

Case study: modeling the life cycle of an automotive NCM622 battery pack with HiQLCD and ecoinvent databases

openLCA Version:	2.6.2
Document version:	1.2
Date:	October 13th 2026

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HiQLCD
High Quality-Life Cycle Database

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Calculated screening case: literature-based inventory, EF 3.1 results, foreground sensitivity and 500 Monte Carlo iterations. Not an independently verified PCF or EPD.

I Goal and Scope

Goal

This case study models a 72.5 kWh NCM622 traction battery pack manufactured in China, distributed to Europe, used in a passenger vehicle and treated at end of life in Europe. The finished battery pack has a net mass of 380.8 kg, excluding production losses and transport packaging. The model was implemented in openLCA 2.6.2.

The foreground combines cell materials and manufacturing energy from von Drachenfels et al. (2023), Table 1 [1], with pack components and assembly electricity from Sun et al. (2020), Tables S5–S6 [2]. Additional supplementary-table transcriptions are treated as adopted screening inputs, as explained in Section II and Resources. This composite scenario brings the sources onto a common pack and service basis; it does not represent one observed industrial battery design.

Model A combines selected HiQLCD and lithium-battery industry-pack providers with ecoinvent background data. Model B uses ecoinvent 3.12 background providers exclusively. Both models share the same foreground inventory. The comparison illustrates sensitivity to selected background datasets, including their technology, geography and boundaries.

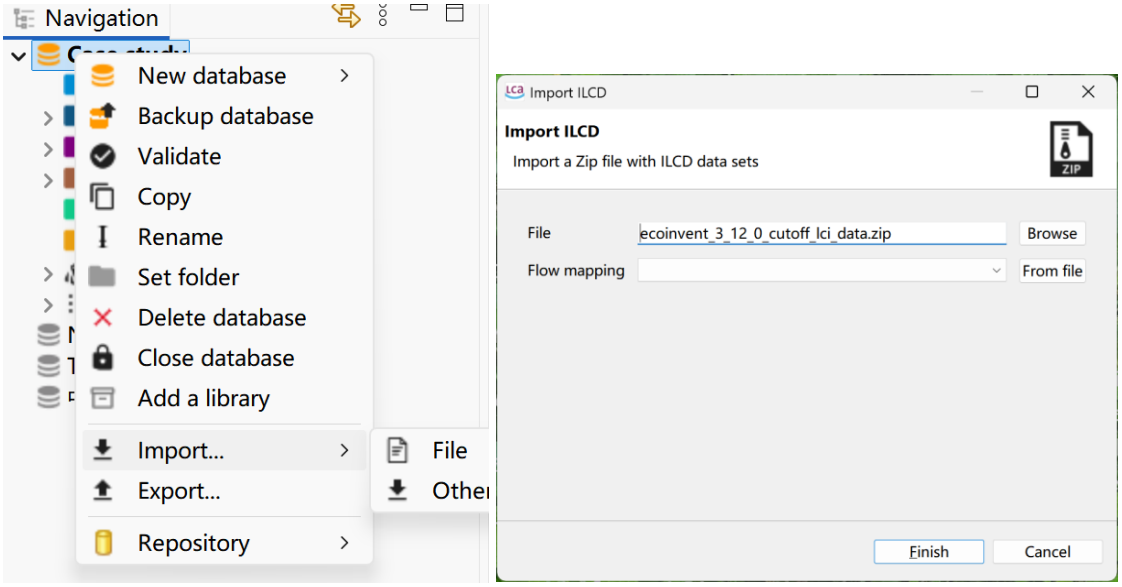


Figure 1. Database import and model setup in openLCA. Database versions are specified in the appendix.

Functional unit, reference flow and system boundaries

The functional unit (FU) is 1 kWh cumulatively delivered over automotive service life. A case-assumed 200,000 km lifetime and 7.05 km/kWh vehicle efficiency from Ihlbrock et al. [4], Table 2, give approximately 28,369 kWh lifetime service. The reference flow is 3.525×10^{-5} pack/FU, equivalent to 1.342×10^{-2} kg retained pack mass/FU. At 72.5 kWh initial capacity, this is approximately 391 kWh delivered per kWh of initial capacity. One pack serves the assumed lifetime, without replacement or an explicit capacity-fade trajectory; this allocation is not a demonstrated durability rating.

The boundary includes material supply, cell manufacturing and pack assembly, packaging and China-to-Europe distribution, use-phase electricity losses, collection, disassembly and downstream treatment. Useful traction electricity is excluded: the use stage adds only round-trip losses. Pack housing, electronics and thermal-management materials are included; the vehicle, charging infrastructure and auxiliary operating demand are outside the boundary.

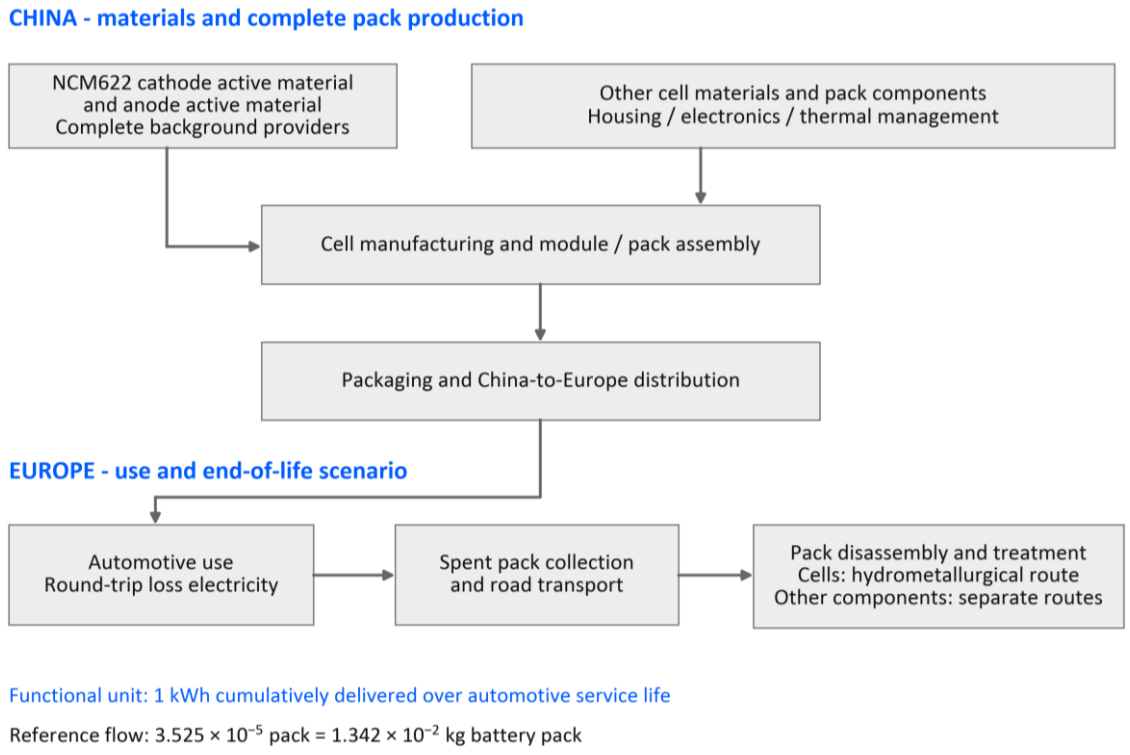


Figure 2. System boundary and foreground links. Background burdens are included once through each selected provider.

LCIA Method

Environmental impacts were calculated in openLCA 2.6.2 using the Environmental Footprint 3.1 (EF3.1) midpoint method provided in the HiQLCD method package. Results are reported for the sixteen primary EF impact categories. Official JRC EF3.1 normalization factors and EF weighting factors [9,10] were applied in post-processing for normalized and weighted interpretation. Method-selection details are documented in the appendix.

Interpretation and comparability

The comparison holds the physical foreground constant and evaluates the effect of the selected background-provider substitutions. Characterized midpoint results are the primary comparison, with climate change as the lead indicator. Results describe the two modeled configurations rather than a general ranking of database quality.

Temporal and geographical scope

The foreground combines publications from different years and assigns manufacturing to China and distribution, use and end of life to Europe. Background providers retain their own regional and technological coverage, including global and European proxies. Table 14 identifies the selected provider pairs; geographic, technology and dataset-boundary differences remain part of the comparison.

Study limitations

This literature-based screening model closes the total wet mass of the foreground inventory. Its main constraints are the composite pack architecture, unverified supplementary-table transcriptions, simplified component production and material yield, generic treatment routes and missing supplier-specific data. Aggregated backgrounds constrain interpretation to provider-level contributions. Total-mass closure does not establish elemental, chemical or constituent-specific loss balances; the sensitivity and Monte Carlo analyses do not cover all these structural uncertainties.

II Life Cycle Inventory

The inventory combines cell inputs from von Drachenfels et al. [1], Table 1; pack components from Sun et al. [2], Tables S5–S6; logistics scenarios from CATL [3], §§3.1 and 3.4–3.7; and use-stage parameters from Ihlbrock et al. [4], Table 2. Nominal cell energy, electrolyte composition and laminate constituents are screening inputs based on transcribed values attributed to [1], SI Tables S2/S18; their agreement with the original supplementary tables has not been independently verified. Tables 1–9 distinguish literature inputs, calculated conversions and case assumptions.

The foreground follows material sourcing, cell manufacturing and pack assembly, distribution, use, collection and treatment. Separate pouch-film and tab submodels supply component demands. Cathode active material and downstream cell treatment are supplied as complete background inventories, avoiding duplication of their constituent operations.

