Supplementary Information

for the publication

Carbon Footprint Distributions of Lithium-Ion Batteries and Their Materials

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1. Methods and data

1.1. General S&P Global modelling remarks

S&P Global's Capital IQ Pro offers the "Mine Economics" tool[1], an effort to model mine-level costs for various commodities including lithium, cobalt, and nickel. The rest of this section summarises methodological details pertinent to this work and is entirely based on their methodological description[2]. For further questions regarding the modelling decisions of S&P Global, please contact the corresponding author.

Their team uses a bottom-up approach for estimating mining and ore processing costs, focusing on the required process flowsheet, equipment, and operational workforce. This includes assessing consumable costs. Analyses typically begin with a technical, feasibility, or pre-feasibility report on the asset and other related corporate disclosures, such as presentations, financial reports, and conference call transcripts. S&P Global's analysts enhance this data with direct communications with the owning company and site visits. When detailed cost breakdowns are lacking, they apply industry benchmarks or calculations for factors like reagent consumption and electricity usage. All modelled figures are aligned with available reported disclosures, and a reconciliation is provided in the notes page of each model.

Analysts initiate their cost modelling with a detailed mine plan, drawing from technical reports and historical data. They model the process flowsheet (i.e., individual processing steps), including ore and waste handling, processing methodologies, and the requisite labour and equipment. This granular approach extends to assessing input costs, including consumables like fuel and chemicals, as well as labour and energy costs, to accurately determine the cost per tonne of ore processed.

The team then aligns these modelled estimates with actual operational and financial data from companies, refining their models to ensure they reflect real-world operations. This results in a granular breakdown of costs, categorised by labour, energy, fuel, and reagents, among others, closely mirroring company disclosures. This blend of bottom-up and top-down analysis offers a nuanced view of mining and milling expenses, detailed in the study's appendix.

Treatment and Refining Charges (TC/RCs) for intermediate products like concentrates are based on global benchmarks, tailored for specific impurities and concentrate grades, and set within the framework of annual or multi-year agreements. S&P Global bases these benchmarks on its own market intelligence and external sources like S&P Global Platts, ensuring that the modelled TC/RCs remain relevant and accurate over time, providing a stable basis for future projections. Cost data are finally provided on a per metal paid basis, accounting for varying product types and grades. In the case of lithium, S&P Global provided costs in Lithium Carbonate Equivalent (LCE) units but were stoichiometrically converted by the authors to per metal paid for consistency with other metals.

1.2. Preparing S&P Global data

1.2.1. By- vs. co-product

For assets with multiple mining outputs, S&P Global provides two different allocation approaches: by-product and co-product. These methods offer different means of distributing the total cost among the metals produced.

In by-product costing, all shared mining, milling, and processing costs are attributed to the primary metal, while costs specific to each metal, such as refining costs, are allocated accordingly. For instance, in the case of a mine that primarily produces copper but also cobalt as a sellable side product, all shared costs are attributed to copper products. Shared costs refer to processes treating both copper and cobalt, such as ore extraction or flotation. Refining charges for by-products are subtracted from their gross revenue to calculate the by-product credit, which is then deducted from the primary metal's cash operating cost.

Co-product accounting, on the other hand, divides costs based on the revenue contribution of each metal in the intermediate product. After refining charges are subtracted from each metal's revenue, treatment and freight charges are allocated proportionally to the contained metals, based on their share of net revenue. For example, if copper accounts for 76% of net revenue, it will bear a corresponding percentage of shared production costs.

For this work, costs on a co-product allocation were chosen. This decision was made because it aligns well with the economic allocation approach of the LCA literature, whereas "by-product" on the other hand does not conceptually match the LCA mass-based allocation method. With "by-product", cobalt, as it is typically mined as a secondary metal, would miss the majority of costs and thus emissions.

1.2.2. Exclusion of assets

As explained in the method section of the main text, technical fields of all assets (e.g., geology, flowsheet properties, output products, and modelling choices) were manually checked and harmonised for plausibility and consistency. In the next step, for every commodity, assets were grouped into output products (lithium: lithium carbonate and lithium concentrate; nickel: nickel concentrate; cobalt: cobalt hydroxide and cobalt concentrate). Assets with multiple or unclear output products were excluded from the shortlist. Furthermore, assets with inconsistent flowsheet cost information were removed. Nickel assets producing exclusively ferronickel were also excluded since there is no commercially established practice for converting ferronickel into nickel sulfate (refer to SI Section 1.7 for nickel supply chain modelling choices).

1.3. Selection of cost categories

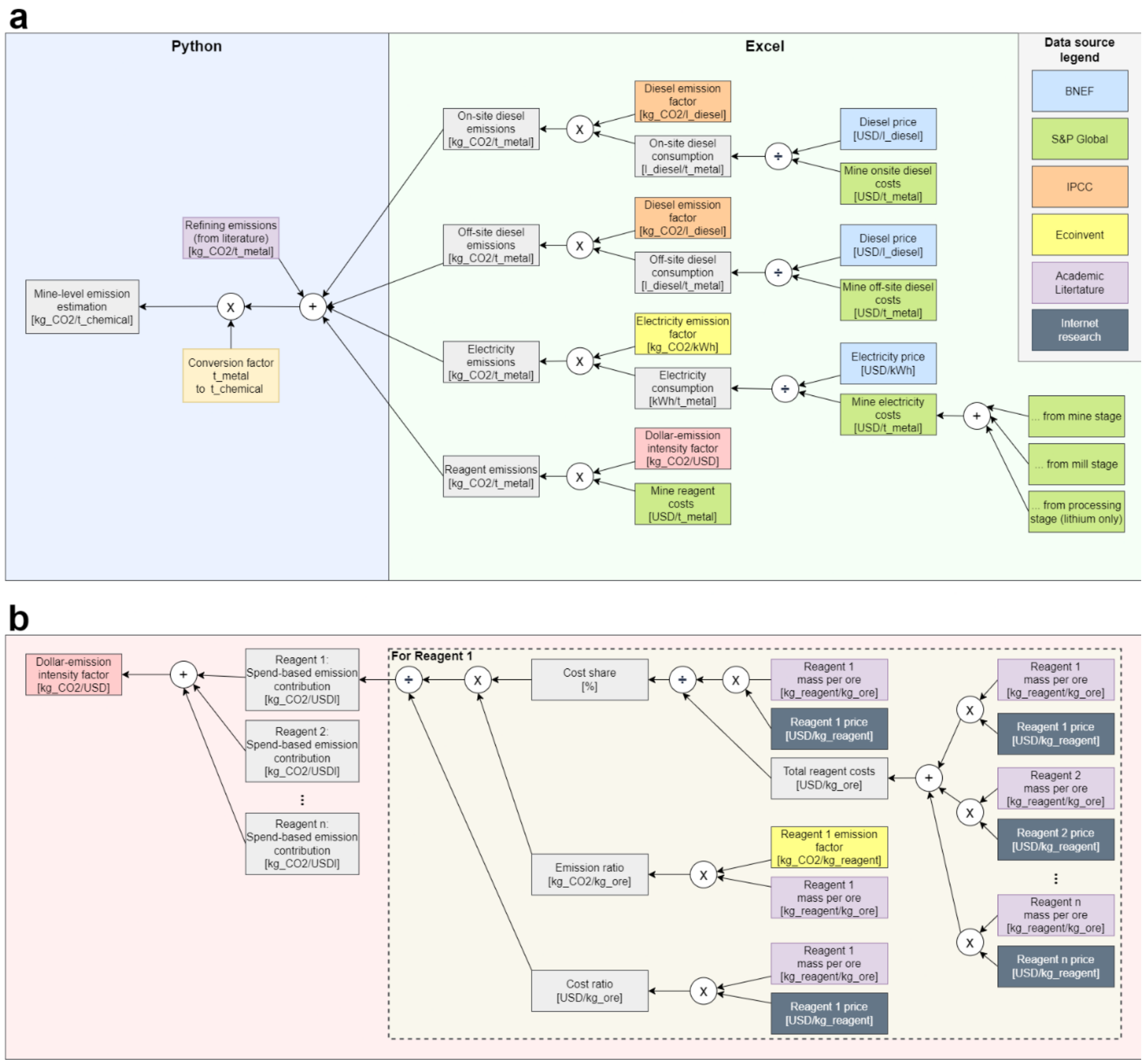
For every asset, S&P Global provides Total Production Costs that are composed of All-in-Costs plus Reclamation, Depreciation, and Inventory Changes amongst others (Capitalised costs refer to S&P Global nomenclature). All-in-Costs, in turn, are the sum of Cash Operating Costs, Royalties and Taxes, Corporate Overhead, Sustaining and Expansion Capex, and Interest Charges. So far, these cost categories are not directly tied to operating GHG emissions. However, Cash Operating Costs are composed of Offsite Transport costs, Treatment and Refining Charges (TC/RC), and Total Minesite Costs that, in turn, comprise Labour, Fuel, Electricity, Reagent, and Other costs for mine and mill stages.

Amongst those, the methodology proposed in this work incorporates Offsite Transport costs and the Minesite Costs components – Labour, Fuel, Electricity, and Reagent – for estimating emissions at the mine and mill stages. Additionally, TC/RC are considered to have a signalling effect on refining emissions (see below). “Other” mill and mine costs encompass blasting and geologic consulting costs in varying proportions (and thus varying GHG implications), which is why this cost category cannot be utilised for determining emissions. Royalties, labour, and other sustaining costs do not carry meaningful information for deducing emissions.

TC/RC are fees charged by smelters for processing intermediate metal products, with rates influenced by global benchmarks, the presence of impurities, and the grade of the concentrate. These charges can vary based on contract terms and are often negotiated based on the specific conditions of the supply, such as the quantity and quality of the metal being processed[2]. Due to the fluctuating and market-dependent nature of TC/RC, they cannot be directly included in the bottom-up emission model. However, acknowledging their significance in relation to GHG emissions, TC/RC are utilised as indicators to approximate the most likely positioning of assets within the refining emissions spectrum. As a conservative modelling approach, we maintained the full range of uncertainty for refining emissions based on literature values but applied TC/RC to determine the most probable emission values.

1.4. Further information on the emission modelling of output products

SI Figure 1 graphically explains the modelling steps to arrive from S&P Global cost data to emissions, using various data sources. This Figure corresponds to Formulas (1)-(8) in the main text's method section.



SI Figure 1: a. Modelling workflow for emission calculations in Excel and Python. b. Detailled workflow for determining the spend-based emission factors for the emission modelling of reagents.

Note that for four nickel assets in South Africa, the Dense Media Separation (DMS) process step is omitted, with only flotation being considered. Given that these are the only assets necessitating DMS modelling and their combined production share is minimal (less than 0.08%), it was determined that the extra effort for modelling DMS is unwarranted.

1.4.1. Modelling on site electricity production

While most assets are physically connected to the grid, other remote assets produce their electricity on-site. Naturally, the differentiation between grid and on-site electricity production is crucial for emission model accuracy. Thus, based on S&P Global's modelling comments, we explicitly calculated electricity emissions for on-site production through diesel and natural gas (NG) routes. As for on-site and off-site transportation, diesel prices and emissions are taken from BNEF[3] and IPCC[4], respectively. For the two countries where NG is used for electricity production (Argentina, Australia), NG prices were retrieved from internet research. Sources and modelling details can be found in the sheet "Natural Gas Prices 2022 (MC)" of "SP_CIQ_Lookup_File.xlsx".

