Facilitating a Sustainable Future: Lithium-Ion Battery Reprocessing

Analysis of the Feasibility of Wide-spread Adoption of Battery Recycling Technology in California

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction:

In July 2023, a recycling plant in North Georgia went up in flames due to hazardous scrap batteries being illegally dumped there by a local EV battery manufacturer. In October 2024, the battery manufacturer settled with the recycling company for $31 million (Edwards, 2024). Similar stories of garbage trucks exploding due to used batteries being mixed in with normal garbage, have started becoming popular. This trend is due to the lack of consensus on what to do with used batteries. The goal of my capstone team's technical project is to answer that question by scaling up a novel method of battery recycling to a commercial scale. The process will be recycling valuable metals, from specifically Tesla EV Batteries, into battery-grade materials that can be reused. The commercial scale process will be simulated using software such as AspenPlus, alongside specific data packages from AspenTech that can operate the necessary calculations and estimations to predict the required inputs and potential outputs of the system. To supplement the software estimations, we will also cite reaction parameters from theory, research papers, and estimations from professionals in the industry. As the world moves towards renewable energy, batteries are expected to be an integral part of that transition. Currently, the materials for these batteries come from ethically problematic sources, such as Lithium mines in Argentina or Cobalt mines in the Democratic Republic of Congo (Backhaus, 2021, pp. 10–11). By developing a process to recycle batteries at the end of their lifecycle, the global market won't be as dependent on these questionable sources.

While the economic prospects of the technology may be important, it is equally important to conduct an analysis on the societal implications of the technology, both on a national level and a community level (Mattison & Norris, 2005). Therefore, my STS paper will be using Actor Network Theory to investigate the interconnected web of actors that battery recycling technology affects and is affected by. After defining these actors and their relationship with battery recycling technology, I will propose methods currently utilized by other battery recycling plants and suggested by experts in the field, that can mitigate any negative effects, maximize the potential for long-term success of the technology, and ensure the safety of its connected actors. Due to the scarcity of battery-recyclers world-wide and the novelty of the industry, data from well-established chemical plants will also be used to predict the social effects a large-scale battery recycling plant may have on a community and identify methods of mitigating any negative consequences (Wong, 2016). The ultimate goal of this paper would be to have these suggestions implemented via a government code or legislation in the battery recycling industry and potentially become a standard across several chemical processing industries. These new standards will promote safety and responsible process design which may have higher initial costs, but history has shown that improves in chemical process safety are almost always more profitable in the long run (Benson et al., 2024). Basically, that is because it's cheaper to implement safety measures than pay large amounts of money in lawsuits and replace damaged facilities.

In this prospectus, I will provide an overview of my capstone group's technical project and introduce the motivations and circumstances that inspired its development. The overview will go over the general process of battery-recycling that we will further define and provide more details in the STS research paper. I will also provide an overview of the various actors that influence battery recycling technology and their relationships with each other.

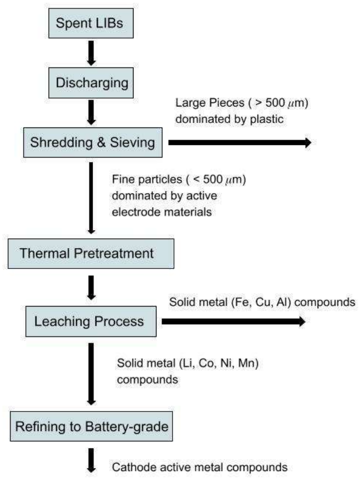
<u>Technical Project:</u>

Our project looks to take advantage of the rising popularity of electric vehicles (EVs) by creating a process to recycle valuable metals from spent lithium-ion batteries (LIBs). The lithium-ion battery has become one of the most popular forms of rechargeable battery, largely due to its high voltage and energy density. For example, cobalt is often used as part of the cathode materials for such batteries, contributing to the stability and shelf life of the battery (*Cobalt Life Cycle | Cobalt Institute*, 2021). Due to their lack of supply and difficulty to mine, lithium and cobalt tend to be the most valuable materials used in batteries today. Currently, over 70 percent of cobalt is mined in the Democratic Republic of the Congo, and most of the lithium is mined from brine deposits in Australia and Chile (Backhaus, 2021, pp. 10–11). The demand is currently dominated by the electric vehicle industry, which is only expected to increase due to increased electrification of transportation to meet climate change initiatives. As these rechargeable technologies are used and disposed of, a large amount of "e-waste" (electronic waste including batteries and circuit boards) accumulates, which is only expected to accelerate as more electrified technologies are popularized. Our process intends to use e-waste (specifically, spent LIBs) as a feedstock to produce battery-grade lithium and cobalt in the form of lithium carbonate and solid cobalt, and potentially other valuable metals such as aluminum, copper, gold, and nickel, all of which can then be recycled back into markets of EV's, consumer electronics, energy storage, and more. In addition to these products, there will also be a waste stream that will have to be disposed of or repurposed accordingly.

