Life Cycle Analysis of Lithium-ion Batteries for Automotive Applications

Supplementary Materials

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Table S1. BOM of the reference 23.5 kWh NMC111 battery pack

	Mass (kg)	Note
Cell components		
NMC111 powder	41.52	
Graphite	23.18	
Carbon black	2.80	In cathode
Binder (PVDF)	3.55	2.33 kg in cathode, 1.22 kg in anode
Copper	18.84	14.83 kg in anode current collector, 4.01 kg in negative terminal assembly
Aluminum	9.80	6.40 kg in cathode current collector, 1.21 kg in positive terminal assembly, 2.18 kg in cell container
Electrolyte: LiPF6	2.66	1 mole LiPF6/L electrolyte solvent
Electrolyte: EC	7.43	
Electrolyte: DMC	7.43	
Plastic: PP	1.82	1.68 kg in separator, 0.15 kg in cell container
Plastic: PE	0.42	20 wt % of separator
Plastic: Polyethylene Terephthalate (PET)	0.34	12.7 wt % of cell container
Subtotal: Cell	119.77	
Module components sans cells (kg)		
Copper	0.43	80 wt % of module terminal
Aluminum	7.22	3.96 kg in heat conductors, 3.26 kg in module enclosure
Plastic: PE	0.18	Spacers for gas release
Insulation	0.11	20 wt % of module terminal
Electronic parts	1.12	Module state-of-charge regulator assembly
Subtotal: Module sans cell	9.06	
Pack components sans modules (kg)		
Copper	0.09	75 wt % of battery pack terminals
Aluminum	22.33	97 wt % of battery jacket
Steel	1.02	Module compression plates and straps
Insulation	0.69	25 wt % of battery pack terminals, 3 wt % of battery jacket
Coolant	7.10	3.55 kg ethylene glycol, 3.55 kg water
Electronic parts	4.91	4.0 kg BMS, 0.2 kg battery pack heaters, 0.71 kg module inter-connect
Subtotal: Pack sans module	36.15	
Total: Pack	164.98	

Table S2. Cradle-to-gate LCA results for 1 kWh of NMC111 battery

	Total energy (MJ)	GHG (kgCO2e)	SOx (g)	NOx (g)	PM10 (g)	Water (L)
NMC111 Powder	409.33	28.49	508.59	46.15	31.71	238.76
Graphite/Carbon	99.23	5.37	88.14	14.89	6.09	26.16
Binder	5.47	0.36	0.47	0.30	0.04	1.06
Copper	36.59	2.54	119.79	5.53	0.53	11.02
Wrought Aluminum	203.38	12.39	44.52	8.94	7.31	382.25
Electrolyte: $LiPF_6$	20.25	1.37	15.59	1.16	0.17	7.05
Electrolyte: EC	3.20	0.15	0.09	0.15	0.01	0.21
Electrolyte: DMC	11.82	0.54	0.32	0.56	0.03	0.74
Plastic: PP	6.10	0.20	1.83	0.25	0.02	0.39
Plastic: PE	2.06	0.07	0.66	0.09	0.01	0.15
Plastic: PET	1.12	0.05	0.18	0.07	0.01	0.10
Steel	1.36	0.12	0.41	0.10	0.07	0.73
Thermal Insulation	0.88	0.06	0.11	0.14	0.05	1.43
Coolant: Glycol	5.98	0.53	1.88	0.71	0.13	0.47
Electronic Parts	102.33	6.79	9.05	5.04	0.68	26.08
Cell Production	216.20	13.85	8.84	12.81	1.01	55.55
Total	1125.31	72.87	800.46	96.89	47.87	752.16

Table S3. Impact intensities per-kg materials in the NMC battery

	Total energy (MJ)	GHG (kg CO2e)	SOx (g)	NOx (g)	PM10 (g)	Water (L)
NMC111 Powder	231.28	16.11	288.22	26.12	17.97	135.28
Graphite/Carbon	89.87	4.86	79.84	13.48	5.52	23.70
Binder	36.20	2.39	3.12	2.01	0.24	7.05
Copper	44.47	3.08	145.59	6.72	0.64	13.40
Wrought Aluminum	121.60	7.41	26.62	5.34	4.37	228.57
Electrolyte: $LiPF_6$	179.07	12.15	137.88	10.25	1.54	62.34
Electrolyte: EC	10.19	0.47	0.28	0.48	0.03	0.66
Electrolyte: DMC	37.44	1.72	1.01	1.78	0.10	2.36
Plastic: PP	78.59	2.53	23.64	3.21	0.29	5.05
Plastic: PE	80.96	2.93	25.89	3.45	0.34	6.05
Plastic: PET	77.08	3.38	12.25	4.68	0.37	6.66
Steel	30.96	2.68	9.46	2.39	1.51	16.84
Thermal Insulation	26.58	1.90	3.22	4.14	1.55	41.93
Coolant: Glycol	19.82	1.75	6.23	2.36	0.44	1.55
Electronic Parts	399.24	26.48	35.29	19.67	2.64	101.75
NMP	100.22	5.13	1.78	4.95	0.28	3.88

