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Explorative Carbon Footprint of Product Study for Nordic NMC811 and LFP Battery Cells

Battery Norway

11/07/2025

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Our Statement

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Carbon Footprint of Product (CFP) is a climate change focussed method utilising Life Cycle Assessment (LCA) for greenhouse gas (GHG) emission accounting with an inherent level of uncertainty, and it should not be seen as having the same level of precision as financial accounting. CFP requires a very large amount of data, particularly to calculate all the inputs and outputs for every step.

Primary data inputs were collected from Morrow Batteries, but most data were based on secondary sources given the study scope. Databases are often used for secondary data since it is impractical to collect all the necessary data from the original sources. The report does not claim to be exhaustive, nor does it claim to cover all relevant products. While steps have been taken to ensure accuracy, the listing or featuring of a particular product or company does not constitute an endorsement by Minviro.

 This CFP has undergone an independent critical panel review and is intended to support comparative assertions.

Battery Norway commissioned Minviro Ltd. as a LCA practitioner in March 2025 to produce a CFP that exploratively investigates Nordic lithium-ion battery cell production and raw materials. The intended application was to evaluate the CO_2 eq. value-proposition of Nordic battery supply-chains, with the study outcomes to be publicly communicated.

The goal and scope are defined to be consistent with the study's intended application, the reason for conducting the LCA, and the data available. No bias has been given toward the intended audience.

Signature

Joris Šimaitis

Dr Joris Šimaitis, 11/07/2025

Table: Document details.

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Version	**Revision**	**Date**	**Authors**	**Reviewers**	**Comments**
Version 1.0	1	28.05.2025	Joris Šimaitis, Haley McKercher	Haley McKercher	Editorial changes and corrections, internal QA.
Version 1.1	2	10.06.2025	Joris Šimaitis, Haley McKercher	Battery Norway and Consortium	Minor changes to declare Battery Norway funding and contributions. Vianode requested small inclusion of detail surrounding Fortum collaboration and further insight into their process impact reductions.
Version 1.2	3	11.07.2025	Joris Šimaitis, Haley McKercher	Mudit Chordia, Eleonora Crenna, Riina Aromaa-Stubb	Several revisions have been implemented for editorial corrections, clarifications, and added discussions. Use phase results have been removed to maintain consistency to study goals. Minor corrections to the recycling model with minor changes to results. Full comments and revisions attached to Appendix B.

Executive Summary

In March 2025, Battery Norway received financial support from The Nordic Council of Ministers to commission Minviro Ltd. to conduct a Carbon Footprint of Product (CFP) study on Nordic lithium-ion battery cell production and raw materials. The goal was to assess the CO_2 eq. value of Nordic supply chains primarily intended for public communications and stakeholder engagement; and not product decision-making purposes. During the execution of the project, a steering committee with representatives from Battery Norway, Finnish Battery Industries and Swedish Energy Agency followed up the progress and gave valuable input.

This partial CFP assessed the potential cradle-to-gate climate change impacts for manufacturing prismatic battery cells using two chemistries: NMC811 and LFP. It evaluated four Nordic raw material routes against global averages for nickel sulfate, cobalt sulfate, lithium hydroxide and graphite, and conducted cell manufacturing comparisons that represented electricity mixes of major battery production locations in China, the United States, and across the European continent ("Europe"). As an additional cradle-to-grave system boundary extension, the study also included a non-comparative independent analysis of the potential impacts of Finnish hydrometallurgical recycling of NMC811 batteries. The functional unit is per 1 kWh of energy capacity.

Cell manufacturing scenarios were based primarily on secondary data from literature and Minviro's Parameterised Battery LCI model to represent Nordic conditions, with additional primary inputs from Morrow Batteries for LFP cells. Minviro's background database was used for Nordic raw material routes, including nickel and cobalt sulfate from Terrafame, lithium hydroxide from Keliber, and synthetic graphite from Vianode, drawing on previous LCAs and technical reports. Global average commodity routes were also modelled for comparison, typically dominated by a single pathway such as the Indonesia–China HPAL route for nickel sulfate. Cell manufacturing comparisons were evaluated using regional electricity mixes, weighted by current battery production capacity.

The NMC811 recycling analysis was based on Minviro's internal model (loosely depicting Fortum) that modelled closed-loop impacts of recovering battery-grade metals. LFP recycling was not considered due to project constraints and is subject to future work. Remaining background data were sourced from ecoinvent 3.10 and Carbon Minds. The impact weighted data quality

assessment rated overall study data as “Good” to “Very Good,” with most datasets reflecting the 2023 reference year.

Key study results are presented in Figures ES-1 and ES-2, and Tables ES-1 and ES-2. Nordic battery raw materials demonstrated 51-85% lower carbon footprints than global averages, driven by efficient processes coupled with low-carbon power. As a result, Swedish NMC811 and Norwegian LFP cells achieved significantly lower impacts. Using global average materials, NMC811 cells showed 13-17% lower impacts with 110.2 kg CO_2 eq. per kWh and LFP cells 25% to 33% lower of 71.1 kg CO_2 eq. per kWh compared to China, Europe, and the United States. With Nordic materials, reductions increased to 53-55% for NMC811 and 49-55% for LFP, lowering absolute impacts to 60.1 and 48.8 kg CO_2 eq. per kWh, respectively.

The uncertainty assessment demonstrated that using the Swedish or Norwegian electricity mix alone in cell manufacturing resulted in discernably lower carbon footprints in 37-49% instances for NMC811 and 74-92% cases for LFP compared to other regions. However, when Nordic-sourced raw materials were also incorporated, lower carbon footprints were discernable in 100% of cases. This highlights the considerable decarbonisation potential of combining both low-carbon Nordic electricity and raw materials. LFP cells also showed more consistently lower carbon footprints than NMC811, as they do not use nickel, which still remained a critical NMC811 hotspots even when Nordic raw materials are used.

The cradle-to-grave extension evaluating Finnish hydrometallurgical recycling for Swedish NMC811 batteries found that the recycling process increased the carbon footprint from 60.1 to 71.6 kg CO_2 eq. per kWh. However, in a closed loop scenario where recovered battery grade metals replace primary production, the footprint was reduced to 56.2 kg CO_2 eq. per kWh. Hence, a net carbon benefit of 6% was achieved, suggesting potential value in circular approaches when integrated with low-carbon supply chains. However, this benefit is modest and the conclusion is subject to several underlying assumptions and uncertainties that require further investigation before definitive conclusions can be drawn.

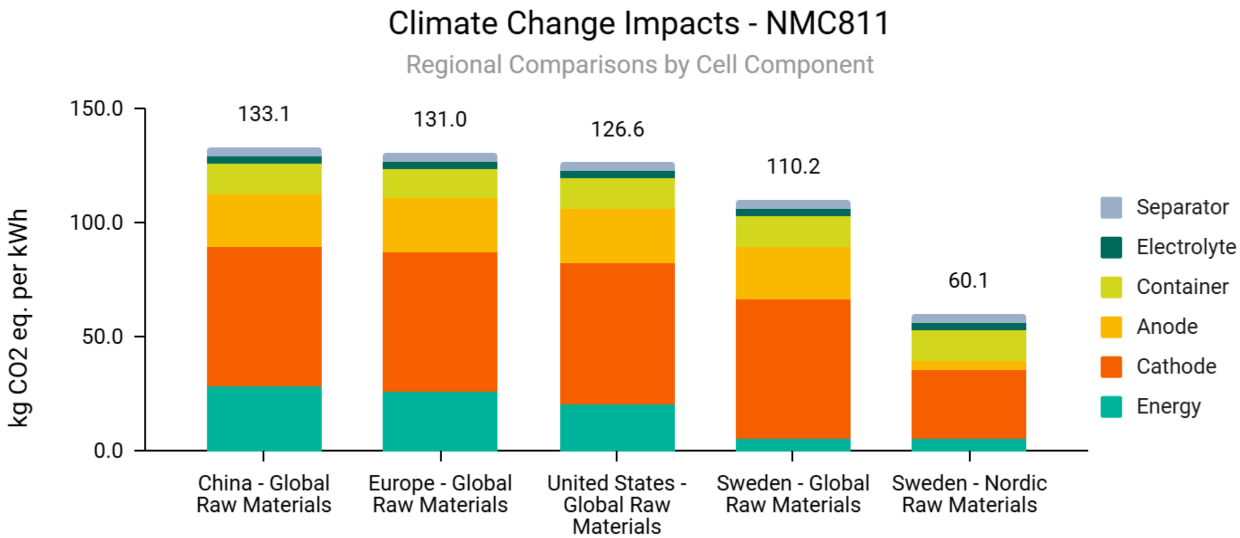

Figure ES-1: NMC811 cell cradle-to-gate comparative climate change impacts by region. Energy refers to the total electricity and natural gas consumption for precursor, active material, and cell production stages.

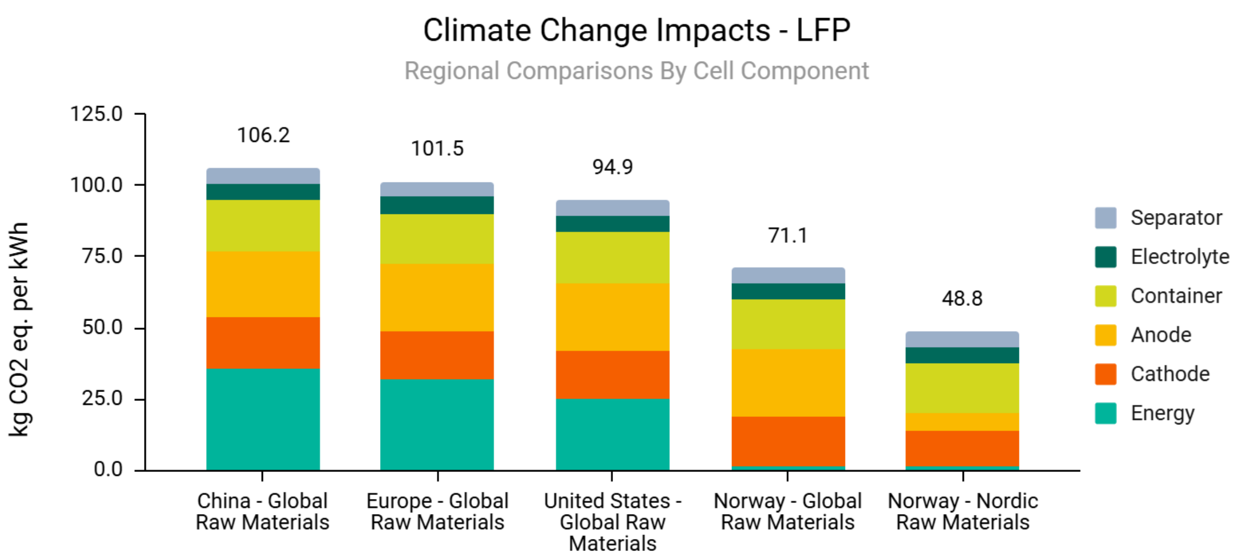

Figure ES-2: LFP cell cradle-to-gate comparative climate change impacts by region. Energy refers to the total electricity and natural gas consumption for precursor, active material, and cell production stages.

Table ES-1: Results summary for NMC811 battery cell scenarios. RM - Raw Materials. Values are rounded to the nearest 1 decimal place. Asterisk indicates independent cradle-to-grave results that should not be used for comparisons.

Climate Change – kg CO_2 eq. per kWh	Sweden (Nordic RM)	Sweden (Nordic RM w recycling)*	Sweden (Global RM)	United States (Global RM)	Europe (Global RM)	China (Global RM)
Total	60.1	56.2	110.2	126.6	131.0	133.1
Biogenic	0.1	0.3	0.1	0.1	0.1	0.1
Fossil	59.4	55.4	109.9	126.4	130.8	132.9
LULUC	0.6	0.5	0.2	0.1	0.1	0.1

Table ES-2: Results summary for LFP battery cell scenarios. RM - Raw Materials. Values are rounded to the nearest 1 decimal place.

Climate Change – kg CO_2 eq. per kWh	Norway (Nordic RM)	Norway (Global RM)	United States (Global RM)	Europe (Global RM)	China (Global RM)
Total	48.8	71.1	94.9	101.5	106.2
Biogenic	0.1	0.1	0.1	0.1	0.1
Fossil	48.3	70.9	94.7	100.8	106.0
LULUC	0.4	0.2	0.2	0.2	0.2

Key study limitations are mainly the use of secondary data, the exploratory scope of the analysis, and global comparisons that illustrate general trends. As such, results cannot be directly applied to specific sites, technologies, or battery formats without further primary data. The recycling analysis is based on a generalised closed-loop model and is intended for standalone insight rather than comparative purposes. Overall, more site-specific and quantitative data are needed to strengthen the robustness and applicability of the findings.

To support robust comparative assertions for decision-making purposes, the study should be expanded to a full cradle-to-grave LCA considering additional life-cycle stages and additional environmental indicators. This study has undergone a critical panel review to improve its transparency and to enhance the reader's confidence in its conduct and conclusions.

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List of Acronyms

Acronym	Meaning
AAM	Anode active materials
BOM	Bill-of-materials
CAM	Cathode active materials
CMC	Carboxymethyl cellulose
CN	China
CO_2	Carbon dioxide
DMC	Dimethyl carbonate
DQR	Data quality rating
DRC	Democratic Republic of the Congo
EC	Ethylene carbonate
EIA	Environmental impact assessments
eq.	Equivalent
HPAL	High pressure acid leaching
IPCC	Intergovernmental Panel on Climate Change
kg	Kilograms
kWh	Kilowatt-hour
LFP	Lithium iron phosphate
$LiPF_6$	Lithium hexafluorophosphate
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
m^2	Metres squared
m^3	Metres cubed
MJ	Megajoules
NMC	Nickel manganese cobalt
NMP	N-Methyl-2-pyrrolidone
NO	Norway
pCAM	Precursor cathode active materials
PEF	Product Environmental Footprint
PVDF	Polyvinylidene fluoride
RKEF	Rotary kiln electric furnace

Glossary

Term	Definition
Allocation	Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.
Background system	Processes over which the LCA-commissioner has little to no direct influence.
Climate change	Increase in the average global temperature resulting from greenhouse gas emissions (GHG). Units are in total radiative forcing as global warming potential – GWP100 (kg CO_2 eq).
Cradle to gate	Refers to a partial life cycle, encompassing all processes from the extraction of raw materials (the "cradle") through material processing, manufacturing, and up to the point the product leaves the manufacturer's facility (the "gate"). This boundary excludes downstream activities such as product distribution, storage, use, and end-of-life treatment.
Cradle to grave	Defines a complete life cycle, covering all stages from raw material extraction and production to distribution, storage, product use, and final disposal or recycling. This approach accounts for all relevant inputs and outputs throughout the product's entire life span.
Foreground system	Processes which are under the control of the LCA commissioner.
Functional unit	Quantified performance of a product system for use as a reference unit.
Goal	States the intended application, the reasons for carrying out the study, the intended audience, and whether the results are to be used in comparative assertions intended to be disclosed to the public.
Interpretation	Phase in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.
Life cycle	Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.
Life Cycle Assessment (LCA)	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.
Life Cycle Impact Assessment (LCIA)	Phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.
Life Cycle Inventory (LCI)	Phase involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.
Reference flow	Measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.
Scope	Defines the breadth, depth, and the detail of the study which are compatible and sufficient to address the stated goal.
System boundary	Set of criteria specifying which unit processes are part of a product system.

1. Life Cycle Assessment

Life cycle assessment (LCA) is a standardised method that quantifies the potential environmental impacts associated with life cycle stages of a product, process, or activity. Importantly, LCA enables the assessment of both direct and indirect impacts that occur throughout the life cycle of a defined product. This holistic approach helps identify how decisions at one life cycle stage affect others, supporting balanced trade-offs, avoiding burden shifting, and can facilitate comparisons between product systems and mitigation options. It should be noted that LCA is a complementary approach to local impact assessments such as environmental impact assessments (EIA) and risk assessments. This LCA follows ISO-14040:2006[1] and ISO-14044:2006[2], and specifically the *Carbon Footprint of Product* (CFP) requirements of ISO-14067:2018[3]. In accordance with these standards, LCA has four fundamental steps (Figure 1):

1. **Goal and Scope Definition:** Establishes the purpose, scope, and boundaries of the assessment, identifying the functions of the product being analysed.
2. **Life Cycle Inventory (LCI):** Collects and quantifies input and output data on energy, materials, intermediary products, natural resources, by-products, waste, and emissions throughout the product life cycle stages.
3. **Life Cycle Impact Assessment (LCIA):** Selects an LCIA method to transform the LCI into potential environmental impact results.
4. **Interpretation:** Evaluates the LCI and LCIA results with respect to their limitations and uncertainty, to help conclude and provide recommendations for informed sustainability decision-making.

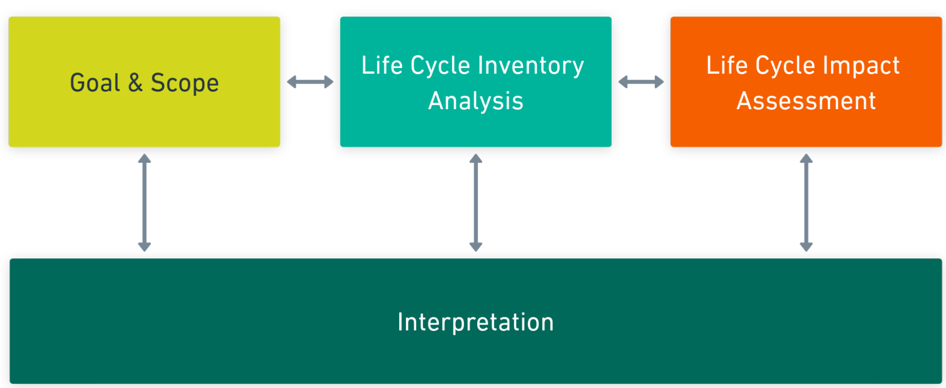

Figure 1: General phases of a life cycle assessment as described by ISO 14040:2006.

2. Methodology

2.1. Goal Definition

The Norwegian Battery Platform ("Battery Norway") commissioned LCA practitioner Minviro Ltd ("Minviro") in March 2025 to explore the potential climate change impacts of manufacturing lithium nickel-manganese-cobalt (NMC811) and lithium iron phosphate (LFP) battery cells in the Nordics, using Nordic raw materials routes, and investigate the effects of recycling.

Study outcomes were intended to be internally and publicly communicated to Nordic battery stakeholders, including but not limited to government, industry, academia, and the public. The project was aimed at supporting efforts to strengthen regional battery supply chains. Involved consortium parties primarily include Battery Norway, Morrow Batteries, Swedish Energy Agency, Finnish Battery Association. The *Carbon Footprint of Product* (CFP) study was conceptual in nature with the following goals:

1. To explore the potential hotspots of Nordic NMC811 and LFP battery cells manufactured using global and Nordic raw material routes. Nordic raw material routes were selected for nickel, cobalt, lithium, and graphite, inclusive of extraction, processing, and refining stages.
2. To compare the potential impacts of Nordic battery cell manufacturing to scenarios using electricity mixes from Europe, United States, and China.
3. To investigate the potential effects of Nordic recycling of NMC811 battery cells and the recovery of battery-grade raw materials. This was selected as an independent analysis and not to be compared with LFP recycling.

