Supplementary information

Environmental Life Cycle Assessment of Electric Vehicles in Canada.

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Every product we enjoy carries an environmental burden. Driving an electric vehicle and a conventional gasoline vehicle (GV) also carries an environmental burden. Therefore, it is essential to compare the environmental life cycle assessment (LCA) of both EVs and GVs in the road transportation sector.

Research Methods, Data and Results

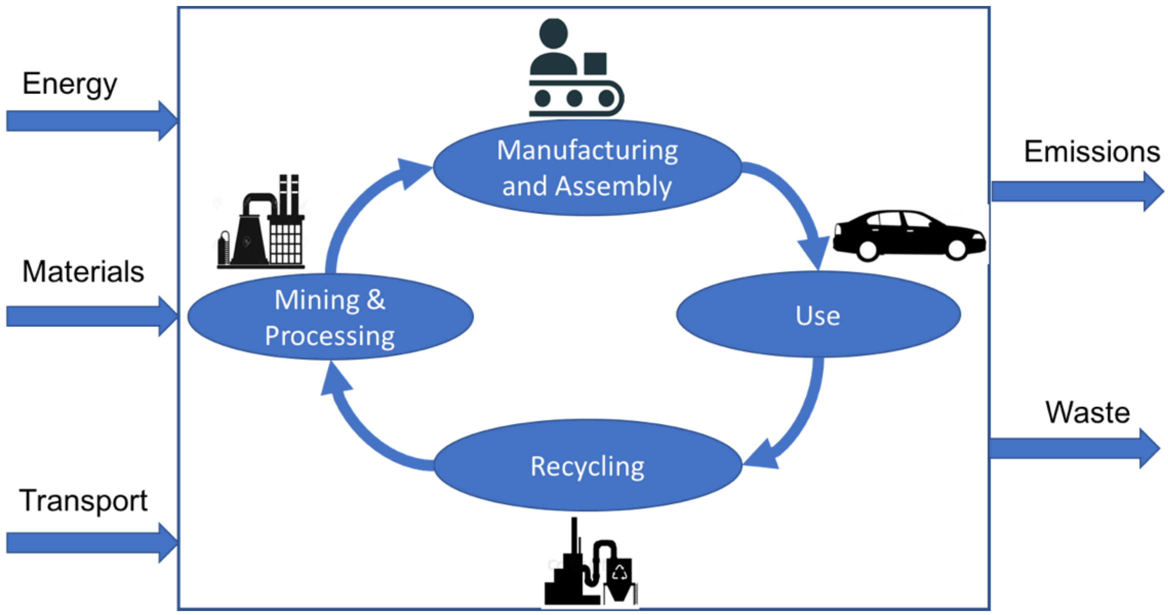

Figure 1 System boundary for the life cycle assessment.

Impact assessments are carried out at vehicle's manufacturing (mining and assembly), use (driving) and end of life (recycling and disposal) phases. In this environmental life cycle assessment of electric vehicles in Canada, the GHG emissions and primary energy consumption are considered as the most significant impact category. Figure 1 shows the boundary of the system analysed. The same phases have also been considered for the GV. For all the phases, indirect and direct emissions are considered in the life cycle models. Transport of the different battery components to the production site is considered. However, transport of the different components to dismantling sites is not considered in this study.

Vehicle Categories

Two different vehicle categories were considered:

1. An electric vehicle (EV), (Nissan LEAF S 2018)
2. A gasoline vehicle (GV), (Nissan Versa S 2018)

Table 1 Vehicle component weight breakdown [1]

Weight in lbs.	EV (Nissan Leaf S)	GV (Nissan Versa S)
Curb Weight	3468.0	2500
Vehicle body	1855.4	1102.5
Powertrain system	59.0	642.5
transmission system	114.4	157.5
Controller	204.6	0
Chassis w/o battery	1002.3	597.5
Traction motor	232.4	0

EV Battery

The EV battery considered in this assessment is a Lithium ion (Li-ion) battery called NMC 811. Where NMC 811 stands for nickel (80%) manganese (10%) cobalt (10%). The characteristics of the 2018 Nissan Leaf, the representative EV in this study, is listed in Table 2 and the mass inventory of Li-ion battery is given in Table 3. Figure 2 establishes the Li-ion battery components and processes with material and energy flows in LCA model.

