A Circular Economy for Energy Materials

University of Michigan School for Environment and Sustainability Master's Project in conjunction with the National Renewable Energy Laboratory (NREL)

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Capstone Introduction

SEAS Master's Project

This project is a 12-month capstone requirement for all M.S. candidates at University of Michigan's School for Environment and Sustainability (SEAS). Projects are primarily sourced by University faculty and staff, overseen by a faculty advisor, and managed by the student team and sponsor advisor. The driving force behind the capstone concept is a platform for students to apply course skills and knowledge to solve real-world problems related to climate change and the environment. Research, managing team dynamics, and external communication are other core elements of student development throughout the project. Regarding project objectives and outcomes, sponsors work with students to refine a mutually agreed-upon scope of work over the first few weeks, followed by structured research and hypothesis testing.

Team Background and Expertise

The project team consists of 5 students with diverse backgrounds and shared interest in accelerating the energy transition in a just and sustainable manner. Names, SEAS Specialization/Track, and brief bios are provided below:

Alex Reid - Sustainable Systems
Former strategy consultant and dual-degree business student focused on new solution innovation and commercialization in renewable energy and climate mitigation technologies.
Emily Brady - Sustainable Development
Environmental engineer with an interest in global climate adaptation and mitigation as well as socially-engaged design.
McKinley Siegle - Sustainable Systems
Environmental psychologist with a background in institutional carbon accounting and behavior change.
Emma Stark - Environmental Policy and Planning; Sustainable Development
Academic background in landscape architecture with an interest in environmental remediation.
Ritvik Jain - Sustainable Systems
Mechanical Engineer with an interest in sustainable energy systems.

Project Background

The National Renewable Energy Laboratory (NREL) serves as the sponsor for the project. As NREL engages with various stakeholders in the clean energy landscape, they seek to better understand particular segments in greater detail. Alongside NREL's research, the team was engaged to dig into the circular economy landscape of solar photovoltaic and large-format battery technologies. Specifically, the UM team split into two teams to focus on the following headline questions:

1. What is the policy and regulatory landscape for solar PV recycling and end-of-life practices?
2. What is the state of the end-of-life electric vehicle battery market, including stakeholders, value-added activities, and focus areas?

Project A: A Circular Economy for Energy Materials: Large-Format Battery Secondary Market Study

Emily Brady, Alex Reid, and McKinley Siegle

Executive Summary

The National Renewable Energy Laboratory (NREL) is interested in better understanding the secondary market for large-format Lithium-ion batteries (LiBs), such as those used to power electric vehicles. In order to dive into this research NREL worked with five graduate students from the University of Michigan School for Environment and Sustainability (SEAS). The main question under investigation is:

> **What is the state of the end-of-life electric vehicle battery market, including stakeholders, value-added activities, and focus areas?**

The United States secondary market for EV batteries was an estimated 350-360 MWh in 2020 and is expected to reach 40 GWh by 2030[1], so it is important to plan for end-of-life operations. The secondary market refers to a potential shift from a linear economy to a circular one for LiBs. A circular economy "reduces material use, redesigns materials to be less resource intensive, and recaptures "waste" as a resource to manufacture new materials and products[2]." Some of the drivers of a circular economy for LiBs include: the potential for economic opportunity, increased supply-chain stability, and environmental justice as well as the introduction of policies mandating the sale of more EVs. Barriers include cost, technology efficiency, and lack of policy around the handling of large-format batteries.

After conducting a literature review and a gap analysis the team narrowed the scope to focus on the recycling, reuse, and recovery parts of circular economy concepts. The team also identified key stakeholders in the circular economy for LiBs, including repair/refurbishers, recyclers, resellers, and reverse logistics companies. Interview questions were drafted for each of these groups, and four interviews were conducted to better understand the secondary market for LiBs.

Key takeaways from these interviews include information on battery chemistry trends and drivers and barriers to circular economy. Market prices of metals like nickel and cobalt will impact chemistry along with environmental justice concerns in mining. Local production, manufacturing, and recycling of LiBs will likely become more prominent with partnerships forming between battery and EV manufacturers. IRA funding will also likely contribute to localization. However, the industry is still new, and there is a lack of awareness around end-of-life processes for EV batteries, and the infrastructure to support these processes is still being built.

The United States and other developed countries have a massive opportunity to embed circularity into the electric vehicle battery supply chain. Recycling and end-of-life processes for large-format LiBs is still a relatively new industry. As the industry grows it will require coordination from a number of stakeholders across the value chain. One question that is still unanswered is what does the process of getting a battery from a car to a recycler

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[1] McKinsey & Company. "Second-life EV batteries: The newest value pool in energy storage." McKinsey & Company, August 2015.

[2] Environmental Protection Agency. "What is a Circular Economy?" EPA, n.d., https://www.epa.gov/recyclingstrategy/what-circular-economy.

or other end user look like? The new lithium-iron phosphate battery is also a newer technology that may impact end-of-life processes. Further information could be gathered from additional interviews with industry experts. Additionally, understanding the battery recycling industry in other countries where EV sales have historically been much higher could provide insight into where the U.S. is headed in the near future.

Background Research

Circular Economy Concepts

The principles of a circular economy stand in contrast to a conventional linear economy, where materials shift from producers to consumers and eventually to waste. In a circular economy, system designers seek to avoid the waste phase of the process by diverting materials back to producers or consumers. According to the United States Environmental Protection Agency (EPA), "a circular economy reduces material use, redesigns materials to be less resource intensive, and recaptures "waste" as a resource to manufacture new materials and products."[3] There are a wide variety of means to reduce material use, including but not limited to reduce, reuse, and recycle. In most cases, the notion of reduction involves design and innovation upstream, where more material-efficient products are built to use less input materials. Reuse involves extending the useful life of a good or material by several means, further defined below.

Reuse is when a product is used again in the same application as it was in its initial application.[4] This is distinct from repurposing, which is the reuse of a product in a secondary form within a novel application. This would include battery energy storage (BES) examples such as with B2U Storage Solutions, who utilize retired EV batteries to store solar energy.[5] Refurbishing is the restoration of a product back to its standard operational value or to improve it past its initial operational potential. Ascend Elements is working in this domain by recapturing battery materials and making them operate 50% longer than newly mined materials, along with an 88% increased power capacity.[6] Repairing a product, similar to refurbishment, is to improve the functioning of a deficient, broken, or in some way underperforming product.

Remanufacturing is when components of a product or a system are reused within the product ecosystem, such as with Ascend Elements. They're working to reduce the amount of mining necessary for cathode manufacturing by shredding used batteries and removing impurities, leaving the materials necessary to create new cathodes. Another example involves the use of lithium-ion manufacturing plants that can be rapidly and seamlessly converted into sodium-ion producing plants to meet demand for both chemistries. Relating to remanufacturing, Recycling is the breaking down of completed products into individual, reusable components, which is similar to recovery, which is the reclamation of materials found within products. Both of these processes can then be utilized in remanufacture. Recovery can be well observed within Li-cycle along with many

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[3] Environmental Protection Agency. "What is a Circular Economy?" EPA, n.d., https://www.epa.gov/recyclingstrategy/what-circular-economy.

[4] Curtis, Taylor. Unreleased (2022)

[5] https://www.b2uco.com

[6] https://ascendelements.com/products/

other companies through the process of shredding batteries, sifting out materials to be recycled, then using hydrometallurgy to isolate metals in the leftover material to allow for recovery [7].

Drivers of CE

One of the strongest drivers are the associated economic opportunities that present themselves upon the development and maturity of a CE market .[8][9] In the U.S., President Biden announced a goal of having half of all new car sales be electric by 2030 while California has an executive order with the target of phasing out the sale of all internal combustion engine vehicles (ICEVS) by 2035[10]. As more regulations around the sale of ICEVs are implemented, there will be a push to move towards a circular economy to save money and resources. Increased infrastructure for LFB recycling and reuse will naturally drive down the overall costs of LFB use. A decrease in overall costs could be instigated through a diminished need for mining virgin materials, the shipping of said materials, and associated production and manufacturing of LFB components.[11] Through these factors, the furthering of any element of a LFB CE could lead to an economically advantageous feedback loop within the system, spurring on quicker progress and further industry growth. The intensifying robustness of the LFB industry could also drive increased job growth, with a circular economy creating jobs and new market opportunities in each part of the value chain.[12]

US Perspective

Another significant driver is the eventual promise of increased supply-chain stability.[13] Currently, the industry has very little translatability between LFBs, which makes it significantly more difficult to obtain a functional CE. Existing today are a plethora of types of LFBs that are different physical sizes, contain differing chemistries, and have various material qualities. This significantly reduces the ability to streamline a recovery/recycling process for LFBs. In turn, development of a more universal industry structure or recovery process could dramatically

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[7] https://li-cycle.com/technology/

[8] Wrålsen, Benedikte, Vanessa Prieto-Sandoval, Andres Mejia-Villa, Reyn O'Born, Magnus Hellström, and Bernhard Faessler. "Circular business models for lithium-ion batteries-Stakeholders, barriers, and drivers." *Journal of Cleaner Production* 317 (2021): 128393.

[9] Curtis, Taylor L., Ligia Smith, Heather Buchanan, and Garvin Heath. 2021. A Circular Economy for Lithium-Ion Batteries Used in Mobile and Stationary Energy Storage: Drivers, Barriers, Enablers, and U.S. Policy Considerations. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77035. https://www.nrel.gov/docs/fy21osti/77035.

[10] https://www.canarymedia.com/articles/electric-vehicles/how-to-prepare-for-the-coming-flood-of-used-ev-batteries

[11] Heath, Garvin A., Dwarakanath Ravikumar, Brianna Hansen, and Elaine Kupets. "A critical review of the circular economy for lithium-ion batteries and photovoltaic modules–status, challenges, and opportunities." *Journal of the Air & Waste Management Association* 72, no. 6 (2022): 478-539.

[12] Curtis, Taylor L., Ligia Smith, Heather Buchanan, and Garvin Heath. 2021. A Circular Economy for Lithium-Ion Batteries Used in Mobile and Stationary Energy Storage: Drivers, Barriers, Enablers, and U.S. Policy Considerations. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77035. https://www.nrel.gov/docs/fy21osti/77035.

[13] Sopha, Bertha Maya, Dwi Megah Purnamasari, and Sholeh Ma'mun. "Barriers and Enablers of Circular Economy Implementation for Electric-Vehicle Batteries: From Systematic Literature Review to Conceptual Framework." *Sustainability*14, no. 10 (2022): 6359.

decrease the barrier to entry for economic viability, leading to further CE progress. With competent processes in place regarding recovery and reuse, there can be more accurate analysis of supply, demand, and material flow, given that significantly more materials within the system can be accounted for. This leads the supply chain to become more predictable, leading to less uncertainty and greater security within operations.

Climate change induced natural disaster plans for cities or communities might also drive an increase in LFB use, given their ability to be a reliable non-grid energy source.[14] Grid-altering events such as natural disasters have the potential to knock out or decrease energy potential for a residence, community, city, or region. In this way LFBs can temporarily or permanently restore an energy deficit, reducing energy uncertainty and increasing energy security.

Global Perspective

Globally, the world has similar drivers of LFB adoption and use. Cost-effective business conditions are still crucially important, going along with another major driver, which is policy and regulation. For instance, the UK government has committed to phasing out the sale of all ICEVs by 2035[15]. Along with policy that mandates EV use in general, policy that incentivizes the responsible recycling/repurposing of LFBs is a critical component to driving LFB market expansion and CE. A US example includes the high level of lead acid battery recycling currently present in today's battery ecosystem.[16] Examples for LFBs could include tax credits for recycling, or general subsidies. Similar to standardizing factors such as the chemistry, size, and quality, standardizing regulation requirements across borders as synonymously as possible would be a large driver in propelling CE principles forward. Simple things like standardizing recycling practices and locations so that citizens feel well-informed could have large recycling rate impacts.

Along with the national and international supply chain security, comprehensive nationally-internal CEs can make nations themselves more independent through a lack of reliance on foreign powers for materials. Cobalt, lithium, and nickel are some of the materials that are often used in the creation of EV batteries. Mining these metals can cause environmental harm and creates dependence on foreign sources for battery production.[17] Alternatively, international agreements could include providing secondary usage application batteries to nations lacking robust EV markets or significant battery energy storage (BES), as such agreements could address energy stability challenges.[18] There may also be some positive environmental-justice implications from reducing mining

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[14] Chen, A. A., A. J. Stephens, R. Koon Koon, M. Ashtine, and K. Mohammed-Koon Koon. "Pathways to climate change mitigation and stable energy by 100% renewable for a small island: Jamaica as an example." *Renewable and Sustainable Energy Reviews* 121 (2020): 109671.

[15] Ahuja, J., Dawson, L. and Lee, R. (2020), "A circular economy for electric vehicle batteries: driving the change", Journal of Property, Planning and Environmental Law, Vol. 12 No. 3, pp. 235-250. https://doi.org/10.1108/JPPEL-02-2020-0011

[16] Heath, Garvin A., Dwarakanath Ravikumar, Brianna Hansen, and Elaine Kupets. "A critical review of the circular economy for lithium-ion batteries and photovoltaic modules–status, challenges, and opportunities." *Journal of the Air & Waste Management Association* 72, no. 6 (2022): 478-539.