This report has been prepared in accordance with ISO-14067:2018[3] which is based on the foundations of ISO-14040:2006[1] and ISO-14044:2006[2]. Since goals (1) and (2) focus on cradle-to-gate and goal (3) on cradle-to-grave, with certain stages such as use not considered, this study is classified as a partial CFP. The partial CFP conducted uses an attributional framework which is a widely accepted approach that quantifies the climate change impacts of a product or service by examining the effects from direct inputs and outputs within a defined system boundary[4]. It provides a "snapshot" of impacts at a specific point in time - often referred to as an "accounting" approach - which typically uses average data and can be used for decision-support. In contrast, consequential LCA assesses the broader systemic impacts of large-scale decisions, including indirect effects and market responses. This approach typically relies on marginal data to capture changes in supply and demand within constrained markets. Due to these characteristics, it has been evaluated as not suitable for this study.

This report constitutes a reference document and should be made available to any NDA-bound third party to whom the results are communicated. This report has been critically reviewed and is intended to communicate comparative assertions to the public. It is recognised that the data provided by this partial CFP study may be used by others for comparative assertions in separate future studies. These comparisons should be made on a product system basis only and carried out in accordance with the ISO-14040:2006[1], ISO-14044:2006[2], and ISO-14067:2018[3] standards. Due to the exploratory nature of the study it is not intended for decision-making purposes since a full LCA considering broad environmental impacts and other life-cycle stages is recommended[3].

2.2. Scope Definition

The following chapter describes the scope of the LCA study according to goals stated above. This includes, but is not limited to, a project description, the product function(s), functional unit and reference flows, the system boundary, and cut-off criteria of the study.

2.2.1. Project Description

Battery Norway is a national industrial initiative focused on developing a sustainable and competitive battery value chain in the Nordics. It brings together stakeholders across the supply chain to support innovation, infrastructure, and alignment with European strategies, from raw materials to recycling. This project explored Nordic battery supply-chain scenarios summarised in Table 1, using a combination of routes for raw materials, cell manufacturing, and recycling across Sweden, Norway, and Finland. It also included cell manufacturing scenario comparisons representing the European continent ("Europe"), United States, and China regions based on varying electricity mixes.

Table 1: Scope overview of routes and scenarios.

<table>
<tr><th>Routes / Scenarios</th><th>Chemistry / Material</th><th>Production Routes</th></tr>
<tr><td rowspan="6">Nordic Cell Manufacturing</td><td rowspan="3">NMC811</td><td>Sweden - Regional production as a proxy to Northvolt using global average raw materials.</td></tr>
<tr><td>Sweden - Regional production as a proxy to Northvolt using Nordic raw materials.</td></tr>
<tr><td>Europe, United States, and China using global average raw materials.</td></tr>
<tr><td rowspan="3">LFP</td><td>Norway - Regional production representation with some input from Morrow Batteries, using global average raw materials.</td></tr>
<tr><td>Norway - Regional production representation with some input from Morrow Batteries, using Nordic raw materials.</td></tr>
<tr><td>Europe, United States, and China with global average raw materials.</td></tr>
<tr><td rowspan="4">Nordic Raw Materials</td><td>$NiSO_4.6H_2O$</td><td rowspan="2">Nickel and cobalt sulfate hydrates from Finland based on Terrafame sulfide ore bioleaching and battery-grade chemical refining.</td></tr>
<tr><td>$CoSO_4.7H_2O$</td></tr>
<tr><td>$LiOH.H_2O$</td><td>Lithium hydroxide monohydrate from Finland based on the planned Keliber spodumene project.</td></tr>
<tr><td>C-Gr</td><td>Synthetic graphite from Norway based on Vianode.</td></tr>
<tr><td>Nordic Recycling</td><td>NMC811</td><td>Hydrometallurgical recycling regionalised to Finland to depict Fortum based on the Minviro model but an independent, non-comparative analysis.</td></tr>
</table>

2.2.2. Product Function

The main products were prismatic NMC811 and LFP battery cells for energy storage applications, such as battery electric vehicles, with electricity stored and used on a kilowatt-hour (kWh) basis. Table 2 provides the key cell characterisations. Morrow Batteries provided key assumptions, including cell capacity and gravimetric energy density, for deriving the Norwegian prismatic LFP cell model. The NMC811 characterisation was then derived based on functional equivalence to meet the same cell capacity but accounting for a greater gravimetric energy density as typically seen[5,6]. Sweden was chosen to reflect Northvolt's operational region, but the analysis is not based on data from Northvolt and does not directly represent its operations. The same characterisations were applied to the Europe, United States, and China scenarios.

Table 2: Battery cell characterisations.

Parameter	NMC811	LFP	Sources
Location of cell manufacturing facilities	Sweden	[redacted]	Morrow Batteries and Minviro Parameterised Battery LCI Model.
Gravimetric energy density (kWh/kg)	0.240	[redacted]	
Cell capacity (kWh)	0.323	[redacted]	
Cell mass (kg)	1.35	[redacted]	

2.2.3. Functional Unit and Reference Flow

LCA uses a *Functional Unit (FU)* as a reference to evaluate the potential impacts associated with the production of components within a single system or among multiple systems on a common basis. This serves as a quantitative reference for all inventory calculations and impact evaluations. The reference is specific to each product system and defines the amount of product(s) needed to fulfil the function. The main function was energy storage and the study focussed on manufacturing impacts, therefore, the FU was defined as ***per kWh of battery cell energy capacity*** with the reference flow defined as the cell masses required to meet the FU.

2.2.4. Study System Boundaries and Cut-Off Criteria

Table 3 presents the key system boundary inclusions and omissions. The partial CFP was primarily a cradle-to-gate study, assessing the battery life cycle impacts from resource extraction - including both direct and indirect raw material inputs - up to the point where the battery cell is manufactured and ready for application. Transport to application, use, end-of-life, and other downstream activities are outside the study's primary scope. This scope was also used for the Europe, United States, and China comparison routes. A cradle-to-grave system boundary extension was independently evaluated for Nordic NMC811 cells with hydrometallurgical recycling.

Table 3: System boundary inclusions and omissions with asterisks indicating only applicable for independent cradle-to-grave analysis. These only apply to the foreground system and may not be reflected in the background datasets used.

Included in System Boundary	Omitted from System Boundary
• Background production of all major raw materials and energy inputs required to produce NMC811 and LFP battery cells, including all upstream chains. • Direct "foreground" transport of key battery-specific materials of nickel and cobalt sulfates, lithium hydroxide, and graphite. • Indirect "background" transport of other input materials and chemicals accounted for by "market for" activities. • Production of: precursor cathode active materials (pCAM), cathode active materials (CAM), cathodes, anode active materials (AAM), anodes, electrolyte, cell container, and cell assembly. • Hydrometallurgical recycling of NMC811 cells*.	• Capital goods and infrastructure such as production of machinery and construction of buildings. • Employee transport and accommodation. • Production and use of emergency materials and energy such as fire water and emergency generator power. • Reagent and product packaging materials. • Non-GHG emissions to air, land and water associated with the deposition of tailings and waste sludges in tailings ponds/piles. • On-site maintenance and detailed generated waste such as wastewater. • Use- and end-of-life phases including transport of the final product to consumers.

Certain areas were excluded from the system boundaries such as capital goods and product packaging. However, it is important to note that such exclusions only apply to the foreground, and may not be reflected in the background databases used such as in ecoinvent. Cut-off criteria refers to the amount of material or energy flow, or the level of significance of environmental impacts, to be excluded from a LCA study. No cut-off criteria were applied to the foreground data. However, there is inherent uncertainty for some flows that may have not been captured (e.g. dust and particulate emissions from manufacturing activities) due to the limitations such as the use secondary data; but the practitioner deems that all major flows contributing to climate change impacts and the scope of this work have been captured.

2.2.4.1. Cradle-to-Gate Cell Manufacturing

Figure 2 shows the study product system under the system boundaries which also applied to the Europe, United States, and China comparison scenarios. The foreground system for cell manufacturing considers an integrated process from precursor materials to cell assembly. To simplify the scenario, unit processes are grouped based on key cell component areas, encompassing specialised stages such as slurry mixing, drying, calendering, stacking, and formation. The areas were grouped and described under the following unit processes:

1. **Precursor cathode active materials (pCAM):** This process is specific to production NMC811 precursor hydroxides[7,8] and is not applicable to LFP since the CAM is directly synthesised. Nickel, manganese, and cobalt sulfate precursors are combined in an 8:1:1 molar ratio and dissolved in deionised water. Ammonium hydroxide complexing agent and sodium hydroxide base are added at rates of 0.33 mol NH_3 eq. and 1.03 mol NaOH eq. per mol of metal contained in sulfate precursors. The reactor is heated to 50 °C using steam generated from natural gas combustion (45 MJ per kg pCAM), facilitating the co-precipitation of NMC811 hydroxide. The process assumes a conversion efficiency of 100%.

2. **Cathode active materials (CAM):** For NMC811, the pCAM is mixed with a stoichiometric amount of lithium hydroxide to form the final CAM[7,8]. The synthesis involves a two-stage calcination, beginning with the mixing of the NMC811 hydroxide and lithium hydroxide, followed by high-temperature calcination steps exceeding 1000 °C. The process assumes

a 100% material conversion rate (near 100% is reported) and has an estimated electricity use of 8 kWh per kilogram of final CAM produced. For LFP, the process follows a solid-state reaction using stoichiometric ratios of magnetite, diammonium phosphate, and lithium hydroxide[7,8]. The materials are typically mixed and subjected to heating steps ranging from 500 °C to 900 °C, although this does not directly represent the process by Morrow Batteries. However, Morrow Batteries have confirmed that it is powered by 100% electricity and have directly provided the estimated energy consumption.

3. **Cathode:** The NMC811 CAM is mixed with polyvinylidene fluoride (PVDF) binder and conductive carbon, each comprising less than 5% of the final cathode mass, using N-Methyl-2-pyrrolidone (NMP) solvent[7,8]. The resulting slurry is coated onto aluminium foil current collectors, followed by sequential processing steps including solvent drying, calendering, and slitting. Although NMP solvent recovery is technically feasible, this assessment conservatively assumes total NMP use, evaporation, and emission. While NMP emissions are reported and may cause other environmental impacts, NMP is not a greenhouse gas and does not affect the carbon footprint. For LFP, a similar electrode fabrication process is used, with carboxymethyl cellulose (CMC) serving as the primary binder in a water-based solvent system[7,8].

4. **Anode active materials (AAM):** For both NMC811 and LFP cells, battery-grade graphite (sources discussed in Table 6) is mixed in a water-based solvent with conductive carbon and CMC binder, each comprising less than 5% of the final anode mass[7,8]. The slurry is coated onto copper foil current collectors, followed by drying, calendering, and slitting steps to complete the anode fabrication process.

5. **Container, Electrolyte, and Separator:** These components are assumed to be manufactured off-site but are included as unit processes to represent their mixing or assembly on-site[7,8]. The polymer-based separator is introduced during the cell stacking stage, followed by the addition of the container - primarily an aluminium can along with other insulating plastic materials - during cell assembly. The cells then undergo vacuum drying and electrolyte filling, with the electrolyte composed of a salt mixture in the ratio of 4:4:1.4 for ethylene carbonate (EC), dimethyl carbonate (DMC), and lithium hexafluorophosphate ($LiPF_6$), respectively.

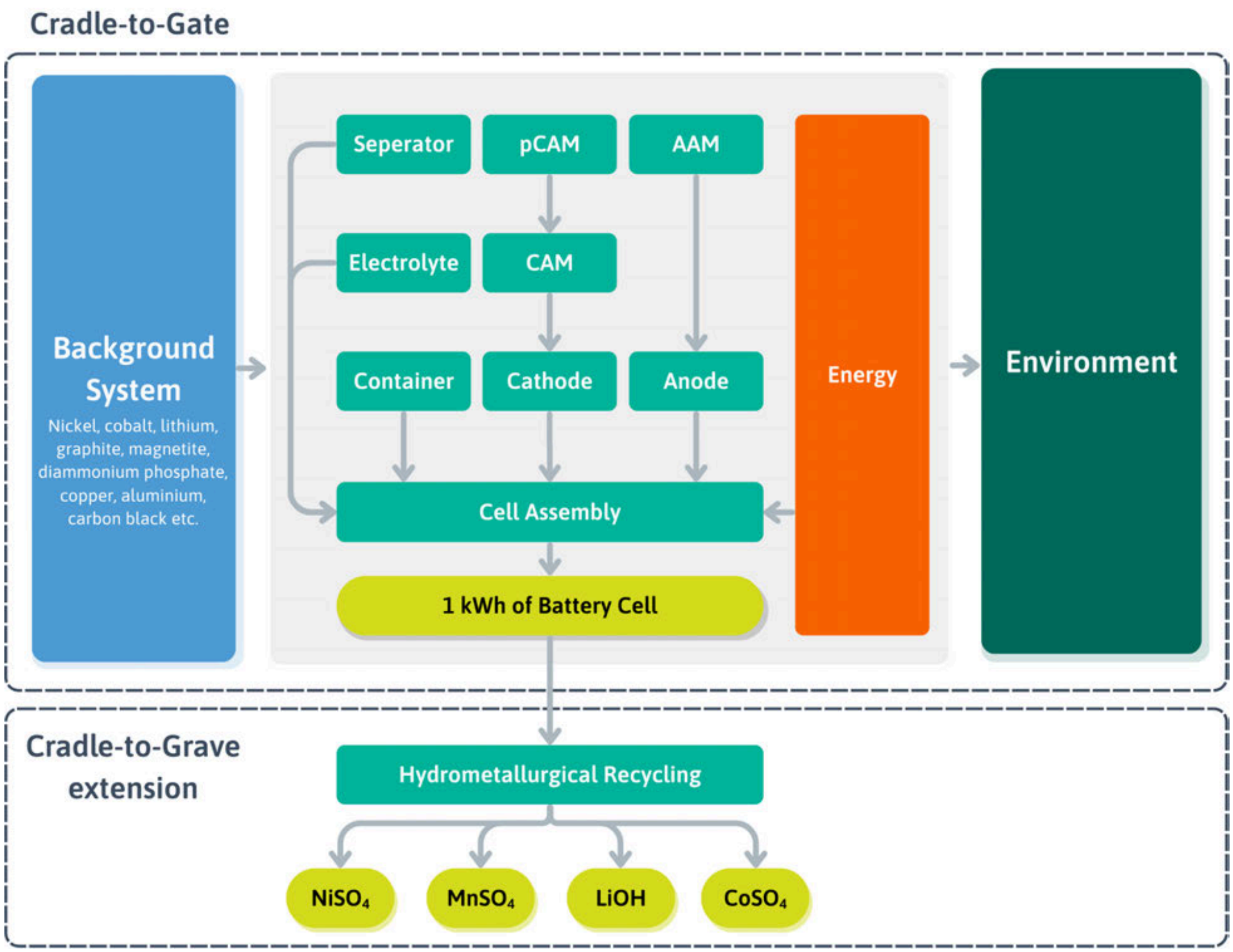

Figure 2: System boundaries of battery cells. Hydrometallurgical recycling only applies to the NMC811 cell. The figure provides a conceptual overview of the CFP system and does not represent detailed bill-of-materials or the full hierarchy of components and sub-tiers.

6. **Cell Assembly:** The final stages of cell assembly include formation, aging, and testing. During formation, cells are charged and discharged to stabilise internal chemistry, followed by an aging period and quality control checks. These steps ensure the cells meet performance and safety standards before being finalised as end products.

7. **Energy:** For simplification, all energy demands associated with pCAM, CAM, and cell production stages are consolidated into a single unit process supplying the cell assembly stage. Morrow Batteries reports a total energy consumption of [redacted] powered by electricity. This figure encompasses the entire production chain - from CAM synthesis to final cell assembly. For NMC811 cells, direct comparison is more

challenging due to differences in the manufacturing processes, specifically the additional pCAM step and different CAM synthesis.

These contributions are detailed in points (1) and (2). However, to enable comparability where possible, it is assumed that the entire NMC811 cell assembly process is powered by 100% electricity. Under this assumption, cell assembly alone is estimated to consume 23 kWh per kWh of cell capacity[9]. It should be noted that the original estimate included some natural gas consumption; hence, this assumption was sensitivity tested (Table 9, 16, and 17). When including the upstream pCAM and CAM production stages[7,8], the total estimated energy demand for NMC811 cells approximated to 50 kWh per kWh of cell capacity.

2.2.4.2. Cradle-to-Grave Hydrometallurgical Recycling

NMC811 battery cell recycling was assumed to take place in Finland based on Fortum, a Finnish recycling company. Fortum deploys mechanical treatment followed by hydrometallurgical processing of battery cells declaring a 95% recovery rate for metals from black mass (individual metals or more specifications are not given), producing battery-grade nickel, cobalt, and manganese sulfates, and lithium hydroxide[10].

Primary data was not available; therefore, Minviro's pre-reviewed hydrometallurgical model based on literature and stoichiometric calculations was used as a proxy process, outlined in Figure 3. However, it is important to note that a 95% net recovery of metals from the battery cell is not assumed. A 95% recovery rate of black mass is assumed from the shredded cells and subsequent metal extraction efficiency losses occur in several hydrometallurgical processes. The values and assumptions should be interpreted with caution as further work would be needed with primary data from Fortum. Graphite recovery was not considered as it is not offered by Fortum at present, though it is important to mention this may be a future offering due to the recently announced collaboration with Vianode and Fortum. Although the model can include graphite recovery, the recovered material is not battery-grade and would require extensive additional processing to meet required specifications.

Battery cells are subjected to pretreatment[11], beginning with shredding and sieving, followed by low-temperature calcination to remove binder and electrolyte residues. The shredded material then undergoes mechanical separation to remove non-metallic impurities such as plastic separators and metallic foils like aluminum and copper scraps, yielding a mixed black mass with a 95% recovery rate.

This black mass is then hydrometallurgically processed, beginning with leaching[12] in a 2M sulfuric acid solution with 13.5% hydrogen peroxide at 60°C for two hours to dissolve lithium, nickel, cobalt, manganese, aluminum, and copper into the leachate, while graphite and other solid impurities are filtered out. Next, chemical precipitation removes aluminum as $Al(OH)_3$ using sodium hydroxide, and copper is displaced by iron chips and precipitated as Cu sponge. Iron is subsequently removed as $Fe(OH)_2$ with further NaOH addition, maintaining a pH of 5.0–5.5 for selective removal. The solid $Al(OH)_3$, $Fe(OH)_2$ and Cu sponge are filtered out from the stream and considered solid wastes in this study.

