Matters Needing Further Consideration

<u>Overarching considerations</u>

- Which, if any, recommendations can be implemented without legislative amendments?
- What data collection is needed prior to implementing recommendations (e.g., regarding state's current recycling capabilities, volume of equipment already deployed, etc.)?
- Should Connecticut require solar panel manufacturers to provide TCLP data to help facilitate handling and recycling of panels?
- Should consideration be given to implementing different recommendations at different times/in a staged manner?
- With respect to measures to educate customers/installers on recycling options, who should develop those measures? How would that educational outreach actually be carried out, and by whom?
- What, if any, consideration should Connecticut give to favoring or requiring recycling in the US or in other countries specified in the "Critical Mineral and Battery Component Requirement" section of the Inflation Reduction Act?
- Should Connecticut consider providing a Transfer-Based Exclusion (TBE) that allows certain materials to be excluded from hazardous waste regulations if they are transferred to a third party for recycling; 33 other states provide this exemption.

Matters Needing Further Consideration

<u>Applicability</u>

- How should projects already in operation, or equipment already manufactured/sold, be treated?
- Should any new policy (and applicable fees or funding allocations) apply only on a go-forward basis?
    - Acknowledging industry concerns about retroactivity, if recycling costs are only levied on a go-forward basis, how should the recycling of existing equipment be funded? And who should bear responsibility for recycling that equipment?
- If existing equipment is to be captured under any new policy on a retroactive basis, how should that be funded? e.g.:
    - Is lump-sum funding an appropriate way to ensure that existing equipment is equitably recycled? If so, who should provide it?
    - Alternatively, should an AFA/EPR framework include an adder/overcollection to fund recycling of existing equipment?
    - For decommissioning bonds where there is a more direct link to a single owner (and therefore payor), how could retroactive imposition of recycling costs be done fairly?
    - In all cases, how would the amount to be collected in respect of existing infrastructure be calculated?

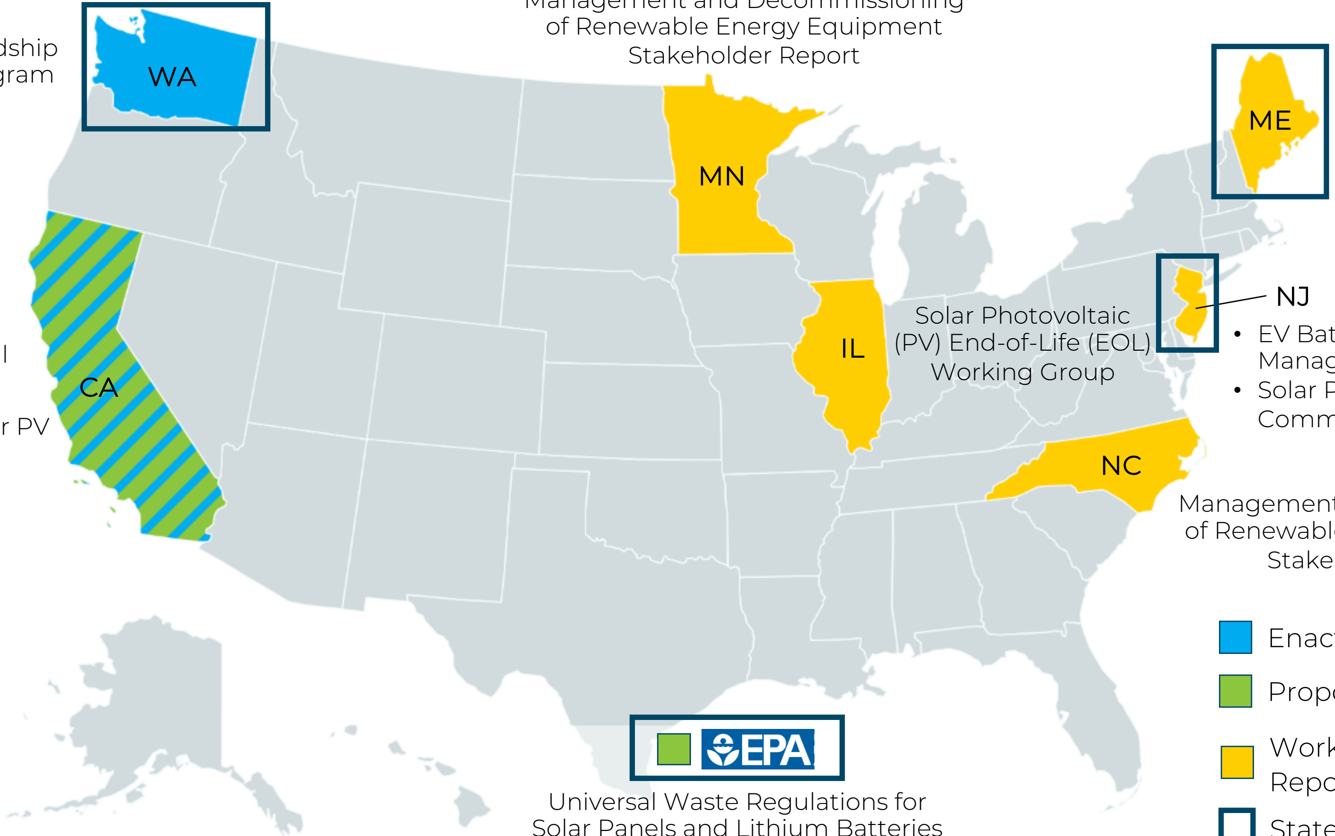
Andrew Kinross
Director
akinross@poweradvisoryllc.com
(508) 740-9638

Rakesh Puram
Manager
rpuram@poweradvisoryllc.com
(202) 641-7855

Avi Lipsitz
Senior Consultant
alipsitz@poweradvisoryllc.com
(416) 294-3117

Appendix A: State Policy and Working Groups

End of Life Related Activities Reviewed



WA: PV Module Stewardship and Takeback Program

MN: Management and Decommissioning of Renewable Energy Equipment Stakeholder Report

ME: Evaluation of Recycling of Solar Panels and Wind Turbine Blades

CA:
- PV Module Universal Waste Regulation
- AB 2: Recycling Solar PV Modules

IL: Solar Photovoltaic (PV) End-of-Life (EOL) Working Group

NJ:
- EV Battery Management Act
- Solar Panel Recycling Commission

NC: Management & Decommissioning of Renewable Energy Equipment Stakeholder Report

EPA: Universal Waste Regulations for Solar Panels and Lithium Batteries

- Enacted Legislation
- Proposed Legislation
- Working Groups and Reports
- State/Federal agencies interviewed by Power Advisory/Green Bank

A.1 Enacted State Policies

Washington State – PV Takeback Program

Statute	• S.B. 5939 'Photovoltaic Module Stewardship and Takeback Program'
Enacted	• 2017 (amended 2020)
Policy	• Extended Producer Responsibility (EPR)
Who pays?	• Program management, panel collection, re-use, and recycling must be financed by the manufacturer, with no costs assessed to the module owner.
Participants	• The Solar Energy Industries Association, First Solar, and NREL participated in the Stakeholder Advisory Group.
Key Elements	• Requires PV manufacturers to finance and implement a takeback and recycling (or reuse) plan for modules sold in the State. The Program is limited to PV modules installed on or connected to buildings and that were sold after July 2017. • Modules that are recycled are not required to be classified as 'dangerous waste', reducing liability and compliance requirements for eligible modules. • Stewardship plans must be submitted by July 2024 and outline, among other things, the financing of the Take-Back program, a plan for accepting all PV modules sold in WA after July 2017, the availability of take-back locations or alternatives in each region of the State, program information dissemination to consumers, and performance goals to reuse or recycle at least 85% of collected PV modules • Beginning July 1, 2025, solar panel manufacturers whose stewardship plans have not received approval from the WA Dept. of Ecology will be prohibited from selling their products in the State of Washington and may face fines of up to $10,000 per panel sold if non-compliance continues after 30-day notification window. • Beginning in 2026, manufacturers must provide annual reports detailing implementation of the program and performance metrics for achieving re-use or recycling of 85% of collected modules • Manufacturers may satisfy these requirements participate in a national program, provided it is deemed 'substantially equivalent'.
Timeline	• Stewardship Plans due July 2024, implementation begins July 2025.

California – PV Universal Waste

Statute	• R-2017-04 PV Module UW Approval
Enacted	• September 2020
Policy	• Universal Waste (UW) Regulation
Participants	• The Solar Energy Industries Association and First Solar provided comments on UW rulemaking

Key Elements	• The California Department of Toxic Substances Control (DTSC) approved regulations allowing Solar PV modules to be classified as 'Universal Waste' (UW), rather than more stringently regulated 'Hazardous Waste', to streamline management and reporting requirements for disposal and transportation.
	  • Eligibility for UW regulations requires either record of manufacturing materials, or costly toxicity testing, limiting the ability of private owners to benefit.
	• While clarification that more stringent Hazardous Waste requirements may not apply to Solar PV modules, UW requirements continue to impose restrictions on PV recycling.
	  • PV modules destined for recycling in another State must undergo additional Hazardous Waste determination and could fall under complex and unclear Resource Conservation and Recovery Act (RCRA) requirements. Stringent permitting requirements have prohibited Solar PV recycling facilities from operating within California, limiting options.
	• PV modules that are refurbished or reused are not waste, and thus not subject to waste regulations.

Implementation	• September 2021-Present (Ongoing). Due to its short history, little data is available on the success of this program.