It should be noted that the emission factors for both diesel and natural gas (NG) are treated without regional differentiation because the variations across regions are considered negligible, as indicated by the IPCC in Tables 1.4 and 1.6 in [4]. Additionally, for diesel, no distinction is made between stationary and mobile combustion sources, as the discrepancy in values is minimal, with an error of less than 0.1% ([4] Table 1.5 and Table 1.6).

1.4.2. Sources for and production volume for graphite and nickel laterite

Since only CF data for Chinese graphite production is available, only Chinese natural and artificial production volumes are of interest. The production volumes for Chinese graphite are taken from the previously developed battery-specific Graphite supply chain. The same approach is applied to determine the nickel laterite production volumes for Indonesia, the Philippines and New Caledonia (sui generis collectivity of France). These are the only countries of interest as there are only CF estimates available for them. The sources providing nickel sulfate CF estimates from laterite mining break down Indonesian operations into processing limonite via High-Pressure Acid Leaching (HPAL) and saprolite via Rotary Kiln Electric Furnace (RKEF) mining. Both limonite and saprolite are a subcategory of laterite deposits.

To make use of this differentiation, it was necessary to determine the share of saprolite in laterite mining in Indonesia. To this end, we turned to internet research as the industrial processing of saprolite via Nickel Pig Iron (NPG) and nickel matte to nickel sulfate using RKEF processes is not well established and currently only done by Chinese Tsingshan Holding Group[5]. Typical process flowsheets for sulphide and laterite (limonite and saprolite) can be found in [5,6]. Tsingshan announced that in 2021, they plan to produce 100 kt of nickel matte in that year[7]. As this is the only available figure, we use the nickel content in matte (ca. 75%[8]) and nickel sulfate (22%, stoichiometrically determined) to convert it to 341 kt of nickel sulfate derived from saprolite. We assume that the rest of Indonesia's laterite supply and all of the Philippines' and New Caledonia's (sui generis collectivity of France) stem from limonite ore and are processed using HPAL.

1.5. Input distributions and uncertainties for material Monte-Carlo simulation

For the uncertainty modelling of the output products' emissions, uncertainty distributions of the input parameters (cf. SI Figure 1) had to be defined. As explained in the main text's method section *Uncertainty quantification - material Monte-Carlo simulation*, the Excel plugin @risk was used for operationalisation. The following input uncertainty distributions are chosen:

SI Table 1: Uncertainty distributions of input variables for emission modelling of S&P Global's output products. These fields correspond to the input fields in SI Figure 1.

Input variable	Value	Distribution type	Comment / Source
S&P Global cost data	+- 10 %	Triangular	Generic uncertainty for S&P Global data (based on expert interview with data provider)
Diesel prices	+- 5 %	Triangular	Generic uncertainty for BNEF data
Natural Gas (NG) prices	NA	Uniform	Sampled over all monthly 2022 country-specific prices and FX rates retrieved from the internet
Reagent prices	NA	Uniform	If sources provide range
	NA	Triangular	If multiple values from multiple sources
	+- 10%	Triangular	Generic uncertainty if only singular value is available
Diesel / NG CF	NA	NA	No uncertainty assumed based on IPCC work[4]
Electricity grid CF	NA	Uniform	Based on 600 Monte Carlo samples of "market [group] for electricity, high voltage" [kgCO2e/kWh] for every

			country/region using IPCC2021 no LT GWP100 LCIA method and Ecoinvent 3.9.1
Reagent CF	NA	Uniform	Based on 600 Monte Carlo samples of the Ecoinvent chemical activity [kgCO2e/kg] for every reagent using IPCC2021 no LT GWP100 LCIA method and Ecoinvent 3.9.1

1.6. Aggregating modelled and refining emissions and margins of error

The general approach for adding refining emissions and margins of error is described in the main method section. Specifically, for cobalt sulfate derived from cobalt hydroxide, it should be noted that there was no existing work meeting the requirements (mainly no breakdown along processing steps) outlined in the main method section *Comparing modelled emissions to literature and database values* and SI Section 3. Given this lack of existing literature, the Ecoinvent 3.9.1 activity for converting cobalt hydroxide to cobalt sulfate was used. First, the unit CFs of all exchanges of this activity were separately calculated 500 times via Monte-Carlo simulations. Next, the mean CFs were recombined according to the exchanges' weighting defined by the Ecoinvent activity. Lastly, the relative 5^{th} and 95^{th} percentile unit CF deviations from the mean CF were calculated for every exchange and applied to the exchanges' average CF contributions to arrive at the activity's minimum (5^{th} percentile) and maximum (95^{th} percentile) refining emissions.

1.7. Building global battery-specific supply chains

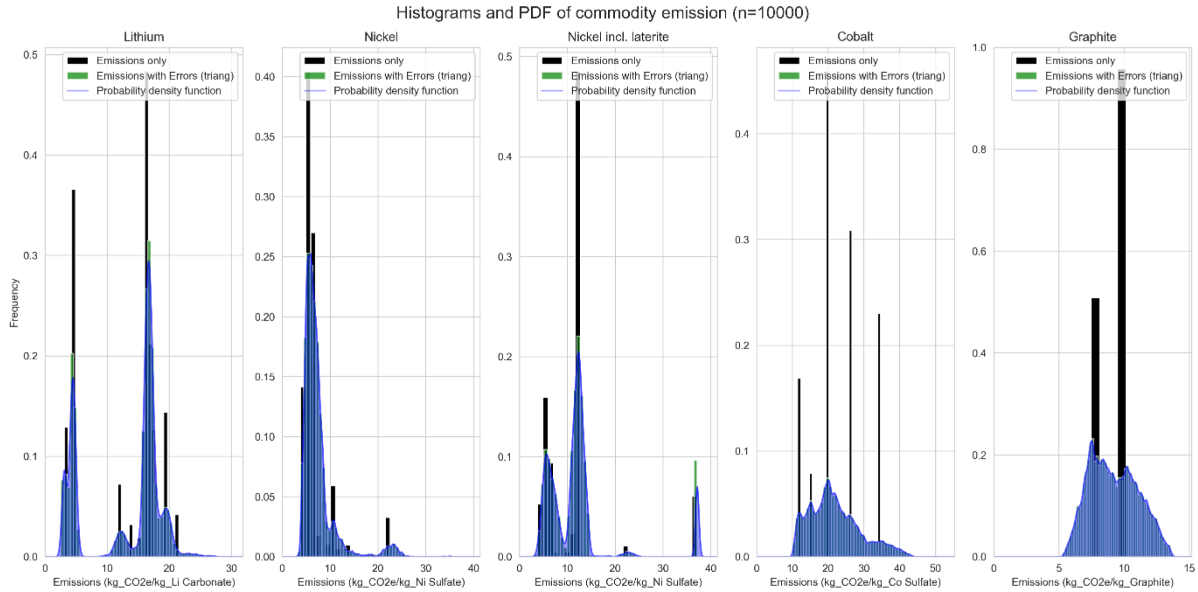
Referring to the main method section *Constructing and mapping global battery supply chains*, in constructing a global supply chain specific to batteries, we account for all mining products that could potentially be utilised in battery production. Specifically, all intermediate products that could be refined to battery chemicals are counted towards the global battery-specific supply chain and the y-axis of Figure 1c,f,h. This is only relevant for nickel as the global nickel value chain involves many different end products with varying content grades, where the majority of mined nickel is used for steel production[9].

The specific calculation for the nickel supply chain is accessible in "Country_Production_Shares_Mining.xlsx". Our analysis builds on USGS[10], BGS[11], and S&P Global data[1] and a 2020 McKinsey study[9] and conceptually starts, similar to lithium and cobalt, with 2022 USGS national production volumes that are imputed with 2021 BGS data. We aggregate asset-level S&P Global data and combine it with USGS, BGS, and DERA[12] information to determine the sulphide vs. laterite production shares of all relevant producing countries. We note from the McKinsey study that 46% of all mined nickel is – at some point – converted to Nickel Class 1, that we define as the intermediate product that could be refined to nickel sulfate. Thus, combining this share with laterite and sulphide shares of producing countries, the absolute sulphide and laterite production volumes for Class I Nickel can be determined. We corroborate McKinsey's finding with a Nickel industry expert interview and assume that all mined nickel sulphide is converted to Class 1 Nickel. Ultimately, we arrive at the global share of nickel laterite that is converted to Class 1 Nickel (33%).

Country- and deposit-specific data coverage shares in Figure 1c,f,h are computed by comparing the cumulative production of S&P Global assets with the battery-specific supply chain based on USGS and BGS data. In instances where the cumulative production capacity of S&P Global assets surpassed the country- and deposit-specific volume from the previous step, the data coverage value was set to 100% of the country- and deposit-specific volume. This was the case for Australian and Zimbabwean spodumene production.

1.8. Turning emission curves into probability distributions

The emission curves shown in Figure 1 build the basis for the construction of emission probability density functions for each commodity. To this end, non-parametric Gaussian kernel estimates from the Python statistical library "scipy" are used, and the automatic bandwidth selection according to Scott's rule[13] was amended by the value .05, yielding a better balance between fit and smoothness. This approach was chosen in light of the highly varying shapes of distributions. SI Figure 2 below shows in black for each four + one (nickel including laterite) commodities the assets' most likely CF (x-axis) and respective production volume (y-axis), normalised to one. In green, the figure shows the assets' discrete CF distribution (N=10,000 and normalised to one), but considering the lower and upper margin of errors using a triangular distribution and the most likely emission as mode. Based on the green histograms, the above-described probability density functions (blue) were derived. Visible peaks in the functions correspond to (groups of) assets with large production volumes in Figure 1a,d,g.



SI Figure 2: Normalised most likely material CF values (black), discrete material CF distribution based on assets' most likely CF and margins of error (green) and continuous probability density functions (blue) for lithium carbonate, nickel sulfate, nickel sulfate (incl. laterite), cobalt sulfate and graphite.

1.9. LCA library Brightway 2 and setting up Monte-Carlo simulations

The refining step and margins of error calculation for battery materials, the entire battery CF Monte-Carlo simulation, and all figures are generated using Python. The LCA library Brightway2 lies at the heart of the battery CF Monte-Carlo simulation. Ecoinvent 3.9.1 was loaded as a database into the Brightway2[14] project and supplemented with a standalone database where battery-cell-specific activities are transferred from Ecoinvent[15] into the foreground for streamlined access and modifications. While the repository used for this work is made publicly accessible, all files containing proprietary data (including S&P Global cost data, BNEF, Ecoinvent) have to be withheld for licensing reasons. For further information regarding the organisation of the repository and library versions, please refer to the readme.md and the environment.yml files, respectively. Both can be found in the root directory of the repository.