Table 2 Characteristics of the Nissan Leaf battery[2]

	EV (Nissan Leaf S 2018)
Weight (lbs.)	400
Cathode type	NMC 811
Range (km)	175
Energy per km (wh)	136
Electric motor power (kW)	80

Table 3: Mass inventory of Li-ion battery[3]

		Wt %
Cathode material	NMC 442	29
Anode material	Graphite	20
Binder	PVDF	2.6
Metals	Copper	10
	Wrought aluminum	19
	Steel	1.4
Electrolyte	Lithium hexafluorophosphate (LiPF6)	1.9
	Ethylene Carbonate (EC)	5.4
	Dimethyl carbonate (DMC)	5.4
Plastic	Polypropylene (PP)	1.5
	Polyethylene (PE)	0.24
	Polyethylene terephthalate (PET)	1.2
Thermal insulation	Thermal insulation	0.3
Battery thermal management system	BMS	1.0
Battery management system	Electronic parts	1.4

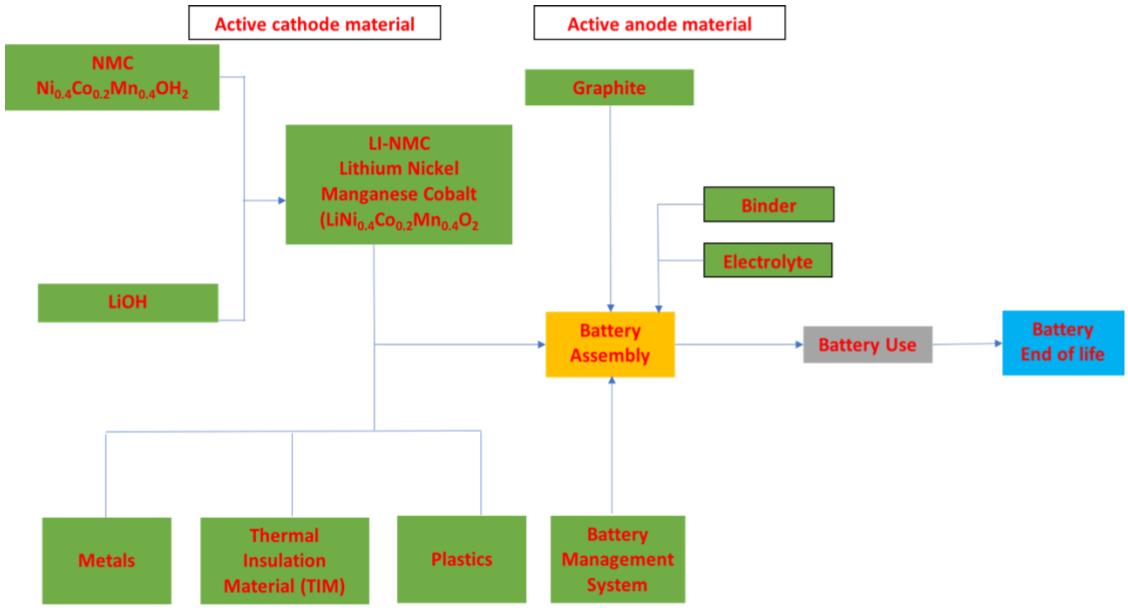

Figure 2 Li-ion battery components and processes with material and energy flows in our LCA model

Functional Unit

The service provided by these vehicles is the distance driven, and so the functional unit is based on kilometres driven. The GHG emissions and primary energy consumption are calculated/presented as a function of 1 km driven by one vehicle (e.g. MJ/km driven, kg CO2-equivalent emissions/km driven). To account for the manufacturing and the end of life phases, an assumption of the total km driven in the entire life cycle of the vehicle was made. A total life cycle of 150,000 km is considered for both EVs and GVs.

