Supporting Information to the manuscript entitled

Life Cycle Environmental Impact of High Capacity Lithium Ion Battery with Silicon Nanowires Anode for Electric Vehicles

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This supporting information includes the LCA system boundary, material compositions for the battery pack using both silicon nanowire and carbon graphite anodes, life cycle inventory data, life cycle impacts assessment results and sensitivity analysis results.

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Material Composition

Table S1 Material composition of lithium ion battery with SiNW anode (total mass: 120kg)

Component	Material name	Mass (kg)	Percent mass (%)
Anode (7:2:1)	Silicon nanowire	10.80	9.0
	Carbon black	3.12	2.6
	Copper foil (12μm)	9.36	7.8
Cathode(92:4:4)	Aluminum foil	10.26	8.6
	Carbon black	0.54	0.4
	Umicore NMC $(LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2)$	11.88	9.9
Binder	SBR+CMC binder (10-20μm, 1:1)	1.56	1.3
Separator	PE (20μm, 1.2 g/cm3)	2.64	2.2
Casing	Poly-aluminum-poly (200μm)	14.76	12.3
Electrolyte	Lithium hexaflourophosphate (LiPF6, 1M)	12.24	10.2
	Ethyl carbonate: ethyl-methyl carbonate (EC:EMC) 1:1		
Battery Management System	Copper wires	1.20	1.0
	Stainless steel	0.96	0.8
	Printed circuit board	0.24	0.2
Pack housing	Polyethylene terephthalate	20.40	17.0
Passive cooling system	Stainless steel	0.60	0.5
	Aluminum	19.44	16.2

Table S2 Material composition of lithium ion battery with graphite anode (total mass: 360kg)

Component	Material name	Mass(kg)	Percent mass (%)
Anode (94:3:3)	Artificial Graphite	45.00	12.5
	Carbon black	1.44	0.4
	Copper foil	19.08	5.3
Cathode(92:4:4)	Aluminum foil	17.28	4.8
	Carbon black	2.16	0.6
	Umicore NMC $(LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2)$	48.60	13.5
Binder	SBR/CMC	1.44	0.4
	PVDF	2.16	0.6
Separator	Celgard Polyethylene	7.92	2.2
Casing	Poly-aluminum-poly	44.28	12.3
Electrolyte	Lithium hexaflourophosphate (LiPF6, 1M)	4.32	1.2
	Ethyl carbonate and ethyl methyl carbonate	37.80	10.5

	(EC:EMC 1:1)		
Battery Management System	Copper wires	3.60	1.0
	Stainless steel	2.88	0.8
	Printed circuit board	0.72	0.2
Pack housing	Polyethylene terephthalate	61.20	17.0
Passive cooling system	Stainless steel	1.80	0.5
	Aluminum	58.32	16.2

Silicon Nanowire Preparation Process

325 Mesh silicon powders (Aldrich, 99.99%) were firstly cleaned sequentially by acetone, ethanol, and deionized water to remove the organic containments and followed by hydrophilic treatment using boiling solution of $NH_3{\cdot}H_2O$, H_2O_2 and H_2O (1:1:5, volume ratio) for 10 minutes. The dioxide layer was etched away in the following procedure to form nanowire structures. The pretreated Si powders were placed in PTFE beaker and then add certain amount of H_2O, HF, and $AgNO_3$ solution (1:1:3, volume ratio) successively. Silver plating took 30 seconds for processing. Then certain amount of H_2O_2 was slowly added using syringe. The resultant porous silicon was rinsed with copious water and then split into two portions. One was dried directly in vacuum oven and the other portion was washed with concentrated nitric acid (5%) for 15 minutes in order to remove the residual silver. The prepared porous Si material was mixed with carbon black and CMC glue (8:1:1, weight ratio) and coated onto copper foil (5 μm) to make disk-like electrode (1/2 inch).

The reduction of Ag^+ process and the chemical etching process can be expressed as follows:

$$4Ag^+ + Si + 6F^- \rightarrow 4Ag + [SiF_6]^{2-} \quad (1)$$

$$\mathrm{Si} + 2H_2O_2 + 6F^- + 4H^+ \rightarrow [SiF_6]^{2-} + 4H_2O \quad (2)$$

Table S3 Nano-particle emissions in various sizes from the SiNW synthesis process.

Particle size (nm)	G(d)	C(d)	Particle size (nm)	G(d)	C(d)
255.0	26	5	655.0	99	55

309.4	44	10	700.8	97	60
352.7	58	15	751.8	93	65
391.1	70	20	809.6	87	70
427.7	80	25	877.0	80	75
463.3	87	30	959.1	70	80
498.9	93	35	1063.5	58	85
535.2	97	40	1212.4	44	90
572.7	99	45	1471.0	26	95
612.4	100	50			

G(d) represents relative percentage contribution of the size range. C (d) represents cumulated percentage contribution

