Hydrometallurgy for EV batteries

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Key Messages

- Hydrometallurgy is the best technology to date for recycling EV batteries.
- Hydrometallurgy is environmentally benign compared to other recycling techniques such as pyrometallurgy and reduces the need for mining virgin materials.
- It can contribute to creating a circular economy for high-value minerals such as Lithium, Manganese, Nickel, and Cobalt.
- It can be scaled down to fit the needs of developing countries and is the safest way to prepare for the upcoming battery tsunami, thus ensuring a resilient urban mobility system.

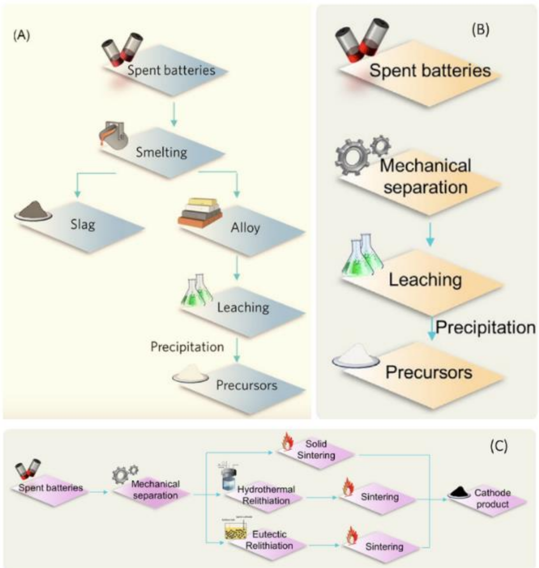
Introduction

There is an urgent need for clean and affordable energy around the planet. Transportation contributed to 23% of total global GHG emissions in 2016.[1] To achieve carbon neutrality in the transportation sector, many approaches are being utilized and different technologies have been deployed. Among them, Electric vehicles (EVs) are projected to play a key role in the decarbonization of the future mobility system. At the end of 2020, the number of electric cars surpassed 10 million. The global EV fleet is expected to reach 230 million vehicles in 2030 (excluding two/three-wheelers), with a stock share of 12%.[2] The growing deployment of EVs will be proportional to the growth in demand for EV batteries, thus raising concerns about an upcoming battery 'tsunami'. The mining of virgin materials raises concerns about forced and child labor as is the case for cobalt ore in the Democratic Republic of Congo (DRC). Moreover, lithium mining and improper disposal of lithium-ion batteries also raise environmental concerns such as soil and water pollution and the risk of fire.[3] Recycling provides a sustainable way to return battery materials into the market, which is critical for supporting the infrastructure driving global electrification. There are three main recycling routes for EV batteries:

- ***Smelting*** (pyrometallurgy) treats the batteries as if they were an ore exposing them to high temperatures (over 1100°C) to melt or burn the components of the cell.[4] This process allows recovery of only about 50% of the black mass, which is the mixture of high-value elements such as graphite, manganese, cobalt, nickel, and lithium obtained after mechanical treatment of spent batteries. This process also releases harmful gases into the atmosphere.
- ***Direct recycling*** is the recovery, regeneration, and reuse of battery components directly without breaking down their chemical structure. This recycling process provides the quickest pathway for cathode powder and other materials to get back into the battery supply chain. This method of recycling is still in the R&D stage, and additional work is needed to make direct recycling a profitable process.[4]
- ***Hydrometallurgy*** is a wet process that converts a mixture of cell chemistries into a product that can be reintroduced as cathode precursors. In this process, most of the battery components can be recovered as metals (copper, aluminum) or salts (lithium, nickel, cobalt, manganese, etc.). This process can allow an overall recovery rate of up to 95 % of the black mass.[4]

The urgent need for Lithium-Ion Battery (LIB) recycling and the potential for hydrometallurgy as a technology to address these needs will be investigated. Life Cycle Analysis assesses the environmental friendliness of hydrometallurgy technology. Materials Flow Analysis provides information about the impact of hydrometallurgy in the flow of valuable battery materials. Expert contributions provide insights, concerns, and recommendations about EV batteries both globally, and from the perspective of developing countries. The recycling of EV batteries will address issues related to human health and wellbeing, sustainable transport in cities and communities, responsible consumption and production, and reduce environmental and climate impact.