1.10. Additivity of variances

We follow the analytical derivation in the SI of [16] for the additivity property and the corresponding variance interaction term. Let the carbon footprint be expressed as the function *CF* of a multitude of exchanges and variables. In this context, we can group all exchanges that are not samples during the Monte Carlo simulation as a constant *c*. For simplicity, we show the additivity property for two variables *Li*, representing the unit CF of lithium carbonate, and *Ni*, representing the unit CF of nickel sulfate. The CF can consequently be written as

$$CF = f(Li, Ni)\ (1)$$

As Li and Ni are both independent random variables, the variance of the CF is

$$Var(CF) = Var(CF|Li = Li_0) + Var(CF|Ni = Ni_0) + \Lambda \ (2)$$

where *Var(CF|Li=Li$_0$)* refers to the variance of the CF function when the lithium variable is not varied (i.e., the variance driven through the nickel variable) and Λ to the interaction term. Solving for Λ yields

$$\Lambda = Var(CF) - Var(CF|Li = Li_0) - Var(CF|Ni = Ni_0) (3)$$

As the impact calculation in LCA of multiple exchanges is additive, we can use the linear property and establish for *CF = f(Li, Ni)* that it is of the form *CF = α + β*Li + γ*Ni*. The same logic applies for the full Monte Carlo simulation, where remaining variables cobalt, graphite and production location are also included. Calculating variances yields

$$Var(CF) = \beta^2 Var(Li) + \gamma^2 Var(Ni) \ (4)$$

$$Var(CF|Li = Li_0) = \gamma^2 Var(Ni) \ (5)$$

$$Var(CF|Ni = Ni_0) = \beta^2 Var(Li) \ (6)$$

Inserting (4)-(6) into (3) shows that the interaction term Λ is zero for the case of linear functions like *CF*. Thus, the variance of the total function can be expressed as the sum of variances from individual variables.

1.11. List of expert interviews

SI Table 2: List of expert interviews conducted in the context of this study.

No.	Industry and position	Focus	Date	Duration
1	Raw materials industry, R&D manager	Technical	20.10.2022	45 min
2	Academia & raw materials industry, Materials sustainability manager	Technical & policy	18.01.2022	47 min
3	Raw materials industry, Public policy manager	Technical & policy	16.12.2022	70 min
4	Academia, Senior scientist	Technical & policy	05.10.2022	72 min
5	LCA consultancy, CEO	Technical & policy	05.10.2022	35 min
6	Strategy consultancy, Associate	Policy	19.12.2022	40 min
7	Academia, Research associate	Policy	16.12.2022	30 min
8	Strategy consultancy, Associate	Policy	16.12.2022	37 min
9	Chemical industry, Executive employee	Policy	14.12.2022	38 min
10	Academia, Research principal	Technical	12.09.2023	60 min
11	Chemical industry, Sustainability manager	Technical	25.09.2023	45 min
12	LCA consultancy, R&D manager	Technical & policy	25.10.2023	30 min
13	Data provider, Senior analyst	Technical	31.10.2023	45 min
14	Battery industry, LCA analyst	Technical & policy	03.11.2023	50 min
15	Battery consultancy, CEO	Technical	03.11.2023	60 min

16	Battery industry association, Manager	Policy	11.12.2023	45 min
17	Cathode producer, CEO	Technical	29.01.2024	10 min

2. Supplementary Results

2.1. Tabulated results supporting main figures

2.1.1. Numerical boxplot results (underlying data for Figure 2b and 3b)

SI Table 3: Statistical values (5th, 50th, 95th percentile, standard deviation and variance) for datasets underlying Figure 2 and 3 and SI Figure 7,8 and 9.

	Region	5th percentile [kg_CO2/kWh]	50th percentile [kg_CO2/kWh]	95th percentile [kg_CO2/kWh]	Standard deviation [kg_CO2/kWh]	Variance [(kg_CO2/kWh)^2]
NMC	all	54.56	67.30	84.57	9.99	99.83
	CN	58.07	70.17	86.18	9.39	88.19
	US	54.25	63.95	81.58	8.86	78.56
	EU	51.32	62.06	79.37	9.73	94.64
	KRJP	58.54	67.84	84.51	8.40	70.51
LFP	all	53.99	62.32	68.56	4.60	21.14
	CN	54.28	62.49	68.61	4.54	20.64
	US	51.60	59.27	64.66	4.10	16.77
	EU	50.15	58.44	65.15	4.57	20.87
	KRJP	53.98	61.47	66.24	3.81	14.54
NMC (laterite included)	all	58.00	73.98	112.31	14.39	207.02
	CN	61.55	76.72	114.79	14.06	197.61
	US	56.91	70.71	108.52	13.20	174.19
	EU	54.49	68.92	108.87	14.28	204.06
	KRJP	60.66	74.89	112.77	13.40	179.44
LFP (solid state)	all	53.53	61.23	67.11	4.23	17.88
	CN	53.89	61.37	67.16	4.17	17.37
	US	51.50	58.13	63.14	3.67	13.47
	EU	50.59	57.23	63.95	4.12	17.01
	KRJP	53.85	60.31	65.03	3.51	12.32
LFP (hydrothermal)	all	56.47	73.18	80.68	8.13	66.17
	CN	56.72	73.32	80.81	8.12	65.98
	US	54.20	70.58	76.55	7.87	61.88
	EU	53.06	69.52	77.54	8.22	67.55
	KRJP	56.22	72.44	78.60	7.92	62.79

2.1.2. Breakdown of CF contributions (underlying data for Figure 2c and 3c)

For the sake of brevity, this SI contains only the CF breakdowns supporting main Figures 2c and 3c. The breakdown of the NMC scenario using the Nickel emission curve excluding laterite deposits and LFP batteries with purely solid-state and hydrothermal active material synthesis can be found in the accompanying Excel file “CF_breakdown (Fig2c_3c)”. Note that for the main figures, activities (rows in the tables below) were grouped together according to minimum thresholds and other criteria defined in “dict_labels_for_barcharts.xlsx” located on the Github repository.

2.1.2.1. NMC811 cathode (Figure 2c)

SI Table 4: Disaggregated relative and absolute CF contributions of exchanges and activities for the production of NMC811 battery cells (including laterite).

Exchange	**Input amount [variable]**	**Abs. CF contribution (min_electricity) [kg_CO2/kWh]**	**Abs. CF contribution (max_electricity) [kg_CO2/kWh]**	**Abs. CF contribution (weighted) [kg_CO2/kWh]**	**Rel. CF contribution (weighted) [%]**	**Exchange hierarchy**
NMC_battery_cell production	1.00	66.90	83.22	73.99	100.00	$NMC_battery_cell production
Graphite production	1.79	7.16	7.16	7.16	9.68	$NMC_battery_cell production$Anode_paste_for_NMC production$Graphite production
market for carbon black	0.00	0.02	0.02	0.02	0.03	$NMC_battery_cell production$Anode_paste_for_NMC production$market for carbon black
market for carboxymethyl cellulose, powder	0.01	0.11	0.11	0.11	0.14	$NMC_battery_cell production$Anode_paste_for_NMC production$market for carboxymethyl cellulose, powder
market for chemical factory, organics	0.00	0.05	0.05	0.05	0.07	$NMC_battery_cell production$Anode_paste_for_NMC production$market for chemical factory, organics
market for electricity, medium voltage	0.10	0.09	0.49	0.27	0.36	$NMC_battery_cell production$Anode_paste_for_NMC production$market for electricity, medium voltage
market for heat, district or industrial, natural gas	1.85	0.28	0.28	0.28	0.38	$NMC_battery_cell production$Anode_paste_for_NMC production$market for heat, district or industrial, natural gas
market for latex	0.00	0.05	0.05	0.05	0.07	$NMC_battery_cell production$Anode_paste_for_NMC production$market for latex
market for silicon, metallurgical grade	0.00	0.19	0.19	0.19	0.26	$NMC_battery_cell production$Anode_paste_for_NMC production$market for silicon, metallurgical grade
market for wastewater, average	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$Anode_paste_for_NMC production$market for wastewater, average
market for water, deionised	0.21	0.00	0.00	0.00	0.00	$NMC_battery_cell production$Anode_paste_for_NMC production$market for water, deionised
Calcium II	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$Calcium II
Carbonate	0.01	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$Carbonate

Hydroxide	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$Hydroxide
Lithium I	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$Lithium I
Lithium_carbonate production	1.82	7.29	7.29	7.29	9.86	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$Lithium_carbonate production
Water	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$Water
Water	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$Water
Water, cooling, unspecified natural origin	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$Water, cooling, unspecified natural origin
Water, river	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$Water, river
Water, well, in ground	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$Water, well, in ground
market for chemical factory, organics	0.00	0.03	0.03	0.03	0.05	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for chemical factory, organics
market for electricity, medium voltage	0.06	0.06	0.29	0.16	0.21	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for electricity, medium voltage
market for heat, from steam, in chemical industry	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for heat, from steam, in chemical industry
market for heat, from steam, in chemical industry	0.02	0.01	0.01	0.01	0.02	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for heat, from steam, in chemical industry
market for inert waste	-0.14	0.00	0.00	0.00	0.01	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for inert waste
market for inert waste	-0.04	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for inert waste
market for inert waste	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for inert waste
market for lime, hydrated, loose weight	0.00	0.00	0.00	0.00	0.01	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for lime, hydrated, loose weight
market for lime, hydrated, loose weight	0.14	0.54	0.54	0.54	0.72	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for lime, hydrated, loose weight

market for wastewater, average	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for wastewater, average
market for wastewater, average	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for wastewater, average
market for wastewater, average	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for wastewater, average
market for wastewater, average	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market for wastewater, average
market group for heat, district or industrial, natural gas	0.31	0.05	0.05	0.05	0.07	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market group for heat, district or industrial, natural gas
market group for tap water	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Li_hydroxide production$market group for tap water
Ammonia	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$NMC_hydroxide production$Ammonia
Co_sulfate production	1.19	4.78	4.78	4.78	6.46	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$NMC_hydroxide production$Co_sulfate production
Ni_sulfate production	4.80	19.19	19.19	19.19	25.94	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$NMC_hydroxide production$Ni_sulfate production
Water, cooling, unspecified natural origin	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$NMC_hydroxide production$Water, cooling, unspecified natural origin
market for ammonia, anhydrous, liquid	0.00	0.04	0.04	0.04	0.06	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$NMC_hydroxide production$market for ammonia, anhydrous, liquid
market for chemical factory, organics	0.00	0.15	0.15	0.15	0.20	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$NMC_hydroxide production$market for chemical factory, organics
market for heat, district or industrial, natural gas	13.30	2.03	2.03	2.03	2.74	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$NMC_hydroxide production$market for heat, district or industrial, natural gas
market for manganese sulfate	0.05	0.19	0.19	0.19	0.25	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$NMC_hydroxide production$market for manganese sulfate
market for sodium hydroxide, without water, in 50% solution state	0.29	1.50	1.50	1.50	2.03	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$NMC_hydroxide production$market for sodium hydroxide, without water, in 50% solution state