New Jersey – EV Battery Management Act

Statute	• Electric and Hybrid Vehicle Battery Management Act (S3723/A5365)
Enacted	• January 2024
Policy	• First in the nation battery recycling legislation
Participants	• Various EV makers
Key Elements	• New Jersey will require battery producers submit a battery management plan to the State Department of Environmental Protection (DEP). These management plans will include planned methods for the acceptance and transport of batteries. It must also outline the means of recycling, reuse, or repurposing of batteries. It allows for new material or other recycling companies to utilize the batteries or components, and supports manufacturers in their own recycling efforts.
Implementation	• Beginning in January 2025, New Jersey EV battery producers will be required to register with New Jersey's Department of Environmental Protection (DEP), and in January 2026 they must annually report to the DEP the quantity of EV batteries they sold, offered for sale, or distributed in New Jersey. • The DEP will develop and provide the EV battery-producing industry with a framework of "standards and criteria" covering the entire recycling process that includes the collection, transportation, recycling, reuse, repurposing, or ultimate disposal of EV batteries. Once the DEP finalizes this framework, each New Jersey battery producer must develop a written management plan that addresses its EV battery recycling system and specifically provides for "take-back" programs for the collection of used EV batteries the producers sold within the state. Such programs "may include a complete vehicle take-back program, a battery take-back program, or any other [DEP-approved] program." • Producers are required to fund their management plans. In addition, all entities authorized to manage used EV batteries as part of a producer's management plan, including repair facilities, authorized propulsion battery recyclers, scrap yards, dealerships, showrooms, or used car lots, are required to manage the used EV batteries according to the approved plan

Quebec – Regulation Respecting the Recovery and Reclamation of Products by Enterprises

Statute	• Environment Quality Act, chapter Q-2, r. 40.1
Enacted	• June 2022
Policy	• Exclusion of EV batteries from Quebec's mandatory battery EPR policy
Participants	• Various EV makers
Key Elements	• Quebec has high EV deployment and therefore was an early mover in seeking to address end-of-life EV batteries • In 2021 the government of Quebec proposed to expand its EPR regulations to encompass EV batteries (and various other products), which would have included setting targets/required minimum rates for recovering EV batteries • Following industry concerns about the implications of having minimum recovery rates for EV batteries (which are tied to expected lifespan of the batteries), the province did not move forward with including EV batteries in its revised EPR regulations • In the meantime, the EV industry established its own voluntary program to collect and manage EV batteries in Quebec • Government of Quebec still intends to regulate EV batteries under an EPR framework, but has gone back to stakeholders for additional consultation and refinement of its approach
Implementation	• In summer 2023, the industry-led program was launched (EVBatteryRecovery.ca); it connects owners of end-of-life EV batteries to either the manufacturer (if the EV manufacturer has chosen to directly recover its batteries) or to one of two third-party recycling organizations that will receive and recycle spent batteries • Implementation date of EPR for EV and other battery types remains to be determined

A.2 Proposed Policies

Federal (EPA) – Universal Waste Regulation

Statute	• 2050-AH32 'Improving Recycling and Management of Renewable Energy Wastes: Universal Waste Regulations for Solar Panels and Lithium Batteries'
Status	• NPRM (Notice of Proposed Rulemaking) expected June 2025; final rule expected December 2026
Policy	• Universal Waste (UW) Regulation

Key Elements	• EPA is planning to propose new rules to improve the management and recycling of end-of-life solar panels and lithium batteries, prompted (with respect to solar panels) by a 2021 Petition for Rulemaking from a coalition of electric power industry associations.
	• EPA is working on a proposal to add hazardous waste solar panels to the universal waste regulations, which would:
	    • Ease regulatory burdens on generators of solar panel waste
	    • Promote the collection and recycling of solar panels
	    • Encourage the development of municipal and commercial programs to reduce the quantity of these wastes going to municipal solid waste management
	• These efforts include additional standards tailored for Li Batteries to improve safety standards and promote recycling

California – PV Recycling

Statute	• AB 2 'Recycling: solar photovoltaic modules'
Status	• September 2023 Held In Committee, Reintroduction possible Q1 2024
Policy	• Advanced Fee Administration
Who pays?	• Customer-Owned: Fee charged to customer at time of solar panel purchase, to be determined by CalRecycle • Non-Customer-Owned: Undefined, may be determined in CalRecycle's required EOL Plan Guidelines
Participants	• Sponsored by the California Product Stewardship Council

Key Elements	• Categorize customer-owner Solar PV modules as Electronic Waste (E-Waste).
	  • Reclassification requires retailers to collect an E-Waste recycling fee at the time of sale, which is to be used for recycling fee refunds and payments.
	  • By October 2026, the Department of Resources Recycling and Recovery (CalRecycle) must establish a Solar PV specific E-Waste recycling fee, to be assessed annually.
	• Rulemaking to define mechanics for use of the 'Covered Solar PV Module Recycling Fee Subaccount' to be determined
	• Beginning in 2028, Non-Customer-Owned Solar PV modules must provide an EOL plan outlining:
	  • A management plan for the module after end of useful life
	  • Parties responsible for implementing the management plan
	  • Either a plan for re-use or identification of a recycler, membership in a national recycling program (such as SEIA's National PV Recycling Program), or in-house capabilities to be used for recycling.

A.3 Studies and Working Groups

Takeaways – Other Jurisdictions' Working Groups

- Common challenges identified include:
  - Complex interactions between federal, state, and local waste handling regulations
  - High costs and limited capacity of current U.S. recycling technologies
  - Limited clean energy technology specific recycling regulation or policy levers in place
  - Lack of existing industry standards and best practices
- Consensus was commonly reached on interim steps to ease solar PV module handling under existing waste regulation frameworks, such as:
  - Seeking to standardize toxicity testing, such as TCLP (Toxicity Characteristic Leaching Procedure)
  - Classifying PV modules as Universal Waste (UW) to limit barriers to handling, transportation, and recycling.
  - Landfill bans for PV modules emerged as another lever with which to encourage recycling.
- Stakeholder opinions vary on how to ensure modules are recycled. Some recommend implementing programs to take advantage of existing capabilities elsewhere in the U.S., while others (such as New Jersey) look to create PV recycling capacity locally to meet needs.
- Many Working Groups look to Washington as a leader in enacting mandated PV recycling programs but implementation has been delayed, thus there is no track record for a given policy
- Commonly, stakeholders expressed the need for federal agencies to provide guidance on Battery Energy Storage end of life management best practices, rather than a state-led approach, due to safety concerns.

North Carolina – Solar PV (1/3)

Study	• 'Activities Conducted to Establish a Regulatory Program for the Management and Decommissioning of Renewable Energy Equipment'
Impetus	• House Bill 329
Status	• Completed, final report published January 2021
Participants	• Participating H329 Stakeholders include First Solar, NREL, SEIA, Solterra, PV Cycle, and Electronics Recyclers International

Scope	• To inform the development of rules governing the management of end-of-life (EOL) PV modules and energy storage battery systems in 9 sections:
	  • Hazard Characterization
	  • Preferred Management Methods
	  • Costs and Benefits of Management Methods
	  • Life-Cycle of currently deployed equipment
	  • Volume impacts of landfill capacity
	  • Jurisdictional Scan of regulatory requirements
	  • Financial Assurance for decommissioning
	  • Infrastructure for collection and transport
	  • Manufacturer Stewardship Program considerations

Key Findings	• DEQ (Department of Environmental Quality) does not recommend a manufacturer stewardship program at this time
	  • Current availability and cost of PV recycling is prohibitive and may disincentivize investment in the State
	  • As infrastructure and technology improve, such a program may be considered in the future, following additional stakeholder feedback, with the following recommendations:
	    • Differences between utility-scale and distributed solar should be considered
	    • An effective and convenient program would need to include a collection network, transportation, and recycling
	    • Evaluate language to explicitly state that the full cost of collection and recycling be covered by the program to avoid financial challenges like those experienced with the electronics legislation

North Carolina – Solar PV (2/3)

Key Findings (Continued)	

Key Findings (Continued)

- The Report also outlined future manufacturer stewardship program structure and finance options for comment:
    - Status Quo – End-of-life management decisions for utility-scale PV modules made and fully financed by the owners of the modules. If modules are not being reused or refurbished, owners are responsible for determining whether or not a PV module is a hazardous waste and can make end-of-life management decisions accordingly
    - Extended Product Stewardship (EPS) – Require a product stewardship program for all PV modules used or sold in or into the state following a certain date. Manufacturers or their stewardship organization will operate the program to fully finance the convenient takeback and recycling of all PV modules used or sold in or into the state after the implementation date. (Modeled after Washington State's Takeback program)
    - Advanced Recycling Fee – Establish an advanced recycling fee to be charged for PV modules used or sold in or into the state following a certain date. The advanced recycling fee funds would be transmitted to an entity operating a statewide collection program to manage PV modules being removed from service. (Similar to California's proposed e-waste categorization methodology)
- Discarded PV Modules to undergo TCLP (Toxicity Characteristic Leaching Procedure) testing to determine if managed as solid waste or hazardous waste
    - TCLP testing uncertainty requires development of standard preparation procedure to ensure accuracy
    - DEQ may classify PV modules under UW, eliminating the need for TCLP. This has not yet been implemented
- There are no decisions on final rules and regulations, legislative language may vary from final report findings
- This report contains feedback received from stakeholders throughout NC's process. Review of these at a high level may be useful, particularly the comments solicited to suggest options outside of the three outlined above, including:
    - Monthly recycling fees charged to the utility rate payer
    - Landfill bans, increased landfill tipping fees, and other indirect financial incentives to recycle
    - Market development of more recycling infrastructure, such as tax credits for recyclers

North Carolina – Solar PV (3/3)

Study	• 'Plan and Recommendations for Financial Resources for Decommissioning of Utility-Scale Solar Panel Projects'
Impetus	• House Bill 329 (Part 2)
Status	• Additional report on utility-scale projects published March 2022
Scope	• To inform the development of rules governing the management of end-of-life (EOL) PV modules and energy storage battery systems and the decommissioning of utility-scale solar projects and wind energy facilities
Participants	• "The Department recommended that a future study on FA involve stakeholders and participation from the North Carolina Utilities Commission (NCUC)"

Key Findings	• "Recycling capacity for solar PV modules is still in development and noted that in the future, sufficient infrastructure to support transportation and recycling of EOL PV modules will need to be developed"
	• Discarded PV Modules to undergo TCLP testing to determine if managed as solid waste or hazardous waste
	  • TCLP testing uncertainty requires development of standard preparation procedure to ensure accuracy
	  • DEQ may classify PV modules under UW regulations, eliminating the need for TCLP, though this has not yet been implemented.
	• "The establishment of a fee system paid for by manufacturers to support a stewardship program may create a disincentive for recycling, especially given the lack of accessible recycling facilities"
	• "A network of collection and consolidation points for EOL utility-scale PV modules would not be needed; instead, utility-scale PV system owners are advised to anticipate and evaluate collection and transportation costs during the facility's decommissioning planning"
	• No adoption of final rules and regulations, legislative language may vary from final report findings
	• Does not address rooftop or residential systems

North Carolina – Battery Storage

Study	• 'Activities Conducted to Establish a Regulatory Program for the Management and Decommissioning of Renewable Energy Equipment'
Impetus	• House Bill 329
Status	• Completed, final report published January 2021
Scope	• To inform the development of rules governing the management of end-of-life (EOL) PV modules and energy storage battery systems in 9 sections: 1. Hazard Characterization 2. Preferred Management Methods 3. Costs and Benefits of Management Methods 4. Life-Cycle of currently deployed equipment 5. Volume impacts of landfill capacity 6. Jurisdictional Scan of regulatory requirements 7. Financial Assurance for decommissioning 8. Infrastructure for collection and transport 9. Manufacturer Stewardship Program considerations
Key Findings	• Existing Hazardous materials regulations for batteries should apply similarly to ESR batteries • "The Department supports the adoption of a federal regulatory program for EOL management for energy storage system batteries based on information and comments provided by stakeholders and industry experts who expressed concern about the development of a viable reuse and recycling market absent a federal strategy."