The lithium-nickel-manganese-cobalt-rich leachate then enters a series of solvent extraction steps. The first solvent extraction process using Cyanex 301 in kerosene (as diluent - 0.35 M, mole/L extractant concentration)[13] extracts the nickel-cobalt-rich solution which is sent to the second solvent extraction process using Cyanex 272 in kerosene (as diluent - 0.1 M, mole/L extractant concentration) to selectively separate cobalt ions (in organic solution) from nickel ions (in aqueous solution) and strip with H_2SO_4. The manganese-lithium-rich solution is sent to the third solvent extraction process using D2EHPA in kerosene (as diluent - 0.2 M, mole/L extractant concentration) to selectively separate manganese ions (in organic solution) from lithium ions (in aqueous solution), followed by stripping using H_2SO_4. After metal stripping with sulfuric acid, metal sulfates are precipitated and crystallised under heating lithium is initially recovered as lithium carbonate by adding sodium carbonate (96% efficiency), then upgraded with calcium hydroxide to lithium hydroxide[14].

The wastewater generated is treated by applying an evaporation-crystallisation process [15]. The wastewater is firstly agitated and mixed at 48°C and then fed into a series of evaporators. Once the wastewater has been evaporated and condensed, the remaining stream is a concentrated sodium sulfate solution, which is fed into a crystalliser to recover the anhydrous sodium sulfate from the solution while remaining wastewater is discharged. Although sodium sulfate is a low-value co-product in some cases, a conservative assumption is applied in this study whereby it is landfilled along with other solid waste outputs. However, this assumption has a negligible impact on the overall study results. This process consumes both heat and electricity.

Extractant regeneration rates were conservatively assumed to be 95% meaning a 5% annual replacement[13]. Accounting for recovery efficiencies across all processing stages, the overall yield from cell to final battery-grade products is approximately 90% for nickel and cobalt, 50% for lithium (including conversion losses from lithium carbonate to lithium hydroxide based on the dataset used), and 65% for manganese. These values may represent more conservative estimates than those claimed by Fortum.

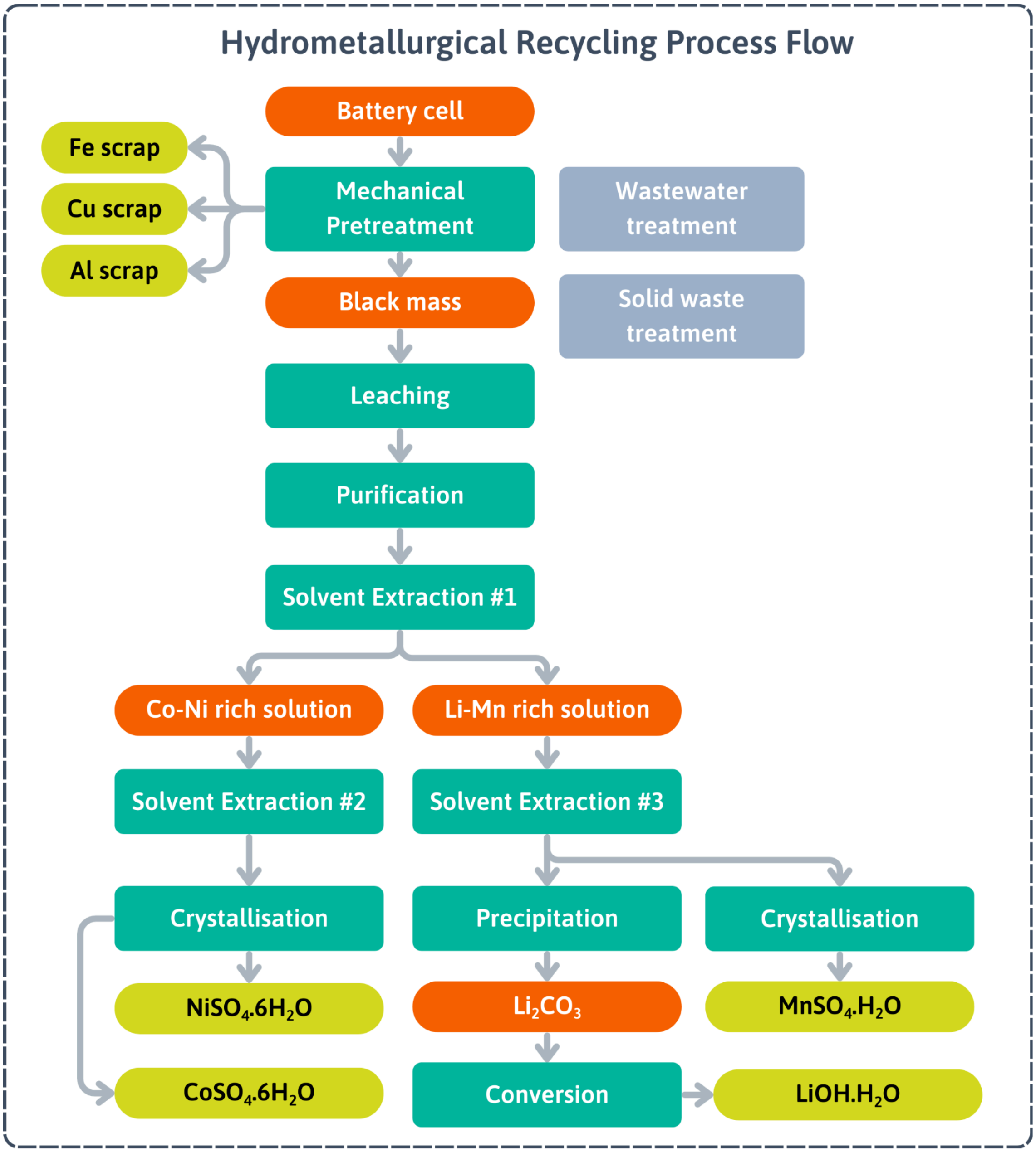

Figure 3: Process flow of NMC811 hydrometallurgical recycling.

2.3. Life Cycle Inventory

2.3.1. Data Collection and Calculation

This study was desk-based and data was primarily constructed using input from Morrow Batteries and secondary sources including databases, literature, and models. Data for this study was collected in 2025; however, individual data points originate from various reference years spanning 2014 to 2025. The complete LCI is presented in Table A1, and detailed spreadsheet-based calculations are available upon request under a NDA.

2.3.1.1 Cell Manufacturing

Foreground data refers to the specific inputs, outputs, and processes directly related to the system under study. Foreground data for LFP battery cells was generated based on a bill-of-materials (BOM) derived from assumptions provided by Morrow Batteries. For the NMC811 cell, Minviro's internal *Parameterised Battery LCI Model* was used primarily based on the gravimetric energy density input and cell component ratios adjusted for a prismatic configuration. Further differences in ratios between the NMC811 and LFP cells arose from differing underlying assumptions: NMC811 values were derived from literature sources listed in Table 4, while LFP data was based on assumptions by Morrow Batteries. Next, the generated BOMs in Table 5 were disaggregated into a LCI based on sources in Table 4 and stoichiometric equivalence according to system boundaries in Figure 1. Assumptions are declared in Section 2.3.5., while the full LCI is provided in Appendix A.1.4.

Table 4: Foreground data sources.

Description	Source
Battery cell overall BOMs	Morrow Batteries and Minviro Parameterised Battery LCI Model.
Reagents, solvents, binders, conductive carbon, electrolyte mixes, foils, NMC811 pCAM natural gas and CAM electricity demands, LFP CAM production	Argonne National Laboratory and GREET model[7,8,16,17]
NMC811 cell assembly energy demands	23 kWh per kWh cell from Degen *et al.* 2023[9]
Cell container	Based on Ellingsen *et al.*[18], the pouch cell composition has been adapted for a prismatic form factor. 80% of mass was assigned to aluminium and 20% to other materials such as tabs, insulation, and plastics based on expert judgement.
LFP cell manufacturing energy demands	Morrow Batteries

Table 5: Cell bill-of-materials based on percentage contributions to total cell mass.

Parameter	NMC811	LFP
CAM	39%	[redacted]
Aluminium current collector	3%	[redacted]
AAM	24%	[redacted]
Copper current collector	5%	[redacted]
Electrolyte	12%	[redacted]
Separator	2%	[redacted]
Aluminium can packaging	17%	[redacted]
Total mass - kg	**1.36**	[redacted]

Background data refers to the material and energy inputs that are delivered to the foreground system under study. These datasets typically consist of aggregated, representative average values for a given region or industry sector and are sourced from reference databases. In this study, several background datasets were used, as shown in Table 6. Ecoinvent 3.10, which was updated in 2023, was used for several common materials, chemicals, and energy processes. Carbon Minds' datasets were used for more specific chemicals such as PVDF and ammonium hydroxide. For key battery-specific raw materials, Minviro's proprietary datasets were utilised to represent both global averages and Nordic-specific routes, which are derived from pre-reviewed work based on a mix of technical reports, literature, and models. Further details and descriptions are available in Appendices A.1.5. Additionally, transport distances from various origins and destinations were also estimated for the selected battery materials, considering a mix of ocean container and lorry modes, available in Appendix A.1.4.[19]

Table 6: Background data sources.

Description	Region	Database	Sources and Comments
Non-battery specific materials, chemicals, and natural gas demands	European (RER), Rest-of-world (RoW), Global (GLO).	Ecoinvent 3.10 and Carbon Minds	For each activity, the most regionally representative "market for" activity was selected for Norway, Sweden, Europe, United States, and China scenarios[20,21].
$NiSO_4.6H_2O$	Global	Minviro	The global production market mix, dominated by the Indonesian-China route from laterite ores processed via high-pressure acid leaching (HPAL), with a significant share from the rotary kiln electric furnace (RKEF) route, and smaller contributions from sulfide ores in Australia, Russia, and Canada[22,23].
	Finland	Minviro, Terrafame	Sulfide ore bioleaching and battery chemical refining from Terrafame developed based on public reports and EIA

			documents[24,25].
$CoSO_4.7H_2O$	Global	Minviro, Terrafame	The global production market mix, dominated by the Democratic Republic of Congo (DRC)-China from cobalt-copper mines, and significant shares of Indonesian-China route from laterite ores processed via HPAL[22,23].
	Finland	Minviro	Sulfide ore bioleaching from Terrafame developed based on public reports and EIA documents[24,25].
$LiOH.H_2O$	Global	Minviro	The global production market mix, dominated by the Australian-China spodumene routes, with smaller but significant shares of Chilean and Argentinian brine[22,23].
	Finland	Minviro, Keliber	Finnish spodumene based on public reports and literature on prospective Keliber project[26].
C-Gr	Global	Minviro	Global battery-grade graphite that is predominantly supplied by China, estimating a 60:40 mix of synthetic and natural graphite informed by industry experts, primarily from Inner Mongolia and Heilongjiang hydrofluoric acid routes[23,27].
	Norway	Minviro, Vianode	Synthetic graphite from Vianode (Via ONE plant) using their proprietary process, with data directly based on a previous LCA study[28].

While ecoinvent 3.10 average electricity mixes were used for Sweden, Norway, and Finland, the “market group for electricity” datasets were not applied for Europe, the United States, and China, as these broader regional mixes are not representative of current battery manufacturing activity. In the Nordic countries, national electricity mixes were considered appropriate because battery manufacturing is limited to a small number of locations with relatively homogeneous and low-carbon electricity profiles, resulting in minimal deviation from national averages. In contrast, battery production in Europe, the United States, and China occurs across numerous facilities situated in regions with widely varying grid compositions. As such, national or regional market mixes could significantly misrepresent actual electricity use. To better reflect the diversity of supply in these larger regions, weighted electricity mixes were developed based on the locations of existing lithium-ion battery gigafactories (≥1 GWh annual capacity), which were mapped to their most representative ecoinvent 3.10 locations (see Table 7).

Table 7: Weighted electricity mixes based on existing battery production locations of > 1 GWh annual output.

Aggregate Region	Main Factory	Specific Location	Share	Ecoinvent Region	Sources
Europe	LG Chem	Poland	49%	PL	VDI/VDE Innovation +
	Samsung	Hungary	33%	HU	

	CATL	Germany	8%	DE	Technik GmbH, 2024[29]
	ACC	France	8%	FR	
	AESC	UK	1%	GB	
United States	Ultium	Southeast	42%	US-SERC	ElectronsX, 2025[30]
	Tesla	Western	19%	US-WECC	
	Ultium	Midwest	18%	US-MRO	
	Tesla	Texas	16%	US-TRE	
	Magnis	Northeast	5%	US-NPCC	
China	CATL	East	52%	CN-ECGC	
	CATL	Southwest	37%	CN-SWG	
	EVE	Central	11%	CN-CCG	

2.3.1.2 Hydrometallurgical Recycling

The foreground data was based on Minviro's hydrometallurgical model as outlined in Section 2.2.4.2 based on literature and stoichiometric calculations. All materials, chemicals, and energy inputs and outputs were linked to representative background datasets from ecoinvent 3.10. "Organophosphorus-compound production, unspecified" is declared used as a proxy for D2EHPA, and kerosene as the diluent. For Cyanex extractants, Minviro's own database is used, based on custom synthesis routes developed due to limited public data availability. Remaining wastewater and solid waste outputs are linked to waste treatment activities, while metal scrap co-products are typically used as secondary feedstock in industrial operations and are therefore assigned a burden-free status under the end-of-life cut-off approach (Section 2.3.4). The complete LCI is disclosed in A.1.4.

2.3.3. Multifunctionality

The foreground system does not produce co-products, hence, no multifunctionality procedures were needed e.g. allocation. The background datapoints used in ecoinvent and Carbon Minds adopts the "Allocation, cut-off by classification" system model which addresses multifunctionality primarily through economic allocation, distributing the LCI and the resulting LCIA among the different co-products by price-based value. The Minviro proprietary database also follows economic allocation procedures. This is primarily influential for the nickel and cobalt supply-chains where several base metal co-products occur in early mining stages, therefore, Table 8 declares the 10-year averages used that account for the historic volatility of cobalt and nickel prices.

Table 8: 10-year average base metal used for background system economic allocation.

Base Metal	10-year price ($/ton)	Source
Cobalt	48,800	Trading Economics, 2015-2025[31]
Nickel	16,500	
Copper	7,000	
Zinc	2,650	

2.3.4. End-of-Life Modelling

For all modelling within the cradle-to-gate assessments, the end-of-life approach follows the recycled content cut-off method. This method only applies to the 1% of scrapped battery cells at the gate, which are linked to the *"market for used Li-ion battery"* activity in ecoinvent. This represents the impacts associated with downstream waste treatment. However, no benefits or credits are claimed under this approach.

In the cradle-to-grave system boundary extension, the end-of-life substitution approach was used. This approach accounts for both the impacts from hydrometallurgical recycling and the recycling credits from recovered metals that displace their original production processes depicting a closed loop system. The 1% scrap at the gate was then also assumed to enter this recycling process in this case.

To avoid double counting of recycling benefits, this approach excludes pre-existing recycled content in input materials; thus, only virgin metal production was considered including for aluminium. This was applied across both cradle-to-gate and cradle-to-grave scopes to maintain consistency. This is a conservative approach and aluminium hotspots for example could be overestimated but this was not directly relevant to the primary study goals.

2.3.5. Assumptions

Table 9 outlines all key assumptions and modelling choices used to generate the LCIs, along with their significance to the results. Section 2.5 further discusses these assumptions in terms of limitations and sensitivity testing.

Table 9: Key study assumptions and their potential effects on results. The significance is qualitatively judged by the LCA practitioner based on study goals and is revisited as results are generated, in line with the iterative nature of LCA.

Area	Assumption	Significance
Foreground	Transport of selected battery raw materials was estimated using assumed container ship and lorry routes, with origin-destination distances rounded to the nearest 500 kilometres.	**Low** - Minor contributor to impacts.
	Cell manufacturing is grouped into key cell areas and not specific processes such as drying, calendering etc.	**Low** - Main inputs accounted for; further disaggregation is beyond scope.
	1% scrap rate is applied to all battery cells assuming a highly mature future manufacturing process[32]. This scales all inputs by 1% to account for additional demand and adds 1% of cells to waste treatment.	**Low** - This affects only the absolute scores and is applied consistently across all scenarios.
	NMC pCAM production energy source is heat, while for CAM it is electricity based on GREET[8]. Cell assembly is estimated at 23 kWh and assumed to be 100% electricity. LFP production is 100% electricity, based on input from Morrow Batteries.	**Medium** - Energy is a likely hotspot, and cell assembly processes may vary in their reliance on electricity versus heat.
	A conservative estimate of 0.2 kg nitrogen per kg of product is assumed at each production stage to account for inert atmosphere requirements.	**Low** - Minor contributor to impacts.
	The prismatic cell containers are mostly aluminium[6], and assumed to be 80% with the remaining composition accounting for copper tabs and plastics.	**Medium** - Aluminium is expected to be a key hotspot.
	In the mixing stages, typical binders assumed PVDF for NMC cathodes with NMP solvent, CMC for anodes, and CMC in water solvent for LFP cells.	**Low** - Minor contributor to impacts.
Background	Raw materials for the cell container, foils, electrolyte, and separator are modeled using "market for" averages from ecoinvent.	**Medium** - Their combined effect is expected to represent a significant hotspot.
	Non-battery-specific raw materials are linked to their respective "market for" activities to reflect average transport requirements.	**Low** - Most are expected to be minor hotspots; alternative routes have minimal impact and are outside the study's scope.
	Regional electricity mixes for battery production are based on plants with >1 GWh output, not directly on Europe, United States, and China regions from ecoinvent.	**High** - The resulting carbon intensities will significantly impact the cell results.
	Credits from hydrometallurgical recycling are assumed to displace original Nordic raw material routes in a closed-loop with battery-grade quality.	**High** - Displacing alternative routes or material quality variations could significantly influence results.

2.3.6. Data Quality Assessment

In evaluating the quality of the foreground and background data used in the base case model, the Product Environmental Footprint (PEF) Data Quality Rating method[33] is used for key criteria:

- **Representativeness:** The degree to which the data set reflects the true population of interest (i.e. geographical representativeness, GeR; time representativeness, TiR; and technological representativeness, TeR).
- **Precision (P):** Measure of the variability of each data value expressed (e.g. variance).
- **Completeness:** Percentage of total flow that is measured or estimated.
- **Methodological appropriateness and consistency:** Qualitative assessment of whether or not the study methodology is applied uniformly to the various components of the analysis.

The DQRs and the corresponding data quality levels are presented in Table 10. Completeness and methodological appropriateness and consistency are pre-requisites of the PEF method and are ranked qualitatively. As this is an explorative study utilising predominantly secondary data, and not a specific PEF study, the DQR has been adapted accordingly.

Table 10: DQRs and corresponding quality levels according to the PEF method.

