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EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model

Energy Systems Division

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by
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ACRONYMS

Argonne	Argonne National Laboratory
BatPaC	Battery Performance and Cost
BC	black carbon
BEV	battery electric vehicle
BMS	battery management system
BOM	bill-of-materials
CEPCI	chemical engineering plant cost index
CO	carbon monoxide
CO_2	carbon dioxide
CSTR	continuous stirred tank reactor
DMC	dimethyl carbonate
EC	ethylene carbonate
EIA	Energy Information Administration
EOL	end-of-life
EPA	Environmental Protection Agency
EV	electric vehicle
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GHG	greenhouse gas
GSA	general, sales, administration
IEA	International Energy Agency

LCA	life cycle analysis
LCI	life cycle inventory
LCO	lithium cobalt oxide ($LiCoO_2$)
LFP	lithium iron phosphate ($LiFePO_4$)
LIB	lithium-ion battery
LME	London Metal Exchange
LMO	lithium manganese oxide ($LiMn_2O_4$)
NCA	lithium nickel cobalt aluminum oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$)
NMC	lithium nickel manganese cobalt oxide ($LiNi_{x/x+y+z}Mn_{y/x+y+z}Co_{z/x+y+z}O_2$)
NMC111	$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$
NMC622	$LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$
NMC811	$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$
NMP	N-Methyl-2-pyrrolidone
NO_x	nitrogen oxides
OC	organic carbon
PE	polyethylene
PET	polyethylene terephthalate
PHEV	plug-in hybrid electric vehicle
PM10	particulate matter with diameters of 10 micrometers and smaller
PM2.5	particulate matter with diameters of 2.5 micrometers and smaller
PP	polypropylene
PVDF	polyvinylidene difluoride
R&D	research and development

SO_x sulfur oxides

T&D transmission and distribution

tonne metric ton

USGS United States Geological Survey

VOC volatile organic compound

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1 INTRODUCTION

The cumulative global electric vehicle (EV) sales surpassed 3.1 million units in 2017, with 1.9 million units of battery electric vehicles (BEVs), and 1.2 million units of plug-in hybrid electric vehicles (PHEVs). Of the cumulative global EV sales, The U.S. accounted for 0.40 million BEV sales, and 0.36 million PHEV sales (IEA 2018). Assuming a lifespan of 10 years for EVs, an average battery pack weight of 300 kg for BEVs, and an average battery pack weight of 200 kg for PHEVs, by 2027, 0.2 million metric tons of EV batteries would reach their end-of-life (EOL) in the U.S. Globally, the volume of spent automotive batteries would amount to 0.8 million metric tons by 2027. As the annual global EV sales are expected to grow from 1.4 million in 2017 to 21.5 million in 2030 (IEA 2018), the volume of spent automotive batteries would increase markedly beyond 2027.

The retired batteries from EV applications could be reused (that is, batteries are refurbished and then used again in EVs) and/or repurposed (that is, batteries are tested, oftentimes repacked, and then used in less demanding applications such as stationary energy storage). Ultimately, the foreseeable avalanche of spent automotive batteries underscores the need for infrastructure and technologies that will be able to responsibly and sustainably handle and dispose of the spent batteries even if they are used multiple times beforehand. Recycling is one of the most promising EOL management options, because it has the potential to considerably reduce the environmental impacts of batteries, while simultaneously helping guard against possible price surges and supply disruptions of battery materials, especially when the recovered cobalt, nickel, and lithium from the spent batteries are incorporated back into the battery supply chain (i.e., closed-loop recycled). On the other hand, since lithium-ion batteries (LIBs) are classified as hazardous materials, proper disposal of spent automotive batteries incurs substantial costs and poses significant challenges to the LIB industry.

Aiming to enhance stakeholders' understanding of the cost and environmental performance of battery recycling, and to inform the planning and development of battery recycling towards an environmentally friendly and economically feasible future, we at Argonne

National Laboratory (Argonne) developed EverBatt, the first publicly available closed-loop battery recycling cost and environmental impacts model, with the support of the Department of Energy, to help evaluate the performance of different battery recycling technologies, and identify R&D opportunities and challenges.

2 EverBatt Model Overview

2.1 Goal and Scope

The overarching goal of the EverBatt model is to help inform battery recycling decisions and accelerate the development of a more sustainable supply chain for batteries. Specifically, EverBatt allows users to (1) benchmark production with recycled materials against production with virgin materials to provide a holistic picture of the benefits and tradeoffs of battery recycling, (2) estimate the cost and environmental impacts of existing industrial practices along the battery supply chain, identify cost and environmental hotspots, and evaluate potential consequences of business decisions and market dynamics, and (3) benchmark new technology/processes against existing practices of the battery industry, and analyze how the cost and environmental impacts could change as the new technology/process scales up.

The schematic of the EverBatt model is depicted in Figure 1. The model consists of six modules: battery manufacturing with virgin materials, battery collection and transportation, battery recycling, materials conversion, cathode powder production, and battery manufacturing with recycled materials, among which battery manufacturing with virgin materials is a stand-alone module and serves as the benchmark, whereas the remaining five modules comprise the closed-loop recycling. The battery collection and transportation module, together with the recycling module can also be used independently to evaluate open-loop recycling, or in combination with the materials conversion module and the cathode material production module to evaluate closed-loop recycling at the materials level. Depending on the battery recycling process under analysis, the material conversion module and cathode powder production module can be bypassed. It should be noted that the battery use-phase is not included in EverBatt, because unlike the other life-cycle stages of a battery, the use-phase cannot be modeled independently of the product the battery powers and/or the service the battery provides. For instance, modeling the use-phase of an automotive battery necessitates modeling of the EV use-phase, which is beyond the scope of EverBatt.

For battery recycling processes, EverBatt considers pyrometallurgical, hydrometallurgical, and direct cathode recycling routes, which are discussed in detail in Chapter 5. For battery cathode chemistries, EverBatt covers $LiCoO_2$ (LCO), $LiMn_2O_4$ (LMO), $LiFePO_4$ (LFP), $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC111), $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC622), $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811), and $LiNi_{0.85}Co_{0.1}Al_{0.05}O_2$ (NCA). For geographic regions, EverBatt currently includes California, U.S. national average, China, and Korea.

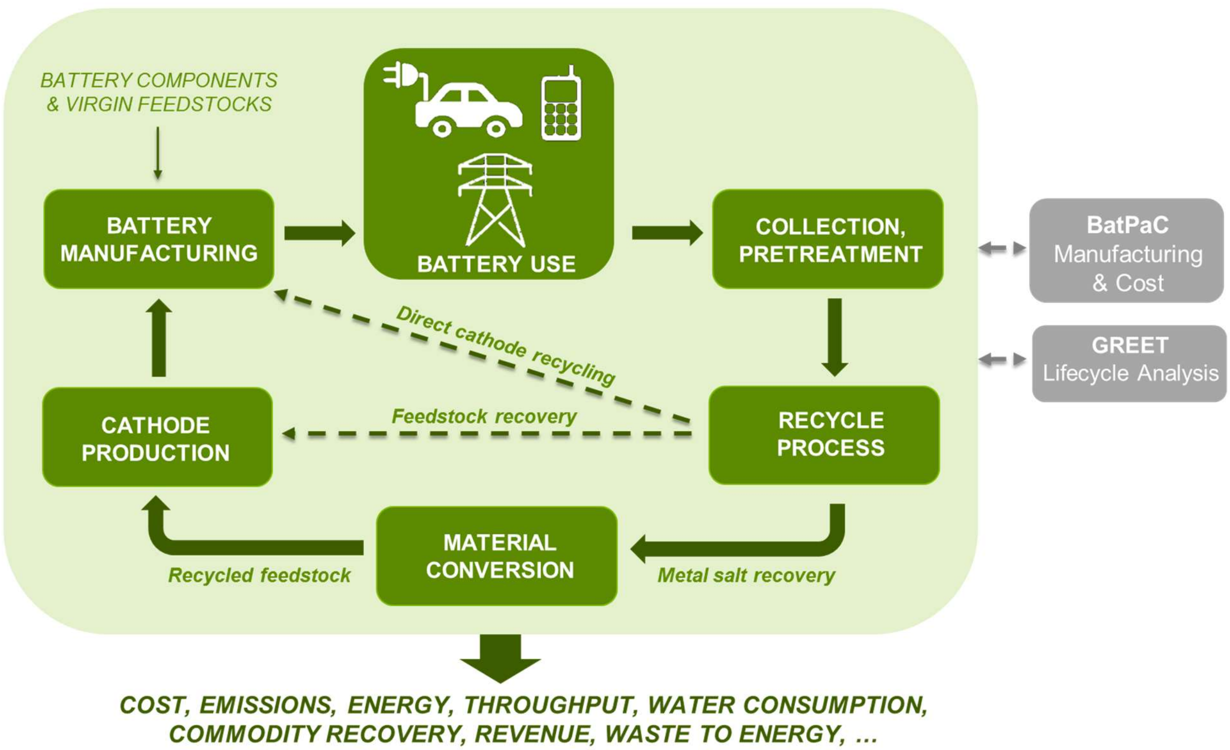

Figure 1. Schematic of the EverBatt Model.

In general, the inputs for each module include the materials and energy flows through the processes, the equipment used for the processes, and the throughput and geographic location of the processes. With these inputs, EverBatt then estimates (1) the cost of the processes based on Argonne's Battery Performance and Cost (BatPaC) model (Argonne 2019a, version BatPaC 3.1 – 28June2018) and a cost model for general chemical plants proposed by Peters *et al.* (Peters *et al.* 2003), and (2) the environmental impacts of the processes based on background data from Argonne's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (Argonne 2019b, version GREET 2018). The methodology used for the cost and environmental impacts calculation is further discussed in Section 2.2, and the nuances of the calculations specific to each module are discussed in Chapters 3-8, respectively.

It should be noted that the current version of EverBatt models batteries at the cell level, because information on recycling of battery pack components, particularly the battery management system (BMS), is still lacking. We will bridge this gap in future versions of EverBatt. It should also be noted that the current version of EverBatt focuses on LIBs, because they are the predominant battery type for traction applications. Future versions of EverBatt, however, will be expanded to cover other battery types beyond traction applications.

2.2 METHODOLOGY

2.2.1 Cost Analysis

The cost analysis for battery manufacturing, with both virgin materials and recycled materials, is based on Argonne's BatPaC model. The price of the battery includes the costs of materials, direct labor, depreciation of capital investment, variable overhead, general, sales, administration (GSA), research and development (R&D), profit, and warranty. Details of the battery manufacturing cost model are discussed in Chapter 3.

The cost analysis for recycling and cathode material production is based on a production cost model for generic chemical plants developed by Peters *et al.* (Peters *et al.* 2003), which is summarized in Table 1, with a few modifications.

Table 1. Production cost model for generic chemical plants (adapted from Peters et al. 2003)

I. Direct Costs = material and labor involved in actual installation of complete facility (70-85% of fixed capital investment)
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)
1. Purchased equipment (15-40% of fixed capital investment)
2. Installation, including insulation and painting (25-55% of purchased equipment)
3. Instrumentation and controls, installed (6-30% of purchased equipment)
4. Piping, installed (10-80% of purchased equipment)

5. Electrical, installed (10-40% of purchased equipment)
B. Buildings, process and auxiliary (10-70% of purchased equipment)
C. Service facilities and yard improvements (40-100% of purchased equipment)
D. Land (1-2% of fixed capital investment or 4-8% of purchased equipment)
II. Indirect Costs = expenses which are not directly involved with material and labor of actual installation of complete facility (15-30% of fixed capital investment)
A. Engineering and supervision (5-30% of direct costs)
B. Construction expense and contractor's fee (6-30% of direct costs)
C. Contingency (5-15% of fixed capital investment)
III. Fixed Capital Investment = direct costs + indirect costs
IV. Working Capital (10-20% of Total Capital Investment)
V. Total Capital Investment = Fixed Capital Investment + Working Capital
VI. Manufacturing Costs
A. Direct product costs
1. Raw materials (10-50% of total product cost)
2. Operating labor (10-20% of total product cost)
3. Direct supervisory and clerical labor (10-25% of operating labor)
4. Utilities (10-20% of total product cost)
5. Maintenance and repairs (2-10% of fixed capital investment)
6. Operating supplies (10-20% of cost of maintenance and repairs, or 0.5-1% of fixed capital investment)
7. Laboratory charges (10-20% of operating labor)
8. Patents and royalties (0-6% of total product cost)
B. Fixed charges (10-20% of total product cost)
1. Depreciation (10% of fixed capital investment and 2-3% of building value)
2. Local taxes (1-4% of fixed capital investment)
3. Insurance (0.4-1% of fixed capital investment)
4. Rent (8-12% of value of rented land and buildings)
5. Financing (interest) (0-10% of total capital investment)
C. Plant overhead costs (50-70% of operating labor, supervision and maintenance or 5-15% of total product cost)
VII. General Expenses
A. Administrative costs (15% of operating labor, supervision, and maintenance or 2-6% of total product cost)
B. Distribution and selling costs (2-20% of total product cost)
C. R&D costs (2-5% of every sales dollar or 5% of total product cost)
VIII. Total Product Cost = Manufacturing Costs + General Expenses

Modifications to the cost model as shown in Table 1 include (1) modeling purchased equipment cost (item I.A.1) as the sum of the costs for individual equipment items used in the process, instead of as a percentage of fixed capital investment; (2) modeling raw materials cost (item VI.A.1) as the sum of the costs for each raw material consumed in the process, instead of as a percentage of total product cost; (3) modeling operating labor (item VI.A.2) as the product of total operating labor requirement for the process in person hours and the hourly labor rate, instead of as a percentage of total product cost; and (4) modeling utility (item VI.A.4) cost as the sum of electricity cost, fuel cost, water cost, and waste disposal cost, instead of as a percentage of total product cost. In addition, a profit component, estimated to be 5% of the total capital investment, is added to the total product cost (item VIII) to determine the cost of the product to the recipient. Users can choose whether or not to include this profit component in the cost calculation. Specific input parameters (i.e. cost percentages) used in the cost calculation for recycling and cathode materials production are discussed in Chapter 5 and Chapter 7, respectively.

The costs for individual equipment items are list in Appendix A. These costs are obtained from vendor price quotes, public database, expert opinions, and literature. Bulk pricing data for each raw material are obtained in a similar fashion, and are summarized in Appendix B. A direct labor rate of $18/hr, based on the BatPaC model, is assumed for battery manufacturing in the U.S., and a rate of $20/hr is assumed for recycling and cathode production. The unit cost for utilities and waste disposals as shown in Table 2 are based on U.S. national averages, and used for all cost calculations for activities occurring in the U.S.