market for wastewater, unpolluted	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$NMC_hydroxide production$market for wastewater, unpolluted
Water	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$Water
market for chemical factory, organics	0.00	0.16	0.16	0.16	0.22	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$market for chemical factory, organics
market for electricity, medium voltage	2.60	2.42	12.52	6.80	9.20	$NMC_battery_cell production$NMC_cathode_paste production$Li_NMC_active_material production$market for electricity, medium voltage
N-methyl-2-pyrrolidone	0.00	0.00	0.00	0.00	0.00	$NMC_battery_cell production$NMC_cathode_paste production$N-methyl-2-pyrrolidone
market for N-methyl-2-pyrrolidone	0.00	0.06	0.06	0.06	0.08	$NMC_battery_cell production$NMC_cathode_paste production$market for N-methyl-2-pyrrolidone
market for carbon black	0.01	0.09	0.09	0.09	0.12	$NMC_battery_cell production$NMC_cathode_paste production$market for carbon black
market for chemical factory, organics	0.00	0.09	0.09	0.09	0.12	$NMC_battery_cell production$NMC_cathode_paste production$market for chemical factory, organics
market for electricity, medium voltage	0.18	0.16	0.85	0.46	0.62	$NMC_battery_cell production$NMC_cathode_paste production$market for electricity, medium voltage
market for heat, district or industrial, natural gas	10.59	1.61	1.61	1.61	2.18	$NMC_battery_cell production$NMC_cathode_paste production$market for heat, district or industrial, natural gas
market for polyvinylfluoride	0.01	0.60	0.60	0.60	0.81	$NMC_battery_cell production$NMC_cathode_paste production$market for polyvinylfluoride
market for aluminium collector foil, for Li-ion battery	0.03	1.79	1.79	1.79	2.41	$NMC_battery_cell production$market for aluminium collector foil, for Li-ion battery
market for aluminium, wrought alloy	0.03	1.57	1.57	1.57	2.12	$NMC_battery_cell production$market for aluminium, wrought alloy
market for battery separator	0.02	2.51	2.51	2.51	3.39	$NMC_battery_cell production$market for battery separator
market for chemical factory, organics	0.00	0.24	0.24	0.24	0.33	$NMC_battery_cell production$market for chemical factory, organics
market for copper collector foil, for Li-ion battery	0.12	4.33	4.33	4.33	5.85	$NMC_battery_cell production$market for copper collector foil, for Li-ion battery
market for copper, anode	0.03	0.80	0.80	0.80	1.08	$NMC_battery_cell production$market for copper, anode
market for electricity, medium voltage	1.26	1.17	6.07	3.30	4.46	$NMC_battery_cell production$market for electricity, medium voltage
market for electrolyte, for Li-ion battery	0.17	3.24	3.24	3.24	4.38	$NMC_battery_cell production$market for electrolyte, for Li-ion battery
market for extrusion, plastic film	0.00	0.01	0.01	0.01	0.01	$NMC_battery_cell production$market for extrusion, plastic film

market for heat, district or industrial, natural gas	13.29	2.02	2.02	2.02	2.74	$NMC_battery_cell production$market for heat, district or industrial, natural gas
market for polyethylene terephthalate, granulate, amorphous	0.00	0.04	0.04	0.04	0.05	$NMC_battery_cell production$market for polyethylene terephthalate, granulate, amorphous
market for polypropylene, granulate	0.00	0.01	0.01	0.01	0.01	$NMC_battery_cell production$market for polypropylene, granulate
market for sheet rolling, aluminium	0.03	0.07	0.07	0.07	0.10	$NMC_battery_cell production$market for sheet rolling, aluminium
market for sheet rolling, copper	0.03	0.07	0.07	0.07	0.10	$NMC_battery_cell production$market for sheet rolling, copper
market for sheet rolling, aluminium	0.03	0.11	0.11	0.11	0.17	$LFP_battery_cell production$market for sheet rolling, aluminium
market for sheet rolling, copper	0.03	0.10	0.10	0.10	0.16	$LFP_battery_cell production$market for sheet rolling, copper

2.1.2.2. LFP cathode (Figure 3c)

SI Table 5: Disaggregated relative and absolute CF contributions of exchanges and activities for the production of LFP battery cells (90% solid-state share).

Exchange	**Input amount [variable]**	**Abs. CF contribution (min_electricity) [kg_CO2/kWh]**	**Abs. CF contribution (max_electricity) [kg_CO2/kWh]**	**Abs. CF contribution (weighted) [kg_CO2/kWh]**	**Rel. CF contribution (weighted) [%]**	**Exchange hierarchy**
LFP_battery_cell production	1.00	58.08	68.15	62.32	100.00	$LFP_battery_cell production
Graphite production	1.36	8.51	8.51	8.51	13.66	$LFP_battery_cell production$Anode_paste_for_LFP production$Graphite production
market for carbon black	0.00	0.03	0.03	0.03	0.04	$LFP_battery_cell production$Anode_paste_for_LFP production$market for carbon black
market for carboxymethyl cellulose, powder	0.01	0.13	0.13	0.13	0.22	$LFP_battery_cell production$Anode_paste_for_LFP production$market for carboxymethyl cellulose, powder
market for chemical factory, organics	0.00	0.07	0.07	0.07	0.11	$LFP_battery_cell production$Anode_paste_for_LFP production$market for chemical factory, organics
market for electricity, medium voltage	0.08	0.14	0.71	0.38	0.61	$LFP_battery_cell production$Anode_paste_for_LFP production$market for electricity, medium voltage
market for heat, district or industrial, natural gas	1.38	0.33	0.33	0.33	0.53	$LFP_battery_cell production$Anode_paste_for_LFP production$market for heat, district or industrial, natural gas
market for latex	0.00	0.06	0.06	0.06	0.10	$LFP_battery_cell production$Anode_paste_for_LFP production$market for latex

market for wastewater, average	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$Anode_paste_for_LFP production$market for wastewater, average
market for water, deionised	0.18	0.00	0.00	0.00	0.00	$LFP_battery_cell production$Anode_paste_for_LFP production$market for water, deionised
Calcium II	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$Calcium II
Carbonate	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$Carbonate
Hydroxide	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$Hydroxide
Lithium I	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$Lithium I
Lithium_carbonate production	0.32	1.99	1.99	1.99	3.19	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$Lithium_carbonate production
Water	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$Water
Water	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$Water
Water, cooling, unspecified natural origin	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$Water, cooling, unspecified natural origin
Water, river	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$Water, river
Water, well, in ground	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$Water, well, in ground
market for chemical factory, organics	0.00	0.01	0.01	0.01	0.01	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for chemical factory, organics
market for electricity, medium voltage	0.01	0.02	0.07	0.04	0.06	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for electricity, medium voltage
market for heat, from steam, in chemical industry	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for heat, from steam, in chemical industry
market for heat, from steam, in chemical industry	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for heat, from steam, in chemical industry
market for inert waste	-0.02	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for inert waste
market for inert waste	-0.01	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for inert waste
market for inert waste	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for inert waste

market for lime, hydrated, loose weight	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for lime, hydrated, loose weight
market for lime, hydrated, loose weight	0.02	0.12	0.12	0.12	0.18	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for lime, hydrated, loose weight
market for wastewater, average	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for wastewater, average
market for wastewater, average	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for wastewater, average
market for wastewater, average	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for wastewater, average
market for wastewater, average	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market for wastewater, average
market group for heat, district or industrial, natural gas	0.04	0.01	0.01	0.01	0.02	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market group for heat, district or industrial, natural gas
market group for tap water	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Li_hydroxide production$market group for tap water
Water	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$Water
market for chemical factory, organics	0.00	0.02	0.02	0.02	0.03	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$market for chemical factory, organics
market for heat, district or industrial, natural gas	0.88	0.21	0.21	0.21	0.34	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$market for heat, district or industrial, natural gas
market for iron sulfate	0.03	0.05	0.05	0.05	0.07	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$market for iron sulfate
market for phosphoric acid, industrial grade, without water, in 85% solution state	0.02	0.14	0.14	0.14	0.23	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$market for phosphoric acid, industrial grade, without water, in 85% solution state
market for tap water	1.16	0.01	0.01	0.01	0.01	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$market for tap water
market for wastewater, average	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_hydrothermal production$market for wastewater, average
Ammonia	0.06	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_solid_state production$Ammonia
Carbon dioxide, fossil	0.04	0.26	0.26	0.26	0.41	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_solid_state production$Carbon dioxide, fossil
Lithium_carbonate production	1.12	6.98	6.98	6.98	11.20	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_solid_state production$Lithium_carbonate production

Oxygen	0.01	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_solid_state production$Oxygen
Water	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_solid_state production$Water
market for chemical factory, organics	0.00	0.21	0.21	0.21	0.33	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_solid_state production$market for chemical factory, organics
market for diammonium phosphate	0.25	3.22	3.22	3.22	5.17	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_solid_state production$market for diammonium phosphate
market for electricity, medium voltage	0.22	0.40	1.98	1.07	1.71	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_solid_state production$market for electricity, medium voltage
market for magnetite	0.14	0.83	0.83	0.83	1.33	$LFP_battery_cell production$LFP_cathode_paste production$Market_LFP production$LFP_solid_state production$market for magnetite
N-methyl-2-pyrrolidone	0.00	0.00	0.00	0.00	0.00	$LFP_battery_cell production$LFP_cathode_paste production$N-methyl-2-pyrrolidone
market for N-methyl-2-pyrrolidone	0.00	0.15	0.15	0.15	0.25	$LFP_battery_cell production$LFP_cathode_paste production$market for N-methyl-2-pyrrolidone
market for carbon black	0.02	0.33	0.33	0.33	0.52	$LFP_battery_cell production$LFP_cathode_paste production$market for carbon black
market for chemical factory, organics	0.00	0.14	0.14	0.14	0.22	$LFP_battery_cell production$LFP_cathode_paste production$market for chemical factory, organics
market for electricity, medium voltage	0.13	0.24	1.18	0.64	1.02	$LFP_battery_cell production$LFP_cathode_paste production$market for electricity, medium voltage
market for heat, district or industrial, natural gas	10.83	2.58	2.58	2.58	4.14	$LFP_battery_cell production$LFP_cathode_paste production$market for heat, district or industrial, natural gas
market for polyvinylfluoride	0.02	1.83	1.83	1.83	2.94	$LFP_battery_cell production$LFP_cathode_paste production$market for polyvinylfluoride
market for aluminium collector foil, for Li-ion battery	0.05	4.87	4.87	4.87	7.81	$LFP_battery_cell production$market for aluminium collector foil, for Li-ion battery
market for aluminium, wrought alloy	0.03	2.25	2.25	2.25	3.61	$LFP_battery_cell production$market for aluminium, wrought alloy
market for battery separator	0.02	3.36	3.36	3.36	5.39	$LFP_battery_cell production$market for battery separator
market for chemical factory, organics	0.00	0.38	0.38	0.38	0.60	$LFP_battery_cell production$market for chemical factory, organics
market for copper collector foil, for Li-ion battery	0.11	5.98	5.98	5.98	9.60	$LFP_battery_cell production$market for copper collector foil, for Li-ion battery
market for copper, anode	0.03	1.11	1.11	1.11	1.78	$LFP_battery_cell production$market for copper, anode
market for electricity, medium voltage	0.96	1.76	8.69	4.68	7.50	$LFP_battery_cell production$market for electricity, medium voltage
market for electrolyte, for Li-ion battery	0.22	6.66	6.66	6.66	10.69	$LFP_battery_cell production$market for electrolyte, for Li-ion battery
market for extrusion, plastic film	0.00	0.01	0.01	0.01	0.02	$LFP_battery_cell production$market for extrusion, plastic film

market for heat, district or industrial, natural gas	10.10	2.40	2.40	2.40	3.86	$LFP_battery_cell production$market for heat, district or industrial, natural gas
market for polyethylene terephthalate, granulate, amorphous	0.00	0.06	0.06	0.06	0.10	$LFP_battery_cell production$market for polyethylene terephthalate, granulate, amorphous
market for polypropylene, granulate	0.00	0.02	0.02	0.02	0.03	$LFP_battery_cell production$market for polypropylene, granulate
market for sheet rolling, aluminium	0.03	0.11	0.11	0.11	0.17	$LFP_battery_cell production$market for sheet rolling, aluminium
market for sheet rolling, copper	0.03	0.10	0.10	0.10	0.16	$LFP_battery_cell production$market for sheet rolling, copper