The Gabi Model of Battery Manufacturing

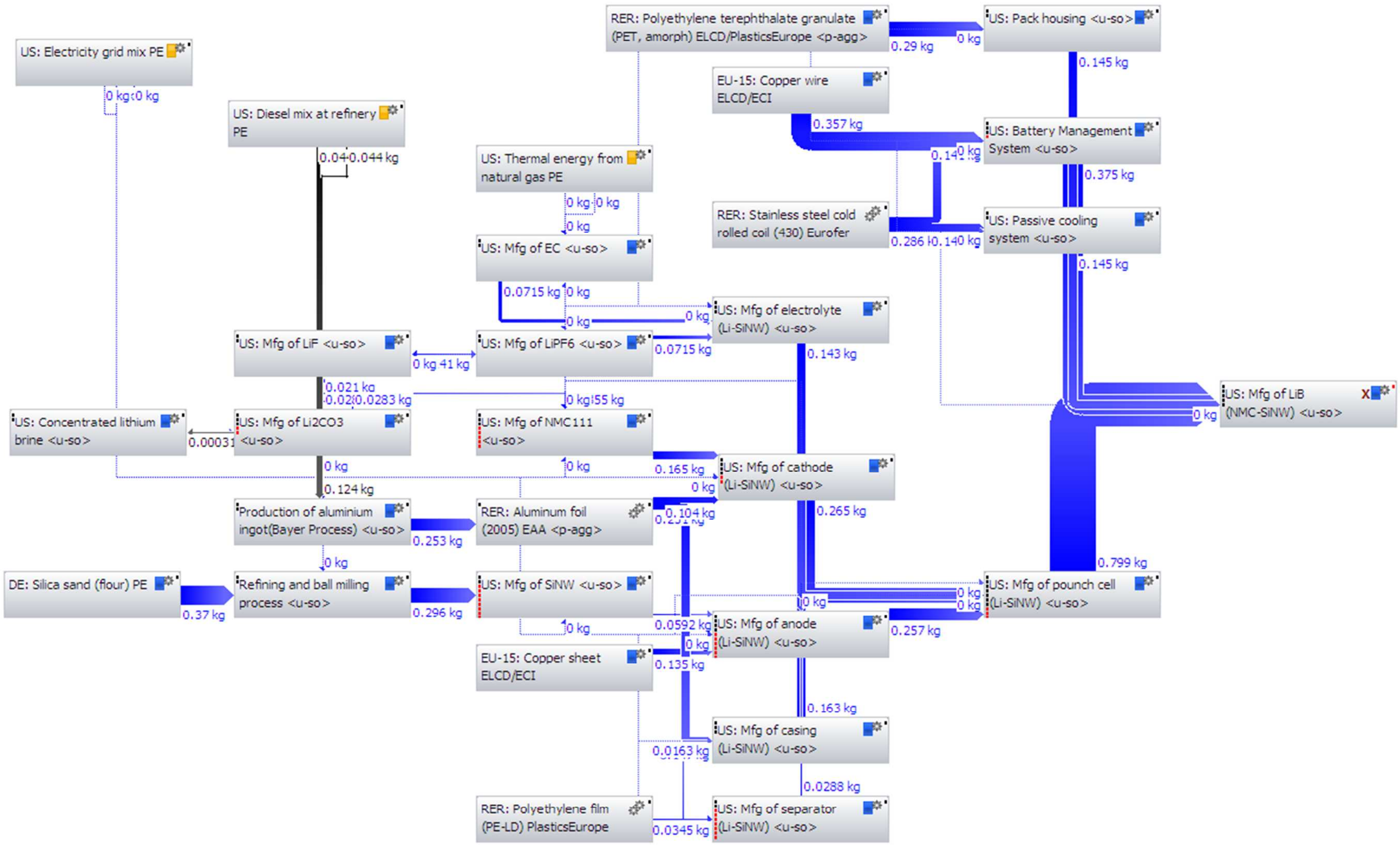

Figure S1 GaBi model structure of battery manufacturing

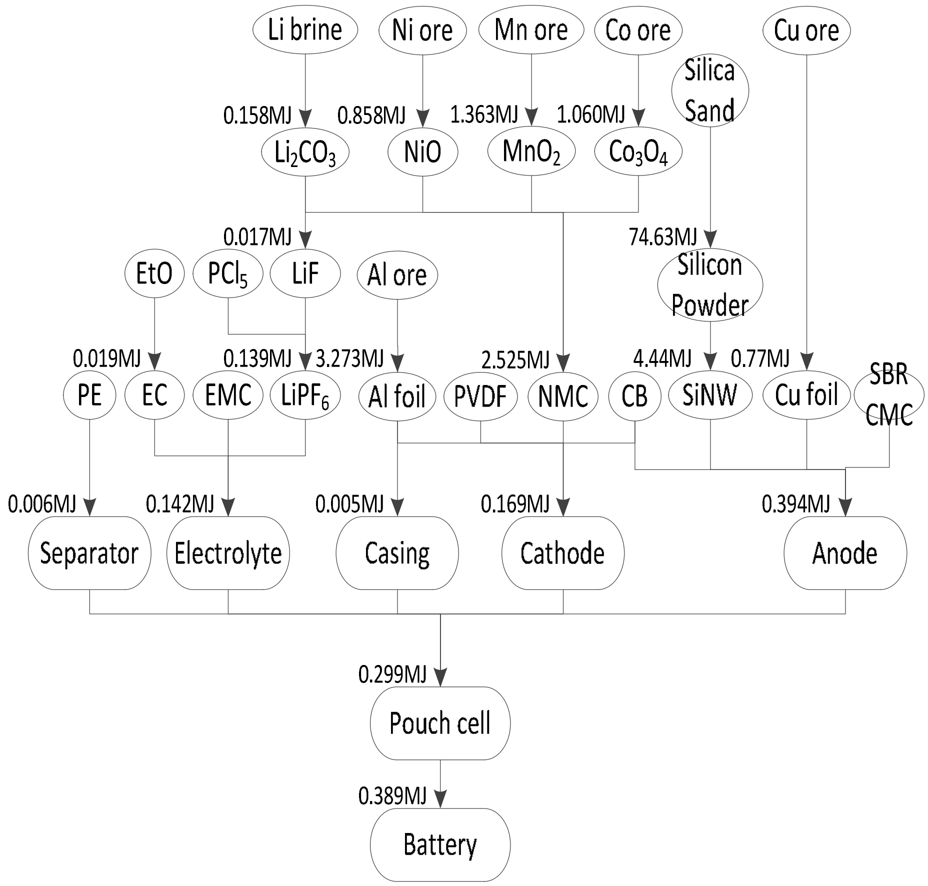

Figure S2 Energy consumption of manufacturing processes for 1kg LiB with SiNW anode

Life Cycle Inventory of Battery Manufacturing

Table S4 Production of aluminum ingot

Flow	Quantity	Amount	Unit
Inputs			
Diesel [Refinery products]	Mass	0.4888	kg
Electricity [Electric power]	Energy (net calorific value)	2	MJ
Bauxite [Non renewable resources]	Mass	132	kg
Outputs			
Aluminum ingot [Metals]	Mass	1	kg

The production of aluminum ingot is based on Bayer process. The process dissolves the aluminum component of bauxite ore in hot sodium hydroxide (caustic soda), removes impurities from the solution, precipitates alumina trihydrate, which is then calcined into aluminum oxide[1].

Table S5 Production of Concentrated lithium brine

Flow	Quantity	Amount	Unit
Inputs			
Diesel [Refinery products]	Mass	0.194	kg
Electricity [Electric power]	Energy (net calorific value)	0.32	MJ
Lithium ore (3%) [Non renewable resources]	Mass	0.067	kg
outputs			
GLO: concentrated lithium brine (6.7 % Li), at plant [inorganics]	Mass	1	kg

The basic approach of production of concentrated lithium brine is to concentrate the lithium even more by putting brine into evaporation ponds[2].

