Economic and Environmental Viability of Lithium-Ion Battery Recycling—Case Study in Two Canadian Regions with Different Energy Mixes

Giovanna Gonzales-Calienes[1±], Miyuru Kannangara[1], Farid Bensebaa[1±]

[1] Energy, Mining and Environment Research Centre, National Research Council Canada, 1200 Montreal Road, Ottawa, ON, Canada, K1A 0R6

[±]Correspondence: giovanna.gonzalescalienes@nrc-cnrc.gc.ca (G.G.-C.); farid.bensebaa@nrc-cnrc.gc.ca (F.B.), Tel: +1-613-9931700 (G.G.-C.)

Supplementary information

Contents

S1. Capital costs

A summary of the direct capital costs for the hydrometallurgical solvent extraction process plant by process area is presented in Table S1.

Table S1: Breakdown of direct cost estimate by area (CAD)

Process area	Total
PROCESS PLANT	**125,947,573**
Reagent Preparation	2,390,918
Black Mass Cake Re-Pulp	211,515
Reductive Acid Leach	3,429,749
Primary Neutralization	2,299,887
Secondary Neutralization	1,571,634
Mixed Hydroxide Precipitation	1,871,503
Scavenger Precipitation	908,977
Manganese and Magnesium Precipitation	7,076,368
Calcium Precipitation	2,621,175
Lithium Carbonate Precipitation	3,402,975
Glauber Salt Crystallization	12,558,345
Off-Gas Handling	1,283,813
Fresh and Process Water Distribution	361,449
MHP Leaching	2,378,870
Mn Solvent Extraction1	4,218,244
Co Solvent Extraction1	9,716,285
Ni Solvent Extraction1	27,454,060
Mn Crystallization	1,504,699
Co Crystallization	6,020,134
Ni Crystallization	22,176,904
Steam Generation	937,090
Reverse Osmosis	2,293,193
Miscellaneous Equipment (10% of Unit Cost)	9,259,788
ANCILLARY FACILITIES	**174,031**
Total Direct costs	**126,121,604**

(1) Includes first fill of extractants and diluents

S2. Operating costs

A summary of the operating costs for the hydrometallurgical solvent extraction process plant is presented in Table S2.

Table S2: Breakdown of operating cost

Reagent Consumption	**Unit Cost**	**Annual Cost**
	CAD/t	**CAD/y**
Sulphuric Acid (98 wt.%)	535	17,391,052
Lime	469	4,733,643
Sulphur Dioxide	1,540	4,075,003
Magnesia	469	2,032,147
Sodium Hydroxide (pellets)	870	469,884
Sodium Carbonate (100 wt.%)	870	15,910,450
Flocculant	4,217	20,081
Fresh Water Makeup	3	198,128
Makeup DEHPA	13,588	921,026
Makeup C272	56,426	1,317,281
Makeup Diluent	1,352	950,477
Miscellaneous Consumables (5% of total reagent cost)		2,240,984
Shipping and disposal	**CAD/t**	**CAD/y**
Manganese sulfate packaging and shipping	268	93,709
Cobalt sulfate packaging and shipping	268	1,024,106
Nickel sulfate packaging and shipping	268	4,307,937
Li_2CO_3 packaging and shipping	268	852,752
Reductive acid leach residue disposal	27	235,611
Primary neutralization residue disposal	27	192,773
Manganese and magnesium precipitation residue	27	720,221
Mixed hydroxide precipitation leaching residue	27	49,532
Glauber Salt	27	1,848,745
	CAD/m^3	**CAD/y**
Natural Gas	0.17	99,064
	CAD/kWh	**CAD/y**
Power	0.12	2,621,175
Labour		12,041,607
Maintenance and Supplies (2.5% Direct Cost)		3,152,639
Contingency (10%)		7,749,734

S3. Battery Characterization

The LIB cathode chemistry and battery design have evolved in recent years toward higher specific energy and lower cobalt content. The updated bill of materials and cathode materials of EV LIB chemistries from the GREET model were used [1]. The EV LIB chemistry selected for this LCA study is $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811).

The battery characteristics of this EV LIB pack is based on Dai et al.'s, 2019a, study and Argonne's Battery Performance and Cost (BatPaC) Model [2] that is shown in Table S 3. Detailed material compositions at the cell, module, and pack levels are presented in Table S 4 [3].

