MONTANA LEGISLATURE
OFFICE OF RESEARCH & POLICY ANALYSIS

ADDITIONAL ELECTRIC VEHICLE RECYCLING RESOURCES – PART 2

TRANSPORTATION INTERIM COMMITTEE
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The following information is provided in response to questions on the cost of EV battery recycling. **In brief, it's complicated to produce an estimate because of the many variables involved.** The review below may help to provide some clarification.

EverBatt: A Closed-Loop Battery Recycling Cost and Environmental Impacts Model. Energy Systems Division, Argonne National Laboratory, April 2019.

Link to Full Report: https://publications.anl.gov/anlpubs/2019/07/153050.pdf

Electric vehicle lithium-ion battery recycled content standards for the US – Targets, Costs, and Environmental Impacts. Jessica Dunn, et al. Resources, Conservation & Recycling 185 (2022) 106488.

Link to Journal Article: https://doi.org/10.1016/j.resconrec.2022.106488

The first report provides a methodology (the EverBatt model) for calculating the recycling costs to recover EV battery materials that can then be reused and/or repurposed. That methodology was utilized in the journal article (second link above); the goal of the research from that article was to look at calculation of feasible recycled content standards, which mandate a percent of constituent material in a product to be from recovered sources, possibly increasing recycling rates by creating a market for the reclaimed materials.

The following equation from the first report is a very basic overview used in the EverBatt model to calculate the net cost of recycling:

$$Net\ recycling\ cost = transportation\ cost + recycling\ cost - Revenue$$

OVERVIEW OF RECYCLING VARIABLES

There are many variables to consider in terms of calculating the cost of electric vehicle battery recycling. For example, there are different types of recycling, and each type has its own costs and varies in terms of what materials are recovered and efficiency to recover those materials.

The three main types of recycling covered in the report include:

1. **Pyrometallurgical**, which involves sending the batteries to a smelter where electrolytes and plastics in the batteries are burned off to supply heat; there is also a process of solvent extraction and precipitation

involved to produce the cobalt and nickel compounds which can be used for new cathode materials production. This is currently the most common method in the U.S. The following flow chart provides a general illustration of the steps in the process:

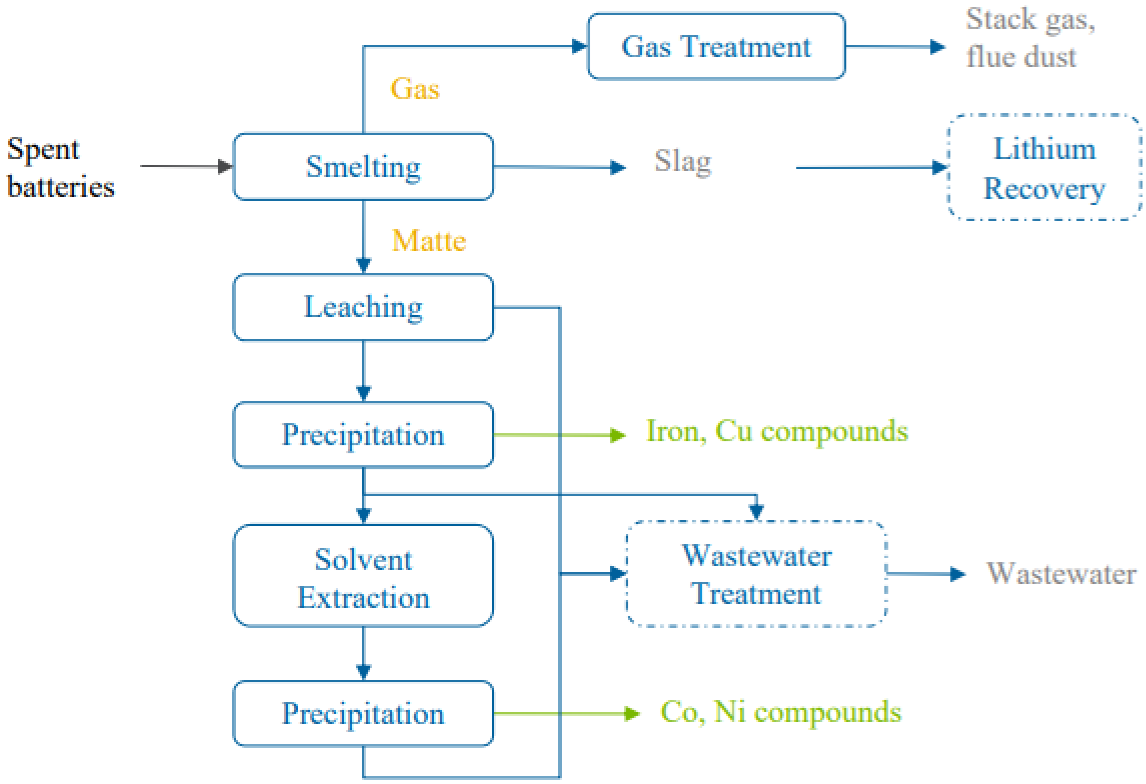

Figure 2. Process diagram of a generic pyrometallurgical recycling process. Solid boxes denote common unit operations; dashed boxes denote optional unit operations; green denotes products; yellow denotes intermediate products; grey denote wastes.

Source: Argonne National Laboratory

2. **Hydrometallurgical**, in which the discharged and disassembled batteries are shredded and then undergo a low temperature heating process (calcination) to burn off the binder and electrolyte, then several physical separation processes occur, followed by a leaching process and a solvent extraction to produce the cobalt, nickel, manganese, and potentially lithium carbonate for new cathode materials. The following flow chart provides a general illustration of the hydrometallurgical process:

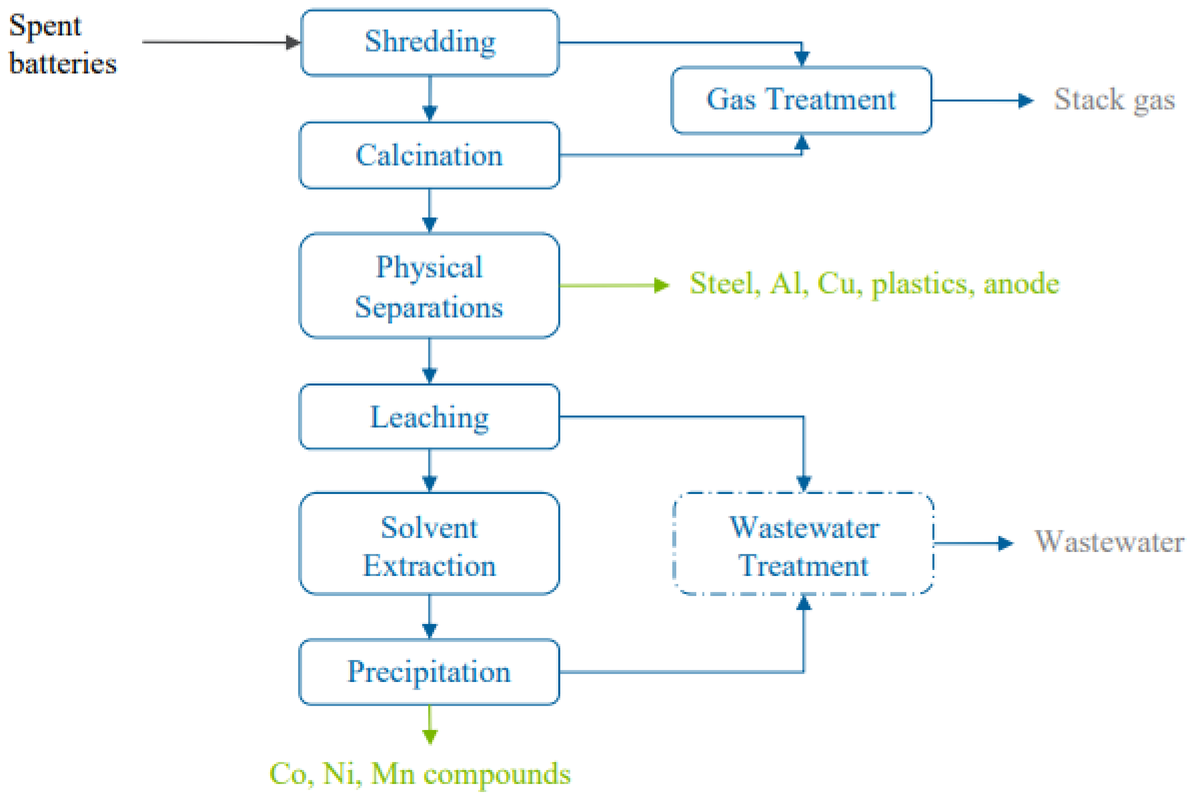

Figure 3. Process diagram of a generic hydrometallurgical recycling process. Solid boxes denote common unit operations; dashed box denotes optional unit operation; green denotes products; grey denotes wastes.

Source: Argonne National Laboratory

3. **Direct recycling**, in which disassembled batteries are perforated first, and then undergo an extraction process to recycle the electrolyte solvents and salts. The rest of the battery material is then shredded and goes through a series of physical separation processes to recover materials. Finally, the recovered cathode materials are then relithiated (a process that restores lithium content to cathode materials) to produce rejuvenated cathode powder. The following flow chart provides a general illustration of the direct recycling process:

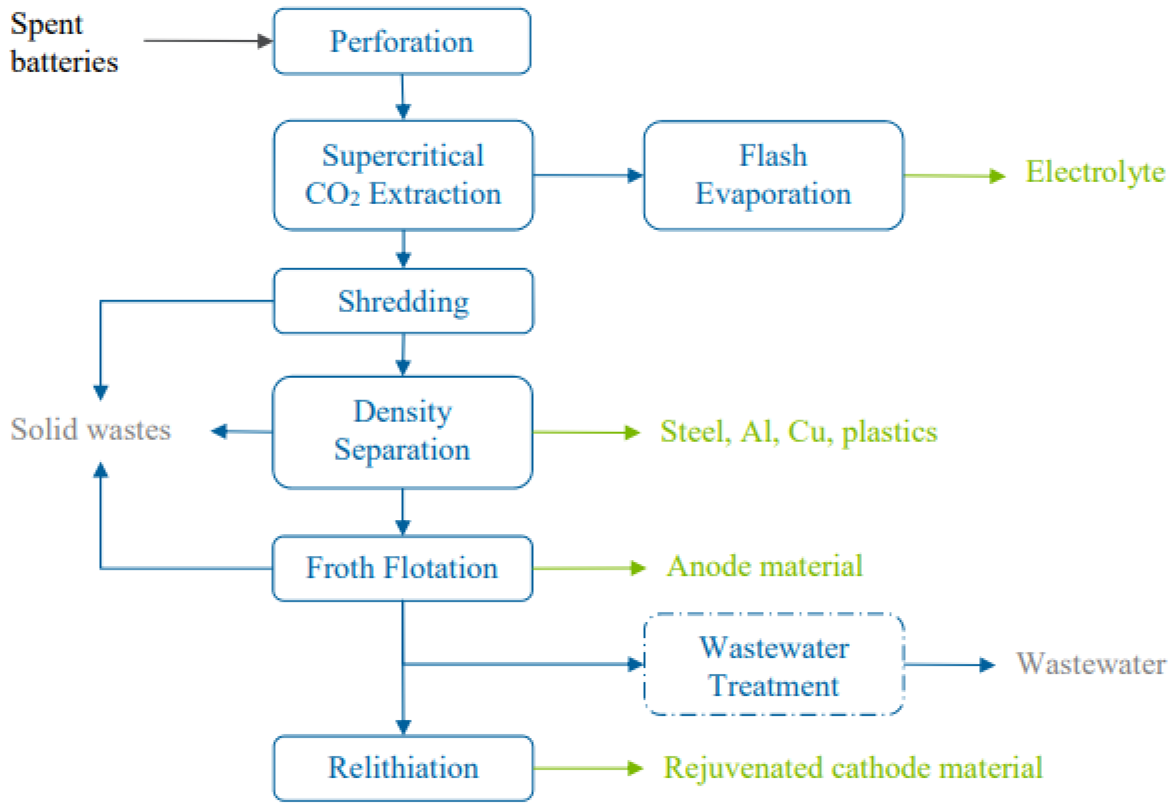

Figure 4. Process diagram of a generic direct recycling process. Solid boxes denote common unit operations; dashed box denotes optional unit operation; green denotes products; grey denotes wastes.

Source: Argonne National Laboratory

Depending on the recycling process, material recovery efficiency can vary. For both cobalt and nickel, the recovery efficiency is about 98% for the pyrometallurgical and hydrometallurgical recycling.

TRANSPORTATION COSTS

Transportation in the EverBatt model considers transportation to be the entire transportation process from the last user to the collection site to transportation of material and scrap to their end points. Lithium-ion batteries are considered class 9 hazardous materials for transportation, which increases the cost of transport, as shown in the following table detailing the default unit cost in $/ton-mile for different transportation modes. For clarification, ton-mile is a unit of measurement that represents the transportation of one ton of freight for a distance of one mile.

Table 8. Default unit cost ($/ton-mile) for different transportation modes

	Class 9 Hazardous ($/ton-mile)	Non-hazardous ($/ton-mile)
Rail	0.97[a]	0.05[c]
Heavy heavy-duty truck	6.28[a]	0.14[c]
Medium heavy-duty truck	9.4[a]	0.15[c]
Ocean tanker	0.5[b]	0.02[d]
Barge	0.5[b]	0.02[e]

a. 2012 U.S. national average, United States Census Bureau 2015
b. Own estimate
c. 2007 U.S. national average, Austin, D. 2015
d. Assumed to be the same as barge cost
e. 2004 U.S. national average, United States Department of Transportation 2019

Source: Argonne National Laboratory

As shown in the table, medium and heavy-duty trucks represent the highest cost per ton-mile for transportation, whereas ocean tanker and barge have the lowest unit costs.

TOTAL COST (HYDROMETALLURGICAL RECYCLING)

The following table from the Dunn et al. journal article shows a breakdown of the total cost of recycling, using the hydrometallurgical recycling method, including transportation, collection, disassembly, and recycling. The article notes that recycling is highly affected by economies of scale, as well as the location of recycling, mode of transportation, and level of disassembly.