POWER ADVISORY

New Jersey – Solar Panel Recycling

Study	• New Jersey Solar Panel Recycling Commission Final Report
Impetus	• Senate Bill 601
Status	• Completed, final report published November, 2023.
Participants	• First Solar, Panasonic
Scope	• The Bill established the New Jersey Solar Panel Recycling Commission to develop recommendations and report recycling and end-of-life management options for the state.

Key Findings	• Challenges Identified:
	  • Access to "High-value Recycling" is needed for recovery of harmful (Pb, Cd, Se) and valuable (Ag, In, Te) materials.
	  • The highest revenue generation for solar panel recycling would be to process all components of the panel separately, but removal of the polymer adhesive is difficult from both a cost and processing perspective
	  • Disassembly and recycling of EOL solar panels is unlikely to be a profitable operation and may require funding sources, such as a per module fee on all future installations
	  • Price increases due to fees (deposits, advanced recovery fees (ARFs), or Extended Producer Responsibility (EPR) fees), may dampen demand for solar panel modules
	• The Commission's Recommendations are based on two goals for PV module EOL management:
	  • Enabling Recycling
	    • Construct New Solar Panel Recycling Centers in NJ no later than 2030. Potentially using economic incentives (e.g., tax abatement, performance and employment rebates) or regulatory changes (e.g. streamlined permitting, UW regulations)
	    • Explicitly ban disposal of EOL solar panels in New Jersey landfills
	  • Extending use and enabling re-use
	    • Encourage and/or mandate extended use of solar panels with greater than 80% efficiency remaining.
	    • Establish a threshold efficiency above which panels are re-used, either through direct donations to non-profits, affordable housing installations, or international organizations

Maine – Options for Solar Panel Recycling

Study	• 'Resolve to Evaluate Options for the Recycling of Solar Panels and Wind Turbine Blades'
Impetus	• L.D. 466
Status	• Complete, analysis published by the Maine Department of Environmental Protection (DEP)
Participants	• "The Department reached out to nine solar panel providers and the Maine Renewable Energy Association based in Maine and informed them of our intent to evaluate solar panels as a candidate for a product stewardship program. The Department has not received written responses at the time of this report but will continue to solicit feedback from these providers."
Scope	• The Resolve required that the Maine Department of Environmental Protection (MEDEP) evaluate whether solar panels met the criteria to be a candidate for a product stewardship program. MEDEP publishes an annual Product Stewardship Report, which tracks current and proposed products subject to EPR requirements • MEDEP provided considered both grid-scale and residential solar projects in their evaluation
Key Findings	• The MEDEP did not recommend the development of a product stewardship program for Solar PV module recycling, citing uncertainty around changing EPA RCRA regulations and a lack of recycling capacity

Illinois – PV Working Group

Study	• 'Solar Photovoltaic (PV) End-of-Life (EOL) Working Group'
Impetus	• House Bill 329
Status	• Ongoing, limited information past 2019
Participants	• U.S. EPA, NREL, SEIA, Product Stewardship Institute, and PV module manufacturers
Scope	• Examine options for a PV EOL management plan for Illinois, recycling, and consider reuse of viable modules • The Illinois Sustainable Technology Center (ISTC) partnered with the Illinois Environmental Protection Agency (IEPA) to form the Working Group in the spring of 2018. Minimal information is available on the group's findings

Key Findings	• The overall group has confirmed there is a need for funding mechanisms and resources for a state-wide feasibility study including:
	    • Strategic Plan for the state;
	    • Solutions for reuse/redeployment, refurbishment, and recycling; and
	    • Assessment of policy options that can help to drive PV EOL requirements

California

Impetus	• This study is among California agencies including CPUC, CalRecycle, CDTSC, CARB, California Energy Commission
Status	• Ongoing, limited results to date
Key Elements	• The Memorandum of Understanding (MOU) outlines an agreement to cooperatively developing consistent approaches for the proper collection and management of used or damaged photovoltaic (PV) panels, electric vehicle (EV) batteries, energy storage systems based on lithium ion technology, and related equipment
Findings	• Study ongoing

Minnesota – Recycling PV Modules

Impetus	• HF 2310 Recycling and Re-Using Solar PV Modules and Installation Components
Status	• Ongoing, limited results to date
Participants	• TBD

Key Elements	• A coalition led by the MN Pollution Control Agency must report on developing a statewide Solar PV re-use and recycling program, including:
	  • Analysis of options for a statewide program that is 'convenient and accessible', and recovers 100% of discarded components, maximizes value of materials recovery.
	    • Must include consideration of system infrastructure and technology needs, in-state employment and development, net costs, environmental justice, projected PV EOL volumes, and status-quo management.
	• The results of the report must be presented to the advisory working group to develop policy recommendations.

Findings	• Study ongoing, statutory deadline January 2025

POWER ADVISORY

A.4 Decommissioning Requirements

North Carolina – Decommissioning

Statute	S.L. 2023-58
Enacted	September 2020
Mechanism	Decommissioning Requirements

Key Elements	• Requires the owner of a utility-scale solar project (greater than or equal to 2MW) to:
	  • Properly decommission the project upon cessation of operations and restore the property.
	  • Register with the DEQ and pay a fee (to be established in rulemaking)
	  • Submit a decommissioning plan and establish financial assurance for new and rebuilt/expanded utility-scale solar projects

Financing	N/A
Implementation	Proposed Rulemaking and Outreach is ongoing, draft rules are expected in July 2024, to become effective in November 2025

Appendix B: Stakeholder Perspectives

Stakeholder Perspectives on Solar and Battery End-of-Life Management

- To understand the responsibilities and contributions of solar developers, manufacturers, and recyclers in managing the end-of-life stage of solar panels and batteries, Power Advisory surveyed a wide range of industry stakeholders

- The interviews focused on gaining insights around in key areas to enable the Working Group advance their collective thinking on EOL options for batteries and solar panels:
  - Considerations in end-of-life (EOL) management:
    - Need for sustainable practices to minimize environmental impact
    - Importance of adhering to regulations such as the Resource Conservation and Recovery Act (RCRA). Balancing cost-effective EOL solutions with environmental benefits
  - Challenges:
    - Addressing the potentially high costs associated with recycling and disposal
    - Assessing the market's readiness to adopt and implement advanced EOL solutions
  - Perspectives
    - Concerns about the cost and logistics of recycling programs (Solar Developers)
    - Challenges related to designing products with EOL management in mind (Manufacturers)

DEEP Perspective

Throughout the Working Group process, DEEP provided key insights into Connecticut's current end-of-life management practices. In several areas, the DEEP team's recommendations diverged from the rest of the Working Group. DEEP has contributed the following perspective:

- Extended Producer Responsibility programs have been proven to successfully address a wide array of waste streams in CT:
  - CT has several EPR programs, which could be used as a model for solar including:
    - Electronic Wastes(CGS Sections 22a-629 through 22a-640, Regulations of Connecticut State Agencies 22a-638-1 and 22a-630(d)-1)
    - Mercury Thermostats (Public Act 12-54)
    - Paint (CGS 22a-209a)
    - Mattress. (CGS 22a-905)
    - Gas Cylinders (CGS-905h)
    - Tires (Public Act 23-62)
  - Each EPR program involved stakeholder engagement which included manufacturers.
  - Extended Producer Responsibility approach for the end-of-life provides numerous benefits including:
    - Efficient recycling and waste management can reduce overall costs associated with waste disposal and landfill management.
    - EPR encourages cost-effective solutions by involving producers in the process.
    - End of life costs are not passed to the consumer which leads to an increase in recycling and responsible disposal.
  - EPR programs have not led to manufacturers leaving Connecticut or refusing to do business in Connecticut
  - EPR programs implore 3rd party entities (Stewardship Organizations) to track products and administer the programs
- CT electric ratepayers should not be responsible for the end-of-life cost for product even if the impact on their bill is modest

Solar Developers – End-of-Life Management and Challenges

- Considerations in End-of-Life Management:
    - Economic Viability: The high cost of recycling, currently around $18 per panel plus $20 for shipping, makes it economically challenging for asset owners. If recycling is not profitable, it imposes an undue financial burden on asset owners.
    - Project Economics: Current solar projects have not accounted for the costs associated with recycling or decommissioning bonds/advanced fee administration (AFA). This creates a potential risk for existing projects.
    - Contractual Challenges: For future projects, accurately pricing in the cost of recycling into Power Purchase Agreements (PPAs) or project budgets is difficult

- Challenges:
    - High Cost of Recycling: The current cost structure for recycling solar panels is not economically viable, presenting a significant financial burden on developers and asset owners.
    - Underdeveloped Recycling Market: There are few recycling facilities and processes available, leading to logistical challenges in managing EOL solar panels. The market for recycled materials from solar panels is still developing. And there are no local facilities (in the state).
    - Policy and Compliance Risks: New recycling policy mandates could increase operational and cost burdens on developers, potentially driving them out of Connecticut. The lack of clear policies and support for recycling initiatives adds to the uncertainty and risk.