Table S4. Comparison of reported LCIs for NMC powder production

	Majeau-Bettez et al. (NMC442)	Ellingsen et al.* (NMC111)	GREET2018 (NMC111)
Calcination			
Material inputs (kg/kg NMC)			
$NMC(OH)_2$	0.95	0.95	0.95
LiOH	0.25	0.25	
Li_2CO_3			0.38
Energy inputs (MJ/kg NMC)			
Heat	0.55	0.55	
Electricity			25.2
Co-precipitation			
Material inputs (kg/kg $NMC(OH)_2$)			
$NiSO_4$	0.68	0.57	0.56
$MnSO_4$	0.66	0.55	0.55
$CoSO_4$	0.34	0.57	0.56
NaOH	0.88	0.88	0.89
NH_4OH			0.12
Energy inputs (MJ/kg $NMC(OH)_2$)			
Heat			42.6

*Adapted from the LCI for $LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$ (NMC442) production reported by Majeau-Bettez et al.

Table S5. Cradle-to-gate LCA results for 1 kg of NMC111 powder

	Total energy (MJ)	GHG (kg CO2e)	SOx (g)	NOx (g)	PM10 (g)	Water (L)
$NiSO_4$	27.07	1.82	244.18	7.82	2.86	27.56
$CoSO_4$	55.96	3.79	25.35	5.79	13.04	72.37
$MnSO_4$	3.06	0.36	7.14	0.32	0.65	1.00
Li_2CO_3	16.23	1.46	2.38	5.11	0.18	2.85
NaOH	27.37	1.82	2.52	1.60	0.01	12.15
NH_4OH	2.40	0.15	0.05	0.14	0.66	0.17
Co-precipitation	46.97	2.94	0.48	3.09	0.16	1.16
Calcination	52.23	3.76	6.12	2.26	0.41	18.03
Total	231.28	16.11	288.22	26.12	17.97	135.28

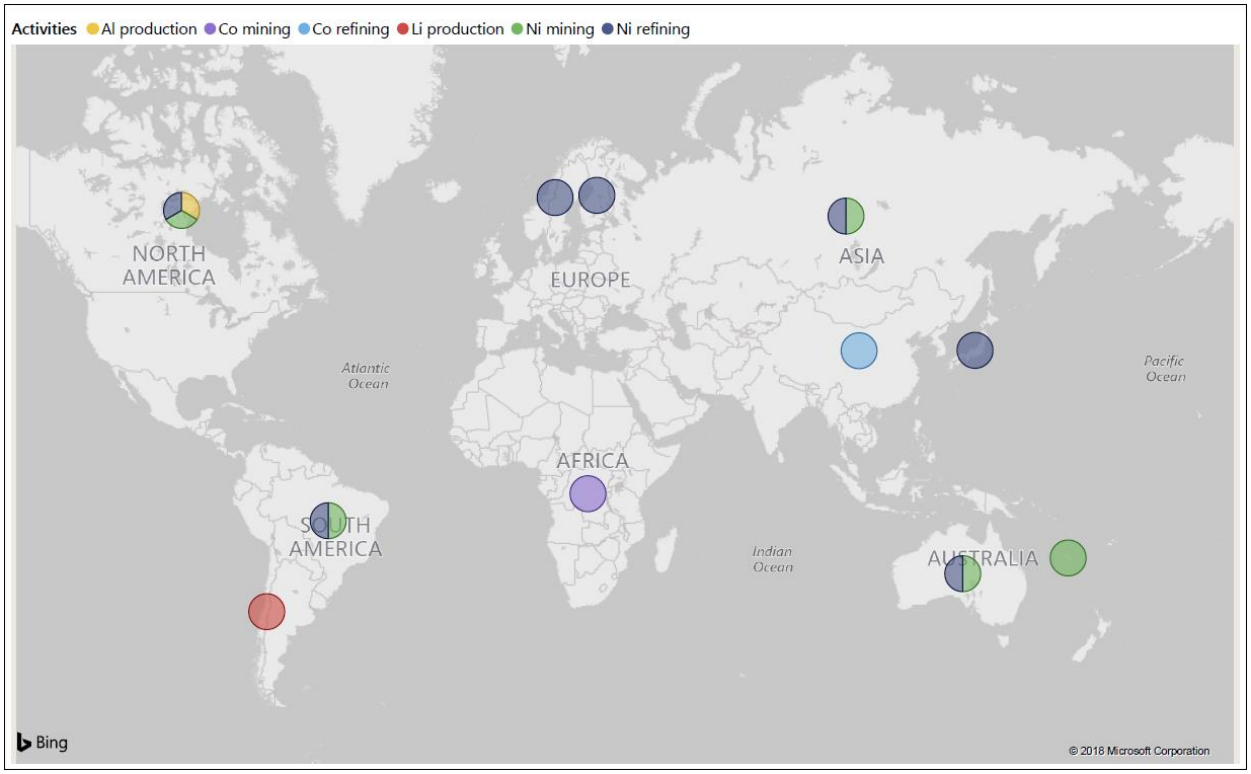

Figure S1. Geographical distribution of NMC111 battery production activities. Activities not shown here are assumed to occur in the United States.