Table 2. U.S. national average utilities and waste disposal costs

	Unit Cost	Reference Year	Data Source
Electricity ($/kWh)	$0.0688	2017	EIA 2019a
Natural gas ($/1000 ft^3)	$4.10	2017	EIA 2019b
Water ($/gal)	$0.0036	2012-2013	Black & Veatch 2013
Wastewater discharge ($/gal)	$0.0053	2012-2013	Black & Veatch 2013
Landfill/tip fee ($/ton)	$45	2012	EPA 2014

2.2.2 Life Cycle Analysis (LCA)

The life-cycle environmental impact and emission categories evaluated in EverBatt include total energy use, water consumption, air pollutant emissions, and greenhouse gas (GHG) emissions. The total energy use can be broken down into fossil fuel use and non-fossil fuel use, and the fossil fuel use can be further broken down into coal, natural gas, and petroleum. Air pollutant emissions modeled in EverBatt include volatile organic compound (VOC), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter with diameters of 10 micrometers and smaller (PM10), particulate matter with diameters of 2.5 micrometers and smaller (PM2.5), black carbon (BC), and organic carbon (OC). GHGs include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These environmental impact and emission categories are output attributes of the GREET LCA model.

The life-cycle environmental impacts of each process in EverBatt are calculated based on the materials and energy flows through the process, and the environmental impacts intensities of each raw material and energy input obtained from the GREET model, by the following equation:

$$EI_k = \sum_i m_i \times ei_{i,k} + \sum_j q_j \times ei_{j,k} + P_k \qquad \text{Eq.1}$$

Where EI_k denotes the life-cycle environmental impact/emission category k for the process (for clarity's sake, let's assume the environmental impact/emission category k is GHG emissions hereinafter, but it could be any of the environmental impact/emission categories listed above);

m_i denotes the mass (in kg) of material i consumed in the process;

$ei_{i,k}$ denotes the GHG emissions for 1kg of material i in GREET;

q_j denotes the quantity (in MJ) of energy type j consumed in the process;

$ei_{j,k}$ denotes the GHG emissions for 1 MJ of energy type j in GREET;

and P_k denotes GHG emissions from the process as a result of combustion or thermal decomposition of the raw materials (e.g., combustion of graphite in the pyrometallurgical recycling process, thermal decomposition of Li_2CO_3 in the NMC cathode powder production process).

It should be noted that the material combustion and decomposition process emission term P_k in Equation 1 only applies to CO_2 emissions, and is estimated in EverBatt based on stoichiometric calculations.

2.2.3 Process Scaling-Up/Down

As mentioned previously, the EverBatt model can analyze how the cost and environmental impacts will change as the technology or process scales up or down. Particularly, this version of EverBatt can estimate how the production cost will change with plant throughput for battery manufacturing, recycling, and cathode material production, with few inputs from the user. The analyses of changes in environmental impacts in response to changes in plant throughput, however, are limited in scope in this version of EverBatt, and will be improved in future versions.

For the cost modeling of battery manufacturing, the cost of active cathode material, the cost of active anode material, the direct labor requirement, the capital equipment, and the plant area for a plant are determined as follows

$$C = C_0(\frac{R}{R_0})^p$$

Eq. 2

Where C is a cost attribute (e.g., material cost, direct labor, capital equipment) of the plant under analysis;

C_0 is the corresponding cost attribute of the reference battery manufacturing plant in BatPaC;

R is the processing rate (throughput) of the plant under analysis;

R_0 is the processing rate of the reference plant in BatPaC;

p is the power factor for the cost attribute in BatPaC.

The reference battery manufacturing plant in BatPaC produces 100,000 battery packs per year, which amounts to a production capacity of 6 GWh/yr, and the production cost modeling in BatPaC is suitable for battery manufacturing plants with a throughput between 20,000-500,000 battery packs per year. Since the cost modeling for battery manufacturing in EverBatt is based on BatPaC, EverBatt supports cost modeling for battery manufacturing plants with the same throughput range, which is roughly 1,000 -100,000 metric tons (hereinafter tonnes) of battery cells per year. In contrast, the environmental impacts for battery manufacturing will not change automatically with plant throughput in this version of EverBatt, unless the user provides different materials and energy inputs for battery manufacturing plants of different throughputs.

For the modeling of battery recycling and cathode material production, EverBatt accounts for changes in equipment cost and plant energy consumption with plant throughput. Cost data for different equipment of various sizes are collected from vendor price quotes, public database, expert opinions, and literature, and then used to derive equipment cost curves (i.e., equipment costs as functions of equipment sizes). Equipment energy rating curves (i.e., equipment energy ratings as functions of equipment sizes) are developed in a similar fashion. The cost and energy rating curves for all equipment included in EverBatt are listed in Appendix C. For each type of equipment used in a process, EverBatt assumes that two pieces of the equipment are needed, each with a design capacity that can meet 75% of the desired plant throughput. Once the equipment size is determined, EverBatt will look up the corresponding cost and energy rating of the equipment, which will be used subsequently for the production cost and environmental impacts calculation.

2.2.4 Geographical Variation

In light of the global battery supply chain, EverBatt also evaluates how the cost and environmental impacts associated with different life-cycle stages of batteries change across geographic locations. EverBatt currently covers four geographical locations: California, U.S.

national average, China, and Korea, while also allowing users to define their own geographic location.

For cost modeling, EverBatt considers geographical variations in utilities cost, waste disposal cost, direct labor cost, equipment cost, building cost, and transportation cost. The same material costs, however, are assumed for all geographical locations, because the materials consumed by the battery industry are typically global commodities. The cost parameters for the four built-in geographic locations are summarized in Appendix D. It should be noted that this version of EverBatt aims to provide a framework to examine the geographical variations. Some of the cost parameters listed in Appendix D, especially those for China and Korea, are based on our conjectures rather than actual data, and should be improved in future versions of EverBatt.

For environmental modeling, again, EverBatt does not consider geographical variations for materials, neither does EverBatt consider geographical variations for natural gas, as natural gas production is not expected to vary substantially across geographic locations. EverBatt does, however, take into account the geographical variations in electricity generation mix, because they are often conspicuous and can affect the environmental impacts of electricity to a large degree. The environmental impacts for the electricity in California and the 2017 U.S. national average are taken directly from GREET 2018, while the environmental impacts for the electricity in China and Korea are calculated in GREET 2018 based on their 2016 electricity mixes and transmission and distribution (T&D) losses as shown in Table 3, which are obtained from the International Energy Agency (IEA).

Table 3. 2016 national average electricity mix and T&D loss for China and Korea

		Electricity mix						
	T&D loss	Coal	Oil	Natural gas	Nuclear	Hydro	Biomass	Other
China[a]	5%	68.2%	0.2%	2.7%	3.4%	19.2%	1.0%	5.2%
Korea[b]	3%	41.7%	3.2%	22.5%	28.8%	1.2%	1.0%	1.7%

a. IEA 2019a

b. IEA 2019b

3 BATTERY MANUFACTURING WITH VIRGIN MATERIALS

The battery manufacturing with virgin materials module in EverBatt evaluates the cost and environmental impacts for the production of LCO, LMO, LFP, NMC111, NMC622, NMC811, and NCA cells. Users interested in the cost and environmental impacts for the production of battery packs should refer to BatPaC and GREET, respectively. The current version of EverBatt only considers the prismatic cell type, because it is the one modeled in BatPaC. Future versions of EverBatt will be expanded to include other cell types such as cylindrical and pouch cells. Again, EverBatt supports cost modeling for battery manufacturing plants with an annual production capacity of 1,000 – 100,000 tonnes of battery cells.

3.1 MODULE INPUTS

For battery manufacturing with virgin materials, the required inputs include the cathode chemistry of the battery, the throughput (tonnes of cells per year) of the battery plant, the location of the battery plant, and the material and energy demands for cell manufacturing. The first three need to be specified by the users, while for the material and energy demands the users can choose to define their own or use the default values built into the module.

The materials demands for cell manufacturing are determined based on the bill-of-materials (BOM) of the cell (i.e., the mass percentage of each material in the cell), the material yields of the cell manufacturing process, and the cell acceptance rate, by the following equation:

$$Demand_i = \frac{\frac{Mass\ percentage_i}{Yield_i}}{Cell\ acceptance\ rate}$$

Eq.3

Where i denotes material i among all battery constituents.

The default cell BOMs for different cathode chemistries in EverBatt are derived from EV battery 5 in BatPaC, to be consistent with GREET. The methodology used to compile the cell BOM based on the cell design parameters in BatPaC is described in two GREET documentations (Dunn *et al.* 2014, Dai *et al.* 2018a). EV battery 5 in BatPaC is for EVs with an all-electric range of 100 miles, and consists of 140 cells, each with an energy capacity of 0.168 kWh. The derived cell BOMs, together with the cell mass, which is also obtained from BatPaC, are listed in Table 4.

Table 4. EverBatt default cell BOM and mass

	NMC(111)	NMC(622)	NMC(811)	LCO	NCA	LMO	LFP
Cell BOM							
Active cathode material	34.7%	32.4%	31.1%	35.3%	30.6%	40.8%	32.7%
Graphite	19.4%	21.0%	20.6%	18.5%	22.1%	14.1%	16.8%
Carbon black	2.3%	2.2%	1.7%	2.4%	2.1%	2.7%	2.2%
Binder: PVDF	3.0%	2.9%	3.6%	3.0%	2.9%	3.0%	2.7%
Copper	15.7%	16.1%	15.7%	16.1%	16.7%	15.0%	13.9%
Aluminum	8.2%	8.4%	8.2%	8.1%	8.6%	7.8%	7.5%
Electrolyte: LiPF6	2.2%	2.2%	2.6%	2.2%	2.3%	2.2%	3.4%
Electrolyte: EC	6.2%	6.3%	7.2%	6.0%	6.3%	6.1%	9.4%
Electrolyte: DMC	6.2%	6.3%	7.2%	6.0%	6.3%	6.1%	9.4%
Plastic: PP	1.5%	1.5%	1.5%	1.8%	1.6%	1.5%	1.3%
Plastic: PE	0.3%	0.4%	0.3%	0.3%	0.4%	0.3%	0.3%
Plastic: PET	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Cell mass (kg)	0.856	0.772	0.803	0.866	0.750	1.045	1.054

PVDF: polyvinylidene difluoride; EC: ethylene carbonate; DMC: dimethyl carbonate; PP: polypropylene; PE: polyethylene; PET: polyethylene terephthalate

In addition to the materials contained in the battery, EverBatt also accounts for the solvents consumed for cell manufacturing. It is assumed that N-Methyl-2-pyrrolidone (NMP) is the solvent used for cathode slurry preparation, and water for the anode slurry. Based on BatPaC, the quantity of the solvent needed is determined as 24 times that of the binder in the cell. It is also assumed that 99.5% of the NMP is recovered and reused for cell manufacturing, while water is not recovered.

The default material yields are from BatPaC, as listed in Table 5. The yield of active cathode material also applies to NMP, and active anode material also to water. The yield of separator applies to PP and PE, and the yield of electrolyte applies to its all three components: $LiPF_6$, EC and DMC. The cell acceptance rate is also from BatPaC, and is assumed to be 95%, which means that 95% of the manufactured cells can pass the quality tests and are deemed acceptable for their intended applications. Cells that fail to pass the tests are rejected, and can be used for some less demanding applications (e.g. rejected cells intended for traction applications can be used for stationary energy storage), or sent to battery recyclers, together with the manufacturing scrap generated during the manufacturing process.

Table 5. EverBatt default material yields for cell manufacturing

	Material yield (%)
Active cathode material	92.2%
Active anode material	92.2%
Aluminum foil	90.2%
Copper foil	90.2%
Separator	98.0%
Electrolyte	94.0%

The default energy demand for cell manufacturing in EverBatt is based on the value in GREET, which is 170 MJ/kWh cell produced, of which 82.4% is natural gas, and 17.6% is electricity (Dai *et al.* 2017). This per-kWh cell manufacturing energy demand is converted into per-kg cell manufacturing energy demand based on the specific energy (kWh/kg) of cells calculated by the cell energy capacity (0.168 kWh) and the cell mass as shown in Table 4.

3.2 COST CALCULATION

The cost calculation for battery manufacturing in EverBatt is based on BatPaC, with several simplifications. First, BatPaC calculates cell materials cost based on detailed cell design parameters, which include the dimensions of each cell component. This allows the user to determine the quantity of a material embodied in different components, and apply different unit prices to the material accordingly. In contrast, in the absence of cell dimension information, EverBatt calculates cell material cost based on the cell material composition without further differentiation of the same type of material. For instance, aluminum content in the positive current collector, the positive terminal assembly, and the cell container are considered the same in EverBatt, and the unit price of aluminum foil is applied to them all. Similarly, the unit price of copper foil is applied to copper contained in the negative current collector and the negative terminal assembly. In addition, EverBatt does not adjust for hardware (positive terminal assembly, negative terminal assembly, and cell container) costs based on production capacity, as done in BatPaC, because such adjustment requires information on the dimensions of these components. These simplifications, however, are not expected to cause considerable differences in cell material cost between BatPaC and EverBatt.

For direct labor cost, capital equipment cost, and building cost, the differences between BatPaC and EverBatt may be more pronounced. These three cost attributes for seven cell manufacturing processes, including positive electrode coating, negative electrode coating, positive electrode calendaring, negative electrode calendaring, materials handling, electrode slitting, and electrode drying, change with the annual electrode area processed in the battery plant based on Equation 2. In the absence of cell dimension information, EverBatt adopts the electrode area of battery 5 in BatPaC and applies it to all cells of the same cathode chemistry. As a result, for cells with considerably different electrode area from battery 5 in BatPaC as shown in Table 6, the direct labor cost, capital equipment cost, and building cost can vary substantially between EverBatt and BatPaC.

Table 6. Default cell (0.168kWh) electrode area in EverBatt

	NMC(111)	NMC(622)	NMC(811)	LCO	NCA	LMO	LFP
Cell electrode area (cm^2)	19,986	18,159	18,363	19,422	18,347	23,925	21,416

Except for these differences, the cost model of the battery manufacturing module in EverBatt is the same as BatPaC, as summarized in Table 7. Simply put, EverBatt can provide cost estimates for cell manufacturing with information on the battery plant that is often publicly available, while users who have access to cell design parameters can use BatPaC to derive more refined and detailed cost estimates.

Table 7. Cost model for battery manufacturing

Cost Item	Estimated as
I. Total Variable Cost	I.1 + I.2 +I .3
1. Materials Cost	Sum of all materials costs
2. Direct Labor Cost	Total direct labor-hour requirement × hourly labor rate
3. Variable Overhead	40% of I.2 + 20% of III.1
II. Total Investment	II.1 + II.2 + II.3 + II.4
1. Launch Cost	5% of I.1 + 10% of I.2 + 10% of I.3
2. Working Capital	15% of I.2 + 15% of I.3
3. Capital Equipment	Sum of all capital equipment costs
4. Building Cost	Total building area × per-m^2 building cost
III. Fixed Expenses	III.1 + III.2 + III.3
1. Depreciation	16.7% of II.3 + 5% of II.4
2. GSA Cost	25% of I.2 + 25% of I.3 + 25% of III.1
3. R&D Cost	40% of III.1
IV. Profit	5% of II
V. Warranty	5.6% of I + 5.6% of III + 5.6% of IV
VI. Total Cost	I + III + IV + V

3.3 ENVIRONMENTAL IMPACTS CALCULATION

The environmental impacts for battery manufacturing are calculated based on Equation 1. No material combustion or decomposition process emissions are considered for battery manufacturing.

