Development of a Reverse Logistics Modeling for End-of-Life Lithium-Ion Batteries and Its Impact on Recycling Viability—A Case Study to Support End-of-Life Electric Vehicle Battery Strategy in Canada

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Supplementary information

Contents

S1. New zero-emissions electric vehicles registrations

Statistics Canada provides data for annual registrations of new EVs purchased in Canada by province from 2011 to 2021 (Table S1), including full battery electric vehicles (BEVs), hybrid electric vehicles (HEV), and plug-in hybrid electric vehicles (PHEVs). ZEVs include BEVs and PHEVs. Conventional Hybrid EVs are not considered as they don't use LIBs [1].

Table S1: Annual new electric vehicle registrations [2]

	Canada										
	Total, vehicle type [1,2]										
	Number of ZEVs										
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Battery electric	215	646	1,602	2,839	4,151	4,990	8,921	22,544	35,523	39,036	58,726
Plug-in hybrid electric	303	1,343	1,548	2,533	2,737	7,019	11,405	21,111	20,642	15,317	27,306
Total ZEV's	**518**	**1,989**	**3,150**	**5,372**	**6,888**	**12,009**	**20,326**	**43,655**	**56,165**	**54,353**	**86,032**

(1) Data for Newfoundland and Labrador, Nova Scotia and Alberta are currently not available due to contractual limitations of the existing data sharing agreement.
(2) Total vehicle type excludes buses, trailers, recreational vehicles, motorcycles, snowmobiles, golf carts.

S2. Baseline MFA scenario for EV LIBs

The forecast for the baseline scenario is based on the extrapolated annual number of passenger vehicle sales resulting from a 6% retirement rate of passenger vehicle stock estimated in the C.D. Howe study [3], and a 1-percentage point increase of the annual share of ZEVs in total light-duty vehicle sales based on the historic values from 2018 to 2021. Table S2 shows the Baseline MFA scenario for EV LIBs.

S3. Net-zero MFA scenario for EV LIBs

The net-zero target scenario is based on the same annual number of passenger vehicle sales resulting from a 6% retirement rate of passenger vehicle stock estimated in the C.D. Howe study [3], and the net-zero GHG emissions target by increasing the ZEVs share in total passenger vehicle sales to 100% in 2035, including mandatory interim targets of at least 20% of all new light-duty vehicles offered for sale by 2026 [4]. The net-zero MFA scenario takes into account 10% of battery losses before EoL due to unexpected accidents. Table S3 shows the Net-zero MFA scenario for EV LIBs.

Table S2: Baseline MFA scenario for EV LIBs

Battery inflow		EV Lifespan Distribution (# of EV LIBs)				End-of-life LIBs from EVs	LIBs viable for recycling 70%
Year	Canada EV Registrations	6 yr	8 yr	10 yr	15yr		
2011	518	0	0	0	0	0	0
2012	1989	0	0	0	0	0	0
2013	3150	0	0	0	0	0	0
2014	5372	0	0	0	0	0	0
2015	6888	0	0	0	0	0	0
2016	12009	0	0	0	0	0	0
2017	20326	52	0	0	0	52	36
2018	43655	199	0	0	0	199	139
2019	56165	315	207	0	0	522	366
2020	54353	537	796	0	0	1333	933
2021	86034	689	1260	207	0	2156	1509
2022	107380	1201	2149	796	0	4145	2902
2023	130559	2033	2755	1260	0	6048	4233
2024	145210	4366	4804	2149	0	11318	7923
2025	164571	5617	8130	2755	0	16502	11551
2026	184304	5435	17462	4804	52	27753	19427
2027	204408	8603	22466	8130	199	39399	27579
2028	224885	10738	21741	17462	315	50256	35179
2029	245734	13056	34413	22466	537	70473	49331
2030	263787	14521	42952	21741	689	79903	55932
2031	284965	16457	52224	34413	1201	104295	73007
2032	306491	18430	58084	42952	2033	121499	85049
2033	328362	20441	65828	52224	4366	142858	100001
2034	350581	22489	73721	58084	5617	159911	111937
2035	373147	24573	81763	65828	5435	177600	124320
2036	396059	26379	89954	73721	8603	198658	139060
2037	419318	28497	98294	81763	10738	219292	153504
2038	442924	30649	105515	89954	13056	239174	167422
2039	466877	32836	113986	98294	14521	259637	181746
2040	491176	35058	122596	105515	16457	279626	195738