Vehicle Manufacturing

The inventory for the EV and GV manufacturing phase is based on GREET ® 2017 database (The greenhouse gases regulated emissions and energy use in Transportation model). The model was scaled up to mass inventories of Nissan Leaf and Nissan Versa. The Excel-based GREET Vehicle-cycle model can be downloaded here: https://greet.es.anl.gov/greet_2_series. Table 4 lists the GHG emissions and primary energy consumption of both EVs (without battery) and GVs.

Table 4 GHG emissions and energy consumption data[4]

	EV		GV	
	GHG-100 (kg CO2/km)	**Energy Consumption (MJ/km)**	**GHG-100 (kg CO2/km)**	**Energy Consumption (MJ/km)**
Vehicle body	1.6E-02	0.31	9.6E-03	0.14
Powertrain system	5.7E-04	0.01	4.8E-03	0.08
transmission system	1.3E-03	0.03	1.8E-03	0.03
Controller	1.8E-03	0.04		
Chassis w/o battery	8.2E-03	0.13	4.9E-03	0.06
Traction motor	2.1E-03	0.04		
Vehicle assembly	9.5E-03	0.14	6.7E-03	0.10

Battery pack Manufacturing

Cradle to gate energy consumption of battery components (MJ/kg), and GHG emissions of battery components ($kgCO_2e/km$) are listed in Table 5.

Table 5 GHG emissions and energy consumption data for the NMC 422 Li-ion battery[5], [6]

		GHG-100 (kg CO2/km)	**Energy Consumption (MJ/km)**
Cathode material	NMC 422	1.6E-02	7.0E-02
Anode material	Graphite	2.4E-03	3.1E-02
Binder	PVDF	6.0E-04	1.2E-03
Metals	Copper	1.0E-04	5.6E-03
	Wrought aluminum	1.0E-03	3.1E-02
	Steel	7.4E-04	6.0E-04
Electrolyte	Lithium hexafluorophosphate (LiPF6)	2.2E-04	4.3E-03
	Ethylene Carbonate (EC)	1.1E-05	6.7E-04
	Dimethyl carbonate (DMC)	1.2E-04	2.4E-03
Plastic	Polypropylene (PP)	1.7E-04	1.4E-03

	Polyethylene (PE)	2.6E-05	4.2E-04
	Polyethylene terephthalate (PET)	1.0E-05	1.1E-03
Thermal insulation	Thermal insulation	2.8E-05	1.2E-04
Battery thermal management system	BMS	7.7E-06	2.5E-04
Battery management system	Electronic parts	3.5E-04	7.0E-03
Battery assembly		3.7E-04	5.3E-03

Vehicle Use Phase

In the use phase LCA accounts for the emissions due to the driving of the vehicles (direct emissions) and for the emissions due to the production of the fuel (indirect emissions), (i.e. electricity for EVs and E10 gasoline for GVs). In this study, we assumed a vehicle lifetime of 150,000 km for both the EV and the GV, in line with literature (Notter et al., 2010). The electric energy consumption to drive 1 km was assumed equal to 13.6 kWh/100km. No battery package replacement was considered during the use phase of the vehicle. We have assumed electricity from British Columbia grid, Alberta grid and the Canada mix grid.

Table 6 Electricity generation by source[7]

	Canada	Alberta	BC
Hydroelectric Power Generation	60%	14%	85%
Nuclear Power Generation	15%	0%	0%
Natural Gas-Fired Power Generation	11%	19%	7%
Coal-Fired Power Generation	10%	67%	0%
Biomass Power Generation	1%	0%	4%
Oil-Fired Power Generation	1%	0%	0%
Wind	0%	0%	3%
Other Power Generation	2%	0%	1%

Table 6 lists the share of electricity generation by sources. For the GV use phase we have assumed the same lifetime of the EV, which is 150,000 km. The fuel consumption is assumed to be 7.2L/100km. The CO_2 emissions were modeled based on data from Natural Resources Canada, see table 7.