[17] Ahuja, J., Dawson, L. and Lee, R. (2020), "A circular economy for electric vehicle batteries: driving the change", Journal of Property, Planning and Environmental Law, Vol. 12 No. 3, pp. 235-250.

[18] Rallo, H., L. Canals Casals, David De La Torre, Robert Reinhardt, Carlos Marchante, and B. Amante. "Lithium-ion battery 2nd life used as a stationary energy storage system: Ageing and economic analysis in two real cases." *Journal of cleaner production* 272 (2020): 122584.

operations with a circular economy as they often negatively impact indigenous communities.[19] Regardless, dynamic CEs can aid in a number of governmental strategies, which could help drive their development.

Barriers to CE

There also exist many barriers to the development of a CE, and as noted, nearly all notable CE drivers also function as barriers when unaddressed. Cost-effectiveness in relation to all parts of a CE is currently one of the largest barriers, where the industrial system processes that batteries go through are not configured in a circular manner. This can be seen through the lack of efficiency present in the processes of hydrometallurgy and pyrometallurgy, which have suboptimal material recovery rates, or through the significant lack of cost-effectiveness when shipping hazardous materials, which most battery chemistries fall under.[20]
There is also a deficit of clear constructive legislation on the LFB space surrounding policy and regulatory measures. This current absence of a foundational policy structure can lead to a lack of investor interest, along with low recovery/repurposing/recycling rates within companies or countries. Effective policy can lead to standardized safety and physical battery requirements and can spur on investment and innovation within the space ranging from the small-scale technological to the large-scale infrastructural level.

Market Size & Forecast

Definitions

- Power capacity (W, kW, MW, GW): the instantaneous power capacity, on a scale of units of energy per unit of time, that can be discharged from a power source, including battery storage devices
- Energy capacity (Wh, kWh, MWh, GWh): the total amount of energy that can be stored in a battery storage device
- Battery electric vehicle: vehicle that is powered only by a battery while in operation; excludes plug-in hybrid electric vehicles that utilize a gas-powered engine and a battery during operation
- Passenger vehicle: cars and light-duty trucks (e.g., pickups) that are used by individual consumers/drivers; excludes commercial vehicles and medium- and heavy-duty trucks]
- NMC battery: a battery storage device that is comprised of a lithium ion electrolyte, typically graphite anode, and nickel-manganese-cobalt cathode; the numbers that follow NMC (e.g., NMC-111) denote the relative mix of metals in the cathode
- LFP batteries: a battery storage device that is comprised of a lithium ion electrolyte, typically graphite anode, and lithium-iron (ferrous)-phosphate cathode

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[19] Canary Media. "How to Prepare for the Coming Flood of Used EV Batteries." Canary Media, n.d.,

[20] Curtis, Taylor L., Ligia Smith, Heather Buchanan, and Garvin Heath. 2021. A Circular Economy for Lithium-Ion Batteries Used in Mobile and Stationary Energy Storage: Drivers, Barriers, Enablers, and U.S. Policy Considerations. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77035. https://www.nrel.gov/docs/fy21osti/77035

Electric Vehicles

The global secondary market of end-of-life electric vehicle batteries (EVBs) from passenger vehicles was estimated to be ~1 GWh of energy capacity in 2020. This figure is expected to grow to 112-227 GWh by 2030 at a compound annual growth rate (CAGR) of 60-70% per year.[21] The United States secondary market was an estimated 350-360 MWh in 2020 and is expected to reach 40 GWh by 2030. In addition to EVBs, this study also considered the secondary supply of stationary battery energy storage systems.

Among the global EV battery capacity, the predominant cathode chemistries of the 2010s were nickel-manganese-cobalt based, or, NMC batteries. The year 2021 marked an inflection point in chemistries, where lithium-iron-phosphate, or LFP, batteries represented almost 40% of new passenger vehicles.[22] This trend marks an interesting signal to recyclers on the supply base of battery materials reaching EOL in the coming decades. NMC batteries tend to have greater material value across the primary cathode inputs, whereas only lithium represents an associated recycled value in LFP batteries.[23]

Stationary Energy Storage

Utility-scale stationary battery power capacity has expanded rapidly in the US in recent years, reaching 4.6 GW in 2021, which represents more than triple the installed power capacity in 2020 (1.4 GW). The vast majority of installed capacity is lithium-ion batteries, which is the focus of this study.[24] Utility-scale storage typically has a storage capacity on the MWh scale, from a few MWh to a few hundred MWh (and higher).[25]

Additional research, especially primary research, is required to gain a deeper understanding of the segmentation of the secondary market by application. Reuse represents a large portion of the secondary market activity to date, while recycling operations have begun over the last few years to address the future demand from EV market growth.

Interview Methodology

Stakeholder Overview

This study will focus mainly on stakeholders that are actively involved in the secondary market value chain, including potential off-takers of reusable or recyclable materials and/or products, however, stakeholders were identified in all parts of the value chain for this initial research to get a better understanding of everyone involved.

Research Institutes

NREL, ReCell, University of Michigan, Robert Mondavi Institute at UC Davis, ReCell Center

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[21] McKinsey & Company. "Second-life EV batteries: The newest value pool in energy storage." McKinsey & Company, August 2015.

[22] BNEF 2022

[23] Ajay Kochhar, "A Future with Sustainable, Profitable Lithium-Ion Battery Recycling is Closer Than You Think," DatacenterDynamics, January 20, 2022.

[24] EIA

[25] International Renewable Energy Agency (IRENA), "Electricity Storage and Renewables: Costs and Markets to 2030," September 2019.

Trade Organizations

Institute of Scrap Recycling Industries, State of California Automotive Dismantlers Assoc.

Standards Organizations

Responsible Battery Coalition (UofM), Department of Transportation, Environmental Protection Agency

Vehicle Manufacturers

Nissan, Tesla, Renault, Porsche, Audi, Volvo, Ford, etc.

Battery Manufacturers[26]

Crown Battery Mfr., Lithion Battery/Valence Technology Inc., Contemporary Amperex Technology Co. Limited, LG Energy Solution, Panasonic, Samsung SDI, American Battery Solutions

Energy Storage Companies[27]

B2U, NextEra Energy, General Electric, Samsung Excel, etc.

Secondary Market Stakeholders

The relevant stakeholders are ordered sequentially below, beginning with the moment a battery reaches EOL. More detailed information on these companies can be found in Appendix A.

Reverse Logistics - third-party logistics (3PL) providers transport batteries and materials from owner/operator to one of several steps in the secondary value chain. The process involves scheduling and pickup from disparate or centralized sources

- Representative companies: Battery Solutions, Aesir Logistics, Battery Recyclers of America

Resellers - responsible for aftermarket sales of LFBs, usually in an open marketplace platform that connects buyers to sellers

- Representative companies: Battago, Ebay, Green Tec Auto

Repair/Refurbishers - add value to the EOL battery by repairing damaged/worn parts and restoring the battery to a working condition (in the case of reuse, this is likely ~80% of original capacity)[28]

- Representative companies: Spiers New Technologies, Cox Automotive Mobility,

Recyclers -

- Representative companies: American Battery Technology, Ascend Elements, KBI, Li-cycle, Nth Cycle, ReCell Center, Redwood Materials

Battery Customers - organizations with a potential use case for an EOL battery, before or after repair/refurbishment

- Representative companies: Utilities, Research Institutes, Nissan & other manufacturers

Material Customers - off takers of raw material inputs that are recycled from EOL batteries (cobalt, nickel, lithium, aluminum, steel, etc.)

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[26] Top 10 Lithium-Ion Battery Manufacturers. (2022, April 25). [web log]. Retrieved August 19, 2022, from https://www.imarcgroup.com/top-lithium-ion-battery-manufacturers

[27] Top 50 Energy Storage Companies in 2021. (2021, January 12). [web log]. Retrieved August 19, 2022, from https://www.ysgsolar.com/blog/top-50-energy-storage-companies-2021-ysg-solar

[28] McKinsey

- Representative companies: Battery manufacturers, Car manufacturers

Interview Questions

After conducting the background research a gap analysis was performed to identify focus areas for interviews with industry stakeholders (See appendix B). The main topics of the gap analysis include further defining project scope, circular economy concept clarifications, drivers and barriers of circular economy, chemistry standardization, and market forecast. From the gap analysis, sets of interview questions were formed for three different stakeholder groups that would be interviewed: Recyclers, Reverse Logistics providers, and Reuse/Repurposing companies. These questions were drafted and iterated on with NREL multiple times to try and get the most out of our interviews in the limited time we had (See appendix C). The three stakeholder groups interviewed were chosen because most of the companies identified in the stakeholder analysis process fit into one of these categories, and they are a good representation of the secondary market for large-format LiBs. The questions focused on professional background, an overview of the companies' services/technology and processes, questions about the economics of their processes, policy and regulation, and finally the future of circular economy for large-format LiBs.

Process of Selecting Interviewees

The main goals with selecting interviewees were to get the greatest chance of response and to have a good representation of the LiB secondary market. The team started by reaching out to internal NREL experts and then to contacts adjacent to NREL such as folks who had been on panels with NREL employees.
The team completed four interviews with:

- Mike O'Kronley, CEO of Ascend Elements
- Jeffrey Battaluco, Sr. Account Manager at Cirba Solutions
- Ahmad Pesaran, Chief Energy Storage Engineer at NREL
- Nate Blair, Group Manager - Distributed Systems and Storage Analysis at NREL

Interview Takeaways

Chemistry Information

LFB chemistry has changed as technology and industry evolve, and as both of those things continue to change given the rapid growth of the battery industry, it's safe to assume that chemistry prominence will also continue to shift. Moving forward, the lithium-ion family of battery chemistries, which currently dominate the chemistry market, will continue to remain prominent in the LFB space.[29][30] Currently, enough lithium exists in an extractable/recyclable state to meet our needs for EVs and LFB storage, but the main uncertainty surrounds who will control the lithium supply chain, as this could significantly affect battery costs and market growth potential.[31]

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[29] Alternative Fuels Data Center, "Electric Vehicle Batteries", https://afdc.energy.gov/vehicles/electric_batteries.html.

[30] Blair, Nate. Interview by McKinley Siegle. January 19, 2023.

[31] Ibid.

Despite the lithium-ion family's future market prevalence, the specific chemistry combination associated with future production will most likely shift given a variety of factors. Market prices of specific metals, such as nickel, can change year to year and therefore impact a company's bottom line profits, which could spur on the production of other chemistries. Cobalt will most likely be one of the first metals to be phased out of EV manufacturing, given the associated mining implications, such as logistics and human rights issues, and its overall expensive nature. Despite this, it will most likely continue to be used in high-energy-density applications.[32] This shift away from cobalt is already being actuated, with Ford partnering with CATL in February to build a $3.5 billion LFP plant in Michigan, along with most currently produced Tesla batteries currently consisting of LFP batteries as well.[33][34]

Market Drivers/Policy/Self-Sufficiency

Some of the current barriers to LFB market growth, such as ethical issues surrounding mining and human rights abuses, can be assuaged through the development of a robust LFB recycling infrastructure, negating the need for substantial foreign import. This local nature of battery circular economy is not only founded in its ethical benefits, but also consists of economical and logistical advantages. Due to safety concerns of shipping potentially hazardous batteries, along with the considerable weight of shipping, it becomes significantly more important to localize battery production to the general region where they are being utilized.[35] Constructing a secure domestic supply chain of recycled materials could also greatly improve the ability for systems of local infrastructure to form and iterate through improved economic viability.

Local production, manufacturing, and recycling of LFBs is also seeing greater development locally through battery and EV manufacturing partnerships to achieve greater overall efficiency. Although this has been happening in various industries for some time, these partnerships between battery and EV manufacturers are relatively new and have the effect of expediting localized industry, with the idea of gradually implementing recycling processes to further improve production efficiency through circularity.

Market localization of LFBs is being recognized as an important market driver by more than just industry, as federal policy support is also being instituted. The Inflation Reduction Act (IRA) is contributing to localization by mandating the use of at least 40% of a battery materials composition being locally sourced in order to qualify for the federal tax credit, increasing up to 80% by 2027.[36] Because of the rapidly evolving landscape of LFBs and recycling, there is still funding provided by the IRA that has yet to be deployed, allowing for the evolution of the

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[32] Pesaran, Ahmad. Interview by McKinley Siegle. February 7, 2023.

[33] Ford Motor Company, "Ford Taps Michigan for New LFP Battery Plant, New Battery Chemistry as it Expands Electrification Plans," press release, February 13, 2023, https://media.ford.com/content/fordmedia/fna/us/en/news/2023/02/13/ford-taps-michigan-for-new-lfp-battery-plant--new-battery-chemis.html.

[34] EV Database, "Tesla Model 3 Standard Range Plus LFP," https://ev-database.org/car/1320/Tesla-Model-3-Standard-Range-Plus-LFP.

[35] Blair, Nate. Interview by McKinley Siegle. January 19, 2023.

