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Designing a Recycling Facility for Energy Materials

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ME Senior Design Project II 001

Design of a Recycling Facility for Energy Materials

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Introduction of Energy Materials

The purpose of this project was to design a recycling facility for energy materials. Our attention was focused on the following energy systems: catalyst converters, wind turbines, lithium ion batteries, and photovoltaic cells. These systems require materials that may be precious, rare-earth materials, not easily attainable in the US, and can be harmful to our environment. This project had two main focuses: research and design. The fall semester of 2019 was focused primarily on researching possible energy system materials for recycling, while the spring semester was devoted to the design of the recycling facility. The research done for this project included: identifying different energy materials used in energy systems available in the market, determining an economically appropriate energy material to recycle, creating and analyzing different recycling processes feasible for this material, and choosing to develop one to two of these recycling processes. Ultimately, we decided to focus on designing recycling facilities that could recycle wind turbine blades and lithium-ion battery cells. While we were able to complete the design for the lithium-ion battery recycling facility, the design of the wind turbine blade facility was cut short due to time constraints caused by the COVID-19 pandemic. The design for the lithium-ion battery facility includes designing a cost-effective recycling facility for separating energy materials, picking machines to fulfill these requirements, and performing an economic analysis of recycling these materials.

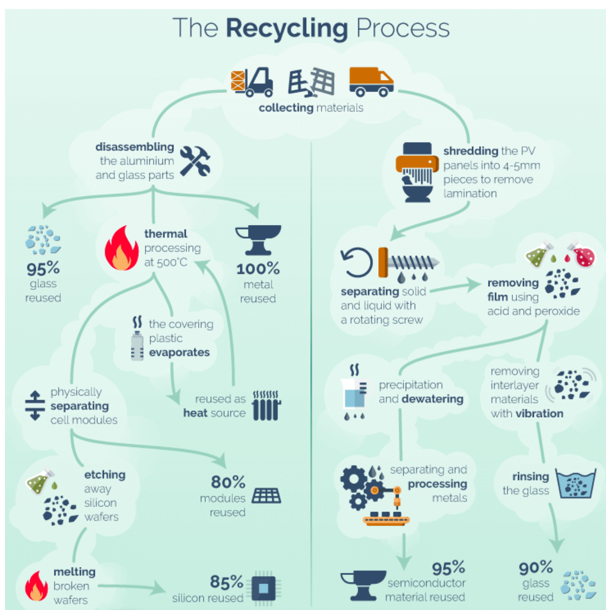
The motivation behind this work stems from multiple sources. The United States has a strong dependency on China, and other countries, to obtain rare-earth materials used in most of our high energy applications. Since the recycling of these materials is not well-developed, or feasible at this time, most of them are thrown away or shipped back to China to be disposed of. This is not an economically sound decision for the US in the long term. If these high energy applications are to become more widespread and easier to implement, then a better recycling infrastructure needs to be developed. The use of renewable energy materials is still underutilized, therefore, the engineering process for these materials can be extended beyond being thrown away. Reusing and recycling these materials completes this process and helps to protect our environment from the harmful effects of dumping these materials in landfills. Being able to recycle these materials also means that less harmful mining will take place on our Earth.

The following information highlights some of the key concepts behind the need and general understanding of why recycling methods for these energy materials need to be researched. As previously mentioned, our group ultimately decided to design facilities for the recycling of wind turbine blades and lithium-ion batteries but information on the other two energy materials are listed below as well. Since the focus of this project was on lithium-ion battery recycling, information regarding this topic was placed under its own heading in this report. Research concerning the other three energy materials is as follows:

<u>Photovoltaic Cells</u>

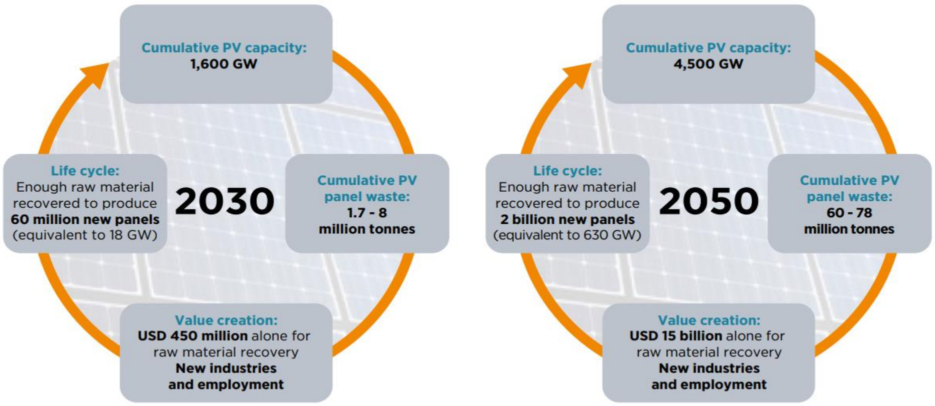
The lifetime of photovoltaic cells is approximately 30 years. They have a 20% decrease in power capacity over their lifespan. Efficiency drops 6-8% after 25 years. PV panels may reach 30-40 years of operation with decreasing efficiency. When recycling PV cells, silicon based solar panels are more common. Studies show 96% possible recycling efficiency. To recycle a silicon module, these are the steps:

- Removing aluminum frame (100% reusable)
- Separating glass along a conveyor belt (95% reusable)
- Thermal processing @ 500 degrees Celsius
- Etching away silicon wafers and smelting them into usable slabs (85% reusable) [1]



[2]

In recent years, photovoltaic cells have greatly increased in popularity. The creation of proficient recycling methods for photovoltaic cells can net a large sum of saved money. The following figures dive into more detail relating to the economics opportunity in recycling photovoltaic cells:



[3]

- Ohio Solar
  - **MW Installed:** 231.11
  - **Installations:** 4,357
  - **Solar Jobs:** 7,162
- West Virginia Solar
  - **MW Installed:** 8.53
  - **Installations:** 867
  - **Solar Jobs:** 341
- Indiana Solar
  - **MW Installed:** 354.87
  - **Installations:** 2,427
  - **Solar Jobs:** 3,114
- Pennsylvania Solar
  - **MW Installed:** 452.24
  - **Installations:** 26,863
  - **Solar Jobs:** 4,219
- Kentucky Solar
  - **MW Installed:** 43.77
  - **Installations:** 679
  - **Solar Jobs:** 1,410
- Michigan Solar
  - **MW Installed:** 160.31
  - **Installations:** 5,316
  - **Solar Jobs:** 4,196

[4]

Numerous recycling programs have sprung up recently in the U.S to combat the pile up of out of service photovoltaic cells. They are listed below [5] [6]:

- 17 recycling facilities in the US
  - Based on ENF Solar directory
- Recycle PV
  - Partnered with PV Cycle
  - Goal: Send solar panels from the US to Europe to be recycled
- Solar Energy Industries Association (SEIA)
  - Benefits for partners
  - Cleanlites
- Manufacturers Recycling
  - SunPower
  - First Solar

Catalytic Converters

Catalytic converters are used for exhaust emission control that reduces toxic gasses and pollutants from engines. They became a standard for new vehicles starting around 1975. The different energy materials inside include:

- Platinum
  - Jewelry
  - Dental Work
  - Permanent Magnets
- Palladium
  - Jewelry
  - Dental Work
  - Capacitors
- Rhodium
  - Lab Crucibles
  - Thermocouples
  - Aircraft Spark Plugs

The recycling process starts by splitting the outer casing to separate and crush honeycomb into powder. Sodium hydroxide solution filters the 3 catalysts that are extracted. These catalysts are separated using screening/filtering, chemical treatments, and electrolysis.