Table 7 Use phase CO_2 emissions and energy consumption

	EV (BC grid)	EV (Alberta grid)	EV (Canada mix)	GV
GHG-100 (kg CO_2/km)	0.003	0.113	0.023	0.256
Energy consumption (MJ/km)	0.490	1.306	0.682	2.760

Source: GREET ® 2017 database

Vehicle End of Life (EOL) Phase

In the end of life phase models of the EV, the valuable outputs considered by system expansion are metals, mainly nickel, cobalt, and copper.

Spent batteries are received at Retriev Technology's facilities in Trail, British Columbia and are processed in the Lithium Ion Line. Lithium ion batteries are dismantled to the cell or module level, depending on construction. Various steel, electrical, and plastic components are recycled.

Cells are crushed and size-reduced under a process solution. The crushed cells undergo a size separation, separating the material into a metal and plastic fraction, and a slurry.

The slurry is filtered to produce a nickel-cobalt filter cake. The metals and plastic fragments go through a sink- float separation, to produce a mixed metal (copper-aluminum mixture) and a plastic fraction. Solution from the filtration step contains the organic portion of the electrolyte and is reused in the crushing process.

The organic components are consumed by Archaea microbes, which are added to holding tanks within the process. Figure depicts the process flow of the Li-ion battery recycling at Retriev Technology. Nickel-Cobalt filter cake is sent to an offsite location to recover Nickel and Cobalt.

Mixed metals (Copper-Aluminum) is also shipped to an offsite location to recover Copper. At the offsite recycling plant, Nickel-Cobalt filter cake and mixed metals undergo metallurgical processes. Mixed metal fluff is disposed either as landfill or sent for waste to an energy conversion facility. Table 8 lists the energy consumption and CO_2 emissions per unit pound of batteries processed from Retriev Technology process.

Table 8 Energy consumption and CO_2 emissions from Retriev Technology process

Total energy consumption	0.3 MJ/lbs. of batteries processed
Total CO_2 emission	0.008 kg/lbs. of batteries processed