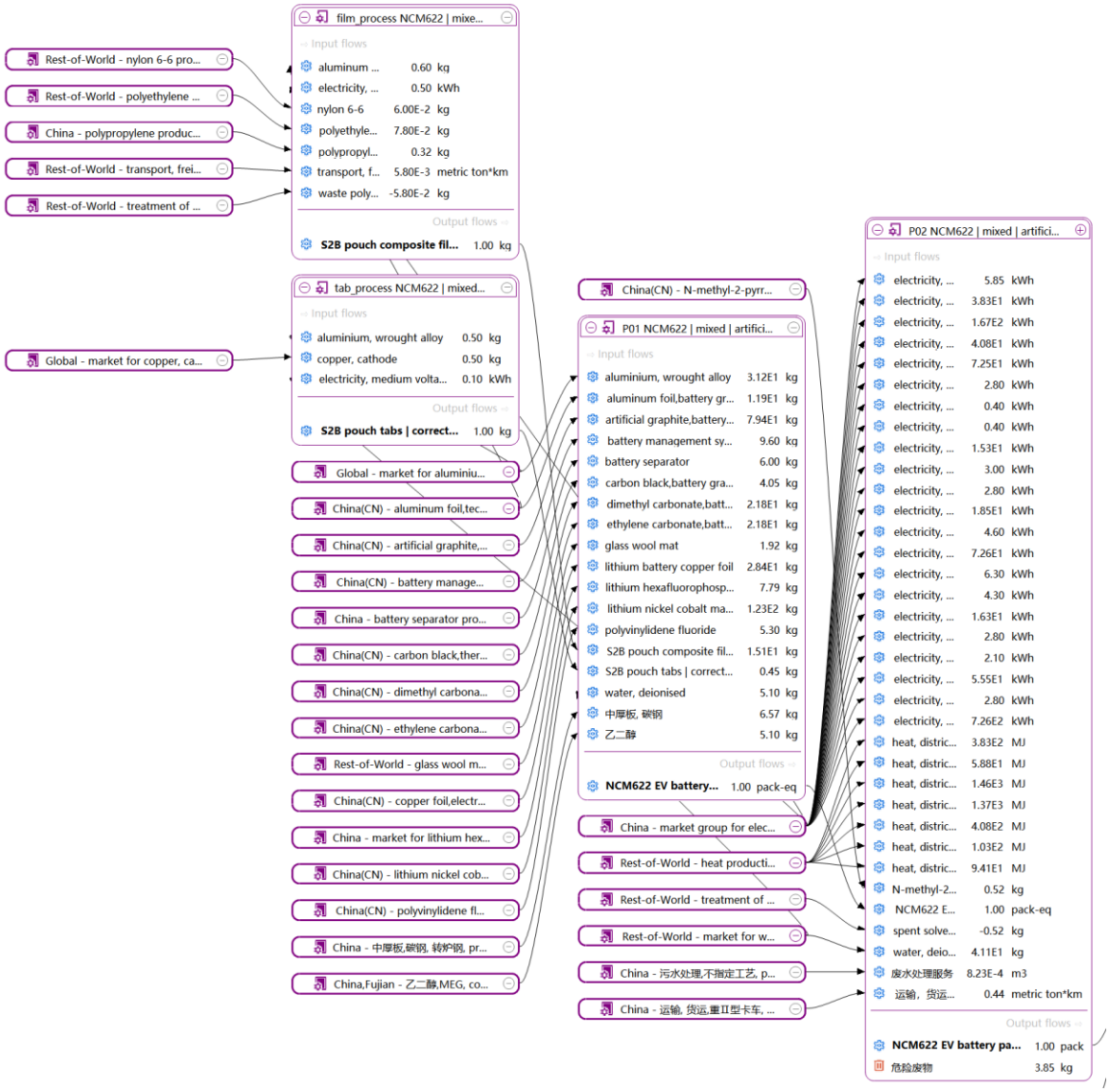


Figure 3a. openLCA model graph showing pouch-film and tab submodels, material sourcing (P01), and cell manufacturing and pack assembly (P02).

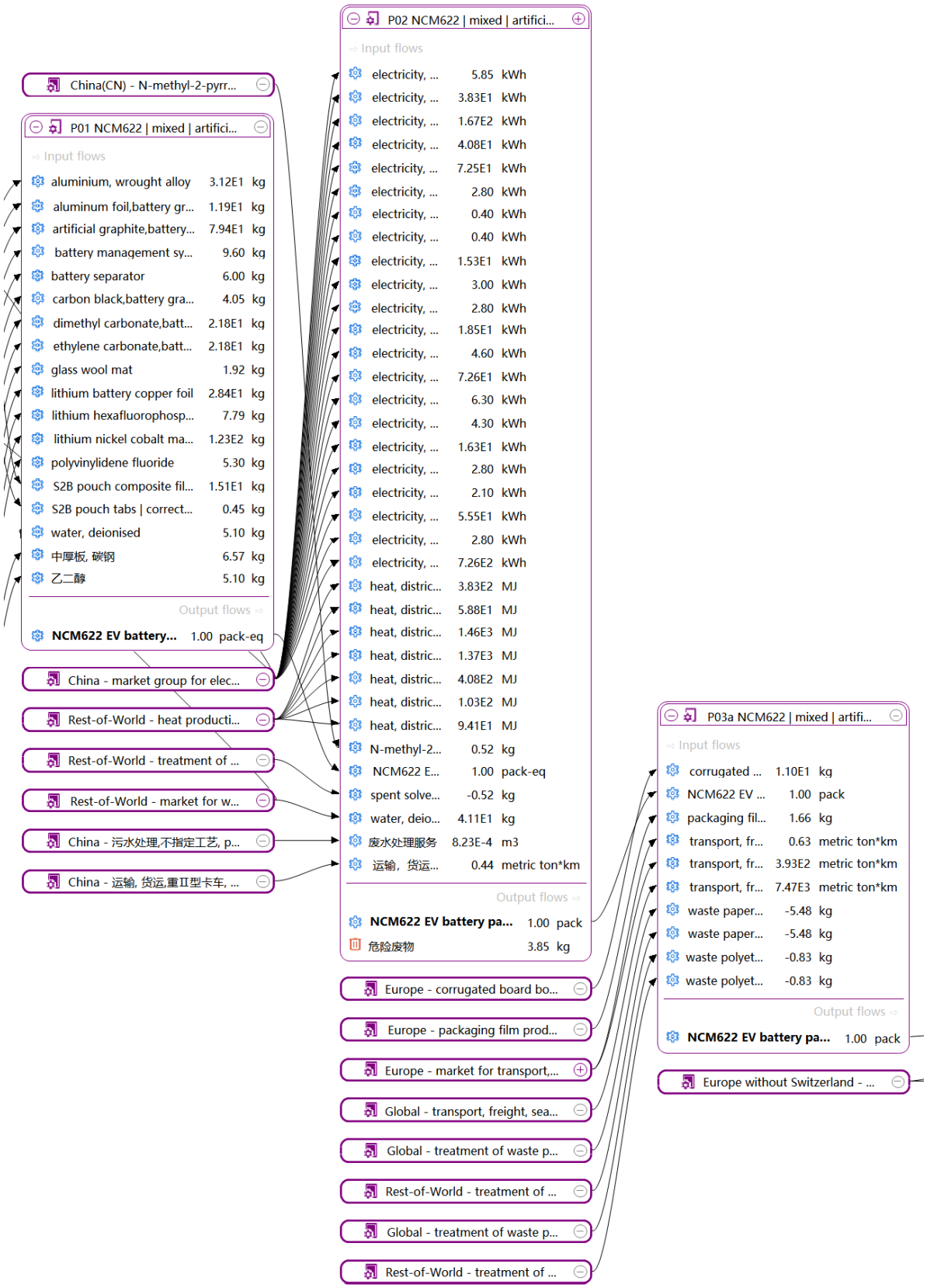


Figure 3b. openLCA model graph showing the connections from material sourcing (P01) through cell manufacturing and pack assembly (P02) to packaging and distribution (P03a).

Connecting the life-cycle stages

All stages use the lifetime-delivered-kWh basis. Pack production is allocated using 3.525×10^{-5} pack/FU; waste treatment follows the corresponding retained spent-pack mass of 1.342×10^{-2} kg/FU. Film and tab submodels use one-kilogram references before scaling into the pack inventory.

Spent mass equals pack intensity × finished pack mass. This coupling scales production, distribution and treatment together in the baseline, sensitivity analysis and Monte Carlo simulation. Figure 4a shows the model connections; Figure 4b summarizes treatment routes.

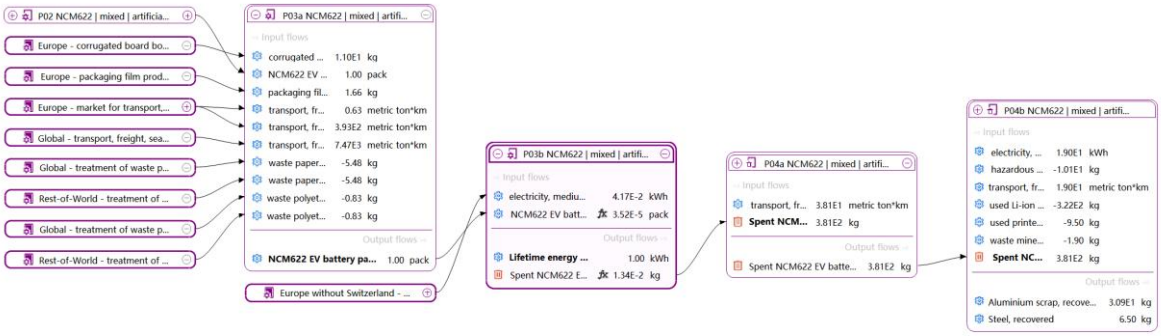


Figure 4a. Detail of the openLCA model graph showing packaging and distribution (P03a), functional-unit conversion and use (P03b), spent-pack collection (P04a), and disassembly (P04b).

Coupled service allocation and end-of-life routing

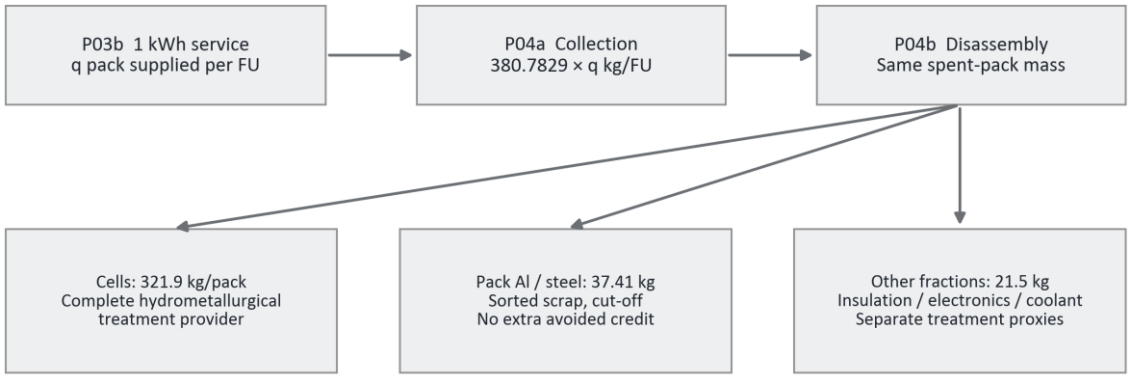


Figure 4b. Collection and treatment routes with coupled supply and spent-pack mass. Electronic parts are represented by an aggregate circuit-board treatment proxy.