[36] Congressional Research Service; Inflation Reduction Act of 2022, H.R. 5376, 117th Cong. (2021-2022)

market to dictate most appropriate use of funds. Additionally, creating and maintaining an internal market for LFBs has bipartisan support, which could lead to further policy that bolsters these initial efforts.[37]

One of the main market drivers of the LFB space that is driving the market forward in parallel with policy efforts is the inherent economic value of LFBs given the rarity of the metals used within current chemistry compositions prevalent in the market today. Rare, expensive metals like cobalt and manganese, although currently being shifted away from, will still continue to remain large players in the market in the coming years, and therefore will drive a competitive recycling/production market.[38] This inherent product value therefore transcends the necessity of policy, though is still assumedly tangentially benefitted. A prevalent example of this is that both California and much of Europe have taken up regulations aimed at incentivizing both customer return of LFBs and company recovery at battery EOL. According to Mike O'Kronley, CEO of Ascend Elements however, batteries currently in circulation would be sought after during EOL anyway, irrespective of existing regulatory measures.

Barriers

Tracking of Batteries:

One barrier limiting a more complex, robust battery ecosystem is the current lack of an identifiable tracking mechanism for determining battery metrics like the overall health of the battery, current capacity, and chemical composition.[39] A reliable and quantifiable method of tracking currently circulating batteries would help the industry reduce confusion surrounding appropriate practices in regard to battery handling and use, and as a result, allow suppliers, transportation companies, and consumers more product safety and security.

Battery Information Dissemination:

Another barrier to accelerating emerging battery infrastructure lies in how novel the industry is, and as a result, how meager the current rates of information dissemination are surrounding battery hazard and recycling practices. Based on surveys from Ascend Elements, 47% of the public is not even aware that LFBs are recyclable.[40] This exposes a multifaceted issue: Sustainability-conscious buyers aren't aware that one of the most influential parts of the product they're purchasing has the potential to be highly circular, along with current customers possibly being uninformed, which muddles the ability for an adequate consumer response to EOL protocols. This inadequate response then facilitates hesitancy within investment groups, further compounding industry advancement.

While information should be distributed about battery EOL procedures to consumers and manufacturers, there are also other relevant parties that require more knowledge about appropriate battery practices. Fire services are

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[37] U.S. Department of Energy, "Bipartisan Infrastructure Law: Battery Recycling and Second-Life Applications,", https://www.energy.gov/eere/vehicles/articles/bipartisan-infrastructure-law-battery-recycling-and-second-life-applications.

[38] McKinsey & Company, "Battery 2030: Resilient, sustainable, and circular,", https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular

[39] Pesaran, Ahmad. Interview by McKinley Siegle. February 7, 2023.

[40] Ascend Elements, "Consumer Research 2022: Executive Summary," December 2022, https://ascendelements.com/wp-content/uploads/2022/12/Consumer-Research-2022-Exec-Summary_Dec-2022.pdf.

one such party, as they have to respond to a lithium-ion battery fire differently than with combustion engine fires. Another example are salvage yards, which have to process and handle batteries with different precautions in comparison to traditional vehicles. If unaware of how to adequately handle these situations, both parties mentioned here can suffer devastating consequences because of a lack of sufficient information dispersal.[41]

Investment:

A surplus of demand, ample amounts of investment, but a current lack of infrastructure is another barrier to industry advancement. As of 2023, there exists almost a combined trillion dollars being put into developing battery plants and associated recycling facilities in the US in the hopes of keeping up with projected EV demand.[42] The IRA aided in establishing small amounts of foundational infrastructure for battery companies, but further funding aimed specifically at initiatives like charging infrastructure and battery material transport could affect meaningful change.

Part of this lack of infrastructure pertained to uncertainty over the industry's future, as car manufacturers were assessing the staying power of battery demand. Within the past year however, uncertainty and manufacturers' hesitancy has been dissipating due to falling battery pack costs, known issues with EVs like range and cold weather exposure being systematically improved, and EVs becoming more accessible to lower-income consumers, therefore expanding the market share.[43]

Other General Potential Barriers:

Investment hesitancy has also surrounded several other industry unknowns. One such question lies in the viability of constructing massive battery production facilities when the speed at which the industry is improving and technological development is occurring is so rapid (Nate). This results in the necessity of retrofit design principles when planning battery factories, as changes in chemistry composition or other unknown factors could significantly change battery production methods. Other barriers include the unknowns pertaining to resource availability and viability: whether enough resources exist, and if they're economically efficient to extract, or if they can be recycled at a sufficient rate. Further questions include long-term production concerns over whether the US has a large enough workforce to continue scaling production according to demand, or whether importing LFBs or exporting manufacturing workload will become necessary.[44]

Different Uses of Batteries/Competition for Resources:

Competition between differing applications of LFBs is also currently a barrier, simply because there is an excess of demand without the necessary accompanying production. Specifically, recycling and second-use applications are in competition, although funding from the DOE has shown that priority presently lies with establishing recycling.[45] Apart from recycling, secondary use also has grid use applications and transportation battery use that

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[41] Pesaran, interview. Pesaran, Ahmad. Interview by McKinley Siegle. February 7, 2023.

[42] O'Kronley, Mike. Interview by Alex Reid, Emily Brady, and McKinley Siegle. January 18, 2023.

[43] Blair, Nate. Interview by McKinley Siegle. January 19, 2023.

[44] Ibid.

[45] Pesaran, interview.

are in conflict. In this case though, a sufficient variation in chemistries should allow for a dispersion of resource use across applications due to intrinsic chemistry advantages or disadvantages, negating strong competition.[46] Second-use applications have a variety of barriers apparent within their current industry use as well. Economical questions exist regarding the cost of shipping, along with the cost of testing LFBs on their current capacity and capacity potential with respect to chemistry, and how to accomplish these tasks in a verifiable yet fluid manner.[47] Inconsistencies have also arisen in regards to how batteries should be broken down, as to whether they should be reused at pack-level, or broken down into constituent parts such as at module or cell-level (Ahmad).[48] More research needs to be conducted regarding how to standardize the battery second-use industry, as current operations reveal numerous incompatibilities in usage and application.

Conclusions and Future Research Recommendations

Transportation Electrification Creates Opportunity for a Circular Economy

The United States and other developed countries have a massive opportunity to embed circularity into the electric vehicle battery supply chain. The growth in demand for raw and processed materials continues to accelerate with new automaker commitments and government targets for fleet electrification. Recently, the Biden administration proposed ambitious EPA regulations that would require two of every three new passenger vehicles sold to be electric by 2032. Domestic and free-trade partner content requirements will bring primary and secondary market supply chains to the U.S., offering direct opportunities to establish recycling and end-of-life parameters to enable a sustainable transition.

Recycling is Still a Nascent Industry

Though there has been rapid improvement and cost reductions in vehicle LiBs over the last 5-10 years, the battery recycling industry is still taking shape. Traditional recycling processes have been effective for management of electronics and small format battery recycling, but new technologies are emerging that promise to reduce costs and emissions, while scaling to meet the demand for EOL vehicles. The secondary value chain in the U.S. is coalescing around a few key, large-scale recycling facilities, but there are many pain points to address related to transportation, traceability, automation, disassembly, responsibility, etc. There are a great many stakeholders involved in setting guidelines and best practices, and lots of learning yet to come for how all of these groups work together toward advancing the circular economy of LiBs.

Governments Have a Role to Play in Safety and Tracking

While markets will drive the underlying circularity of high-value materials, the government has a role to ensure the processes are safe and sustainable. Some of the domestic content requirements attached to the subsidies will help, but enforcement will be increasingly important (and difficult) as the market scales up. Tracking and tracing protocols should be established with public and private entities to allow for effective regulatory schemes. Also, safety requirements related to battery disassembly will be crucial to prevent accidents by unqualified suppliers

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[46] Ibid.

[47] Ibid.

[48] Ibid.

seeking to participate in a profitable market. This is a key future research area, as more and more players enter the value chain and more used batteries flow through facilities to reach a new use.

Evolution of Battery Chemistry Will Have Unforeseen Consequences

Among the many attributes of LiBs, declining cost is the most attractive to automakers. As new research enables commercialization of different chemistries and technologies, new processes for recycling and secondary uses will also be required. Supply chains will need to make adjustments, and understanding the impact of such adjustments will support future sustained growth of efficient secondary markets. If other technologies manage to climb down the cost curve and scale the way LiBs have, demand will pull on different raw materials, which may have consequences for other industries. Looking to the history of biofuel subsidies and crop prices will help to inform the sorts of cycles that can play out when emerging market reach high-growth inflection points.

Project B: Analysis of Solar Decommissioning Cost Estimates

Ritvik Jain and Emma Stark

Introduction

Project Scope

To ensure sustainable deployment of green energy, understanding the end-of-life decommissioning phase is crucial. The energy industry has learned from its past mistakes where decommissioning was an afterthought, and projects were abandoned before meaningful clean-up was completed, resulting in environmental damage and community mistrust. Decommissioning financial insurance requirements is one measure to prevent similar situations with new energy developments. The insurance is payment due before the project development or at some point in operation that covers a portion of or the entirety of project decommissioning [1].

Estimated decommissioning costs inform financial insurance required by some states and localities to begin solar development. As of 2021, California, Illinois, Louisiana, Minnesota, Montana, New Hampshire, North Dakota, Vermont, Virginia, and Washington has state-wide requirements for decommissioning financial insurance [49]. Despite the good-natured intentions, inaccurate estimates can hurt solar development as too high of estimates can make it challenging for developers to secure the necessary financial resources, and too low of estimates can result in surprise costs for developers, which they may not be able to pay.

For additional information on requirements for decommissioning plans by state and locality, consult a survey conducted by NREL in 2021 [1].

Data Collection Method

Past Team

This analysis began with a team from the University of Michigan who led data collection on solar decommissioning as part of their master's project. The team consisted of Matthew Boelens, Christian Koch, Christina Pastoria, and Nolan Woodle. This group collected data from 24 decommissioning plans from Massachusets, Maryland, New York, California, Rhode Island, Connecticut, Hawaii, Rhode Island, and Virginia. Data collected can be found in Appendix D and has the Team listed as "Past".

Current Team

The current team continued the task of data collection from decommissioning plans. Data was collected from 16 decommissioning plans from Minnesota, Maryland, Massachusetts, North Dakota, New York, and South Dakota. To find the plans, the team searched through the dockets of each state's Public Utilities Commissions (or the equivalent). It was found by the past team that there was a limited number of decommissioning plans published for existing projects; hence why the current team chose to collect data on solar facilities that are currently being developed. An effort was made to focus on western states with public land managed by the Bureau of Land Management. These include Alaska, Arizona, California, Colorado, Idaho, Montana, Nevada,

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[49] Curtis, T., Heath, G., Walker, A., Desai, J., Settle, E., & Barbosa, C. (2021). Best Practices at the End of the Photovoltaic System Performance Period. https://www.nrel.gov/docs/fy21osti/78678.pdf.

New Mexico, Oregon, Utah, Washington, and Wyoming [50]. However, no public data was available from these states, and thus the scope of data collection was broadened to include the entire United States. Because this was a continuation of a previous master's project, the decision of what information to collect and compile was heavily influenced by the former team's data collection decisions. However, as the project progressed, information such as who prepared the decommissioning plan, the project developer, decommissioning plan submission date, the type of land the project is located on, and the governing body that approved the decommissioning plan was decided as valuable to include. Thus only the plans analyzed by the current team extracted data on these points. The data underwent a verification process through which the team member who did not initially analyze the plan reviewed the plan and ensured the data was entered into the database correctly.

The final result of the data collection process was decommissioning information on 40 solar facilities across 11 states.

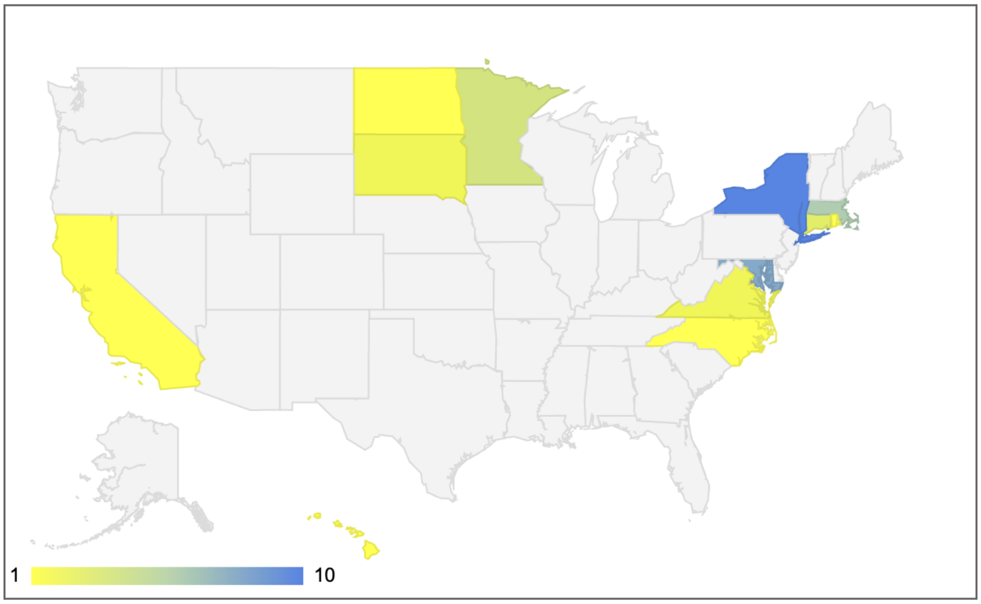

Figure 1: Location of Analyzed Plans by the Past and Current Team

Analysis

Quantitative Analysis

The final dataset was a compilation of 40 decommissioning plans. Based on the limited availability of plans and the timeline of the master's project, the data collection phase had to conclude with this amount. Within the plans, the amount of detail and factors included varied greatly. Some include in-depth, carefully calculated estimates for solar systems subcategories like inverters, fencing, wires, etc. Many plans, however, do not have this level of detail and provide general cost estimates for broad categories without explaining how the value was calculated. This variance made conducting an "apples to apples" comparison among the plans difficult. Figure 2 illustrates this issue.