Figure 1. Illustration of three main EV battery recycling processes A- pyrometallurgy, B-Hydrometallurgy, C-Direct Recycling



Current State of Technology

Hydrometallurgy consists of three main steps which are pretreatment, leaching, and metal deposition. The pretreatment starts with the discharging of the battery, which is followed by a mechanical process to separate the cathode materials from the anode materials. After this process, a mixture of valuable cathode materials in form of a powder called black mass is obtained. Then a pretreatment is necessary, to remove the polymer binder, which is often Polyvinylidene Fluoride (PVDF) and polytetrafluoroethylene (PTFE). Pretreatment can be thermal involving heating around 500-600 °C, mechanical and physical that can include crushing, high voltage fragmentation, or electrohydraulic fragmentation, and ultrasonic washing. Another pretreatment route involves the use of organic and inorganic solvents, as well as supercritical fluids. After these pretreatment steps comes the leaching, which employs strong inorganic acids, organic acids, and reducing agents for the isolation of the battery materials.[3] The last step consists of metal deposition, which can be conducted chemically or electrochemically for the recovery of the final products. With a combination of processes thereof, some companies have achieved commercial-scale recycling of LIBs. More recently, biohydrometallurgy, which uses microorganisms such as fungi and bacteria to replace acid in the leaching process, has been investigated and could ensure a more sustainable future for hydrometallurgy technologies.[5,6]

Benefits and challenges

Table 1. Summary of pros and cons for hydrometallurgy

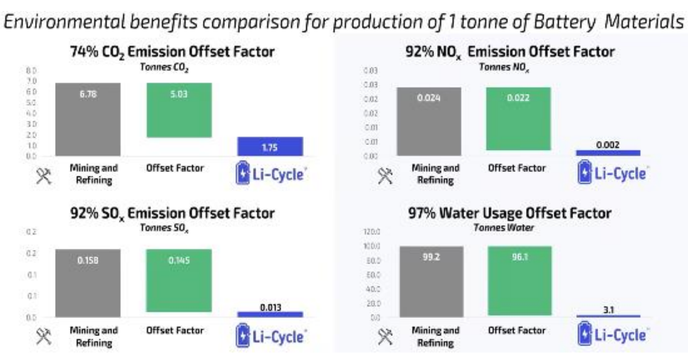
Benefits	Challenges
Life Cycle Analysis results[7] • Reduced GHG emissions, acidification, photochemical ozone, and toxic emissions • Reduced depletion of abiotic resources and fossil fuel	**Battery chemistries** • Technical challenges can be overcome easily • Combined processes (Pyro-Hydrometallurgy) raise concerns • Economic challenges associated with cobalt-free and Nickel-free batteries
Materials flow Analysis[8] • Hydrometallurgy can supply more than half of Cobalt, Lithium, Manganese, and Nickel worldwide by 2040	**Absence of regulations regarding battery manufacturing** • Absent in the U.S. • E.U. towards a new Directive
Competitive advantage • Equally competitive in terms of quality and price • No need for refining and recycled materials can be found in one place • Reduced socio-economic and environmental burden brought by battery materials mining	**Collection** • Need adequate transportation • Spent EV battery Collection might be challenging in developing countries

develop and implement frontier technologies for sustainable development, challenges vary depending on the context in a country or industry. This section highlights two common areas where impacts of frontier technologies may not necessarily produce sustainable development results, namely, 1) the impacts of frontier technologies on jobs, and 2) a new frontier technology divide.

Potential benefits

Life Cycle Analysis (LCA): In one life cycle assessment (LCA), the system boundaries included primary material extraction, cell production, the End-of-Life phase (i.e., recycling processes including emissions and disposal of waste streams) excluding the use phase of batteries.[9]. 1 kWh of storage capacity provided by the battery cell is used as a Functional Unit. It was found that the global warming impact of LIB is reduced by 12-25% of the total impact when recycling through hydrometallurgy to recover precious materials from LIB.