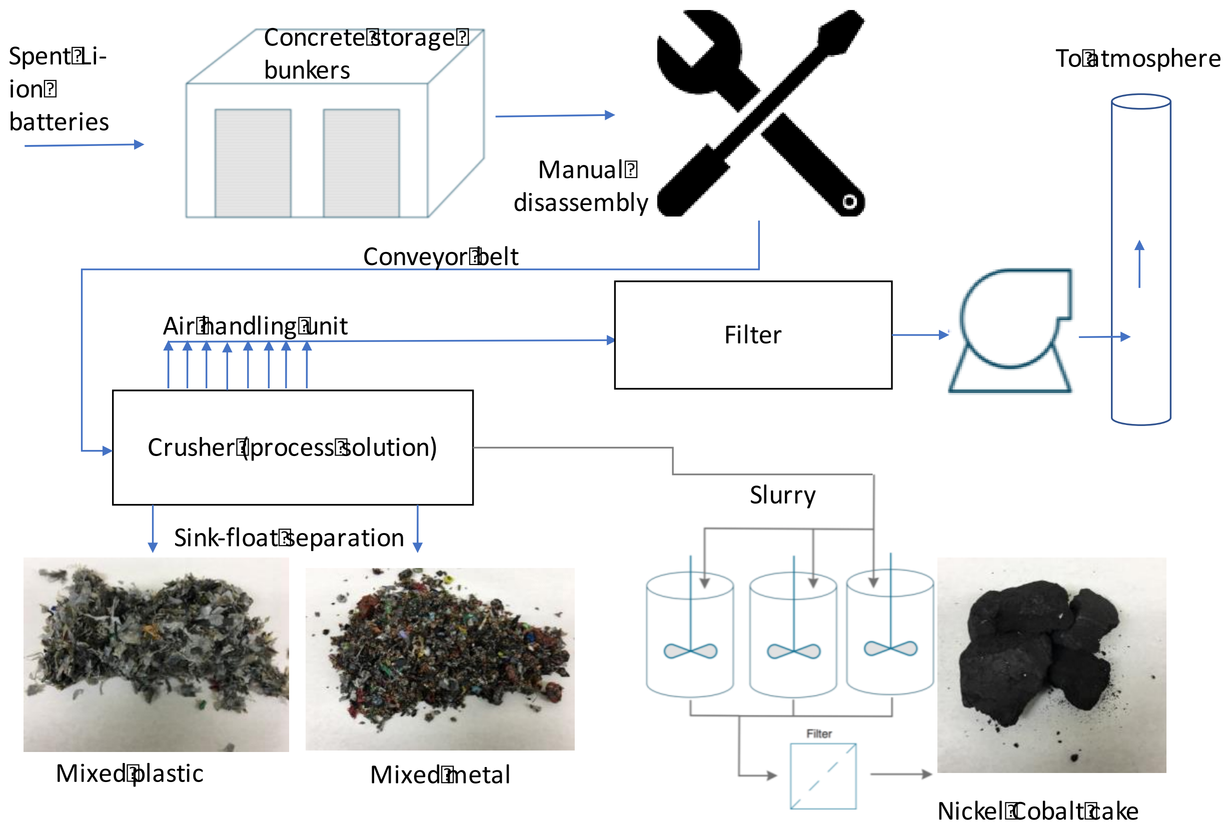

Figure 3 Retriev Technology's recycling process flow.

Table 9 lists the CO_2 emissions and energy consumption in recycling metallurgical process. The recovery of the metals from the pyro and hydrometallurgical processes was based on data elaborated by the literatures "Update of life cycle analysis of Lithium-ion batteries in the GREET model" and "Impact of recycling on cradle to gate energy consumption and GHG emissions of automotive Li-ion batteries".

Table 9 EOL phase CO_2 emissions and energy consumption. GREET ® 2017 database model results.

	Li-ion battery	**EV w/o battery**
GHG-100 (kg CO_2)	2043.6	346.8
Energy consumption (MJ)	49791.0	5895.6

Total life cycle impacts

The total life cycle carbon footprint (all phases) expressed in tons of CO_2 for EVs charged in BC and Alberta, and GVs using gasoline E10 is listed in Table 10. Table 10 Total life cycle carbon footprint. The total life cycle energy consumption (all phases) expressed in GJ for EVs charged in BC and Alberta, and GVs using gasoline E10 is listed in Table 11.

Table 10 Total life cycle carbon footprint.

	BC EV	Alberta EV	GV
Vehicle life	Tons of CO_2		
Manufacturing	9.67	9.67	4.46
10000 km	9.70	10.80	6.70
20000 km	9.73	11.93	8.95
30000 km	9.76	13.06	11.19
40000 km	9.79	14.184	13.44
50000 km	9.83	15.31	15.68
60000 km	9.86	16.44	17.92
70000 km	9.89	17.57	20.17
80000 km	9.92	18.70	22.41
90000 km	9.95	19.83	24.66
100000 km	9.98	20.96	26.90
110000 km	10.01	22.09	29.14
120000 km	10.04	23.21	31.39
130000 km	10.08	24.34	33.63
140000 km	10.11	25.47	35.88
150000 km	10.14	26.60	38.12
End of Life	12.18	28.64	38.42