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[50] *US Bureau of Land Management*. (n.d.). Tethys. Retrieved April 5, 2023, from https://tethys.pnnl.gov/organization/us-bureau-land-management-blm

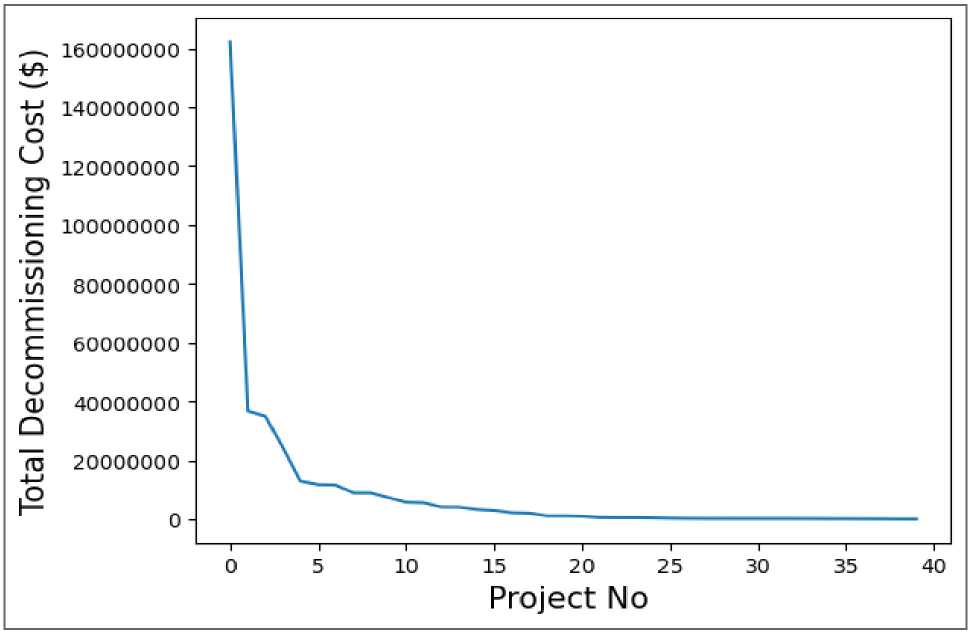

Figure 2: Total Decommissioning Costs of Plans in USD

If one were to look at the total decommissioning cost estimate solely, there is hardly anything of discernable value. However, this comparison shed light on the fact that the Mahi Solar facility in Hawaii was an obvious outlier- the total decommissioning cost of this project is almost the sum of all the other projects combined. Including this in the dataset would skew the analysis, hence why this project is removed from further cost analyses. With this, the final dataset consists of 39 projects - all in the contiguous United States with more than 11 variables (see Appendix D) that impact these costs.

To combat the broad variation in decommissioning plans , the costs were normalized by project capacity in megawatts (MW). Figure 3 shows the costs normalized on a per MW basis.

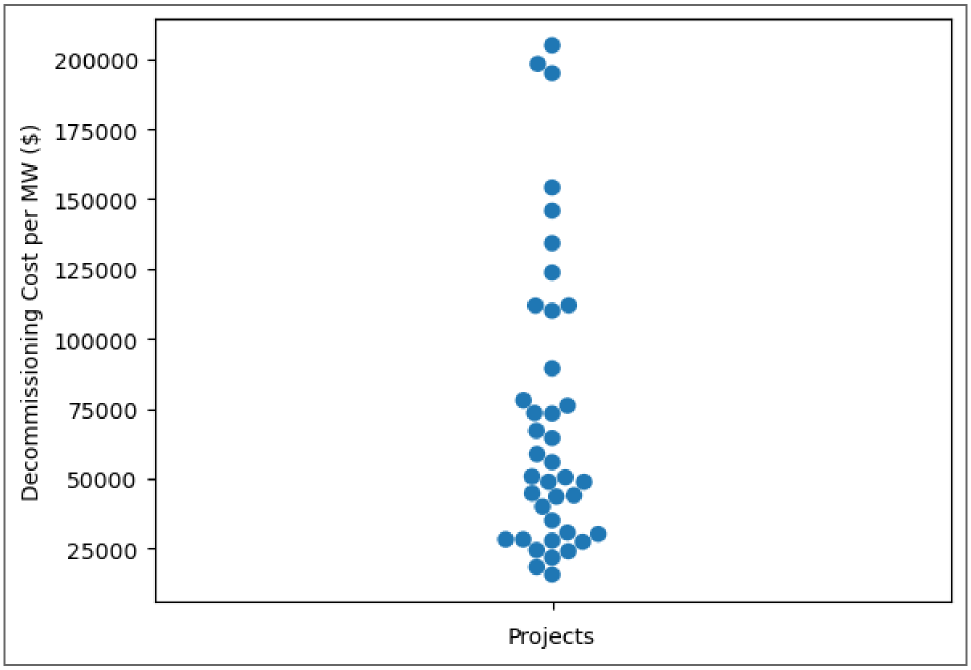

Figure 3: Decommissioning costs for all projects per MW

Figure 3 also gives us an immediate key takeaway on the range of the decommissioning costs per MW, with a maximum of $200,000 and a minimum of about $10,000. Note that the costs presented in Figure 3 are just decommissioning costs and do not include the salvage costs.

Variable Relationships in Decommissioning Costs

Intuitively, one would expect high-capacity projects to have higher decommissioning costs and vice versa. However, there are multiple other complex factors that might make the above claim not as intuitive. This makes it important to investigate the relationships of variables in the cost estimates. This is done visually by creating scatter plots of the total cost ($) on the y-axis and the project size (MW) on the x-axis and quantitatively by calculating the correlation between both variables.

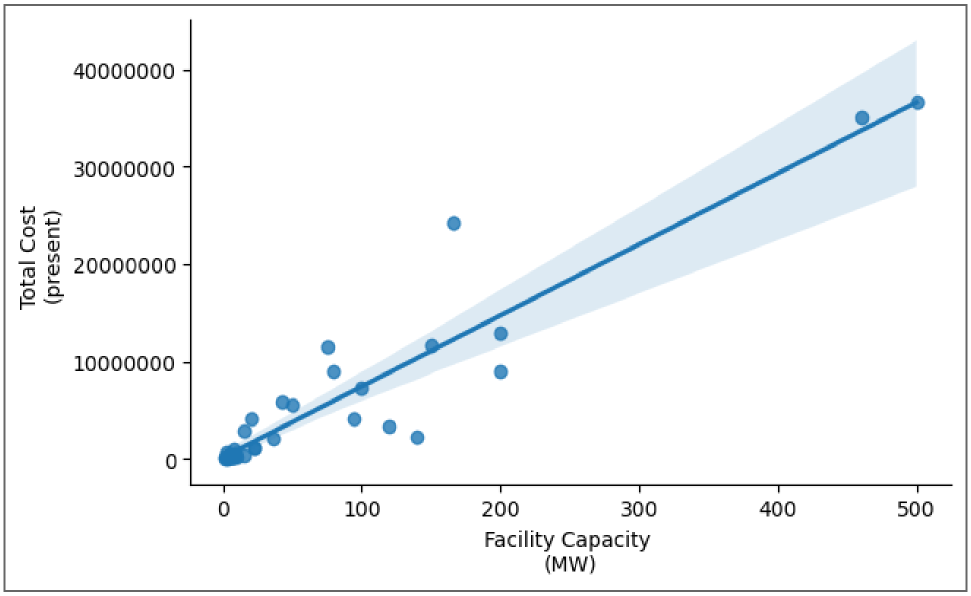

Figure 4: Total Decommissioning Costs vs. Project Size

Here, we find that the correlation between cost and project size is 0.93, very close to unity, indicating that costs are dictated by capacity. Along similar lines, there was also a check of acreage vs. costs, shown in Figure 5, which led to the same correlation.

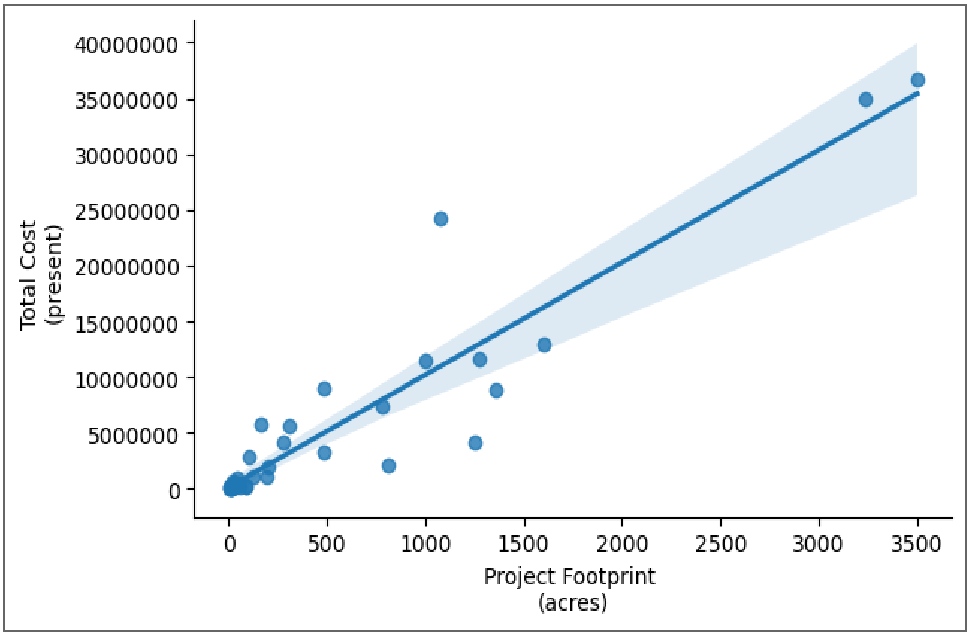

Figure 5: Total Decommissioning Costs vs. Project Footprint

Spatial Variability

Another essential aspect in analyzing these plans is the location of the solar facilities. Each state has a different policy landscape that affects the decommissioning costs through requirements and standards that dictate what variables are included in the decommissioning plan. Figure 6 shows the variability of costs per state.

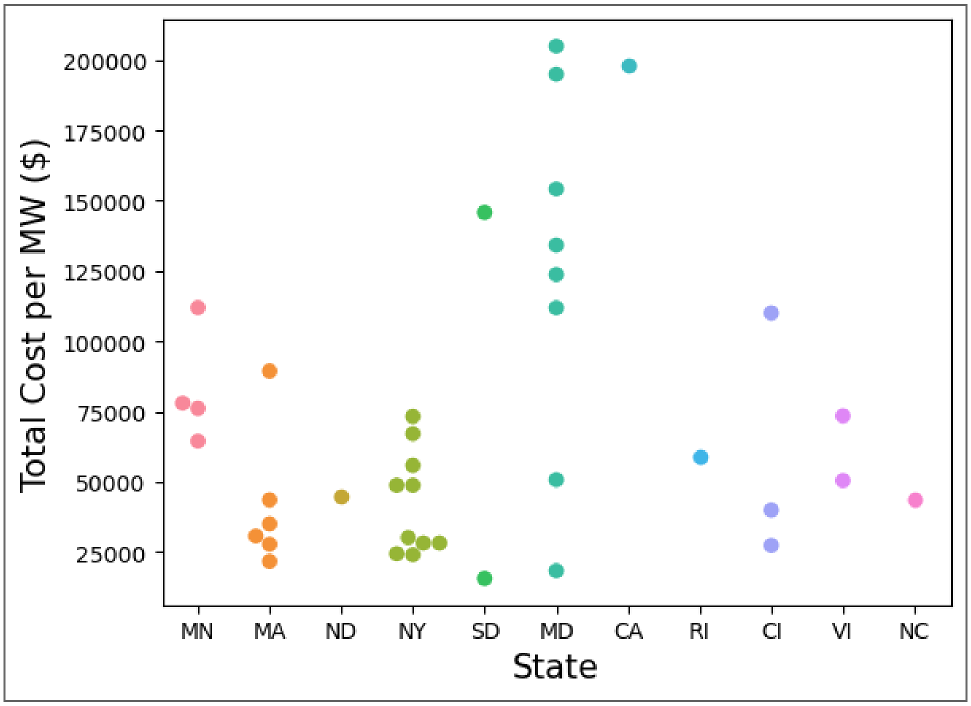

Figure 6: Decommissioning Costs Isolated by State.