Inventory tables report modeled exchanges per functional unit unless a native process reference is explicitly stated. Product, waste and elementary flows retain their distinct roles; the appendix gives implementation details.

1 Raw material acquisition

1.a NCM622 battery pack material sourcing

The finished pack comprises 321.9 kg of cell materials and 58.9 kg of pack components, giving a calculated specific energy of 190.4 Wh/kg. Cell inputs follow [1]; the nominal 146.5 Wh/cell conversion is an adopted SI transcription. Pack-level aluminium is derived from [2], Table S5: 145.1 × 4.9/23 = 30.91 kg. The original cell-material portion of Sun et al.'s pack is replaced, not added a second time.

A common 99% utilization assumption gives 384.6 kg gross material purchases and 3.846 kg production loss per pack. Steel comprises 6.3 kg from [2], Table S5, plus a 0.2 kg case allowance. The source's 10.1 kg coolant entry is represented by an assumed 50:50 glycol/water mixture. Electronic Parts is a 9.5 kg net aggregate, equivalent to 9.596 kg purchased, and uses a BMS functional proxy because the source does not provide a verified component split.

Table 1. Gross materials for one complete battery pack, grouped by cell and pack hierarchy; functional-unit demands are shown alongside pack quantities.

Material / function	Gross kg/pack	Modeled flow	kg per FU	Model A provider	Hierarchy / note
NCM622 cathode active material	123.1	NCM622 cathode active material	4.340×10^{-3}	NCM622 cathode material	Cell material
Synthetic graphite	79.43	Synthetic graphite	2.800×10^{-3}	Synthetic graphite — graphitization mix	Cell: anode; assumed type
PVDF	5.299	PVDF	1.868×10^{-4}	PVDF	Cell material
conductive carbon black	4.049	conductive carbon black	1.427×10^{-4}	Carbon black	Cell material
Copper collector foil	28.39	Copper collector foil	1.001×10^{-3}	Electrolytic copper foil	Cell material
Aluminium collector foil	11.9	Aluminium collector foil	4.194×10^{-4}	Battery-grade aluminium foil	Cell material
PP+PE separator combined once	5.999	PP+PE separator combined once	2.114×10^{-4}	Battery separator	Cell material
pouch tabs from P06b	0.4499	pouch tabs from P06b	1.586×10^{-5}	Internal: P06b (pouch tabs)	Cell: packaging
Pouch aluminium-plastic film	15.15	Pouch aluminium-plastic film	5.339×10^{-4}	Internal: P06a (pouch film)	Cell: packaging
$LiPF_6$	7.793	$LiPF_6$	2.747×10^{-4}	$LiPF_6$ supply	Cell: electrolyte
ethylene carbonate	21.77	ethylene carbonate	7.675×10^{-4}	Ethylene carbonate	Cell: electrolyte
dimethyl carbonate	21.77	dimethyl carbonate	7.675×10^{-4}	Dimethyl carbonate	Cell: electrolyte
pack-level aluminium	31.22	pack-level aluminium	1.101×10^{-3}	Wrought aluminium alloy	Pack component

Material / function	Gross kg/pack	Modeled flow	kg per FU	Model A provider	Hierarchy / note
pack-level steel	6.566	pack-level steel	2.314×10^{-4}	Carbon steel plate	Pack component
insulation layer	1.919	insulation layer	6.765×10^{-5}	Glass wool insulation	Pack component
ethylene glycol	5.101	ethylene glycol	1.798×10^{-4}	Ethylene glycol	Pack component
cooling water	5.101	cooling water	1.798×10^{-4}	Deionised water	Pack component
Electronic parts (aggregate)	9.596	Electronic parts (aggregate)	3.383×10^{-4}	BMS functional proxy	Pack: BMS proxy; unsplit

Sources: [1], Table 1, for cell inputs; [2], Table S5, for pack components. Utilization, synthetic-graphite specification, coolant composition and steel allowance are case assumptions. The hierarchy column places $LiPF_6$, EC and DMC within the cell electrolyte. No complete cell-production provider is added to these constituent inputs.

The cell level comprises electrodes, collectors, separator, electrolyte and pouch packaging. The pack level comprises structure, insulation, coolant and aggregate electronics. Cell aluminium collector foil uses dedicated battery-grade foil in Model A and Li-ion collector foil in Model B. Copper collector foil has its own dedicated provider. The complete NCM622 cathode provider is used once, without an additional precursor-production foreground.

1.b Pouch film and tab component submodels

Pouch aluminium-plastic film uses the same explicit laminate submodel in both configurations. Per kilogram of film, assumed inputs are 0.600 kg aluminium foil, 0.078 kg PET, 0.060 kg nylon and 0.320 kg PP. Their 1.058 kg sum includes 0.058 kg routed to a polyethylene/polypropylene waste-treatment proxy. Total mass is balanced, but the surplus composition and constituent-specific losses are not verified. Purchased demand is 15.15 kg/pack and processing electricity is 0.5 kWh/kg film. Adhesives, surface treatment, drying and lamination are not individually resolved by this simplified submodel.

Table 2. Pouch-film constituent submodel per functional unit.

Input			
Flow	**Amount**	**Unit**	**Provider / route**
aluminium foil for composite film	3.203×10^{-4}	kg	Dedicated battery-grade Al foil
PET for composite film	4.164×10^{-5}	kg	PET production
nylon 6-6 for composite film	3.203×10^{-5}	kg	nylon 6-6 production
polypropylene for composite film	1.709×10^{-4}	kg	polypropylene production, granulate
composite-film processing electricity	2.670×10^{-4}	kWh	Medium-voltage electricity
composite-film scrap treatment	3.097×10^{-5}	kg	Film scrap treatment
film scrap transport	3.097×10^{-6}	t·km	Truck freight, RoW
Output			
Flow	**Amount**	**Unit**	**Provider / route**
Pouch composite film [QR]	5.339×10^{-4}	kg	Reference flow

Source: [1], Table 1, for pouch-film demand. Constituent quantities are screening assumptions based on transcribed values attributed to SI Table S18, not an independently verified laminate specification. Both models use the same decomposed film inventory. The available complete HiQLCD aluminium-plastic-film dataset is therefore excluded to avoid double counting.

Tab component production

Purchased pouch-tab demand is 0.4499 kg/pack, derived from 0.9 g/cell in [1], Table 1, and the utilization assumption. Copper feedstock for pouch tabs means the copper-cathode input to the tab submodel. It is distinct from copper collector foil. Both configurations use the same copper-cathode provider; the assumed 50:50 copper/aluminium split and 0.1 kWh/kg processing do not resolve rolling, plating, welding or finished-tab geometry.

Table 3. Tab constituent submodel per functional unit.

Input			
Flow	**Amount**	**Unit**	**Provider / route**
Copper feedstock for pouch tabs	7.929×10^{-6}	kg	Copper cathode feedstock
aluminium for tabs	7.929×10^{-6}	kg	Wrought aluminium
tab processing electricity	1.586×10^{-6}	kWh	Medium-voltage electricity
Output			
Flow	**Amount**	**Unit**	**Provider / route**
Pouch tabs [QR]	1.586×10^{-5}	kg	Reference flow

Source: von Drachenfels et al. [1], Table 1, reports 0.9 g tabs/cell. The 50:50 copper/aluminium split and 0.1 kWh/kg processing electricity are case assumptions. Scaling gives 0.4499 kg purchased tabs/pack and 3.525×10^{-5} pack/FU.

2 Battery pack production

2.a Cell manufacturing and pack assembly

Cell manufacturing energy is adapted from von Drachenfels et al. [1], Table 1. Module/pack assembly follows Sun et al. [2], Table S6: 3.6 MJ/kWh capacity, equivalent to 72.5 kWh/pack. Combined electricity is approximately 1,262 kWh/pack, with cell-energy scaling based on 99% material utilization.

Modeled delivered heat is approximately 3,868 MJ/pack, including 102.6 MJ for assumed NMP recovery. Literature gas demand is converted to delivered heat at an assumed 90% efficiency. A Rest-of-World industrial natural-gas furnace represents manufacturing heat. Cell production and pack assembly data originate from different sources rather than a single factory. Potential overlap between these inventories, including the coverage of solvent recovery in the reported process heat, is a source of uncertainty.

Von Drachenfels et al. [1], Table 1, reports 103.7 g NMP/cell. Scaled circulation is 51.84 kg/pack; assumed 99% recovery requires 0.5184 kg fresh make-up and produces an equal mass of spent solvent. Recovered solvent is recirculated without an additional purchase. Baseline recovery heat is 2 MJ/kg recovered NMP and follows a triangular distribution in the Monte Carlo simulation. Initial charging and formation are included in cell-manufacturing energy without a separate charging input.

Process water follows 82.3 g/cell in von Drachenfels et al. [1], Table 1, or 41.14 kg/pack. The assumed split is 98% evaporation and 2% wastewater. The common material yield produces 3.85 kg loss per pack; net component mass, rather than purchased input mass, is used for subsequent pack transport and end-of-life treatment. These solvent, water and waste-routing assumptions are held fixed in the uncertainty analysis.

Table 4. NCM622 battery pack manufacturing per functional unit.