4 TRANSPORTATION AND COLLECTION

The transportation and collection module in EverBatt considers (1) transportation of the spent batteries from their last user to the collection site, (2) transportation of the spent batteries from the collection site to the recycler, (3) transportation of recovered materials from the recycler to the cathode producer, (4) transportation of cathode material produced from recycled materials from the cathode producer to the battery manufacturer, and (5) transportation of battery manufacturing scrap and rejected cells from the battery manufacturer to the recycler if the user chooses to include them.

For each of the five transportation segments, EverBatt considers five transportation modes: medium-duty truck, heavy-duty truck, rail, barge, and ocean tanker. LIBs are currently characterized as Class 9 hazardous materials for transportation (Huo *et al.* 2017), but it is possible that they will be exempt from the hazardous materials transportation requirements, following the precedent set by lead-acid batteries. Therefore, for each of the five transportation segments, EverBatt also considers two scenarios: (1) the cargo is subject to hazardous materials transportation requirements; and (2) the cargo is exempt from hazardous materials transportation requirements. It should be noted that packaging the battery for safe storage and transportation is not included in this version of EverBatt, and will be added in future model expansions.

Users are required to determine whether or not to include transportation of manufacturing scrap and rejected cells in the analysis, and specify the distance for each of the five transportation segments. Users can then specify the transportation distance for each transportation mode. If the users choose not to do so, for transportation over distances greater than 70 miles, EverBatt assumes that it is done by heavy-duty trucks; and for transportation over shorter distances, EverBatt assumes that it is done by medium-duty trucks. The default payload is 25 ton for heavy-duty trucks, and 8 ton for medium-duty trucks. Users can specify the truck payload, which affects the environmental impacts calculation. Users can also specify if the cargo is classified as hazardous material. Again, should the users choose not to do so, EverBatt assumes that transportation segments 1, 2, and 5 are subject to hazardous materials transportation requirements, while transportation segments 3 and 4 are not.

The transportation cost is then calculated as follows:

$$Transportaion\ cost = \sum_{i}\sum_{j} Distance_{i,j} \times unit\ cost_j$$

Eq. 4

Where $Distance_{i,j}$ represents the distance transported by mode j for segment i, and $unit\ cost_j$ is the unit transportation cost for mode j.

The unit cost for different transportation modes under different transportation scenarios are based on U.S. national average data, and are summarized in Table 8.

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

Since the environmental impacts of transportation are dictated by the amount of fuel consumed, while whether or not the cargo is classified as hazardous materials is not expected to affect transportation fuel consumption, the environmental impacts for transportation in EverBatt are calculated as follows:

$$EI_k = \sum_i \sum_j Distance_{i,j} \times ei_{j,k}$$

Eq. 5

Where $ei_{j,k}$ denotes the environmental impact/emission category k result for transporting 1 ton of cargo over 1 mile by transportation mode j in GREET.

5 Battery Recycling

The battery recycling module in EverBatt covers processes pertaining to the recovery of materials from spent batteries in usable forms. For the cathode material in particular, this means recovery of it “as is”, or as Co/Ni/Li compounds, to allow for integration with the materials conversion, cathode powder production, and battery manufacturing with recycled materials modules. Depending on the wastewater discharge standards the recycler is subject to, on-site wastewater treatment may also be an integral part of battery recycling. Again, this version of EverBatt models the battery at the cell level. Therefore, unit operations that are often essential to battery pack recycling, such as discharge and disassembly, are not included at present, and will be added in future expansions of EverBatt.

EverBatt considers three recycling technologies/pathways: pyrometallurgical recycling, hydrometallurgical recycling, and direct cathode recycling (hereinafter referred to as direct recycling). In light of the collected data on equipment costing and the corresponding capacity as summarized in Appendix A, EverBatt currently supports cost analyses for recycling plants with an annual capacity up to 50,000 tonnes of cells.

Figure 2 depicts the process flow for a generic pyrometallurgical recycling process, in which spent batteries, either shredded or intact, are sent to a smelter, where electrolyte and plastics in the batteries are burned off to supply heat; graphite/carbon and aluminum in the batteries act as reductants for the metals and are oxidized; cobalt, nickel, copper, and iron in the batteries end up in the matte; and the rest of the materials, including oxidized aluminum end up in the slag. The Co/Ni/Cu/Fe matte is then further processed by acid leaching followed by solvent extraction and precipitation to produce cobalt and nickel compounds that can be used for new cathode materials production. It should be noted that lithium in the slag can potentially be recovered. This version of EverBatt does not include this scenario, however, due to lack of information on the lithium recovery process. It should be also noted that the slag may be used as aggregate for pavement, or as supplementary material for cement production.

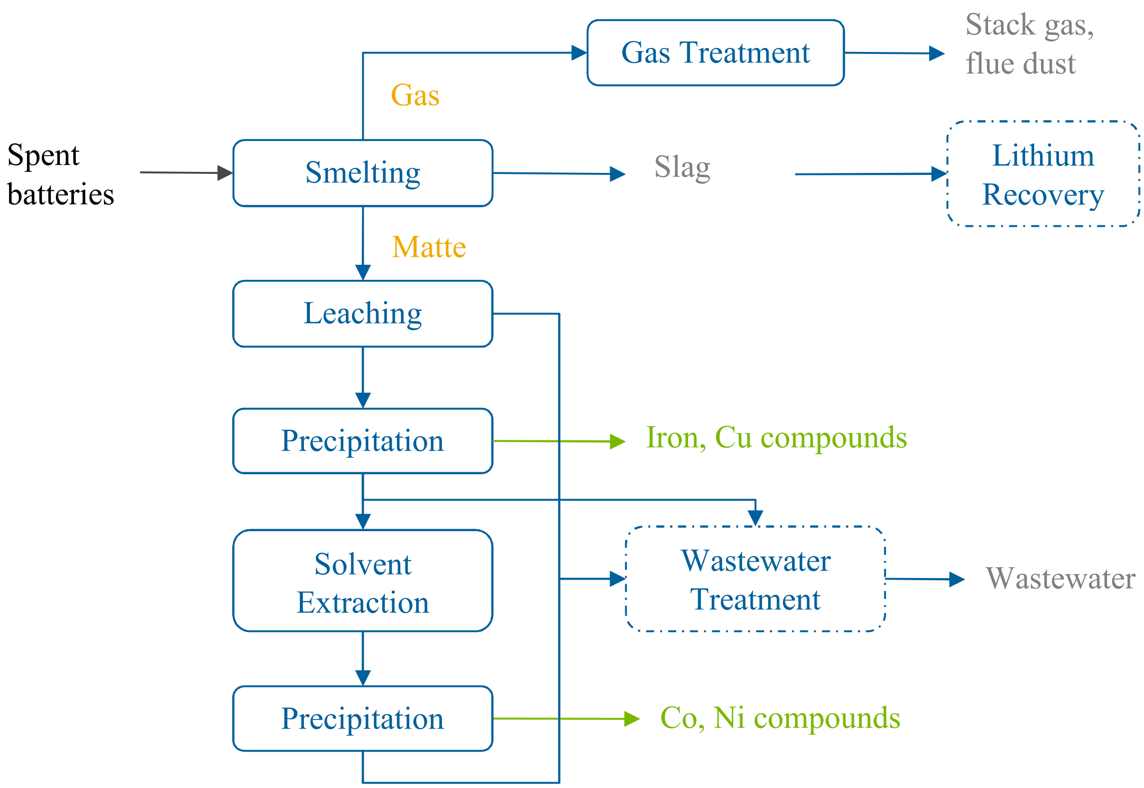

Figure 2. Process diagram of a generic pyrometallurgical recycling process. Solid boxes denote common unit operations; dashed boxes denote optional unit operations; green denotes products; yellow denotes intermediate products; grey denote wastes.

Figure 3 depicts the process flow for a generic hydrometallurgical recycling process. Discharged and dissembled spent batteries are shredded, and then undergo a low temperature calcination process to burn off the binder and electrolyte, several physical separation processes to separate out aluminum, copper, steel as metal scraps and plastics, and a leaching process followed by solvent extraction and sometimes precipitation to produce Co/Ni/Mn compounds, and potentially lithium carbonate for new cathode material production.

Figure 4 depicts the process flow for a generic direct recycling process. Discharged and dissembled batteries are perforated first, and then undergo supercritical CO_2 extraction to recycle the electrolyte solvents and salts. The rest of the batteries are shredded, and go through a series of physical separation processes to recover plastics, metals, anode material, and cathode material, respectively. The recovered cathode material is then relithiated to produce rejuvenated cathode powder.

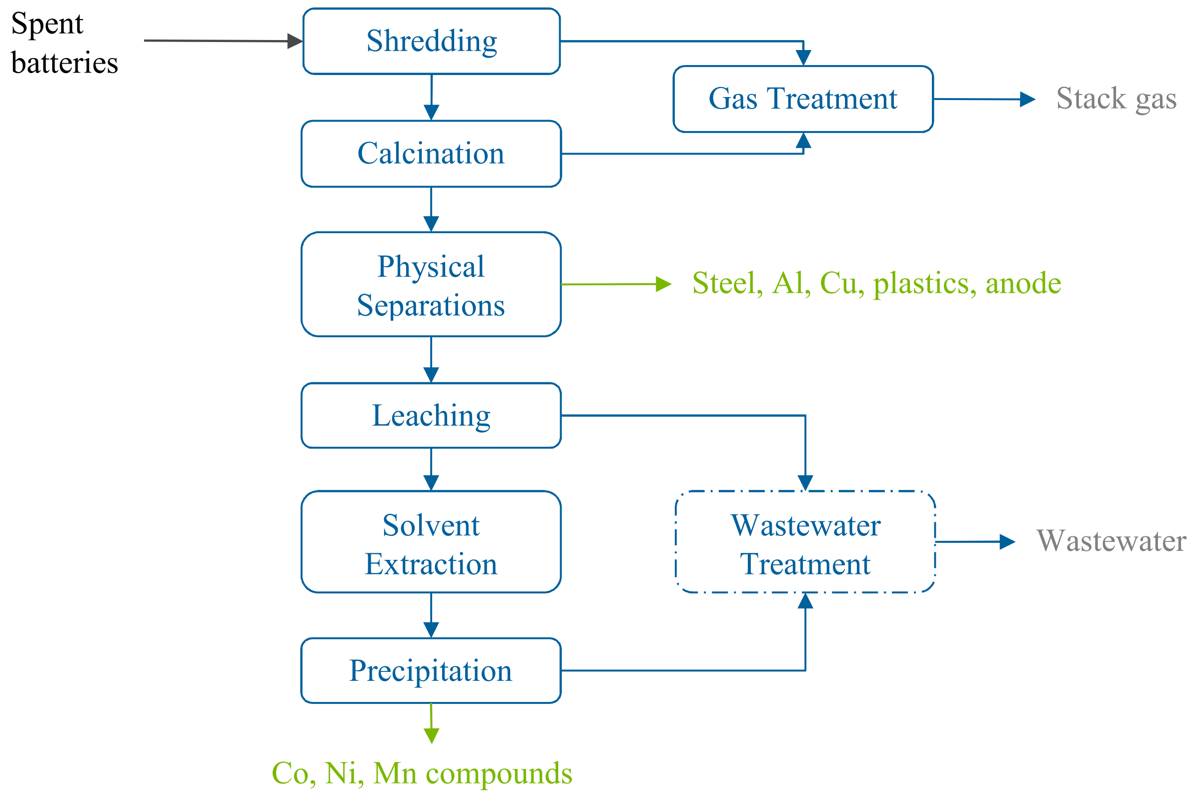

Figure 3. Process diagram of a generic hydrometallurgical recycling process. Solid boxes denote common unit operations; dashed box denotes optional unit operation; green denotes products; grey denotes wastes.

It should be noted that supercritical CO_2 extraction can be incorporated into the hydrometallurgical process to recycle the electrolyte. It could also be excluded from the direct recycling process if electrolyte recovery is not intended by the recycler. If not recycled, the electrolyte is typically removed from the batteries by combustion and/or evaporation, as currently assumed in the generic pyrometallurgical and hydrometallurgical processes, where gas treatment is needed to remove fluoride emissions generated from the combustion and/or decomposition of the electrolyte. Therefore, the three generic recycling technologies in EverBatt could differ from the process used by a specific recycler. To accommodate possible variations of the processes, in EverBatt we allow the users to customize the recycling process they want to analyze, provided that the cathode materials are recovered in chemical forms that can be incorporated back to the battery supply chain. The materials assumed to be recoverable from spent batteries through each of the recycling technologies are summarized in Table 9.

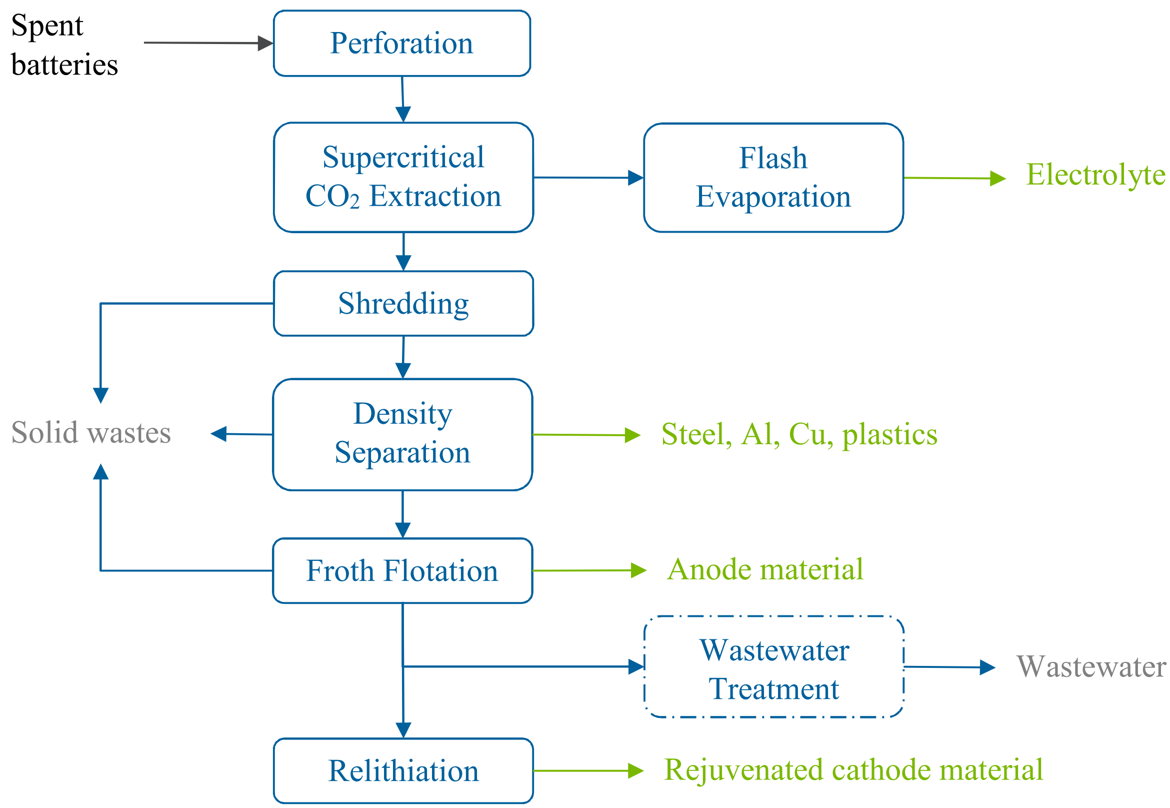

Figure 4. Process diagram of a generic direct recycling process. Solid boxes denote common unit operations; dashed box denotes optional unit operation; green denotes products; grey denotes wastes.