Table S3: Net-zero MFA scenario for EV LIBs

Battery inflow		EV Lifespan Distribution (# of EV LIBs)				End-of-life LIBs from EVs (after 10% of battery losses)	LIBs viable for recycling 70%
Year	Canada EV Registrations	6 yr	8 yr	10 yr	15yr		
2011	518	0	0	0	0	0	0
2012	1989	0	0	0	0	0	0
2013	3150	0	0	0	0	0	0
2014	5372	0	0	0	0	0	0
2015	6888	0	0	0	0	0	0
2016	12009	0	0	0	0	0	0
2017	20326	52	0	0	0	47	33
2018	43655	199	0	0	0	179	125
2019	56165	315	207	0	0	470	329
2020	54353	537	796	0	0	1200	840
2021	86034	689	1260	207	0	1940	1358
2022	344720	1201	2149	796	0	3731	2612
2023	469508	2033	2755	1260	0	5443	3810
2024	555786	4366	4804	2149	0	10186	7130
2025	711417	5617	8130	2755	0	14852	10396
2026	828736	5435	17462	4804	52	24977	17484
2027	928302	8603	22466	8130	199	35459	24821
2028	1101441	34472	21741	17462	315	66591	46614
2029	1207310	46951	34413	22466	537	93931	65751
2030	1334693	55579	137888	21741	689	194307	136015
2031	1403310	71142	187803	34413	1201	265103	185572
2032	1510736	82874	222314	137888	2033	400598	280418
2033	1619896	92830	284567	187803	4366	512609	358826
2034	1730790	110144	331494	222314	5617	602612	421829
2035	1940440	120731	371321	284567	5435	703849	492694
2036	1957780	133469	440576	331494	8603	822729	575910
2037	1975120	140331	482924	371321	34472	926143	648300
2038	1992460	151074	533877	440576	46951	1055230	738661
2039	2009800	161990	561324	482924	55579	1135635	794944
2040	2027140	173079	604294	533877	71142	1244153	870907

S4. Battery mass allocation among Canadian provinces

Note that available spent EV LIB mass per each province can be estimated by assuming an average of 326 kg per battery pack (Table S4 and Table S5).

Table S4: Battery mass allocation among Canadian provinces: baseline scenario

E-o-L EV battery pack	15 years	2040	
Estimated spent battery mass (t)		63,836	
Average battery mass (kg)		326	
Share of spent batteries mass (tons)			
Prince Edward Island	0.2%	129	42677
New Brunswick	0.5%	350	EAST
Nova Scotia	0.2%	128	
Newfoundland and Labrador	0.2%	128	
Quebec	42.8%	27306	
Ontario	22.9%	14637	
Manitoba	0.7%	468	21137
Saskatchewan	0.6%	355	WEST
Alberta	4.1%	2617	
British Columbia and the Territories	27.7%	17697	

Table S5: Battery mass allocation among Canadian provinces: net-zero target scenario

E-o-L EV battery pack	15 years	2040	
Estimated spent battery mass (t)		284,030	
Average battery mass (kg)		326	
Share of spent batteries mass (tons)			
Prince Edward Island	0.2%	574	189,887
New Brunswick	0.5%	1558	EAST
Nova Scotia	0.2%	568	
Newfoundland and Labrador	0.2%	568	
Quebec	43%	121,493	
Ontario	23%	65,124	
Manitoba	1%	2,083	94,046
Saskatchewan	1%	1,578	WEST
Alberta	4%	11,645	
British Columbia and the Territories	28%	78,740	