Figure 6 is an extension of Figure 3, the difference being that the costs are clumped together by state. A key takeaway is that the state of Maryland has the highest variance in cost for a single state, while other states have a fairly uniform range. New York and Massachusetts, in particular, have a constricted range and exhibits consistency. Minnesota also loosely falls in that bracket; all other states either have too few data points or extended cost ranges. If the dataset were to include Mahi Solar, which was deemed an outlier, there would be a monumental shift in scale, as seen in Figure 7.

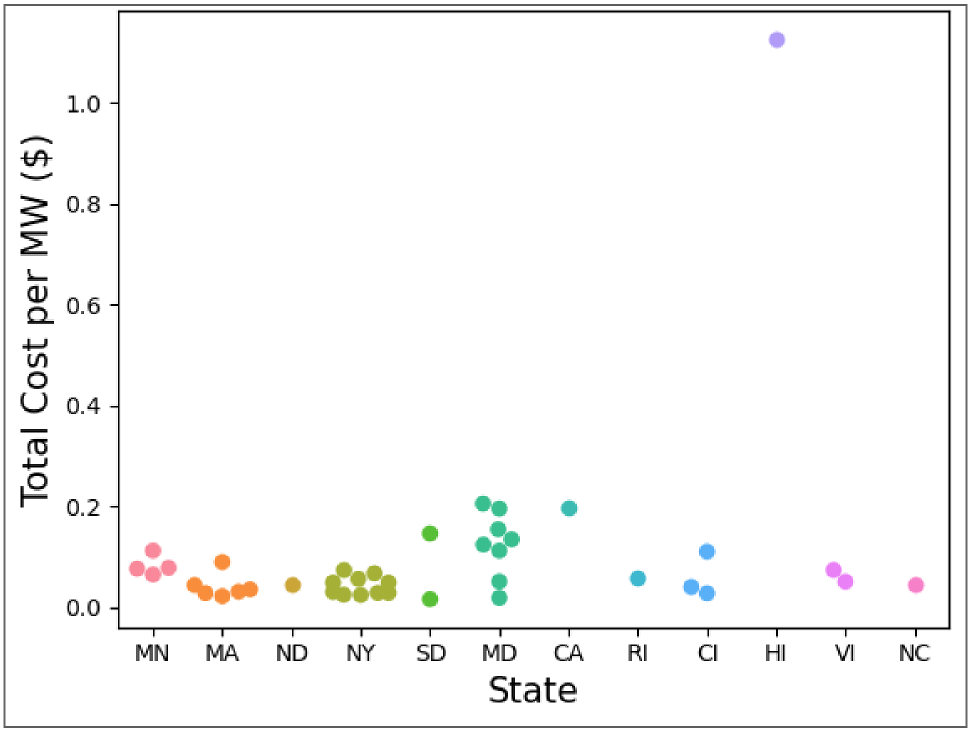

Figure 7: Decommissioning Costs Isolated by State, including Hawaii (Mahi Solar).

Analysis of Expected Costs

So far, the costs that have been analyzed are decommissioning costs, which does not include any salvage value or other forms of credit. However, most plans include a figure that developers expect to make from salvage, recycling of materials, and other means.

$$Expected\ Costs\ =\ Total\ Decommissioning\ costs\ -\ Salvage\ Value\ (Credit)$$

There is high variance in these salvage costs, some plans have salvage values for a myriad of components, and some do not have them at all. The most noticeable cost shifts are observed when plans have a salvage value for the solar array. This is made clear in Figure 8, where the expected costs are plotted by states.

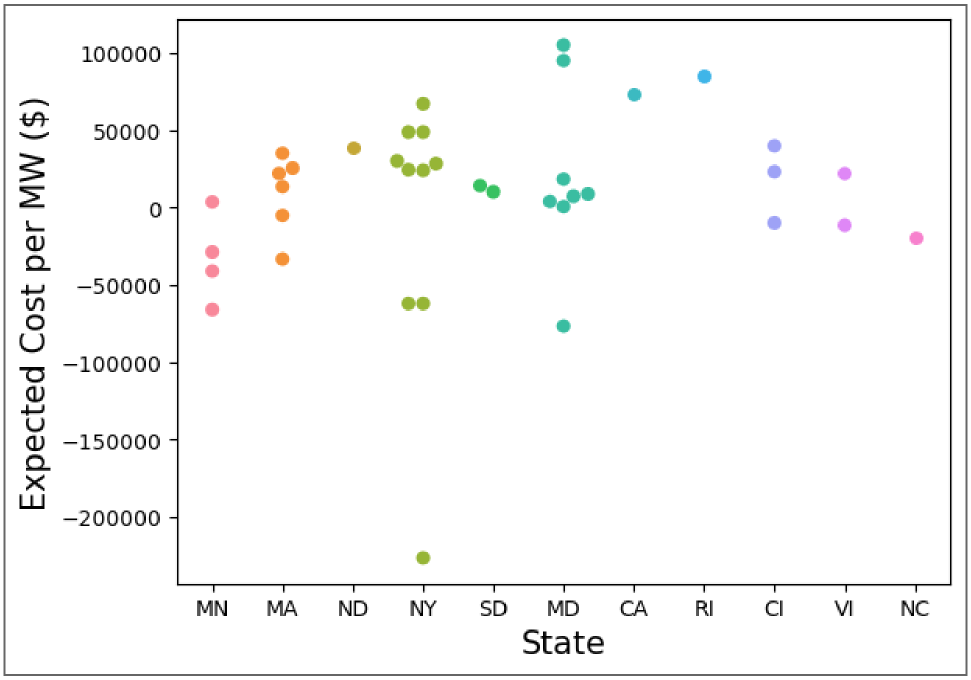

Figure 8: Expected costs per MW, by state.

Including salvage costs, the expected net costs for plans change significantly; some even have a negative cost, indicating that the project would, in theory, stand to make money off the system's decommissioning. The nominal range of costs vacillates between +$100,000 to -$100,000. All plans fall under this boundary, except Mint Solar Facility in New York, which has an expected cost north of -$200,000. Upon further examination, it is observed that this project is the largest of the analyzed plans in the state of New York, with a size of 100 MW. The low negative net cost results from many system components' high expected salvage cost.

Expected costs are a function of the salvage costs, which have no said standards by which they are calculated. A similar pattern emerges when the salvage costs per MW by state are plotted. Flint Mine solar facility stands out, with the highest salvage value of about $300,000, explaining the very low expected costs. All other projects, excluding the ones without salvage information, have a nominal range of about $10,000 to $150,000.

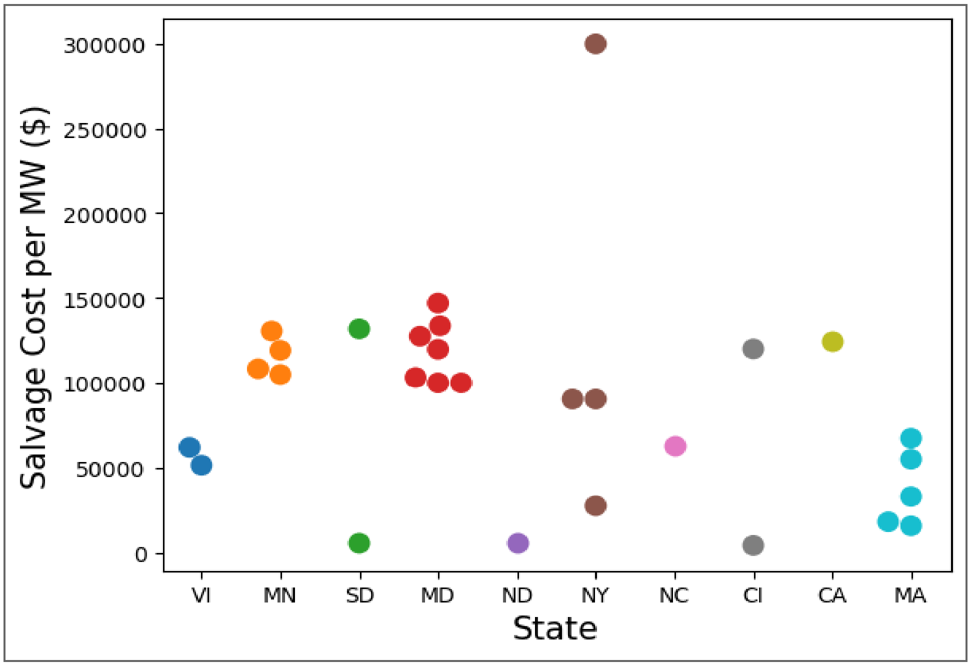

Figure 8: Salvage costs per MW, by state.

Finally, an analysis was conducted on the components that make up the salvage costs. Inverters, Fencing, Racking, Electricals, PV Modules, AC/DC Wires, etc., are noted to have a salvage value. Some of these components are more common than others, and some do not have enough data points to achieve any meaningful outcome from the analyses. Based on the above, Racking, Inverter, PV Module, Other Electricals & Fencing are included as they have more than four plans that explicitly include these costs.

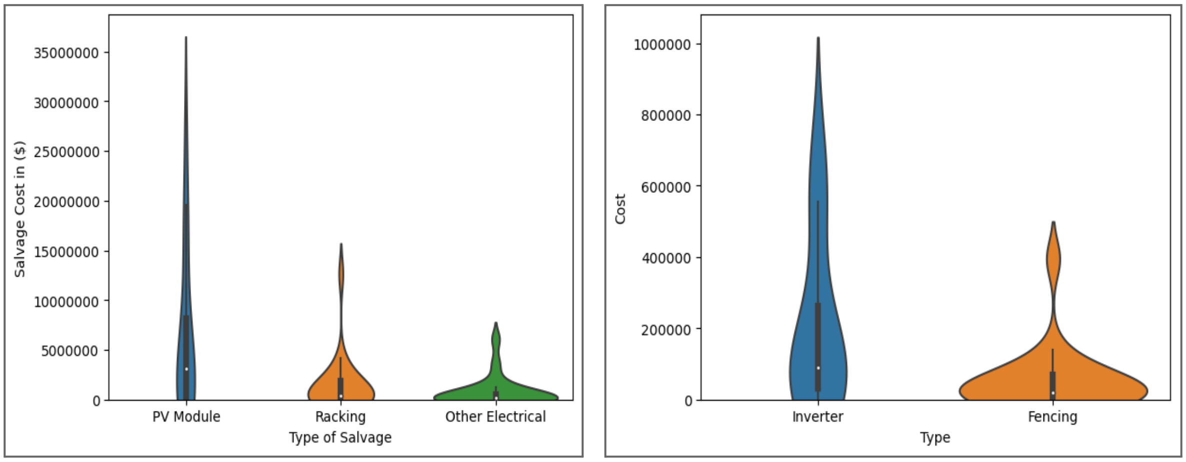

Figure 9 & 10: Salvage Costs by Different Types of Salvage component

The violin plots of the salvage component costs indicate the spread of the cost (length of the violin) and the projects within that spread (breadth of the violin). These costs are not normalized by MW and reflect direct costs that a developer would stand to make from its recycling/repurposing.

Comparative Analysis of Cost Ranges

How the results compare to decommissioning cost ranges that state governments and research institutes have published. It should be noted that this comparison is not exact, as the findings by the master's project team are an aggregate of published decommissioning plans, each of which includes varying levels of detail. There is no standard for what factors or tasks are to be included in a decommissioning cost estimate, contributing to the wide range of cost estimates. Despite the imperfect comparison, this is valuable as it shows the extent to which estimates vary. The comparison utilizes the net value found by the master's project team (total cost to construct the solar array minus the total decommissioning salvage value). This metric was chosen because it most closely resembles the decommissioning cost estimates published by outside sources.

The New York State Energy Research and Development Authority (NYSERDA) produced a 2023 solar guidebook that included estimates of solar decommissioning costs [51]. Estimates were based on findings from the Massachusetts solar market [2]. The estimates conclude that decommissioning would cost $30,100 per MW [3]. This compares to the results of the master's project for projects based in New York at -$27,867.76 per MW.

The Massachusetts Board of Planning created a solar decommissioning template in 2018 that included estimated costs [52]. The board estimated decommissioning to cost $35,127 per MW [4]. This compares to the master's project team findings of $4,455.72 per MW.

The Minnesota Department of Commerce compiled a Solar and Wind Decommissioning Working Group in 2018 to estimate costs [53]. The group found that decommissioning costs between $21,700 to $56,300 per MW [5]. This compares to the findings of the master's project of -$33,116.23 per MW.

Next Steps

Additional Data

If there were to be a subsequent iteration of this project, an effort should be made to review the plans analyzed by the past team and gather data so that the format of both teams' data aligns. This would entail gathering information on who the decommissioning plan was prepared by, the project developer, decommissioning plan submission date, the type of land the project is located on, and the governing body that approved the decommissioning plan. This was not able to be achieved by the current team due to time constraints and the degradation of data sources.