Data Quality Rating (DQR)	Overall Data Quality Level
DQR ≤ 1.5	Excellent
1.5 < DQR ≤ 2.0	Very Good
2.0 < DQR ≤ 3.0	Good
3.0 < DQR ≤ 4.0	Fair
DQR > 4.0	Poor

Each foreground inventory item is rated according to Table 11 and each secondary datapoint (e.g. background data) is rated according to Table 12. While background databases like ecoinvent have independent data quality ratings, these were reviewed and aligned with the PEF DQR to assess the representativeness of the LCI items used in this study. The data needs matrix (DNM; Table 13) is used to assess background data requirements only, as all foreground data would be expected to be company-specific. However it is noted due to the explorative nature of the study, the foreground data is largely based on secondary data with some company-specific data for Morrow Batteries.

Table 11: Matrix used to assess company-specific data according to the PEF method.

Rating	P	TiR	TeR	GeR
1	Measured/calculated and externally verified.	The data refers to the most recent annual administration period regarding the Environmental Footprint (EF) report publication date.	The elementary flows and the activity data explicitly depict the technology of the newly developed dataset.	The activity data and elementary flows reflect the exact geography where the modelling of the process in the newly created dataset takes place.
2	Measured/calculated and internally verified, plausibility checked by reviewer.	The data refers to a maximum of two annual administration periods regarding the EF report publication date.	The elementary flows and the activity data are a proxy of the newly developed dataset's technology.	The activity data and elementary flows partly reflect the geography where the modelling of the process in the newly created dataset takes place.
3	Measured/calculated/ literature and plausibility not checked by reviewer OR qualified estimate based on calculations plausibility checked by reviewer.	The data refers to a maximum of three annual administration periods regarding the EF report publication date.	N/A	N/A
4 – 5	N/A	N/A	N/A	N/A

Table 12: Matrix used to assess secondary data according to the PEF method. Where precision values are unavailable, precision ratings from Table 11 are applied.

Rating	TiR	TeR	GeR
1	The EF report publication date is within the time validity of the dataset.	The technology used in the EF study is exactly the same as the one in scope of the dataset.	The process modelled in the EF study takes place in the country for which the dataset is valid
2	The EF report publication date is no later than 2 years beyond the time validity of the dataset.	The technologies used in the EF study are included in the mix of technologies in scope of the dataset.	The process modelled in the EF study takes place in the geographical region (e.g. Europe) for which the dataset is valid.
3	The EF report publication date is no later than 4 years beyond the time validity of the dataset.	The technologies used in the EF study are only partly included in the scope of the dataset.	The process modelled in the EF study takes place in one of the geographical regions for which the dataset is valid.
4	The EF report publication date is no later than 6 years beyond the time validity of the dataset.	The technologies used in the EF study are similar to those included in the scope of the dataset.	The process modelled in the EF study takes place in a country that is not included in the geographical region(s) for which the dataset is valid, but it is estimated that there are sufficient similarities based on expert judgement.
5	The EF report publication date is	The technologies used in the EF	The process modelled in the EF study

	more than 6 years after the time validity of the dataset, or the time validity is not specified.	study are different from those included in the scope of the dataset.	takes place in a different country than the one for which the dataset is valid.

Table 13: DNM used to assess background data requirements according to the PEF method.

Situation	Option	Data Requirements
Situation 1: process run by the company	Option 1	Gather company-specific data (both activity data and direct emissions) and create a company-specific dataset (DQR≤1.5). Calculate DQR of the dataset.
Situation 2: process not run by the company but with access to company-specific information	Option 1	Gather company-specific data and create a company-specific dataset (DQR≤1.5). Calculate DQR of the dataset.
	Option 2	Use an EF compliant secondary dataset and apply company-specific activity data for transport (distance), and substitute the sub-processes used for electricity mix and transport with supply-chain specific EF compliant datasets (DQR≤3.0). Recalculate DQR of the dataset.
Situation 3: process not run by the company and without access to company-specific information	Option 1	Use an EF compliant secondary dataset in aggregated form (DQR≤3.0). Recalculate DQR of the dataset.

Following normalisation and weighting using EF factors, LCI items are ranked in accordance with their contribution to the total climate change impact. A weighted average DQR is calculated using the following equations:

$$DQR_{Item} = \frac{TeR + GeR + TiR + P}{4}$$

$$DQR_{Total} = \Sigma(DQR_{Item} \times Contribution)$$

Where:

- DQR_{Item} is the DQR for each individual inventory item.
- DQR_{Total} is the overall DQR of the product system under study.
- $Contribution$ is the % contribution of the inventory item to the total environmental impact.

2.3.6.1 Data Quality Assessment Results

The quality of the foreground and background data comprising the base case LCI is evaluated in accordance with the grading systems presented above, assessing criteria such as technological / temporal / geographical representativeness, completeness, precision, and consistency.

As indicated in Table 14, all background data points were classified under situation 3 which were not run by the company and were primarily filled with datasets predominantly from ecoinvent, Minviro Database, and Carbon Minds. This is expected and appropriate due to the explorative nature of the study and the declared goals. Nonetheless, since this is strictly not a PEF study and these classifications are not directly applicable to the main study goals.

Table 14: Background data requirements for the NMC811 (including recycling datapoints) and LFP cells.

Total Background Flows Required	Situation 1	Situation 2	Situation 3
NMC811 (Including recycling): 135 LFP: 50	0	0	NMC811 (Including recycling): 135 LFP: 50

The results of the data quality assessment (DQA) are presented below in Table 15. In general, scores of 3 were assigned across all foreground processes to reflect the generalisation of diverse manufacturing activities using secondary data mostly reflecting up to 2023 updates. More specific scores were applied to background data points, with higher scores for detailed routes (e.g., Minviro database) and more conservative scores for general background data. After weighting key hotspots, the overall DQA score ranged from 2.7 to 3.0, classified as “Good” for both NMC811 and LFP cell scenarios. This is primarily due to the hotspots having higher DQRs for the more specific raw material routes, compared to the lower DQRs of generic ecoinvent activities.

Table 15: Foreground, background and overall DQRs for scenarios using global average and Nordic raw materials. The overall weighted DQR is an average of the foreground and background scores.,

	Foreground		Background		Overall	
Criteria	DQR	Classification	DQR	Classification	DQR	Classification
Technological Representativeness	3.0	Good	1.9-3.0	Good / Very Good	2.5-3.0	Good
Geographical Representativeness	3.0	Good	2.1-2.9	Good	2.5-2.8	Good
Time-related Representativeness	3.0	Good	3.3-4.1	Fair / Poor	3.0-3.6	Good / Fair
Precision	3.0	Good	2.0	Very Good	2.5	Good

Overall weighted:	2.7-3.0	Good

In terms of completeness, the study primarily relies on secondary data and generalised battery production processes, as established in the study scope. For methodological appropriateness, the PEF DQR system is applied, using the most relevant background datasets, including EF-compliant data from ecoinvent 3.10. Since this is not a direct PEF study, core methodology still follows ISO 14067:2018; therefore, conclusions should be interpreted accordingly.

2.4. Life Cycle Impact Assessment

The impact assessment methodology applied to this partial CFP study is based on the 100-year Global Warming Potential (GWP 100) as recommended by the UN's Intergovernmental Panel on Climate Change (IPCC). This method calculates the potential climate change impact by multiplying the mass of each greenhouse gas (GHG) emitted or removed by its corresponding GWP 100 factor, expressed in kg CO_2-equivalent (kg CO_2 eq.) per kg of emission. The GWP 100 factors include carbon feedback effects and are considered the most relevant for assessing climate change impacts over a 100-year time horizon.

The Greenhouse Gas (GHG) Protocol identifies three ‘scopes’ of GHG emissions which have been included in this study, however, it should be noted that scopes of emissions are not a framework inherent to CFP. The GHG Protocol defines the various scopes of emissions as:

- **Scope 1**: Direct GHG emissions (e.g. furnace off-gas, combustion of fuels)
- **Scope 2**: Indirect GHG emissions from consumption of purchased electricity, heat, or steam (e.g. emissions embodied in grid power or embodied in steam at an industrial park)
- **Scope 3**: Other indirect emissions such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities (e.g. transmission and distribution losses) not covered in scope 2, outsourced activities, and waste disposal. Scope 3 emissions can be either “upstream” or “downstream”. In a cradle-to-gate CFP, “upstream” scope 3 must be included.

To model climate change in accordance with the ISO-14067:2018-082 standard, climate change impact is categorised into three distinct types. These categories enable a more detailed analysis of the sources and nature of the emissions. The four types are as follows:

- **Fossil:** This subcategory deals with emissions of GHGs from the breakdown or transformation of fossil fuels, like through combustion or landfilling. It also considers emissions from processes like peat and calcination and accounts for uptakes due to carbonation.
- **Biogenic:** This subcategory focuses on carbon emissions (CO_2, CO, and CH_4) from the transformation or degradation of aboveground biomass, as well as carbon uptake through photosynthesis during biomass growth. It specifically addresses the carbon content in products, biofuels, or residues like plant litter and dead wood. Native forests' carbon exchanges, including soil emissions and derived products, fall under a separate modelling sub-category.
- **Land use and land use change (LULUC):** This subcategory tracks changes in carbon stocks resulting from land use changes, capturing both emissions and removals of CO_2, CO, and CH_4. It includes biogenic carbon exchanges from activities such as deforestation and soil disturbance, covering emissions from native forests, associated soil impacts, and derived products. It also accounts for land use changes driven by economic or production shifts - for example, increased crop demand leading to the expansion of agriculture into previously unused land.

2.5. Interpretation

2.5.1. Limitations

Table 16 outlines the key study limitations and implications across the LCA framework, outlining considerations for study conclusions, further work, uncertainties, and sensitivity test requirements.

Table 16: Key study limitations.

Type	Limitation	Implications
Scope	The study is cradle-to-gate, with recycling analysis limited to NMC811 batteries.	Comparative conclusions based on cradle-to-gate results; recycling analysis is not suitable for comparative claims.
	Only the climate change impact category is considered.	Study conclusions are limited to greenhouse gas emissions and climate change impacts, not broader

		environmental or sustainability claims.
	The study is explorative and not directly based on operational data.	Study conclusions are general and not directly applicable to specific sites or processes in each region.
	Only prismatic cells with NMC811 and LFP chemistries are assessed.	Study conclusions are limited to the assessed chemistries and prismatic form factor.
LCI	The study is primarily based on secondary data, with limited primary data from Morrow Batteries.	General data does not capture site-specific variations, but this is accounted for in the uncertainty assessment.
	Cell assembly for NMC811 assumes 100% electrification.	Heat from natural gas or steam is a major energy source at some sites and will be included in sensitivity testing.
	The regionally weighted electricity mixes for Europe, United States, and China battery production remain aggregated regional values.	Specific battery locations and carbon intensities may be unrepresented and should be sensitivity tested using best- and worst-case scenarios.
	The recycling process is a generalised depiction of Finnish recycling by Fortum using Minviro's internal hydrometallurgical model.	Conclusions only show general insights that are not directly applicable to Fortum. Specific primary data should be collected to form more robust conclusions
	Selected battery-specific raw materials for nickel, cobalt, and lithium are not based on directly collected client operational data.	Conclusions should acknowledge that raw material findings may change with future project updates, reporting, and data releases. A precalculated uncertainty factor is used to reflect this.
	Most non-battery material inputs have a "Fair" DQA score due to reliance on average regional production and outdated data.	Conclusions may change with future supplier-specific data; lower DQA scores are reflected in higher uncertainty variance.
LCIA	The climate change impact category is assessed at the midpoint level.	Linking LCIA results to environmental damage (e.g., human health) is inappropriate without an endpoint analysis.
Interpretation	The uncertainty assessment uses a semi-quantitative pedigree matrix and assumes logarithmic distributions.	Substantial variance in foreground and background data is captured through the DQA, though not empirically derived due to the study's exploratory nature.

2.5.2. Sensitivity Analysis

Sensitivity analysis explored variations in the top five hotspots for Swedish NMC811 and Norwegian LFP batteries using global and Nordic raw materials, incrementally increasing each by 0-20% and measuring the resulting changes. Table 17 lists additional sensitivities tested, assessed based on the importance declared in the assumptions and limitations presented in Tables 9 and 16. The most applicable sensitivity tests focused on evaluating the influence of changing the electricity mix carbon intensities and introducing natural gas consumption for cell assembly.

Table 17: Sensitivity tests conducted.

Parameter	Baseline	Test Cases
NMC811 cell assembly energy supply	100% electricity.	Assume 50% electricity and 50% heat from natural gas.
Electricity mixes	Weighted regions electricity mixes for battery production	A range of electricity mixes are tested which includes the ecoinvent China, Europe, and United States averages, that were separate from the weighted mixes created in Table X. Additional specific regions are added to China 's central grid (CN-CCG) and France (FR).

2.5.3. Uncertainty Analysis

A semi-quantitative pedigree matrix approach was used due to the absence of direct statistical data for input parameters[34]. This method assesses the uncertainty of each input and output, adapted to the EF DQR framework. Each indicator is scored for both foreground and background data, and assigned a multiplicative uncertainty factor - expressed as a contribution to the square of the geometric standard deviation (GSD) (Table 18).

Table 18: Pedigree matrix multiplicative factors.

Rating	P	TiR	TeR	GeR
1	1.00	1.00	1.00	1.00
2	1.05	1.03	1.02	1.01
3	1.10	1.10	1.05	1.02
4	1.20	1.20	1.10	1.02
5	1.50	1.50	1.20	1.10

Firstly, base uncertainty factors were assigned to all data points to account that even “perfect” data (e.g. unanimously scored as ones in Table 18) would expect some variation. A minimum base uncertainty factor of 1.05 is applied to exchanges like energy, materials, and waste services, reflecting moderate variability and high data reliability. Transport services (e.g. tonne-kilometres by road or rail) carry a higher factor of 2.00, accounting for greater uncertainty in vehicle type, load factors, and distance assumptions. These default values are based on expert judgment within ecoinvent's pedigree matrix framework[34].

Foreground data points were uniformly scored as 3, while background processes were evaluated in greater detail, as outlined in Section 2.3.6. Background data - particularly for non-battery-specific chemicals and older sources (e.g., ecoinvent) - were conservatively scored to reflect reliance on aggregated technological and regional data. Battery-specific raw materials were assigned quality indicators based on detailed, context-specific data and used tailored uncertainty factors from the Minviro Database. These pre-calculated values, based on prior pedigree matrix assessments, better capture variability than generic defaults and support a more robust and representative uncertainty analysis that aligns with the broad, exploratory nature of the study and applies conservative assumptions where appropriate (Table 19). The total GSD for foreground and background systems was calculated independently following where U represents the multiplicative factor:

$$SD_{g95} = \sigma_g^2 = exp^{\sqrt{\sum_{i=1}^{5}[ln(U_i)]^2+[ln(U_i)]^2}}$$

The LCI data points were treated as geometric means, and - along with their associated geometric standard deviations (GSDs) - were used to define lognormal probability distributions. This approach yields right-skewed distributions that reflect data uncertainty while ensuring positive and non-zero values. Each foreground and background data point was independently sampled 1,000 times using a Monte Carlo simulation, which propagates uncertainty by randomly drawing values from the defined lognormal distributions. This method generated a range of possible outcomes, enabling statistical analysis of variability and confidence in the results.

Table 19: Summary of uncertainty characterisation.

Battery-Specific Raw Materials	Route	Foreground σ^2_g	Basic	P	TiR	TeR	GeR	Background σ^2_g
$NiSO_4.6H_2O$	FI	1.16	1.18	2	2	1	1	1.19
	GLO	1.16	1.20	2	2	3	3	1.22
$CoSO_4.7H_2O$	FI	1.16	1.18	2	2	1	1	1.19
	GLO	1.16	1.20	2	3	3	3	1.24
$LiOH.H_2O$	FI	1.16	1.08	2	3	1	2	1.14

	GLO	1.16	1.08	2	3	3	3	1.15
C-Gr	NO	1.16	1.07	1	2	1	1	1.09
	GLO	1.16	1.09	2	3	3	3	1.16
Transport activities	Various	2.03	2.00	2	5	3	3	2.24
Electricity mixes	Various	1.16	1.05	2	3	3	1-2	1.14
Materials and chemicals	Various	1.16	1.05	2	4-5	3	2-3	1.22-1.51

The Monte Carlo results were then computed via a modified comparison index to compare the Nordic LFP and NMC811 cells to their comparison scenarios. This quantifies the likelihood that generated scenarios have lower climate impacts than the comparisons[35]. Two versions of the comparison index have been defined:

$$CI_{A,i} = \frac{b_i}{a_i} \text{ and } CI_{B,i} = \frac{a_i}{b_i}$$

The comparison index is calculated for $i = 1, \ldots, n$, where $n = 1000$ Monte Carlo simulations. A minimum threshold value ($\gamma_0 = 1.2$) is selected for assessing the superiority of each product meaning the scenario differs by at least ±20% in impact scores. A 20% threshold ensures that only meaningful differences are considered, avoiding decisions based on statistically significant but practically negligible variations[35]. The final statistical analysis for assessing the superiority (S) of one product (A) over another (B), and vice versa, is defined as:

$$S_A = \frac{1}{n}\sum_{i=1}^{n} \Theta(CI_{A,i} - \gamma_0)$$

$$S_B = \frac{1}{n}\sum_{i=1}^{n} \Theta(CI_{B,i} - \gamma_0)$$

3. Results

Tables 20 and 21 declares the overall study results, broken down by climate change impact sub categories. The following sections provide an in-depth analysis with key findings summarised here:

- When considering global average raw materials, both Swedish NMC811 and Norwegian LFP battery cells show lower total impacts compared to other major region electricity mixes, owing to the advantages of low-carbon energy (Section 3.2.3 and 3.3.2). However, when accounting for uncertainty distributions, there may still be considerable overlap in carbon footprints (Sections 3.2.5 and 3.3.4).
- Implementing Nordic raw materials substantially reduces the impacts of both cells, leading to discernably lower impacts compared to other regions utilising global raw materials (Sections 3.2.5. and 3.3.4). This is because Nordic vs. global raw materials show much lower impacts that employ energy and material efficient processes coupled with low-carbon power (Section 3.1).
- Considering closed-loop hydrometallurgical recycling for NMC811 battery cells could lead to additional climate impact benefits (Section 3.2.3).
- In general, LFP cells show lower impacts than NMC811 cells due to the avoidance of carbon-intensive cathode materials (Section 3.4)

Table 20: Results summary for NMC811 battery cell scenarios. RM - Raw Materials. Values are rounded to the nearest 1 decimal place. Asterisk indicates independent cradle-to-grave results that should not be used for comparisons.

Climate Change – kg CO_2 eq. per kWh	Sweden (Nordic RM)	Sweden (Nordic RM w recycling)*	Sweden (Global RM)	United States (Global RM)	Europe (Global RM)	China (Global RM)
Total	60.1	56.2	110.2	126.6	131.0	133.1
Biogenic	*0.1*	*0.3*	*0.1*	*0.1*	*0.1*	*0.1*
Fossil	*59.4*	*55.4*	*109.9*	*126.4*	*130.8*	*132.9*
LULUC	*0.6*	*0.5*	*0.2*	*0.1*	*0.1*	*0.1*

Table 21: Results summary for LFP battery cell scenarios. RM - Raw Materials. Values are rounded to the nearest 1 decimal place.