Solar Developers – Perspectives

- Perspectives:
  - Future Use Viability: Some developers view solar panels as having a viability of 30+ years, which reduces the immediate need for EOL recycling policy. They support the idea that panels can be repurposed or reused in some form in the future
  - Policy Preferences: There is a preference for policies that do not impose significant additional costs or operational burdens. Developers are concerned that strict recycling mandates could negatively impact the industry
  - Collaborative Solutions: Emphasize the need for collaborative efforts to develop a more robust recycling infrastructure and market. Support from state and federal policies, as well as industry collaboration, is essential for creating viable recycling solutions
  - Innovative Approaches: Developers are open to exploring innovative approaches to recycling, such as integrating recycling costs into project financing or leveraging technological advancements to reduce costs

Solar Manufacturer – End-of-Life Management and Challenges

- Considerations in End-of-Life Management:
  - Some manufacturers conduct Toxicity Characteristic Leaching Procedure (TCLP) tests to ensure panels are non-hazardous, and increasingly focused on incorporating recyclable materials and designing products for ease of disassembly to facilitate end-of-life recycling
  - Manufacturers sell their products to developers and utilities, who are responsible for end-of-life (EOL) management. In specific cases, manufacturers have recently assumed responsibility for EOL management
- Challenges:
  - The high cost and logistical complexity of recycling, particularly for silicon and glass, which lack efficient recycling technologies
  - Market dynamics for recycled materials, such as tight and hesitant markets for recycled glass, impact the cost-effectiveness of recycling panels
  - Regulatory uncertainty across different states creates challenges for establishing consistent recycling practices

Solar Manufacturer – Perspectives

- Perspectives:
  - Strong preference for policies that do not add significant costs to the supply chain, with an emphasis on collaborative and flexible approaches
  - There is a consensus against Extended Producer Responsibility (EPR) for solar panels, favoring decommissioning planning and funding for utility-scale and commercial installations, and advance recovery fees for residential systems
  - Manufacturers and industry organizations advocate for developing and standardizing recycling practices to ensure a level playing field and support the industry's long-term sustainability goals

Solar Recycler – End-of-Life Management and Challenges

- Considerations in End-of-Life Management:
  - Recyclers typically receive pallets of panels from asset owners, who are responsible for dismantling and palletizing the panels before shipping them to recycling facilities
  - They focus on mostly decommissioned panels, followed by broken panels, and panels affected by events such as weather damage or fires
  - Advanced recycling processes aim to recover high-purity materials from panels
- Challenges:
  - The high costs and logistical issues associated with the transportation and recycling of solar panels. Transportation is particularly impacted by whether states have Transfer Based Exclusion (TBE) for solar panels, affecting the need for permits under the Resource Conservation and Recovery Act (RCRA)
  - Limited infrastructure and advanced technologies needed to efficiently recycle solar panels, especially in terms of separating materials at a cost-effective rate
  - Market readiness and demand for recycled materials are still developing, creating uncertainty in the economic viability of large-scale solar panel recycling

Solar Recycler – Perspectives

- Perspectives:
  - Recyclers advocate for including recycling in decommissioning plans to ensure that panels are recycled rather than disposed of in landfills
  - There is a strong push for policies that make it easier and more cost-effective for asset owners to store and transport EOL panels to recycling facilities
  - Emphasis on the importance of state policies that recognize high-purity recycling methods and discourage less effective methods, such as using recycled panels as roadbed fill
  - Some see the potential for significant price reductions in recycling as the industry scales up and becomes more prevalent, similar to the cost reductions seen in solar panel production
  - The industry supports developing a robust domestic market for recycled materials, aligning with incentives for domestic content under frameworks like the Inflation Reduction Act (IRA)

Battery Manufacturer/Recycler – End-of-Life Management and Challenges

- Considerations in End-of-Life Management:
  - Collection and Recycling: Batteries, especially from energy storage systems, are collected and recycled by specialized recyclers. The process involves dismantling the systems, palletizing the battery cells, and shipping them to recycling facilities
  - Material Recovery: Recyclers recover over 95% of critical minerals from batteries, including nickel, cobalt, lithium, and copper, which are then used to remanufacture battery components
  - Partnerships: Companies often partner with intermediaries for collection, aiming to offset collection costs through the revenue from selling recycled materials
- Challenges:
  - High Costs and Logistics: The high cost of transportation and recycling, particularly due to logistical issues, remains a significant challenge. Transportation expenses often make or break the economics of battery recycling
  - Market Readiness: The US currently has limited recycling capacity for batteries, with much of the recycling happening overseas. There is a need for increased domestic recycling infrastructure
  - Regulatory Barriers: Compliance with regulations, such as obtaining RCRA (Resource Conservation and Recovery Act) permits for hazardous materials, adds complexity and cost to the recycling process

Battery Manufacturer/Recycler – Perspectives

- Perspectives
    - Some developers…
        - Advocate for a ban on landfilling due to environmental and safety concerns
        - Support Extended Producer Responsibility (EPR) models but opposes overly bureaucratic Producer Responsibility Organizations (PROs). Some also advocate for legislated EPR frameworks, while citing challenges with current recycling economics and logistics
        - Believe in partnering with intermediaries to create a cost-effective collection system at scale
        - Prefer in-house recycling capacity supplemented by third-party recyclers
        - Support developing a reverse logistics chain for product take-back at the customer's request
    - There are also voices that…
        - Emphasize a market-based approach with minimal government intervention, highlighting the success of lead battery recycling
        - Support industry-led recycling programs, while cautioning against the inefficiencies of centralized EPR schemes
        - Recommend mandatory participation schemes for stationary batteries, ensuring all stakeholders handle collection and recycling responsibilities

Appendix C: Environmental Impact

An Overview of the Environmental Impacts of End-of-Life Solar Panels and Batteries

Solar Panels

- Solar panels are primarily made of crystalline silicon or thin-film materials. The environmental impacts of landfilling solar panels can include the leaching of hazardous materials such as cadmium, lead, and copper into the environment, which can contaminate soil and groundwater
- Recycling processes for solar panels include mechanical recycling (crushing and separating) and smelting, aimed at recovering valuable materials like silver, polysilicon, copper, aluminum, and glass

Lithium-Ion Batteries

- Lithium-ion batteries contain valuable metals like lithium, cobalt, nickel, and manganese. Landfilling lithium-ion batteries poses risks of leaching toxic substances, causing soil and water contamination, and potential fire hazards
- Battery technology continues to evolve. Various processes such as pyrometallurgy, and hydrometallurgy have advantages and disadvantages respect to environmental impact. The Worcester Polytechnic Institute (WPI) process is an innovative and potentially more environmentally friendly approach to recycling lithium-ion batteries, emphasizing the recovery of high-purity materials
- While recycling of both batteries and solar panels are beneficial, they also have toxic by-products that need to be managed

Types of Solar Panels

- Crystalline silicon (mono- and poly-crystalline)
    - Crystalline-silicon solar PV represents ~80% of solar panels sold today. This type of panel contains solar cells made from a crystal silicon structure. These solar panels typically contain small amounts of valuable metals embedded within the panel, including silver and copper
- Thin-Film
    - Thin-film solar cells contain thin layers of semiconductor material, such as cadmium telluride (CdTe) or copper indium gallium diselenide (CIGS), layered on a supporting material such as glass, plastic, or metal. CdTe is the second-most common PV material after crystalline silicon

Relative Impact of Materials by Component in Crystalline Silicon Solar Panels

Component	Materials used	Environmental impact
Frame	Aluminum	Low
Modular cover	Glass	Low
Solar cell	Silicon, silver	Low
Solar cell coating	Silicon dioxide, titanium dioxide	Moderate
Cell module and interconnections	Lead, copper, tin	High
Backsheet	Polymer	Moderate to high

Several of the hazardous materials commonly found in solar panels can leach into the environment through landfills.

Relative Impact of Materials by Component in Thin-film Panels

Component	Materials used	Environmental impact
Frame	Aluminum	Low
Modular cover	Glass	Low
Solar cell	Silicon	Low
Solar cell	Cadmium, tellurium, copper, indium, gallium, selenium compounds ("thin film")	High
Solar Cell coating	Silicon dioxide, titanium dioxide	High
Cell module and interconnections	Lead, copper, tin	High
Backsheet	Polymer	Moderate to high

Several of the hazardous materials commonly found in solar panels can leach into the environment through landfills.

Environmental Impacts of Hazardous Materials Found in Thin-film and Silicon Solar Panels

Dependent on panel chemistry, the varied materials found in panels can have adverse environmental impacts

Material	Environmental impact
Cadmium telluride (CdTe)	• Highly toxic and can leach into groundwater from landfills, posing serious health risks such as kidney damage and bone fractures. • Also a known carcinogen.
Silicon dioxide, titanium dioxide	• Silicon dioxide is considered inert but does not degrade and contributes to bulk of the landfill. • Titanium dioxide considered relatively inert. However, can be toxic to aquatic organisms, causing oxidative stress and other harmful effects.
Copper Indium Gallium Selenide (CIGS)	• Improper disposal can lead to the release of these elements into the environment, posing risks to ecosystems, particularly embryonic development of various species
Ethylene Vinyl Acetate (EVA)	• As a plastic material it can degrade over time, potentially releasing toxic chemicals into the environment. • It is not biodegradable and contributes to plastic pollution.
Lead (Pb)	• While occurring in small amounts, it has the possibility of contaminating soil and water, affecting plant, animal, and human health. • Particularly harmful to the nervous systems of both children and adults, causing cognitive impairment and other health issues.

POWER ADVISORY

Process of Landfilling Solar Panels

1. **Collection and transportation:** Decommissioned solar panels are collected from various sources such as solar farms, residential installations, and commercial facilities. These panels are then transported to a landfill site.

2. **Sorting and pre-treatment:** At the landfill site, solar panels may undergo basic sorting and pre-treatment to separate components that can be easily removed, such as aluminum frames and junction boxes. However, this step is often limited due to the lack of specialized facilities and economic incentives for thorough pre-treatment.

3. **Disposal:** The panels are then disposed of in the landfill. They are usually crushed and compacted to save space. Over time, the panels break down and may release hazardous substances into the environment.