Input			
Flow	**Amount**	**Unit**	**Provider / route**
material set from P01	3.525×10^{-5}	pack-eq	P01 battery-pack material acquisition
Anode mixing electricity	2.220×10^{-4}	kWh	Medium-voltage electricity
Anode coating/drying electricity	1.440×10^{-3}	kWh	Medium-voltage electricity
Anode coating/drying heat	0.05129	MJ	Natural-gas industrial heat, RoW
Anode calendering electricity	5.762×10^{-4}	kWh	Medium-voltage electricity
Anode slitting electricity	1.621×10^{-4}	kWh	Medium-voltage electricity
Anode vacuum drying electricity	1.057×10^{-4}	kWh	Medium-voltage electricity
Anode vacuum drying heat	0.01439	MJ	Natural-gas industrial heat, RoW
Anode cutting electricity	1.410×10^{-5}	kWh	Medium-voltage electricity

Input			
Flow	**Amount**	**Unit**	**Provider / route**
Cathode mixing electricity	2.062×10^{-4}	kWh	Medium-voltage electricity
Cathode coating/drying electricity	1.352×10^{-3}	kWh	Medium-voltage electricity
Cathode coating/drying heat	0.04815	MJ	Natural-gas industrial heat, RoW
Cathode calendering electricity	5.410×10^{-4}	kWh	Medium-voltage electricity
Cathode slitting electricity	1.515×10^{-4}	kWh	Medium-voltage electricity
Cathode vacuum drying electricity	9.868×10^{-5}	kWh	Medium-voltage electricity
Cathode vacuum drying heat	0.01351	MJ	Natural-gas industrial heat, RoW
Cathode cutting electricity	1.410×10^{-5}	kWh	Medium-voltage electricity
Stacking electricity	6.520×10^{-4}	kWh	Medium-voltage electricity
Tab welding electricity	9.868×10^{-5}	kWh	Medium-voltage electricity
Cell assembly electricity	9.868×10^{-5}	kWh	Medium-voltage electricity
Pouch packaging electricity	9.868×10^{-5}	kWh	Medium-voltage electricity
Electrolyte filling electricity	1.958×10^{-3}	kWh	Medium-voltage electricity
Sealing electricity	7.401×10^{-5}	kWh	Medium-voltage electricity
Formation electricity	0.02561	kWh	Medium-voltage electricity
Formation heat	2.072×10^{-3}	MJ	Natural-gas industrial heat, RoW
Ageing heat	3.317×10^{-3}	MJ	Natural-gas industrial heat, RoW
Testing electricity	2.560×10^{-3}	kWh	Medium-voltage electricity
Dry room electricity	5.894×10^{-3}	kWh	Medium-voltage electricity
Module/pack assembly electricity	2.556×10^{-3}	kWh	Medium-voltage electricity
NMP recovery heat	3.618×10^{-3}	MJ	Natural-gas industrial heat, RoW
process water	1.450×10^{-3}	kg	market for water, deionised
fresh NMP make-up	1.827×10^{-5}	kg	NMP
spent NMP treatment	1.827×10^{-5}	kg	Spent-solvent incineration, RoW
industrial wastewater service	2.900×10^{-8}	m^3	Wastewater treatment
production waste transport	1.539×10^{-5}	t·km	Freight transport
Output			
Flow	**Amount**	**Unit**	**Provider / route**
1 pack at plant [QR]	3.525×10^{-5}	pack	Reference flow
water evaporated to air	1.421×10^{-6}	m^3	Elementary: air
production material loss treatment	1.356×10^{-4}	kg	Hazardous waste treatment

Sources: von Drachenfels et al. [1], Table 1 (process electricity, gas, NMP and water); Sun et al. [2], Table S6 (pack assembly). Material yield, 90% gas-to-heat efficiency, solvent recovery and waste routing are case assumptions. Values are calculated per functional unit.

3 Distribution and use

3.a Battery pack packaging and distribution

Packaging is adapted from CATL's LFP-cell EPD [3], §§3.1 and 3.5: 0.172 kg paper/wood and 0.026 kg plastics per 5.978 kg reference product. Scaling to the finished pack gives 10.96 kg paper/cardboard and 1.656 kg LDPE. Mapping paper/wood to cardboard and plastics to LDPE is a case assumption.

The transported gross mass is 393.4 kg, including packaging, while the finished pack mass remains 380.8 kg. CATL [3], §3.4, supplies the transferred distribution scenario of 19,000 km by sea and 1,000 km by road. These correspond to approximately 7,475 and 393.4 t·km/pack, respectively, before functional-unit allocation. The generic packaging and route assumptions do not resolve supplier-specific logistics, warehousing or temperature-control requirements.

Table 5. Packaging and distribution inputs per functional unit (part 1 of 2).

Input			
Flow	**Amount**	**Unit**	**Provider / route**
pack at plant from P02	3.525×10^{-5}	pack	P02 battery-pack production
paperboard packaging	3.862×10^{-4}	kg	corrugated board box production
LDPE packaging	5.838×10^{-5}	kg	packaging film production, low density polyethylene
China-to-Europe sea freight	0.2635	t·km	transport, freight, sea, container ship, heavy fuel oil
EU road delivery	0.01387	t·km	market for transport, freight, lorry, unspecified

Source: CATL [3], §3.4, pp.9–10 (19,000 km sea and 1,000 km road); §§3.1/3.5, pp.7/10 (product and packaging masses).

Transport is calculated as gross mass in tonnes × distance. These generic EPD scenarios are transferred to this case.

Packaging disposal and delivered pack

At delivery, packaging enters the 50% energy-recovery / 50% landfill scenario with 50 km transport adopted from CATL [3], §3.5, p.10. Selected treatment burdens are included once, without an additional foreground avoided-production credit. Packaging remains within this study's boundary, although the cited EU draft [11] excludes it.

Table 5. Packaging disposal demands and delivered-pack output per functional unit (part 2 of 2).

Input			
Flow	**Amount**	**Unit**	**Provider / route**
Paperboard incineration	1.931×10^{-4}	kg	treatment of waste paperboard, municipal incineration
paperboard landfill	1.931×10^{-4}	kg	treatment of waste paperboard, sanitary landfill
LDPE incineration	2.919×10^{-5}	kg	treatment of waste polyethylene, municipal incineration
LDPE landfill	2.919×10^{-5}	kg	treatment of waste polyethylene, sanitary landfill
packaging waste transport	2.223×10^{-5}	t·km	market for transport, freight, lorry, unspecified
Output			
Flow	**Amount**	**Unit**	**Provider / route**
1 pack delivered to EU [QR]	3.525×10^{-5}	pack	Reference flow

Source: CATL [3], §3.5, p.10, for packaging disposal fractions and distance; calculated with the adopted packaging masses. Selected treatment burdens are included once, without an additional foreground avoided-production credit.

3.b Battery pack use

The 72.5 kWh capacity follows Sun et al. [2], Table S5. Ihlbrock et al. [4], Table 2, provides 7.05 km/kWh and 96% round-trip efficiency (RTE) for the large-BEV NMC622/graphite scenario. Footnote a derives RTE from NMC811 measurements extrapolated to 0.2C; transferring this constant cell-level proxy to the present pack, together with the assumed 200,000 km lifetime without replacement or explicit degradation, is the principal use-stage limitation.

The resulting lifetime service is approximately 28,369 kWh. Allocation requires 3.525×10^{-5} pack/FU, equivalent to 0.002556 kWh of initial pack capacity/FU. Only round-trip losses are charged to use: 1/0.96 − 1 = 0.04167 kWh/FU. Useful traction electricity, charging-station and inverter equipment, vehicle production and auxiliary operation are excluded; European electricity is identical in both models.

Table 6. Automotive battery pack use per 1 kWh lifetime-delivered electricity.

Input			
Flow	**Amount**	**Unit**	**Provider / route**
charge/discharge loss electricity per FU	0.04167	kWh	Medium-voltage electricity
delivered pack per FU	3.525×10^{-5}	pack	P03a finished-pack distribution
Output			
Flow	**Amount**	**Unit**	**Provider / route**
1 kWh lifetime delivered electricity [QR]	1	kWh	Reference flow
spent pack per delivered kWh	1.342×10^{-2}	kg	P04a spent-pack collection

Sources: Ihlbrock et al. [4], Table 2 and footnote a (vehicle efficiency and RTE); Sun et al. [2], Table S5 (capacity). The 200,000 km lifetime is a case assumption; service allocation and use losses are calculated from these inputs.

Baseline spent-pack demand is 1.342×10^{-2} kg/FU. Supplied packs and spent-pack mass use the same pack-intensity parameter. Loss electricity is a separate per-delivered-kWh input. Varying service allocation changes production, distribution and treatment together; loss electricity changes only when its own input is varied.

4 End-of-life

4.a Spent battery pack collection and transport

The baseline collects 1.342×10^{-2} kg spent pack/FU. A 100 km road route is transferred from CATL [3], §3.7, p.11, giving 38.08 tkm/pack or 0.001342 tkm/FU. Full collection is a case assumption. Disassembly electricity is separately modeled at 0.05 kWh/kg pack, or 19.04 kWh/pack; route, collection rate and disassembly energy are not site-specific observations.

Table 7. Spent battery pack collection and transport per functional unit.

Input			
Flow	**Amount**	**Unit**	**Provider / route**
Spent battery pack, at collection [QR]	1.342×10^{-2}	kg	Reference flow
spent-pack collection transport	1.342×10^{-3}	t·km	transport, freight, lorry, 3.5-7.5 metric ton, diesel,…
Output			
Flow	**Amount**	**Unit**	**Provider / route**
pack at recycler from P04b	1.342×10^{-2}	kg	P04b spent-pack disassembly and downstream treatment

Source: CATL [3], §3.7, p.11 (100 km collection distance), applied to calculated pack mass. Full collection is a case assumption. [QR] denotes the treatment process's input waste reference, following openLCA's convention [8].

4.b Disassembly and hydrometallurgical treatment

After disassembly, 321.9 kg cells/pack enter the complete global hydrometallurgical treatment inventory [7], without additional foreground recycling reagents or recovered-cell products. Structure, insulation, electronics and coolant follow separate routes. The entire 9.5 kg electronics fraction is assigned to waste-circuit-board treatment as an aggregate proxy; separate BMS, metal and plastic treatment fractions are not established by the source inventory.

The generic treatment provider does not resolve NCM622-specific recovery performance or European facility conditions. The inventory closes total retained wet mass, not elemental balances, fluorine fate or detailed treatment chemistry. Supplier-specific recovery data and emissions would be needed to refine these aspects.

Table 8. Disassembly reference input and energy per functional unit.