Climate Change – kg CO_2 eq. per kWh	Norway (Nordic RM)	Norway (Global RM)	United States (Global RM)	Europe (Global RM)	China (Global RM)
Total	48.8	71.1	94.9	101.5	106.2
Biogenic	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
Fossil	*48.3*	*70.9*	*94.7*	*100.8*	*106.0*
LULUC	*0.4*	*0.2*	*0.2*	*0.2*	*0.2*

It should be noted that the vast majority of the climate impact falls under the fossil category, which forms the primary focus of the analysis. LULUC and biogenic emissions are not examined in detail, as their contributions are minimal. However, in general, their dominant contributor is electricity generation related to upstream land occupation and transformation, and linked biogenic emissions required for power production.

3.1. Nordic Battery Raw Materials

Figure 4 compares climate change impacts by scope for Nordic raw materials, expressed as percentages relative to global average raw materials.

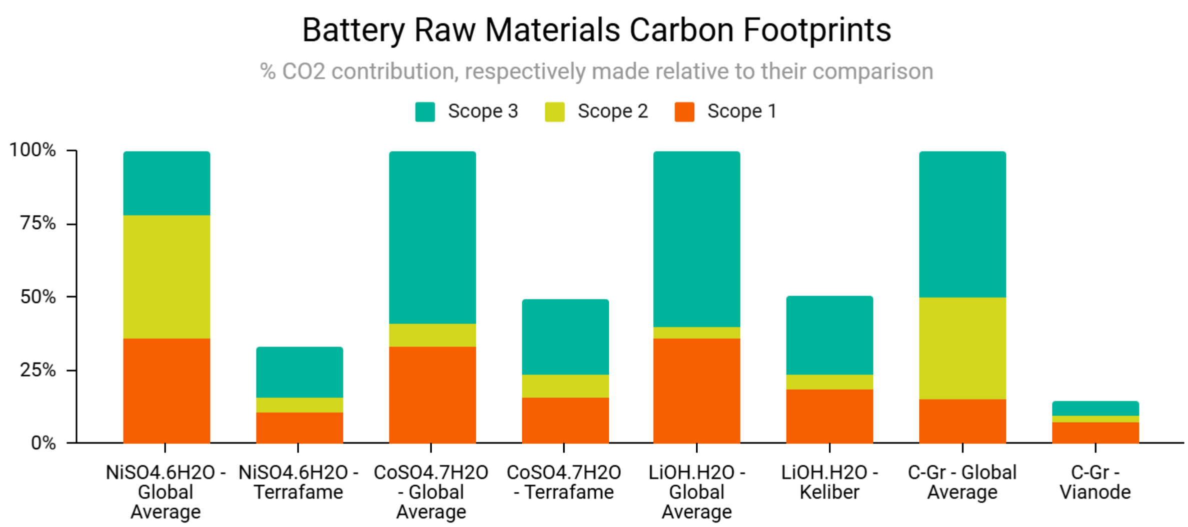

Figure 4: Total climate change impacts of Nordic raw materials. For each Nordic raw material, the percentage difference is normalized relative to its corresponding global average production route.

Due to proprietary constraints, detailed results and contribution analyses are not disclosed. It should also be noted that Terrafame's nickel and cobalt is included within the global average estimates as Finnish output proxies in the Minviro Database (Section A.1.5); though other routes have the dominant influence. As such, if Terrafame's products were isolated from the global average, the global average would expect a minor increase in impact. The key impact reduction drivers are provided below, resulting in Nordic raw materials being 51-85% lower impact than global production routes:

- **Terrafame's nickel sulfate** demonstrates a 67% lower impact, mainly in Scope 1 and 2. This is due to the combined factors of the energy-efficient sulfide ore bioleaching process that is coupled with Finland's low-carbon electricity and low-carbon fuels for heat (peat and woodchips). In contrast, the dominant global production route includes Indonesian-China laterite ore HPAL processing in addition to some shares of RKEF. Both are highly energy-intensive and rely on coal feedstock and electricity, leading to consequential carbon footprints, exceptionally in scope 2.

- **Terrafame's cobalt sulfate** finds a 51% lower impact, primarily in Scope 1 and 3, due to the benefits of the sulfide ore bioleaching as outlined for nickel sulfate. In comparison, the conventional sulfide ore mining in DRC followed by refining in China, leads to much higher impacts. This is due to increased diesel (mostly scope 1) and reagent (scope 3) use such as sodium hydroxide, explosives, lime, among others.
- **Keliber's lithium hydroxide** shows a 50% lower impact, mainly in Scope 1 and 3 emissions, as a result of the integrated approach of spodumene mining followed by refining. This leads to markedly lower scope 1 emissions due to reduced diesel and natural gas demands compared to the dominant global route of spodumene mining in Australia followed by refining in China.
- **Vianode's synthetic graphite** achieves an 85% lower impact across all scopes. This is owed not only to the tremendously lower energy demand coupled with Norway's low-carbon electricity, but also to Vianode's innovative and resource-efficient technology compared to conventional production in China. This technology significantly reduces the use of energy , raw materials, and consumables, and leads to substantially lower GHG emissions across all scopes.

3.2. NMC811 Cells

3.2.1. Cradle-to-Gate Contribution Analysis

Figure 5 displays the total climate change impact by key components for Swedish NMC811 cells using global average and Nordic raw materials as described in Section 3.1. Figures 6 and 7 provide further insight by individual inputs. The Nordic case offers a combined lower impact of 46% compared to global raw materials. This is driven by the following:

- **Cathode** hotspot is halved from 61.1 to 30.2 kg CO_2 eq. per kWh due to greatly lower impacts in nickel (from 31.9 to 10.1 kg CO_2 eq. per kWh) and cobalt (from 4.9 to 2.3 kg CO_2 eq. per kWh) provided by Terrafame's route; and meaningfully lower impacts in lithium through the Keliber project (from 13.6 to 7.0 kg CO_2 eq. per kWh).

- **Anode** hotspot is extensively cut from 23.0 to 3.9 kg CO_2 eq. per kWh due to lower impact of Vianode's synthetic graphite (from 21.3 to 2.2 kg CO_2 eq. per kWh).

The cathode remains the main hotspot in the Nordic case, contributing 50% of total cell impact due to nickel and lithium. NMP solvent and aluminium foil also contribute notably at 5.6 (9%) and 2.7 kg CO_2 eq per kWh (4%), respectively. The container is the next major hotspot, contributing 13.1 kg CO_2 eq per kWh (22%), mostly from the aluminium can and tab (11.7 kg CO_2 eq per kWh). Energy demand remains a minor contributor, due to Sweden's low-carbon electricity mix, with impacts largely from natural gas heating in pCAM production. Other minor hotspots include lithium hexafluorophosphate electrolyte, the battery separator, the anode copper foil and graphite.

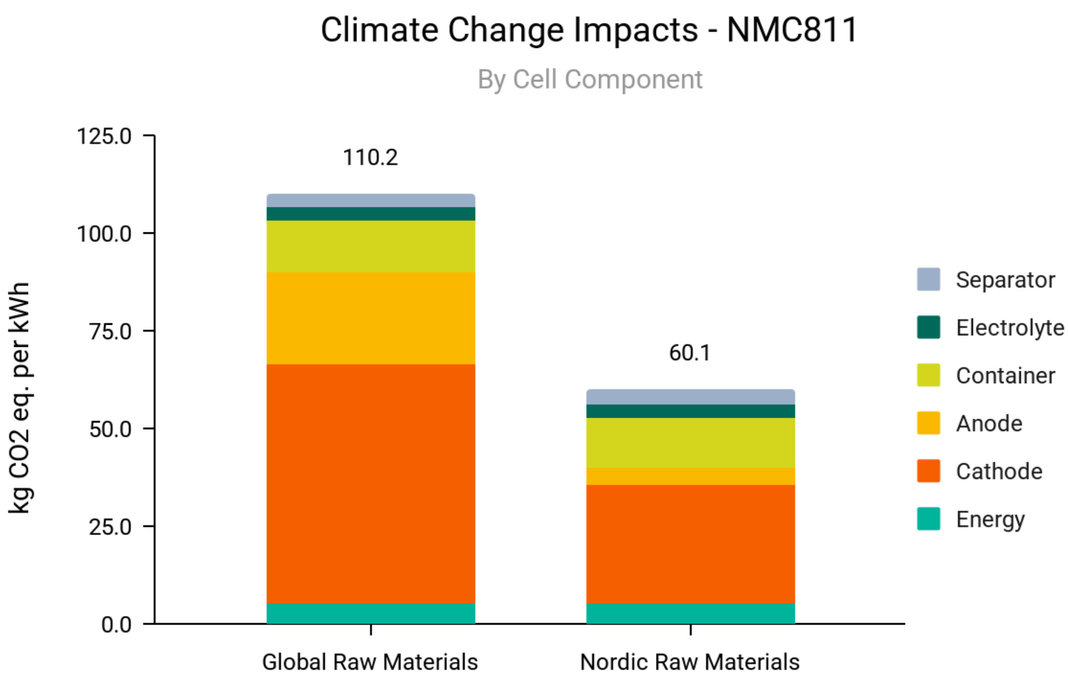

Figure 5: NMC811 cell total climate change impact by key component. Energy refers to the total electricity and natural gas consumption for precursor, active material, and cell production stages.

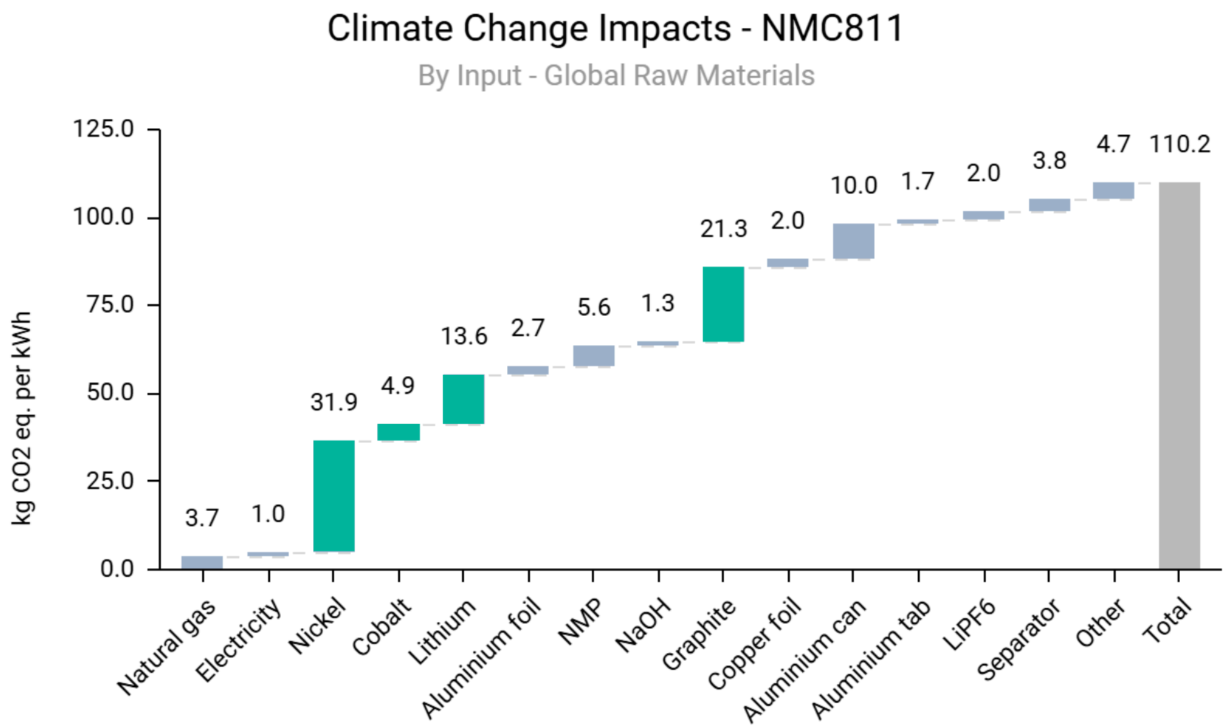

Figure 6: NMC811 cell contribution analysis by input for global average raw material scenario. For nickel, cobalt, and lithium, this corresponds to their sulfate and hydroxide precursor forms.

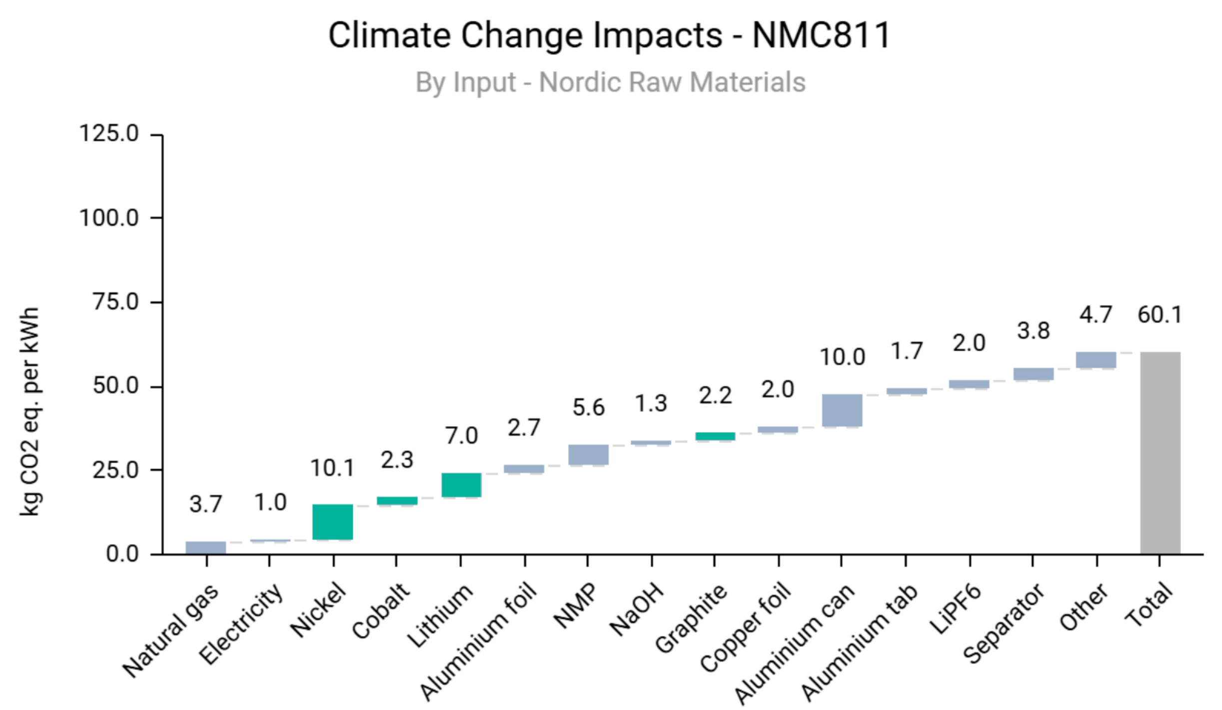

Figure 7: NMC811 cell contribution analysis by input for Nordic raw material scenario. For nickel, cobalt, and lithium, this corresponds to their sulfate and hydroxide precursor forms.

3.2.2. Cradle-to-Grave System Boundary Extension

Figure 8 shows the impacts associated with Finnish closed-loop hydrometallurgical recycling of the Swedish NMC811 battery cell using Nordic raw materials. This is an independent analysis that investigates the potential climate change impact effects of recycling and should not be used for comparative assertions in the later sections. The recycling process adds 11.5 kg CO_2 eq. per kWh leading to a cell impact increase of 19%. Figures 9 and 10 provide further insight.

- This is driven by solvent extraction of metals and is the main hotspot making up 7.3 kg CO_2 eq. per kWh. This is largely due to the demand for high-carbon kerosene dilutant (3.0 kg CO_2 eq. per kWh) and extractants (2.9 kg CO_2 eq. per kWh) of Cyanex 301 and D2EHPA.
- Other stages have more minor hotspots, but incrementally contribute to the rest of the recycling impact. Key drivers include natural gas heating (1.7 kg CO_2 eq. per kWh) in several stages and reagents such as sodium hydroxide, hydrogen peroxide, and sulfuric acid.
- Electricity consumption is a minor hotspot of only 0.5 kg CO_2 eq. per kWh owing to the low-carbon power provided by the Finnish electricity mix.

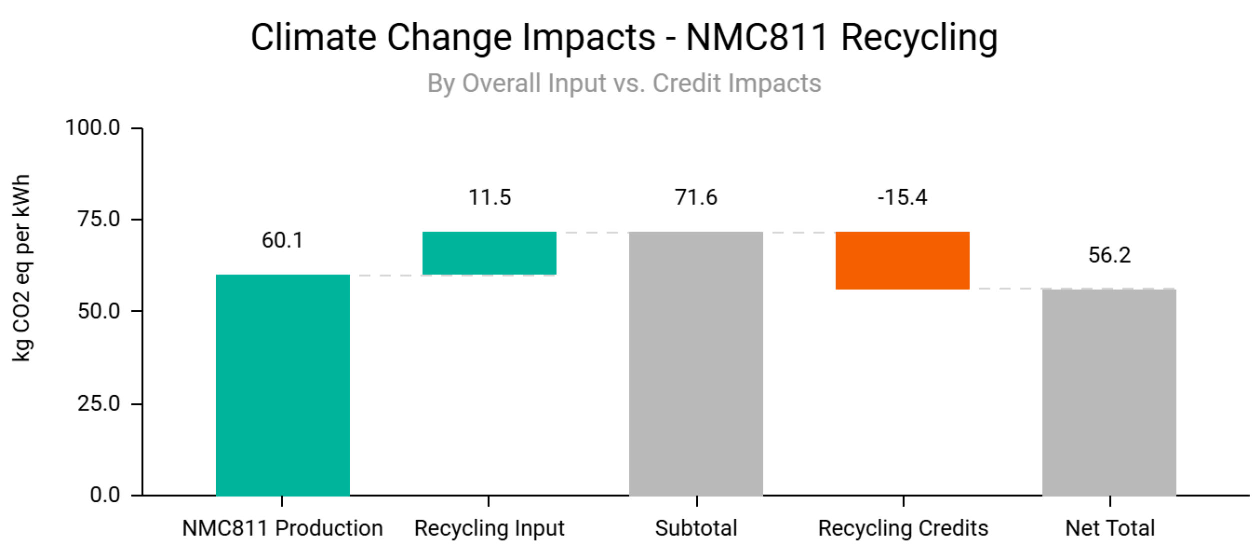

Figure 8: NMC811 climate change impacts of cradle-to-grave system boundary extension.

Subsequently, the yielded recycling metal co-products offer recycling credits of 15.4 kg CO_2 eq. per kWh yielding a reduced cell net impact by 6% relative to production. The main drivers are the recovery of nickel sulfate, lithium hydroxide, and cobalt sulfate that avoid their Nordic primary production impacts. This means that the secondary production of these metals via hydrometallurgical recycling could provide a potentially lower carbon route compared to the primary routes. Therefore, Finnish hydrometallurgical recycling of NMC811 cells may reduce the climate change impacts associated with their upstream raw materials and manufacturing.