- In the United States, more than 13.1 million new light vehicles were sold in 2016. Using the trickle-down model, roughly 19.7 million scrap converters would have been available for recycling

- In North America, we can roughly estimate that for every new vehicle sold, 1.5 scrap converters theoretically become available

- Recycled platinum contributes 20 percent on average to the total net stock, while recycled palladium contributes 30 percent on average. With demand growing at a rate of 2 percent annually moving toward 2021. [7]

The following table best summarizes the distribution of vehicle recycling facilities in the states surrounding Ohio. As you can see, states like West Virginia have a relatively low catalytic converter per facility rate compared to states like Pennsylvania and Michigan. [8]

Location	**Number of Facilities**	**Population**	**Vehicles per person**	**Number of CC per facility**
Ohio	65	11.7M	0.91	245,700
Indiana	50	6.7M	0.91	182,910
West Virginia	30	1.9M	0.88	93,600
Pennsylvania	40	12.8M	0.83	398,400
Kentucky	30	4.46M	0.94	209,620
Michigan	50	10M	0.84	252,000

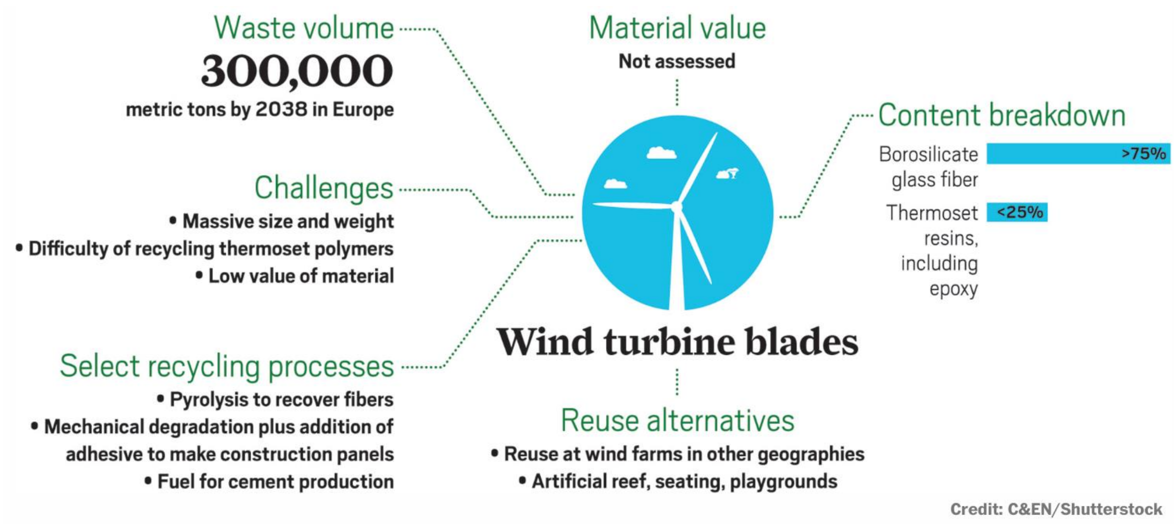
Wind Turbines

The purpose of wind turbines is to convert the kinetic energy in the wind into mechanical power. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity. There are two types of wind turbines, Horizontal-axis- like the traditional farm windmills used for pumping water and Vertical-axis- like the eggbeater-style Darrieus model. The blades of the wind turbine are the toughest part to recycle. The U.S. will have more than 720,000 tons of blade material to dispose of over the next 20 years. The reason these blades are tough to recycle is because they are the highest cost component. Blades can be 150 feet long or longer and weigh up to 8 tons each. Blade materials [9] [10]:

- Glass fiber (E-glass) [Most common]
  - Alternatives: Carbon fibers, Aramid and basalt fibers, Hybrid composites, Natural fibers
- Thermosets [Most common]
  - Alternatives: Thermoplastic, Nanoengineered polymers and composites
  - Also, may contain a core of PS foam, polyurethane foam or balsa wood to reduce weight and alter stiffness.

Wind Turbine recycling is still in its infancy. Namely, the recycling processes for wind turbine blades are still in its early stages. As it stands, the complex composite material that makes up a wind turbine blade is very tricky to recycle back to its original components. However, some people have still found creative ways of dealing with this problem.