Table S 3: Battery technical characteristics of the two selected LIB chemistries [2, 3]

Technical Characteristics	**NMC 811**	
	Amount	Units
Functional unit	1	kg of BEV battery pack
LIB anode chemistry	Graphite	
LIB cathode chemistry	NMC	$Li(Ni_{0.8}Mn_{0.1}Co_{0.1})O_2$
Nominal voltage, cell	3.75	V
Nominal capacity, pack	23.5	kWh
Number of cells	164	cells
Type of cell	Prismatic-811	
Weight of the cells	132	kg
Weight of the battery pack	158	kg
Energy density—cell level	178	Wh/kg
Energy density—pack level	149	Wh/kg
Weight one cell	0.803	kg
Energy one cell	0.143	kwh

Table S 4: Mass contribution of NMC 111 and NMC 811 EV LIB batteries [3]

Cell components	**NMC 811 (kg)**	**Total mass contribution (%)**
Active cathode material	34.93	22.2%
Graphite	23.15	14.7%
Carbon black	1.94	1.2%
Binder (PVDF)	4.01	2.5%
Copper	17.65	11.2%
Aluminum	9.25	5.9%
Electrolyte: LiPF6	2.89	1.8%
Electrolyte: Ethylene Carbonate	8.07	5.1%
Electrolyte: Dimethyl Carbonate	8.07	5.1%
Plastic: Polypropylene	1.68	1.1%
Plastic: Polyethylene	0.39	0.2%
Plastic: Polyethylene Terephthalate	0.34	0.2%
Subtotal: Cell	112.37	71%
Module components excluding cell		
Copper	0.44	0.3%
Aluminum	7.15	4.5%
Plastic: Polyethylene	0.18	0.1%
Thermal Insulation	0.11	0.1%
Electronic part	1.12	0.7%
Subtotal: Module without cells	9	5.7%
Pack components without module		
Copper	0.09	0.1%
Aluminum	22.29	14.1%
Steel	1.01	0.6%
Thermal Insulation	0.69	0.4%
Coolant: Glycol	7.3	4.6%
Electronic part -BMS	4.93	3.1%
Subtotal: Battery pack without module	36.31	23.0%
Total: Battery pack	157.68	100%

S4. Life cycle inventory

Life cycle inventories are provided in the NRC collaboration server, which can be accessed using the following URL.

https://eeecc.nrc-cnrc.gc.ca/openlca/NRC_CNRC/Lithium_Battery_Recycling_Pathways_Public/datasets

A short description of each dataset and its inputs and outputs are described. The datasets can be download as either JSON-LD or ILCD formats, which permits their importation into commonly used LCA software such as OpenLCA. Table S5 shows the provided inventories in the NRC collaboration server.

Table S5: Life cycle inventories included in the NRC collaboration server repository.

Process	**Inventory name**
Black mass treatment	black mass treatment, solvent extraction, hydrometallurgical process; at plant; NMC 811 battery cell type (Geographies Ca-ON and Ca-QC)
Cathode active material production	cathode active material; production using calcination of recycled precursor; at plant; NMC 811 battery cell type (Geographies Ca-ON and Ca-QC)
Precursor cathode active material production	lithium nickel cobalt manganese hydroxide; production using co-precipitation of recycled sulfates; at plant; NMC 811 battery cell type (Geographies Ca-ON and Ca-QC)
Lithium hydroxide production	lithium hydroxide; production from recycled lithium carbonate; at plant; NMC 811 cell type (Geographies Ca-ON and Ca-QC)

It should be noted that the Ecoinvent database is required for cradle-to-gate impact assessment using the above LCI datasets. When using openLCA, users must first import the Ecoinvent database into an empty database and then import the above datasets to establish correct flow and provider connections. Both Ecoinvent and openLCA reference impact assessment methods can be used for impact assessment.

References

1. Dai, Q., et al., *Update of Bill-of-materials and Cathode Materials Production for Lithium-ion Batteries in the GREET Model* 2018, Argonne National Laboratory.
2. Dai, Q., et al., *EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model*. 2019b, Argonne National Laboratory. p. 88.
3. Dai, Q., et al., *Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications.* Batteries, 2019a. **5**(2): p. 48.