S5. Geo-locations of spent EV batteries collection sites across Canada

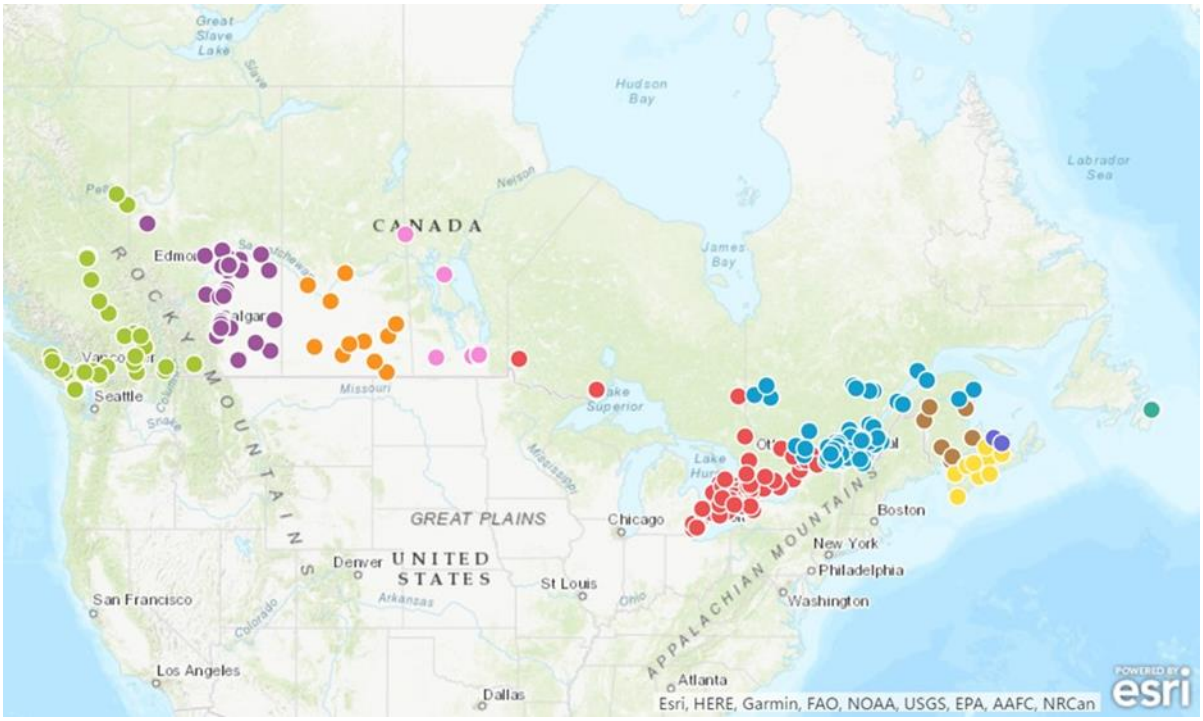

Figure S1: Geo-locations of spent EV batteries collection sites across Canada

S6. Geographical location of population centers in Canada

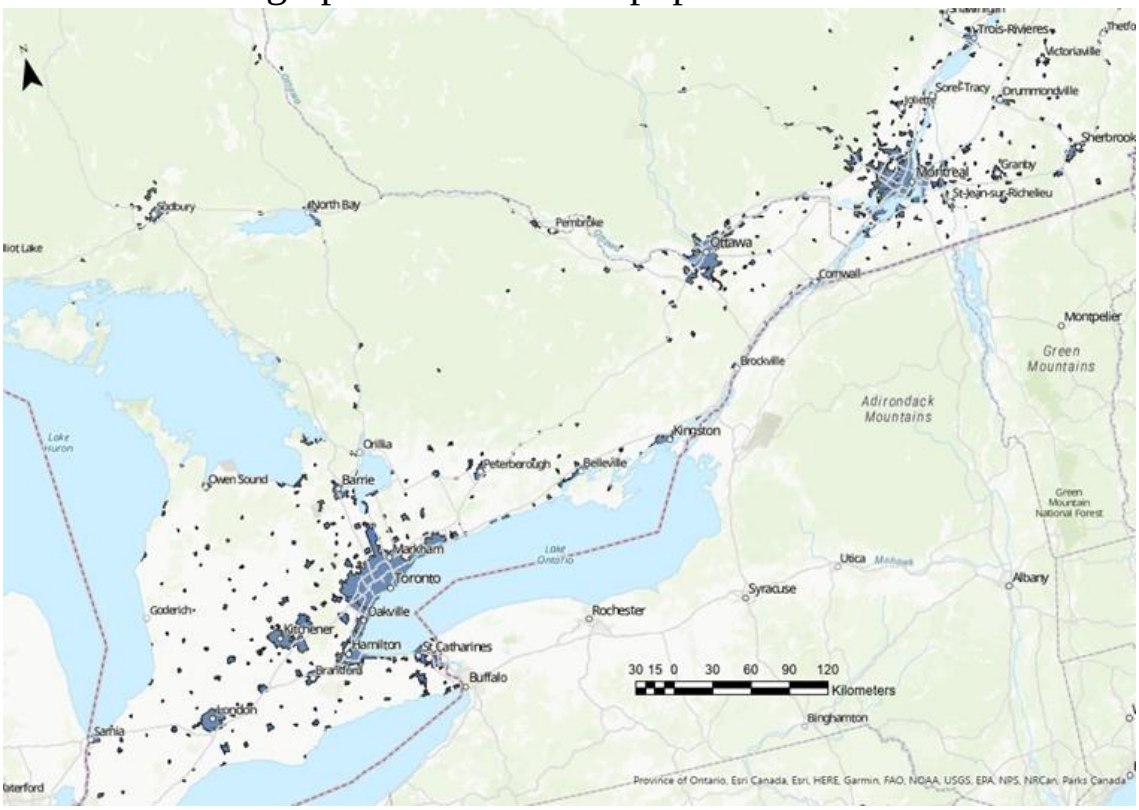

Figure S2: Geographical location of population centers in the East clusters

Figure S3: Geographical location of population centers in the West clusters

S7. Workflow for the allocation of battery mass among collections sites in population centers

This workflow consists of the following tasks:

(i) Filter PCs for each provincial cluster by using definition query and the Near geoprocessing tool with a geodesic method to remove all PCs that are classified as small PCs with a population between 1,000 and 29,999 and that do not have a collection site either within them or within 30 km outside of their borders.

