An adaptable life cycle greenhouse gas emissions assessment framework for electric, hybrid, fuel cell and conventional vehicles: Effect of electricity mix, mileage, battery capacity and battery chemistry in the context of Canada

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Supplemental Information

S1 Vehicle end-of-life treatment life cycle inventories.

This section provides the life cycle inventories compiled for vehicle and battery end-of-life treatment.

Table A1.
Material and energy process inventory for Vehicle glider end-of-life

Process	Amount	Source data	Sub-inventory
Functional unit output			
Vehicle glider end-of-life (p)	1		
Material requirements			
Vehicle glider parts re-use	11.6%	(Sawyer-Beaulieu, 2009)	
Vehicle glider shredding and separation	88.4%	(Sawyer-Beaulieu, 2009)	Table A2

Table A2.
Material and energy process inventory for vehicle glider shredding and separation (Belboom et al., 2016; Hao et al., 2017)

Process	Amount	Source data	Sub-inventory
Functional unit output			
Vehicle glider shredding and separation (p)	1		
Material and energy requirements			
Magnetite {GLO)(kg)	0.0045	EcoInvent 3	
Electricity (kWh)	0.0536	EcoInvent 3	
Natural gas, high pressure {CA-AB) (m^3)	0.0147	EcoInvent 3	
Transport, freight, lorry > 32 MT, EURO5 (GLO} (tkm)	0.1	EcoInvent 3	
Metal recovery efficiencies*			
Steel	95.9%		Table A3
Aluminium	96.8%		Table A4
Coppers	77.6%		Table A5
Ferro metals	100%		Table A3
Unrecovered auto shredder residue (ASR)*			
Plastics	100%		Table A6
Non-Ferro metals	100%		Table A6
Other materials	100%		Table A6

* The implementation of inventories given in percentages require the use of waste types and waste scenarios functionalities in SimaPro software.

Table A3.
Material and energy process sub-inventory for steel scrap production (Argonne National Laboratory (ANL), 2018)

Process	Amount	Source data
Functional unit output		
Steel/Ferro metal scrap production (kg)	1	
Material and energy requirements		
Electricity (kWh)	6.8249	EcoInvent 3
Natural gas, high pressure {CA-AB} (m^3)	96.2472	EcoInvent 3
Petroleum coke {GLO} (kg)	5.3512	EcoInvent 3
Emissions to air		
VOC, volatile organic compounds (g)	182.01	
Carbon monoxide (g)	3138.93	
Nitrogen oxides (g)	68.16	
Particulates <10 µm (g)	607.27	

Particulates <2.5 µm (g)	303.64	
Sulfur oxides (g)	363.51	
Methane (g)	0.141	
Carbon dioxide (g)	24339.03	

Table A4.
Material and energy process for aluminum scrap production

Process	Amount	Source data
Functional unit output		
Aluminum scrap production (kg)	1	
Outputs to technospere, Waste and emissions to treatment		
Aluminium scrap, post-consumer {GLO} (kg)	1	EcoInvent 3

Table A5.
Material and energy process inventory copper scrap production

Process	Amount	Source data
Functional unit output		
Copper scrap production (kg)	1	
Outputs to technospere, Waste and emissions to treatment		
Copper scrap, sorted, pressed {GLO} (kg)	1	EcoInvent 3

Table A6.
Material and energy process inventory for plastic/non-ferrous metals/others disposal

Process	Amount	Source data
Functional unit output		
Plastic/non-ferrous metals/others disposal (kg)	1	
Outputs to technospere, Waste and emissions to treatment		
Inert waste, for final disposal, inert material landfill {RoW} (kg)	1	EcoInvent 3

Table A7.
Material and energy process inventory for Li-Ion battery repurposing (Bobba et al., 2018)

Process	Amount	Source data	Sub-inventory
Functional unit output			
Li-iron batter re-purposing (kg of battery)	1		
Material and energy requirements			
Battery tray replacement (kg)	0.1043		Inventories given in
Battery retention replacement (kg)	0.0382		(Ellingsen et al., 2013)
Electricity (kWh)	0.0611		
Transport, freight lorry 16-32 t, EURO5 {GLO} (tkm)	0.1	EcoInvent 3	
Avoided emissions			
Specific case, grid connected house, PV installation with repurposed battery (eq.CO_2)	5.82		

Table A8.
Material and energy process inventory for Li-Ion battery recycle using hydrometallurgical process (Dunn et al., 2012)