One solution is to shred the blade and use it as an additive in solid fuel or cement. Due to the gigantic size of these blades, they are often shredded on site before being transported to their corresponding cement/fuel facility. In some instances, they can even be reused as park benches or playground equipment. The following figure outlines some of the challenges associated with wind turbines.



[12]

Unfortunately, the increase in usage of wind turbines recently has only made these challenges more urgent. In the last 20 years, roughly 100,000 new wind turbines have been installed in the U.S. The following table shows this drastic increase in wind turbine usage [13]:

Year	Ohio	Texas	California	US
1999	0	180	1,646	2,500
2000	0	181	1,646	2,566
2001	0	1,096	1,714	4,261
2002	0	1,096	1,822	4,685
2003	3.6	1,293	2,043	6,374
2004	7.2	1,293	2,096	6,740
2005	7.2	1,995	2,150	9,149
2006	7.4	2,739	2,376	11,575
2007	7.4	4,296	2,439	16,596
2008	7.4	7,116	2,517	25,410
2009	7.4	9,403	2,798	34,863
2010	9.6	10,089	3,252	40,267
2011	112	10,394	3,917	46,916
2012	428	12,214	5,542	60,005
2013	428	12,355	5,830	61,107
2014	435	14,098	5,917	65,880
2015	443	17,713	6,108	74,471
2016	545	20,321	5,662	82,171
2017	617	22,637	5,609	89,078
2018	729	24,899	5,855	96,487

[14]

Wind Turbine Recycling Design Progress

The purpose of this design was to come up with a process for recycling wind turbine blades. Turbine blades are particularly tricky to recycle as explained in the previous section of this report. One way a turbine blade can be reused is by shredding it and adding it to a cement or solid fuel mixture. We ultimately decided on coming up with a system that disassembles, shreds, and transports the blade material. Unfortunately, continuation for this portion of the project was terminated due to time constraints caused by the COVID-19 pandemic. However, three possible designs were created by our team. These designs are on-going and cannot be released at this time.

I-Corps Experience

I-Corps was created in 2011 by the National Science Foundation. The goals of the program are to reduce time and risk for technologies from laboratories; teach inventors to elicit and understand customer needs to guide pathway to commercialization. The focus is rather than jumping into product development, investigate what a buyer demands in the solution first. The number one reason why businesses fail is due to a lack of customer need.

The purpose of determining customer need is to give value to the customer. The initial value proposition was:

- Small size machine of regional LIBs recycling. This solves the unsafe transportation issue of retired LIBs and significantly reduces the cost of LIB transportation to a central plant. The expected cost saving of regional LIB recycling will be expected to be about 20%.
- Recycling LIBs (separation) can be done by spending about 10% of the selling price of new LIBs
- Regeneration of the separated materials to build new LIBs can be done by spending less than one-third of the cost of new LIB's materials.

The initial focus of the customer interviews was 5 specific customer segments:

- General Recycling Facilities
- General Consumers
- Car and Done Makers
- Defense Industry
- Battery Manufacturers

Based on the customer interviews it was determined that general consumers were not the target segment, they had nothing below surface level interest in what the product had to offer. Once this was determined we moved to contacting local junk yards and batter collection facilities. This came with to conclusions:

- Most local recycling facilities do not currently have a LIB recycling facility
- Collection facilities had very little information on where the batteries were sent, once they left the location.

From this point we switched to attempting to contact those in the LIB industry. Using LinkedIn engineers at A123 Systems, Altairnano, and LG Chem we contacted. The tactic was to send them messages while trying to become connections. In this time frame over 10 engineers were contacted and only 2 responded to the initial message, and after that no response. After speaking to those in the I-Corps program who have worked with people within the LIB industry it was discovered that it is a very reserved sector. This caused getting an inside technical knowledge on LIB to be difficult.

Since getting interviews were proving to be difficult the customer segment was changed again. The next group was broader, we moved toward the National Science Foundation Small Business Innovation Research team. There were 4 members of that team contacted, those focused on Chemistry and Environmental factors. Once again, those who responded declined the interview and others did not answer.