(ii) Connect collection sites to their PCs by using the Spatial Join geoprocessing tool, which finds the closest PC for each collection site (as long as it is within 30 km) and joins its attributes one to one.

(iii) Filter additional PCs by using the Summary Statistics tool to count the number of collection sites associated with each PC. Remove additional PCs without collection sites associated with them.

(iv) Weighted allocation of total provincial battery mass between selected PCs is based on the number of households with an income over CAD 100,000 per PC, which are estimated by using the Enrich tool and Business Analyst data source.

(v) The allocation of PC's spent battery pack mass between individual scrapyards is obtained by using the Join Field tool, which connects each collection site with the population center associated with it, to calculate the battery mass for each collection site by dividing total battery mass assigned to each PC between the total number of collection sites associated with it.

S8. Dismantling and recycling facilities candidates

The location of dismantling and recycling facilities candidates is assumed to be industrial zones, which are preferably placed up to 15 km from cities centroids in most major Canadian cities. Facilities candidates are located in 59 medium and large urban population centers, with a population of 50,000 or more. The initial selection of dismantling hub locations can be filtered to those inside or within 30 km from large urban population centers, and a preferred distance of recycling processing facilities candidates from rail stations is set up as 5 km that may facilitate shipments to battery production facilities (Table S6).

Table S6: Dismantling and recycling facilities location candidates

City	Province	Lat	Long	Population
Toronto	ON	43.697563	-79.62038	5429524
Montreal	QB	45.60562	-73.84223	3519595
Vancouver	BC	49.269488	-123.0853	2264823
Calgary	AB	51.000059	-113.974	1237656
Edmonton	AB	53.547246	-113.3981	1062643
Ottawa/Gatineau	ON	45.408287	-75.6231	989567
Winnipeg	MB	49.899047	-97.20827	711925
Quebec	QB	46.819598	-71.32952	705103
Hamilton	ON	43.262958	-79.81515	693645
Kitchener	ON	43.402825	-80.46589	470015
London	ON	42.920042	-81.2577	383437
Victoria	BC	48.44338	-123.3764	335696
Halifax	NS	44.626926	-63.66733	316701
Oshawa	ON	43.867069	-78.88279	308875
Windsor	ON	42.2288	-82.94775	287069
Saskatoon	SK	52.167795	-106.6632	245181
St Chatherines/ Niagara Falls	ON	43.175192	-79.20852	229246
Regina	SK	50.479111	-104.5778	214631
St John's	NL	47.556885	-52.76929	178427
Kelowna	BC	49.859119	-119.5999	151957
Barrie	ON	44.333792	-79.66983	145614
Sherbrooke	QB	45.399565	-71.95155	139565
Guelph	ON	43.542216	-80.31283	132397
Abbotsford	BC	49.046202	-122.3787	121279
Kingston	ON	44.264319	-76.51603	117660
Kanata	ON	45.349305	-75.92536	117304
Trois-Rivieres	QB	46.332854	-72.58749	114203
Moncton	NB	46.085371	-64.84517	108620
Chicoutimi-Jonquiere	QB	48.399102	-71.11866	104222
Milton	ON	43.537768	-79.89298	101715
Red Deer	AB	52.168645	-106.6511	99718
Brantford	ON	43.157737	-80.24638	98179
Thunder Bay	ON	48.464372	-89.28177	93952
White Rock	BC			93729
Nanimo	BC	49.199433	-123.9963	92004
Sudbury	ON	46.501493	-80.9689	88054
Lethbridge	AB	49.734261	-112.7883	87572
Saint Jean sur Richelieu	QB	45.312864	-73.27863	84685
Peterborough	ON	44.258613	-78.38226	82094
Kamloops	BC	50.665291	-120.3664	78026
Saint Jerome	QB	45.754803	-73.99486	77146
Chilliwack	BC	49.146193	-122.0046	73161
Sarnia	ON	42.975726	-82.34061	72125
Chateauguay	QB	45.351851	-73.68819	71164
Drummondville	QB	45.880757	-72.52279	68601
Belleville	ON	44.204943	-77.36822	67666
Fort McMurray	AB	56.667684	-111.3371	66573
Sault St Marie	ON	46.521485	-84.36911	66313
Prince George	BC	53.868113	-122.7316	65510
Medicine Hat	AB	50.062967	-110.7216	62935
Welland Pelham	ON	42.967809	-79.21644	62388
Grande Prairie	AB	55.163546	-118.8371	62320
Airdrie	Ab	51.304076	-113.9841	61082
Granby	QB	45.373606	-72.77705	59691
Fredricton	NB	45.916827	-66.62677	59405
Saint John	NB	45.261199	-66.06886	58341
Beloeil	QB	45.59586	-73.21854	50845
North Bay	ON	46.309026	-79436173	50396
Saint Hyacinthe	QB	45.633456	-72.97696	50032