Table S6 Manufacturing of Li2CO3

Flow	Quantity	Amount	Unit
Inputs			
Diesel [Refinery products]	Mass	0.284	kg
Electricity [Electric power]	Energy (net calorific value)	5.6	MJ
GLO: concentrated lithium brine (6.7 % Li), at plant [inorganics]	Mass	0.0571	kg
RER: natural gas, burned in industrial furnace >100kW [heating systems]	Energy (net calorific value)	6.09	MJ
RER: natural gas, high pressure, at consumer [fuels]	Energy (net calorific value)	2	MJ
CH: quicklime, milled, loose, at plant [additives]	Mass	0.0144	kg
DE: bentonite, at processing [additives]	Mass	0.176	kg
DZ: natural gas, liquefied, at freight ship [Appropriation]	Standard volume	9.53E-5	Nm3
GLO: solvents, organic, unspecified, at plant [organics]	Mass	0.00475	kg
RER: 2-methyl-2-butanol, at plant [organics]	Mass	0.00119	kg
RER: chemical plant, organics [organics]	Number of pieces	4E-10	pcs.
RER: hydrochloric acid, 30% in H2O, at plant [inorganics]	Mass	9.38	kg
RER: soda, powder, at plant [inorganics]	Mass	3.73	kg
RER: sodium hydroxide, 50% in H2O, production mix, at plant [inorganics]	Mass	0.000188	kg
RER: sulphuric acid, liquid, at plant [inorganics]	Mass	0.0357	kg

RER: transport, lorry 16-32t, EURO3 [Street]	Ecoinvent quantity ton kilometer (tkm)	2.59	tkm
RER: transport, lorry 3.5-7.5t, EURO3 [Street]	Ecoinvent quantity ton kilometer (tkm)	0.0024	tkm
outputs			
GLO: lithium carbonate, at plant [inorganics]	Mass	1	kg
CH: disposal, decarbonising waste, 30% water, to residual material landfill [residual material landfill facility]	Mass	6.41	kg
DE: disposal, hazardous waste, 0% water, to underground deposit [underground deposit]	Mass	0.000205	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	0.00202	MJ

Table S7 Manufacturing of NMC111

Flow	Quantity	Amount	Unit
Inputs			
Cobalt oxide [Inorganic intermediate products]	Mass	0.306	kg
Electricity [Electric power]	Energy (net calorific value)	0.0180	MJ
GLO: lithium carbonate, at plant [inorganics]	Mass	0.215	kg
Manganese oxide [Inorganic intermediate products]	Mass	0.306	kg
Nickel oxide [Inorganic intermediate products]	Mass	0.306	kg
RER: nitrogen, liquid, at plant [inorganics]	Mass	0.786	kg
RER: oxygen, liquid, at plant [inorganics]	Mass	0.715	kg
Thermal energy (MJ) [Thermal energy]	Energy (net calorific value)	15.3	MJ
CH: water, deionised, at plant [Appropriation]	Mass	3.4	kg
RER: chemical plant, organics [organics]	Number of pieces	4E-10	pcs.
RER: transport, lorry >16t, fleet average [Street]	Ecoinvent quantity ton kilometer (tkm)	0.564	tkm
US: transport, freight, rail, diesel [Railway]	Ecoinvent quantity ton kilometer (tkm)	3.23	tkm
outputs			
Lithium nickel-cobalt-manganese oxide [Inorganic intermediate products]	Mass	1	kg
CH: disposal, inert waste, 5% water, to inert material landfill [inert material landfill facility]	Mass	0.0566	kg
CH: heat, biowaste, at waste incineration plant, allocation price [municipal incineration]	Energy (net calorific value)	0.018	MJ
RER: potassium carbonate from manganese dioxide oxidation, at plant [inorganics]	Mass	0.128	kg
Water vapor (sewage correction) [Thermal energy]	Mass	3.4	kg

Table S8 Manufacturing of cathode

Flow	Quantity	Amount	Unit
Inputs			
Aluminum foil [Metals]	Mass	0.393	kg
Electricity [Electric power]	Energy (net calorific value)	0.6377	MJ
GLO: Carbon black, at plant [inorganics]	Mass	0.0264	kg
Lithium nickel-cobalt-manganese oxide [Inorganic intermediate products]	Mass	0.623	kg
RER: sheet rolling, aluminum [processing]	Mass	0.393	kg
Thermal energy (MJ) [Thermal energy]	Energy (net calorific value)	0.646	MJ
CH: water, deionised, at plant [Appropriation]	Mass	0.2	kg
RER: chemical plant, organics [organics]	Number of pieces	4E-10	pcs.
RER: latex, at plant [organics]	Mass	0.00989	kg
RER: sodium hydroxide, 50% in H2O, production mix, at plant [inorganics]	Mass	0.13	kg
RER: transport, freight, rail [Railway]	Ecoinvent quantity ton kilometer (tkm)	0.758	tkm
RER: transport, lorry >16t, fleet average [Street]	Ecoinvent quantity ton kilometer (tkm)	0.126	tkm
Sulfamic acid [Inorganic emissions to air]	Mass	0.0808	kg
RER: transport, lorry >16t, fleet average [Street]	Ecoinvent quantity ton kilometer (tkm)	0.126	kg
outputs			
CN: Cathode, lithium-ion battery, lithium manganese oxide, at plant [Parts]	Mass	1	kg
CH: disposal, residues, shredder fraction from manual dismantling, in MSWI [municipal incineration]	Mass	0.0526	kg
CH: treatment, sewage, to wastewater treatment, class 3 [wastewater treatment]	Volume	0.000105	m3
Waste heat [Other emissions to air]	Energy (net calorific value)	0.0072	MJ
Water vapor [Inorganic emissions to air]	Mass	0.2	kg

Table S9 Refining and ball milling process

Flow	Quantity	Amount	Unit
Inputs			
Electricity [Electric power]	Energy (net calorific value)	252.144	MJ
Silica flour (fine) [Minerals]	Mass	1.25	kg
Outputs			
325 Mesh Silicon Powder (44 microns) [Non renewable resources]	Mass	1	kg

The basic process of processing silicon from silica sand (80% purity) to mesh silicon powder (99.99% purity) is carbothermic reduction, chemical purification (fluid bed combustion technology, distillation, CVD deposition) and ball milling. The energy requirement is from literature[3, 4].

Table S10 Manufacturing of silicon nanowire

Flow	Quantity	Amount	Unit
Inputs			
325 Mesh Silicon Powder (44 microns) [Non renewable resources]	Mass	5	kg
Acetone (dimethyl ketone) [Organic intermediate products]	Mass	14.5	kg
Ammonium hydroxide (NH4OH) [Inorganic intermediate products]	Mass	4.4	kg
Electricity [Electric power]	Energy (net calorific value)	75	MJ
Ethanol (96%) [Organic intermediate products]	Mass	14.4	kg
Hydrogen fluoride [Inorganic intermediate products]	Mass	142	kg
Hydrogen peroxide (100%) [Inorganic intermediate products]	Mass	63.6	kg
Nitric acid (5%) [Inorganic intermediate products]	Mass	3.7	kg
Silver nitrate [Inorganic intermediate products]	Mass	1.2275	kg
outputs			
Silicon nanowire [Non renewable resources]	Mass	1	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	3.72	MJ
Solid waste Ag	Mass	0.78	kg
Si waste	Mass	4	Kg
Solution waste	Mass	314.3275	kg

Table S11 Manufacturing of anode

Flow	Quantity	Amount	Unit
Inputs			
CN: graphite, battery grade, at plant [inorganics]	Mass	0.494	kg
Copper sheet [Metals]	Mass	0.524	Kg
Electricity [Electric power]	Energy (net calorific value)	1.5331	Kg
GLO: Carbon black, at plant [inorganics]	Mass	0.0159	MJ
RER: copper, at regional storage [Benefication]	Mass	0.524	Kg