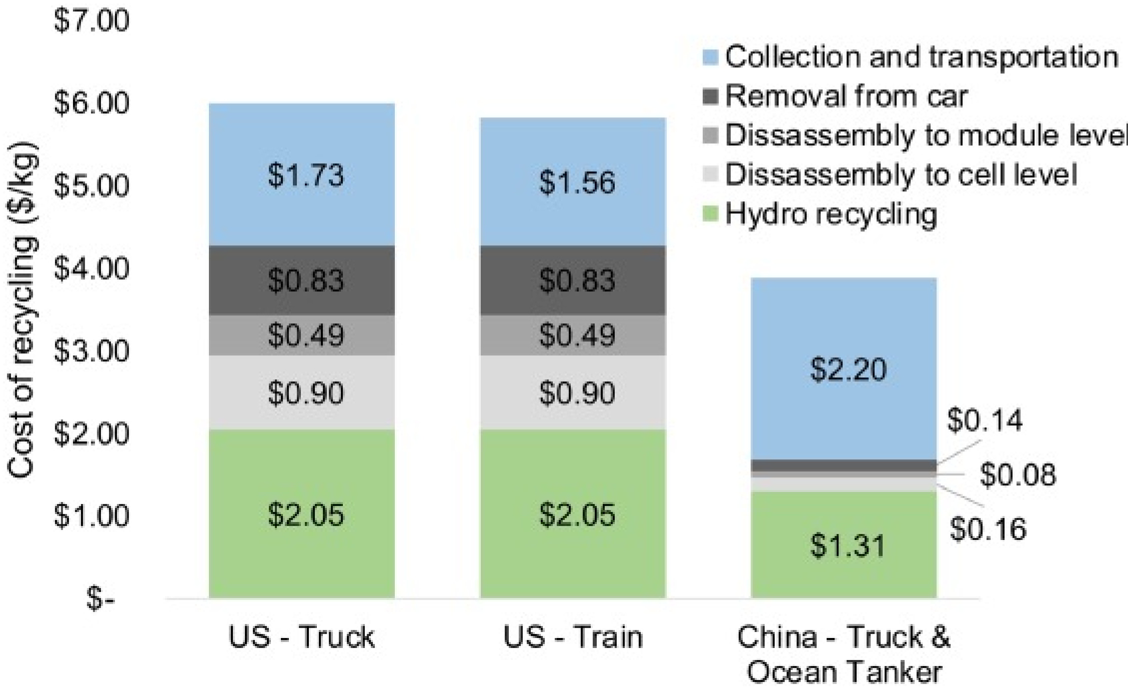

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Fig. 3. The cost ($/kg) of a hydrometallurgical recycling facility in 2020 broken out by the cost of disassembly, the cost of hydrometallurgical recycling, and the cost of collection and transportation.

Source: Dunn et al.

As shown in the chart, recycling in China has the overall cheapest cost, despite having the highest cost of collection and transportation. This is due to a lower estimated cost of labor and equipment. The article notes that in the EverBatt model, disassembly is modelled to be performed by hand, and thus the cost is mostly labor. The article states that recycling in the U.S. is estimated to cost $50/hour while recycling in China is estimated to be $7.50/hour. Also, per the article, due to a lack of battery standardization, it is difficult to automate the disassembly process.

REVENUE - MATERIAL RECOVERY UNIT PRICES

For the revenue portion of the net cost of recycling equation, that is calculated as the mass of material recovered from the spent batteries times the unit price of the material.

The following chart provides unit prices of recovered battery materials ($/kg). Metals, plastics, and graphite are assumed to be recovered and sold as scrap. Recovered cobalt, nickel, manganese, and lithium compounds from cathode materials are assumed to be considered good as new by cathode powder producers and to sell at the same prices as their newly mined counterparts.

Table 14. Unit prices of recovered battery materials ($/kg)

Materials	Unit Prices ($/kg)
Aluminum	$1.30[a]
Copper	$6.60[a]
Steel	$0.30[a,b]
Plastics	$0.10[c]
LCO	$35.00[d]
NMC(111)	$20.00[d]
NMC(622)	$17.00[d]
NMC(811)	$16.00[d]
Lithium carbonate	$7.90[d]
Ni2+ in output	$11.00[d]
Co2+ in output	$55.00[d]
Mn2+ in output	$2.00[d]
LMO	$10.00[d]
NCA	$24.00[d]
LFP	$14.00[d]
Electrolyte solvents	$0.15[e]
Graphite	$0.28[f]

a. Scrap Register 2019
b. United States Geological Survey (USGS) 2016a
c. Plastics Markets 2019, assumed to be recovered as mixed film
d. Assumed to sell at the same price as virgin material
e. Own estimate
f. Recycler's World 2019

Source: Argonne National Laboratory

As shown in the table, cobalt (Co2), lithium cobalt oxide (LCO), and nickel cobalt aluminum (NCA) have the highest unit prices of recovered materials, while graphite, electrolyte solvents, and plastics have the lowest.