Figure 2. Third-party Life cycle Analysis[11]



A leading battery recycling company uses hydrometallurgy to recover materials from spent EV batteries. A third-party LCA of their hydrometallurgy recycling process was performed[10]. The system boundaries of LCA included the production of 1 ton of battery materials recovered from recycling of EV spent batteries through hydrometallurgy excluding production of original batteries and their use phase. Their LCA results are displayed in Fig. 1 showing that emission reduction is 74% for carbon dioxide, 92% for nitrates and sulfates, and 97% for water usage. The company claims that its technology does not generate liquid waste in the recycling process, and all liquids are recirculated and contained within the process.[10]

In another LCA[7], 1 kg of EV battery waste was used as a functional unit and the system boundary included a collection of spent EV battery waste and treatment of that waste to recover active materials excluding the production and use phase of batteries.[7] They found that the recycling of LIB through hydrometallurgy and using the recovered materials for producing new LIB reduced GHG emissions by 37.7%, acidification by 94.5%, photochemical ozone by 93.2%, toxic emissions by 81.2%, abiotic resource depletion by 78.2%, and fossil fuel depletion by 13.8% when compared to extraction of virgin materials to manufacture LIB[7].

Materials Flow Analysis: In the study (see appendix 1),[8] based on the assumptions that the materials are recycled by hydrometallurgy at a recovery rate of 95%, it was predicted that recycled batteries could supply 60% of cobalt, 53% of lithium, 57% of manganese, and 53% of nickel globally in 2040.[8]

Competitive advantage: End-of-life lithium-ion batteries and battery scrap contain several different highly valuable metals, such as lithium, cobalt, nickel, manganese, graphite, and others. contains all these materials – and mined materials need to be refined. Battery recycling is more cost-effective than mining in the long term because it recovers all the materials from one source, and they do not need to be refined. There will always be a need for mining, to a certain extent, but from a cost, efficiency, and environmental perspective for both quality and price, battery recycling is advantageous.[11] Lithium-Ion Battery manufacturing companies find recycled batteries equally competitive to mined batteries in terms of quality and price.[12]

Developing Countries: Developing countries can address the battery 'tsunami' in one of these two ways. The first one is battery collection. This is already a big concern for recycling facilities in developed countries. One solution is a partnership between the automobile manufacturers and the recycling facilities. The same approach should be considered in developing countries so that the collection task is performed by the automobile manufacturers' representatives. Second, the hydrometallurgy process can be scaled down enough, this means that developing countries can develop their own technologies, based on the current findings to develop local hydrometallurgy facilities.[13]

According to a reputable EV battery recycling company,[10] their hydrometallurgy technologies are patented and require a substantial level of expertise. One of the biggest advantages is that they started developing their technology in 2016 and were able to operate their first commercial facility in 2020. On top of the experience and expertise needed to develop lithium-ion recycling technologies, it takes time to get to the commercial scale that this recycling company has achieved.[10] Developing countries could either invest in research to reach similar commercial scale of the technology or collaborate with companies to use their existing patented technologies.

Challenges

Battery Chemistries: Five major types of cathodic compounds are commercially available, namely lithium-cobalt oxide (LCO), lithium-nickel-manganese-cobalt (NMC), lithium-manganese oxide (LMO), lithium-nickel-aluminum oxide (NCA), and lithium-iron phosphate

(LFP). According to Avicenne Energy, in 2015, NMC represented the largest percentage of the worldwide LIB market (~29%), followed by LCO (26%) and LFP (23%).[14] A resilient hydrometallurgical process should be able to isolate precious materials from all these chemistries. The EV battery recycling company claims to have future-proofed technology that can handle all those chemistries.[10] Battery experts consider that recovering materials from different battery chemistries is not a big technological challenge for hydrometallurgy companies.[12] However, hydrometallurgy is a broad term that can take multiple forms in its implementation, and governments should make sure that the process applied by each company is environmentally friendly. This latter concern is also shared by a global watchdog group that tracks global waste materials. They observed that many companies combine both smelting and hydrometallurgy for LIB recycling. Smelting is the most harmful process, causing emissions of metal and organic volatile compounds.[13]

Economic viability: Another challenge regarding battery chemistries is the economic viability of the recycling process. As of 2019, one ton of Cobalt, Nickel, and Lithium cost USD 35,500, USD 13,200, and USD 10,000, respectively.[3] The emergence of Cobalt-free and metal-free batteries has the benefit of lowering the burden on mining scarce virgin materials, and lowering the production cost LIBs, however, it may make the recycling of the batteries less attractive since the most expensive materials such as Cobalt and Nickel tend to be replaced.

Absence of regulation regarding recyclability of batteries*:* The recyclability of battery products is not yet regulated around the world *(see appendix 1, table 2)*. In the United States, only battery research programs are initiated. Europe is working towards issuing a new directive, and a proposal has been released in 2021 to replace the directive (2006/66/EC).[13,15] The purpose of these regulations is to ensure that batteries are designed in a way that makes their end-of-life and recyclability easier. For instance, PTFE is used in most LFP batteries as a binder. This compound can be more difficult to remove under mild chemical conditions later in the recycling process. Only China issued an order in 2018 to put accountability on automobile manufacturers for the collection and recycling of spent EV batteries.[16] This is a rare example that should be followed by other countries.