RER: latex, at plant [organics]	Mass	0.0185	Kg
RER: sodium hydroxide, 50% in H2O, production mix, at plant [inorganics]	Mass	0.132	Kg
Silicon nanowire [Non renewable resources]	Mass	0.23	Kg
Sulfamic acid [Inorganic emissions to air]	Mass	0.0808	MJ
Thermal energy (MJ) [Thermal energy]	Energy (net calorific value)	1.22	kg
CH: water, deionised, at plant [Appropriation]	Mass	0.424	Tkm
RER: transport, lorry >16t, fleet average [Street]	Ecoinvent quantity ton kilometer (tkm)	0.113	tkm
US: transport, freight, rail, diesel [Railway]	Ecoinvent quantity ton kilometer (tkm)	0.47	tkm
outputs			
CN: Anode, lithium-ion battery, graphite, at plant [Parts]	Mass	1	kg
CH: treatment, sewage, to wastewater treatment, class 3 [wastewater treatment]	Volume	0.000106	m3
Waste heat [Other emissions to air]	Energy (net calorific value)	0.0072	MJ
Water vapor [Inorganic emissions to air]	Mass	0.424	kg

Table S12 Manufacturing of LiF

Flow	Quantity	Amount	Unit
Inputs			
RER: heat, natural gas, at industrial furnace >100kW [heating systems]	Energy (net calorific value)	1.21	MJ
CH: water, deionised, at plant [Appropriation]	Mass	2.21	kg
GLO: hydrogen fluoride, at plant [inorganics]	Mass	0.806	kg
GLO: lithium carbonate, at plant [inorganics]	Mass	1.49	kg
RER: ammonia, liquid, at regional storehouse [inorganics]	Mass	0.0328	kg
RER: chemical plant, organics [organics]	Number of pieces	4E-10	pcs.
RER: transport, lorry >16t, fleet average [Street]	Ecoinvent quantity ton kilometer (tkm)	0.233	tkm
US: transport, freight, rail, diesel [Railway]	Ecoinvent quantity ton kilometer (tkm)	1.4	tkm
outputs			
CN: lithium fluoride, at plant [inorganics]	Mass	1	kg
Carbon dioxide [Inorganic intermediate products]	Mass	0.886	kg
Hydrogen fluoride [Inorganic intermediate products]	Mass	0.0363	kg
Ammonium [Inorganic emissions to air]	Mass	0.0347	kg
CH: treatment, sewage, to wastewater treatment, class 1 [wastewater treatment]	Volume	0.00357	m3
GLO: lithium carbonate, at plant [inorganics]	Mass	0.067	kg

Table S13 Manufacturing of $LiPF_6$

Flow	Quantity	Amount	Unit
Inputs			
CN: lithium fluoride, at plant [inorganics]	Mass	0.197	kg
CN: phosphorous pentachloride, at plant [inorganics]	Mass	1.98	kg
GLO: hydrogen fluoride, at plant [inorganics]	Mass	4.04	kg
RER: nitrogen, liquid, at plant [inorganics]	Mass	0.00125	kg
US: electricity, medium voltage, at grid [supply mix]	Energy (net calorific value)	1.9476	MJ
RER: chemical plant, organics [organics]	Number of pieces	4E-10	pcs.
RER: transport, lorry >16t, fleet average [Street]	Ecoinvent quantity ton kilometer (tkm)	1.37	tkm
US: transport, freight, rail, diesel [Railway]	Ecoinvent quantity ton kilometer (tkm)	8.19	tkm
outputs			
CN: lithium hexafluorophosphate, at plant [inorganics]	Mass	1	kg
CN: lithium fluoride, at plant [inorganics]	Mass	0.0262	kg
CH: disposal, limestone residue, 5% water, to inert material landfill [inert material landfill facility]	Mass	8.61	kg
CH: treatment, sewage, to wastewater treatment, class 1 [wastewater treatment]	Volume	0.00361	m3
Phosphorus trichloride [Inorganic emissions to air]	Mass	0.263	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	1.95	MJ

Table S14 manufacturing of EC

Flow	Quantity	Amount	Unit
Inputs			
RER: carbon dioxide liquid, at plant [inorganics]	Mass	0.505	kg
RER: chemical plant, organics [organics]	Number of pieces	4E-10	pcs.
RER: ethylene oxide, at plant [organics]	Mass	0.501	kg
RER: heat, natural gas, at industrial furnace >100kW [heating systems]	Energy (net calorific value)	0.143	MJ
RER: transport, lorry >16t, fleet average [Street]	Ecoinvent quantity ton kilometer (tkm)	0.101	tkm
US: electricity, medium voltage, at grid [supply mix]	Energy (net calorific value)	0.042	MJ
US: transport, freight, rail, diesel [Railway]	Ecoinvent quantity ton kilometer (tkm)	0.351	tkm
outputs			
CN: ethylene carbonate, at plant [organics]	Mass	1	kg
Ethylene oxide [Group NMVOC to air]	Mass	0.00025	kg
Carbon dioxide [Inorganic emissions to air]	Mass	0.0053	kg
CH: disposal, catalyst base Eth.oxide prod., 0% water, to residual material landfill [residual material	Mass	0.005	kg

landfill facility]			
Waste heat [Other emissions to air]	Energy (net calorific value)	0.0072	MJ

Table S15 Manufacturing of separator

Flow	Quantity	Amount	Unit
Inputs			
DE: silica sand, at plant [additives]	Mass	0.218	kg
Electricity [Electric power]	Energy (net calorific value)	0.2083	MJ
GLO: hexafluorethane, at plant [organics]	Mass	0.0262	kg
Polyethylene-film (PE) [Plastic parts]	Mass	1.2	kg
RER: acetone, liquid, at plant [organics]	Mass	0.144	kg
RER: fleece, polyethylene, at plant [polymers]	Mass	0.351	kg
RER: heat, natural gas, at industrial furnace >100kW [heating systems]	Energy (net calorific value)	0.193	MJ
RER: phthalic anhydride, at plant [organics]	Mass	0.291	kg
US: polyvinyl fluoride, at plant [organics]	Mass	0.192	kg
RER: chemical plant, organics [organics]	Number of pieces	4E-10	pcs.
RER: transport, lorry >16t, fleet average [Street]	Ecoinvent quantity ton kilometer (tkm)	0.0984	tkm
US: transport, freight, rail, diesel [Railway]	Ecoinvent quantity ton kilometer (tkm)	0.525	tkm
outputs			
CN: separator, lithium-ion battery, at plant [Parts]	Mass	1	kg
Acetone (dimethyl ketone) [Group NMVOC to air]	Mass	0.0144	kg
CH: disposal, residues, shredder fraction from manual dismantling, in MSWI [municipal incineration]	Mass	0.0539	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	0.0072	MJ