Table 9. Recoverable materials through different recycling technologies

Pyrometallurgical	Hydrometallurgical	Direct
• Copper compounds • Iron compounds • Co2+ in output • Ni2+ in output • Lithium compounds* • Aggregate (from slag)*	• Copper • Steel • Aluminum • Graphite • Plastics • Lithium carbonate • Co2+ in output • Ni2+ in output • Mn2+ in output • Electrolyte solvents • Electrolyte salts*	• Copper • Steel • Aluminum • Graphite • Plastics • LCO • NMC(111) • NMC(622) • NMC(811) • NCA • LMO • LFP • Electrolyte solvents • Electrolyte salts*

* Not currently included in EverBatt

5.1 Module Inputs

For battery recycling, the required inputs include the chemistry of the battery to be recycled, the throughput (tonnes of cells per year) of the recycling plant, the location of the recycling plant, whether or not to recycle manufacturing scrap and rejected cells, the materials and energy flows associated with the recycling process, the equipment used for the process, the unit prices of chemicals and utilities consumed for the process, the unit prices of materials recovered from the process, and information regarding the operation of the plant. The users need to specify the first four inputs, while for the rest of the inputs the users can choose to provide their own values, or use the default values built into EverBatt.

5.1.1 Process-related Inputs

For the chemistry of the recycled battery, the user can choose any of the seven chemistries included in EverBatt. The recycling module in EverBatt can model a spent battery feedstock of one cathode chemistry, or a mixed feedstock of up to five different chemistries. Based on the specified shares of different chemistries in the spent batteries, EverBatt calculates the material composition of the feedstock to the recycling plant, assuming that the BOMs of the spent batteries are the same as the new batteries as shown in Table 4. The users can also specify their own material compositions for the spent batteries.

By default, the recycling plant, regardless of chosen recycling technology, is assumed to operate 320 days per year, 20 hours per day. The assumed lifetime for the plant is 10 years. These inputs are used to determine the amortized capital investment for the plant as part of the recycling cost calculation.

The default material and energy requirements for the three generic recycling technologies are obtained from literature, patents, and expert opinions, and are summarized in Table 10. The diesel consumption for all three technologies is for wheel loaders, and it is assumed that a wheel loader with a diesel consumption rate of 20 liters/hr (model 980H or similar, Caterpillar 2012) works on a 300kg battery pack for 15 minutes to load/unload it and transport it within the recycling plant. The water consumption for the generic hydrometallurgical recycling technology is estimated by subtracting the water consumption for commercial NMC powder production in GREET (Dai *et al.* 2018a) from that for closed-loop recycling of NMC from spent batteries. The closed-loop recycling of NMC includes hydrometallurgical recycling of batteries to recover cobalt, manganese, and nickel as salts, and subsequent NMC powder production from these recovered salts, as reported by a leading recycler (Dai *et al.* 2017). The natural gas consumption for the generic hydrometallurgical recycling technology is calculated in the same manner. The direct recycling technology is still in its infancy, and even laboratory-scale process data are scarce. In the absence of data, the water consumption for the generic direct recycling technology is assumed to be the same as that for the generic hydrometallurgical technology.

Table 10. Materials and energy requirements to recycle 1 kg of spent battery through different technologies

	Pyrometallurgical	Hydrometallurgical	Direct
Material inputs (kg)			
Ammonium Hydroxide	---	0.031[d]	---
Hydrochloric Acid	0.21[a]	0.012[d]	---
Hydrogen Peroxide	0.06[a]	0.366[d]	---
Sodium Hydroxide	---	0.561[d]	---
Limestone	0.30[b]	---	---
Lithium Carbonate	---	---	0.003[a]
Sand	0.15[b]	---	---
Carbon Dioxide	---	---	2.2[a]
Sulfuric Acid	---	1.08[d]	---
Soda Ash	---	0.02[d]	---
Water consumption (gal)	---	1[c]	1[c]
Energy consumption (MJ)			
Diesel	0.6[c]	0.6[c]	0.6[c]
Natural gas	---	2.5[c]	---
Electricity	4.68[b]	0.125[d]	2.73[a]

a. Dunn *et al.* 2014

b. Huelens *et al.* 2016
c. Own estimate
d. Xie *et al.* 2015

Table 11 summarizes the default assumption in EverBatt for what happens to the materials in the batteries if they are recycled via each of the generic recycling technologies. The users can opt to select the fates of battery constituents for their own process. If "burn for energy" is specified as the fate for a material, the emissions from combustion of this material will be included in the environmental impacts calculation.

Table 11. Fates of battery constituents for different recycling technologies

	Pyrometallurgical	Hydrometallurgical	Direct
Active cathode materials	Recycle	Recycle	Recycle
Graphite	Burn for energy	Recycle	Recycle
Copper	Recycle	Recycle	Recycle
Aluminum	Landfill	Recycle	Recycle
Steel	Recycle	Recycle	Recycle
Plastics	Burn for energy	Burn for energy	Recycle
Electrolyte	Burn for energy	Burn for energy	Recycle
Carbon black	Burn for energy	Landfill	Recycle
PVDF	Burn for energy	Landfill	Recycle

The amounts of materials recovered from each of the recycling technologies are determined by the amount of each material in the feedstock, and the default recovery efficiency of each material assumed in EverBatt, which is summarized in Table 12. The recovery efficiencies for cathode materials and metals via the pyrometallurgical and hydrometallurgical technologies are based on what have been achieved in commercialized processes (Huelens *et al.* 2016, Xie *et al.* 2015), but slightly more conservative than those reported by the recyclers, to represent the average process performance. For plastics and electrolyte solvents, a material recovery efficiency of 50% is assumed, as the recycler may not be as incentivized to recycle these materials compared with cobalt and nickel, which have high values, or with metals, for which there are often steady demands. Again, in the absence of data for direct recycling technology, it is assumed to have the same materials recovery efficiencies as the other two recycling technologies, except for cathode materials. Considering the challenges associated with separating the cathode material from the rest of the battery constituents while maintaining its structural integrity, a material recovery efficiency of 90% is assumed for the cathode materials.

Table 12. Material recovery efficiencies for different recycling technologies

	Pyrometallurgical	Hydrometallurgical	Direct Physical
Copper	90%	90%	90%
Steel	90%	90%	90%
Aluminum	N/A	90%	90%
Graphite	N/A	90%	90%
Plastics	N/A	50%	50%
Lithium	N/A	90%	N/A
LCO	N/A	N/A	90%
NMC(111)	N/A	N/A	90%
NMC(622)	N/A	N/A	90%
NMC(811)	N/A	N/A	90%
NCA	N/A	N/A	90%
LMO	N/A	N/A	90%
LFP	N/A	N/A	90%
Co2+ in output	98%	98%	N/A
Ni2+ in output	98%	98%	N/A
Mn2+ in output	N/A	98%	N/A
Electrolyte solvents	N/A	50%	50%
Electrolyte salts*	N/A	50%	50%

* Not currently included in EverBatt

The equipment assumed for the generic pyrometallurgical, hydrometallurgical, and direct technologies in EverBatt is depicted in Figure 5, Figure 6, and Figure 7, respectively.

5.1.2 Cost Inputs

The unit costs of consumed raw materials and utilities are summarized in Appendix B, and the equipment costs are summarized in Appendix A. In addition to the consumed chemicals, the recyclers may be required to pay for the batteries they process. How much they pay (i.e., the battery fee) depends on the battery chemistry. Generally speaking, the recyclers need to pay a premium to get batteries with a higher cobalt content. The battery fees to the recyclers assumed in EverBatt for different chemistries, which we solicited from industry sources, are summarized in Table 13.

Table 13. Battery fees to the recyclers for different battery chemistries ($/kg battery)

	LCO	NMC(111)	NMC(622)	NMC(811)	NCA	LMO	LFP
Fee ($/kg)	$2.00	$0.20	$0.00	$0.00	$0.00	-$1.00*	-$2.00*

*Negative values indicate that the recyclers get paid for taking the batteries.

The unit prices of recovered materials are also required costing inputs. The spot prices of recovered battery constituents on the North American market are summarized in Table 14. Metals, plastics, and graphite are assumed to be recovered and sold as scrap. Recovered Co/Ni/Mn/Li compounds from cathode materials via pyrometallurgical and hydrometallurgical recycling routes are typically considered “good as new” by cathode powder producers, and are therefore assumed to sell at the same prices as their virgin counterparts. Cathode materials recovered “as is” via the direct recycling route are also assumed to be equally priced as their virgin counterparts, because they should have comparable, if not superior electrochemical properties as the virgin materials, in order for the direct recycling route to be viable. Electrolyte solvents recovered by supercritical CO_2 extraction can be used as fuel in the worst case scenario, and therefore are assumed to be priced slightly less than gasoline, diesel and residual oil of the same energy content.

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

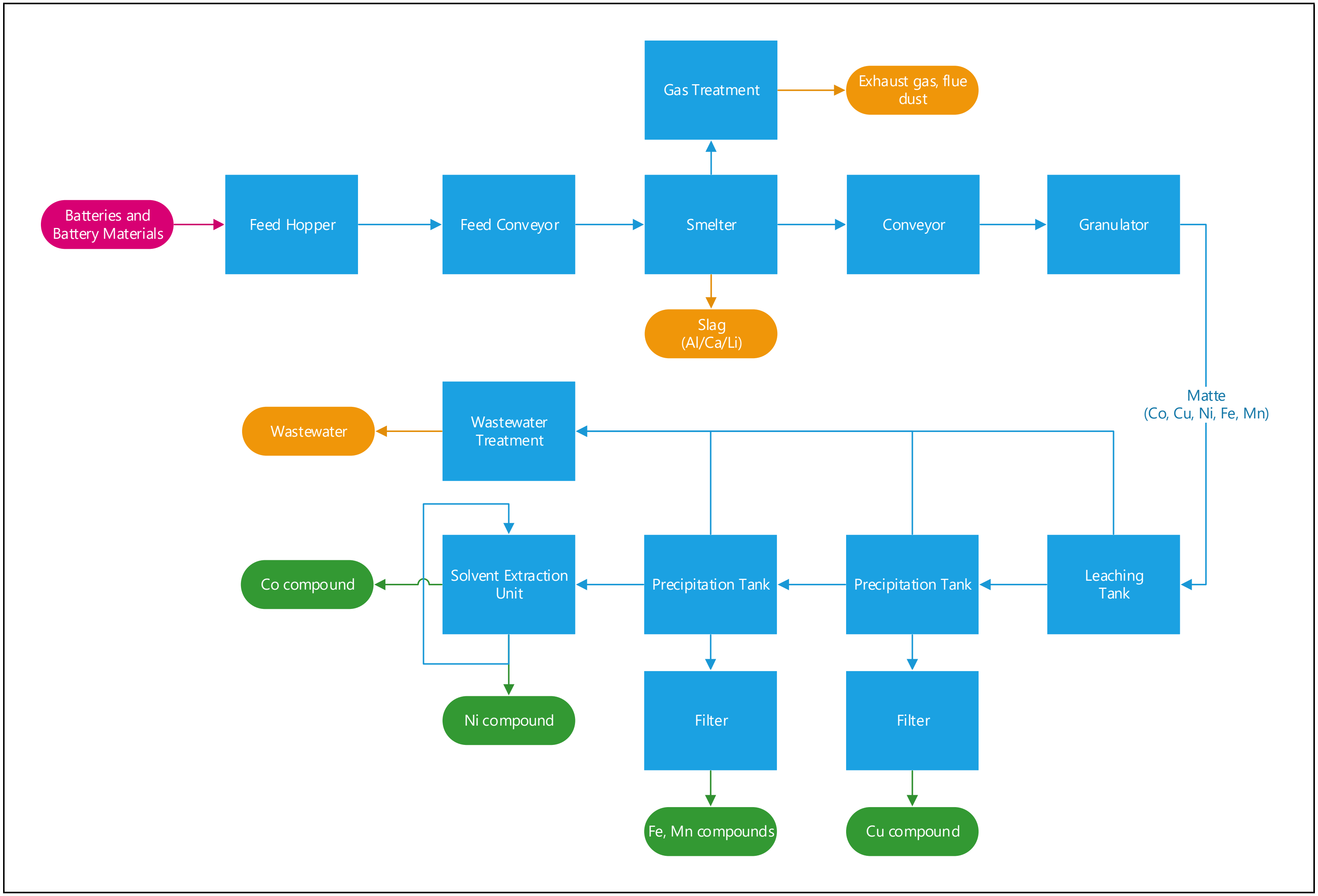

Figure 5. Equipment assumed for generic pyrometallurgical recycling. Green denotes products. Orange denotes wastes.