Some EV companies, specifically Tesla, have made promises to replace their consumers' batteries if their battery capacity has dropped below 70% in the first 8 years of operation. Additionally, most EV batteries are expected to last for about 10 years before needing to be replaced (*How Often Do Tesla Batteries Need To Be Replaced?*, 2024). This short LIB lifespan gives rise to a significant and consistent supply of used batteries within the next decade, as current EV batteries come out of service (Scott, 2023). This will also create a significant increase in demand for battery materials as companies, like Tesla, will be scrambling to produce enough batteries to supply new EV car sales and replace old batteries (*Lithium-Ion Battery Demand Forecast for 2030 | McKinsey*, 2023). If a commercial-scale method of recycling these batteries were to be developed, that would provide an additional source of battery materials to the market, stabilizing the volatility within the market, easing the cost-related challenges associated with electrifying the national energy market, and reducing the potential environmental impact of battery in hazardous waste landfills (*Lithium-Ion Car Battery Recycling Advisory Group*, 2022, p. 9).

Figure 1

Process Flow Diagram for Recycling of Spent LIBs



Note. Process and streams are generalized, and each block has many intermediate, complex processes.

The process begins with collecting used LIBs and discharging them. LIBs are very reactive due to the lithium atoms in the anode graphite layers in addition to other organic electrolytes and fluoro-compounds (Pinegar & Smith, 2020, p. 147). Discharging takes place in large batches of brine (saltwater) which completely discharge most LIBs. To extract the contents inside, LIBs are shredded and sieved to separate the valuable components. Electrode-active materials are contained in a "black mass" <500 μm in size (Pinegar & Smith, 2020, p. 145). Material larger than 500 μm contains mostly waste but can hold a non-negligible amount of valuable product, so choosing the correct method of shredding and sieving is important. The resulting black mass containing valuable components is then thermally pre-treated by burning off any organic binding agents that may cause issues for extraction (Pinegar & Smith, 2020, p. 154). Metals are extracted from the pile of black mass using hydrometallurgy (acid leaching). Transition metals can be leached with many different solvents including sulfuric acid, hydrochloric acid, nitric acid, and organic acids all resulting in different product purities. Additional processes to extract the metal involve taking advantage of chemical and physical changes associated with heating (pyrometallurgy). In hydrometallurgy, metals leached by the solvent can be extracted by precipitation or cementation by the addition of a different solvent (Pinegar & Smith, 2020, p. 147).

Further refining of our product dictates our exit point in our process. Ideally, we look to refine our product to be battery grade through ion exchange or crystallization methods, but our product could be produced to be recycled as industry grade (*Lithium Extraction and Refining*, 2024). A generalized outline of the entire process is depicted in Figure 1. Our plan to design this process will initially focus on the extraction of lithium carbonate and cobalt from black mass sourced from car batteries. After the initial process has been developed, the team can run a cost-benefit analysis to determine if additional metals of value can be extracted. Tesla battery teardowns will be used to estimate a range of concentrations of significant metals within the black mass.

Lithium-ion battery recycling also addresses some human needs. The first and primary human needs of this project are natural resource management and the development of a circular economy. Natural resources like cobalt, lithium, and nickel are finite resources, so to sustain a growing population and need for electronics, we need to find other long-term solutions. A circular economy does two things: it guarantees that we will have continuous access to these important resources, and it lowers the price of the existing natural resources. A circular economy also provides more jobs and less reliance on unpredictable sources. This means that individual manufacturers can become more self-reliant and efficient (Ellen Macarthur Foundation, n.d.).