Scenario Planning

Additionally, an effort should be made to conduct a scenario planning analysis to determine the most influential factors in decommissioning cost estimates. The current team would recommend normalizing the costs on a

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[51] NYSERDA. (2023). *Solar Guidebook for Local Governments*. https://www.nyserda.ny.gov/SolarGuidebook.

[52] Massachusetts Board of Planning. (2018). *Solar Decommissioning Template*. https://www.mass.gov/prevailing-wage-program

[53] Minnesota Department of Commerce, S. and W. D. W. G. (2018). *Solar and Wind Decommissioning Working Group Report and Recommendations*. https://www.edockets.state.mn.us/EFiling/edockets/searchDocuments.do?method=showPoup&documentId=%7BF0DC9065-0000-C734-8DCC-76C867A06CD8%7D&documentTitle=20188-146145-02

$/MW basis. Then conduct an analysis of the most expensive and least expensive plans to understand what included factors or lack thereof had the most significant impact on the estimate.

Conclusion

The decommissioning costs of solar systems are an essential aspect to consider in the overall financial analysis of renewable energy projects. The decommissioning costs will become more pressing as solar projects reach the end of life periods, and developers must take action on the next steps. Thus, project developers and policymakers must account for decommissioning costs in solar project planning and design phases. It is important to consider the short-term benefits of solar energy and the long-term costs and impacts. By designing solar systems with decommissioning in mind and choosing materials that are easy to recycle, the decommissioning process can be made more efficient and cost-effective.

In conclusion, decommissioning costs are an important factor to consider in the overall sustainability of solar energy. While solar energy offers numerous benefits, decommissioning must be done responsibly and efficiently to minimize adverse environmental impacts. By considering decommissioning costs in the planning and design phases, solar energy can continue to be a sustainable and responsible choice for our energy needs.

Appendix A: Stakeholder Overview

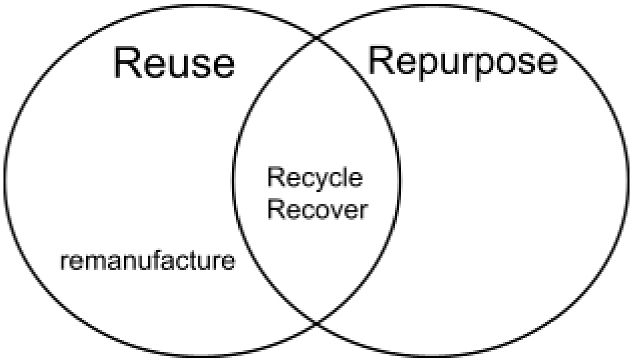
Link to Spreadsheet

Part of Circular Economy	Company	Website	Description of Services	Additional Notes
logistics management	Aesir Logistics	http://aesirlogistics.com/services/batteries/	Manages battery shipments	
recover	American Battery Technology Company (ABTC)	https://americanbatterytechnology.com/about-us/#	Recovery of every critical metal through recycling process; mineral extraction and processing technology. They basically run the battery manufacturing process in reverse. First breaking down battery packs into cells and then extracting materials from the anodes, cathodes, and separators.	
recycle	Ascend Elements	https://ascendelements.com/innovation/	Shred old batteries, remove impurities, and produce cathodes that go back into producing new batteries.	
repurpose	B2U	https://www.b2uco.com/	Using EV batteries for energy storage	
reuse, repurpose	Battago	https://battago.com/	Marketplace for used EV batteries. Owned by Titan.	
repurpose	Green Tec Auto	https://www.greentecauto.com/product-category/repurposed-batteries	Marketplace for used EV batteries	
recycle, logistics management	Battery Recyclers of America	https://www.batteryrecyclersofamerica.com/battery-recycling-faq/#general	Pickup in every state for LiBs for both personal and commercial customers in all 50 states. Quoting form on website. Offer payment and a recycling certificate, but no details on how they recycle. Components are returned into the new product materials stream.	
recycle, logistics management	Battery Solutions/Retriev Technologies	https://batterysolutions.com/ https://www.retrievtech.com/	They provide end-to-end battery management with services including disasembly, logistics, deinstallation, storage, and sorting for all battery chemistries.	
repair, remanufacture, reuse, logistics mana	Cox Automotive Mobility	https://www.coxautoinc.com/mobility/ev-battery/	Building a "global service network" for battery EOL.	"building a global service network focused on management and innovation within the entire EV battery lifecycle" They recently aquired Spiers New Technologies
recover, recycle	KBI	https://www.kbirecycling.com/	Recovery of platinum group metals (Platinum, Paladium, Rhodium), reclaiming and repurposing, mostly in CA	
recycle, recover, logistics management	Li-cycle	https://li-cycle.com/	Recycle thium-ion batteries of all size using a water based method for intial separation and then further processing black mass at a central facility to produce battery-grade lithium, nickel, and cobalt. Recovered materials are then resold. They also provide logistics services.	
repurpose	Nissan	https://global.nissanstories.com/en/releases/4r	Nissan has multiple projects investingating repurposing LEAF batteries	
recycle, reduce	Nth Cycle	https://nthcycle.com/	Alternative technology to hydrometallurgy and pyrometallurgy for recycling Li-Ion batteries	
recycle, recover	ReCell Center	https://recellcenter.org/	DOE battery recycling R&D center. Their goal is to develop cheaper, less energy-intensive recycling technologies for lithium-ion batteries. They are focusing on direct recycling methods ("recovery, regeneration, and reuse of battery components directly without breaking down the chemical structure"). They use the EverBatt model for evaluating technologies.	
recycle, refurbish, remanufacture	Redwood Materials	https://www.redwoodmaterials.com/recyclewithus	Collecting and recycling hybrid and EV battery packs in California.	
repurpose	RePurpose Energy	https://www.repurpose.energy/	Goal to use EVs to create energy storage systems. Prototype in 2023	
refurbish, repair, reuse, recycle, logistics ma	Spiers New Technologies	https://www.spiersnewtechnologies.com/#snt	Provide logistics management and repair, refubish, and prep batteries for recycling.	
repair, recycle	Titan Energy Solutions	https://www.titanaes.com/	Use ultrasound technology to "diagnose" batteries at different stages of the life cycle. They have a product that can detect defects in manufacturing. The technology can also be used to help make decisions about whether the can go to secondary market or should be recycled.	
recycle, recover (but through Redwood?)	Tesla			
recycle, refurbish, recover	Call2Recycle	https://www.call2recycle.org		
	Prioritize these (from Taylor			

Appendix B: Gap Analysis

Research Scope

Generally after the battery has already been created (rethink + reduce are out of scope)



This following is a list of gaps in knowledge the team identified after completing background research. The gaps are formulated as questions to ask during interviews and “they” refers to any of the stakeholders involved in the ev battery secondary-market.

CE Concepts

- How do they see themselves fitting into the circular economy?
- Do they see a difference between recycling and recovery?
    - Legally they may mean different things, but this question is mostly to make sure we are all using consistent language during interviews and in our report writing
- What do they think the future of CE looks like?
    - How will the market be segmented into the different “Rs”
    - What trends are most impactful in driving the circular economy?
        - What are the outcomes associated with those trends? (e.g., if regulatory pressure is increasing, what does that mean for the role of automakers, recyclers, etc.)
        - What are the largest variables affecting the direction of said trends?
        - Rank the 'winners/losers' in the secondary market based on the trends. Could be submarkets (different Rs) or companies

Drivers/Barriers

Policy

- How is policy affecting them today? (including infrastructure bills)
- How will it impact them in the future?
- What are policies (preexisting or novel) that would have the largest impact on the recycling (or any R) space, and why aren’t they being implemented?
- What does/will enforcement look like? Is there any lobbying involved?
    - Who is enforcing these policies and what is their resource pool?
    - What are the penalties associated with violations?

    - Why is (x) policy being implemented in the first place? Who is it benefitting/harming?
    - How have/are these elements changed/changing?
- Is the current lead-acid regulation the type of policy they would like to see replicated for other chemistries?
    - See EPA Hazardous Waste guidelines for lead-acid batteries: https://archive.epa.gov/epawaste/hazard/web/html/batteries.html
- At the city/local level does natural disaster planning related to climate change affect them or are they included in it?
    - Generally how does climate change adaptation policy affect the ev battery market?
    - Are these planning efforts explicitly addressing battery recycling?
    - Is there a sense that there will be more linkage of these themes in the next few years/decade?
- Are there any international policies that they see either impacting or being replicated in the US?

Global Supply Chain

- What do they see as the risks here? How is their company or technology going to combat this?
- Specific policy questions related to supply chain
    - The IRA EV tax credit has several qualifications related to material sourcing - what are the implications for the battery secondary markets in the US? Globally?
    - Are the IRA/CHIPS+Science/BIL going to drive R&D in this space? What other factors may affect continued research efforts and investment?
    - In re: China, what are the implications of current trade tension AND leading position of China in the global battery market
- Does this play a role in funding?
    - Does ability to address US SC concerns open up federal/state funding opps (esp. from recent laws/acts)?
    - What are the best near-term opportunities for [companies] to leverage funding to strengthen battery supply chains?

Standardization

- How do they currently deal with different chemistries? What are the challenges associated with this?
- Do they work with manufacturers?
- Do they see this as a barrier to CE? (this should be more pathway specific depending on the stakeholder group we are interviewing

Economy

- Is technology cost a barrier?
- What needs to happen to make recycling economically viable? Is it only regulation or will market forces get it there?
- Is lack of EV supply a current barrier

Market Forecast

NMC vs. LFP

- What do they currently see coming in (especially for recycling companies)? Will that change in the future (for example because we want to stop sourcing cobalt internationally)?
- Forecasted economies of each

Supply Chain

- How organized is the supply chain for recovered materials?
- Who sells directly to who? (flow chart)

Distribution of secondary market actions

- What percent of batteries are being reused vs. repurposed vs disposed of?

Appendix C. Interview Questions

General: Background and Introductions

Professional Background

1. Can you tell us about your professional background?
    a. What got you into the business of recycling batteries?
2. Can you tell us about your company?
    a. Origin story / early problem space
    b. Evolution of offering (if applicable)
    c. Current offering

Subject Matter: Reverse Logistics

Technology / Processes

1. Validate our view of the value chain, add nuance
    a. [Preread materials - value chain overview]
        i. Within the secondary market for EV batteries, we want to understand in better detail how end-of-life batteries reach recyclers and other secondary market streams
    b. How does our view vary across states, companies, processes, etc.?
    c. What else would you add to our view of the key stakeholders in the secondary market, including recycling?
    d. Detailed overview of the following items:
        i. Incoming supply sources - where do they get it
        ii. Outgoing 'customers' - where do they send it
            1. If applicable, get a sense for the breakdown by:
                a. Recycle
                b. Disposal/waste
                c. Reuse/Repurpose
                d. Other
        iii. Variance by product/material/other
        iv. Specific services - validate from list below
        v. Compare/contrast to other reverse logistics participants - is this the norm?
        vi. Consolidation/fragmentation - where does/will this happen and why?
2. [Based on research] We see your company provides the following services:
        i. Pickup from dealers/auto scrap
        ii. Testing
        iii. Transportation of hazardous materials
        iv. Bulk services
        v. 3rd Party Logistics

    b. Can you talk a bit about each of these value-added services and how they're evolving as more vehicles reach end-of-life?
    c. What has changed the most over the past five years?
    d. What do you expect to change most dramatically over the next five years?

Economics / Market

3. Can you give us a sense for the scale of the batteries you're handling?
    a. Order of magnitude of quantity
    b. How does that translate to revenue?
        i. +/- unit economics
4. Regarding transportation and safety, what is the current regulatory environment for shipping end-of-life batteries and battery materials?
    a. [Reference pending EU policy]
    b. Have there been recent or proposed changes to these regulations in the U.S.?
5. What are the current weaknesses of the secondary market supply chain?
    a. Where are there gaps in the value chain?
    b. Where are the bottlenecks today?
        i. How has/will this evolve(d)?
    c. What are the drivers/barriers to strengthening the supply chain?
        i. Probe for specifics on:
            1. Inflation Reduction Act
            2. CHIPs and Science
            3. Bipartisan Infrastructure Law
6. Compare and contrast the hub-and-spoke models to more distributed secondary supply chains (e.g., Redwood vs. Nth Cycle)
    a. What are the advantages and disadvantages of a centralized system?
    b. What are the advantages and disadvantages of a distributed system?