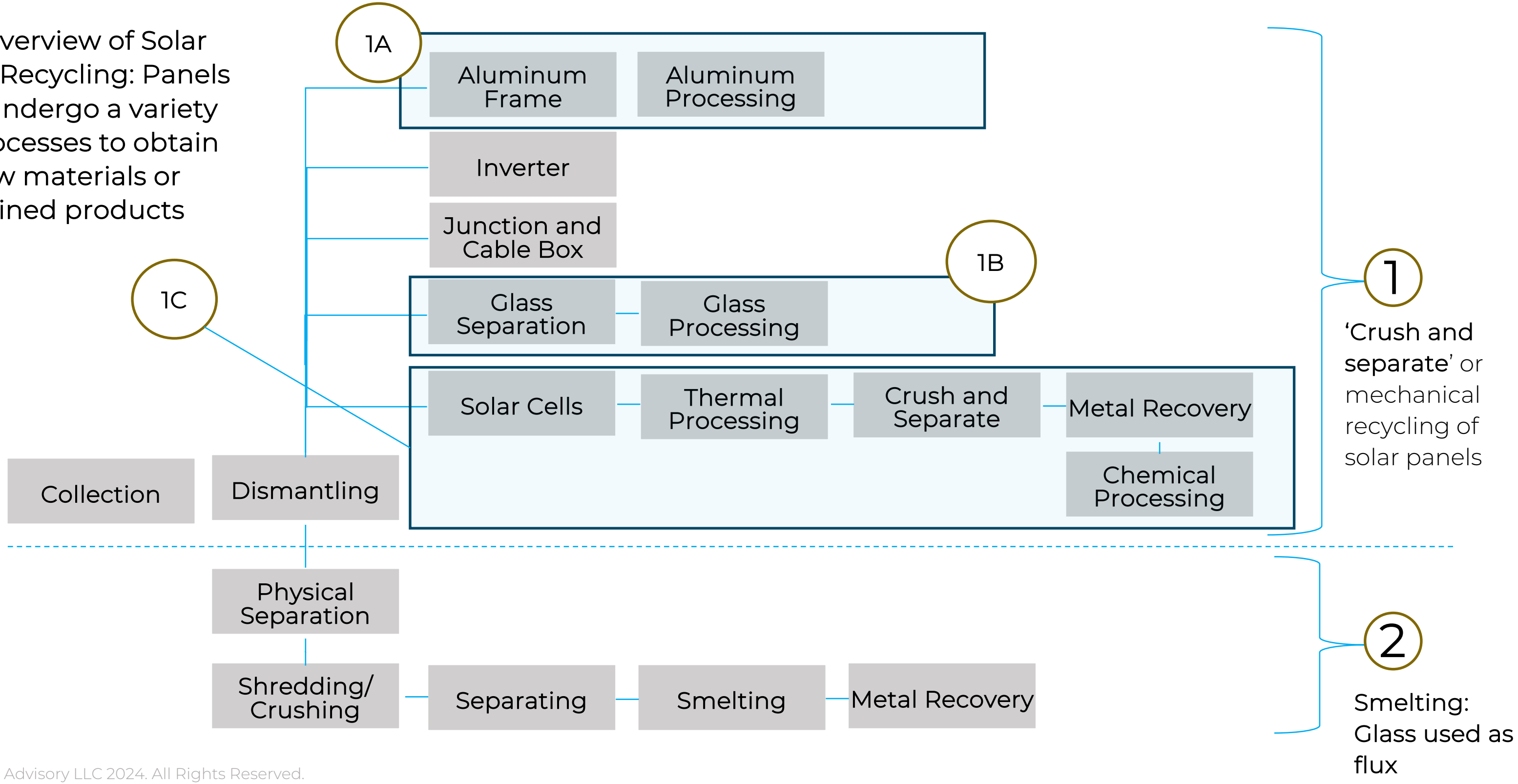
4. **Monitoring:** Modern landfills are required to have systems in place for monitoring potential environmental impacts, such as leachate collection systems and groundwater monitoring. However, these systems may not completely prevent contamination.

Environmental Impacts of Landfilling Solar Panels

- Resource waste
    - Solar panels contain valuable materials that can be recycled and reused. Landfilling these panels results in a loss of these materials, leading to unnecessary resource extraction and associated environmental degradation
- Space utilization
    - Solar panels take up significant space in landfills, contributing to the growing problem of landfill space availability. This can lead to the need for additional landfills, which in turn affects local ecosystems and land use
- Carbon footprint/inefficient resource use
    - Landfilling solar panels without proper recycling efforts exacerbates the carbon footprint associated with their lifecycle
- Leaching of toxic substances
    - Over time, as solar panels break down, toxic substances can leach into the soil and groundwater, posing risks to human health and the environment. For instance, cadmium and lead can contaminate water sources, leading to harmful effects on aquatic life and potentially entering the human food chain

Approaches to Recycling Solar Panels

An overview of Solar Panel Recycling: Panels can undergo a variety of processes to obtain raw materials or refined products



Approaches to Recycling Solar Panels

- Solar panel recycling can be considered a gray space. While there are a menu of recycling processes and options available, panels do not go through a singular process. The recycler recycles or reuses components in a combination of reselling, landfilling, or reuse
- Direct recycling
    - In **'crush and separate'** or mechanical recycling of solar panels are mechanically crushed, and the materials are separated based on their physical properties
    - This method typically yields separated glass, metals, and other materials
    - The recovered metals can be reused, while the glass and other components may be repurposed or further processed; glass can also be processed separately
- 2 - Smelting
    - In the **smelting process**, the glass is not recycled separately in the traditional sense
    - Instead, it is used as a flux material during the smelting process
- Solar panel recycling also consumes energy and creates by-products and waste which have to be managed to minimize environmental impact

1A Aluminum Frame Processing

Aluminum Frame → Shredding → Melting → Casting

Shredding: Frames are shredded into smaller pieces.

Melting: Shredded aluminum is melted in a furnace at high temperatures. to remove any remaining impurities.

Casting: Molten aluminum is then cast into ingots or other shapes, which can be used as raw material for manufacturing new aluminum products.

Recovered Materials/Outputs:

- Aluminum Ingots

By products and impact:

- Dross
- Chemical waste
- Emissions
- Energy Consumption

Environmental Impacts of Aluminum Recycling of Solar Panels

Impact	Description
Emissions of pollutants	• Melting process in aluminum recycling can release pollutants such as carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO_x). These emissions contribute to air pollution and climate change.
Dust and particulate emissions	• Shredding and melting aluminum can generate dust and particulates, which, if not properly controlled, can contribute to air pollution and pose health risks to workers.
Generation of Dross	• The aluminum recycling process generates dross, a by-product that contains aluminum oxides, impurities, and other metals. Dross needs to be managed properly to avoid environmental contamination.
Energy consumption	• While recycling aluminum is less energy-intensive than primary production, it still requires energy, primarily from electricity and fossil fuels. This energy use contributes to environmental impacts depending on the energy source, such as greenhouse gas emissions from fossil fuel-based power plants.
Waste from chemical treatments	• Some recycling processes involve the use of chemicals to clean and purify aluminum. The disposal of spent chemical solutions and sludge must be managed carefully to prevent environmental contamination.

1B

Glass Recycling

Glass Separation

The glass layer is carefully separated from the silicon cells and the other components.

Cleaning

The separated glass is cleaned to remove any residual adhesive, coatings, or other contaminants.

Processing

The cleaned glass is then processed into cullet.

Recovered Materials/Outputs:

- Recovered Glass: Cleaned and processed glass, often in the form of cullet, can be used as raw material for producing new glass products.

By-Products and Impact:

- Energy Consumption
- Residual Contaminants
- Emissions
- Wastewater Generation

Environmental Impacts of Glass Recycling in Solar Panels

Impact	Description
Emissions of pollutants	• Melting process in aluminum recycling can release pollutants such as carbon dioxide (CO2), sulfur dioxide (SO2), and nitrogen oxides (NOx). These emissions contribute to air pollution and climate change.
Wastewater generation	• Cleaning the glass to remove coatings, adhesives, and other contaminants can produce wastewater that needs to be treated to remove pollutants before discharge. Improper treatment can lead to water pollution.
Energy consumption	• Recycling glass is less energy-intensive than producing new glass, it still requires energy, primarily for the processes of collection, cleaning, crushing, and melting. The environmental impact depends on the energy source used, with fossil fuel-based energy contributing to greenhouse gas emissions.
Contaminated residues	• The recycling process may generate residues, such as fine glass particles and contaminants (e.g., metals, plastics), that need to be managed properly to avoid environmental contamination.

1C Solar Cell Processing: Crush and Separate

The Crush and Separate Process for Solar Panels: involves mechanically crushing the panels to break them into smaller pieces, followed by separation techniques to extract and recover valuable materials such as glass, silicon, and metals.

Thermal Processing

Sometimes used to remove and recover the encapsulating polymers (such as EVA, ethylene-vinyl acetate) and other organic materials in temperature is high enough to burn off the polymers but not damage the silicon cells.

Crushing

Solar panels are fed into a crusher or shredder that breaks them into smaller fragments.

Separation

Various separation techniques such as magnetic, density, electrostatic, optical are used to recover valuable metals such as silver, copper, and tin.

Chemical Treatment

Silicon wafers undergo chemical treatments in acid or alkaline baths to remove any residual impurities, metals, and coatings.

Solar Cell Processing: Recovered Materials and By-products

- Recovered Materials/Outputs:
  - Purified silicon: silicon wafers
  - Metals: Silver, copper, tin
  - Recycled polymers: Residual polymers encapsulating the solar cells; partially recoverable based on efficiency of thermal processing
- By-Products/Impact:
  - Emissions
  - Ash residue
  - Silicon and dust particulates
  - Precipitates and sludge
  - Spent acid solutions
  - Electrolyte waste
  - Filter cake

Environmental Impacts of Thermal Processing, Crushing, and Separation in Solar Panels

Impact	Description
Emissions of pollutants	• Thermal processing releases gases such as carbon dioxide (CO2), carbon monoxide (CO), and volatile organic compounds (VOCs). These emissions can contribute to air pollution and have environmental and health impacts
Ash residue	• The combustion of organic materials and polymers generates ash and solid residues. These residues can contain metals and other materials that need to be further processed or safely disposed of
Particulates	• Fine particulate matter can be released during thermal processing. These particulates need to be captured using filtration systems to prevent air pollution
Silicon and dust particulates	• Mechanical processes like crushing and milling generate fine silicon dust and particulates. These need to be collected using dust extraction systems to prevent inhalation hazards and to keep the workplace safe.
Precipitates and sludge	• Chemical reactions during the cleaning process can produce solid precipitates and sludge, which may contain impurities removed from the silicon wafers. These materials must be handled as hazardous waste if they contain toxic substances.
Gaseous emissions	• Some processes may release gases, such as chlorine or hydrogen fluoride, which need to be captured and treated in scrubbers to prevent environmental harm.

Environmental Impacts of Chemical Treatment Recycling of Solar Panels

Impact	Description
Spend acid solutions	• Chemical treatments often involve the use of acids to dissolve metals. After the metals are recovered, the spent acid solutions contain dissolved impurities and need to be treated before disposal. This can result in the generation of neutralized sludge, which must be handled properly to prevent environmental harm
Electrolyte waste	• Electrochemical processes use electrolytes to facilitate the recovery of metals. Over time, the electrolytes become contaminated with impurities and need to be replaced, generating waste that requires treatment.
Filter cake	• Filtration of liquid waste streams during metal recovery produces filter cake, a solid by-product that contains concentrated impurities and residual metals. This by-product must be managed carefully to avoid environmental contamination

② Smelting

The Smelting Process for Solar Panels: Where Glass is Used as Flux

Pre-Smelt Preparation → **Crush and Separate** → **Furnace** → **Metal Recovery**

Pre-Smelt Preparation

The panels are disassembled to remove components such as aluminum frames and junction boxes, which are usually recycled separately.

Crush and Separate

Solar panels including the silicon cells, glass, and polymer layers are fed into a crusher or shredder that breaks them into smaller fragments. After crushing, various separation techniques such as magnetic, density, electrostatic, optical are used.