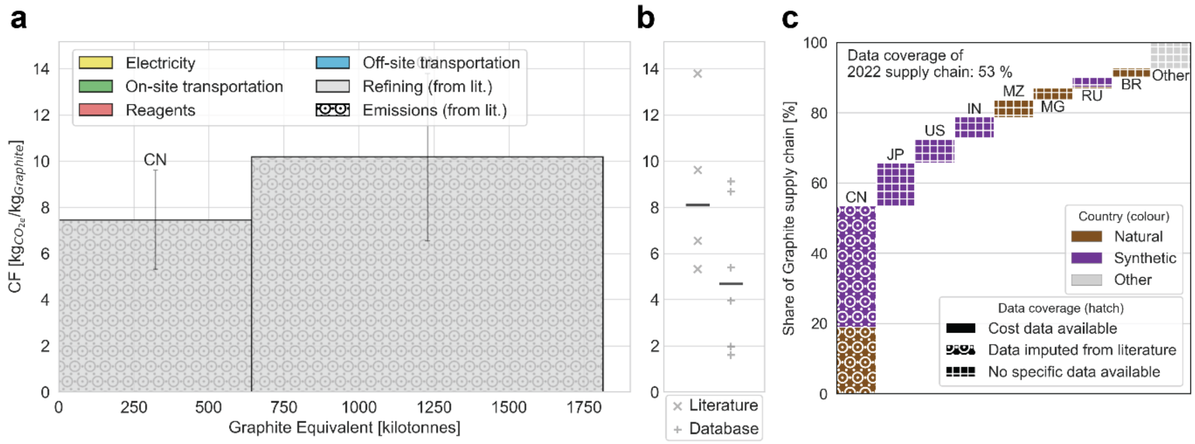
2.1.3. Tabulated variance breakdown for all chemistries and variations

SI Table 6: Variance of MC simulations with single parameter sampling and sums thereof. The sum is defined as 100 % (indicated by ≡) and contrasted to the variance of the MC simulation with simultaneous parameter sampling.

		Production location (Electricity)	Nickel distribution	Lithium distribution	Cobalt distribution	Graphite distribution	TOTAL (individual MC runs)	TOTAL (all parameters sampled)
NMC	Variance (abs.) [(kg_CO2 /kWh)^2]	27.45	50.58	12.80	2.65	2.32	95.80	99.83
	Variance (rel.) [%]	28.65	52.80	13.36	2.76	2.43	≡ 100.00	104.20
LFP	Variance (abs.) [(kg_CO2 /kWh)^2]	5.20	na	11.56	na	3.83	20.59	21.14
	Variance (rel.) [%]	25.25	na	56.17	na	18.58	≡ 100.00	102.69
NMC (laterite included)	Variance (abs.) [(kg_CO2 /kWh)^2]	27.27	154.85	12.65	2.71	2.34	199.83	207.02
	Variance (rel.) [%]	13.65	77.49	6.33	1.36	1.17	≡ 100.00	103.60
LFP (solid state)	Variance (abs.) [(kg_CO2 /kWh)^2]	5.46	na	8.88	na	3.90	18.23	17.88
	Variance (rel.) [%]	29.92	na	48.70	na	21.38	≡ 100.00	98.08
LFP (hydrothermal)	Variance (abs.) [(kg_CO2 /kWh)^2]	4.25	na	58.25	na	3.95	66.45	66.17
	Variance (rel.) [%]	6.40	na	87.66	na	5.94	≡ 100.00	99.58

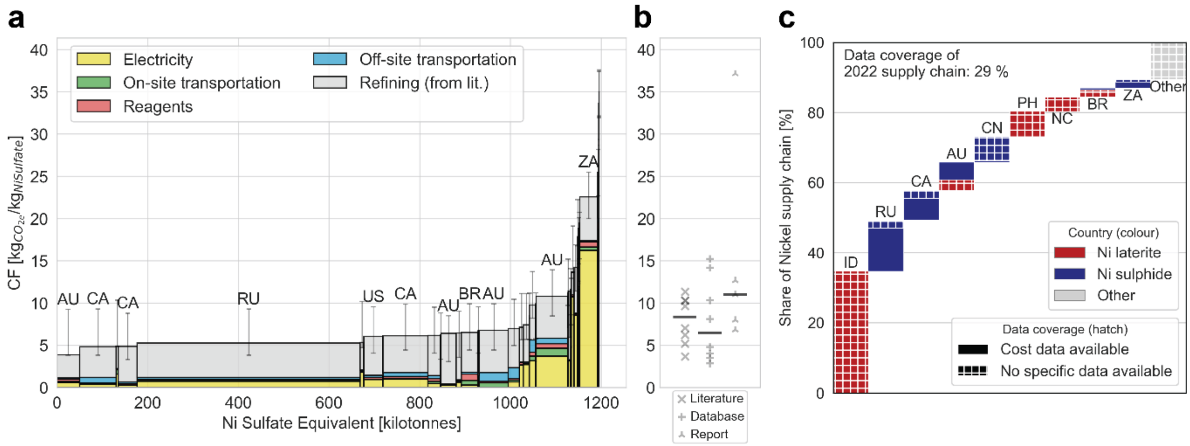
2.2. Additional emission curves + supply chain

2.2.1. Graphite



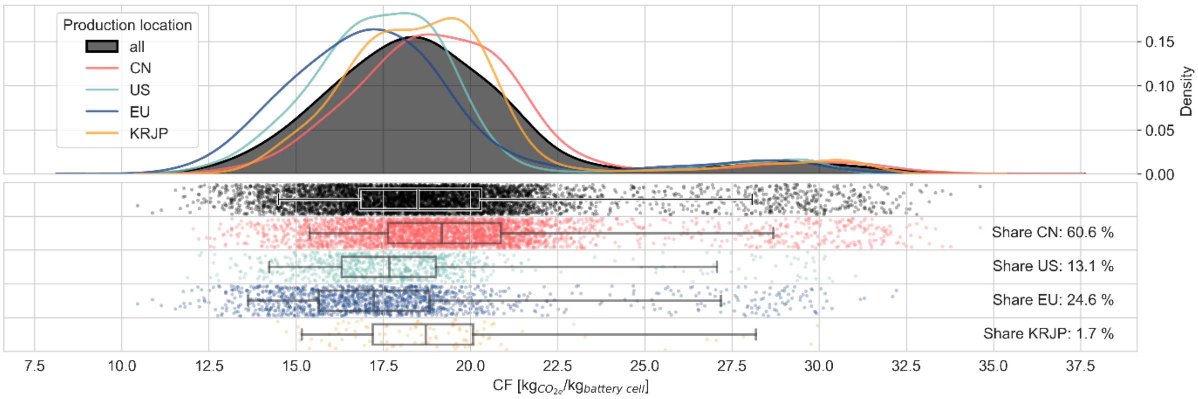
SI Figure 3: a: Emission curves for graphite. Dotted-grey bar segments refer to imputation-based data sources. Production volumes on the x-axis are indicated in chemical equivalents, i.e., encompassing all intermediate products that could be refined to battery-grade chemicals. b: Literature and database (Ecoinvent 3.9.1 and GREET 2021) values. Horizontal lines indicate respective medians. See SI Section 3 for underlying review work. c: Waterfall charts representing global 2022 battery-specific supply curves, i.e., encompassing all intermediate products that could be refined to battery-grade chemicals. Dotted bar segments refer to imputed data and chequered segments *indicate no data availability. Country acronyms: BR: Brazil, CN: China, IN: India, JP: Japan, MG: Madagascar, MZ: Mozambique, RU: Russia, US: United States of America.*

2.2.2. Nickel excluding laterite deposits

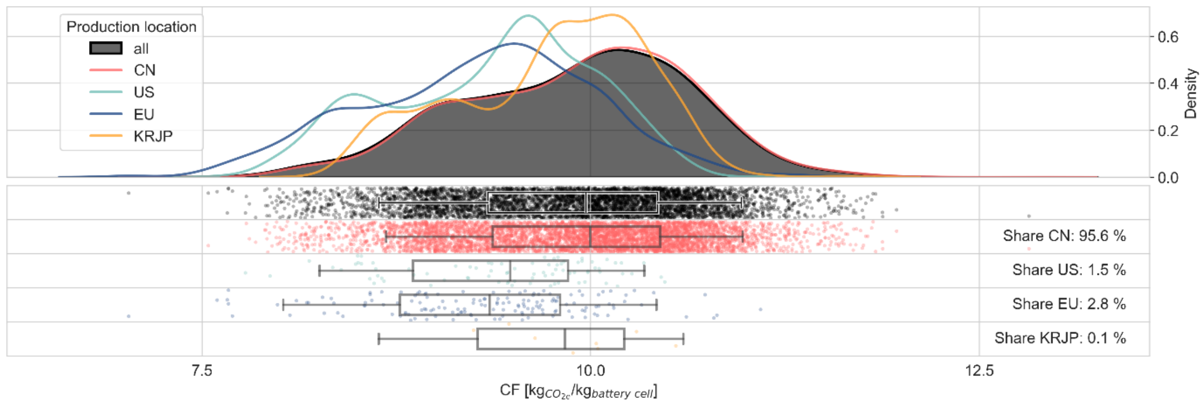


SI Figure 4: a: Emission curves for nickel sulfate excluding laterite mining. Coloured bar segments correspond to modelled-, and solid-grey to literature-based data sources. Production volumes on the x-axis are indicated in chemical equivalents, i.e., encompassing all intermediate products that could be refined to battery-grade chemicals. All sulfate products are in their anhydrous form. b: Literature, report and database (Ecoinvent 3.9.1 and GREET 2021) values. Horizontal lines indicate respective medians. See SI Section 3 for underlying review work. c: Waterfall charts representing global 2022 battery-specific supply curves, i.e., encompassing all intermediate products that could be refined to battery-grade chemicals. Chequered bar segments indicate no data availability. Country acronyms: AU: Australia, BR: Brazil, CA: Canada, CN: China, ID: Indonesia, NC: New Caledonia (sui generis collectivity of France), PH: Philippines, RU: Russia, ZA: South Africa.