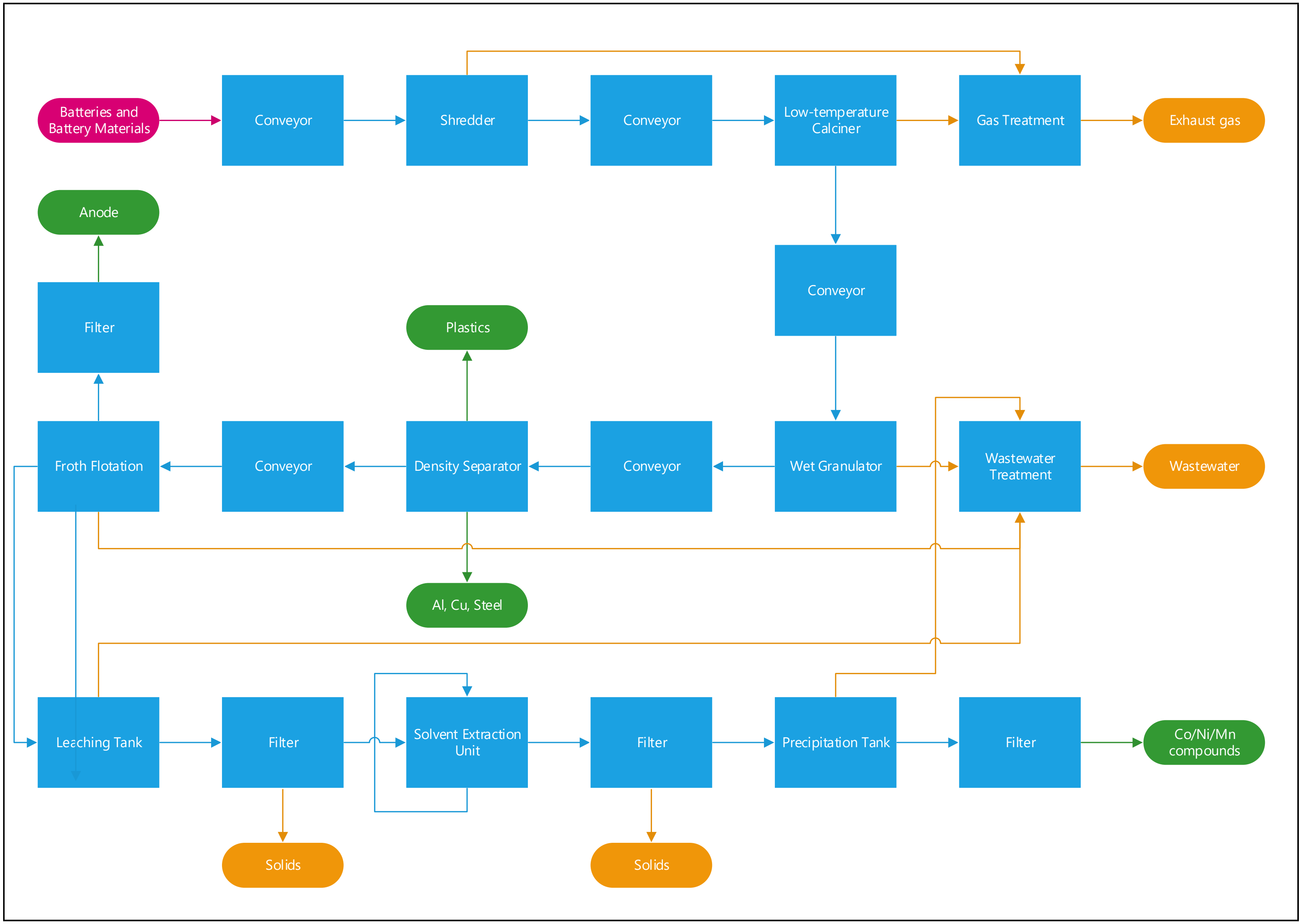

Figure 6. Equipment assumed for generic hydrometallurgical recycling. Green denotes products. Orange denotes wastes.

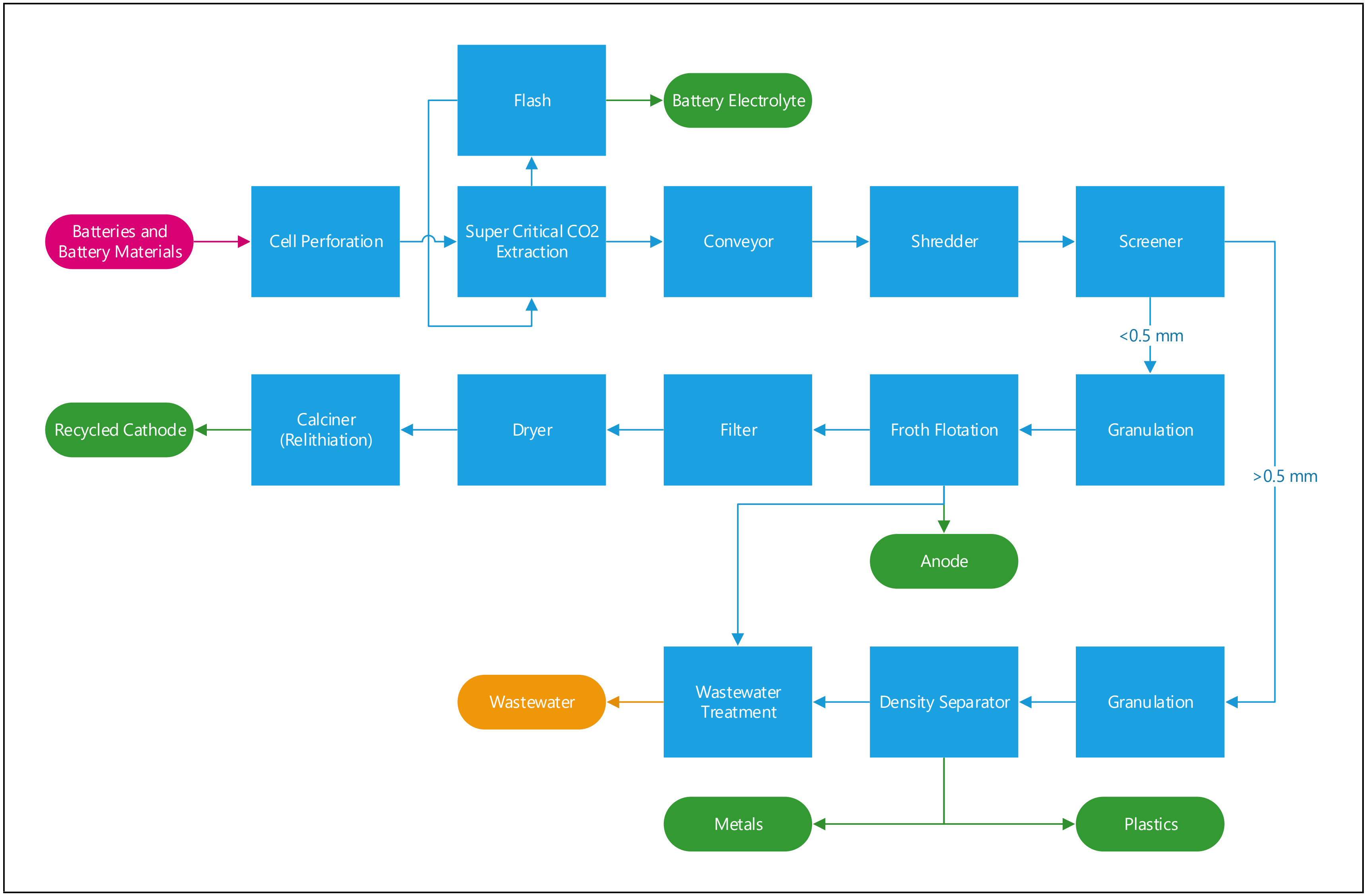

Figure 7. Equipment assumed for generic direct recycling. Green denotes products. Orange denotes wastes.

5.2 Cost Calculation

The cost of battery recycling at the plant is estimated based on the production cost model for generic chemical plants as shown in Table 1. The specific cost parameters chosen for the recycling plant, as well as the modifications, are summarized in Table 15. The total battery recycling cost in EverBatt is the sum of transportation cost as calculated by Equation 4, and recycling cost at the plant as estimated by Table 15.

Table 15. Default parameters for recycling cost modeling

Cost Item	Estimated as
I. Direct Costs	I.A+I.B+I.C+I.D
A. Equipment	I.A.1+I.A.2+I.A.3+I.A.4+I.A.5
1. Purchased equipment	Sum of equipment costs
2. Installation, including insulation and painting	40% of I.A.1
3. Instrumentation and controls, installed	20% of I.A.1
4. Piping, installed	20% of I.A.1
5. Electrical, installed	10% of I.A.1
B. Buildings, process and auxiliary	25% of I.A.1
C. Service facilities and yard improvements	60% of I.A.1
D. Land	8% of I.A.1
II. Indirect Costs	II.A+II.B+II.C
A. Engineering and supervision	10% of I
B. Construction expense and contractor's fee	10% of I
C. Contingency	5% of III
III. Fixed Capital Investment	I+II
IV. Working Capital	10% of V
V. Total Capital Investment	III+IV
VI. Manufacturing Costs	VI.A+VI.B+VI.C
A. Direct product costs	VI.A.1+VI.A.2+VI.A.3+VI.A.4+ VI.A.5+VI.A.6+VI.A.7
1. Raw materials	Sum of raw materials costs
2. Operating labor	Total labor-hour requirement × hourly labor rate
3. Direct supervisory and clerical labor	15% of VI.A.2
4. Utilities	Sum of utilities costs
5. Maintenance and repairs	5% of III
6. Operating supplies	15% of VI.A.5

7. Laboratory charges	10% of VI.A.2
8. Patents and royalties	1% of VIII
B. Fixed charges	VI.B.1+VI.B.2+VI.B.3+VI.B.4+ VI.B.5
1. Depreciation	(III-I.D)/plant lifetime
2. Local taxes	4% of III
3. Insurance	1% of III
4. Rent	5% of (I.B+I.D)
5. Financing (interest)	5% of V
C. Plant overhead costs	50% of (VI.A.2+ VI.A.2+ VI.A.2)
VII. General Expenses	VII.A+VII.B+VII.C
A. Administrative costs	15% of (VI.A.2+ VI.A.2+ VI.A.2)
B. Distribution and selling costs	6% of VIII
C. R&D costs	5% of VIII
VIII. Total Product Cost	VI+VII
IX. Profit (optional)	5% of V
X. Cost to Recipient	VIII+IX+battery fee

Besides expenditures, the cost calculation for battery recycling also considers revenues, which are calculated as

$$Revenue = \sum_i m_i \times up_i$$

Eq.6

Where m_i is the mass of material i recovered from spent batteries, and up_i is the unit price of material i as shown in Table 14.

For both open-loop and closed-loop recycling scenarios, the net cost of recycling is determined as

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

Eq.7

For closed-loop recycling scenarios, the cost of recovered materials that are incorporated back into the battery supply chain is needed for the cost calculation of cathode powder production and battery manufacturing, and is determined as

$$Cost_{recycled\ materials} = transportation\ cost + recycling\ cost - \sum_{j} m_j \times up_j$$

Eq.8

Where m_j is the mass of material j that is not closed-loop recycled, and up_j is its unit cost.

5.3 Environmental Impacts Calculation

The environmental impacts of battery recycling are calculated using Equation 1. Process emissions from both material combustion and material decomposition are considered in the battery recycling module, and are discussed in detail below. This section also discusses how the environmental impacts of battery recycling are allocated to each recovered material.

5.3.1 Process Emissions Calculation

Battery recycling processes often involve burning off some of the battery constituents to facilitate material separation, while also helping reduce energy demands of the plant. EverBatt accounts for CO_2 emissions from burning off graphite, carbon black, binder material, electrolyte, and plastics in the battery, and estimates these emissions as

$$P_{CO2,combustion} = \sum_{i} m_i \times \frac{Carbon\ content_i}{Carbon\ content_{CO2}}$$

Eq.9

Where $P_{CO2,\ combustion}$ denotes process CO_2 emissions from material combustion, m_i denotes the mass of material i that is combusted in the recycling process, and $Carbon\ content_i$

denotes the carbon content of material i, as summarized in Table 16. Material combustion emissions other than CO_2 are not considered in EverBatt at present.

Table 16. Carbon contents of battery constituents

	Graphite	Carbon black	Plastics			Electrolyte solvents		PVDF
			PET	PP	PE	EC	DMC	
Carbon content (mass %)	100%	100%	63%	86%	92%	41%	40%	36%

For process emissions from material decomposition in the recycling processes, EverBatt currently accounts for CO_2 emissions from thermal decomposition of lithium carbonate, calcium carbonate (limestone), and sodium carbonate (soda ash). These process CO_2 emissions are estimated based on stoichiometry. For recycling processes that deploy supercritical CO_2 extraction, a 10% CO_2 loss is assumed based on our communication with Dr. Steve Sloop. This CO_2 loss is also included in the process CO_2 emission calculation. In summary, the process CO_2 emissions from battery recycling are calculated as

$$P_{CO2} = P_{CO2,combustion} + P_{CO2,decomposition} + P_{CO2,loss} \quad \text{Eq.10}$$

5.3.2 Allocation

Recycling processes typically recover multiple materials from the spent batteries, but not all the recovered materials are used to make new batteries, which necessitates allocation to estimate the environmental impacts in the closed-loop recycling scenarios. In short, allocation is the practice of partitioning the environmental impacts of a multi-product process to its individual products. EverBatt includes four allocation options: no allocation, mass-based allocation, economic value-based allocation, and system expansion.

Since only cathode materials are closed-loop recycled at present, in the “no allocation” scenario, all environmental impacts of the recycling process are assigned to recovered cathode materials or their precursors (e.g., cobalt and nickel compounds for pyrometallurgical recycling, cathode powder for direct recycling).

For "mass-based allocation", the environmental impacts of the recycling process are partitioned based on allocation factors estimated as follows (for clarity's sake, the equation calculates the allocation factor for recovered copper, but it can be any other material recovered from recycling)

$$Allocation\ factor_{mass,Cu} = \frac{m_{Cu}}{\sum_i m_i}$$

Eq.11

Where m_i denotes the mass of recovered material i, and m_{Cu} denotes the mass of recovered copper.

Similarly, the allocation factor used in "economic value-based allocation" is estimated as

$$Allocation\ factor_{economic\ value,Cu} = \frac{m_{Cu} \times up_{Cu}}{\sum_i m_i \times up_i}$$

Eq.12

Where up_i denotes the unit price of recovered material i, and up_{Cu} denotes the unit price of recovered copper.

In the "system expansion" scenario, a credit is given to each recovered material, based on the process it displaces. Since the ultimate goal of closed-loop recycling is to reuse any recovered material for its original application, if the users opt for the "system expansion" option, it is assumed in EverBatt that all recovered materials displace the production of their virgin counterparts. The environmental impacts of recovered cathode materials or their precursors are calculated as

$$EI_{cathode,k} = EI_{recycling,k} - \sum_{j} m_j \times ei_{j,k}$$

Eq.13

Where m_j is the mass of recovered material j other than cathode materials or their precursors, and $ei_{j,k}$ is the result of environmental impact/emission category k for 1kg of virgin material j in GREET.

The choice of allocation methods is a hotly debated issue of LCA. Generally speaking, "no allocation" results in the highest environmental impacts for the desired products and is the most conservative option, while "system expansion" returns the most optimistic estimates. The "no allocation" option is the default allocation method in EverBatt.

6 MATERIALS CONVERSION

The materials recovered from the recycling processes are not necessarily in a chemical form that can be directly used to produce new cathode powder. For instance, cobalt can be recovered as cobalt chloride from pyrometallurgical or hydrometallurgical recycling, while cobalt sulfate is needed to produce NMC, and cobalt oxide (Co_3O_4) is needed to produce LCO. The materials conversion module in EverBatt fills in the missing link, and models the conversion of recovered lithium carbonate into lithium hydroxide, recovered cobalt compounds into cobalt sulfate or cobalt oxide (Co_3O_4), and recovered nickel compounds into nickel sulfate.