S9. Smelting facilities candidates

There are 10 primary aluminum smelters in Canada: one is located in Kitimat, British Columbia, and the other nine are in Quebec. There is also one alumina refinery located in Jonquière, Quebec [5]. Steel smelters are distributed along many Canadian provinces. Regarding copper smelters in Canada, Glencore's Horne Smelter in Rouyn-Noranda is now the only copper smelter in Canada as, from 2015 to 2018, Vale's Copper Cliff Sudbury smelter was converted to process nickel concentrate (Table S7). The Horne Smelter in Rouyn-Noranda is a custom copper smelter which uses both copper concentrates and precious metal-bearing recyclable materials as its feedstock to produce a 99.1% copper anode. The Horne smelter has a total reported processing capacity of 840,000 tonnes/year (Glencore) [6]. It is important to note that this study does not consider transportation of waste batteries outside of Canada. Due to the lack of copper smelters in the West cluster, this study assumes that copper scrap from dismantling facilities is stockpiled as waste and is not shipped to overseas smelting facilities. For instance, the metal concentrates from the Teck Resources' Highland Valley Copper facility in Trail, BC are processed and then are all exported, where the majority is sold under long-term sales contracts to overseas smelters.

Table S7: Locations of smelting facilities candidates[1] [2] [3]

Name	Address	City	Province	Post Code	Lat	Long	Sources
ALUMINUM							
Rio Tinto	270 City Centre	Kitimat	BC	V8C 2H7	54.001865	-128.6982	http://www.genisim.qc.ca/aluminum/namerica.htm#canada
Rio Tinto Alcan	1954 Rue Davis	Jonquière	QC	G7S3B6	48.424454	-71.182533	http://www.genisim.qc.ca/aluminum/namerica.htm#canada
Rio Tinto Alcan Grande-Baie	Works 6000 6TH AV	La Baie, Saguenay	QC	G7B 4G9	48.339511	-70.998576	https://panjiva.com/Rio-Tinto-Alcan-Grande-Baie-Plant/4343541
Rio Tinto Alcan- Laterriere	6301 Bd Talbot	Laterrière	QC	G7N 1A2	48.309261	-71.141144	https://www.riotinto.com/can/news/releases/2020/Rio-Tinto-augmente-sa-capacit-de-recyclage-daluminium--lUsine-Laterrire-
Rio Tinto Alcan - Alma	3000 Rue des Pins Ouest	Alma	QC	G8B 5W2	48.57262	-71.654535	https://www.dnb.com/business-directory/company-profiles.rio_tinto_alcan_inc.5534f5d1fdc651e847ca090a86bde23e.html
Rio Tinto Alcan- Arvida	1955 Boulevard Mellon	Jonquiere	QC	G7S 3G7	48.429952	-71.166289	https://www.industryabout.com/country-territories-3/2091-quebec/aluminium-industry/32037-rio-tinto-alcan-arvida-aluminium-smelter
Aluminerie Alouette Inc	400 Chemin de la Pointe Noire	Sept-Îles	QC	G4R5M9	50.243171	-66.385497	http://www.genisim.qc.ca/aluminum/namerica.htm#canada
Alcoa Lte Aluminiere	100 Route Maritime	Baie-Comeau	QC	G4Z 2L6	49.249917	-68.150814	http://www.genisim.qc.ca/aluminum/namerica.htm#canada
Alcoa Lte	1 Boulevard des Sources	Deschambault	QC	G0A 1S0	46.70406	-71.944844	http://www.genisim.qc.ca/aluminum/namerica.htm#canada
Alcoa Lte	5555 Rue Pierre-Thibault	Bécancour	QC	G9H 2T7	46.39127	-72.382474	http://www.genisim.qc.ca/aluminum/namerica.htm#canada
STEEL							
Alta Steel	9401 - 34 St.	Edmonton	AB	T6B 2X6	53.530218	-113.39392	https://www.altasteel.com/