Input			
Flow	**Amount**	**Unit**	**Provider / route**
Spent battery pack, at recycler [QR]	1.342×10^{-2}	kg	Reference flow
safety discharge and disassembly electricity	6.711×10^{-4}	kWh	Medium-voltage electricity

Source: case-assumed disassembly electricity of 0.05 kWh/kg pack and the calculated pack mass. This is not a literature-measured dismantling inventory. Complete background cell treatment and the other downstream routes are listed in Table 9.

Recycling products, waste and emissions

The downstream partition comprises approximately 321.9 kg cells, 30.91 kg aluminium, 6.5 kg steel, 1.9 kg insulation, 9.5 kg electronics and 10.1 kg coolant per pack. Table 9 records the routed exchanges at the modeled precision. The steel total includes the 0.2 kg case allowance in addition to Sun et al.'s 6.3 kg [2].

Table 9. Downstream treatment demands and cut-off outputs per functional unit.

Input			
Flow	**Amount**	**Unit**	**Provider / route**
cell fraction to complete hydrometallurgical treatment	0.01135	kg	Cell hydrometallurgical treatment
insulation waste treatment	6.698×10^{-5}	kg	treatment of waste mineral wool, inert material landfill
Aggregate electronics treatment	3.349×10^{-4}	kg	Scrap circuit-board treatment proxy
spent coolant treatment	3.560×10^{-4}	kg	treatment of hazardous waste, hazardous waste…
disassembly output transport	6.711×10^{-4}	t·km	market for transport, freight, lorry, unspecified
Output			
Flow	**Amount**	**Unit**	**Provider / route**
sorted pack-level aluminium scrap; cut-off, no avoided credit	1.090×10^{-3}	kg	Reference / cut-off
sorted pack-level steel scrap; cut-off, no avoided credit	2.291×10^{-4}	kg	Reference / cut-off

Sources: finished cell mass calculated from von Drachenfels et al. [1], Table 1; pack fractions adapted from Sun et al. [2], Table S5. Treatment-provider selection and cut-off routing are case choices [7]. Values are net component masses, not gross purchases.

Under the adopted cut-off setting, foreground metal-scrap outputs do not receive an additional avoided-primary-material credit. Other selected treatment inventories retain their modeled burdens and outputs. No additional foreground assumptions are introduced for recovered products, sludge quantities or recovery yields.

III Life cycle impact assessment

EF 3.1 results are reported for the sixteen primary midpoint categories (Table 10), followed by normalized and weighted interpretation, uncertainty, sensitivity and provider-level hotspots. All results use the lifetime-delivered-kWh functional unit. Climate change is the lead indicator; mineral-resource and water-use results provide complementary views of material supply chains.

Table 10. Main EF 3.1 impact categories and reporting units.

Impact category	**Unit**
Climate change	kg CO_2-eq
Ozone depletion	kg CFC-11-Eq
Particulate matter	disease incidence
Ionising radiation	kBq U235-Eq
Photochemical ozone formation	kg NMVOC-Eq
Acidification	mol H+-Eq
Terrestrial eutrophication	mol N-Eq
Freshwater eutrophication	kg P-Eq
Marine eutrophication	kg N-Eq
Freshwater ecotoxicity	CTUe
Human toxicity, cancer	CTUh
Human toxicity, non-cancer	CTUh
Land use	dimensionless
Water use	m^3 world eq. deprived
Resource use, fossils	MJ, net calorific value
Resource use, minerals and metals	kg Sb-Eq

Normalized and weighted analysis

The sixteen primary EF categories are normalized with JRC EF 3.1 global-2010 per-capita factors and weighted using the EF factors [9,10]. Normalized = characterized result / normalization factor; weighted = normalized × weight fraction. Weighted contribution is each category's share of the primary-category sum. Nine diagnostic subcategories are excluded from that sum. All factors are fixed across both models and every Monte Carlo draw.

Model A has an auxiliary weighted total of 0.0811 mPt/FU. Its leading shares are resource use, minerals and metals 39.5%; human toxicity, cancer 23.3%; climate change 10.3%; resource use, fossils 6.8%. Weighting expresses the adopted EF preference scheme and is interpreted alongside, rather than in place of, characterized midpoint results.

Table 11. Model A characterization, Monte Carlo standard deviation, normalization, weighting and contribution.

Impact category	Result	Std. dev.	Normalized	Weighted	Contribution
Climate change	0.3001	0.0512	3.973×10^{-5}	8.367×10^{-6}	10.32%
Ozone depletion	4.025×10^{-9}	6.801×10^{-10}	7.689×10^{-8}	4.852×10^{-9}	0.01%
Particulate matter	1.868×10^{-8}	3.297×10^{-9}	3.137×10^{-5}	2.811×10^{-6}	3.47%
Ionising radiation	0.03605	5.454×10^{-3}	8.541×10^{-6}	4.279×10^{-7}	0.53%
Photochemical ozone formation	1.059×10^{-3}	1.837×10^{-4}	2.593×10^{-5}	1.239×10^{-6}	1.53%
Acidification	2.166×10^{-3}	3.748×10^{-4}	3.898×10^{-5}	2.417×10^{-6}	2.98%
Terrestrial eutrophication	3.368×10^{-3}	5.840×10^{-4}	1.905×10^{-5}	7.069×10^{-7}	0.87%
Freshwater eutrophication	1.313×10^{-4}	2.131×10^{-5}	8.171×10^{-5}	2.288×10^{-6}	2.82%
Marine eutrophication	3.227×10^{-4}	5.557×10^{-5}	1.651×10^{-5}	4.887×10^{-7}	0.60%
Freshwater ecotoxicity	3.178	0.5605	5.603×10^{-5}	1.076×10^{-6}	1.33%
Human toxicity, cancer	1.528×10^{-8}	2.720×10^{-9}	8.854×10^{-4}	1.886×10^{-5}	23.26%
Human toxicity, non-cancer	6.119×10^{-9}	1.072×10^{-9}	4.753×10^{-5}	8.746×10^{-7}	1.08%
Land use	1.316	0.2272	1.606×10^{-6}	1.275×10^{-7}	0.16%
Water use	0.5161	0.0906	4.500×10^{-5}	3.829×10^{-6}	4.72%
Resource use, fossils	4.294	0.7171	6.606×10^{-5}	5.496×10^{-6}	6.78%
Resource use, minerals and metals	2.702×10^{-5}	4.807×10^{-6}	4.247×10^{-4}	3.206×10^{-5}	39.55%

Result and Std. dev. use the units in Table 10. Std. dev. is the population standard deviation of 500 scenario draws. Normalized is person-equivalent/FU; Weighted is Pt/FU, with 1 mPt = 0.001 Pt; Contribution is the share of the deterministic weighted total.

Monte Carlo analysis

The openLCA Monte Carlo simulation comprises 500 draws from seven foreground exchange distributions and one shared pack-intensity parameter (Table 12). This parameter jointly scales supplied packs and spent-pack mass. The 58 distinct background processes across the two systems are aggregated LCI_RESULT inventories without encoded exchange or parameter uncertainty. Background inventories and characterization factors are fixed throughout the simulation. No additional input correlations are specified.

Model A climate change has a mean of 0.3219, median of 0.3152 and population standard deviation of 0.0512 kg CO_2-eq/FU. The P2.5–P97.5 interval is 0.2361–0.4220 kg CO_2-eq/FU, against a deterministic baseline of 0.3001. This conditional scenario distribution does not estimate the confidence interval of a measured product. The triangular modes are baseline inputs; their means need not equal those modes.

Applying the fixed factors to each of the 500 category vectors gives a weighted mean of 0.0867 mPt/FU, median 0.0847, standard deviation 0.0142 and P2.5–P97.5 of 0.0630–0.1139. Yield, electronics composition, graphite-route representativeness, laminate recipe and treatment-route choice are not sampled. Only Model A is simulated; the A/B difference is not tested for statistical significance.

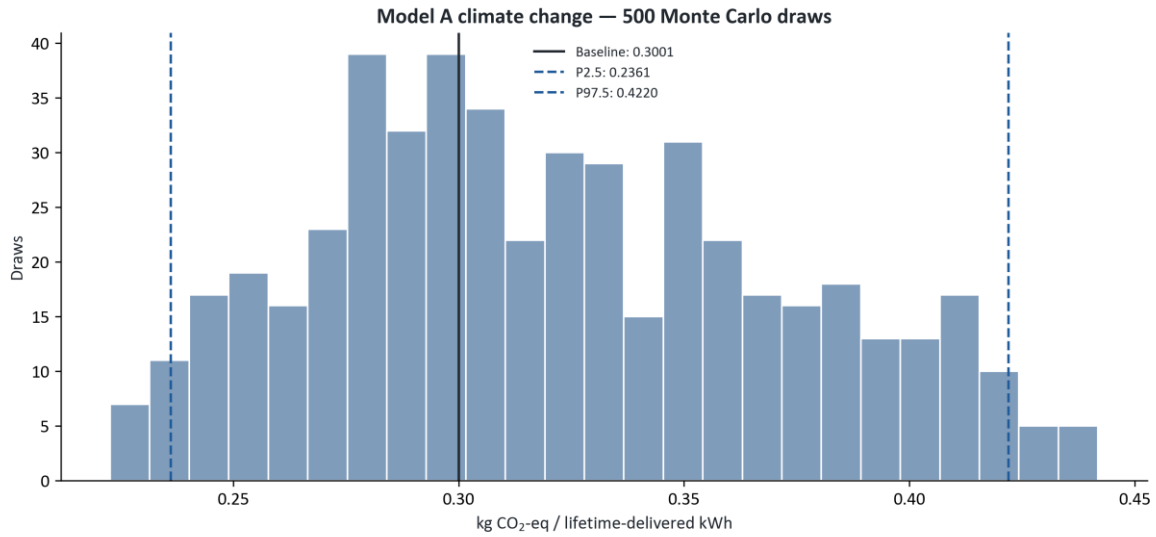


Figure 5. Model A climate distribution from 500 native Monte Carlo draws, with coupled pack supply and spent-pack mass and fixed background inventories.

Sensitivity analysis

Eight inputs are varied one at a time between their stated minimum and maximum, producing sixteen endpoint calculations. The pack-intensity endpoint changes supply and spent-pack mass together. Other tested inputs are assembly electricity, NMP recovery heat, use-loss electricity, sea and road distribution, collection transport work and disassembly electricity. Inputs not being tested remain at their baseline values.