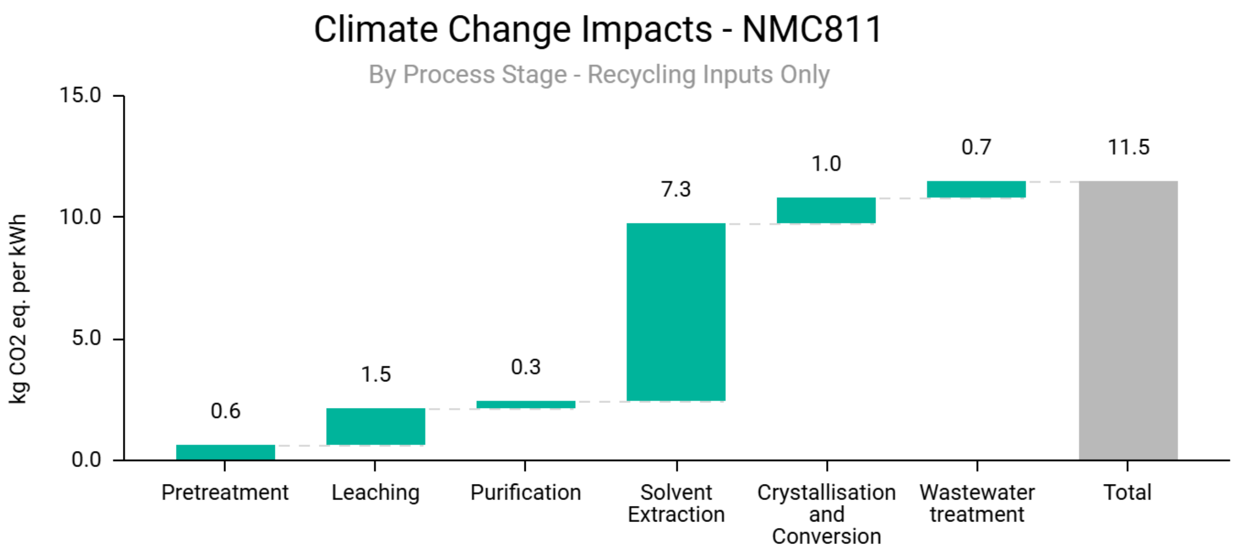

Figure 9: NMC811 climate change impacts by process of recycling inputs only. This is inclusive of all energy and material inputs and outputs of waste and emissions.

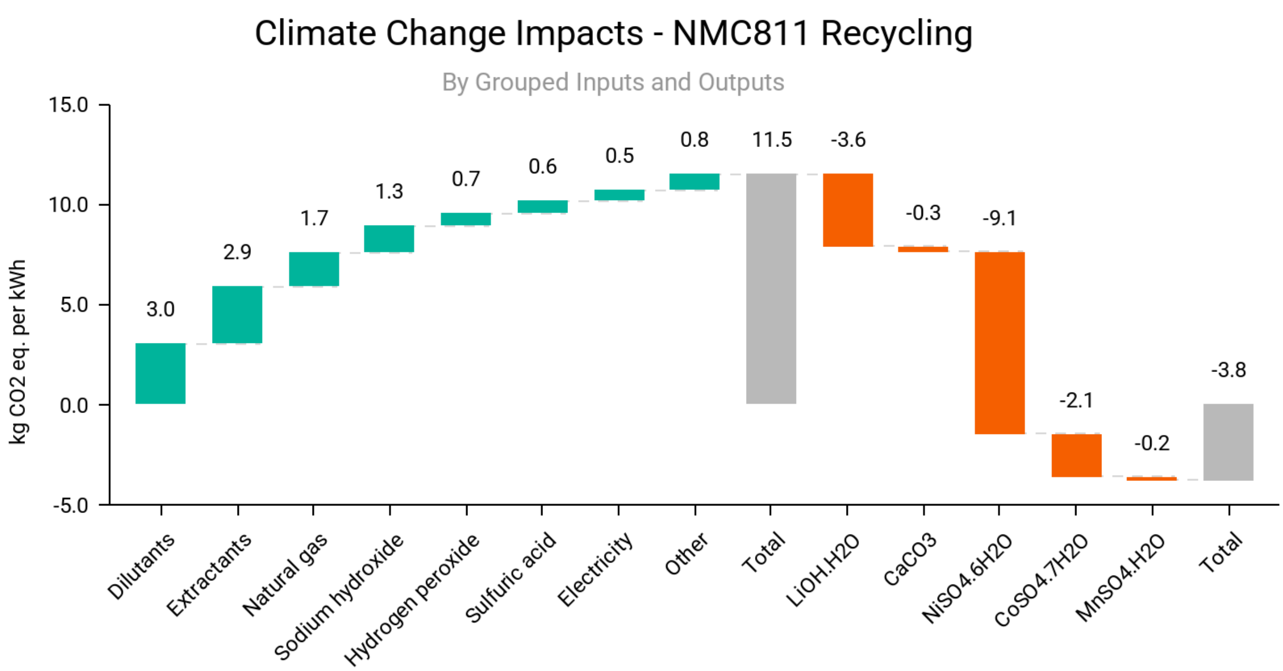

Figure 10: NMC811 cell climate change impacts by grouped inputs and outputs of recycling process.

However, the potential 6% benefit is modest, and it must be acknowledged that Minviro's hydrometallurgical model was used as a proxy due to the absence of primary operational data from Fortum. As such, the overall conclusions are subject to several key assumptions and significant uncertainties that require further validation. Critical parameters - including actual metal recovery rates, reagent and energy consumption, graphite recovery potential, and variations across different processing stages - should be examined in detail and compared against Fortum's primary data once available to strengthen the robustness of the findings.

3.2.3. Regional Cradle-to-Gate Comparisons

Figure 11 presents a regional comparison of total climate change impacts for Swedish (SE) NMC811 cells using global average and Nordic raw materials, alongside scenarios for China, Europe, and the United States using global average raw materials - with the primary variable being electricity mix.

With global average raw materials, the Swedish scenario shows a 13-17% lower impact than other regions, primarily due to lower energy hotspots of 5.4 kg CO_2 eq. per kWh compared to 20.5-28.0 kg CO_2 eq. per kWh. This advantage stems from Sweden's highly renewable electricity mix - dominated by hydropower, nuclear, and wind - resulting in a grid carbon intensity below 30 g CO_2 eq. per kWh electricity generated. In contrast, other regions have a weighted battery production electricity mix with carbon intensities of 400-700 g CO_2 eq. per kWh electricity generated, largely from significant shares of coal and natural gas. The Swedish scenario shows further reductions of 53-55% compared to other regions when using Nordic raw materials that utilise the efficient and low-carbon processes (Section 3.1). This underscores the importance of adopting low-carbon solutions not only in cell manufacturing, but even more so in the upstream sourcing of raw materials.

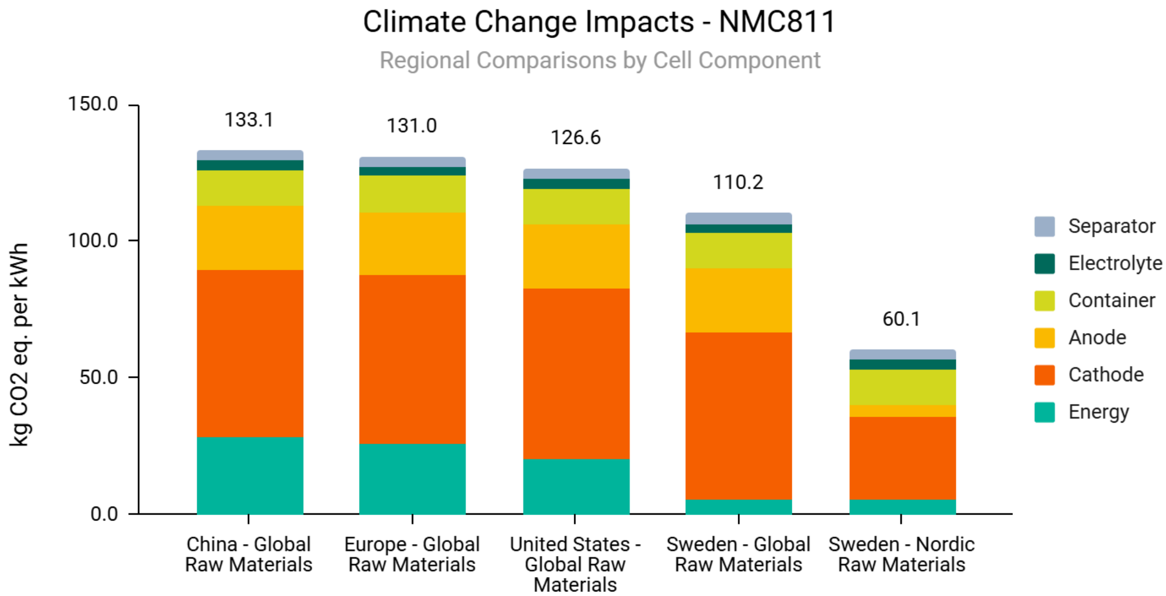

Figure 11: NMC811 cell comparative climate change impacts by region. Energy refers to the total electricity and natural gas consumption for precursor, active material, and cell production stages.

3.2.4. Sensitivity Tests

Figure 12 shows the sensitivity analysis of the top five contributors for Swedish NMC811 in the global raw materials and Nordic raw materials cases, reflecting independent variations of ±20%:

- **Nickel:** 103.7-116.5 (Global) and 58.1-62.1 kg CO_2 eq. per kWh (Nordic). Nickel remains the most sensitive parameter in both scenarios, even when the low-carbon Nordic route is used in the cathode due to remaining hotspots discussed in Sections 3.1. and 3.2.1.
- **Graphite:** 105.9-114.4 kg CO_2 eq. per kWh (Global). It is not among the top five most sensitive parameters in the Nordic raw materials scenario, suggesting that its impact has been effectively mitigated in the anode.
- **Lithium:** 107.4-112.8 (Global) and 58.7-61.5 kg CO_2 eq. per kWh (Nordic). Lithium remains a sensitive cathode parameter in the Nordic scenario.
- **Aluminium can:** 108.1-112.1 (Global) and 58.1-62.1 kg CO_2 eq. per kWh (Nordic). It becomes, on an equal basis to nickel, one of the most sensitive parameters in the Nordic scenario.
- **NMP solvent:** 109.0-111.2 (Global) and 58.9-61.2 kg CO_2 eq. per kWh (Nordic). NMP solvent is one of the most sensitive hotspots in both scenarios.

- **Separator:** 59.3-60.8 kg CO_2 eq. per kWh (Nordic), appearing only in the Nordic case to become one of the most significant hotspots.

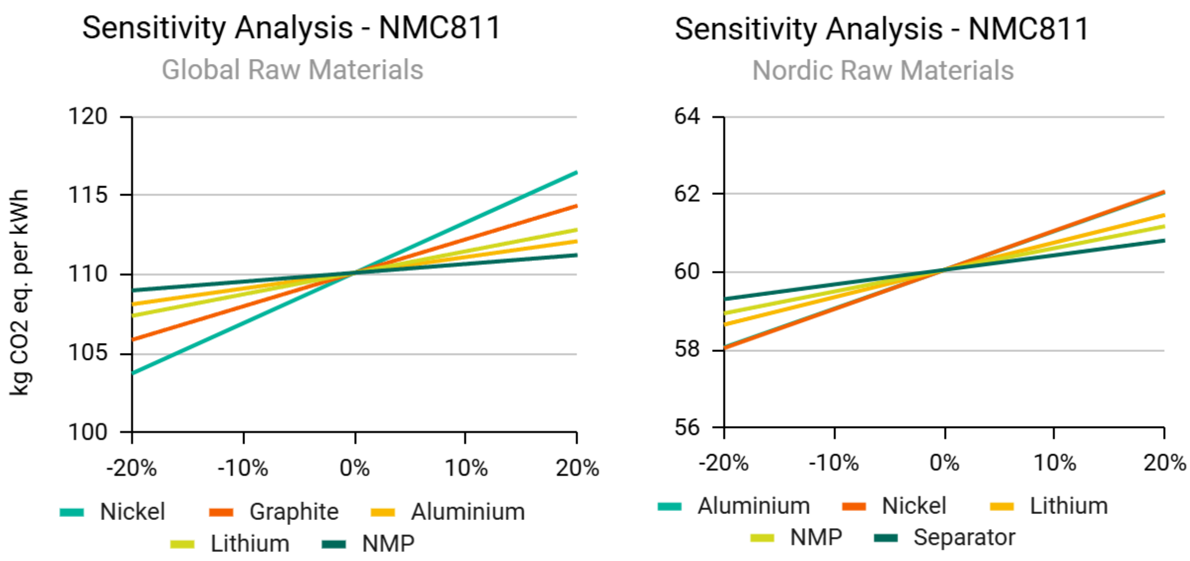

Figure 12: NMC811 sensitivity analysis of the top 5 climate change impact contributors.

Data collected for nickel, graphite, and lithium, achieved good to very good DQRs (Table 17), appropriately reflecting their importance in the sensitivity analysis. While their impacts are considerably reduced when using Nordic raw materials, they still remain the most influential and sensitive hotspots. In contrast, components such as the aluminium can, NMP, and separator emerge as key hotspots in scenarios using Nordic raw materials. However, while not central to the study goals, these rely on more generic data and assumptions with lower DQRs. Therefore, their prominent hotspots have greater uncertainty.

Figure 13 further presents sensitivity tests on the assumptions for regional electricity mixes and natural gas use during cell assembly, identified as the most uncertain assumptions relevant to the study goals. Due to the focus on energy, the hotspot breakdown is provided by scope. Firstly, across the comparison regions, various selections of ecoinvent datapoints were made from worst (e.g. Ecoinvent China - “market group for electricity, medium voltage - CN”) to best (e.g. Ecoinvent France - “market for electricity, medium voltage - FR”). These were separate selections from the weighted averages used in Table 7 for sensitivity testing declared in Table 17. The regional averages showed variations from the baseline cases, with China being a greater value, United States being similar, and Europe being lower. In any instance, the conclusions for Swedish scenarios are retained for being lower impact in most cases within Europe, United States, and

China, except for regions with exceptionally low-carbon electricity such as France which have competitive cell impacts.

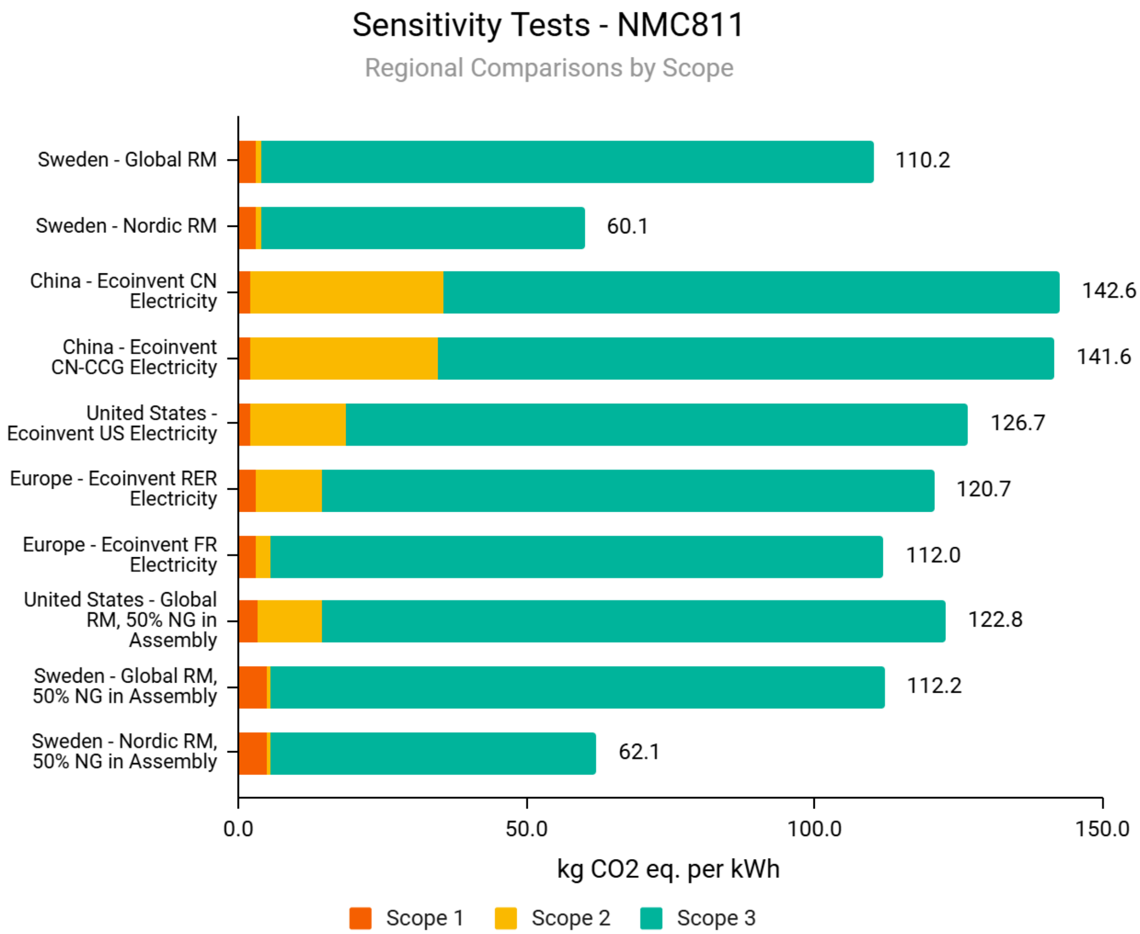

Figure 13: NMC811 sensitivity tests for alternative assumptions for regional electricity mixes. RM - Raw materials. The Swedish baseline cases (top two bars) are compared to various regional electricity mix assumptions from ecoinvent instead of the weighted battery production averages used. Furthermore, assumptions on 50% natural gas and 50% electricity use during cell assembly are also included (bottom two bars) compared to the 100% electricity used in the baseline.

Furthermore, the baseline US case was used to assess the sensitivity of natural gas consumption during cell assembly, with comparisons also made to the baseline SE scenarios for both global average and Nordic raw materials. In the SE scenarios, assuming that 50% of the energy demand for cell assembly comes from natural gas has only a minor increase in the overall impacts. For example, in the SE scenario using global average raw materials, impacts increase by just by 2%, primarily due to added scope 1 emissions. Interestingly, the US case shows a small 3% decrease in impacts since natural gas supply is lower impact as electricity still carries significant carbon intensity in addition to differences in natural gas emission factors between European and Rest-of-World datasets. However, these results should be interpreted with caution as more detailed modelling is needed to accurately reflect the energy demand split between natural gas and electricity. In any case, the Swedish cells consistently produce lower impacts than other regions when using various assumptions for electricity mixes and natural gas consumptions.