Furnace

Prepared mixture of shredded panel materials, including silicon cells and glass, is fed into a high-temperature smelting furnace where high temperatures (typically above 1,200°C or 2,192°F), causing the materials to melt. The glass in the mixture melts and acts as a flux, which helps to purify the metal by allowing impurities to rise to the surface.

Metal Recovery

Molten metals are extracted from the bottom of the furnace, then poured into molds to cool and solidify into ingots or other forms suitable for reuse. slag, including the glassy byproduct, is skimmed off from the top of the molten metal.

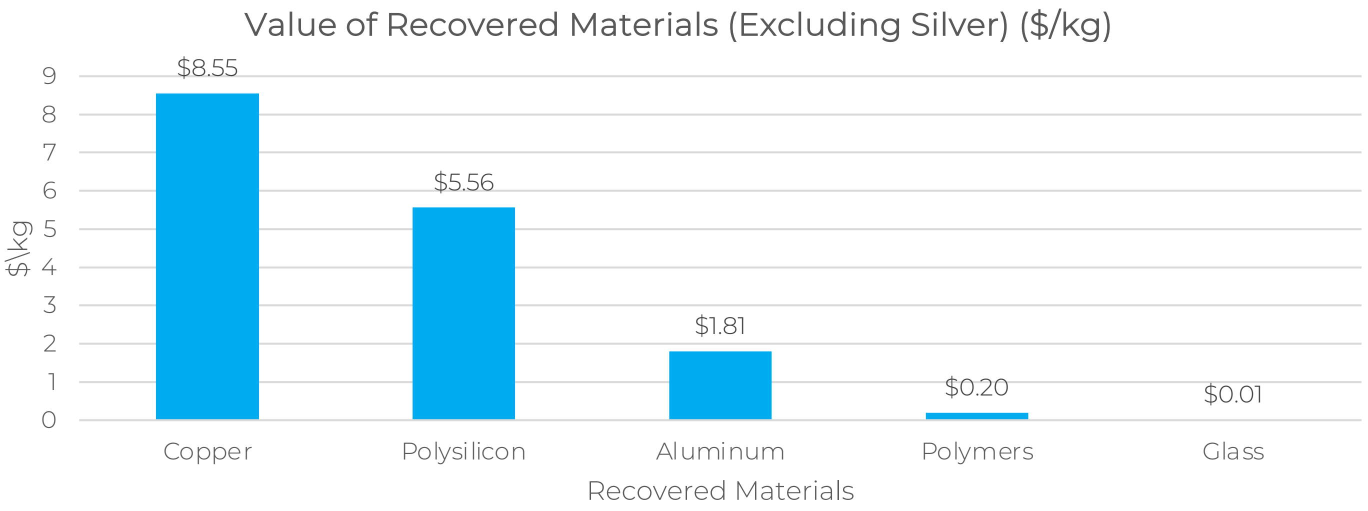
Smelting: Recovered Materials and By-products

- Recovered Materials/Outputs:
  - Metals: Silver, copper, and sometimes aluminum.
  - Slag:
    - The melted glass and other impurities form a slag, which can be repurposed for industrial applications or require proper disposal.
    - If slag is landfilled, it has a much higher negative environmental impact.
- By-Products/Impact:
  - Emissions: CO_2, SO_2, and other gases that need to be treated to minimize environmental impact.

Recovered Materials from Solar Panels

Material	Value	Recovery
Silver	High	The price of silver in 2020 fluctuated greatly, reaching a seven-year high in September 2020. Currently, recycling processes are not able to recover silver at scale. However, recyclers have the option to sell it to refinery companies that would consequently extract the silver.
Polysilicon	High	The price of polysilicon in 2020 was characterized by a high degree of volatility and fluctuated dramatically, with a historically low level reached in mid-2020 due to the COVID-19 pandemic. The silicon recovered from the recycling process could theoretically be utilized in the solar industry; however, current recycling processes are not able to reach such high purity levels. Alternatively, recycled silicon could end up being used for a variety of metallurgical applications or even in the production of lithium batteries.
Copper	Medium	Similarly to aluminum, the demand for recycled copper risks being affected by its cyclical pricing. More consistent pricing will positively impact the industry. Recovered copper can also be reinserted in the metal industry.
Aluminum	Medium	The price of silver in 2020 fluctuated greatly, reaching a seven-year high in September 2020. Currently, recycling processes are not able to recover silver at scale. However, recyclers have the option to sell it to refinery companies that would consequently extract the silver.
Glass	Low	Recovered glass (glass cullets) are usually contaminated and therefore have little value and cannot be re-used in the glass or PV module industry. Alternative uses include glass foam to provide insulation in the shipping industry or production of reflective paint. The growing “double-glass” module trend will increase the quantity of recycled glass.
Polymers	Low	The polymers recovered from the recycling of PV modules have low value. Scrap polymer or plastic flakes can be utilized in the cement industry or rubber industry. Alternatively, the polymers can be incinerated to provide energy.

Value of Recovered Materials



Silver

- Recovered silver (not shown in graph) has the highest value (~$800/kg) but existing recycling processes make the recovery challenging and expensive.
- Percentage use of silver in manufacturing modules has declined over time and the trend is expected to continue.

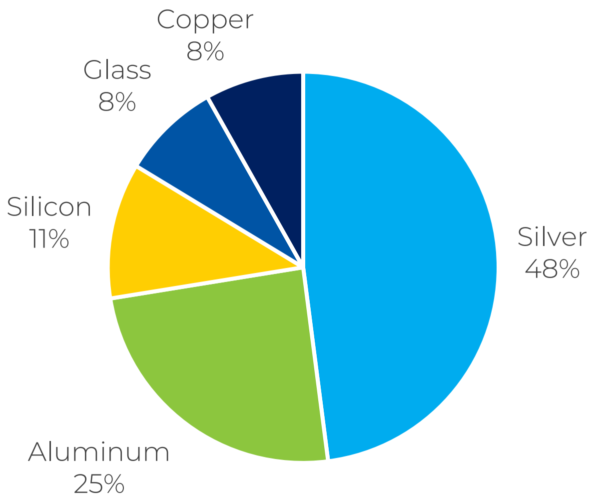
The recycling market for **copper** is mature	Contaminated **silicon** has lower purity than virgin silicon. It is challenging for current recycling processes to isolate silicon	Scrap **aluminum** is easily recoverable, and market is mature	**Plastics** recovered from recycling process could be reused; however, polymers are often incinerated	Recovered **glass cullet** has a low value ($0.01/kg) due to contamination

Source: Scrapmonster, Bernreuter, Resource Recycling

Value Distribution of Raw Materials in Solar Panels

- **Silver:** Despite its high relative value, it is important to note that solar panels contain very little silver by weight. The high value is attributed to the significant role silver plays in the efficiency and performance of the panels.
- **Aluminum:** Aluminum constitutes a quarter of the raw material value, primarily used in the frame and structural components of the panels.
- **Silicon:** Silicon, being the primary material for photovoltaic cells, represents 11% of the value.
- **Glass:** Glass is used as the protective layer, contributing 8% to the total value.
- **Copper:** Copper is essential for electrical connections within the panel and also represents 8% of the value.

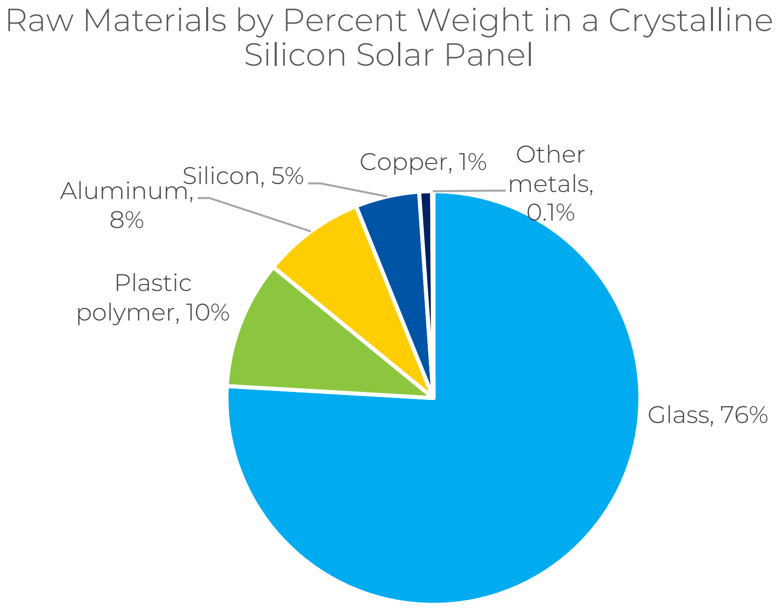
Relative Value of the Raw Materials in a New Solar Panel



Source: IRENA

Weight Distribution of Raw Materials in Crystalline Solar Panels

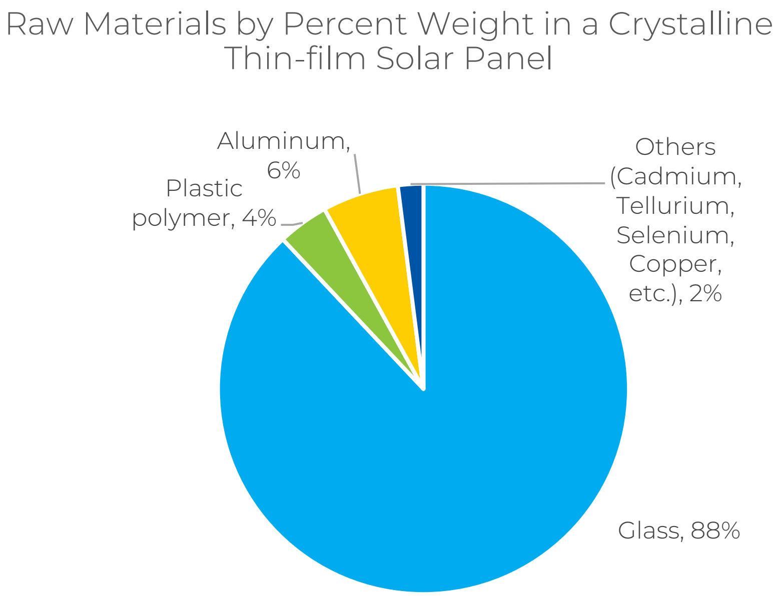
- With crystalline silicon, the panel's glass surface makes up 76% of the total weight.
- About 10% goes on polymer encapsulant, 8% on the aluminum frame, 5% on silicon from solar cells, 1% on copper from interconnectors, and less than 0.1% on silver, tin, and lead.