Table 12. Adopted triangular minimum, mode and maximum in each input's native process reference.

Parameter	Minimum	Mode	Maximum	Unit
Pack intensity (supply + end-of-life)	2.400×10^{-5}	3.525×10^{-5}	5.333×10^{-5}	pack/FU
Use-stage loss electricity	0.02041	0.04167	0.07527	kWh/FU
Pack assembly electricity	36.25	72.5	145	kWh/pack
European road transport work	196.7	393.4	590.1	t·km/pack
Collection transport work	19.04	38.08	76.16	t·km/pack
Sea freight transport work	5901	7475	8655	t·km/pack
Disassembly electricity	3.808	19.04	38.08	kWh/pack
NMP recovery heat	51.32	102.6	205.3	MJ/pack

Transport inputs in Table 12 are transport work in t·km per pack, not distance in km. Pack-intensity values are pack/FU; use losses are kWh/FU; manufacturing, freight and dismantling quantities use the native one-pack process reference. The ranges are screening assumptions, not fitted statistical distributions.

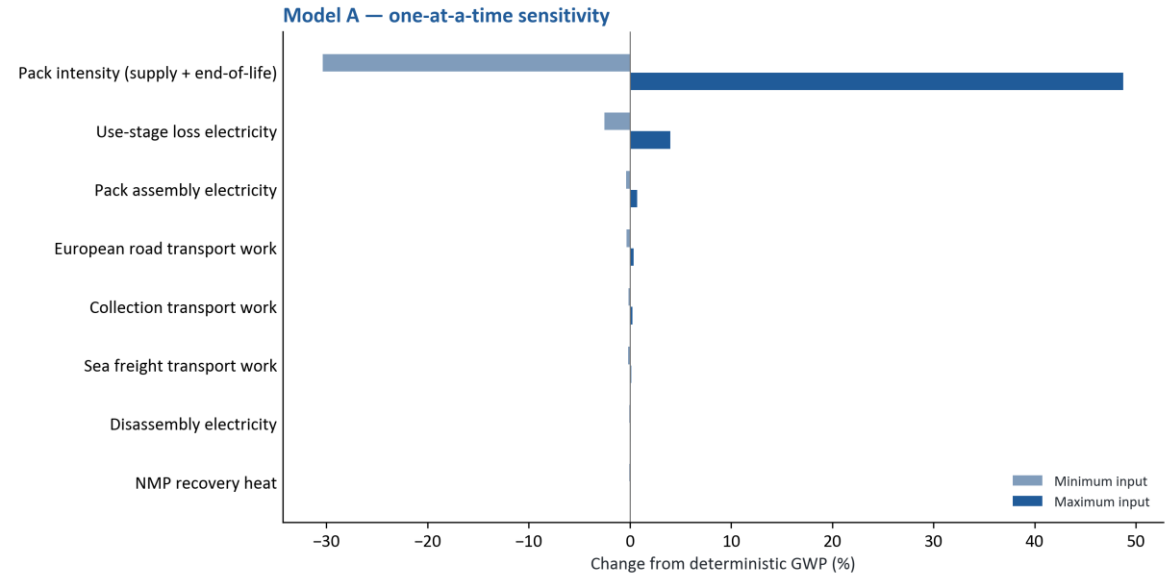


Figure 6. Signed one-at-a-time climate changes for Model A. The supply-intensity parameter also scales spent-pack mass.

Table 13. Climate endpoints and changes relative to the mixed-model baseline.

Parameter	Low result	High result	Low change	High change
Pack intensity (supply + end-of-life)	0.209	0.4464	-30.34%	+48.77%
Use-stage loss electricity	0.2925	0.312	-2.52%	+3.98%
Pack assembly electricity	0.299	0.3023	-0.36%	+0.73%
European road transport work	0.299	0.3011	-0.35%	+0.35%
Collection transport work	0.2997	0.3008	-0.13%	+0.25%
Sea freight transport work	0.2995	0.3005	-0.18%	+0.13%
Disassembly electricity	0.2999	0.3003	-0.06%	+0.08%
NMP recovery heat	0.2999	0.3003	-0.04%	+0.09%

Pack intensity changes climate impact by -30.3% to +48.8%; use losses change it by -2.5% to +4.0%. The weighted total changes by -31.3% to +50.4% for pack intensity. These responses describe the specified parameter ranges and do not establish feasible combinations of factory operating conditions.

Coupled lifetime-intensity interpretation

At 2.400×10^{-5} pack/FU, spent-pack mass is 9.139×10^{-3} kg/FU and climate impact is 0.2090 kg CO_2-eq/FU. At 5.333×10^{-5} pack/FU, mass is 2.031×10^{-2} kg/FU and impact is 0.4464. The same relationship applies in Monte Carlo simulation. Process requirements in ten sampled iterations confirm a constant waste-to-supply ratio of 380.7829 kg/pack as supply varies. This verifies the implemented coupling, not the assumed lifetime range.

Contributions by impact category

The following interpretation focuses on climate change, mineral resources and water use. Contributions are resolved to the linked background provider, rather than to individual upstream unit processes or foreground life-cycle stages.

Climate change

Model A gives 0.3001 kg CO_2-eq per lifetime-delivered kWh. Over 28,369 kWh service, this corresponds to 8.513 t CO_2-eq for the modeled pack life cycle. The result includes the stated use losses and end-of-life boundary and is not a manufacturing-only footprint.

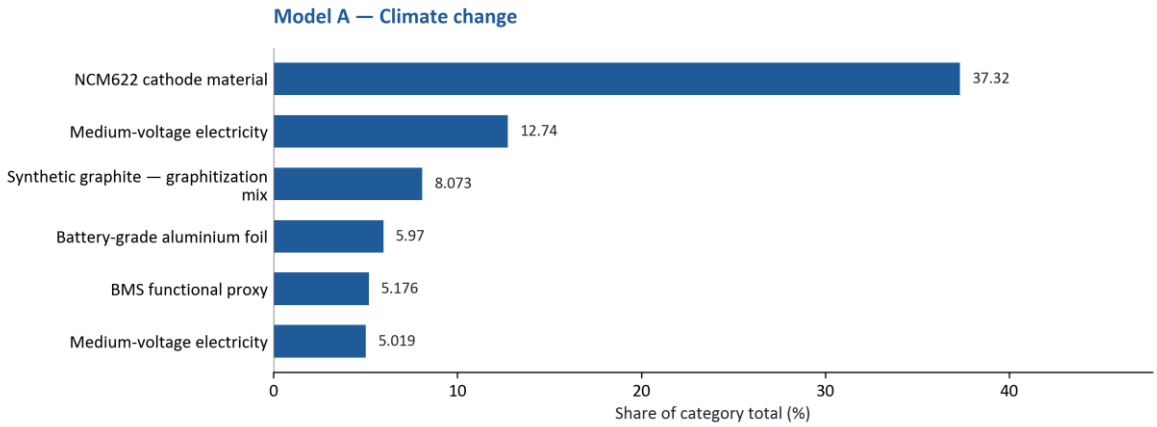


Figure 7. Leading provider contributions to Model A climate change.

The leading climate contributors are NCM622 cathode material (37.3%), medium-voltage electricity supplied in China for production (12.7%), synthetic graphite — graphitization mix (8.1%) and battery-grade aluminium foil (6.0%). In Figure 7, the two identically abbreviated electricity labels refer to different providers: China at 12.7% and Europe without Switzerland at 5.0%. The latter supplies use-phase losses and the selected disassembly demand. These are provider-level contributions, not a breakdown of upstream unit processes.

The aggregate electronics production proxy contributes 5.18% of Model A climate impact and 4.45% of Model B. BMS data provide a functional proxy for the aggregate electronics demand, not a verified component composition. Sun et al.'s below-7% material-stage contribution [2, Section 3.1] uses a different system boundary and impact method and is not directly comparable with these full-life-cycle EF results. The aggregate circuit-board treatment proxy introduces additional uncertainty at end of life.

Material resources

Resource use, minerals and metals contributes 39.5% of Model A's weighted total. Its leading linked providers are Electrolytic copper foil (36.3%), NCM622 cathode material (30.7%), BMS functional proxy (30.3%). The adopted cut-off foreground adds no avoided-primary-material credit for sorted scrap.

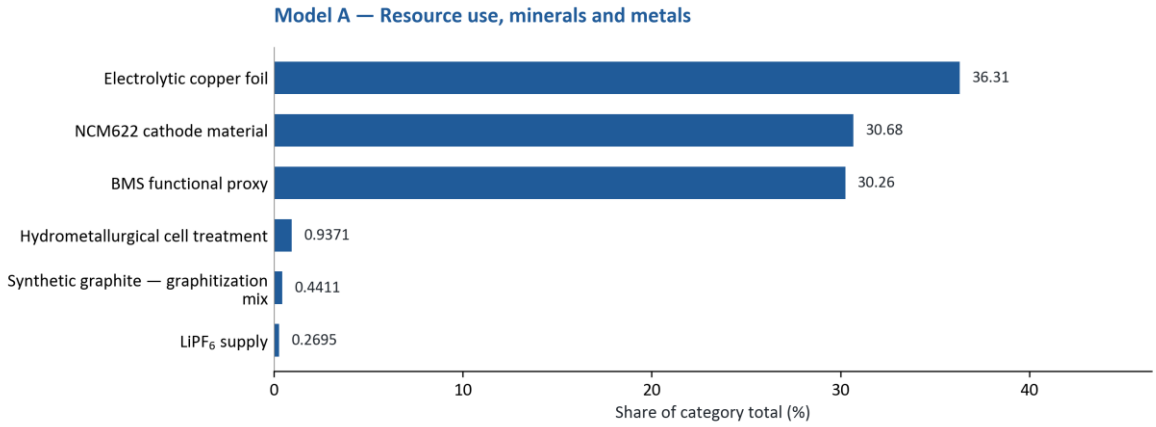


Figure 8. Leading Model A contributions to resource use, minerals and metals.

Water use

EF water use is a deprivation-weighted impact indicator rather than physical factory water intake. Figure 9 shows where the selected providers contribute to this impact along the supply chain.