3.2.5. Uncertainty Analysis

Figure 14 presents a comparative uncertainty analysis of cradle-to-gate climate change impacts across regional scenarios with detailed results disclosed in Appendix A.2.1. While there is substantial overlap among all regions using global average raw materials, the Swedish scenario interquartile range (Q1-Q3) does not overlap with others, indicating more consistently lower impacts. A comparative superiority analysis shows that the Swedish scenario is discernibly lower (by at least a threshold 20% lower impact) in 37-49% of cases compared to other regions. This suggests that low-carbon electricity does offer potential advantages, though not conclusively. In contrast, when using Nordic raw materials, 100% of Swedish cases show at least a 20% lower impact, confirming a robust benefit from combining low-carbon electricity cell manufacturing and Nordic raw materials.

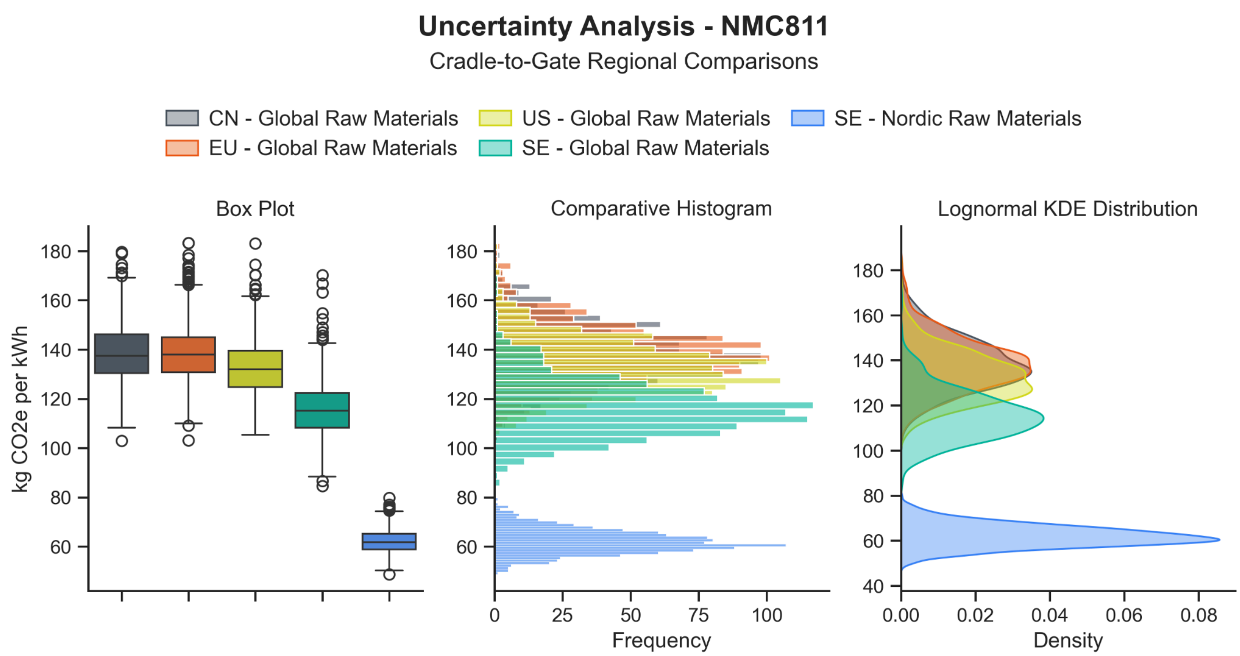

Figure 14: Comparative Monte Carlo climate change results for NMC811 cradle-to-gate comparisons.

Table 22: The superiority analysis, based on Monte Carlo results, indicates the percentage of cases where the Sweden scenario shows at least 20% lower climate change impacts compared to the regions listed in each column.

PRODUCT vs. PRODUCT	United States – Global Raw Materials	Europe – Global Raw Materials	China – Global Raw Materials
Sweden - Global Raw Materials	37%	48%	49%
Sweden - Nordic Raw Materials	100%	100%	100%

3.3 LFP Cells

3.3.1. Cradle-to-Gate

Figure 15 shows the total climate change impact by key components for Norwegian LFP cells using global average and Nordic raw materials. Figures 16-17 provide further breakdowns by specific inputs. The Nordic case offers a combined lower impact of 31%, due to the following:

- The **Anode** hotspot drops from 23.6 to 5.9 kg CO_2 eq. per kWh, largely due to a significant decrease in graphite impacts, from 19.7 to 2.0 kg CO_2 eq. per kWh.
- The **Cathode** hotspot is reduced by half, from 17.1 to 12.5 kg CO_2 eq. per kWh, primarily due to lower lithium impacts, falling from 8.9 to 4.5 kg CO_2 eq. per kWh.

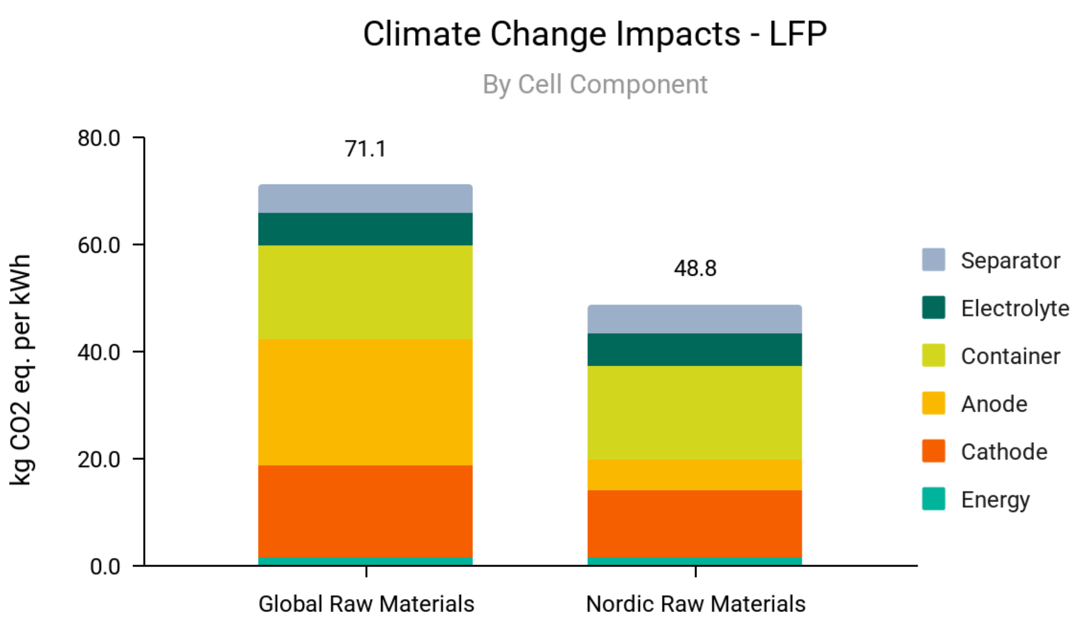

Figure 15: LFP total climate change impacts by key component. Energy refers to the total electricity and natural gas consumption for precursor, active material, and cell production stages.

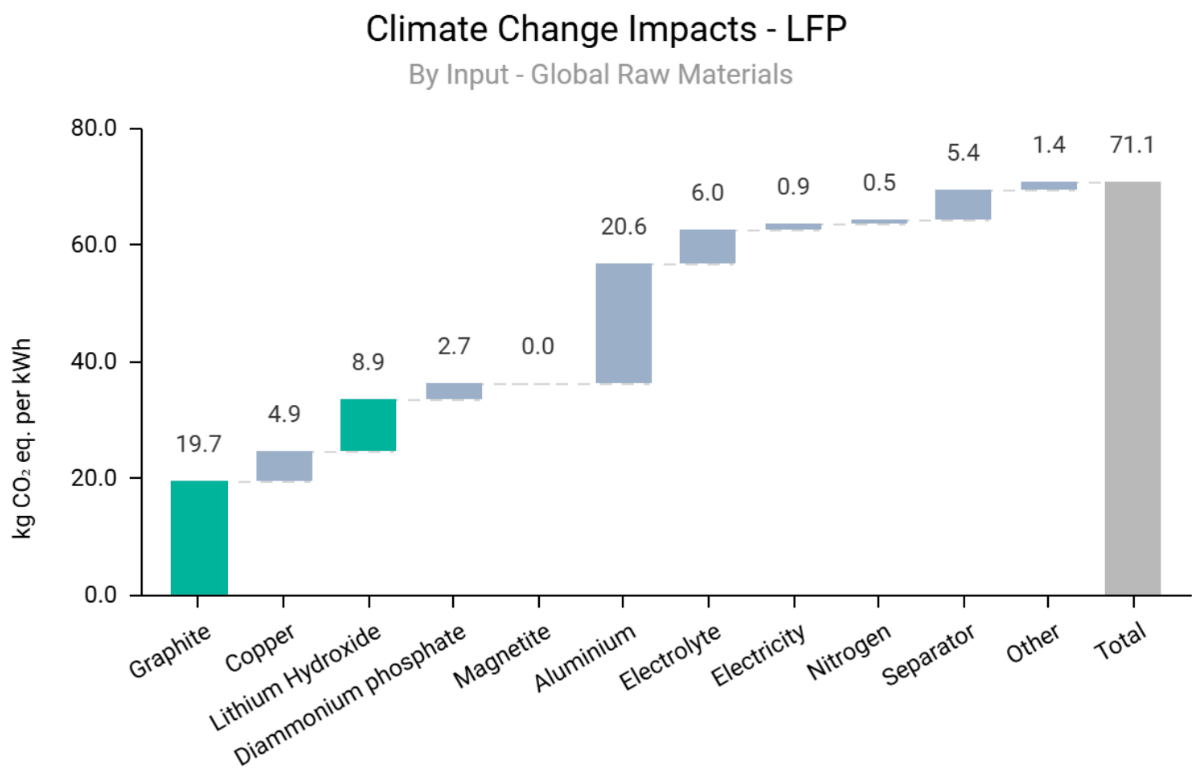

Figure 16: LFP contribution analysis by input for global raw materials.

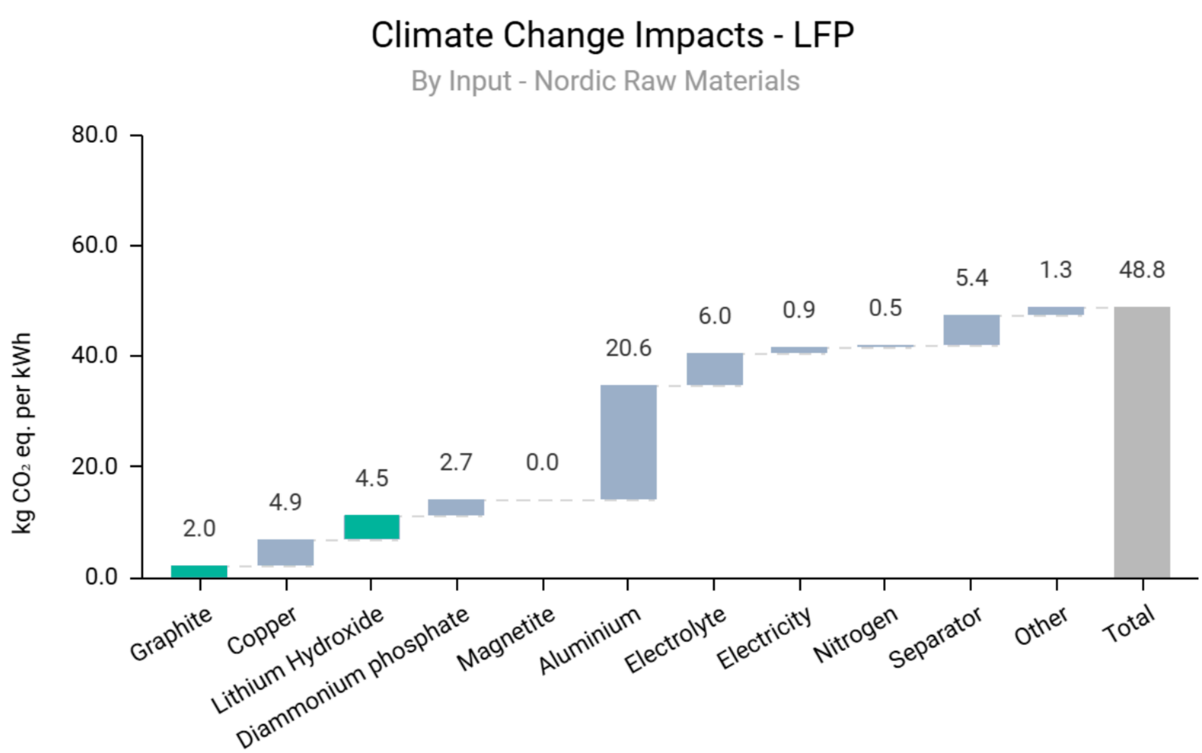

Figure 17: LFP contribution analysis by input for Nordic raw materials.

The cathode remains a key contributor, contributing 24% of the LFP cell impact. This is primarily driven by the aluminium foil (4.9 kg CO_2 eq. per kWh), lithium hydroxide (4.5 kg CO_2 eq. per kWh), and diammonium phosphate (2.7 kg CO_2 eq. per kWh). However, the cell container is the largest contributor, accounting for 17.5 kg CO_2 eq. per kWh (37%), mainly due to the aluminium can and tab, which alone contribute 15.2 kg CO_2 eq. per kWh. Energy demand remains a minor contributor due to Norway's low-carbon electricity mix and the absence of natural gas used for LFP processing. Other notable hotspots include lithium hexafluorophosphate in the electrolyte, the battery separator, and copper and graphite used in the anode.

3.3.2 Regional Cradle-to-Gate Comparisons

Figure 18 presents a regional comparison of total climate change impacts for Norway LFP cells using global average and Nordic raw materials, alongside cases for Europe, United States, and China - with the primary variable being electricity mix.

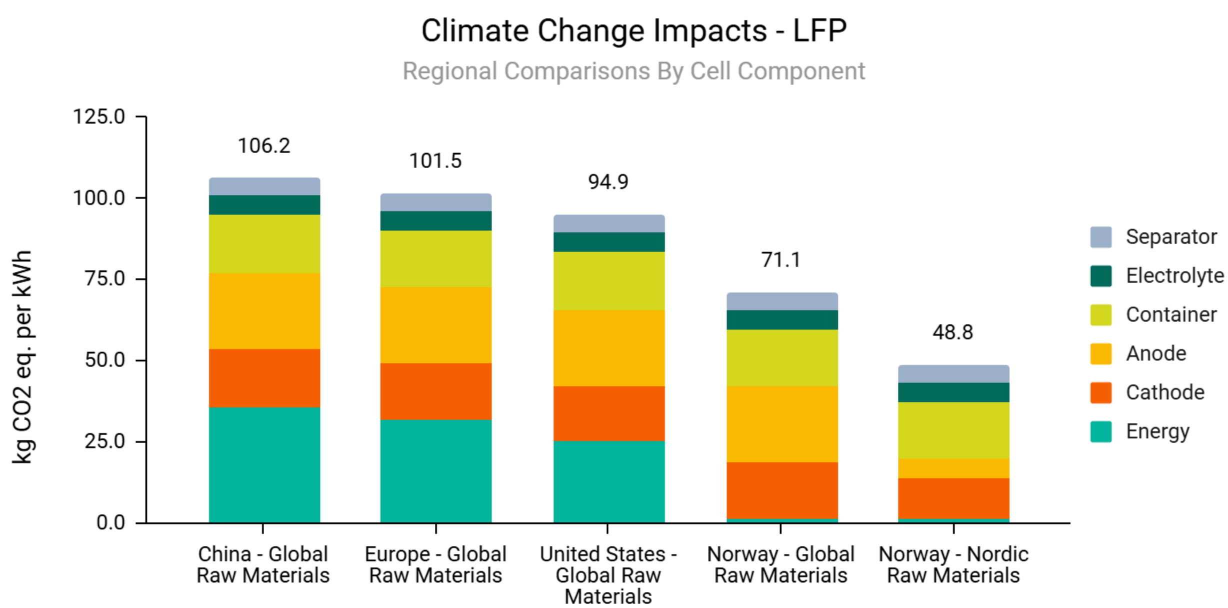

Figure 18: LFP cell comparative climate change impacts by region. Energy refers to the total electricity and natural gas consumption for precursor, active material, and cell production stages.

With global average raw materials, Norway shows considerable 25-33% lower impacts than other regions, primarily due to its low energy impacts of 1.5 kg CO_2 eq. per kWh, compared to 25.0-35.6 kg CO_2 eq. per kWh in other regions. This advantage stems from Norway's highly renewable electricity mix - dominated by hydropower, nuclear, and wind - resulting in a grid carbon intensity below 20 g CO_2 eq. per kWh electricity generated. In contrast, other regions have weighted battery production mix electricity carbon intensities of 400-700 g CO_2 eq. per kWh electricity generated, largely due to coal and natural gas shares. Implementing Nordic raw materials further drives the impact reduction to 49-55% compared to other regions using global average raw materials.

3.3.4. Sensitivity Tests

Figure 19 shows the sensitivity analysis of the top five contributors for Norway LFP in the global raw materials and Nordic raw materials cases, reflecting independent variations of ±20%.

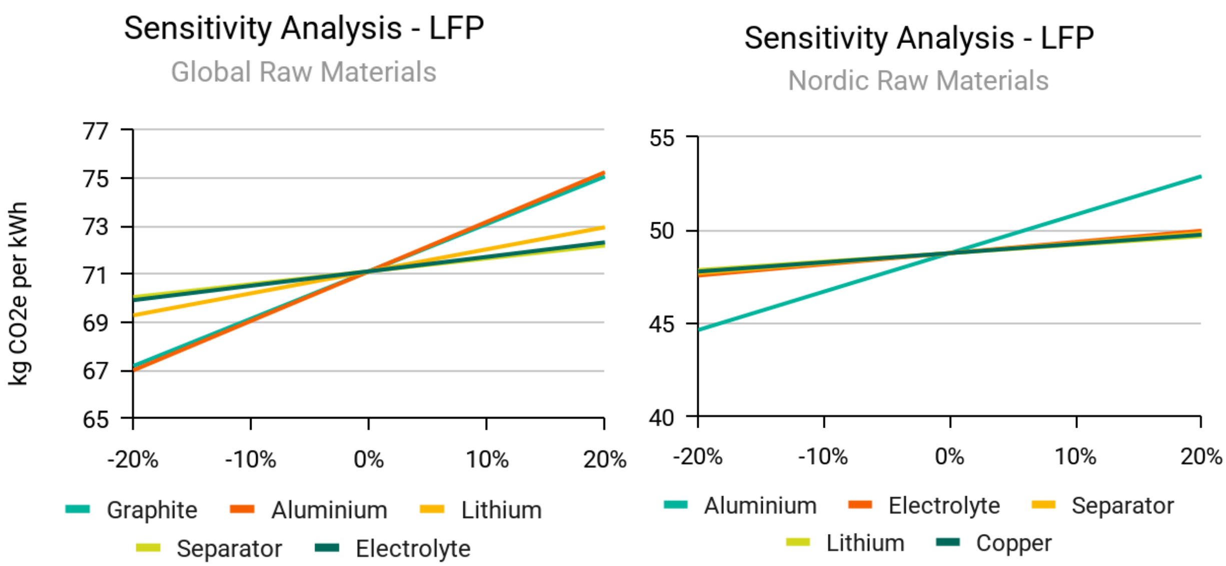

Figure 19: LFP sensitivity analysis of the top 5 climate change impact contributors.