Table S16 Manufacturing of electrolyte

Flow	Quantity	Amount	Unit
Inputs			
CN: ethylene carbonate, at plant [organics]	Mass	0.5	kg
CN: lithium hexafluorophosphate, at plant [inorganics]	Mass	0.5	kg
Electricity [Electric power]	Energy (net calorific value)	0.0209	MJ
outputs			
Electrolyte [Operating materials]	Mass	1	kg

Table S17 Manufacturing of casing

Flow	Quantity	Amount	Unit
Inputs			
Aluminum foil [Metals]	Mass	0.9	kg
Electricity [Electric power]	Energy (net calorific value)	0.0306	MJ
Polyethylene-film (PE) [Plastic parts]	Mass	0.1	kg
outputs			
Casing [Assemblies]	Mass	1	kg

Table S18 Manufacturing of pouch cell

Flow	Quantity	Amount	Unit
Inputs			
Casing [Assemblies]	Mass	0.204	kg
CN: Anode, lithium-ion battery, graphite, at plant [Parts]	Mass	0.322	kg
CN: Cathode, lithium-ion battery, lithium manganese oxide, at plant [Parts]	Mass	0.332	kg
CN: separator, lithium-ion battery, at plant [Parts]	Mass	0.036	kg
Electricity [Electric power]	Energy (net calorific value)	0.3816	MJ
Electrolyte [Assemblies]	Mass	0.179	kg
RER: aluminum, production mix, wrought alloy, at plant [Benefication]	Mass	0.0165	kg
RER: extrusion, plastic film [processing]	Mass	0.0733	kg
RER: nitrogen, liquid, at plant [inorganics]	Mass	0.01	kg
RER: polyethylene, LDPE, granulate, at plant [polymers]	Mass	0.0733	kg
RER: sheet rolling, aluminum [processing]	Mass	0.0165	kg
Stainless Steel Hot Rolled Sheet (ELCD) [Metals]	Mass	0.0235	kg
Thermal energy (MJ) [Thermal energy]	Energy (net calorific value)	0.0652	MJ
RER: chemical plant, organics [organics]	Number of pieces	4E-10	pcs.
RER: transport, lorry >16t, fleet average [Street]	Ecoinvent quantity ton kilometer (tkm)	0.0278	tkm
US: transport, freight, rail, diesel [Railway]	Ecoinvent quantity ton kilometer (tkm)	0.0278	tkm
outputs			
CN: single cell, lithium-ion battery, lithium manganese oxide/graphite, at plant [Parts]	Mass	1	kg
GLO: disposal, Li-ions batteries, mixed technology [Recycling]	Mass	0.0525	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	0.38	MJ

Table S19 Battery Management System

Flow	Quantity	Amount	Unit
Inputs			
Copper wire [Metals]	Mass	0.95	kg
Electricity [Electric power]	Energy (net calorific value)	0.002	MJ
Testing Electricity	Energy (net calorific value)	0.003	MJ
GLO: printed wiring board, surface mounted, unspec., solder mix, at plant [Module]	Mass	0.05	kg
Stainless steel cold rolled coil (430) [Metals]	Mass	0.375	kg
Outputs			
Battery BMS [Product model]	Mass	1	kg

Table S20 Pack housing

Flow	Quantity	Amount	Unit
Inputs			
Electricity [Electric power]	Energy (net calorific value)	0.235	MJ
Testing Electricity	Energy (net calorific value)	0.0013	MJ
Polyethylene terephthalate granulate (PET) [Plastics]	Mass	2	kg
Outputs			
Battery Housing [Product model]	Mass	1	kg

The battery testing platform includes three key points: BMS development (Hardware-in-the-loop (HIL), BMS validation and verification), pack development (environmental testing, pack validation and verification), and pack manufacturing (end of line functional testing, pack cycling and balancing).

Table S2119 Passive cooling system

Flow	Quantity	Amount	Unit
Inputs			
Electricity [Electric power]	Energy (net calorific value)	0.002	MJ
Testing Electricity	Energy (net calorific value)	0.005	MJ
Stainless steel cold rolled coil (430) [Metals]	Mass	1	kg
Outputs			
Battery Cooling [Product model]	Mass	1	kg

Table S2220 Assembly of battery

Flow	Quantity	Amount	Unit
Inputs			

Battery BMS [Product model]	Mass	0.37528	kg
Battery Cooling [Product model]	Mass	0.145	kg
Battery Housing [Product model]	Mass	0.145	kg
CN: single cell, lithium-ion battery, lithium manganese oxide/graphite, at plant [Parts]	Mass	0.799	kg
Electricity [Electric power]	Energy (net calorific value)	0.3888	MJ
Testing Electricity	Energy (net calorific value)	0.021	MJ
GLO: cable, three-conductor cable, at plant [Parts]	Length	0.373	m
OCE: transport, transoceanic freight ship [Water]	Ecoinvent quantity ton kilometer (tkm)	7.81	tkm
RER: metal working factory [General manufacturing]	Number of pieces	4.58E-10	pcs.
RER: transport, lorry >16t, fleet average [Street]	Ecoinvent quantity ton kilometer (tkm)	1.02	tkm
outputs			
GLO: battery, LiIo, rechargeable, prismatic, at plant [Module]	Mass	1	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	0.378	MJ

Table S213 Life cycle inventories of End of life

Material	Recycling process	Energy consumption (MJ/kg)	Reference
Steel	Physical	52	[5]
Aluminum	Physical	49	[5]
Copper	Physical	75	[5]
Plastic	Physical	31	[5]
Li	Hydrometallurgical	73	[6]
Cobalt	Pyrometallurgical	17	[7]
Manganese	Pyrometallurgical	22	[7]
Nickel	Pyrometallurgical	27	[7]

Life Cycle Impact Assessment

Table S224 Environmental impacts by 6 main life cycle stages for EV lithium-ion battery pack (NMC-SiNW)

	Material extraction	Material processing	Component manufacture	Battery assembly	Battery use	End of life
ADP(kg Sb-eq/km)	0.0002	3.781E-04	2.24E-05	6.25E-05	7.06E-04	2.37E-05
GWP (kg CO2-eq/km)	0.0187	0.0476572	0.00346904	0.00717	0.1051	0.00582

AP(kg H+ Mol-eq/km)	0.015	0.0121655	0.0010411	0.00303	0.0458	0.0104
EP(kg N-eq/km)	9.1E-07	7.192E-06	6.97341E-07	8.71E-07	1.21E-05	2.03E-06
ODP(kg CFC 11-eq/km)	5.51E-10	6.8E-11	4.68E-11	1.11E-11	8.59E-12	2.69E-10
POP(kg O3-eq/km)	0.000951	0.0037176	5.9292E-05	0.000453	0.00641	2.47E-04
ETP(PAF m3 day/km)	0.00244	1.807E-05	4.5629E-07	2.95E-06	4.08E-05	3.56E-04
HTP(cases/km)	2.96E-13	1.659E-12	6.15162E-14	1.47E-13	2.3E-12	6.23E-14