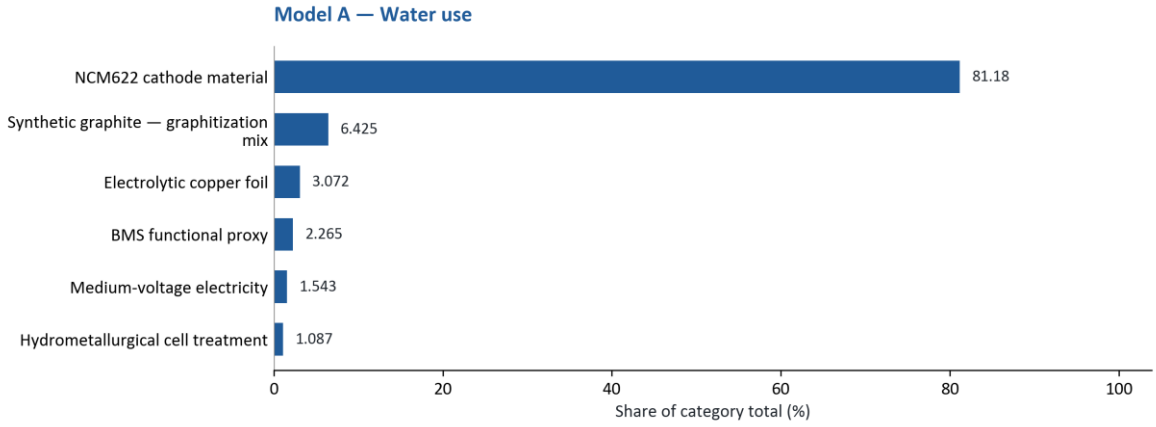


Figure 9. Leading Model A contributions to water use.

The leading Model A water-use contributors are NCM622 cathode material (81.2%), Synthetic graphite — graphitization mix (6.4%), Electrolytic copper foil (3.1%). Model B's category total is 0.5596 m^3 world-eq deprived/FU, compared with 0.5161 for Model A. These are deprivation-weighted indicators and must not be read as litres of factory water consumption.

IV Comparison with an ecoinvent-only model

4.1 Comparison setup

Both configurations use the same physical foreground, synthetic-graphite specification, functional unit, EF 3.1 method and coupled service-allocation structure. Model A combines selected HiQLCD providers with ecoinvent; Model B uses ecoinvent backgrounds. The comparison changes background selection while preserving all modeled foreground quantities.

The selected provider pairs differ in geography, technology and dataset boundary. In particular, the synthetic-graphite production mix in Model A and Acheson powder route in Model B are not a verified same-process pair. Table 14 distinguishes the shared copper-tab feedstock provider from the separately substituted copper collector-foil providers.

Table 14. Selected background-provider pairs and demands per functional unit.

Flow	Amount per FU	Model A Provider	Model B Provider	Location match (A → B)
Copper feedstock for pouch tabs	7.929×10^{-6} kg	Copper cathode feedstock	Copper cathode feedstock	Global → Global
NCM622 cathode material	4.340×10^{-3} kg	NCM622 cathode material	NMC622 cathode material	China(CN) → China
Synthetic graphite	2.800×10^{-3} kg	Synthetic graphite — graphitization mix	Synthetic graphite — Acheson route	China(CN) → China
PVDF	1.868×10^{-4} kg	PVDF	PVDF	China(CN) → Global
Carbon black	1.427×10^{-4} kg	Carbon black	Carbon black	China(CN) → Global
Copper collector foil	1.001×10^{-3} kg	Electrolytic copper foil	Li-ion copper collector foil	China(CN) → Global
Ethylene carbonate	7.675×10^{-4} kg	Ethylene carbonate	Ethylene carbonate	China(CN) → China
Dimethyl carbonate	7.675×10^{-4} kg	Dimethyl carbonate	Dimethyl carbonate	China(CN) → Rest-of-World
Carbon steel plate	2.314×10^{-4} kg	Carbon steel plate	Low-alloy steel	China → Rest-of-World
Ethylene glycol	1.798×10^{-4} kg	Ethylene glycol	Ethylene glycol	China,Fujian → Rest-of-World
Electronic parts (BMS proxy)	3.383×10^{-4} kg	BMS functional proxy	BMS functional proxy	China(CN) → Global
NMP supply	1.827×10^{-5} kg	NMP supply	NMP supply	China(CN) → Rest-of-World
Industrial wastewater treatment	2.900×10-8 m^3	Industrial wastewater treatment	Wastewater treatment	China → Rest-of-World
Hazardous-waste incineration	1.356×10^{-4} kg	Hazardous-waste incineration	Hazardous-waste incineration	China → Rest-of-World
Truck freight	1.539×10^{-5} t·km	Truck freight	market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 3	China → Rest-of-World
Cell aluminium collector foil	4.194×10^{-4} kg	Battery-grade aluminium foil	Li-ion aluminium collector foil	China → Global
Pouch-film aluminium input	3.203×10^{-4} kg	Battery-grade aluminium foil	Li-ion aluminium collector foil	China → Global

Provider labels are abbreviated English names; original names, locations and UUIDs can be provided in a supporting results workbook on request. Pouch-film aluminium and cell collector foil are separate demands on dedicated foil providers. Contributions from each shared provider are allocated between its uses without double counting.

Identical ecoinvent providers remain shared where no substitution is made, including copper-cathode feedstock for tabs. The full exchange-level mapping also identifies internal foreground links and environmental exchanges, which are not background substitutions.

Both configurations use aggregated LCI_RESULT backgrounds. This is not an aggregated-versus-unit-process comparison. Shared-provider climate contributions are allocated to their foreground uses in proportion to the corresponding reference-product demand; substituted uses are then differenced. The resulting provider-pair changes reconcile to the total A/B climate difference.

4.2 Climate-change comparison

For these two specified background configurations, Model B gives 0.3973 kg CO2-eq/FU and Model A gives 0.3001: a difference of 32.39%, or 0.09720 kg CO2-eq/FU. Across the assumed lifetime service, the difference is 2.757 t CO2-eq. The percentage uses Model A as its denominator.

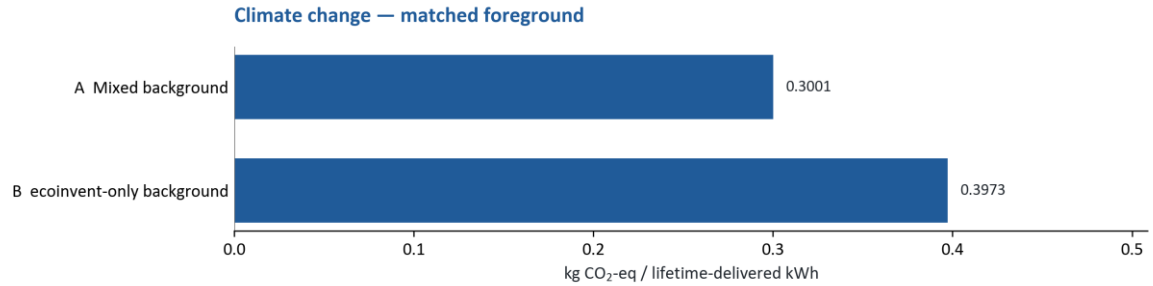


Figure 10. Climate comparison at identical foreground quantities and functional unit.

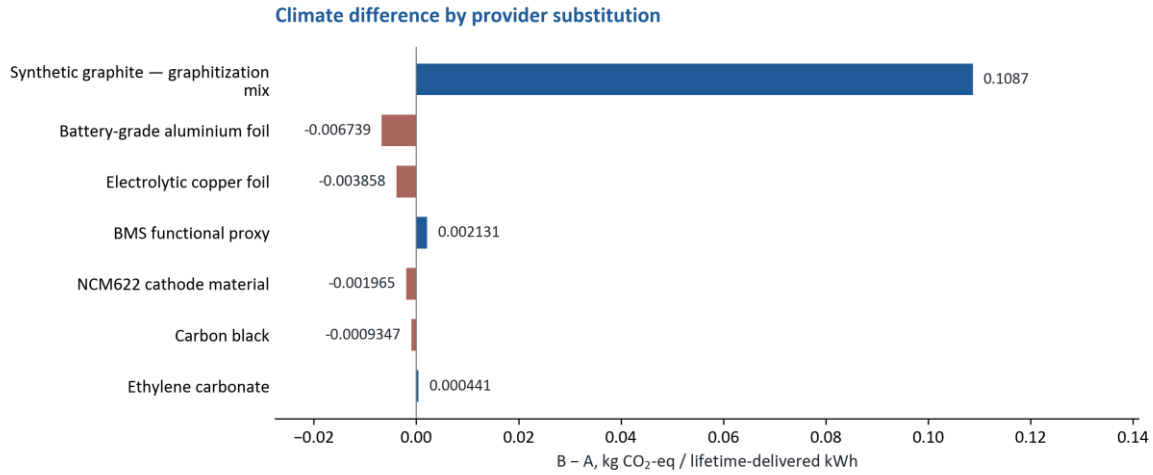


Figure 11. Largest absolute climate changes attributable to replaced provider pairs (B minus A).

The largest provider-pair change is Synthetic graphite — graphitization mix: +0.10871 kg CO_2-eq/FU. All remaining substituted providers together contribute -0.01151 kg CO_2-eq/FU. Thus the graphite-route difference exceeds the net total increase, because other substitutions partly offset it. Figure 11 uses a reconciled decomposition and does not count the same aggregate provider once for each linked row.

The comparison demonstrates sensitivity to this set of background datasets. It does not isolate database brand from production route, regional electricity, allocation or inventory coverage. The source does not establish the actual anode specification, so the synthetic-graphite pair is a declared material scenario. Its difference must not be generalized as a database-quality ranking or a verified product advantage.

4.3 Results across the EF midpoint categories

Table 15. Characterized EF 3.1 results for the two fixed-foreground configurations.