The materials conversion module does not require any user input. It runs automatically based on built-in inputs. In addition, for materials conversion, only the materials and energy consumptions are considered in the cost and environmental impacts calculation, since in closed-loop recycling scenarios, the materials conversion steps presumably occur at the recycling plant or the cathode powder production plant, with minimal additional capital investment and labor requirements.

The default inputs for materials conversion include the materials and energy flows associated with the material conversion process as shown in Table 17, and the unit prices of chemicals and utilities consumed for the process as summarized in Appendix B. Lithium hydroxide is assumed to be produced commercially by reacting lithium carbonate with lime (CaO) mixed with water (Kamienski *et al.* 2004); cobalt sulfate is assumed to be produced by reacting recovered cobalt compounds with sulfuric acid in the closed-loop recycling scenarios; cobalt oxide (Co_3O_4) is assumed to be produced commercially by reacting recovered cobalt compounds with sodium hydroxide followed by calcination (Dai *et al.* 2018b); and nickel sulfate is assumed to be produced by reacting the recovered nickel compounds with sulfuric acid in the closed-loop recycling scenarios. The materials and energy requirements for cobalt oxide production are based on industry data (Dai *et al.* 2018b), while the materials requirements for the production of lithium hydroxide, cobalt sulfate, and nickel sulfate are determined based on stoichiometry assuming 100% conversion efficiency. Since none of the assumed processes for lithium hydroxide, cobalt sulfate, and nickel sulfate production requires heating, the energy requirements for these processes are assumed to be negligible. A process water consumption of 0.2 gallon per kg precursor produced is used in EverBatt as a place holder.

Table 17. Material and energy requirements to convert recovered materials into 1kg of cathode precursors

	Lithium Hydroxide	Cobalt Sulfate	Cobalt Oxide (Co_3O_4)	Nickel Sulfate
Material inputs (kg)				
Lime	1.17[a]	---	---	---
Sulfuric Acid	---	0.63[a]	---	0.63[a]
Sodium Hydroxide	---	---	0.47[b]	---
Ammonium Bicarbonate	---	---	1.36[b]	---
Water consumption (Gal)	0.20[a]	0.20[a]	2.66[b]	0.20[a]
Energy inputs (MJ)				
Electricity	0.00[a]	0.00[a]	0.10[b]	0.00[a]
Natural gas	0.00[a]	0.00[a]	15.78[b]	0.00[a]

a. Own estimate
b. Dai *et al.*, 2018b

The cost of materials conversion is then calculated as

$$Cost_{materials\ conversion} = \sum_i m_i \times up_i + \sum_j q_j \times up_j + water\ use \times up_{water}$$

Eq.14

Where m_i denotes the mass of material i consumed for the process, q_j denotes the quantity of energy type j consumed, and *up* denotes the unit price of chemicals (by mass), utilities (by energy content) , and process water (by volume).

Similarly, the environmental impacts of materials conversion is calculated as

$$EI_{materials\ conversion,k} = \sum_i m_i \times ei_{i,k} + \sum_j q_j \times ei_{j,k} + water\ use \times ei_{water,k}$$

Eq.15

Where ei_k denotes the environmental impact/emission category k result for unit mass of material, unit energy content of energy, and unit volume of water in GREET.

It should be noted that various leaching processes, including bioleaching, alkaline leaching, organic acid leaching, and inorganic leaching, have been proposed to recover cobalt and nickel from the intermediate products of pyrometallurgical and hydrometallurgical recycling routes (Lv *et al.* 2018). EverBatt is designed to be inclusive of all possible variations of the recycling processes, and the cobalt/nickel-containing outputs from the recycling processes are therefore generically defined as cobalt/nickel ion in the product, which is subsequently treated as a generic salt in the materials conversion module. For recycling processes that already recover cobalt/nickel in a form that can be used directly for cathode powder production (e.g., recover cobalt as cobalt sulfate), such configuration will lead to double counting. The effect of this potential double counting on the final cost and environmental impacts estimates, however, is negligible.

7 CATHODE POWDER PRODUCTION

The cathode powder production module in EverBatt evaluates the production of LCO, NMC111, NMC622, NMC811, and NCA, from both virgin and recycled Ni/Co/Mn/Li precursors. LFP and LMO powder production is not included in EverBatt at present, as LFP and LMO production from recycled precursors is not deemed to be economically viable, due to the relatively low costs of their virgin feedstocks. It should be noted, however, that EverBatt does include direct cathode recycling of LFP and LMO, which can be modeled in the battery recycling module. EverBatt also allows comparison of direct-recycled LFP and LMO powder with their virgin counterparts, based on virgin production costs from BatPaC, and environmental impacts from GREET. It should be also noted that the chemistry of the cathode powder being produced can be different from that of the battery recycled, provided that at least one of the recycled materials can be used as a precursor (with or without material conversion) for the new cathode powder. For instance, materials (cobalt and nickel salts) recycled from NMC111 batteries may be used for the production of NMC111, NMC622, NMC811, and NCA powders, while the recycled cobalt salts may be also for the production of LCO powder.

NMCs and NCA cathode powders are produced commercially by the co-precipitation method, as depicted in Figure 8, while LCO cathode powder is produced by the solid state method, as depicted in Figure 9 (Dai *et al.* 2018a).

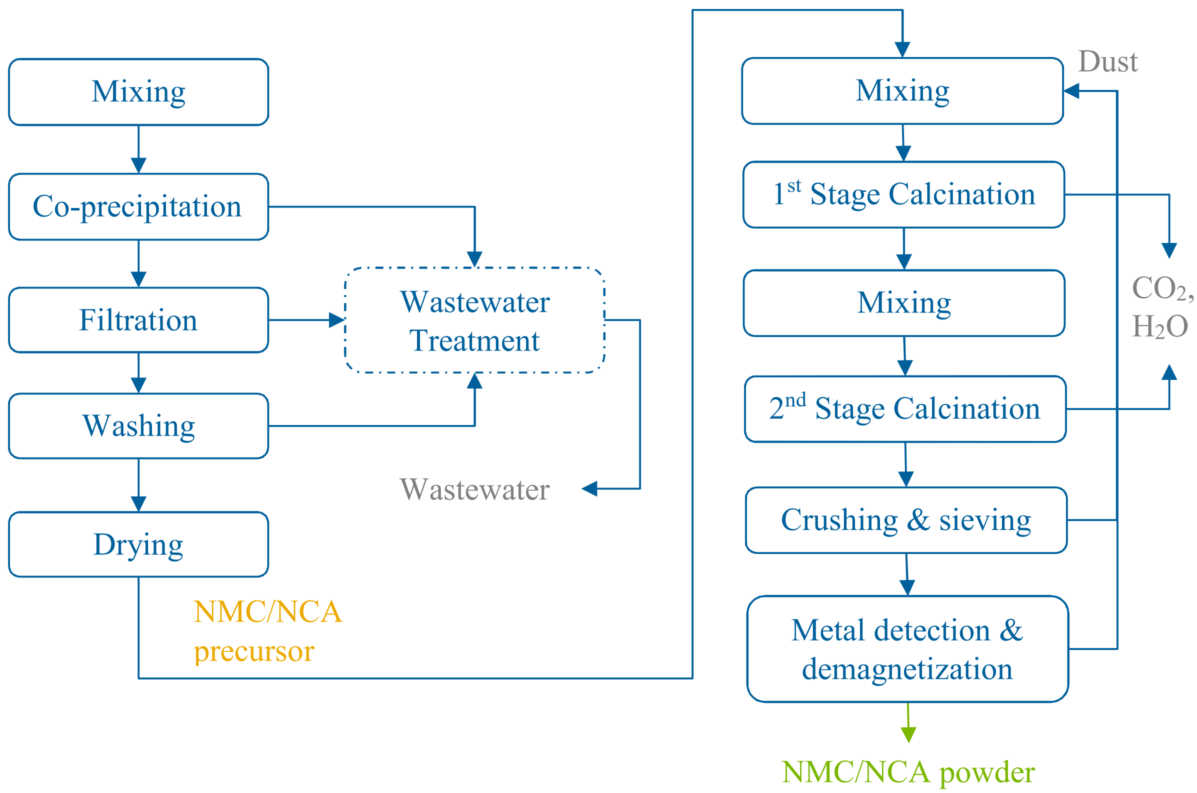

Figure 8.Process diagram of NMC/NCA powder production. Solid boxes denote required processes, and dashed box denotes optional process. Green denotes product; yellow denotes intermediate product; grey denotes wastes.

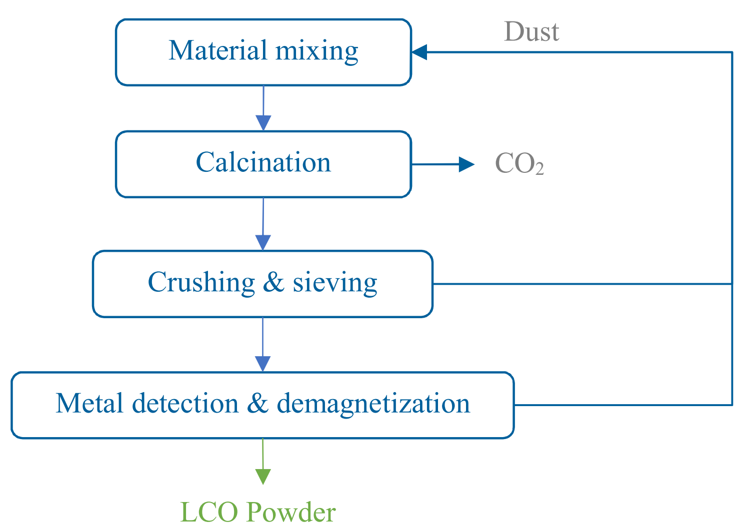

Figure 9.Process diagram of LCO powder production. Green denotes product, and grey denotes wastes.

7.1 MODULE INPUTS

For cathode powder production, the required inputs include the chemistry of the cathode powder being produced, the location of the production plant, the throughput (tonnes of cathode powder per year) of the plant, the materials and energy flows associated with the production process, and the unit prices of chemicals and utilities consumed for the process. The users need to specify the first two inputs, while for the rest of the inputs the users can choose to provide their own values, or use the default values built in EverBatt. Since cathode powder production processes are well-established, we do not expect considerable variations in the process design. Therefore, we do not make the equipment used for the process and the plant operation information customizable, as in the battery recycling module.

The cathode powder production plant is assumed to operate 320 days per year, with a 10-year life span. Again, these inputs are used to determine the amortized capital investment for the plant in cost calculation. Since current recycling processes primarily focus on cobalt recovery, by default, the throughput of the cathode powder plant is set equal to the amount of cathode powder that can be produced by depleting all recovered cobalt salts from spent batteries, as a best approximate of closed-loop recycling. Users can choose a throughput that is higher or lower than the default value, however, and EverBatt will account for the virgin materials requirement or excess recovered materials accordingly.

The equipment used for cathode powder production is based on a process model developed by the BatPaC team led by Dr. Ahmed (Ahmed *et al.*, 2017) as well as information we obtained from cathode producers (Dai *et al.*, 2018a), and is summarized in Figure 10. Since the process model developed by Ahmed *et al.* represents a plant producing 6,500 kg of NMC111 powder per day (equivalent to 2,080 tonnes per year as the plant operates 320 days per year) from one production line, and the industry data we obtained are based on a plant with multiple production lines, each of which has a production capacity of 2,000 tonnes per year, the cathode powder production module in EverBatt also assumes a maximum production line capacity of 2,000 tonnes per year. As a result, when the throughput of the cathode powder production plant falls between 2,001 and 4,000 tonnes per year, two production lines will be needed; when the throughput of the cathode powder production plant falls between 4,001 and 6,000 tonnes per year, three production lines will be needed; et cetera. The throughput of each production line is then determined by dividing the throughput of the plant by the number of production lines, and used subsequently to derive the costs of equipment.

Table 18. Materials and energy requirements to produce 1 kg cathode power

	LCO	NMC(111)	NMC(622)	NMC(811)	NCA
Material inputs (kg)					
Sodium Hydroxide	---	0.844	0.844	0.845	0.836
Lithium Hydroxide	---	---	---	0.246	0.250
Lithium Carbonate	0.377	0.383	0.381	---	---
Hydrochloric Acid	---	---	---	---	---
Sodium Chlorate	---	---	---	---	---
Cobalt Oxide (Co_3O_4)	0.820	---	---	---	---
Oxygen	---	---	---	---	0.040
Nickel Sulfate	---	0.535	0.958	1.273	1.292
Cobalt Sulfate	---	0.536	0.320	0.159	0.247
Manganese Sulfate	---	0.522	0.312	0.155	---
Ammonium Hydroxide	---	0.117	0.117	0.117	---
Aluminum Sulfate	---	---	---	---	0.086
Ammonia	---	---	---	---	0.352
Manganese Oxide	---	---	---	---	---
Phosphoric Acid	---	---	---	---	---
Iron Sulfate	---	---	---	---	---
Process water (gal)	---	0.2	0.2	0.2	0.2
Energy inputs (MJ)					
Electricity	21.60	25.20	25.20	28.80	28.80
Natural gas	---	42.62	42.63	42.62	42.66

The default materials and energy requirements for cathode powder production, as shown in Table 18, are based on industry data (Dai *et al.* 2018a). Again, the unit costs of consumed chemicals and utilities are summarized in Appendix B. It should be noted that the NMC111 powder production process as described in Ahmed *et al.* is based on the carbonate pathway (i.e., co-precipitating Ni/Mn/Co as carbonate), while the production process as described in Dai *et al.* is based on the hydroxide pathway (co-precipitating Ni/Mn/Co as hydroxide). However, except for the reagents used for the co-precipitation step, there is no substantial differences between the two pathways, especially with regard to equipment. Therefore, although EverBatt adopts the hydroxide pathway for the production of NMCs and NCA via co-precipitation, assuming the same equipment as the carbonate pathway is not expected to have any noticeable effect on the cost modeling result.