Source: Renewable Energy Vermont, The Green Citizen, Green Match

Weight Distribution of Raw Materials in Thin-film Solar Panels

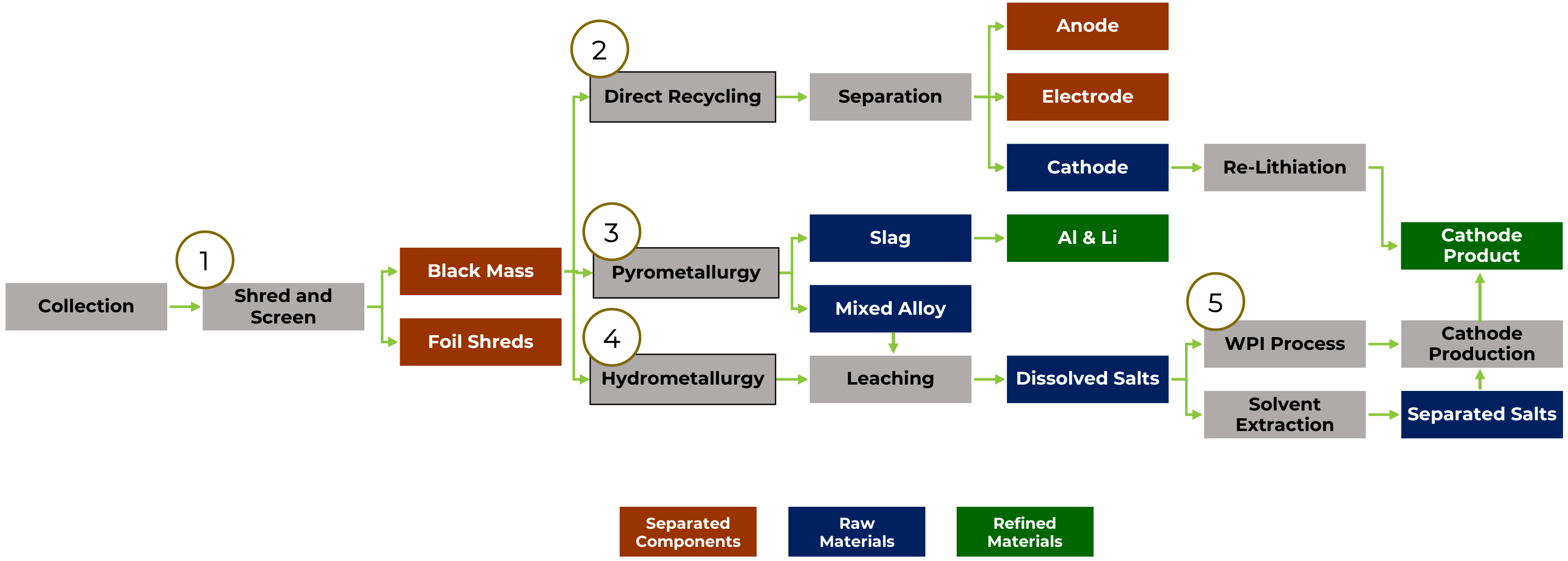
- In Thin-film modules, the percentage of glass is significantly higher at around 88% and can reach 95% in some of the cases.
- This is due to a higher optical absorption coefficient as compared to crystalline silicon PV modules.



Source: Renewable Energy Vermont, The Green Citizen, Green Match

An Overview of Lithium-Ion Battery Recycling

Batteries can undergo a variety of processes to obtain raw materials or refined products



Approaches to Recycling Lithium-Ion Batteries

- Due to the complex structure and number of materials in lithium-ion batteries, they must be subjected to a variety of processes prior to recycling. Lithium-ion batteries must be first classified and most often pretreated through discharge or inactivation, disassembly, and separation after which they can be subjected to direct recycling, pyrometallurgy, hydrometallurgy, or a combination of methods
    - Direct methods: Involves the disassembly of lithium-ion batteries to remove and reuse or recondition the cathode material. Battery renovation often requires disassembly to replace faulty components
    - Hydrometallurgy: A chemical refinement process to recover the metals in ion form from the black mass. This process extracts materials with purification and extraction rates that make them materially and commercially viable for reuse in the battery supply chain
    - Pyrometallurgy: While hydrometallurgy involves using water for the extraction of metals, pyrometallurgy is a heat-based extraction and purification process
- Battery recycling is also an evolving field with innovations within established processes such as hydrometallurgy, pyrometallurgy, direct recycling, and other sub-processes. There are also emerging processes such as the Worcester Polytechnic Institute (WPI) Process that shows promise to reducing environmental impact and increasing the efficiency of materials
- While battery recycling beneficial, it also consumes energy and creates by-products and waste which must be managed to minimize environmental impact

1 Shred and Screen

The Shred and Screen process for Batteries: Battery components are shredded and crushed for further recycling or processing

Crushing	Shredding	Screening	Separation
Use mechanical force to break the batteries into smaller pieces. This process opens up the battery cells and liberates the internal components such as electrodes, separators, and electrolyte.	Shred the materials into smaller, more uniform pieces to facilitate subsequent separation and processing.	Use vibrating screens or rotary screens to separate materials based on size.	Ferrous metals are attracted to the magnetic field and separated from the non-magnetic materials, such as aluminum and copper foils.

Shred and Screen: Recovered Materials and By-Products

- Recovered Materials/Outputs:
  - Black mass: A mixture of finely ground active materials from the electrodes, including valuable metals like lithium, cobalt, nickel, and manganese
  - Metallic foils:
    - Separated pieces of metallic foils used as current collectors in the battery, typically aluminum (from the cathode) and copper (from the anode)
    - Can be directly sent to smelting processes to recover pure aluminum and copper
- By-Products/Impact:
  - Metallic fragments
  - Plastic and insulation
  - Electrolyte residue
  - Particulars

Environmental Impacts of Shredding and Screening in Lithium-ion Battery Recycling

Impact	Description
Metallic fragments	• If not properly managed, these metals can contribute to soil and water contamination. However, they are typically recycled, reducing their environmental footprint.
Plastic and insulation materials	• Plastics can be challenging to recycle and may contribute to microplastic pollution if not properly processed. Incineration of plastics can release toxic gases.
Electrolyte residues	• Electrolyte residues can be flammable and toxic. If released into the environment, they can contaminate water sources and pose health risks to humans and wildlife.
Fine particulate/dust	• Inhalation of fine particulate matter can pose serious health risks to workers. Additionally, these particles can contaminate air and water sources if not properly contained.

2 Direct Recycling

Direct Recycling for Batteries: direct recycling involves recovering valuable materials from end-of-life batteries through processes that preserve their chemical structure, making them suitable for reuse in new batteries

Disassembly

The batteries are carefully disassembled to separate the various components, such as the cathode, anode, separator, and electrolyte.

Cathode/Anode Recovery

The active materials from the cathode and anode are extracted and preserved. This step might involve physical separation techniques or mild chemical treatments to remove impurities without degrading the material.

Reconditioning

The extracted materials, such as the cathode active material, are reconditioned or re-lithiated to restore their original electrochemical properties. This may include processes like annealing or chemical treatments to repair any structural damage.

Reassembly

The recovered and reconditioned materials are then used to manufacture new battery cells. This step aims to produce batteries with performance characteristics comparable to those made from virgin materials.

Environmental Impacts of Direct Recycling

By product	Impact
Electrolyte residue	• During the disassembly and separation process, the electrolyte (a liquid or gel-like substance within the battery) is often extracted and may not be fully reusable. • Contain toxic and flammable solvents such as ethylene carbonate and dimethyl carbonate. Improper disposal can lead to soil and water contamination, posing risks to human health and the environment.
Separator materials	• These are typically polymer films that separate the cathode and anode within the battery. • These materials are not biodegradable and can contribute to plastic waste if not properly managed. Incineration can release toxic fumes..
Impurities and contaminants	• Small amounts of impurities and degraded materials may be separated during the recycling process. • These impurities can be hazardous. Proper disposal or treatment is necessary to avoid environmental contamination.
Spent chemicals	• Chemicals used in the reconditioning and purification processes, such as acids or solvents, may become spent and need to be managed. • Improper handling or disposal of these chemicals can lead to pollution. They may require neutralization or special treatment to mitigate their environmental impact.

POWER ADVISORY

3 Pyrometallurgy

Pyrometallurgy for Batteries: A heat-based extraction and purification process to recover valuable metals, such as cobalt, nickel, and lithium,

Thermal Treatment → Smelting → Reduction → Separation and Recovery

Thermal Treatment

Black mass is subjected to high temperatures in an incinerator or calciner to burn off any remaining organic materials, such as binders and electrolytes.

Smelting

The treated black mass is fed into a furnace where it is smelted at high temperatures. This process melts the metals and allows them to separate based on their densities and affinities. Impurities and less valuable components form a slag layer on top, while valuable metals form a matte layer below.

Reduction

Metal oxides present in the matte are reduced to their respective metals using reducing agents like carbon or hydrogen.

Separation and Recovery

Techniques such as selective precipitation, electrolysis, or solvent extraction are used to separate individual metals from the mixture; pure metals lithium, cobalt, nickel, and manganese are recovered in usable forms.

Pyrometallurgy: Recovered Materials and By-Products

- Recovered Materials/Outputs:
  - Pure metals: Lithium, cobalt, nickel, manganese, copper.
  - Mixed alloys:
    - Sometimes, metals are recovered as alloys, which can be directly used in various applications.
    - Examples: Nickel-cobalt alloys, used in specialized industrial applications.
  - Slag
    - Non-metallic by-product formed from impurities in the ore and flux during smelting.
    - Contains silicates, aluminates, and other compounds and used in construction materials, road aggregate, and cement production.
- By-Products/Impact:
  - Metallic by-products
  - Particulates
  - Wastewater
  - Emissions

Environmental Impacts of Crushing and Shredding in Pyrometallurgy

Impact	Description
Metallic fragments	• If not properly managed, these metals can contribute to soil and water contamination. However, they are typically recycled, reducing their environmental footprint.
Plastic and insulation materials	• Plastics can be challenging to recycle and may contribute to microplastic pollution if not properly processed. Incineration of plastics can release toxic gases.
Electrolyte residues	• Electrolyte residues can be flammable and toxic. If released into the environment, they can contaminate water sources and pose health risks to humans and wildlife.
Fine particulate/dust	• Inhalation of fine particulate matter can pose serious health risks to workers. Additionally, these particles can contaminate air and water sources if not properly contained.
Energy consumption	• The process requires significant energy input, particularly during thermal treatments and electrowinning steps. • This can contribute to carbon emissions depending on the energy source.