Impact category	Model A	Model B	B/A – 1	Unit / FU
Climate change	0.3001	0.3973	+32.4%	kg CO_2-eq
Ozone depletion	4.025×10^{-9}	4.145×10^{-8}	+929.9%	kg CFC-11-Eq
Particulate matter	1.868×10^{-8}	3.369×10^{-8}	+80.4%	disease incidence
Ionising radiation	0.03605	0.04511	+25.1%	kBq U235-Eq
Photochemical ozone formation	1.059×10^{-3}	1.581×10^{-3}	+49.2%	kg NMVOC-Eq
Acidification	2.166×10^{-3}	3.595×10^{-3}	+65.9%	mol H+-Eq
Terrestrial eutrophication	3.368×10^{-3}	5.320×10^{-3}	+58.0%	mol N-Eq
Freshwater eutrophication	1.313×10^{-4}	1.757×10^{-4}	+33.8%	kg P-Eq
Marine eutrophication	3.227×10^{-4}	5.129×10^{-4}	+59.0%	kg N-Eq
Freshwater ecotoxicity	3.178	3.666	+15.4%	CTUe
Human toxicity, cancer	1.528×10^{-8}	2.627×10^{-10}	-98.3%	CTUh
Human toxicity, non-cancer	6.119×10^{-9}	1.230×10^{-8}	+101.0%	CTUh
Land use	1.316	1.451	+10.3%	dimensionless
Water use	0.5161	0.5596	+8.4%	m^3 world eq. deprived
Resource use, fossils	4.294	5.346	+24.5%	MJ, net calorific value
Resource use, minerals and metals	2.702×10^{-5}	2.450×10^{-5}	-9.3%	kg Sb-Eq

4.4 Interpreting the category differences

Of sixteen primary categories, 14 increase and 2 decrease in Model B. The largest relative shifts are ozone depletion (+929.9%), human toxicity, non-cancer (+101.0%), human toxicity, cancer (-98.3%) and particulate matter (+80.4%). Interpret these percentages alongside the absolute results in Table 15.

Toxicity and resource indicators depend on the selected inventories and EF characterization. Provider totals do not isolate individual substances or operations as causes. Toxicity indicators are not estimates of disease incidence.

Water use increases by 8.4%, whereas mineral-resource use decreases by 9.3%. Climate change alone therefore cannot summarize the environmental profile, even with identical foreground material quantities.

The weighted total falls from 0.0811 to 0.0711 mPt/FU (-12.3%). Its direction differs from climate change because it combines sixteen normalized categories with different weights. This auxiliary result neither replaces the midpoint comparison nor establishes overall superiority.

V Conclusions

This case models a 72.5 kWh NCM622/synthetic-graphite traction battery with a finished mass of 380.8 kg. Cell and pack inputs are combined from literature within an explicit screening scenario, manufactured in China and used and treated in Europe. The same foreground is retained across the mixed HiQLCD/ecoinvent and ecoinvent-only configurations.

For the specified background configurations, EF 3.1 climate change is 0.3001 kg CO2-eq/FU for Model A and 0.3973 for Model B (+32.39%). The difference is driven mainly by the synthetic-graphite routes and partly offset by other substitutions. It cannot be attributed to database choice alone or interpreted as product emission reduction or database-quality superiority.

The inventory distinguishes cell electrolyte and pouch packaging from pack-level components, uses dedicated aluminium and copper collector-foil datasets, and represents tab feedstock separately from collector foil. Both models use the same decomposed pouch-film structure. Electronics production is represented by a BMS functional proxy; component composition and aggregate circuit-board treatment are sources of structural uncertainty.

Joint variation of pack supply and spent-pack mass produces the strongest tested climate response, with -30.3% to +48.8% endpoint changes. The 500-draw Model A simulation gives a P2.5–P97.5 range of 0.2361–0.4220 kg CO_2-eq/FU under the stated foreground distributions. The interval excludes uncertainty in background inventories and material specifications.

The case supports hotspot identification and transparent comparison of background configurations. Its applicability is limited by the assumed anode specification, aggregate electronics and treatment proxies, supplementary inputs without independent source verification, simplified film/tab production and non-site-specific energy and recovery data. The results characterize a literature-based screening scenario, not a verified product PCF, EPD or regulatory declaration.

Resources

[1] von Drachenfels et al. (2023). Life Cycle Assessment of the Battery Cell Production: Using a Modular Material and Energy Flow Model to Assess Product and Process Innovations. Energy Technology, 11, 2200673.

https://doi.org/10.1002/ente.202200673

Inventory basis: Table 1 for cell material quantities, process energy, water and NMP. Nominal cell energy (146.5 Wh/cell), electrolyte composition and laminate constituents are screening inputs based on transcribed values attributed to SI Tables S2/S18. These values have not been independently verified against the original supplementary file and are not treated as verified product specifications.

[2] Sun et al. (2020). Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. Journal of Cleaner Production, 273, 123006.

https://doi.org/10.1016/j.jclepro.2020.123006

Used: SI Table S5, SI p.5, for pack capacity and component masses, and Table S6 for assembly electricity. S5 explicitly distinguishes cell materials and battery components. Electronic Parts is an undivided 9.5 kg entry; Table S2 identifies GREET 2018/CALCD sources. The below-7% electronics contribution belongs to the paper's material-preparation analysis, not the present full-life-cycle EF result.

[3] CATL (2024). Lithium iron phosphate battery cell 280 Ah. Environmental Product Declaration, EPDItaly registration 0565.

https://www.epditaly.it/en/epd/lithium-iron-phosphate-battery-cell-280ah/

Used: §3.1, p.7 (reference mass); §3.4, pp.9–10 (distribution); §3.5, p.10 (packaging/disposal); §3.7, p.11 (collection). LFP chemistry, service life and recovery yields are not transferred.

[4] Ihlbrock, L., Sehnal, A., Gutsch, M. and Lux, S. (2025). Future energy demand for automotive and stationary lithium- and sodium-ion battery production towards a European circular economy. Energy & Environmental Science, 18, 8724–8743.

https://doi.org/10.1039/D5EE02287H

Used: Table 2 and footnote a for NMC622/graphite large-BEV efficiency and the 96% cell-level RTE proxy. The 200,000 km lifetime and constant efficiency over service are assumptions of this case.

[5] Dai et al. (2019). EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model. Argonne National Laboratory, ANL-19/16.

https://publications.anl.gov/anlpubs/2019/07/153050.pdf

Used for recycling process-boundary cross-checks; Chapter 5 and Tables 10–12, PDF pp. 40–42. Not the primary numerical recycling LCI.

Resources — continued

[6] HiQLCD. China's High-Quality LCI Database, introduction (2025).

https://www.openlca.org/wp-content/uploads/2025/01/HiQLCD-1.1-Introduction.pdf

Database context only. Provider choices are reported in the inventory and comparison tables; this brochure does not establish the representativeness of an individual dataset.

[7] ecoinvent. About Different System Models and the Key Concepts Applied.

https://support.ecoinvent.org/system-models-1

System-model basis and ecoinvent 3.12 provider documentation. Cell treatment: "treatment of used Li-ion battery, hydrometallurgical treatment", Global; European recycling data used as a global proxy. Foreground cut-off outputs receive no additional avoided-material credit.

[8] GreenDelta. openLCA 2 Manual, Waste modelling.

https://greendelta.github.io/openLCA2-manual/waste_modelling.html

Used for the waste-output to waste-input Quantitative Reference convention.

[9] European Commission, Joint Research Centre (2023). Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method. JRC130796. doi:10.2760/798894.

https://publications.jrc.ec.europa.eu/repository/bitstream/JRC130796/JRC130796_01.pdf

Normalization: [9], Table 10, pp.22–23; exact values from the official factor workbook. Weighting: Sala et al. [10]. Accessed 18 September 2026. Official factor workbook.

[10] Sala, S., Cerutti, A. K. and Pant, R. (2018). Development of a weighting approach for the Environmental Footprint. EUR 28562 EN. European Commission, Joint Research Centre. doi:10.2760/945290.

Used for EF category weights. Applied factor values come from the official JRC EF3.1 factor workbook linked in [9]. Characterization, normalization, sensitivity and Monte Carlo outputs are calculations of this study.

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https://commons.wikimedia.org/wiki/File:Battery_Manufacturing_Lab_(50954228316).jpg

https://creativecommons.org/licenses/by/2.0/

[11] European Commission (2024). Draft Commission Delegated Regulation supplementing Regulation (EU) 2023/1542: carbon footprint calculation methodology. Ref. Ares(2024)3131389, 29 April 2024.

Used: §2 for functional unit and reference flow, and §2.2 for complete-battery boundaries. This case retains mileage-derived throughput, packaging and use losses; it is not a declaration under that draft. Initial usable capacity and warranty-based parameters have not been established.

[12] UAB Elinta Motors (2025). NMC Battery ESS7 EPD, EPD-IES-0026979, version 18 November 2025, pp.3–6. System-boundary context only; the 42 kWh inventory is not adopted.

Appendix — Modeling and implementation notes

This appendix documents the model implementation, provider configuration and calculation procedures to support reproducibility.

EF 3.1 implementation

Method source: HiQLCD method package. EF v3.1 method UUID: e954a8a3-614a-458d-977f-e7808b95d866. Of 25 returned indicators, only the sixteen primary categories enter the normalized/weighted total; nine diagnostic subsets are excluded. JRC factors [9,10] are applied to full-precision outputs. Main tabulated results generally use four significant digits; prose and percentages are rounded for readability without changing the calculations.

Database version and model configuration

Model A uses the HiQLCD lithium-battery industry pack 1.1, HiQLCD 1.5.0 and ecoinvent 3.12 cut-off.

Model B uses only ecoinvent 3.12 cut-off backgrounds. Both retain eight custom foreground processes, 51 total processes and 85 links.

Exchange types and connection checks

Elementary flows exchange with the environment and have no provider; units alone do not determine flow type. Collection accepts spent-pack waste as its Quantitative Reference and passes the same mass to disassembly through the shared waste flow. These internal links are not additional pack purchases or independent disposal demands. Complete background inventories are used once, without duplicating their constituent operations or adding unsupported foreground emissions or avoided-production credits.

Sensitivity and uncertainty analysis

Sensitivity analysis comprises sixteen OAT endpoints, with baseline reproducibility checked after parameter restoration. Monte Carlo analysis comprises 500 result vectors; supply/waste coupling was verified in ten sampled iterations. No random seed was specified, and the 58 distinct backgrounds have no encoded uncertainty. Reported percentiles characterize the assumed foreground scenarios, not full product uncertainty. No paired-model significance test or formal convergence assessment was performed.

Table 16. Material-sourcing reference flow: an example of foreground scaling.

Direction	Flow	Amount	Unit / type
Input	Purchased materials and component links	As Table 1	kg / Product
Output	Material set [QR]	3.525×10^{-5}	pack-eq / Product