The goal of I-corps was to have 21 interviews after 7 weeks. With the Covid-19 pandemic along with this industry we did not reach this goal. Moving forward based on what was learned there are still questions to be answered to fully understand what the customer segment should be. To continue the focus should be:

1. Finding a way into the LIB industry in order to get some inside industry information.
2. Finding where LIB go to be recycled
3. Seeing if current recycling industries are looking for this technology
4. Look into government agencies

Listed are also tentative interview questions that Dr. Farhad had that were used as a steppingstone for the direction of the interviews.

- Do you currently have a plan to recycle your LIBs, or will you have such a plan soon? (this is a question from LIB manufacturers and consumer companies)
- Do you currently have a plan to add a LIB recycle section to your facilities, or will you have such a plan soon? (this is a question from recycling companies)
- How much should be the net profit of recycling LIBs (per pound) to make you interested in adding a LIB recycle section to your facility? (this is a question from recycling companies)
- If the materials are separated and regenerated, are you interested to use your batteries' materials to make new batteries? (this is a question from LIB manufacturers)

- If LIBs are built from recycled materials, are you interested to buy and use recycled LIBs? (this is a question for LIBs' consumer companies)
- Which model is more desirable for you? (a) own your plant to recycle your LIBs, (b) sign a contract with recycling plants to recycle your LIBs (this is a question from LIB manufacturers and consumer companies)
- Which model is more desirable for you? (a) Regionally collection and separation of LIBs materials, or (b) collecting the retired batteries and shipping them to a central location for recycling (this is a question from general recycling companies)
- If materials are separated, are you interested in buying the separated materials from a recycling facility for possible regeneration in your company and reusing to build a new battery? (this is a question from LIB manufacturers)
- If materials are separated and regenerated to an acceptable state, are you interested to buy the regenerated materials to build a new battery? (this is a question from LIB manufacturers)
- Which materials are more desired for separation from retired LIBs? (a) cathode materials (metal oxides), (b) anode materials (graphite and Si/C), (c) copper current collector, and (d) aluminum current collector. Rank them from the most to least desired ones. (this is a question from LIB manufacturers)
- Which materials are more desired for regeneration and reusing? (a)cathode materials (metal oxides), (b) anode materials (graphite and Si/C), (c) copper current collector, and (d) aluminum current collector. Rank them from the most to least desired ones. (this is a question from LIB manufacturers)

Lithium Ion Battery Recycling Research

A lithium-ion battery is a type of rechargeable battery that is commonly used for portable electronics and electric vehicles and is growing in popularity. Lithium ions move from the negative electrode through an electrolyte to the positive electrode during discharge, and back when charging. Each battery is made up of cathode and anode materials.