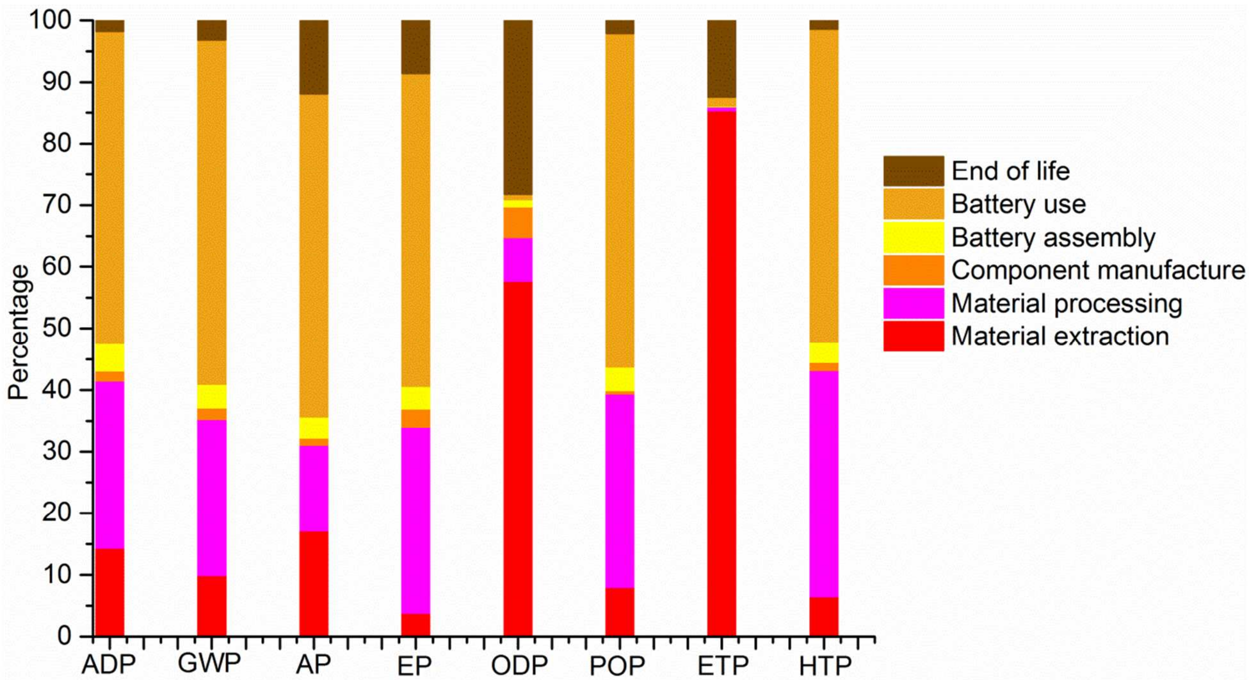

Figure S3 Environmental impacts from 6 main life cycle stages for EV lithium-ion battery pack (NMC-SiNW)

Table S235 Cradle-to-gate environmental impacts of battery components (NMC-SiNW)

	Anode	Cathode	Separator	Electrolyte	Cell casing	BMS	Pack housing	Passive cooling
ADP(kg Sb-eq/km)	2.5E-04	5.7E-05	1.715E-06	2.376E-05	1.642E-05	4E-06	7.149E-06	6.415E-05
GWP (kg CO2-eq/km)	2.8E-02	1.05E-02	1.769E-04	3.154E-03	9.785E-04	9E-04	1.352E-03	7.301E-03

AP(kg H+ Mol-eq/km)	8.9E-03	1.45E-02	3.737E-05	7.798E-04	7.992E-04	4E-04	2.765E-04	3.110E-04
EP(kg N-eq/km)	4E-06	3.82E-06	2.938E-08	6.631E-07	1.804E-07	3E-07	4.32E-06	8.510E-07
ODP(kg CFC 11-eq/km)	7.1E-11	3.43E-10	5.033E-11	7.517E-11	6.437E-14	2E-11	3.823E-12	1.160E-11
POP(kg O3-eq/km)	2.1E-03	7.65E-04	1.056E-05	1.717E-04	5.551E-05	5E-05	4.622E-05	4.450E-04
ETP(PAF m3 day/km)	8.9E-06	4.38E-04	1.125E-07	3.089E-06	1.216E-06	7E-05	1.663E-03	2.916E-06
HTP(cases/km)	4.4E-13	1.45E-13	2.765E-15	9.007E-14	2.7E-14	2E-14	5.702E-14	1.531E-13

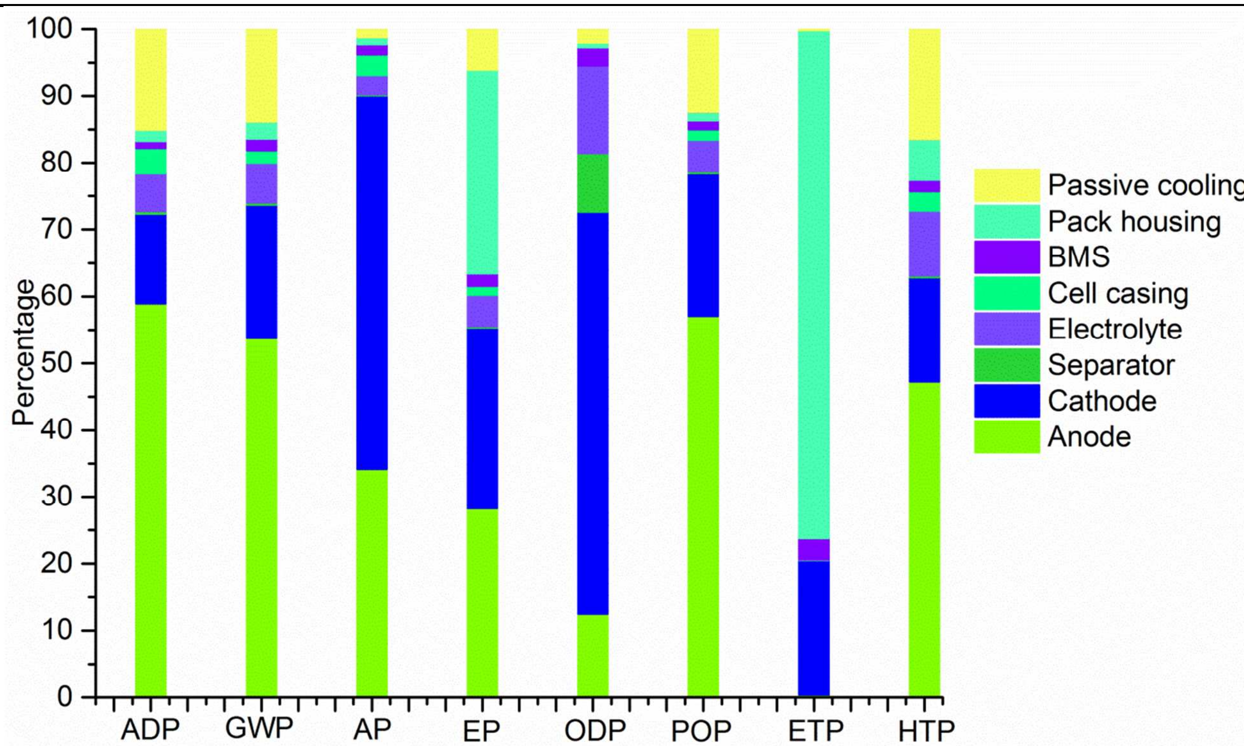

Figure S4 Cradle to gate environmental impacts of batterycomponents

Table S246 Comparison with other studies

		Battery production	Battery use	End of life
Energy (MJ/km)	NMC-SiNW	1.9632	1.4718	0.0547
	NMC-Graphite	0.4550	1.6800	0.0674
	Notter[2]	0.2078	1.7	0.061