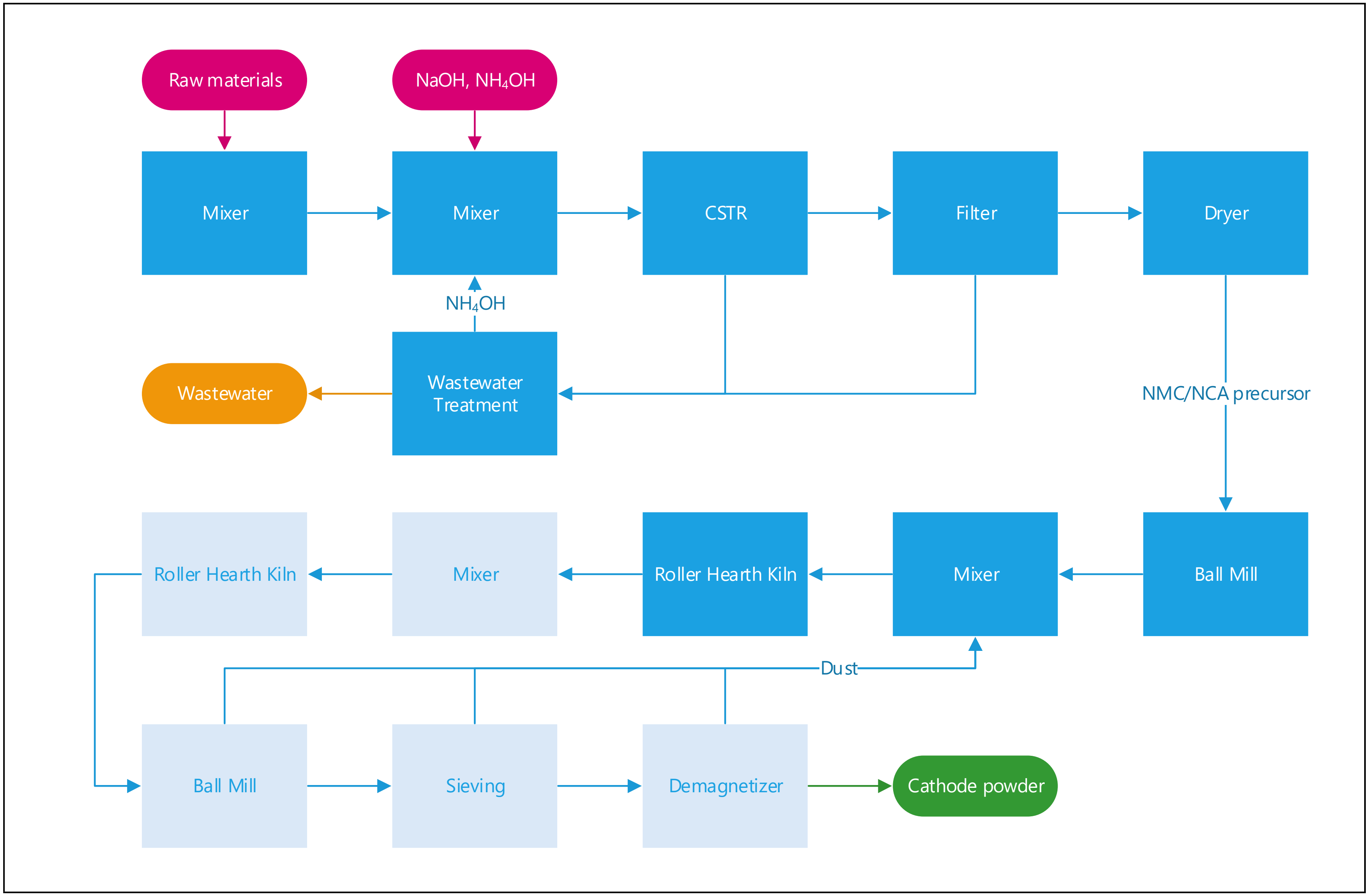

Figure 10. Equipment assumed for cathode powder production. Light blue boxes denote equipment that is needed for LCO powder production. Red denotes reagents. Green denotes product. Yellow denotes waste.

7.2 Cost Calculation

The cost calculation for cathode production, except for the profit, is based on the production cost model developed by the BatPaC team (Ahmed *et al.*, 2017). The specific cost parameters chosen for the cathode production plant are summarized in Table 19.

Table 19. Default parameters for battery powder production cost modeling

Cost Item	Estimated as
I. Direct Costs	I.A+I.B+I.C+I.D
A. Equipment	I.A.1+I.A.2+I.A.3+I.A.4+I.A.5
1. Purchased equipment	Sum of equipment costs
2. Installation, including insulation and painting	40% of I.A.1
3. Instrumentation and controls, installed	20% of I.A.1
4. Piping, installed	20% of I.A.1
5. Electrical, installed	10% of I.A.1
B. Buildings, process and auxiliary	25% of I.A.1
C. Service facilities and yard improvements	60% of I.A.1
D. Land	8% of I.A.1
II. Indirect Costs	II.A+II.B+II.C
A. Engineering and supervision	10% of I
B. Construction expense and contractor's fee	10% of I
C. Contingency	5% of III
III. Fixed Capital Investment	I+II
IV. Working Capital	10% of V
V. Total Capital Investment	III+IV
VI. Manufacturing Costs	VI.A+VI.B+VI.C
A. Direct product costs	VI.A.1+VI.A.2+VI.A.3+VI.A.4+ VI.A.5+VI.A.6+VI.A.7
1. Materials cost	Sum of raw materials costs for virgin production; determined by Equation 16 for production with recycled materials
2. Operating labor	Total labor-hour requirement × hourly labor rate
3. Direct supervisory and clerical labor	15% of VI.A.2
4. Utilities	Sum of utilities costs
5. Maintenance and repairs	5% of III
6. Operating supplies	15% of VI.A.5

7. Laboratory charges	10% of VI.A.2
8. Patents and royalties	1% of VIII
B. Fixed charges	VI.B.1+VI.B.2+VI.B.3+VI.B.4+ VI.B.5
1. Depreciation	(III-I.D)/plant lifetime
2. Local taxes	4% of III
3. Insurance	1% of III
4. Rent	5% of (I.B+I.D)
5. Financing (interest)	5% of V
C. Plant overhead costs	50% of (VI.A.2+ VI.A.2+ VI.A.2)
VII. General Expenses	VII.A+VII.B+VII.C
A. Administrative costs	15% of (VI.A.2+ VI.A.2+ VI.A.2)
B. Distribution and selling costs	6% of VIII
C. R&D costs	5% of VIII
VIII. Total Product Cost	VI+VII
IX. Profit (optional)	5% of V
X. Cost to Recipient	VIII+IX

For cathode production with recycled materials, EverBatt first determines whether there is enough recycled material(s) to meet the production demand. If there is a shortage of recycled material(s), virgin material(s) will be used to meet the remainder of the demand. Since the chemistry of recycled batteries is not necessarily the same as that of the cathode powder being produced, and the throughput of the recycling plant can be higher than that of the cathode production plant, a surplus of recycled material(s) is also possible. For instance, recovered cobalt material from 1,000 tonnes of spent NMC111 batteries may be more than enough to produce the cathode powder needed for 1,000 tonnes of new NMC811/NCA batteries. EverBatt considers all possible scenarios, and the materials cost for cathode production with recycled materials is therefore calculated as

$$Cost_{materials} = \sum_i m_{virgin,i} \times up_{virgin,i} + Cost_{recycled\ materials} + Cost_{mateiasl\ conversion} - \sum_j m_{surplus,j} \times up_{surplus,j}$$

Eq. 16

Where $m_{virgin,i}$ is the mass of virgin material i consumed for cathode production, and $up_{virgin,i}$ is its unit price; $Cost_{recycled\ materials}$ is the aggregate cost of recycled materials as determined in Section 5.2; $Cost_{materials\ conversion}$ is the material conversion cost as determined in Chapter 6; $m_{surplus,j}$ is the mass of surplus material j recovered from battery recycling, and $up_{surplus,j}$ is its unit price.

7.3 ENVIRONMENTAL IMPACTS CALCULATION

The environmental impacts of cathode production are calculated by Equation 1. CO_2 emissions from thermal decomposition of lithium carbonate in the calcination step are considered for cathode production, and are estimated based on stoichiometry.

Similar to the cost, the environmental impacts of materials for cathode production with recycled materials are calculated as

$$EI_{materials,k} = \sum_{i} m_{virgin\ i} \times ei_{virgin\ i,k} + EI_{recycled\ materials,k} + EI_{mateiasl\ conversion,k} - \sum_{j} m_{surplus\ j} \times ei_{surplus\ j,k}$$

Eq.17

Where $ei_{i,k}$ is the environmental impact/emission category k result for unit mass of virgin material i in GREET; $EI_{recycled\ materials,k}$ is the environmental impacts of recycled materials as determined in Section 5.3; $EI_{materials\ conversion,k}$ is the material conversion environmental impacts as determined in Chapter 6; $ei_{surplus\ j,k}$ is the environmental impact/emission category k result for unit mass of recovered material j, and is dependent upon the selected allocation option in the battery recycling module. If the "no allocation" option is selected, $ei_{surplus\ j,k}$ is set to zero; If the "system expansion" option is selected, $ei_{surplus\ j,k}$ is equal to the environmental impact/emission category k result for unit mass of virgin material j in GREET; If the "mass-based allocation" or "economic value-based allocation" is selected, $ei_{surplus\ j,k}$ is calculated based on the corresponding allocation factor for recovered material j as described in Section 5.3.2.

8 BATTERY MANUFACTURING WITH RECYCLED MATERIALS

The battery manufacturing with recycled materials module is identical to the battery manufacturing with virgin materials module, except that for manufacturing with recycled materials, the users also need to specify what recycled material(s) they would like to use in the new battery, and the recycled content(s) (i.e., what percentage of a battery's material is sourced from spent batteries).

The current version of EverBatt allows the use of recycled cathode material, graphite, and electrolyte solvents for new battery manufacturing, as they are most likely to be closed-loop recycled from processes that are already commercialized or under development.

The materials cost for battery manufacturing with recycled materials is estimated as

$$Cost_{materials} = \sum_i m_i \times up_{virgin,i} \times (1 - RC_i) + \sum_i m_i \times cost_{recycled,i} \times RC_i$$

Eq.18

Where m_i is the mass of material i in the battery; RC_i is its recycled content; $up_{virgin,i}$ is the unit price of virgin material i; and $cost_{recycled,i}$ is the per kg cost of recycled material i as calculated in Section 7.2 for recycled cathode material, and in Section 5.2 for non-cathode materials.

Similarly, the environmental impacts for materials used for battery manufacturing with recycled materials is calculated as

$$EI_{materials,k} = \sum_i m_i \times ei_{virgin\ i,k} \times (1 - RC_i) + \sum_i m_i \times ei_{recycled\ i,k} \times RC_i$$

Eq.19

Where $ei_{i,k}$ is the environmental impact/emission category k result for unit mass of virgin material i in GREET; and $ei_{recycled\ i,k}$ is the environmental impact/emission category k result for unit mass of recovered material i, as calculated in Section 7.3 for recycled cathode material, and in Section 5.3 for non-cathode materials.

The rest of the cost and environmental impacts calculations are the same as those for battery manufacturing with virgin materials.

9 CONCLUSIONS

In summary, EverBatt has been developed as a closed-loop battery recycling cost and environmental impacts model that draws on both Argonne's BatPaC and GREET models, aiming to inform battery recycling decisions, and help accelerate the development of a sustainable battery supply chain. The model can be used to benchmark cathode material production and/or battery manufacturing from recycled materials against that from virgin materials, or compare different recycling scenarios, to provide a holistic picture of the benefits and tradeoffs of battery recycling. The model can also help identify cost and environmental hotspots, both along the supply chain and within a specific process, to inform and direct battery recycling R&D efforts, and help overcome potential barriers to process commercialization.

The current version of EverBatt strives to provide a framework to evaluate the cost and environmental impacts of any stages or the entirety of the battery life cycle sans the use-phase. As noted throughout this document, some of the data assumed, as well as the parameters chosen for cost calculations in this version of EverBatt, are based on our best estimates. We will continue to update and improve the model to overcome limitations of the current version of EverBatt. Meanwhile, we also encourage users to supply their own data, if available, to produce results that are more representative of their process, and explore the sensitivity of results of their interest to model inputs.

Looking forward, we will continue to interact with the battery industry and battery researchers to improve the data quality in EverBatt, as well as the model usability. We will also continue to expand EverBatt to include any new processes as they come into existence.

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APPENDIX A EQUIPMENT COSTS

Equipment costs in 2002, 2003, and 2014 dollars are converted into 2017 dollars, based on the annual chemical engineering plant cost index (CEPCI) reported in chemical engineering magazine.

Table 20. CEPCI annual index (1957-1959 = 100)

2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002
567.5	541.7	556.8	576.1	567.3	584.6	585.7	550.8	521.9	575.4	525.4	499.6	468.2	444.2	402	395.6

The costs and power ratings of equipment are summarized in Tables 21-37. These data are collected from engineering handbooks (Peters *et al*. 2003, Couper *et al*. 2005), literature (Rocha-Uribe *et al*. 2014, Rosa and Meireles 2005), and publicly available database (Matche).

Table 21. Costs and power ratings of ball mill (0.25 inch to 200 mesh)

Size (Diameter x longitude. in ft)	Capacity (ton/day)	Capacity (ton/hr)	Horsepower	Couper *et al*. 2005 2003$	Matche 2014$	Matche 2003$
3x2			10			
3x3			15			
3x4	7	0.29	15	$26,068		
3x6	9	0.38	20	$31,004		
3x9	13	0.54	25	$39,958	$92,100	$64,267
4x3	12	0.50	20	$37,811		
4x5	16	0.67	30	$46,113		
4x10	26	1.08	50	$64,464	$168,900	$117,858
5x3	22	0.92	40	$57,445		
5x6	33	1.38	60	$75,990		
5x12	54	2.25	125	$106,742	$270,500	$188,754

Table 22. Costs of incinerator (cylindrical, low-harzard)

Duty (MBtu/hr)	Capacity (ton/hr)	Cost (2014$ from Matche)
10	0.5	$921,300
25	1.25	$1,472,900
40	2	$1,873,600
50	2.5	$2,100,300
65	3.25	$2,402,300
75	3.75	$2,584,900
90	4.5	$2,837,800

Table 23. Costs of incinerator (rotary kiln, hazardous feed material, atmospheric pressure)

Duty (MBTU/hr)	Capacity (ton/hr)	Cost (2014$ from Matche)
10	0.5	$4,400,800
20	1	$6,138,000
25	1.25	$6,831,900
30	1.5	$7,456,700
35	1.75	$8,029,400
40	2	$8,560,900
50	2.5	$9,528,800
100	5	$13,290,200

Table 24. Costs of incinerator (catalytic, low-hazard feed material, atmospheric pressure)

Duty (MBTU/hr)	Capacity (ton/hr)	Cost (2014$ from Matche)
5	0.25	$172,300
10	0.5	$291,900
15	0.75	$397,200
20	1	$494,300
25	1.25	$585,600
30	1.5	$672,700

Table 25. Cost of conveyor (belt)

Description	Cost (2014$ from Matche)
Belt, open, short, 42 inch width, 100 ft length	$102,600

Table 26. Costs of conveyor (Screw conveyor, 12 inch diameter)

Length (ft)	Cost		
	Couper *et al*. 2005 (2003\$) Cost = 0.85Length^0.78*1000 in 2003\$, 7<Length<100ft	Matche (2014\$)	Matche (2003\$)
25	\$10,467	\$6,700	\$4,675
40	\$15,102	\$8,800	\$6,141
50	\$17,973	\$10,000	\$6,978
70	\$23,367	\$12,200	\$8,513
80	\$25,932	\$13,200	\$9,211
100	\$30,862	\$15,000	\$10,467