Gerdau Manitoba Steel Mill	27 Main St.	Selkirk	MB	R1A 2B4	50.163195	-96.867288	https://www2.gerdau.com/sites/gln_gerdau/files/downloadable_files/epd_gerdau_manitoba_structural_steel.pdf
EVRAZ REGINA	100 Armour Road	Regina	SK	S4P 3C7	50.513399	-104.63096	https://www2.gerdau.com/metals-recycling
Essar Steel Algoma, Algoma Steel Inc.	105 West Street	Sault Ste. Marie	ON	P6A 7B4	46.519968	-84.359999	
ArcelorMittal Dofasco	1330 Burlington St. E.	Hamilton	ON	L8N 3J5	43.269255	-79.804858	https://www.gem.wiki/ArcelorMittal_Dofasco_steel_plant
ArcelorMittal Recycling center	3185, route Marie-Victorin	Contrecoeur	QC	J0L 1C0	46.519968	-84.359999	https://www.gem.wiki/ArcelorMittal_Contrecoeur_steel_plant
ArcelorMittal Contrecoeur East/ West	800, Montée de la Pomme d'Or	Contrecoeur	QC	J0L 1C0	45.835148	-73.254957	https://www.gem.wiki/ArcelorMittal_Contrecoeur_steel_plant
ArcelorMittal Montreal (St. Patrick)	5900, rue Saint-Patrick	Montreal	QC	H4E 1B3	45.458079	-73.608826	
Stelco - Hamilton works	386 Wilcox Street	Hamilton	ON	L8L 8K5	43.267548	-79.810777	https://www.stelco.com/about/contact-us
Atlas Tube Inc.	200 Clark St.	Harrow	ON	N0R 1G0	42.061007	-82.918723	
Gerdau Cambridge Steel Mill	160 Orion P	Cambridge	ON	N1T 1R9	43.370909	-80.28092	https://www2.gerdau.com/sites/gln_gerdau/files/downloadable_files/epd_gerdau_cambridge_%20mbq.pdf
Gerdau Whitby Steel Mill	1801 Hopkins St	Whitby	ON	L1N 5T1	43.854246	-78.909593	https://www2.gerdau.com/sites/gln_gerdau/files/downloadable_files/epd_gerdau_whitby_rebar.pdf
Ivaco Rolling Mills Ltd.	1040 County Rd 17,	L'Orignal	ON	K0B 1K0	45.614103	-74.680526	https://www.ivacorm.com/about/quality/
Valbruna ASW Inc -Welland Facility	42 Centre Street	Welland	ON	L3B 0E5	42.999311	-79.23456	https://www.asw-steel.com/facilities/
COPPER							
Canadian Copper Refinery (Glencore)	220 Avenue Durocher	Montreal	QC	H1B5H6	45.62677	-73.509638	https://www.glencore.ca/en/What-we-do/Metals-and-minerals/Copper
Glencore Canada Ltd (Horne Foundry)	101 Avenue Portelance	Rouyn-Noranda	QC	J9X5B6	48.253007	-79.016025	https://www.glencore.ca/en/What-we-do/Metals-and-minerals/Copper

[1] https://canadiansteel.ca/members

[2] https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/aluminum-facts/20510

[3] https://www.canada.ca/en/environment-climate-change/services/environmental-performance-agreements/base-metal-smelters-overview.html

S10. Transportation payload distance

Table S8 presents the aggregated truck transportation distance of each reverse logistics segment for each regional recycling cluster expressed in terms of ton-kilometers (t·km).

Table S8: Truck transportation distance along all of the value chain custody of spent EV LIBs, ON, QC-Maritimes, BC-Prairies recycling clusters, t·km

Truck transportation payload-distance from	East cluster		West cluster
	Ontario (t·km)	Quebec-Maritimes (t·km)	BC-Prairies (t·km)
Collection sites to dismantling facilities	5.87E+05	1.61E+06	2.75E+06
Dismantling to recycling facilities	4.89E+05	5.20E+05	1.84E+04
Dismantling to Al smelter facility	1.61E+06	8.21E+05	5.57E+06
Dismantling to Cu smelter facility	1.26E+06	4.82E+06	
Dismantling to Steel smelter facility	1.88E+04	5.47E+04	4.88E+05
Total truck transportation payload-distance	**3.96E+06**	**7.83E+06**	**8.83E+06**