2.3. Main Figure 2b and 3a in per-kg unit

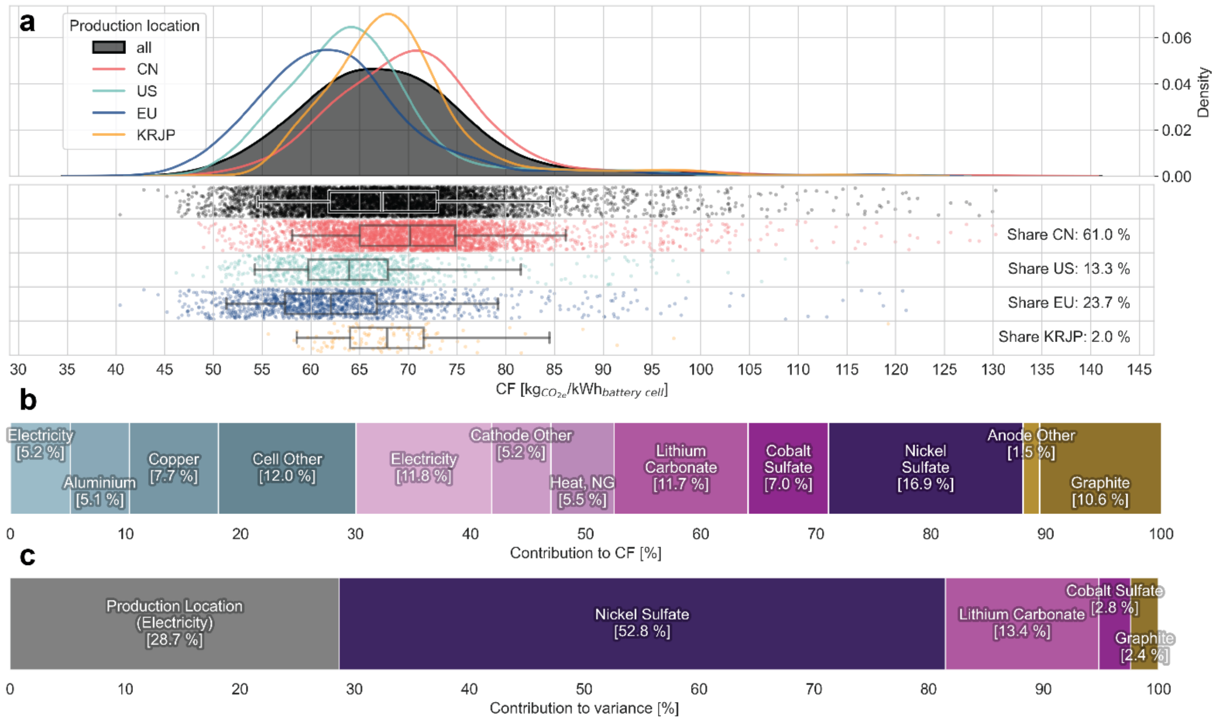


SI Figure 5: Probability density distribution and jitter plot for LIB cell with NMC811 cathode including nickel laterite in per-kg units. Caption comments from Figure 2 apply.



SI Figure 6: Probability density distribution and jitter plot for LIB cell with LFP cathode in per-kg units. Caption comments from Figure 3 apply.

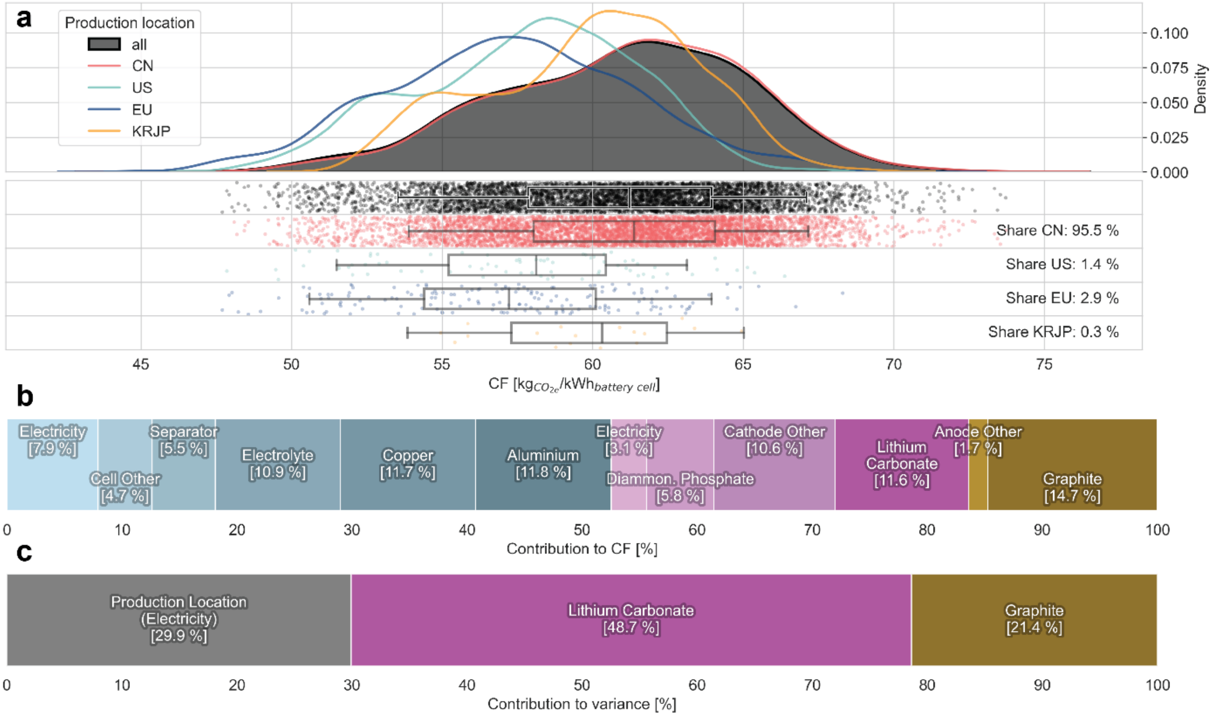
2.4. Battery Carbon Footprint distribution for NMC excluding nickel laterite



SI Figure 7: Probability density functions and jitter plots (a), CF drivers (b) and variance drivers (c) for LIB cell with NMC811 cathode using the emission curve from nickel sulfate excluding laterite, i.e., SI Figure 4a instead of Figure 1d. Caption comments from Figure 2 apply.

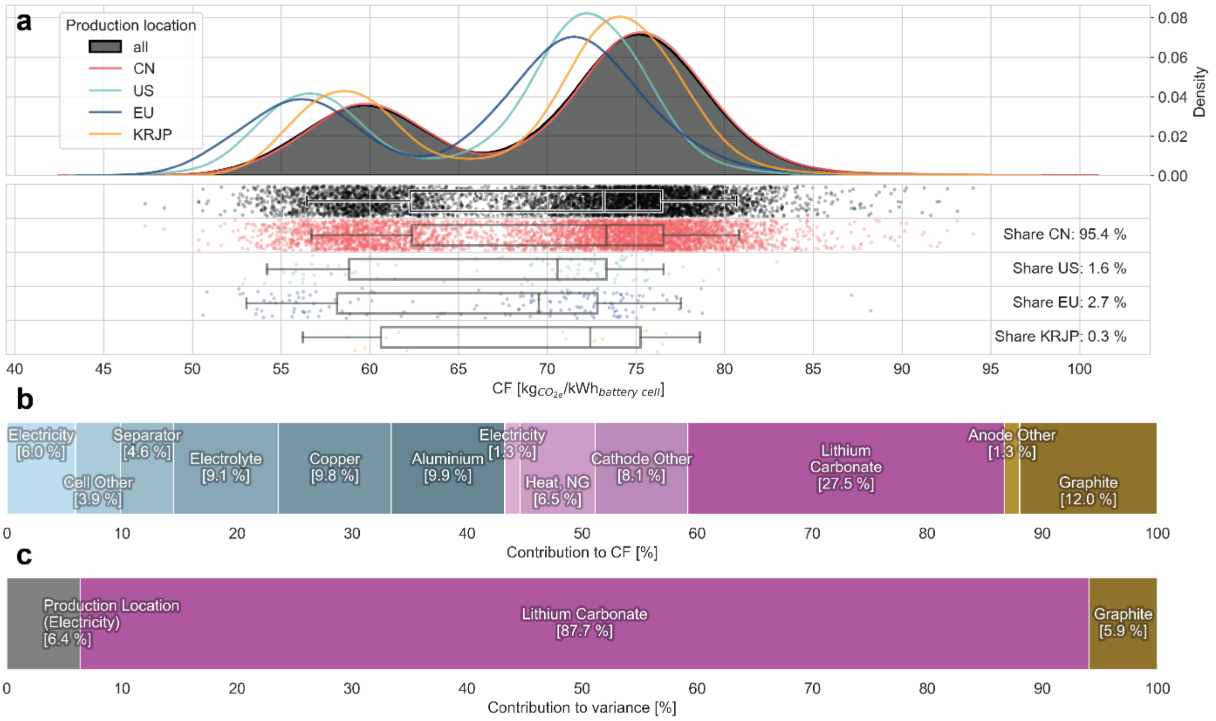
2.5. Battery Carbon Footprint distribution for various LFP synthesis routes

2.5.1. LFP - solid state active material synthesis



SI Figure 8: Probability density functions and jitter plots (a), CF drivers (b) and variance drivers (c) for LIB cell with LFP cathode using exclusively the solid-state synthesis route for LFP active material.

2.5.2. LFP - hydrothermal active material synthesis



SI Figure 9: Probability density functions and jitter plots (a), CF drivers (b) and variance drivers (c) for LIB cell with LFP cathode using exclusively the hydrothermal synthesis route for LFP active material.

3. Extensive literature review of battery material CFs

3.1. Methodology of literature review

The primary goal of this literature review was to compile a database of global warming potential (GWP) values for battery-grade raw materials used in lithium-ion batteries, including natural and synthetic graphite, nickel sulfate, cobalt sulfate, and lithium carbonate. Due to the scarce availability of life cycle assessment (LCA) studies for these materials, the review also encompassed studies on precursor materials, enabling the derivation of equivalent values for the battery-grade substances. These precursors encompass "Class 1 Nickel", nickel hydroxide, nickel metal, cobalt hydroxide, and lithium hydroxide.

To qualify for inclusion in the primary database, a publication must possess its own inventory for LCA calculations or significantly contribute to the understanding of battery-grade materials. The system boundary must be cradle-to-gate for the raw materials when examining battery cells or cathode materials. Exclusions were made for publications focusing on lab or pilot-scale processes, raw material recovery via recycling or phytomining (a.k.a., agromining), or those solely examining energy consumption. Additionally, studies with insufficient methodological clarity or significant errors were disregarded. Studies were also excluded if they did not allow for conversion to a gravimetric battery-grade raw material as the functional unit, particularly if the functional unit was expressed in terms of battery mass (kg), capacity (kWh), or cathode material mass (kg) and no disaggregation was possible.