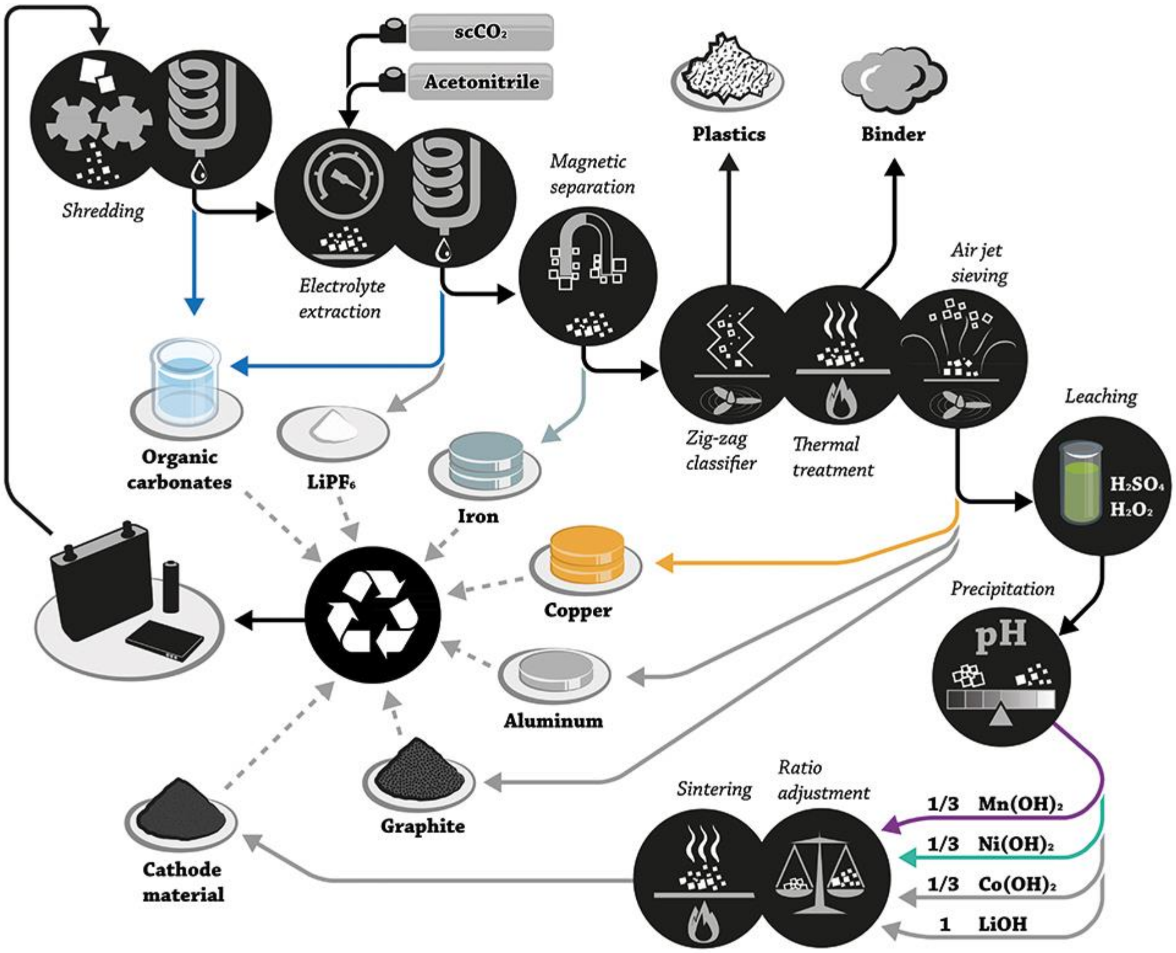
Cathode Materials

- Lithium Cobalt Oxide ($LiCoO_2$)
  The cobalt-based cathodes are ideal due to their high heat capacity, high volumetric capacity, low self-discharge, high discharge voltage, and good cycling performance
- Lithium Manganese Oxide ($LiMn_2O_4$)
  Manganese cathodes are cheaper, and they could theoretically be used to make a more efficient, longer-lasting battery

Anode Materials

- Graphite
  Low cost and good energy density
- Silicone/Carbon
  Abundant and are electrically conducting and can intercalate lithium ions to store electrical charge with modest volume expansion

Less than 5% of spent lithium-ion batteries are recycled today. There are only 2 facilities in the US currently. With current high pricing for cobalt and lithium, and a huge demand wave for Li-ion batteries on the way (currently 26 mega factories planned to be recycled by 2021), the Li-ion recycling industry may soon emerge as a new trend. [15]



In recent years, the use of lithium-ion batteries has drastically increased. This is mainly since as technology progresses, so does our exposure to mobile devices such as cell phones and laptops. With a greater number of mobile devices produced, consequently a greater number of rechargeable lithium-ion batteries are also produced. To give some perspective on exactly how many mobile devices are currently in use, the following statistics are given:

- 300 million cell phones in use [16]
- 50 million laptops sold per year [17]
- 60 million wearable electronics (smartwatches/bluetooth headphones) [18]
- 40 million misc devices (remotes, calculators, hearing aids, etc…) [19]
- 1 million electric vehicles sales [20]