S11. Life cycle GHG emissions and transportation costs

This study used a gate-to-gate approach, which means the starting point of the LCA's system boundary for the transportation of spent batteries is the collection site, and the end of the assessment is at the recycling processing facility. The recycling processing facilities include battery cell recycling processing and other battery pack metals recovery facilities. The life cycle GHG emissions are calculated by multiplying an average GHG emissions factor for truck transportation by the travel distance for each segment route. This study uses the LCA software tool openLCA v.1.10.3. It has a feature to integrate third-party databases such as Ecoinvent v. 3.7.1., which is used as a data source to provide a GHG emissions factor for trucking transportation. The transportation process dataset in Ecoinvent to be used in this study is named "Transport, freight, lorry 16-32 metric ton, EURO3, t·km, ROW". The sub-processes included in this dataset are lorry production, operation, maintenance, road construction, operation and maintenance. The life cycle impact assessment of freight transportation by truck was assigned to the impact category: climate change as global warming potential (GWP) over a time period of 100 years and presented with respect to the functional unit of kg CO_{2e} per kg of spent battery pack. The emission intensity of trucks on transportation networks for the functional unit 1 ton-km for the GWP impact category is 0.17276 kg CO_{2e}/t·km and is evaluated with the method ReCiPe 2016 Midpoint (H). The data regarding the distance to be covered by delivery trucks are estimated in section S10 of this supplementary information and expressed as t·km and are then used to estimate the life cycle GHG emissions of the spent EV batteries transportation to EoL management facilities located in recycling clusters in Canada.

In order to estimate the environmental impact of reverse logistics of EV LIBS on total life cycle GHG emissions of battery pack recycling processing, a total life cycle carbon footprint of battery

pack recycling processes, including battery cell (cathode materials) and other metals recovery, is estimated. Aichberger and Jungmeier [7]'s study presents a compilation of 36 publications from the period of 2005–2020 on LCA of recycling options for LIBs cells (pyrometallurgical, hydrometallurgical, and direct recycling). Their study considers an average life cycle GHG emissions for battery cell recycling as 0.678 kg CO_{2e}/kg battery pack. Other metals (copper, aluminum, and steel) from other battery components are recovered in the smelters facilities. Cusenza, *et al.* [8]'s study provides the life cycle inventory for copper, aluminum, and steel processes recycling, and datasets are obtained from the Ecoinvent life cycle inventory database [9] to estimate the total life cycle GHG emissions for other metals recycling as 0.428 kg CO_{2e}/kg battery pack by using OpenLCA software. Furthermore, total life cycle GHG emissions of battery cathode and battery pack production from virgin materials are estimated as 2.93 and 10.4247 kg CO_{2e}/kg battery pack, respectively [10].

Table S9 shows the life cycle GHG emissions of recycling spent EV LIB packs including the transportation LCA results, expressed in terms of kg CO_{2e}/kg battery pack.

Table S9: Life cycle GHG emissions of recycling spent EV LIB packs, including transportation of 1 kg of spent battery pack from EV collection sites to spent EV LIB processing facilities, ON, QC-Maritimes, BC-Prairies recycling clusters, kg CO_{2e}/kg battery pack

Life cycle environmental impact GHG emissions (kg CO_{2e}/ kg battery pack)	**East cluster**		**West cluster**
	ON	**QC - Maritimes**	**BC - Prairies**
Collection sites to dismantling facilities (A)	9.41E-03	9.23E-03	2.26E-02
Dismantling to recycling facilities (B)	7.76E-03	2.97E-03	1.76E-04
Dismantling to Al smelter facility (C)	2.58E-02	4.70E-03	5.33E-02
Dismantling to Cu smelter facility (D)	2.01E-02	2.76E-02	-
Dismantling to Steel smelter facility (E)	2.86E-04	3.11E-04	4.64E-03
Life cycle GHG emissions of transporting spent EV LIB packs (A+B+C+D+E)	6.34E-02	4.48E-02	8.07E-02
Life cycle GHG emissions of spent EV LIB cell recycling processing (F)	6.78E-01		
Life cycle GHG emissions of other metals recycling from spent EV LIB packs (G)	4.28E-01		
Life cycle GHG emissions of recycling spent EV LIB packs , including transportation (A+B+C+D+E+F+G)	**1.17E+00**	**1.15E+00**	**1.19E+00**

The environmental impact shares of recycled battery cathode materials of total life cycle GHG emissions of battery cathode and pack from virgin materials are indicated in Table S10.