<u>Subject Matter: Recycling/Recovery</u>

Technology / Processes

1. Do you only handle EV batteries or do you also process other large format batteries?
    a. If other large format batteries are processed what application are they from (eg. energy storage)?
2. What is the recycling process? [validate steps and flow]
    a. Collection
    b. Dismantling
        i. Manual or automated?
    c. Sorting
    d. Smelting / alloy formation (Pyro)

    e. Leaching / extraction (Hydro)
    f. Other
3. What does storage look like throughout this process?
4. Where are the major bottlenecks in the process?
    a. Are those caused by technology / regulations / labor?
5. What large format battery chemistries do you handle/recycle?
    a. If more than one, how do you currently deal with different chemistries?
        i. Are there different processes for recycling?
        ii. What are the challenges associated with having to accommodate more than one chemistry?
        iii. Do you do any work directly with manufacturers on standardization to make accommodating different chemistries in the recycling process easier?
6. Can you walk us through the process of receiving batteries from the asset owner to you?
    a. Who?
        i. Logistics companies
        ii. Specialized material handling
        iii. Other
7. What happens to the recovered materials?
    a. What industries do you offtake to? [directional breakdown if possible]
        i. Automotive (OEM/Tier1)
        ii. Energy developers
        iii. Cathode/battery producers
        iv. Resellers / wholesalers
        v. Other
    b. What is the material flow? [who sells to whom?]
    c. Where are the companies you sell to located?
        i. Are locations centralized or distributed?
        ii. Pros/cons of each
8. What volume of batteries do you process each year?
    a. Order of magnitude
9. Why are these batteries being recycled? [directional breakdown if possible]
    a. Efficiency
    b. End of useful life
    c. Damage / event-related
    d. Other
10. Do you recycle batteries that have reuse potential?
    a. If no, how is this avoided?
    b. Do you send batteries to reuse companies?
        i. If yes, what companies and where are they located?

11. Can you tell us about where you see your company fitting into the circular economy? In your opinion is there a difference between recycling and recovery when it comes to EV batteries?

Economics / Markets

1. Generally, is unit economics favorable today?
    a. Does revenue from material sales cover costs of recycling / processing?
2. Discussion of relative importance of the following elements on commercialization of recycling technology:
    a. Information exchange / open sourcing data
    b. Regulations / policy
    c. R&D / innovation
    d. Market drivers
        i. Supply
        ii. Demand
    e. Other

Regulatory Compliance / Policy

1. What are the most relevant regulations and policies for battery material recycling?
    a. Ex. solid/haz waste and DoT hazmat compliance
    b. Challenges?
    c. Enablers?
2. How is recent legislation impacting your industry, now and in the future?
    a. Bipartisan Infrastructure Law
    b. CHIPs and Science
    c. Inflation Reduction Act
    d. Other
3. What are policies (preexisting or novel) that would have the largest impact on the recycling (or any R) space, and why aren't they being implemented?
4. What does/will enforcement look like?
    a. Who is enforcing these policies and what is their resource pool?
    b. What are the penalties associated with violations?
    c. Why is (x) policy being implemented in the first place? Who is it benefitting/harming?
    d. How have/are these elements changed/changing?
5. At the city/local level does natural disaster planning related to climate change affect you/are you included in it?
    a. Generally how does climate change adaptation policy affect the EV battery market?
    b. Are these planning efforts explicitly addressing battery recycling?
    c. Is there a sense that there will be more linkage of these themes in the next few years/decade?
6. Are there any international policies that you see either impacting or being replicated in the US?

<u>Subject Matter: Reuse/Repurposing</u>

Background/Overview

1. Who are some of the main companies/entities in the battery repurposing space?
    a. Are these companies completely novel or have they integrated batteries into their business model?

Technology and Processes

1. What unique processes, technology, or geographical niche does (your company) fill within the battery reuse/repurposing space?
2. [Based on research] We see your company provides the following services:
        i. Acquisition
        ii. Testing / validation
        iii. Remanufacturing / refurbishment
        iv. Breakdown for scrap / recycling
        v. Bulk services
        vi. 3rd Party Logistics
        vii. Others we missed?
    b. Can you talk a bit about each of these value-added services and how they're evolving as more vehicles reach end-of-life?
    c. What has changed the most over the past five years?
3. What are some of the major obstacles that currently accompany repurposing the batteries you use?
    a. How are companies like yours overcoming such obstacles?
4. What does the repurposing value chain look like today?
    a. Are batteries acquired directly from the initial users (Tesla, Ford, Nissan etc), or are they acquired from other parties?
    b. Are there companies acting as middlemen, such as processing and handling companies, or distribution companies?
    c. Are there donations?
        i. If so, how are donations processed compared to directly acquired batteries?
    d. Other methods of repurposed battery acquisition?
5. What is the typical lifespan of a repurposed battery AFTER going back into use?
6. Are there different tiers of previous use capacity that then dictate secondary function?
    a. In other words, are acquired batteries that contain 80% capacity treated differently than ones with 90%?
7. Which chemistries do you see industry shifting toward, if any?
    a. Are there potential chemistries that won't work with reuse, or would be more difficult//less profitable to utilize?
    b. Are there any other major implications of battery chemistry on reuse/repurposing ability?
    c. How would a shift in chemistry affect (your company's) business as a whole?

        i. How would it affect the processes (your company) carries out?

Economics / Markets

8. Who are some of the main suppliers that you acquire batteries from? Are they mostly EV manufacturers or other forms of LFB as well?
    a. Where do these batteries come from geographically?
    b. Do you see a shift in where/who you're acquiring batteries from in the coming years, especially with the supposed rise of international markets?
        i. How will this change your operations?
    c. After being handled by (your company), what are the range of places that the batteries end up?
        i. By what percentage do they end up at these places?
        ii. How is this breakdown determined?
9. What are the main applications these batteries are being used for?
    a. How large is the repurposing market that you operate within?
    b. Are there projections for the future of this market?
    c. Are (your company's) operations scalable?
        i. What are current factors aiding or impeding scalability?
10. Who do you provide services for, or who are the offtakers regarding your operations?
    a. How does this vary by location?
11. What trends do you see happening within the battery reuse space?
    a. How have these trends affected how (your company) performs its operations?
12. What percentage of batteries come to (your company) that aren't able to be reused? (Or, is this not an issue because faulty ones don't make it to (your company)?)
    a. What are the main reasons for a lack of repurposing ability within used batteries?
        i. How do you see these reasons changing over time?
    b. What happens to batteries that lack a reuse potential?
13. What happens to batteries after they fulfill their reuse potential?
    a. What percentage of spent repurposed batteries are:
        i. Recycled
        ii. Disposed
        iii. Other?
    b. Do you see this process changing?

Policy / Regulation

1. Our understanding is that limitations of transport for hazardous waste set out by the DOT don't affect (your company's) reuse/repurposing of batteries, is that correct?
2. How do you guarantee regulatory compliance within your operations?
    a. What processes or checks do you engage in that help fulfill this?
3. What regulations or do you comply with?

   a. Within battery acquisition?
   b. Within your operations (LFB storage, mobile applications, etc)?
   c. Within EOL/transport/etc?
4. Are there current or proposed policies that will significantly (your company's) ability to carry out battery reuse/repurposing, positively or negatively?
   a. Is (your company) doing anything to lobby for/against these policies?

<u>General: Closing Thoughts / Outlook</u>

Challenges/Barriers & Enablers

1. What are the biggest barriers for moving towards a circular economy for EV batteries?
   a. Is lack of EV supply a current barrier?
2. What are some ways you think we can overcome those barriers?
3. What are some things that are enabling CE for EV batteries?

Future of CE

1. What trends do you see in the battery recycling industry right now?
   a. Is there any regulatory pressure that you anticipate?
   b. Any trends in technologies?
   c. Do you see any evidence of sham recycling practices or other unethical activities as the market matures?
2. What percent of batteries are being reused vs. repurposed vs. disposed of?
   a. Do you see this changing in the future?

Appendix D: Solar Decomissioning Data

Plan Title	Team	County	State	Number of Modules	Facility Capacity *(MW)*	Project Footprint * *(acres)*	Plan Prepared By *
Louise Solar Project	Current	Mower	Minnesota	146,692	50	314	Westwood professional services
Spencer Solar Facilty	Current	Spencer	Massachusetts	-	6.5	87	
Boutilier Rd Solar Project	Current	Leicester	Massachusetts	19,924	7	23.13	ZPD-PT Solar Project 2017-020, LLC (“ZPT”)
Harmony Solar	Current	Cass	North Dakota	790,560	200	1,362	Harmony Solar ND, LLC
Hayward Solar	Current	Freeborn	Minnesota	431,568	150	1272	Westwood Professional Services, Inc.
Sherco Solar Project	Current	Sherburne	Minnesota	15,280	460	3236.8	Westwood
Byron Solar Project	Current	Dodge and Olms	Minnesota	596,466	200	1600	Westwood Professional Services, Inc.
Calverton Solar Energy Center	Current	Suffolk	New York	82284	22.9	200	
Delaware River Solar	Current	Tompkins	New York		2.47	10	
County Road 10 Solar Project	Current	Ontario	New York	7000	3.25	3	Bergmann: Architects Engineers Planners
Mohawk View Community Solar	Current	Montgomery	New York	45,455	7.5	32.86	
Bloomfield Community Solar Farm	Current	Saratoga	New York	45,455	7.5	60	Eden Renewables
60 Middleline Road	Current	Saratoga	New York	-	6.279	13.4	
Riverhead	Current	Suffolk	New York	101,236	36	208	AES
Lookout	Current	Oglala Lakota	South Dakota	349,920	140	810	K&S Ingenieurpartnerschaft
Wild Springs Solar	Current	Pennington	South Dakota	755,664	166	1080	Westwood Engineering
Abbey Solar	Past	Worcester	Massachusetts	63,702	14.7	59	
Baker Point Solar Project	Past	Frederick	Maryland	33,282	9	55	
Bigelow Road Solar LLC Solar Project	Past	Worcester	Massachusetts		1.6	10	
Bluegrass Solar Facility (ac)	Past	Queen Anne's	Maryland	271,830	80	487	
Calverton Solar Energy Center	Past	Suffolk	New York	82,824	22.9	126	
Fleshman/Kost Road 3	Past	Sacramento	California		3	20	
Flint Mine Solar Facility	Past	Greene	New York	431,300	100	785	
Frontier Rd Hopkinton PV Plant	Past	Washington	Rhode Island	23,336	9.25	37	
Gravel Pit Solar Project	Past	Hartford	Connecticut		120	485	
Great Bay Solar I	Past	Somerset	Maryland	297,024	75	1000	
Great Bay Solar II	Past	Somerset	Maryland	138,114	43	167	
Hebron Maryland Solar Project	Past	Wicomico	Maryland		15	108	
Mahi Solar	Past	Honolulu	Hawaii	2273376	144	617	
Maryland Solar Project	Past	Washington	Maryland		20	280	
New York Community Solar Facility	Past	Tompkins	New York		2	12	
North Stonington Solar Energy	Past	New London	Connecticut		5	27	
OneEnergy Wye Mills Solar	Past	Queen Anne's	Maryland		10	94	
PV Solar Field	Past	Hampshire	Massachusetts	8262	3.8	13	
Reams Solar I	Past	Dinwiddie	Virginia	16692	5	38	
Spotsylvania Solar Energy Project	Past	Spotsylvania	Virginia	1615762	500	3500	
Sweetleaf Solar	Past	Halifax	North Carolina		94	1250	
Taugwonk Spur Facility	Past	New London	Connecticut	16680	5	16	
Titcomb Landfill Solar PV System	Past	Essex	Massachusetts	9860	2.8	14.4	
Union Bridge	Past	Carroll	Maryland	28260	8.1	41	

Plan Title	Developer *	Submission Date * *(yr)*	Type of Land *	Decommisioning Requirement * *(Federal, State, Local)*	Approval Body *
Louise Solar Project	EDF Renewables	2020	Agriculture	State	Minnesota Public Utilities Commission
Spencer Solar Facilty	Sunpin Solar	2021		Local	Spencer Planning Board
Boutilier Rd Solar Project	Zero-Point Development, Inc.	2018		Local	Leicester Planning Board
Harmony Solar	Harmony Solar ND, LLC	2018	Agriculture	State	North Dakota Public Service Commission
Hayward Solar	Hayward Solar LLC	2021	Agriculture	State	Minnesota Public Utilities Commission
Sherco Solar Project	Xcel Energy	2021		State	Minnesota Public Utilities Commission
Byron Solar Project	EDF Renewables	2021	Rural, agriculture	State	Minnesota Public Utilities Commission
Calverton Solar Energy Center	Calverton Solar, LLC			Local	Town of Riverhead Town Board
Delaware River Solar	Delaware River Solar, LLC	2017		Local	Dryden Town Board
County Road 10 Solar Project	Aura Solar Power USA	2021	Vacant Agriculture	State [1]	Town of Canandaiuga
Mohawk View Community Solar	Mohawk View Solar LLC		Agriculture	State	Town of Glen Planning Board
Bloomfield Community Solar Farm	Bloomfield Solar, LLC	2022		State	Ballston Town Planning Board
60 Middleline Road	Spinny Group + Revenous Solar		Vacant open fields	State	
Riverhead	Riverhead Solar LLC		Agriculture and Forest	State	Town of Riverhead
Lookout	Lookout Solar Park I, LLC	2019			
Wild Springs Solar	Wild Springs Solar LLC	2020		Local	Pennington County
Abbey Solar	SJA Solar LLC	2015		Rural Residential	
Baker Point Solar Project		2017		Agricultural	
Bigelow Road Solar LLC Solar Project		2018		Rural Residential	
Bluegrass Solar Facility (ac)		2019		Agricultural	
Calverton Solar Energy Center		2016		Industrial	
Fleshman/Kost Road 3		2011		Agricultural	
Flint Mine Solar Facility		2020		Agricultural	
Frontier Rd Hopkinton PV Plant		2020		Manufacturing	
Gravel Pit Solar Project		2020		Mining/Agricultural	
Great Bay Solar I		2020		Agricultural	
Great Bay Solar II		2020		Agricultural	
Hebron Maryland Solar Project		2015		Agricultural	
Mahi Solar		2020		Agricultural	
Maryland Solar Project		2013		Agricultural	
New York Community Solar Facility		2017		Agricultural	
North Stonington Solar Energy		2020		Mixed Residential	
OneEnergy Wye Mills Solar		2015		Agricultural	
PV Solar Field		2019		Rural Residential	
Reams Solar I		2019		Agricultural	
Spotsylvania Solar Energy Project		2018		Silvicultural	
Sweetleaf Solar		2020		Farmland & Timber	
Taugwonk Spur Facility		2019		Greenbelt Residential	
Titcomb Landfill Solar PV System		2016		Sited on old landfill	
Union Bridge		2020		Agricultural	