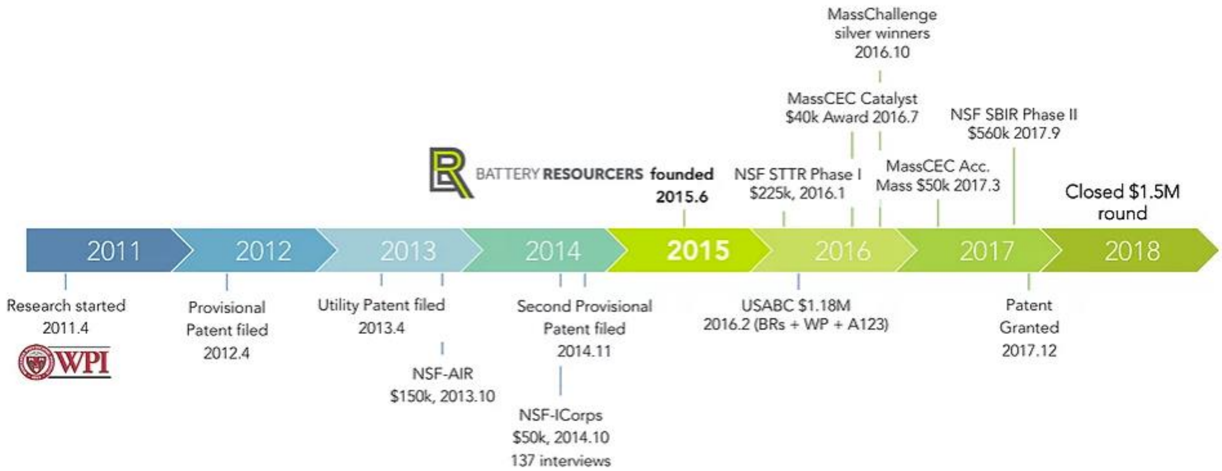
To help recycle this surplus of batteries, many programs have been created across the U.S to help with this problem. Some main programs are listed as follows:

U.S Department of Energy Battery Recycling Research and Development Center (Lemont, Illinois) [21]

- DOE’s first Li-ion battery recycling center (ReCell Center)
- Goal is to make Li-ion battery recycling competitive and profitable to reduce U.S foreign dependence on battery materials
- Recycled battery materials are used to reduce production costs by 10 to 30 percent
- Research is collaborative with multiple universities around the U.S
- Four main research areas:
  - Processes to generate products that go directly back into new batteries (minimizing reprocessing costs)
  - Processes to extract other useful battery materials
  - New Li-ion battery designs to simplify recycling processes
  - Modeling and analysis tools to help efficiently validate work from R&D

Battery Resourcers - Worcester, Massachusetts [22]

- Their process directly synthesizes new cathode materials from spent lithium ion cells
- Battery Resourcers manufactures and delivers low-cost cathode materials to the lithium ion battery market, enabling green technologies and resulting in less landfilled material
- In 2017 Battery Resources was awarded a $50,000 grant from the Massachusetts Clean Energy Center



Lithium-ion Battery Recycling Process

A breakdown of the first process is listed below:

- Collect devices with Li-ion batteries
- Extract batteries from the devices
- Separate materials within the battery
- Recycle each of those materials
- Sell recycled materials

From this, 3 processes were identified:

- Smelting
- Hydrometallurgy
- Direct Recycling

After analyzing profitability, process, mobility, and Market distribution the weighted decision matrix below was formed:

Criteria	Weight	Design Variants		
		Smelting	Hydrometallurgy	Direct Recycling
		1.9	2.4	4.1
Profits	0.5	2	3	4
Process	0.2	2	2	4
Mobility	0.1	1	1	3
Market Distribution	0.2	2	2	5

1 - poor/unusable
2 - barely acceptable
3 - adequate
4 - good
5 - ideal/very good

This project is on-going, and the designs cannot be released at this time. Another design team will be taking this project over as the current members are graduating this semester. The next steps with these designs have been outlined but cannot be shown.

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