The foundation of this database was a Scopus search, initiated by identifying and inputting relevant search keywords in various combinations for each raw material. For instance, keywords for graphite included "graphite", "battery-grade", "LCA", "GWP", and "emission". An outline of the utilised search terms is provided below in SI Section 3.3. Initially, titles were screened and promising publications were shortlisted, followed by an abstract and figure review to filter the relevant studies further. Publications that remained pertinent underwent a full-text review, with those meeting all criteria being catalogued in the primary database. Publications that did not meet all criteria but were still relevant were included in a peripheral database with a rationale for their exclusion from the primary database. Forward and backward citation tracking of the compiled studies was performed similarly, starting with title reviews, then abstracts and figures, and concluding with a full-text analysis. Lastly, studies in the databases were then analysed using connectedpapers.com, which identified additional relevant studies not found on Scopus or in the initial citations.

In the final phase of the literature review, grey literature was searched using Google advanced search and the tool scite.ai, employing the same keywords from the Scopus search. The first two pages of Google search results were examined, primarily yielding reports from private organisations and master's theses. Notably, the two reports covering nickel laterite production[6,18] were included in light of laterites' importance regarding LIB CF and lack for up-to-date peer-reviewed studies.

GWP values reported in all publications within the primary and peripheral databases were extracted. Additionally, contextual information such as the functional unit and allocation type for the LCA, the introduction of primary data, the study's system boundaries, including the production process, geographical scope, and life cycle inventory availability, were documented.

Moreover, our research utilised data from two key databases in life cycle assessment and environmental impact analysis: Ecoinvent 3.9.1 and GREET 2022. These resources were employed to investigate the production pathways of the aforementioned raw materials, from which GWP values were derived.

3.2. Results of literature review

Primary and peripheral databases for lithium, nickel, cobalt and graphite can be found in the Excel file “Literature_values.xlsx” contained in the repository. Sheets containing both qualified and peripheral studies are named “{commodity} - List”.

3.3. Metadata of literature review workflow

3.3.1. Lithium carbonate

SI Table 7: Search metadata for lithium literature review.

Scopus Search Key	# results	# results after title review	# results after abstract review	# results after text review
TITLE-ABS-KEY (lca AND battery AND (li2co3 OR lioh OR (lithium AND carbonate OR hydroxide)))	17	11	8	Schenker et al. (2022) Kelly et al. (2021) Manjong et al. (2021) Jiang et al (2020) Ambrose and Kendall (2019) Jiao et al (2020) Stamp et al. (2012)
TITLE-ABS-KEY (lca AND production OR mining AND li2co3 OR lioh OR (lithium AND carbonate OR hydroxide))	18	10	8	Schenker et al. (2022) Kelly et al. (2021) Manjong et al. (2021) Jiang et al (2020) Ambrose and Kendall (2019) Jiao et al (2020) Stamp et al. (2012)
TITLE-ABS-KEY (lithium AND lib AND gwp AND production)	5	3	3	0
TITLE-ABS-KEY (lithium AND (carbonate OR hydroxide) AND (lca OR lci OR "life cycle assessment" OR gwp) AND battery AND NOT recycling)	13	11	8	Schenker et al. (2022) Chordia et al. (2022) Kelly et al. (2021) Jiang et al (2020) Ambrose and Kendall (2019) Stamp et al. (2012)
TITLE-ABS-KEY (lithium AND battery AND grade AND lca OR lci AND emission* OR gwp AND battery OR batteries OR lib)	5	4	1	Kelly et al. (2021)
TITLE-ABS-KEY (lithium AND (batter* OR lib OR lithium-ion*) AND (emission* OR co? OR ghg OR gwp) AND (lca OR life AND cycle OR inventory) AND (environmental AND impact) AND (production OR manufacture OR manufacturing) AND NOT recycling OR recycled)	95	31	17	Kelly et al. (2021) Dai et al. (2019)
TITLE-ABS-KEY (lithium AND battery OR batteries AND mining OR refining OR production AND brine OR spodumene AND emission* OR lca OR lci)	24	12	9	Khakmardan et al. (2023) Schenker et al. (2022) Kelly et al. (2021) Manjong et al. (2021) Jiang et al (2020) Telsnig et al. (2017) Stamp et al. (2012)
TITLE-ABS-KEY (lca AND (gwp OR emission* OR ghg OR co2) AND battery AND (li2co3 OR lioh OR (lithium AND (carbonate OR hydroxide))) AND (brine OR ore OR spodumene) AND (production OR manufacture OR mining))	3	2	2	Kelly et al. (2021) Manjong et al. (2021)

Scopus Search Key	# results	# results after title review	# results after abstract review	# results after text review
TITLE-ABS-KEY (lca OR (gwp OR emission* OR ghg OR co2) AND battery AND (li2co3 OR lioh OR (lithium AND (carbonate OR hydroxide))) AND (spodumene OR ore OR brine) AND (production OR manufacture OR mining))	17	11	7	Schenker et al. (2022) Kelly et al. (2021) Manjong et al. (2021) Jiang et al (2020) Ambrose and Kendall (2019) Telsnig et al. (2017) Stamp et al. (2012)
TITLE-ABS-KEY (lithium AND (carbonate OR hydroxide) AND (spodumene OR ore OR brine) AND (production OR manufactur* OR mining) AND (lca OR lci) AND (battery OR batteries OR lib))	10	8	6	Schenker et al. (2022) Kelly et al. (2021) Manjong et al. (2021) Jiang et al (2020) Ambrose and Kendall (2019) Stamp et al. (2012)
TITLE-ABS-KEY (lithium AND (carbonate OR hydroxide OR metal) AND (battery AND grade OR "raw material*") AND lca OR ghg OR emission*)	69	13	9	Kelly et al. (2021) Manjong et al. (2021) Ambrose and Kendall (2019) Jiao et al (2020)
TITLE-ABS-KEY (lithium AND (carbonate OR hydroxide) AND (lca OR ghg OR emission*) AND inventory)	10	4	4	Schenker et al. (2022) Manjong et al. (2021) Jiang et al (2020) Stamp et al. (2012)
TITLE-ABS-KEY (lithium AND (lca OR lci) AND (emission* OR co2 OR ghg OR gwp) AND (mining OR refining OR upstream OR production) AND (battery OR lib OR batteries) AND NOT (recycling OR recycled OR spent))	62	20	19	Kelly et al. (2021) Dai et al. (2019)

3.3.2. Nickel sulfate

SI Table 8: Search metadata for nickel literature review.

Scopus Search Key	# results	# results after title review	# results after abstract review	# results after text review
TITLE-ABS-KEY (nickel AND sulfate AND lca)	15	4	3	Jiao et al (2020)
TITLE-ABS-KEY (nickel AND sulfate AND production AND environmental AND impacts)	57	7	3	Jiao et al (2020)
TITLE-ABS-KEY (nickel AND battery AND lca)	92	25	6	Jiao et al (2020) Yin et al (2019) Dai et al (2019) Majeau-Bettez et al (2011)
TITLE-ABS-KEY (nickel AND battery AND grade AND lca)	2	1	1	Jiao et al (2020)
TITLE-ABS-KEY (nickel AND battery AND lci)	7	6	3	Majeau-Bettez et al (2011)

Scopus Search Key	# results	# results after title review	# results after abstract review	# results after text review
TITLE-ABS-KEY (nickel AND battery AND mining AND refining AND emission* OR lca)	5	1	1	0
TITLE-ABS-KEY (nickel AND (mining OR refining OR production) AND (emission* OR co? OR gwp)) AND (LIMIT-TO (EXACTKEYWORD , "Lithium-ion Batteries"))	70	18	5	Dai et al (2019) Yin et al (2019) Winjobi et al (2022)
TITLE-ABS-KEY (nickel AND (sulfate OR sulfate) AND (mining OR refining OR production) AND (emission* OR co? OR gwp)) AND (LIMIT-TO (EXACTKEYWORD , "Lithium-ion Batteries"))	2	0	1	0
TITLE-ABS-KEY (nickel AND (sulfide OR sulphide) AND (batter* OR lib OR lithium-ion*) AND (emission* OR co? OR ghg OR gwp) AND (lca OR life AND cycle))	3	0	0	0
TITLE-ABS-KEY (nickel AND (batter* OR lib OR lithium-ion*) AND (emission* OR co? OR ghg OR gwp) AND (lca OR life AND cycle OR inventory) AND (environmental AND impact))	68	27	12	Majeau-Bettez et al (2011) Dai et al (2019) Winjobi et al (2022)
TITLE-ABS-KEY (nickel AND sulfate OR sulfate AND dataset*)	24	1	1	0
TITLE-ABS-KEY (niso4 AND batter* AND lithium-ion OR lib)	17	3	2	Jiao et al (2020)
TITLE-ABS-KEY (niso4 AND batter* AND lithium-ion OR lib AND emission OR co? OR gwp OR lca)	2	1	1	Jiao et al (2020)
TITLE-ABS-KEY (sulfate OR sulfate AND batter* AND gwp OR emission* OR co? OR impact AND lca)	11	5	4	Jiao et al (2020)
TITLE-ABS-KEY (nickel AND sulfate OR sulfate AND cathode AND material AND gwp OR co? OR emission* OR lca)	25	4	2	Jiao et al (2020)
TITLE-ABS-KEY (nickel AND sulfate OR sulfate AND automotive AND impact* OR lca OR life OR emission* OR ghg OR co?)	14	1	0	0
TITLE-ABS-KEY ("nickel sulfate" OR "nickel sulfate" AND lca OR "life-cycle" OR "life cycle" AND gwp OR emission? OR co? OR "environment* impact" OR energy AND batter* OR lib OR "lithium ion" OR "lithium-ion" OR "cathode material")	8	6	4	Jiao et al (2020)
TITLE-ABS-KEY (nickel AND "class 1" OR "nickel metal" AND lca)	25	9	5	Wei et al (2020) Jiao et al (2020) Majeau-Bettez et al (2011)
"nickel class I" OR "nickel metal" AND production AND "environmental impact?" OR lca AND (LIMIT-TO (EXACTKEYWORD , "Lithium-ion Batteries"))	218	43	18	Winjobi et al (2022) Jiao et al (2020) Yin et al (2019) Dai et al (2019) Majeau-Bettez et al (2011)