Table 27. Costs and power ratings of granulator

Rotating disk granulator (Couper *et al*. 2005)			Agglomerator, disk with motor, stainless 304
Disk size (ft)	Capacity (ton/hr)	Horsepower	Cost (2014\$ from Matche)
3.25	0.5	1	\$19,800
6	3	3	\$51,100
9	5	6	\$95,600
12	10	12	\$149,100
15	18	25	\$210,500
18	30	40	\$279,000

Table 28. Cost of filter

Description	Cost (2014\$ from Matche)
Filter, plate and frame, 200 ft^2 filter area, stainless 304	\$173,000

Table 29. Costs of reactor (mixer/settler, stainless 304, atmospheric to 25 psi)

Volume (gallon)	Capacity (ton/hr)	Cost (2014\$ from Matche)
200	0.2	\$230,400
400	0.4	\$314,300
500	0.5	\$347,400
700	0.7	\$403,900
800	0.8	\$428,800
1,000	1	\$473,900
1,300	1.3	\$533,000
1,500	1.5	\$568,300

Table 30. Costs of reactor (jacketed and agitated, stainless 304, atmospheric to 25psi)

Volume (gallon)	Capacity (ton/hr)	Cost (2014$ from Matche)
500	0.5	$91,000
1,000	1	$131,400
2,000	2	$189,800
2,800	2.8	$226,800
3,500	3.5	$255,300
5,000	5	$308,400

Table 31. Costs of screen (stainless steel, with medium carbon steel wire)

Deck area (ft^2)	Capacity (ton/hr)	Cost (2014$ from Matche)
3	1.5	$5,800
5	2.5	$6,900
7	3.5	$8,000
10	5	$9,700
20	10	$15,600
40	20	$28,300

Table 32. Costs of extruder (roll-type)

Solids flowrate (kg/s)	Capacity (tonne/hr)	Cost (2002$ from Peters *et al. 2003*)
1	3.6	$16,048
2	7.2	$21,111
5	18	$36,300
7	25.2	$46,427
10	36	$61,616

Table 33. Costs of crusher (roll)

Capacity (kg/s)	Capacity (tonne/hr)	Cost (2002$ from Peters *et al. 2003*)
1	3.6	$17,636
5	18	$30,709
10	36	$43,351
50	180	$123,445
100	360	$215,377

Table 34. Costs of crusher (gyratory)

Capacity (kg/s)	Capacity (tonne/hr)	Cost (2002$ from Peters *et al. 2003*)
1	3.6	$106,512
5	18	$69,370
10	36	$75,579
50	180	$161,244
100	360	$277,843

Table 35. Cost of hopper

Description	Cost (2014$ from Matche)
Hopper with bottom, bolted, carbon steel, 5000 ft^3 bin volume	$ 38,700

Table 36. Cost of cyclone

Description	Cost (2014$ from Matche)
Cyclone, wet, ceramic lined, 30inch diameter	$50,300

Table 37. Cost of pump (centrifugal, cast iron, 1035 kpa)

Volumetric flow rate (m^3/s)	Capacity (tonne/hr)	Cost (2002$ from Peters *et al. 2003*)
0.009	3.24	$3,009

The cost of the heavy duty cyclone separator in EverBatt is based on the empirical equation in Couper *et al*. 2005, as shown below

$$C = 1.69 \times Q^{0.96} \times 1000$$

Where C is the cost in 2003$; Q is the flow rate in thousand standard cubic feet per minute (SCFM), and ranges between 2,000 to 40,000 SCFM.

It is assumed in EverBatt that the solids loading of the cyclone is 0.01kg/stand cubic feet.

The cost of the rotary steam tube dryer in EverBatt is based on the empirical equation in Couper *et al*. 2005, as shown below

$$C = 2.23 \times F \times A^{0.6} \times 1000$$

Where C is the cost in 2003$; F is the material coefficient, and equals to 1.75 for 304 stainless steel; A is the tube surface area in square feet, and ranges between 500 and 18,000 square feet.

It is assumed in EverBatt that the heat load of the dryer is 2.6 MJ/kg product/hr, and the heat surface requirement is 4.3 ft^2/kg product/hr.

The cost of the supercritical CO2 extraction unit in EverBatt is based on the cost curve developed by Rocha-Uribe *et al.* 2014, as shown below

$$C = 31901 \times V^{0.6909}$$

Where C is the cost in 2009$; V is volume in liters.

Based on process information reported in Rocha-Uribe *et al.* 2014 and Rosa and Meireles 2005, it is assumed that the extraction time is 1hr, and the solids loading is 0.5kg/L.

APPENDIX B UNIT PRICES OF RAW MATERIALS

Table 38. Unit prices of battery materials

Material	Unit price ($/kg)	Note
LCO	$35.00	Calculated for cathode production plant with a throughput of 10,000 tonnes per year, superseded by new cost from cathode production module if available
LMO	$10.00	BatPaC
LFP	$14.00	BatPaC
NMC111	$20.00	BatPaC, superseded by cost from cathode production module if available
NMC622	$17.00	BatPaC, superseded by cost from cathode production module if available
NMC811	$16.00	Internal version of BatPaC, superseded by cost from cathode production module if available
NCA	$24.00	BatPaC, superseded by cost from cathode production module if available
Graphite	$12.50	BatPaC
Carbon black	$6.60	BatPaC
PVDF	$9.50	BatPaC
Electrolyte	$12.50	BatPaC, converted from $/L
Separator	$159.42	BatPaC, converted from $\$/m^2$
Cu	$13.45	Copper foil unit price in BatPaC, converted from $\$/m^2$
Al	$7.41	Aluminum foil unit price in BatPaC, converted from $\$/m^2$
Cell container	$3.00	BatPaC

Table 39. Unit prices of chemicals ($/kg)

Chemical	Unit price ($/kg)	Note
Aluminum Sulfate	$1.85	99 plus, Integra 2016 bulk quote
Ammonia	$0.46	2014-2018 average, gulf price plus 15% margin, USGS 2019a
Ammonium Bicarbonate	$0.46	Assumed to be the same as ammonia cost
Ammonium Hydroxide	$0.46	Assumed to be the same as ammonia cost
Carbon Dioxide	$0.10	Rocha-Uribe *et al*. 2014
Citric Acid	$0.69	2016 India bulk import price, anhydrous, 1 USD = 67 INR; Zauba 2019a
Cobalt	$51.33	London Metal Exchange (LME) 2016-2018 average, cash; USGS 2019b
Cobalt Oxide (Co_3O_4)	$37.66	Converted from Co cost based on Co content
Cobalt Sulfate	$19.51	Converted from Co cost based on Co content
Coke	$0.09	2018 U.S. export average, not calcined; U.S. Department of Commerce 2019
Hydrochloric Acid	$0.15	2013-2017 average; ICIS 2018
Hydrogen Peroxide	$0.74	2014-2018 China average, 27.5%, 1USD = 6.5 RMB; CEIC Data 2019a
Iron Sulfate	$0.37	Anhydrous, converted from monohydrate granular price; ICIS 2005
Lime	$0.13	2014-2018 average, at plant; USGS 2019c
Limestone	$0.13	Chemical grade; use lime price as a proxy
Lithium Carbonate	$7.90	BatPaC
Lithium Hydroxide	$12.18	Converted from Li_2CO_3 cost based on Li content
Manganese	$3.10	LME 2011-2015 average, cash; USGS 2019d
Manganese Oxide	$2.16	Converted from Mn cost based on Mn content
Manganese Sulfate	$1.13	Converted from Mn cost based on Mn content
Nickel	$11.30	LME 2016-2018 average, cash; USGS 2019e
Nickel Sulfate	$4.29	Converted from Ni cost based on Ni content
NMP	$3.10	BatPaC
Oxygen	$0.20	Chemicool
Phosphoric Acid	$0.92	2014-2018 China average, 85%, 1USD = 6.5 RMB; CEIC Data 2019b
Sand	$0.06	2014-2018 average; USGS 2019f
Soda Ash	$0.15	2014-2018 average; USGS 2019g
Sodium Chlorate	$0.53	2016 India bulk import price, 1 USD = 67 INR; Zauba 2019b
Sodium Hydroxide	$0.40	2015-2018 average; ICIS 2019
Sulfuric Acid	$0.06	2015 import average, USGS 2017

APPENDIX C EQUIPMENT COST AND ENERGY RATING CURVES

The equipment cost and energy rating curves are derived based on information detailed in Appendix A. Below is the general form of the two curves:

$$Cost\ (2017\$) = (a \times Cap^{b} + c) \times adj$$

Where *Cap* is the design capacity of the equipment in tonnes per hour; *a*, *b*, and *c* are equipment-specific cost coefficients, and *adj* is the term to convert reported cost into 2017$.

$$Energy\ rating\ (KW) = m \times Cap^{n} + p$$

Where m, n, and p are equipment-specific energy rating coefficients.

The cost and energy rating coefficients for each equipment are summarized in Table 40.

Table 40. Equipment cost and power rating coefficients

Equipment	Cost coefficient				Power consumption coefficient			Note
	a	b	c	adj.	m	n	p	
Ball mill	61,000	0.69	0	1.412	34	1.006	0	Ball mill 0.25 inch to 200 mesh
Brine soak	31,862	0	0	1.412	7.5*	0	0	Screw conveyor, stainless steel, 12 inch diameter
Briquetter	16,048	0	0	1.435	75*	0	0	Roll-type extruder
Calciner	1,313,832	0.512	0	0.985	5861*	1	0	Incinerator, cylindrical, low-hazard feed material
Cell perforator	17,636	0	0	1.435	75*	0	0	Roll crusher

Conveyor	102,600	0	0	0.985	15*	0	0	Belt, open, short, 42inch wide, 100ft long
Crusher	106,512	0	0	1.435	75*	0	0	Gyratory crusher
Density separator	2,760	0.96	0	1.412	75*	0	0	Cyclone separator, heavy duty
Dryer	591,236	0.6	0	1.412	729	1	0	Steam tube dryer, class II, 304 stainless steel
Filter press	173,000	0	0	0.985	15*	0	0	Filter, plate and frame, 200ft^2 filter area, stainless 304
Froth flotation cell	131,410	0.5301	0	0.985	75*	0	0	Reactor, jacketed and agitated, stainless 304, atmospheric to 25psi
Gas treatment	3,000,000*	0	0	1	1,000*	0	0	
Granulator	29,902	0.6671	0	0.985	1.361	1	-0.5806	Agglomerator, disk with motor, stainless 304
Hopper	38,700	0	0	0.985	15*	0	0	Hopper with bottom, bolted, carbon steel, 5000 ft^3 bin volume
Hydrocyclone	50,300	0	0	0.985	75*	1	0	Cyclone, wet, ceramic lined, 30inch diameter
Leaching tank	473,892	0.4481	0	0.985	15*	1	0	Reactor, mixer/settler, stainless 304, atmospheric to 25 psi
Mixing tank	473,892	0.4481	0	0.985	15*	1	0	Reactor, mixer/settler, stainless 304, atmospheric to 25 psi
Oxidizer	494,284	0.7601	0	0.985	5861*	0	0	Incinerator, catalytic, low-hazard feed material, atmospheric pressure
Precipitation tank	473,892	0.4481	0	0.985	15*	0	0	Reactor, mixer/settler, stainless 304, atmospheric to 25 psi
Pump	3,009	0	0	1.435	3.192	1	0	Centrifugal, cast iron, 1035 kPa
Screener	1,218	1	3752.8	0.985	15*	1	0	DSM screen, stainless steel, with medium carbon steel wire
Skid steer	40,000*	0	0	1	0	0	0	Diesel-fueled

Smelter	6,137,979	0.48	0	0.985	0	0	0	Incinerator, rotary kiln, hazardous feed material, atmospheric pressure
Solvent Extraction Unit	473,892	0.4481	0	0.985	15*	1	0	Reactor, mixer/settler, stainless 304, atmospheric to 25 psi
Super critical CO_2 system	6,088,158	0.6909	0	1.087	1,000*	0	0	
Water treatment	1,000,000*	0	0	1	1,000*	0	0	
Wet granulator	29,902	0.6671	0	0.985	1.361	1	-0.5806	Agglomerator, disk with motor, stainless 304
Wheel loader	150,000*	0	0	0	0	0	0	Diesel-fueled

*Own estimate

APPENDIX D GEOGRAPHIC PARAMETERS

Table 41. Model parameters for different geographic regions

Battery manufacturing w/ virgin materials				
	U.S.	California	China	Korea
Building cost ($/m^2)	$3,000	$3,000	$1,500	$2,000
Direct labor ($/hr)	$18.00	$20.00	$2.00	$10.00
Capital cost adjustment (%)	100%	100%	90%	80%
Battery collection and transportation				
Hazardous materials transportation				
	U.S.	California	China	Korea
Rail	$0.97	$0.97	$0.10	$0.20
Medium-duty truck	$9.40	$9.40	$1.00	$2.00
Heavy-duty truck	$6.28	$6.28	$0.60	$1.20
Barge	$0.50	$0.50	$0.10	$0.10
Ocean tanker	$0.50	$0.50	$0.10	$0.10
Non-hazardous materials transportation				
Rail	$0.05	$0.05	$0.01	$0.02
Medium-duty truck	$0.15	$0.15	$0.03	$0.05
Heavy-duty truck	$0.14	$0.14	$0.03	$0.05
Barge	$0.02	$0.02	$0.01	$0.01
Ocean tanker	$0.02	$0.02	$0.01	$0.01
Battery recycling				
	U.S.	California	China	Korea
Equipment cost adjustment (%)	100%	100%	60%	80%
Direct labor ($/hr)	$20.00	$20.00	$2.00	$10.00
Electricity cost ($/kWh)	$0.069	$0.134	$0.088	$0.076
Natural gas cost ($/1000 ft^3)	$4.20	$7.05	$12.21	$12.21
Water cost ($/gal)	$0.004	$0.004	$0.002	$0.003
Landfill cost (tip fee $/ton)	$45.00	$45.00	$10.00	$20.00
Wastewater discharge cost ($/gal)	$0.005	$0.005	$0.003	$0.003
Cathode production				
	U.S.	California	China	Korea
Equipment cost adjustment (%)	100%	100%	90%	80%
Direct labor ($/hr)	$20.00	$20.00	$2.00	$10.00
Electricity cost ($/kWh)	$0.069	$0.134	$0.088	$0.076
Natural gas cost ($/1000 ft^3)	$4.20	$7.05	$12.21	$12.21

Water cost ($/gal)	$0.004	$0.004	$0.002	$0.003
Battery manufacturing w/ recycled materials				
	U.S.	California	China	Korea
Building cost ($/m^2)	$3,000	$3,000	$1,500	$2,000
Direct labor ($/hr)	$18.00	$20.00	$2.00	$10.00
Capital cost adjustment (%)	100%	100%	50%	80%

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