	Zackrisson	0.386	0.5076	0.032
GWP(kg CO2-eq/km)	NMC-SiNW	0.0749	0.1051	0.0043
	NMC-Graphite	0.0287	0.12	0.0058
	Notter	0.012	0.162	0.007
	Zackrisson	0.0085	0.92	0.0065
ADP(g Sb-eq/km)	NMC-SiNW	0.5631	0.7061	0.0214
	NMC-Graphite	0.2004	0.806	0.0245
	Notter	0.097	0.45	0.23

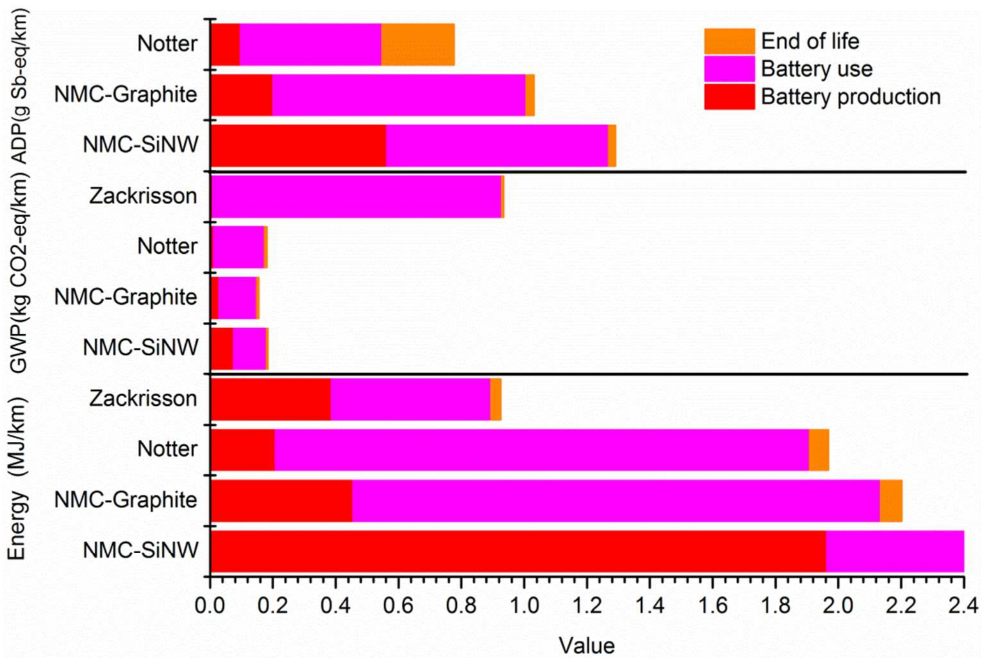

Figure S5 Comparison with other studies

Table S27 Impact saving in usage phase from the increased energy storage capacity and extended driving range

Use phase	Graphite battery	SiNW battery	Impact Savings
Total mass of battery pack (kg)	360	120	66.67%
Primary energy use in battery use phase (MJ/km)	1.68	1.47	12.50%
ADP(kg Sb-eq/km)	0.000806	0.000706	12.42%

GWP(kg CO2-eq/km)	0.12	0.1051	13.42%
AP(kg H+ Mol-eq/km)	0.0523	0.0458	12.43%
EP(kg N-eq/km)	0.0000138	0.0000121	12.32%
ODP(kg CFC 11-eq/km)	9.8E-12	8.59E-12	12.35%
POP(kg O3-eq/km)	0.00732	0.00641	12.43%
ETP(PAF m3 day/km)	0.0000466	0.0000408	12.45%
HTP(cases/km)	2.63E-12	2.3E-12	12.55%

Sensitivity Analysis

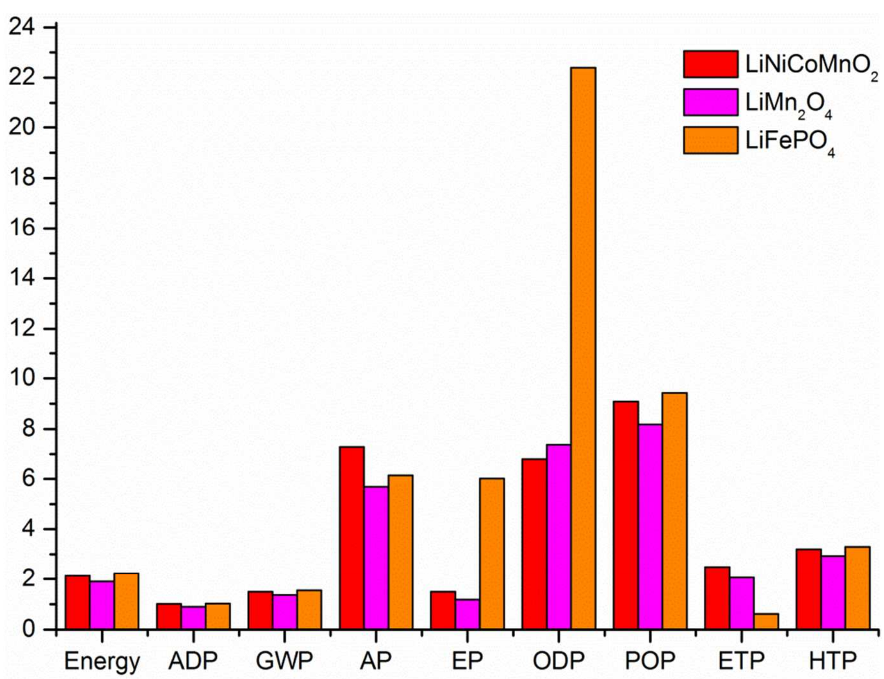

Figure S6 Sensitivity analysis of different lithium based cathodes

Table S258 Sensitivity analysis of different lithium based cathodes

	NMC	$LiMn_2O_4$	$LiFePO_4$
Energy use (MJ/km)	2.13	1.91 (-10.32%)	2.24 (5.16%)
ADP(E-03)	1.01	0.9 (-10.89%)	1.03 (1.98%)

GWP(E-01)	1.49	1.37 (-8.05%)	1.55 (4.03%)
AP(E-02)	7.28	5.69 (-21.84%)	6.14 (-15.66%)
EP(E-05)	1.49	1.18 (-20.81%)	6.01 (303.36%)
ODP(E-10)	6.81	7.37 (8.22%)	22.4 (228.93%)
POP(E-03)	9.08	8.18 (-9.91%)	9.43 (3.85%)
ETP(E-03)	2.49	2.07 (-16.87%)	0.625 (-74.89)
HTP(E-12)	3.19	2.92 (-8.46%)	3.30 (3.44%)

EV is only powered by electricity, so the variation of life time of battery has direct effects on the environmental impacts of the battery use in EV. The sensitivity analysis showed linear relationship between the environmental impact in battery use phase and life time of battery, but insignificant variation of environmental impact in the whole life cycle of battery.