Table S10: Relative share of the environmental impact of recycled battery cathode materials on battery cathode and battery pack produced from virgin materials

Life cycle environmental impact GHG emissions (kg CO_{2e}/ kg battery pack)	**East cluster**		**West cluster**
	ON	**QC - Maritimes**	**BC - Prairies**
Emissions of transporting battery cell to recycling processing facilities (A+B)	1.72E-02	1.22E-02	2.28E-02
Emissions of battery cell recycling processing (F)	6.78E-01		
Emissions of recycled cathode raw materials, including transportation (A+B+F)	6.95E-01	6.90E-01	7.01E-01
Emissions of battery cathode production from virgin materials (H)	2.93E+00		
Emissions of battery pack production from virgin materials (I)	1.04E+01		
Share of the environmental impact of battery cathode of total emissions of battery pack production from virgin materials (H/I)	28%		
Share of the environmental impact of recycled cathode raw materials of total emissions of:			
Battery cathode produced from virgin materials ((A+B+F)/H)	**23.7%**	**23.5%**	**23.9%**
Battery pack produced from virgin materials ((A+B+F)/I)	**6.7%**	**6.6%**	**6.7%**

Regarding the transportation and collection costs, these include spent LIB transportation from end user to the collection sites and transportation costs from battery collector to dismantler and recycler. It is assumed that transportation from end user to EV scrapyards is out of the boundary in this study.

The transportation costs of spent LIBs assume truck transportation as the mode of transportation. Truck transportation on the distance greater than 110 km is assumed to be done with a heavy-duty truck (> 16t). Short-distance transportation (under 110 km) is done by medium-duty trucks (10t). The transportation costs in this study are limited to the truck operational costs. These include diesel fuel prices, driver wages and repair and maintenance, among other costs. In this study, the truck

operational costs are expressed in terms of CAD/t·km and are estimated using information from the B2U Repurposing Cost Calculator [11] and the average marginal cost for truck industry in North America report [12].

LIBs are classified as hazardous wastes in Canada, which makes transport expensive and highly regulated. Canada's Transportation of Dangerous Goods (TDG) Regulations govern the transportation of dangerous goods across Canada in all modes – air, highway, rail and water. Due to additional safety measures and permissions, transportation costs are higher for hazardous wastes. For instance, a handling fee of CAD 59.5/domestic shipment for over 453 kg of dangerous goods and hazardous materials is charged by Day & Ross, a dangerous goods certified logistics provider[4].

Due to a lack of available breakdowns of TDG costs, this study is only considering the handling costs for dangerous goods. Further investigation related to packaging costs for TDG needs to be accomplished. Packaging of DG needs to meet specific requirements. Non-critical and damaged battery packs must be transported in an UN-approved container, including packaging material that prevents the evolution of heat. Damaged and critical batteries require a special steel container for transportation, which includes a built-in fire extinguishing system. Additional costs to uninstall the battery from the vehicle and to package the battery into the container must be taken into consideration. It is necessary to have a certified high-voltage expert present, as the energy density is high and the battery could spontaneously combust, resulting in an immediate fire. In both scenarios, the container or package must be labelled with the UN Class 9 label for lithium-ion batteries and a UN Material Data Safety Sheet must also be filled out [1].

Transportation costs of spent LIBs have two components related to operational costs, which is distance-dependent travel cost and dangerous goods fees, if it is applicable. Hazardous materials transportation cost is related to transportation from collection sites to dismantling facilities; meanwhile, non-hazardous materials transportation cost is related to transportation from dismantling to recycling and smelter facilities. Table S11 shows the unit cost of spent LIBs transportation.

Table S11: Transportation unit cost for spent LIBs

Transport type	Transportation cost (CAD/ton-km)	
	Non-hazardous materials	Hazardous materials
Heavy duty truck (>16 t, payload)	0.050	0.309
Medium heavy-duty truck (10 t, payload)	0.073	1.214

[4] https://dayross.com/Guides

Table S 12 indicates truck transportation cost of 1 t of the spent battery packs from EV collection sites to battery processing facilities for all regional recycling clusters expressed in terms of CAD/t.

Table S 12: Truck transportation cost of spent EV LIB packs to EoL processing facilities, ON, QC-Maritimes, BC-Prairies recycling clusters, CAD/t

Truck transportation from	East cluster		West cluster
	Ontario (CAD/t)	Quebec-Maritimes (CAD/t)	BC-Prairies (CAD/t)
Collection sites to dismantling facilities	4.74E+01	3.87E+01	5.94E+01
Dismantling to recycling facilities	2.63E+00	1.26E+00	4.51E-01
Dismantling to Al smelter facility	7.40E+00	1.40E+00	1.53E+01
Dismantling to Cu smelter facility	5.78E+00	7.92E+00	
Dismantling to Steel smelter facility	1.13E-01	1.05E-01	1.34E+00
Total transportation cost from collection sites to EoL processing	**6.33E+01**	**4.94E+01**	**7.65E+01**

S12. References

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