4 Hydrometallurgy

Hydrometallurgy for Batteries: A chemical refinement process to recover the metals in ion form from the black mass

Leaching → Purification → Metal Recovery

Leaching

Treated with a suitable leaching agent (such as sulfuric acid, hydrochloric acid, or nitric acid) to dissolve the valuable metals (e.g., lithium, cobalt, nickel, manganese) into the solution. This step typically occurs in an aqueous environment.

Purification

Solid residues are separated from the liquid leachate. Impurities are removed from the leachate through various precipitation methods. Specific metals are selectively extracted from the solution using solvent extraction or ion exchange techniques.

Metal Recovery

Metals are recovered from the purified solution by precipitating them out as compounds (salts). Some metals, such as cobalt and nickel, can be recovered in their metallic form using electrowinning techniques.

Recovered Materials/Outputs:

- Pure metals: Lithium, Cobalt, Nickel, Manganese, Copper

By-products/Impact:

- Spent leaching solutions, Solid residues, gas emissions, wastewater

Environmental Impacts of Crushing and Shredding in Hydrometallurgy

Impact	Description
Spent leaching solutions	• The use of strong acids (e.g., sulfuric acid, hydrochloric acid) in the leaching process can pose risks if not handled properly. • Spills or leaks can lead to soil and water contamination.
Solid residues	• These are the undissolved materials left after the leaching process, often containing inert materials and impurities. • Improper disposal can lead to long-term environmental issues, such as leaching of heavy metals into the groundwater.
Gas emissions	• Emissions from thermal treatments and chemical reactions need to be controlled to prevent air pollution.
Wastewater	• The process generates wastewater that contains dissolved metals, acids, and other chemicals. • Treatment is required to remove contaminants before the water can be discharged, ensuring it meets environmental standards.

Pyrometallurgy and Hydrometallurgy in comparison

Aspect	Pyrometallurgy	Hydrometallurgy
Environmental impact	• Higher energy consumption and greenhouse gas emissions, significant air pollution, but simpler waste management.	• Lower energy consumption, lower air emissions, but potential chemical and wastewater management issues.
Efficiencies	• More effective for recovering cobalt and nickel but less efficient for lithium.	• More efficient for a wider range of elements, including lithium, cobalt, nickel, and manganese.
Economic and operational considerations	• Established and scalable, potentially lower initial investment in some cases.	• Can be more cost-effective in the long run due to higher recovery rates but requires investment in chemical management systems.

- Hydrometallurgical methods tend to be more environmentally friendly due to lower energy consumption and higher recovery rates, making them a better choice for comprehensive recovery of all valuable elements, including lithium. However, effective management of chemical wastes is crucial to minimize environmental impact.
- Pyrometallurgical methods, while robust and effective for certain high-value metals, are less efficient for lithium recovery and have a higher environmental footprint due to energy use and emissions.

5 Worcester Polytechnic Institute (WPI) Process for Recycling Lithium-Ion Batteries (1/2)

- The WPI recycling process is an example of an innovative method for recycling lithium-ion batteries developed by researchers at WPI.
- Focuses on selectively extracting valuable metals like lithium, cobalt, and nickel from end-of-life batteries using an environmentally friendly approach.
- The process employs hydrometallurgical techniques, utilizing aqueous solutions to leach metals from the battery components.

Comparison Between WPI process and Traditional Recycling Process

Difference	WPI Process	Traditional Process
Closed-loop system	Where materials from spent batteries are fully recycled and reused to produce new cathode materials for batteries.	Involve open-loop systems where recovered materials are not necessarily reused for the same purposes.
High-purity metal recovery	Achieves high-purity recovery of cathode materials such as nickel, cobalt, manganese, and lithium., which can meet the performance standards of original equipment manufacturers (OEMs)	Often results in lower purity materials due to mixed battery chemistries and less efficient separation techniques; can limit the usability in high-performance applications.

POWER ADVISORY

5 Worcester Polytechnic Institute (WPI) Process for Recycling Lithium-Ion Batteries (2/2)

Comparison Between WPI process and Traditional Recycling Process

Difference	WPI Process	Traditional Process
Economic viability	Significantly reduces the cost of recycled cathode materials by more than 30%, making it more economically viable for large-scale adoption	Often less economically efficient due to higher processing costs and lower recovery rates of valuable materials.
Flexibility/ Scalability	Process is highly adaptable to different battery chemistries and can scale up efficiently. It can handle a variety of lithium-ion battery types, regardless of their size, shape, or chemical composition.	Methods may not be as flexible or scalable, often requiring specific processes for different battery chemistries.
Environmental impact	Focusing on a closed-loop system and high recovery rates, the WPI process greatly reduces the environmental impact associated with battery disposal.	Often have a higher environmental footprint due to lower efficiency and the potential for more waste generation. They may also involve more energy-intensive processes.

LI-ION

Environmental Impacts of End-of-life Lithium-ion Batteries

- Leaching of toxic substances
  - Lithium-ion batteries contain metals like cobalt, nickel, and manganese. When landfilled, or under improper recycling conditions, these metals can leach into the soil and groundwater affecting drinking water sources and disrupting local ecosystems.
- Risk of fires
  - Lithium-ion batteries are prone to thermal runaway, a process where they overheat and potentially catch fire. Fires at landfill or storage sites, or during transport can release harmful pollutants into the air and cause long-lasting environmental damage.
  - For instance, between 2017 and 2020, a landfill in the Pacific Northwest experienced 124 fires linked to lithium-ion batteries.
- Inefficient resource use
  - Landfilling prevents the recovery and reuse of valuable materials contained in lithium-ion batteries. Effective recycling processes can reclaim these materials, reducing the need for new mining and processing, which are both environmentally damaging and resource-intensive

Lithium-ion Batteries: A Heightened Fire Risk

- Lithium-ion batteries have some unique challenges that need to be addressed to minimize its risk in landfills.
- Lithium-ion batteries can prone to fires. There are three main reasons for a battery to ignite:
  - Mechanical harm, such as crushing or penetration. Batteries can be crushed during transport or at a landfill
  - Electrical harm from an external or internal short circuit
  - Overheating. Batteries should not be exposed to high external temperatures, for example from being left in direct sunlight for long periods of time.
- Another factor that makes lithium-ion battery fires challenging to handle is oxygen generation. When the metal oxides in a battery's cathode, or positively charged electrode, are heated, they decompose and release oxygen gas. Fires need oxygen to burn, so a battery that can create oxygen and sustain a fire.
- Thermal runaway. In thermal runaway, a lithium-ion battery enters an uncontrollable, self-heating state that can lead to fire or explosion.
  - Because of the electrolyte's nature, a 20% increase in a lithium-ion battery's temperature causes some unwanted chemical reactions to occur much faster, which releases excessive heat. This excess heat increases the battery temperature, which in turn speeds up the reactions.
  - The increased battery temperature increases the reaction rate, creating a process called thermal runaway. When this happens, the temperature in a battery can rise from 212 F (100 C) to 1,800 F (1,000 C) in a second.

Appendix D: Glossary

Glossary

- **Advanced Fee Administration (AFA)**: A program that charges a fee at the point of sale to fund end-of-life management of products
- **Battery Energy Storage System (BESS):** Systems used to store energy for later use, typically involving rechargeable batteries
- **Cadmium Telluride (CdTe):** A semiconductor material used in thin-film solar cells, known for its efficiency and low-cost production
- **Circular Economy**: An economic system aimed at eliminating waste and the continual use of resources through reuse, recycling, and sustainable design
- **Crystalline Silicon (c-Si)**: A type of solar cell made from silicon crystals, commonly used in photovoltaic technology
- **Decommissioning**: The process of safely removing and disposing of solar panels and battery systems at the end of their operational life
- **Performance (Decommissioning) Bond:** A financial guarantee or assurance that ensures the completion of decommissioning and recycling activities for solar and battery projects at end of life

Glossary

- **Electric Distribution Companies (EDCs):** Companies responsible for distributing electricity to consumers and maintaining the electrical grid infrastructure
- **End-of-Life Management**: Strategies and processes for handling products once they are no longer in use, including recycling and disposal
- **E-Waste:** Discarded electrical or electronic devices, which can include solar panels and batteries
- **Environmental, Social, and Governance (ESG) Metrics**: Criteria used to evaluate a company's operations and impact on society and the environment
- **Extended Producer Responsibility (EPR)**: A policy approach where producers are given significant responsibility for the cotreatment or disposal of post-consumer products., such as lithium-ion batteries
- **Hazardous Materials**: Substances that pose significant risks to health, safety, or the environment
- **Inverter**: A device that converts direct current (DC) generated by solar panels into alternating current (AC) used by electrical grids and home appliances
- **Landfilling**: The process of disposing waste in a designated landfill area, often involving burying it

Glossary

- **Lifecycle Analysis (LCA)**: A systematic analysis of the environmental impacts of a product throughout its entire lifecycle, from production to disposal
- **Module**: Another term for a solar panel, consisting of multiple solar cells connected together
- **Photovoltaic (PV)**: The technology used to convert light into electricity using semiconducting materials
- **Polycrystalline Silicon (poly-Si)**: A material used in the production of some types of solar cells, composed of many small silicon crystals
- **Power Purchase Agreement (PPA)**: A contract between a power producer and a buyer, often used in the context of renewable energy projects
- **Producer Responsibility Organization (PRO):** A professional organization that takes over the responsibilities of an obligated party subject to Extended Producer Responsibility (EPR). The PRO manages the collection and recycling of products subject to EPR requirements on behalf of the obligated producers
- **Recycling**: The process of collecting, processing, and reusing materials that would otherwise be considered waste. It can involve converting these materials into new products, thereby reducing the need for raw materials, minimizing environmental impact, and conserving natural resources. Within the context of this report, recycling occurs the end-of-life of a battery or solar panel. Repurposed batteries and solar panels are not considered recycling

Glossary

- **Repowering:** The process of upgrading or replacing aging energy generation equipment, such as solar panels and inverters, to improve efficiency and extend the lifespan of a project
- **Resource Conservation and Recovery Act (RCRA):** U.S. federal law governing the disposal of solid and hazardous waste
- **Responsible Recyclers (R2) Standard:** A certification for electronic recyclers that ensures responsible recycling practices and data security
- **Thin-film Solar Cells**: A type of solar cell made by depositing one or more thin layers of photovoltaic material on a substrate
- **Transfer Based Exclusion (TBE)**: A regulatory provision under the RCRA that allows certain materials to be excluded from hazardous waste regulations if they are transferred to a third party for recycling
- **Waste Management**: The collection, transport, processing, recycling, or disposal of waste materials