The second human need that this project addresses is environmentally focused. Batteries that are improperly disposed of can easily lead to water, soil, and air contamination. By recycling LIBs, we can reduce the risk that these pollutants have. In addition to LIB recycling lowering the risk of contamination, it also cuts down on the amount of space used up in landfills. Recycling LIBs is also less energy-intensive than mining new raw materials, significantly reducing the total greenhouse gas emissions created from mining. Also, by reducing the need for mining, there would be less habitat destruction and general pollution that comes with mining operations (Biswal, 2024). Overall, LIB recycling has the capacity to heavily reduce the reliance on new raw materials while also combating environmental pollution. This makes our project a key aspect of moving towards a safer and more sustainable future.

Novel methods currently exist for LIB recycling processes on the lab scale which we aim to scale up. As such, our research is centered on lab scale publications involving methods of separating the valuable metals out of LIBs. We also will investigate existing methods for LIB recycling/processing on industrial scales to identify common systems and processes that we may incorporate into our design, including defined processes recycling phone and laptop batteries. We have already identified two such approaches: hydrometallurgy (chemical leaching of metals in the liquid phase using acids) and pyrometallurgy (high-temperature extraction similar to ore refining); as of now we are focused on the hydrometallurgical approach due to the possibility of recycling solvents and acids back into the process and reducing chemical waste. We will use Aspen Plus as a computational tool to model our process for calculations of the thermodynamics (required pressures, temperatures, heats of reaction), kinetics (conversion rates, reaction times), and energy flows (how much heat we will supply/generate, how much power we would need to purchase/if we could sell power generated) of our system. Aspen Plus will also be useful in calculating material balances for the determination of how much product we are making and how much feedstock we will need.

To use kinetic models in Aspen Plus, experimental reaction and rate data (e.g. rate constants, kinetic equations) must be provided. This kinetic data will be sourced from lab-scale publications of LIB recycling processes. Some ASPEN Plus models for LIB recycling are already published online which we may access and adapt to our own process. AspenTech's cathode package may be helpful in some of the metallic chemistry separations. For other data, like LIB material compositions, we will be looking into common manufacturers of LIBs, like Tesla, who use the technology in their electric vehicles. Our preliminary research has already identified that LIB car batteries are generally 5-20 wt.% cobalt and 5-7 wt.% lithium, with other potentially recoverable metals (like nickel and iron) as well (Pistilli, 2024).

STS Project:

The goal of my STS project is to highlight the social and environmental impacts of our battery-recycling process on a local and national level by using Actor Network Theory to draw a web of connections between all participants. This will give us insight into the factors that most technoeconomic analysis reports often overlook as they don't directly affect the profitability of the process. From there, several potential steps will be recommended in order to mitigate any negative effects of the technology on the various actors and increase the long-term viability of the technology. Currently California has 52,000 Tesla EVs in use (as of July 2024), meaning that in the next decade there will be a supply of at least 52,000 used vehicle batteries that need to be recycled (Sriram et al., 2024). Most of these cars are found within California's largest cities, so the project will assume that the recycling plant will be situated in one of the communities on the outskirts of the major cities. The STS project will go over the effects of a potential plant on the following actors and their effect on the technology and each other.

The first main actors will be the natural environment and government, two actors that have the greatest determinants of the success of the technology through unfavorable climate and terrain, government regulations, and subsidies. For example, the USA & Brazil are the largest producers of bioethanol, ethanol from corn or other agricultural products (*Alternative Fuels Data Center*, 2024). This is because their climates and geography allow them to produce a massive surplus of these agricultural goods, to the point where using them for ethanol production doesn't compete with public consumption. Other countries, like India and China, where food stability is an ongoing challenge, can't effectively use this technology due to the competing demand for agricultural products (*India*, 2023). Similarly, the USA only produces less than 1 million tons of lithium and less than 100,000 tons of cobalt in reserve. This scarcity of battery materials makes it very difficult for the US to develop its own domestic battery manufacturing industry (Backhaus, 2021). This scarcity and government push towards energy independence encourages the development of battery recycling technologies. This can be seen in recent legislation, where states like California are passing legislation that requires battery manufacturers to recycle their batteries at the end of their life (California, 2022). This creates a demand for battery recycling and pushes companies to begin investing in and testing novel technologies.