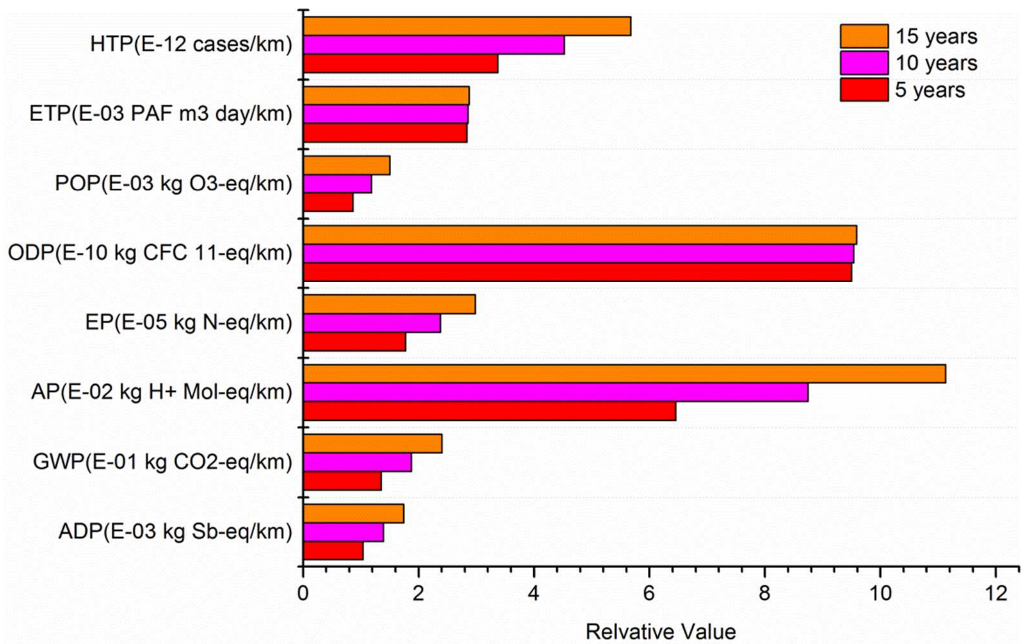

Figure S7 Sensitivity analysis of life time of battery. The relative value is the value in the unit in bracket for each environmental emission category

The variation of electricity grid mix results in considerable differences in the sensitivity analysis of real electricity mix in different states (Washington DC, Alaska, Maine, and Washington). The electricity generation mix in this study is the US average with composition of

89.56% nonrenewable sources (coal, oil and natural gas) and 10.44% renewable sources (nuclear, hydropower, biomass, wind, solar and geothermal).

Besides, the major impacts of the battery pack are from the grid electricity during its use phase. The electricity mix is different from different regions and addition of renewable energies such as solar, wind, and geothermal, could greatly reduce the impacts of the grid power supply. Here we investigated the sensitivity of the LCA results at Washington DC, Alaska, Maine, and Washington. Using eGrid data,[8] the characterized GWP and AP will increase by 104% and 462%, respectively in the Washington D.C., and will decrease by 76% and 93%, respectively, on the Washington State. The results are shown in Figure S8.

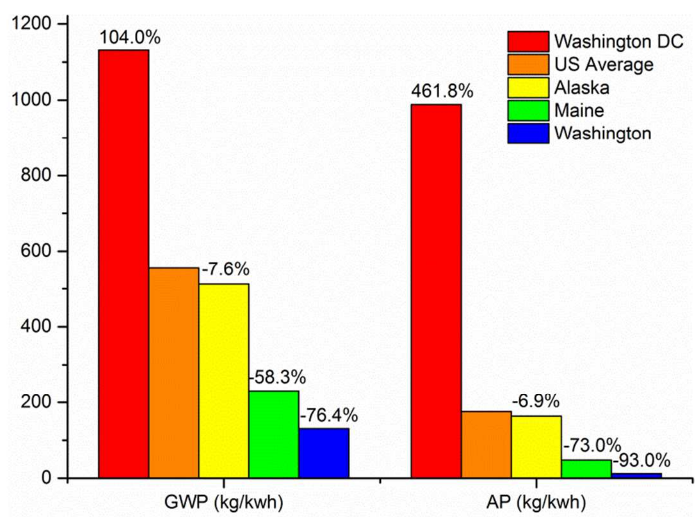

Figure S8 Sensitivity of real grid mix in selected four different US regions on GWP and AP

References

1. Margolis, N. *Energy and environmental profile of the U.S. aluminum industry*; U.S. Department of Energy: Columbia, Maryland, July, 1997; p 119.

2. Notter, D. A.; Gauch, M.; Widmer, R.; Wager, P.; Stamp, A.; Zah, R.; Althaus, H. J., Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles. *Environ. Sci. Technol.* **2010,** *44*, (17), 6550-6556.
3. Xakalashe, B. S.; Tangstad, M., Silicon processing: from quartz to crystalline silicon solar cells. In *Southern African Pyrometallurgy 2011*, Jones, R. T.; Hoed, P. d., Eds. Johannesburg, South Africa, 2011; p 35.
4. Jankovic, A., Variables affecting the fine grinding of minerals using stirred mills. *Miner Eng* **2003,** *16*, (4), 337-345.
5. Ra, D. I.; Han, K. S., Used lithium ion rechargeable battery recycling using Etoile-Rebatt technology. *J. Power. Sources.* **2006,** *163*, (1), 284-288.
6. Li, L.; Zhang, Z.; Li, B.; Gao, F.; Li, L. Q.; Jonas, J. B., E-cadherin and beta-catenin expression in sebaceous eyelid adenocarcinomas. *Graefes Arch. Clin. Exp. Ophthalmol.* **2011,** *249*, (12), 1867-1873.
7. Cheret, D.; Santen, S. Battery recycling. US7169206 B2, January 30, 2007.
8. U.S. EPA *The Emissions & Generation Resource Integrated Database (eGRID) 2012 Version 1.0*; DOE/EE-0603; The U.S. Environmental Protection Agency: Washington, D.C., May 10, 2012.