Plan Title	Total Cost *(present)*	Total Cost *(future)*	Total Cost Per Acre	Expected Net Cost *(present)*	Expected Net Cost *(future)*	Net Cost per MW *(present)*	Total net salvage value/credit *(present)*
Louise Solar Project	$5,597,020.00		$17,824.90	$182,016.00		$3,640.32	$5,415,005.00
Spencer Solar Facilty	$227,500.00		$2,614.94				
Boutilier Rd Solar Project	$214,580.00		$9,277.13	$93,721.00		$13,388.71	$109,818.00
Harmony Solar	$8,932,776.00		$6,558.57	$7,807,610.00		$39,038.05	$1,125,166.00
Hayward Solar	$11,694,711.00		$9,193.96	-$6,180,110.00		-$41,200.73	$17,874,820.00
Sherco Solar Project	$35,000,338.00		$10,813.25	-$13,267,553.00		-$28,842.51	$48,267,891.00
Byron Solar Project	$12,888,300.00		$8,055.19	-$13,212,400.00		-$66,062.00	$26,100,700.00
Calverton Solar Energy Center	$1,116,300.00		$5,581.50	$1,116,300.00		$48,746.72	
Delaware River Solar	$60,200.00	$98,300.00	$6,020.00				
County Road 10 Solar Project	$217,884.00	$394,667.00	$72,628.00				
Mohawk View Community Solar	$211,381.00	$346,372.38	$6,432.78	-$466,456.63		-$62,194.22	$677,837.63
Bloomfield Community Solar Farm	$211,381.00	$346,372.38	$3,523.02	-$466,456.63		-$62,194.22	$677,837.63
60 Middleline Road	$150,523.00	$272,255.00	$11,233.06				
Riverhead	$2,008,893.37		$9,658.14	$1,020,680.90		$28,352.25	$988,212.47
Lookout	$2,179,600.00		$2,690.86	$1,414,331.00	$1,760,627.00	$10,102.36	$765,269.00
Wild Springs Solar	$24,203,784.88		$22,410.91	$2,329,070.00		$14,030.54	$21,874,715.00
Abbey Solar	$318,388			-$490,036.00		-$33,335.78	$808,424.00
Baker Point Solar Project	$456,268			-$690,799		-$76,755	$1,147,067
Bigelow Road Solar LLC Solar Project	$143,000			$35,256		$22,035	$107,744
Bluegrass Solar Facility (ac)	$8,949,917.00			$697,031.00		$8,713	$8,252,886.00
Calverton Solar Energy Center	$1,116,300	$225,900		$1,116,300	$132,100	$48,747	
Fleshman/Kost Road 3	$595,000	$172,805		$220,000		$73,333	$375,000
Flint Mine Solar Facility	$7,322,052	$98,300		-$22,663,157		-$226,632	$29,985,209.23
Frontier Rd Hopkinton PV Plant	$543,255			$785,833		$84,955	-$242,578
Gravel Pit Solar Project	$3,278,000			$2,777,700		$23,148	$500,300.00
Great Bay Solar I	$11,560,000			$542,000		$7,227	$11,018,000
Great Bay Solar II	$5,770,000	$327,000		$25,000	$327,000	$581	$5,745,000.00
Hebron Maryland Solar Project	$2,925,000			$1,425,000		$95,000	$1,500,000.00
Mahi Solar	$162,224,065			$2,159,802		$14,999	$160,064,263.00
Maryland Solar Project	$4,100,000.00			$2,100,000.00		$105,000.00	$2,000,000.00
New York Community Solar Facility	$60,200.00			$60,200.00		$30,100.00	
North Stonington Solar Energy	$550,000.00			-$50,000.00		-$10,000.00	$600,000.00
OneEnergy Wye Mills Solar	$183,150.00			$183,150.00		$18,315.00	
PV Solar Field	$105,458.00			-$19,904.00		-$5,237.89	$125,362.00
Reams Solar I	$252,065.74			-$57,680.26		-$11,536.05	$309,746.00
Spotsylvania Solar Energy Project	$36,705,641.00			$10,972,722.00		$21,945.44	$25,732,919.00
Sweetleaf Solar	$4,132,166.00			-$1,815,904.00		-$19,318.13	$5,948,070.00
Taugwonk Spur Facility	$199,558.00			$199,558.00		$39,911.60	
Titcomb Landfill Solar PV System	$121,800.00			$71,200.00		$25,428.57	$50,600.00
Union Bridge	$1,002,000.00			$32,000.00		$3,950.62	$970,000.00

Plan Title	Total net salvage value/credit *(future)*	Salvage Value per MW *(present)*	PV Module	Racking	Inverter	Fencing	Utility Pole
Louise Solar Project		$108,300.10	$4,123,934.00	$581,606.00	$90,321.00	$32,236.00	$282,743.00
Spencer Solar Facilty		$0.00	$18,000.00	$27,000.00	$30,000.00	$10,000.00	$10,000.00
Boutilier Rd Solar Project		$15,688.29		$62,218.00			
Harmony Solar		$5,625.83	$0.00	$0.00	$544,726.00	$64,092.00	$0.00
Hayward Solar		$119,165.47	$14,040,222.00	$1,889,968.00	$553,707.00	$72,355.00	
Sherco Solar Project		$104,930.20					
Byron Solar Project		$130,503.50	$19,596,984.00	$4,127,779.00	$723,169.00	$39,219.00	$1,351,321.00
Calverton Solar Energy Center		$0.00					
Delaware River Solar		$0.00					
County Road 10 Solar Project		$0.00	$3,500.00	$18,750.00		$11,502.00	$5,000.00
Mohawk View Community Solar		$90,378.35	$300,003.00	$58,405.00			
Bloomfield Community Solar Farm		$90,378.35	$300,003.00	$58,405.00			
60 Middleline Road		$0.00					
Riverhead		$27,450.35				$26,058.82	
Lookout		$5,466.21	$0.00		$112,511.68		
Wild Springs Solar		$131,775.39	$17,135,819.00	$3,039,135.00	$98.00	$72,600.00	
Abbey Solar		$54,994.83	$0.00	$369,137.00	$0.00	$1,760.00	-$2,700.00
Baker Point Solar Project		$127,451.94	$948,540.00	$140,862.00	$17,340.00	$3,826.00	
Bigelow Road Solar LLC Solar Project		$67,340.00					
Bluegrass Solar Facility (ac)		$103,161.08	$5,995,109.00	$2,035,014.00	$262,763.00		
Calverton Solar Energy Center	$93,800						
Fleshman/Kost Road 3		$125,000.00		$200,000.00	$75,000.00	$10,000.00	
Flint Mine Solar Facility		$299,852.09	$27,055,449.00	$2,068,636.00	$225,250.00	$139,073.00	
Frontier Rd Hopkinton PV Plant		-$26,224.65					
Gravel Pit Solar Project		$4,169.17					
Great Bay Solar I		$146,906.67	$5,759,000.00	$1,563,000.00		$10,000.00	
Great Bay Solar II		$133,604.65	$3,083,000.00	$728,000.00		$6,000.00	
Hebron Maryland Solar Project		$100,000.00		$375,000.00	$75,000.00	$75,000.00	$300,000.00
Mahi Solar		$1,111,557.38					
Maryland Solar Project		$100,000.00					
New York Community Solar Facility							
North Stonington Solar Energy		$120,000.00					
OneEnergy Wye Mills Solar							
PV Solar Field		$32,990.00	$123,930.00	$1,140.00			
Reams Solar I		$61,949.20	$65,099.00	$107,154.00	$3,663.00	$976.00	
Spotsylvania Solar Energy Project		$51,465.84	$8,175,756.00	$12,630,276.00		$394,865.00	
Sweetleaf Solar		$63,277.34					
Taugwonk Spur Facility							
Titcomb Landfill Solar PV System		$18,071.43					
Union Bridge		$119,753.09	$650,000.00	$82,000.00		$2,000.00	

Plan Title	Other Electrical	Labor Method	Total Labor Cost *(present)*	Total Labor Cost *(future)*	Labor Cost per MW *(present)*	Wage Rate ($/hr)	Site Restoration Cost
Louise Solar Project	$273,480.00						$96,723.00
Spencer Solar Facilty	$59,500.00						
Boutilier Rd Solar Project	$37,502.00						$20,171.00
Harmony Solar							$939,289.00
Hayward Solar	$6,086,883.00						$556,946.00
Sherco Solar Project							$2,272,232.00
Byron Solar Project							$369,650.00
Calverton Solar Energy Center							
Delaware River Solar							
County Road 10 Solar Project	$7,500.00						
Mohawk View Community Solar	$55,429.00						$9,000.00
Bloomfield Community Solar Farm	$55,429.00						$9,000.00
60 Middleline Road							
Riverhead	$34,991.97						
Lookout							$300,000.00
Wild Springs Solar	$168,692.00						
Abbey Solar	$340,989.00		$450,000.00				$150,000.00
Baker Point Solar Project	$36,498.00						
Bigelow Road Solar LLC Solar Project			$88,168.00				$116,481.00
Bluegrass Solar Facility (ac)							
Calverton Solar Energy Center			$73,000.00	$135,400.00			$10,300.00
Fleshman/Kost Road 3	$13,202.00		$98,958.00				
Flint Mine Solar Facility	$496,800.00						$5,750.00
Frontier Rd Hopkinton PV Plant			$2,921,175.00				$232,080.00
Gravel Pit Solar Project							$23,000.00
Great Bay Solar I	$3,616,000.00						
Great Bay Solar II	$1,887,000.00		$85,102.00				$5,560.00
Hebron Maryland Solar Project	$675,000.00		$2,206,900.00				$891,400.00
Mahi Solar							$81,000.00
Maryland Solar Project							$3,987,671.00
New York Community Solar Facility							$212,571.00
North Stonington Solar Energy							$78,000.00
OneEnergy Wye Mills Solar							$1,240,000.00
PV Solar Field	$292.00						$288,000.00
Reams Solar I	$132,211.00						$109,616.00
Spotsylvania Solar Energy Project	$1,191,207.00						$306,753.00
Sweetleaf Solar							$825,000.00
Taugwonk Spur Facility							
Titcomb Landfill Solar PV System							$1,100,000.00
Union Bridge	$227,000.00						$643,190.00

Plan Title	Reseeding and Regrading Cost	Concrete Pad Removal Cost	Permitting Cost	Insurance Cost
Louise Solar Project			$10,000.00	
Spencer Solar Facilty	$14,000.00	$30,000.00		
Boutilier Rd Solar Project	$48,125.00			
Harmony Solar	$883,200.00		$10,000.00	
Hayward Solar		$10,692.00	$10,000.00	
Sherco Solar Project				
Byron Solar Project			$10,000.00	
Calverton Solar Energy Center				
Delaware River Solar	$4,250.00	$1,500.00		
County Road 10 Solar Project	$49,500.00	$2,496.00	$3,500.00	
Mohawk View Community Solar	$9,000.00	$15,600.00		
Bloomfield Community Solar Farm	$9,000.00	$15,600.00		
60 Middleline Road	$10,625.00	$3,750.00		
Riverhead	$28,673.48	$67,161.75		$7,220.00
Lookout				
Wild Springs Solar	$3,761,892.00	$49,600.00	$10,000.00	
Abbey Solar	$62,500.00			
Baker Point Solar Project	$133,844.00			
Bigelow Road Solar LLC Solar Project				
Bluegrass Solar Facility (ac)	$668,381.00			
Calverton Solar Energy Center	$23,000.00			
Fleshman/Kost Road 3				
Flint Mine Solar Facility	$131,280.00	$168,000.00		
Frontier Rd Hopkinton PV Plant				
Gravel Pit Solar Project	$884,000.00			
Great Bay Solar I	$65,000.00			
Great Bay Solar II	$156,000.00			
Hebron Maryland Solar Project	$825,000.00			
Mahi Solar	$1,100,000.00			
Maryland Solar Project	$6,964.12			
New York Community Solar Facility	$250,000.00			
North Stonington Solar Energy				
OneEnergy Wye Mills Solar				
PV Solar Field	$21,000.00			
Reams Solar I	$7,575,361.10			
Spotsylvania Solar Energy Project				
Sweetleaf Solar	$4,653.67			
Taugwonk Spur Facility	$19,100.00			
Titcomb Landfill Solar PV System	$15,000.00			
Union Bridge				