The second batch of actors that will have significant influence on the technology is the local community, workforce, and public image. Depending on how large the workforce in the area is and how many other plants are in the area, the relationship between the local community and the plant can change drastically. For example, polluting industries are more likely to be in low-income communities of color where other social stressors already make them more vulnerable to health impacts. Even after chemical plants have been closed, harmful chemicals that were released during emergencies have significant generational effects on the community and environment (Johnston & Cushing, 2020). When these incidents occur, the image of the company and technology are damaged to the point that may deter others from utilizing it in the future. A great example of this would be Nuclear Fission energy. Nuclear energy was very popular during the late 1900s, but after the 2011 Fukushima Daiichi accident, society's perspective changed (Kennedy, 2024). The public image of nuclear actively worked against it and encouraged politicians to halt further investment in the technology (ANS Nuclear Cafe, 2023). Similar developments and societal debates are beginning to occur within the battery recycling industry. Earlier this month, a battery recycling plant in Fredericktown, Missouri had a massive fire that led to a city-wide evacuation. A couple days after the incident, many locals began to complain about the thousands of dead fish found in the nearby river due to potentially pre-existing heavy metal contamination (*Fish Kill after Fredericktown Battery Plant Fire Sparks Urgent Questions on Safety and Accountability*, 2024). As a result of this, the locals are pushing for stronger safety protocols and regulations. While in the short term this may be inconvenient for the industry and may increase the bar to entry, improvements in safety protocols almost always translate into long-term improvements in efficiency and productivity (Benson et al., 2024). If these safety protocols are still ineffective in appeasing the locals, another incident may occur that might put the battery recycling industry at risk of ending up like nuclear energy.

The final batch of actors will be the EV manufacturers and EV market. Recently in France, a newly opened battery recycling plant was quickly shut down after start up due to sudden fluctuations in demand and supply of materials (*French Mining Giant Pauses Battery Recycling Project amid EV Setbacks*, 2024). Many regional markets suffer from insufficient infrastructure to gather and transport all the batteries from across the country. These processes are most efficient when centralized into one commercial-scale plant (Yu et al., 2022). While that makes the process more efficient, there is an increased cost to develop the infrastructure to gather the spent batteries, which can lead to a similar situation that happened in France. If plants are built on a smaller scale and decentralized, to be closer to the feed sources, significantly more plants will need to be operated to meet the demand. This balancing act of decentralizing the industry while maintaining economic feasibility introduces uncertainty, which hinders the large-scale adoption of this technology (Yu et al., 2022).

While there is currently very little data available that specifically addresses the effects of a battery-recycling plant on a community and environment, there is substantial data available about how various chemical plants, that utilize similar processes and chemicals, affect the psyche and health of the locals (Johnston & Cushing, 2020). Therefore, an estimate based on previous data from other plants will be used to highlight the potential consequences of building a plant capable of recycling all of California's Tesla batteries. The STS project will also go over how chemical plants have mitigated these effects, proposed solutions from experts, and how successful those methods are.

One suggested solution that has been very popular recently, and has greatly influenced legislation in California, is the idea of a resilient, circular battery value chain. As mentioned before, the US doesn't have a reliable source of lithium and other valuable minerals. Experts suggest that a circular battery market could provide over 90 percent of local battery demand and 60 percent of market demand by 2030 from recycling spent lithium-ion batteries (McKinsey &

Company, 2023). This would help the environment as less hazardous landfills will be required to store the millions of tons of spent batteries every year and less toxic population caused by incorrect or illegal battery disposal. This would also help the EV manufacturer and sustainable energy industry as this new domestic source of battery grade materials would make the manufacturers less reliant on foreign imports which are heavily influenced by regional conflicts, logistical challenges, and international trade (McKinsey & Company, 2023).

Conclusion:

While commercial scale battery-recycling hasn't become popular in the US, US public policy pushes the energy marker to electrify making batteries become the increasingly popular means of energy storage. With our current technology, batteries only last for about a decade before losing too much storage to be usable. When that happens, currently there aren't that many methods of getting rid of the used batteries besides storing them in specialized hazardous waste collection points (US EPA, 2019). In order to make the electrification of the US more sustainable and reduce the US's demand for questionably sources metals, battery recycling is necessary. While battery recycling may assist in the US's transition to sustainable, green energy, it's very important to analyze the societal and environmental impacts that these processes may have. If these nonempirical factors are ignored, once battery recycling begins to gain technical momentum, there may be no way to mitigate or prevent certain negative effects.

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