Table 11 Total life cycle energy consumption

	BC EV	Alberta EV	GV
Vehicle life	GJ		
Manufacturing	105.56	105.56	62.53
10000 km	105.56	243.39	62.53
20000 km	106.05	244.02	65.29
30000 km	120.25	262.56	145.33
40000 km	125.15	268.95	172.93
50000 km	130.04	275.34	200.53
60000 km	134.94	281.74	228.13
70000 km	139.84	288.13	255.73
80000 km	144.73	294.52	283.33
90000 km	149.63	300.91	310.93
100000 km	154.52	307.30	338.53
110000 km	159.42	313.69	366.13
120000 km	164.32	320.09	393.73
130000 km	169.21	326.48	421.33
140000 km	174.11	332.87	448.93
150000 km	179.00	339.26	476.53
End of Life	228.80	389.05	480.79

Results

Comparison of cradle to gate (manufacturing and use phase) GHG emissions for an EV and a GV is shown in Figure 4. The total life cycle GHG emissions as function of vehicle lifetime is depicted in Figure 5. The total life cycle energy consumption as function of vehicle lifetime is shown in Figure 6.

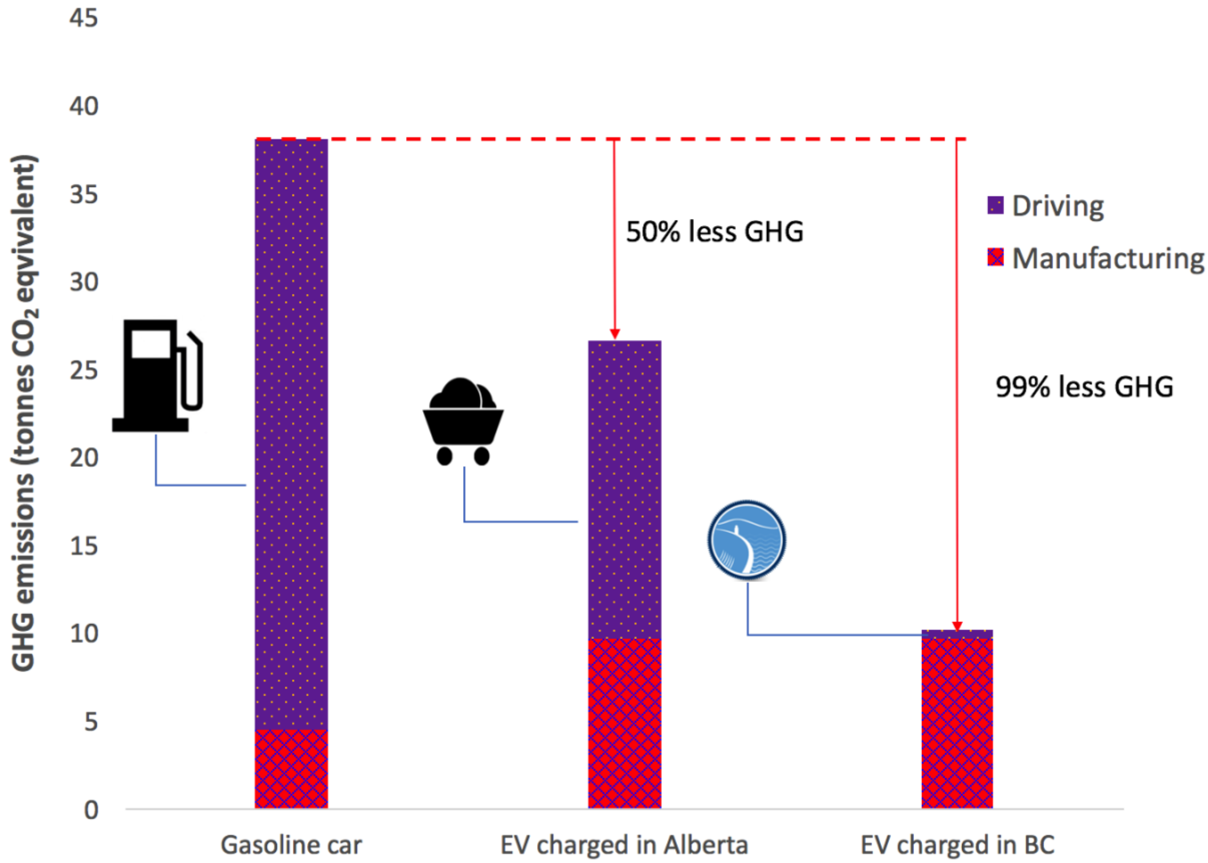

Figure 4 Comparison of GHG emissions in vehicle manufacturing and use phase

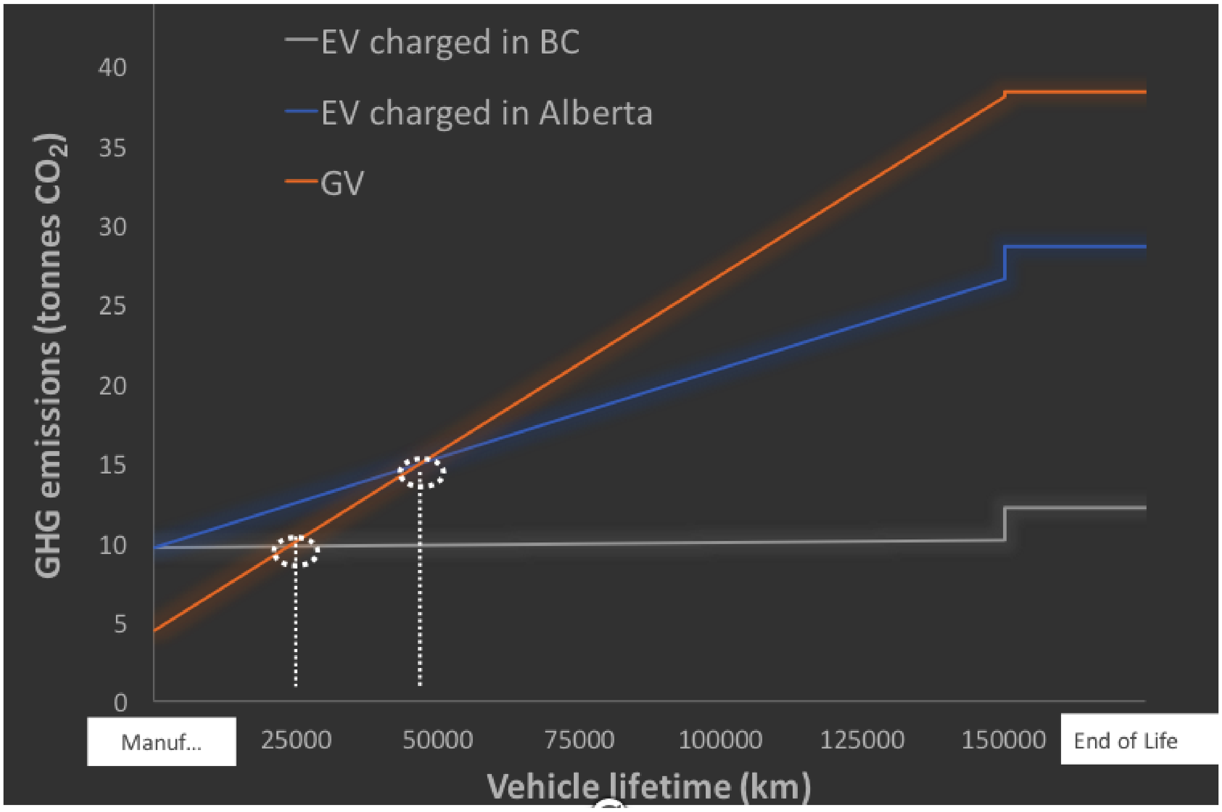

Figure 5 Total life cycle GHG emissions

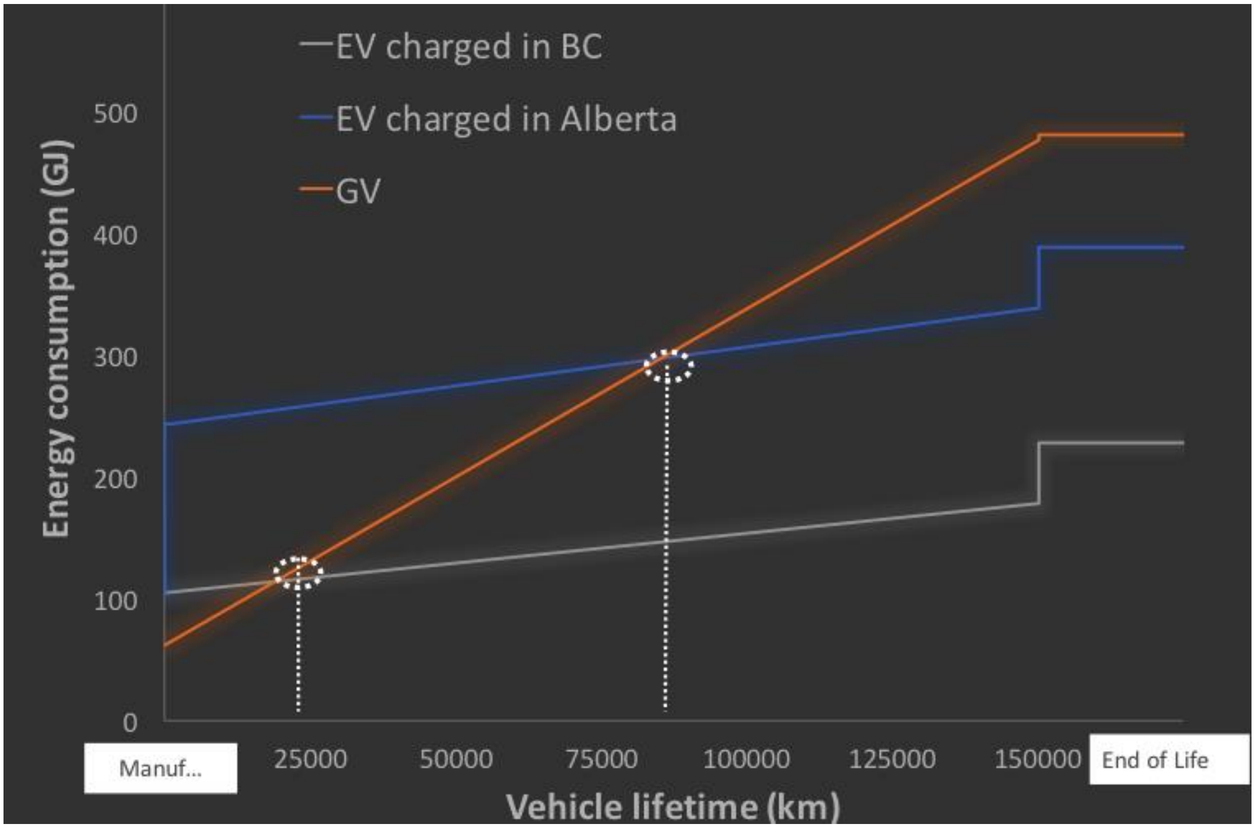

Figure 6 Total life cycle energy consumption

According to our LCA study conducted by Plug-in BC, an EV charged in BC breaks even (pays off its environmental burden) within 30,000 km driven, and any distance driven beyond 30,000 km becomes carbon-negative. In other words, driving a mid-size sedan like Nissan Leaf pays off its environmental burden within three years of driving. Even when electricity is generated from coal, which supplies a significant demand in provinces like Alberta, EV emissions are 50% less compared to a GV and pays off its initial burden within 50,000 km of driving. As far as energy consumption is concerned, the intensity is huge in EV production and EOL stages. However, the use phase energy intensity of GVs are huge in comparison to impacts from manufacturing and recycling of EVs.