Process	Amount	Source data
Functional unit output		
Battery grade recycled lithium (kg)	1	
Energy requirements		
Electricity (kWh)	3.4	
Natural gas, high pressure {CA-AB} (MJ)	6.85	EcoInvent 3
Transport, freight lorry 16-32 t, EURO5 {GLO} (tkm)	0.1	EcoInvent 3

Table A9.
Material and energy process inventory for Li-Ion battery recycle using intermediate physical process (Dunn et al., 2012)

Process	Amount	Source data
Functional unit output		
Recycled lithium carbonate (kg)	1	
Material and energy requirements		
Soda ash {GLO} (kg)	2	EcoInvent 3
Electricity (kWh)	3.1	
Transport, freight lorry 16-32 t, EURO5 {GLO} (tkm)	0.1	EcoInvent 3

Table A10.
Material and energy process inventory for Li-Ion battery recycle using direct physical process (Dunn et al., 2012)

Process	Amount	Source data
Functional unit output		
Recycled lithium carbonate (kg)	1	
Material and energy requirements		
Electricity (kWh)	2.7	
Transport, freight lorry 16-32 t, EURO5 {GLO} (tkm)	0.1	EcoInvent 3

S3 Model coefficients for adaptive framework for GHG emissions estimation

This section provides the coefficients for GHG modeling equations of the adaptive framework for each type of vehicle. For the average vehicles manufacturing in Canadian context, the electricity was assumed to be coming from 75% North American grid and remaining 25% from the rest of the world based on typical North American vehicle parts manufacturing.

Emissions of ICEV, BEV or FCEV production except traction battery

$$E_V = V(C_V + C_{El} \times EI_E) \quad [1]$$

Emissions of HEV or PHEV production except traction battery

$$E_V = V(C_{VC} + C_{ICE} \times (1 - H) + C_{EV} \times H + C_{El-C} \times EI_E + C_{El-ICE} \times EI_E) \quad [2]$$

Emissions of FCEV production except traction battery

$$E_V = V(C_V + C_{FC} + C_{El} \times EI_E) \quad [3]$$

Emissions of traction battery production

$$E_B = B(C_B + C_{El-B} \times EI_E) \quad [4]$$

Emissions of vehicle maintenance

$$E_M = VKT \times V \times C_M$$

ICEV and HEV Life cycle emissions

$$E_{ICEV,\ HEV} = E_V + E_B + \frac{FE_G}{100} \times VKT \times EI_G + eol_V \times V + eol_B \times B + E_M \quad [5]$$

PHEV Life cycle emissions

$$E_{PHEV} = E_V + E_B + \left(\frac{FE_G}{100} \times P_G \times EI_G + \frac{FE_E}{100} \times P_E \times EI_E\right) \times VKT + eol_V \times V + eol_B \times B + E_M \quad [6]$$

BEV Life cycle emissions

$$E_{BEV} = E_V + E_B + \left(\frac{FE_{E,195} + 0.54 \times (B-195)}{100}\right) \times VKT \times EI_E + eol_V \times V + eol_B \times B + E_M \quad [7]$$

FCEV Life cycle emissions

$$E_{FCEV} = E_V + E_B + \frac{FE_H}{100} \times VKT \times EI_H + eol_V \times V + eol_B \times B + E_M \quad [8]$$

Table A11.
Coefficients and variable values used to model the adaptive framework for vehicle GHG estimation.

Variable	Description	Values
E_V	Emissions during vehicle manufacturing	Calculated in terms of kg eq.CO_2
V	Vehicle weight expect traction battery	Parameter value given in kg
C_V	Coefficient representing emissions from vehicle materials and processing	ICEV: 5.294 kg eq.CO_2/kg BEV: 7.813 kg eq.CO_2/kg FCEV: 5.345 kg eq.CO_2/kg
C_{El}	Coefficient representing electricity usage during vehicle production	ICEV: 1.127 kWh/kg BEV: 0.897 kWh/kg FCEV: 0.613 kWh/kg
EI_E	Emission intensity of electricity	Provided in terms of kg eq.CO_2/kWh.
$E_{ICEV,\ HEV}$	Emissions during complete life cycle of the vehicle	Calculated in terms of kg eq.CO_2
C_{VC}	Coefficient representing emissions from vehicle materials and processing – common components of all types of vehicles	4.073 kg eq.CO_2/kg
C_{ICE}	Coefficient representing emissions from vehicle materials and processing – conventional powertrain components	1.139 kg eq.CO_2/kg
C_{EV}	Coefficient representing emissions from vehicle materials and processing – electric powertrain components	3.741 kg eq.CO_2/kg
H	Hybridization factor for hybrid vehicles	Assumptions in this study:

		HEV: 30% PHEV: 60%
C_{El-C}	Coefficient representing electricity usage during vehicle common component production	0.897 kWh/kg
C_{El-ICE}	Coefficient representing electricity usage during vehicle conventional powertrain component production	0.230 kWh/kg
C_{FC}	Coefficient representing emissions from fuel cell materials and processing	1.589 kg eq.CO2/kg
E_B	Emissions during traction battery manufacturing	Calculated in terms of kg eq.CO_2
B	Battery weight	Input variable in kg
C_B	Coefficient representing emissions from battery materials and processing	NCM: 10.9 kg eq.CO_2/kg LFP: 9.49 kg eq.CO_2/kg NCA: 11.7 kg eq.CO_2/kg
C_{El-B}	Coefficient representing electricity usage during battery production	16.8 kWh/kg
C_M	Coefficient representing emissions arising from vehicle service and maintenance (not including traction battery replacement)	ICEV, HEV, PHEV: 0.000010 kg eq.CO_2/kg/km BEV, FECV : 0.000008 kg eq.CO_2/kg/km
FE_G	Fuel consumption – gasoline (average vehicle models)	ICEV: 7.32 L/100 km HEV: 5.37 L/100 km PHEV: 5.14 L/100 km
FE_E	Fuel consumption – electricity (average vehicle models)	PHEV: 19 kWh/100 km BEV: 16.8 kWh/100 km
FE_H	Fuel consumption – hydrogen (average vehicle models)	FCEV: 0.94 kg/100 km
VKT	Lifetime vehicle kilometers	Input variable
EI_G	Emissions intensity of gasoline	Provided in terms of kg eq.CO_2/L. Canadian provincial values are given in Table A12
eol_V	Emissions during end-of-life treatment of vehicle	ICEV: 0.300 eq.CO_2/kg HEV: 0.402 eq.CO_2/kg PHEV: 0.401 eq.CO_2/kg BEV: 0.542 eq.CO_2/kg FCEV: 0.558 eq.CO_2/kg
eol_B	Emissions during end-of-life treatment of battery	0.5 kg eq.CO_2/kg
P_G	Percentage of gasoline vehicle kilometers for PHEV (average vehicle model)	52.5%
P_E	Percentage of electric vehicle kilometers for PHEV (average vehicle model)	47.5%
$FE_{E,195}$	Fuel consumption – electricity (BEV with 195 battery)	16.27 kWh/100 km

References

Argonne National Laboratory (ANL), 2018. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model [WWW Document]. doi:https://greet.es.anl.gov/

Belboom, S., Lewis, G., Bareel, P.-F., Léonard, A., 2016. Life cycle assessment of hybrid vehicles recycling: Comparison of three business lines of dismantling. Waste Manag. 50, 184–193. doi:https://doi.org/10.1016/j.wasman.2016.02.007

Bobba, S., Mathieux, F., Ardente, F., Blengini, G.A., Cusenza, M.A., Podias, A., Pfrang, A., 2018. Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. J. Energy Storage 19, 213–225. doi:https://doi.org/10.1016/j.est.2018.07.008

Dunn, J.B., Gaines, L., Sullivan, J., Wang, M.Q., 2012. Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries. Environ. Sci. Technol. 46, 12704–12710. doi:10.1021/es302420z

Ellingsen, L.A.-W., Majeau-Bettez, G., Singh, B., Srivastava, A.K., Valøen, L.O., Strømman, A.H., 2013. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. J. Ind. Ecol. 0, n/a-n/a. doi:10.1111/jiec.12072

Hao, H., Qiao, Q., Liu, Z., Zhao, F., 2017. Impact of recycling on energy consumption and greenhouse gas emissions from electric vehicle production: The China 2025 case. Resour. Conserv. Recycl. 122, 114–125. doi:https://doi.org/10.1016/j.resconrec.2017.02.005

Sawyer-Beaulieu, S., 2009. Gate-to-Gate Life Cycle Inventory Assessment of North American End-of-Life Vehicle Management Processes. University of Windsor.