Scopus Search Key	# results	# results after title review	# results after abstract review	# results after text review
nickel AND "class I" OR "class 1" OR "nickel metal" AND emission? OR impact OR lca OR lci OR inventory OR gwp OR co? OR ghg AND (LIMIT-TO (EXACTKEYWORD , "Lithium-ion Batteries")) AND (EXCLUDE (EXACTKEYWORD , "Recycling")) AND (LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "EART"))	176	28	8	Winjobi et al (2022) Yin et al (2019) Majeau-Bettez et al (2011)
nickel AND "class I" OR "class 1" OR "nickel metal" AND emission? OR gwp OR co? AND lca AND (LIMIT-TO (EXACTKEYWORD , "Lithium-ion Batteries")) AND (EXCLUDE (EXACTKEYWORD , "Recycling"))	100	35	10	Winjobi et al (2022) Jiao et al (2020) Yin et al (2019) Dai et al (2019) Majeau-Bettez et al (2011)
TITLE-ABS-KEY (nickel AND "class I" OR metal AND batter* AND lca)	49	19	7	Jiao et al (2020) Majeau-Bettez et al (2011)
TITLE-ABS-KEY (nickel AND "class I" OR metal AND batter* AND lci)	3	2	1	Majeau-Bettez et al (2011)
TITLE-ABS-KEY (nickel AND "class I" OR metal AND batter* AND mining OR refining OR production AND emission? OR ghg OR gwp)	63	15	8	Winjobi et al (2022)
TITLE-ABS-KEY (nickel AND "class I" OR metal AND batter* OR lib OR lithium-ion AND emission? OR co? OR ghg OR gwp AND lca OR "life cycle" OR "life-cycle")	46	14	10	Winjobi et al (2022) Majeau-Bettez et al (2011)
TITLE-ABS-KEY (nickel AND "class I" OR metal AND batter* OR lib OR lithium-ion AND emission? OR co? OR ghg OR gwp AND inventory OR "environmental impact")	46	15	9	Winjobi et al (2022) Majeau-Bettez et al (2011)
TITLE-ABS-KEY (nickel AND "class I" OR metal AND dataset AND lithium-ion OR batter* OR lib)	14	1	0	0
TITLE-ABS-KEY (nickel AND "class I" OR "class 1" OR metal AND batter* AND lithium-ion OR lib AND emission OR co? OR gwp OR lca) AND (EXCLUDE (EXACTKEYWORD , "Recycling")) AND (LIMIT-TO (EXACTKEYWORD , "Nickel")) AND (LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "ENVI"))	31	3	2	Majeau-Bettez et al (2011)
TITLE-ABS-KEY (nickel AND "class I" OR "class 1" OR metal AND batter* AND lithium-ion OR lib AND emission OR co? OR gwp OR lca OR impact) AND (LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "ENVI")) AND (LIMIT-TO (EXACTKEYWORD , "Nickel") OR EXCLUDE (EXACTKEYWORD , "Recycling"))	42	3	2	Majeau-Bettez et al (2011)
TITLE-ABS-KEY (nickel AND "class I" OR "class 1" OR metal AND cathode AND material AND gwp OR co? OR emission* OR lca) AND (LIMIT-TO (EXACTKEYWORD , "Lithium-ion Batteries")) AND (EXCLUDE (EXACTKEYWORD , "Recycling")) AND (LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "ENVI"))	36	5	2	0

Scopus Search Key	# results	# results after title review	# results after abstract review	# results after text review
TITLE-ABS-KEY (nickel AND "class 1" OR "class I" OR metal AND automotive AND impact* OR lca OR life OR emission* OR ghg OR co?) AND (EXCLUDE (EXACTKEYWORD , "Recycling") OR LIMIT-TO (EXACTKEYWORD , "Nickel"))	60	2	0	0
TITLE-ABS-KEY (nickel AND "class 1" OR "class I" OR metal AND lca OR life OR "life-cycle" OR "life cycle" AND gwp OR emission? OR ghg OR co? OR "environmental impact" AND batter* OR lib OR "lithium ion" OR "lithium-ion" AND cathode OR "cathode material")	43	13	9	Winjobi et al (2022) Jiao et al (2020)

3.3.3. Cobalt sulfate

SI Table 9: Search metadata for cobalt literature review.

Scopus Search Key	# results	# results after title review	# results after abstract review	# results after text review
TITLE-ABS-KEY (cobalt AND sulfate OR sulfate AND lca)	11	5	4	Chordia et al (2021) Rinne et al. (2021) Jiao et al (2020)
TITLE-ABS-KEY (cobalt AND (sulfate OR sulfate) AND battery AND lca)	**8**	4	1	Chordia et al (2021) Rinne et al. (2021) Jiao et al (2020)
TITLE-ABS-KEY (cobalt AND production AND lca) AND NOT (recycling OR recycled)	11	2	0	0
TITLE-ABS-KEY (cobalt AND battery AND lca) AND NOT (recycling OR recycled)	8	4	3	Majeau-Bettez et al. (2011)
TITLE-ABS-KEY (cobalt AND battery AND grade AND (lca OR lci))	4	3	2	Rinne et al. (2021) Jiao et al (2020)
TITLE-ABS-KEY ("Life Cycle Assessment" AND "cobalt" AND "battery-grade")	2	2	2	Rinne et al. (2021)
TITLE-ABS-KEY (cobalt AND battery AND mining AND refining AND emission* OR lca)	5	2	1	Zhang et al. (2021)
TITLE-ABS-KEY (*cobalt* AND (*mining* OR *refining* OR *production*) AND (*emission** OR *co?* OR *gwp*)) AND (LIMIT-TO (EXACTKEYWORD , *"Lithium-ion Batteries"*))	88	15	10	Winjobi et al (2022) Dai et al. (2019)

Scopus Search Key	# results	# results after title review	# results after abstract review	# results after text review
TITLE-ABS-KEY (*"cobalt sulfate"* OR *"cobalt sulfate"* AND *lca* OR *"life-cycle"* OR *"life cycle"* AND *gwp* OR *emission?* OR *co?* OR *"environment* impact"* OR *energy* AND *batter** OR *lib* OR *"lithium ion"* OR *"lithium-ion"* OR *"cathode material"*)	7	5	3	Chordia et al (2021) Rinne et al. (2021) Zhang et al. (2021)
TITLE-ABS-KEY (*cobalt* AND *"battery grade"* OR *"sulfate"* OR *"sulfate"* OR *"metal"* AND *"production"* OR *"mining"* AND *"life cycle"* AND NOT *"recycling"*)	43	16	6	Chordia et al (2021) Rinne et al. (2021) Zhang et al. (2021) Jiao et al (2020)
TITLE-ABS-KEY (cobalt AND lca OR lci OR "life cycle assessment" OR gwp AND battery AND NOT recycling)	67	20	14	Winjobi et al (2022) Accardo et al. (2021) Chordia et al (2021) Rinne et al. (2021) Zhang et al. (2021) Kelly et al. (2020) Jiao et al (2020) Dai et al. (2019) Majeau-Bettez et al. (2011)
TITLE-ABS-KEY (cobalt AND (sulfate OR sulfate OR chemical OR chemicals OR metal OR "battery grade") AND lca AND NOT recycling)	54	16	7	Chordia et al (2021) Jiao et al (2020) Majeau-Bettez et al. (2011)
TITLE-ABS-KEY (cobalt AND (chemicals OR metal OR powder) AND (production OR mining) AND (lca OR lci OR "impact assessment" OR inventory) AND NOT (recycling OR recycled))	129	6	3	Rinne et al. (2021) Zhang et al. (2021) Jiao et al (2020)
TITLE-ABS-KEY (cobalt AND battery OR batteries AND mining OR refining AND emission* OR lca OR lci)	35	10	5	Chordia et al (2021) Zhang et al. (2021) Kelly et al. (2020) Jiao et al (2020)
TITLE-ABS-KEY (cobalt AND (batter* OR lib OR lithium-ion*) AND (emission* OR co? OR ghg OR gwp) AND (lca OR life AND cycle OR inventory) AND (environmental AND impact))	52	12	10	Winjobi et al (2022) Rinne et al. (2021) Chordia et al (2021) Zhang et al. (2021) Kelly et al. (2020) Dai et al. (2019) Majeau-Bettez et al. (2011)

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3.3.4. Battery-grade graphite

SI Table 10: Search metadata for graphite literature review.

Scopus Search Key	# results	# results after title review	# results after abstract review	# results after text review
TITLE-ABS-KEY (graphite AND battery-grade AND lca)	4	4	3	Surovsteva et al (2022) Engels et al (2022a)
TITLE-ABS-KEY (graphite AND battery AND lca)	27	10	5	Surovsteva et al (2022) Engels et al (2022a) Gao et al (2018)
TITLE-ABS-KEY (graphite AND battery AND lci)	1	1	1	0
TITLE-ABS-KEY (graphite AND battery AND mining OR refining OR production AND lca)	15	8	5	Surovsteva et al (2022) Engels et al (2022a) Gao et al (2018)
TITLE-ABS-KEY (graphite AND battery AND gwp AND lca)	2	2	1	Engels et al (2022a)
TITLE-ABS-KEY (graphite AND battery AND gwp AND lca OR (life AND cycle))	3	2	1	Engels et al (2022a)
TITLE-ABS-KEY (graphite AND (mining OR refining OR production) AND (emission* OR co? OR gwp)) AND (LIMIT-TO (EXACTKEYWORD , "Lithium-ion Batteries"))	35	8	4	Engels et al (2022a)
TITLE-ABS-KEY (graphite AND (batter* OR lib OR lithium-ion*) AND (emission* OR co? OR ghg OR gwp) AND (lca OR life AND cycle))	60	5	3	Engels et al (2022a) Gao et al (2018)
TITLE-ABS-KEY (graphite AND (lca OR life*) AND (emission* OR co? OR ghg OR gwp)) AND (LIMIT-TO (EXACTKEYWORD , "Lithium-ion Batteries"))	81	9	5	Engels et al (2022a)
TITLE-ABS-KEY (graphite AND (lca OR life*) AND (emission* OR co? OR ghg OR gwp) AND (mining OR refining OR upstream))	19	2	2	Engels et al (2022a) Gao et al (2018)
TITLE-ABS-KEY (graphite AND (lca OR life*) AND (emission* OR co? OR ghg OR gwp OR energy) AND (mining OR refining OR upstream OR production)) AND (LIMIT-TO (EXACTKEYWORD , "Lithium-ion Batteries")) AND (EXCLUDE (EXACTKEYWORD , "Recycling"))	51	8	4	Surovsteva et al (2022) Engels et al (2022a)
TITLE-ABS-KEY (graphite AND (primary AND data) AND (lca OR life*))	27	2	2	Engels et al (2022a)
TITLE-ABS-KEY (natural AND graphite AND lca)	12	6	5	Engels et al (2022a) Zhang et al (2018) Surovtseva et al (2022) Gao et al (2018)

Scopus Search Key	# results	# results after title review	# results after abstract review	# results after text review
TITLE-ABS-KEY (natural AND graphite AND lca OR (life AND cycle)) AND (LIMIT-TO (EXACTKEYWORD , "Lithium-ion Batteries"))	42	4	2	Engels et al (2022a) Surovtseva et al (2022)
TITLE-ABS-KEY (natural AND graphite AND primary AND data)	22	1	1	Engels et al (2022a)
TITLE-ABS-KEY (synthetic AND graphite AND lca)	4	2	1	Surovtseva et al (2022)
TITLE-ABS-KEY (synthetic AND graphite AND lca OR (life AND cycle))	51	6	3	Surovtseva et al (2022)
TITLE-ABS-KEY (graphite AND anode AND environmental AND impact)	66	16	4	Engels et al (2022a) Surovtseva et al (2022)
TITLE-ABS-KEY (graphite AND carbon AND footprint AND batter*)	17	1	0	0
TITLE-ABS-KEY (graphite AND (carbon AND footprint OR lca OR gwp) AND automotive)	8	1	1	0

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