Policy Recommendations

- Policymakers should plan a national response based on the forecasted battery waste and make sure sufficient hydrometallurgy recycling facilities are in place.
- Governments should educate their citizens and communities about the dangers of spent unrecycled lithium batteries to foster a mutual effort towards their proper disposal.
- Governments should hold automobile manufacturers accountable for the efficient collection of spent batteries.
- Policymakers should adopt regulations about the entire life cycle of EV batteries including eco-design, manufacturing, disposal, recycling, and international trade of battery recycled materials to ensure the financial, environmental, and social sustainability of EV batteries.

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Annex

ANNEX 1. Analysis

Table 1. Materials flow analysis for Li, Co, Mn, Ni[8]

region/country	material demand or recycled	material name and flow (thousand metric tons)			
		cobalt	lithium	manganese	nickel
China	demand	168.37	150.70	162.05	698.50
	recycled	118.04	90.37	117.23	383.47
Europe	demand	135.23	121.01	130.15	561.02
	recycled	74.38	58.73	74.68	267.13
RoW	demand	229.90	205.74	221.28	953.80
	recycled	123.89	98.77	108.27	468.67
US	demand	113.20	101.30	108.95	469.62
	recycled	73.47	60.24	55.21	300.75

Table 2. Existing regulations and action plans

Country/Region	Legislation/ Action plan	Date passed
United States	EV Everywhere Grand Challenge Blueprint	2013[6]
Europe	Horizon 2020, 114 million euros for battery research and innovation Battery Strategic Action plan, includes recycling Battery 2030+	2010-2020, 10-year plan[6] 2017[6] 2020-2023 (3-year plan)[6]
China	China issued regulation in 2018 to make manufacturers	2018[6,16]

	responsible for collection and recycling of EV recycling	
Japan	Law Regulating the Import and Export of Certain Hazardous Wastes and Other Wastes	2004[6,17]

ANNEX 2. List of interviewees

- **Sailesh Upreti**, CEO of C4V a Lithium-ion battery manufacturing company in Endicott, New York
- **Jim Puckett**, Executive Director, Basel Action Network (BAN), A Non-profit Organization who works to combat exportation of technology toxic waste from developed countries to developing countries, Seattle Washington, United States
- **Lisa Crosby**, Researcher at BAN
- **Harry Nicholas**, Senior Associate ICR Inc., Strategic Communication & Advisory company for Li-Cycle, a major North American Hydrometallurgy company

ANNEX 3. Glossary

Anode: An anode is an electrode through which the conventional current enters into a polarized electrical device.

Cathode: An electrode through which conventional current leaves an electrical device.

Electric Vehicle: An electric vehicle (EV) is a vehicle that uses one or more electric motors for propulsion. It can be powered by a collector system, with electricity from extravehicular sources, or it can be powered autonomously by a battery (sometimes charged by solar panels, or by converting fuel to electricity using fuel cells or a generator). EVs include, but are not limited to, road and rail vehicles, surface and underwater vessels, electric aircraft and electric spacecraft.

Leaching: Leaching is a process widely used in extractive metallurgy where ore is treated with chemicals to convert the valuable metals within into soluble salts while the impurity remains insoluble.

Lithium-ion battery: A lithium-ion battery or Li-ion battery is a type of rechargeable battery in which lithium ions move from the negative electrode through an electrolyte to the positive electrode during discharge, and back when charging

Polytetrafluoroethylene (PTFE): Also known under the commercial name Teflon, it is non-reactive, partly because of the strength of carbon–fluorine bonds. It is widely used for non-stick cookware applications, and as a binder in lithium-ion batteries.

Polyvinylidene Fluoride (PVDF): A specialty plastic used in applications requiring the highest purity, as well as resistance to solvents, acids and hydrocarbons such as lithium-ion battery manufacturing as a polymer binder.

Relithiation: The reincorporation of lithium into an electrode in a lithium-ion battery

Sintering: A process in which the particles of a powder are welded together by pressure and heating to a temperature below its melting point

Slag: stony waste matter separated from metals during the smelting or refining of ore