- **Aluminium can:** 67.0-75.2 (Global) and 44.6-52.9 kg CO_2 eq. per kWh (Nordic). Aluminium remains the most sensitive parameter in both scenarios.
- **Graphite:** 67.2-75.1 kg CO_2 eq. per kWh (Global). It is not among the top five sensitive parameters in the Nordic raw materials case, indicating that its hotspot has been addressed in the anode.
- **Lithium:** 69.3-72.9 (Global) and 47.9-49.7 kg CO_2 eq. per kWh (Nordic). Remains a sensitive cathode parameter in the Nordic scenario.
- **Electrolyte:** 69.9-72.3 (Global) and 47.6-50.0 kg CO_2 eq. per kWh (Nordic). Remains a sensitive cathode parameter in the Nordic scenario.

- **Separator:** 70.0-72.2 (Global) and 47.7-49.8 kg CO_2 eq. per kWh (Nordic). NMP solvent is one of the most sensitive hotspots in both scenarios.
- **Copper total:** 47.8-49.7 kg CO_2 eq. per kWh (Nordic). The total copper used becomes a top five hotspot, but it is the least sensitive among them.

Data collected for graphite and lithium achieved good to very good DQRs (Table 17), appropriately reflecting their importance in the sensitivity analysis. Their impacts are considerably reduced when using Nordic raw materials with lithium still remaining a hotspot, while graphite is no longer a top five hotspot. Other components, in particular the aluminium can, are sensitive hotspots in both global and Nordic scenarios. While not central to the study goals, these rely on more generic data and assumptions with lower DQRs. Therefore, their prominent hotspots have greater uncertainty.

Figure 20 further presents sensitivity tests on the assumptions for regional electricity mixes, identified as the most uncertain assumptions relevant to the study goals. Due to the focus on energy, the hotspot breakdown is provided by scope, though no direct scope 1 emissions are present since no natural gas is used for LFP manufacturing. Firstly, across the comparison regions, various selections of ecoinvent datapoints were made from worst (e.g. Ecoinvent China - “market group for electricity, medium voltage - CN”) to best (e.g. Ecoinvent France - “market for electricity, medium voltage - FR”). The regional averages showed variations from the baseline cases, with China being a greater value, United States being similar, and Europe being much lower. In any instance, the conclusions for Swedish scenarios are retained for being lower impact in most cases within Europe, the United States, and China except for regions with exceptionally low-carbon electricity such as France which have competitive cell impacts.

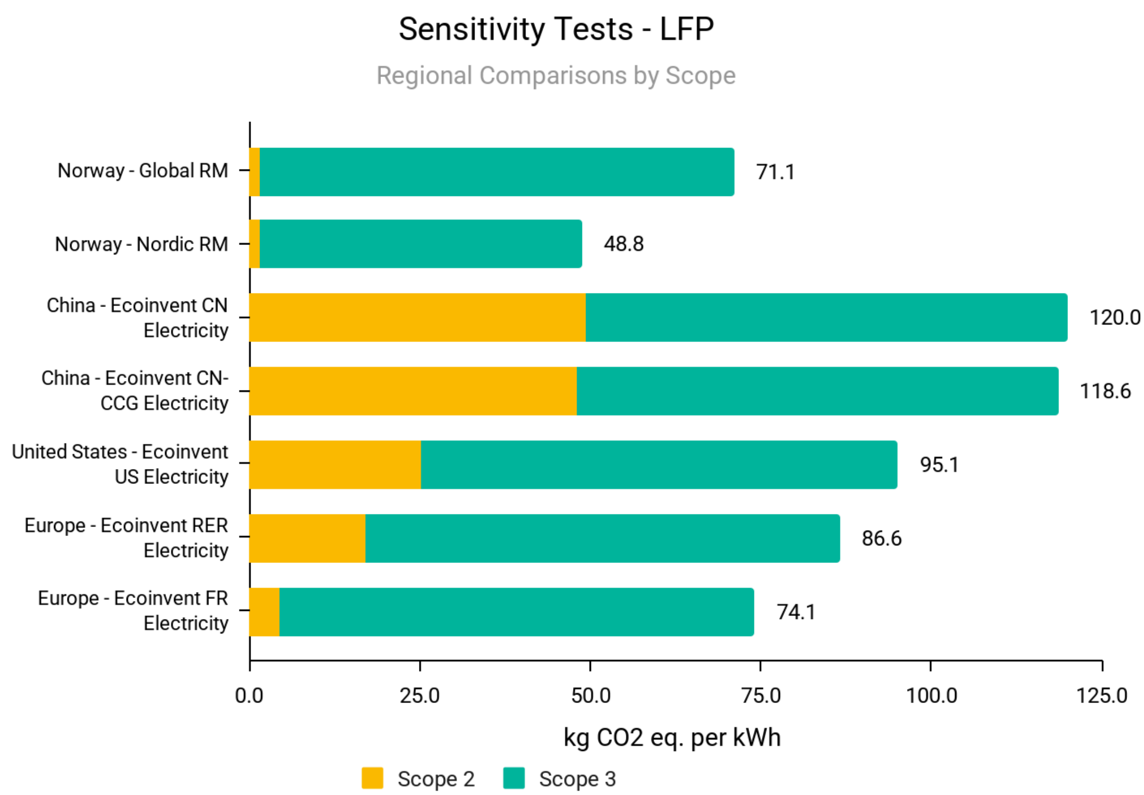

Figure 20: LFP sensitivity tests for alternative assumptions for regional electricity mixes. RM - Raw materials. The Norwegian baseline cases (top two bars) are compared to various regional electricity mix assumptions from ecoinvent instead of the weighted battery production averages used.

3.3.5. Uncertainty Analysis

Figure 21 presents a comparative uncertainty analysis of cradle-to-gate climate change impacts across regional scenarios with detailed results disclosed in Appendix A.2.1. While there is significant overlap among all regions using global average raw materials, the Norway scenario is discernable. Its interquartile range (Q1-Q3) does not overlap with others, indicating more consistently lower impacts. A comparative superiority analysis in Table 23 shows that the Norway scenario is discernibly lower (by at least a threshold of 20% lower impact) in 74%-92% of cases compared to Europe, the United States, and China, respectively. This suggests that low-carbon electricity for cell manufacturing alone, could meaningfully offer a significant advantage. Furthermore, when Nordic raw materials are used in the Norway case, 100% of comparisons show at least a 20% lower impact, confirming a robust benefit from combining low-carbon electricity cell manufacturing and Nordic raw materials.

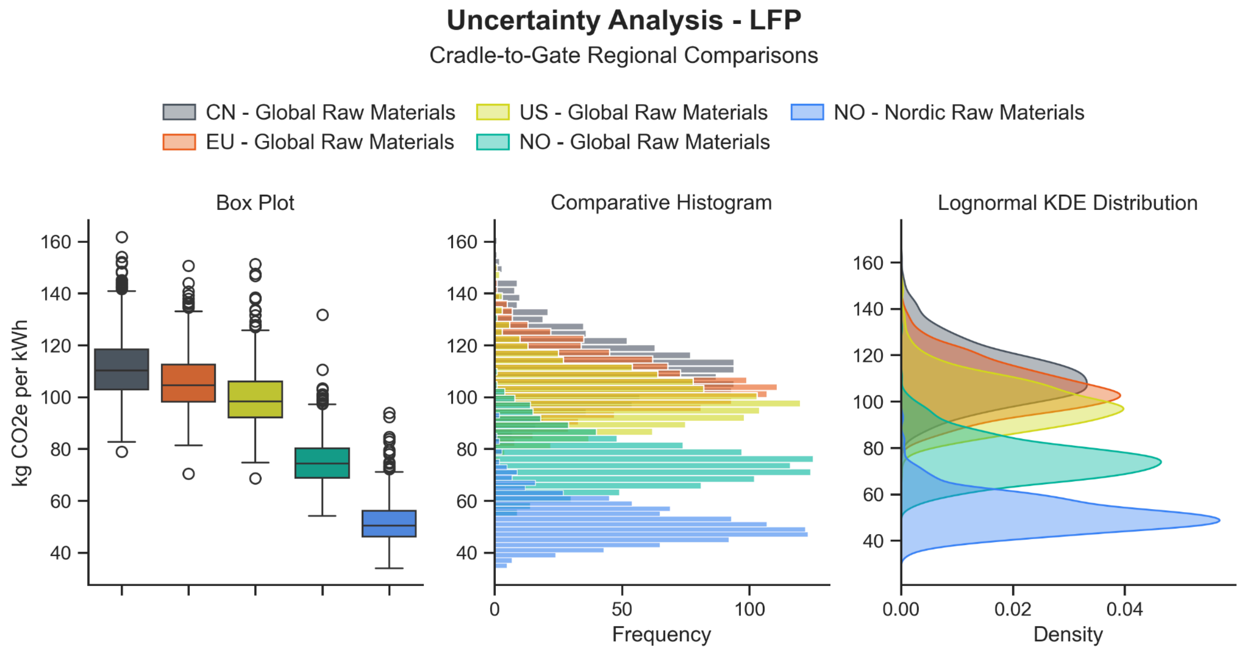

Figure 21: Comparative Monte Carlo climate change results for LFP cradle-to-gate comparisons.

Table 23: The superiority analysis, based on Monte Carlo results, indicates the percentage of cases where the Norway scenario shows at least 20% lower climate change impacts compared to the regions listed in each column.

PRODUCT vs. PRODUCT	United States – Global Raw Materials	Europe – Global Raw Materials	China – Global Raw Materials
NO - Global Raw Materials	74%	86%	92%
NO - Nordic Raw Materials	100%	100%	100%

3.4. Cradle-to-Gate NMC811 vs. LFP

Figure 22 compares the total climate change impact by key components for NMC811 and LFP cells using global average and Nordic raw materials, as detailed in Sections 3.2 and 3.3. Using global raw materials, LFP shows a 35% lower impact than NMC811. While LFP has greater material demands for the container, electrolyte, and separator - due to lower gravimetric energy density - and similar anode impacts, its advantage stems from avoiding high-impact nickel and cobalt in the cathode. Instead, it uses low-impact magnetite sourced from ilmenite and diammonium phosphate, in addition to benefits from eliminating the need for NMP solvent in cathode processing. The differences in energy contributions are due to factors such as Morrow Batteries' use of 100% low-carbon Norwegian electricity for production, whereas the NMC811 cell assumptions include partial reliance on natural gas for heat during CAM production; though both are minor contributors to total cell impacts. However, these energy-related differences are more reflective of manufacturing assumptions used rather than inherent differences between the chemistries.

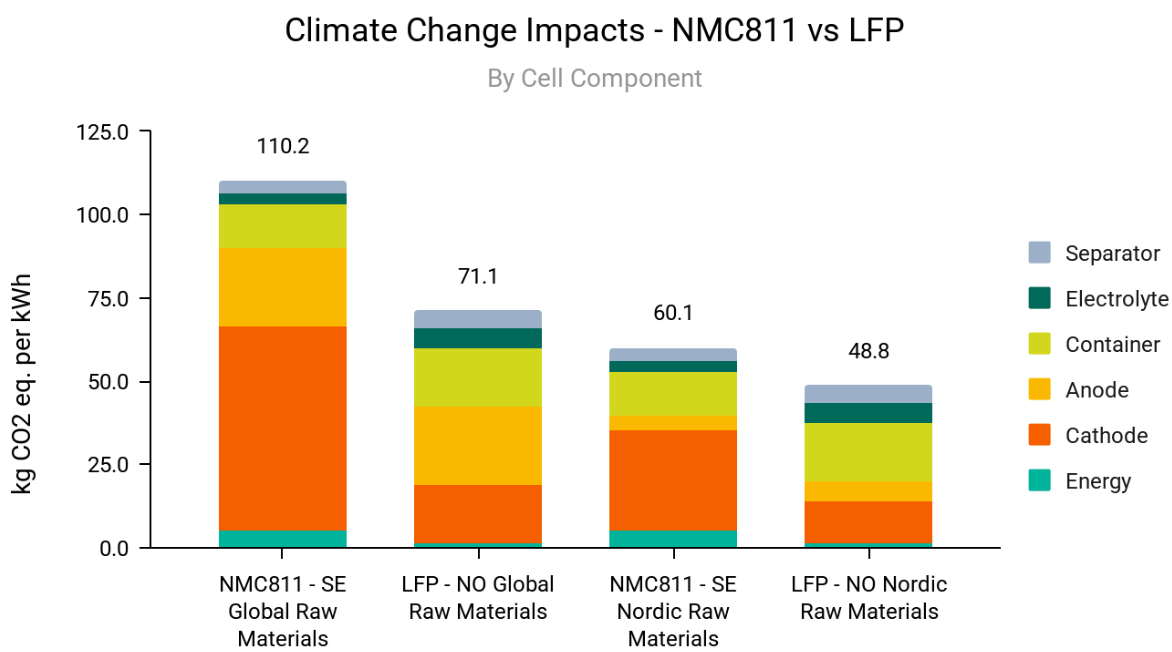

Figure 22: NMC811 vs LFP climate change impacts by key component. Energy refers to the total electricity and natural gas consumption for precursor, active material, and cell production stages.

Even with Nordic raw materials, LFP maintains a 19% lower impact than NMC811. Despite substantial reductions in NMC811 cathode impacts, the cathode still accounts for more than twice the impact of LFP, as nickel remains a significant hotspot. Therefore, LFP consistently achieves lower impacts than NMC811 through the avoidance of high-carbon cathode materials. Figure 23 further compares the uncertainty analysis results between the chemistries. In the global average raw materials case, the LFP battery is at least 20% lower impacts than NMC811 in 96% of cases, confidently demonstrating lower impacts consistently. In the Nordic raw material case, LFP still shows lower impact but to a lower discernability of 59% cases. Therefore, while LFP still retains lower impacts compared to NMC811, the margin and significance is lesser.

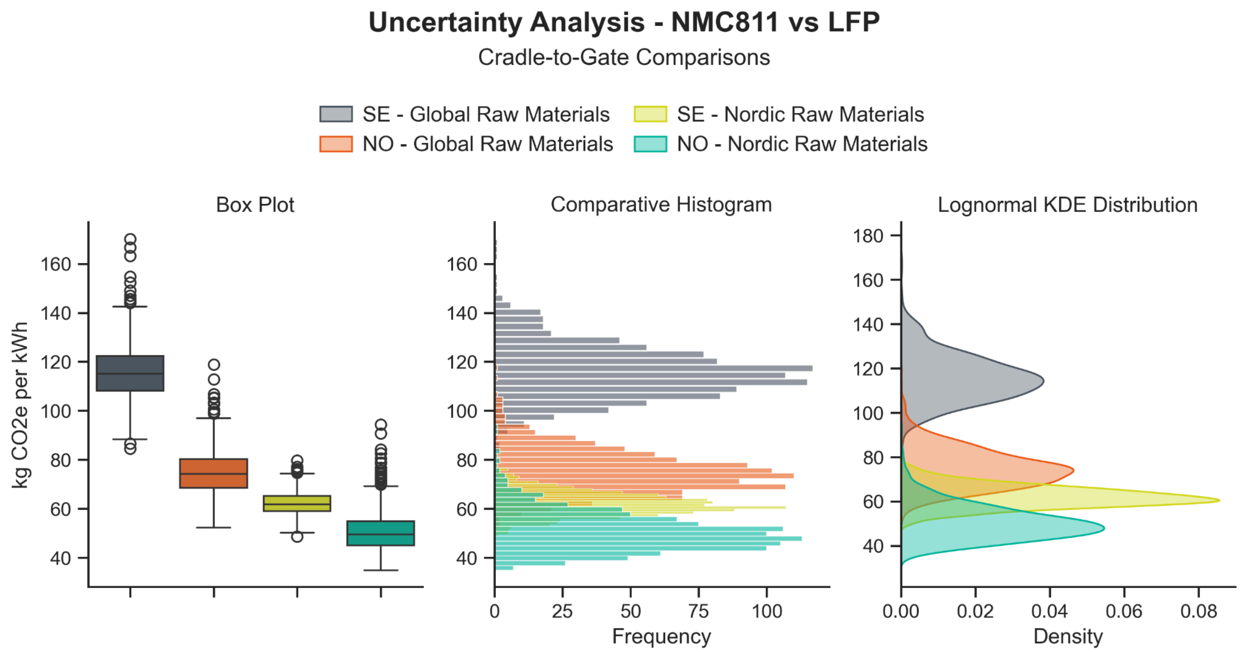

Figure 23: Comparative Monte Carlo climate change results for LFP vs. NMC811 cradle-to-gate comparisons.

Table 24: The superiority analysis, based on Monte Carlo results, indicates the percentage of cases where the Norway scenario shows at least 20% lower climate change impacts compared to the Swedish scenario.

PRODUCT vs. PRODUCT	Sweden – Global Raw Materials	Sweden – Nordic Raw Materials
Norway - Global Raw Materials	96%	0%
Norway - Nordic Raw Materials	100%	59%

It is important to highlight that, based on regional comparison uncertainty assessments (Sections 3.3.5 and 3.2.3), both Nordic LFP and NMC811 battery chemistries show 100% discernibly lower impacts compared to other regions. However, in the global average raw material scenario, LFP shows a discernible reduction in impacts of 74-92%, whereas NMC811 shows a lesser reduction of 37-49%. This suggests that compared to other global regions, Nordic LFP battery cells are more likely to produce lower impacts than NMC811 battery cells. This is a result of the LFP cells avoiding high-impact cathode materials, nickel in particular, which means the manufacturing energy hotspot has much greater weighting to the cell impact. Therefore, changes in electricity mixes have much more confident reductions in the Norway case compared to other regions.

It should be noted that these comparisons are limited to a cradle-to-gate scope, and results may change when use-phase and end-of-life stages are considered. For instance, while NMC811 offers higher energy density, LFP batteries typically exhibit significantly longer cycle life and may deliver greater lifetime energy[36]. Additional differences could also arise from comparing recycling processes between the two chemistries, but such comparisons are beyond the scope and goals of this study.

4. Conclusions

4.1. Key Outcomes

This explorative partial CFP study explored the potential climate change impacts of manufacturing Nordic NMC811 and LFP prismatic battery cells with Nordic raw material routes with the FU of per 1 kWh of energy capacity. Cell manufacturing scenarios were built using secondary data, Minviro's Parameterised Battery LCI Model, and inputs from Morrow Batteries, while Minviro's database was used for selected Nordic and global average raw materials. Cell manufacturing scenarios using Global average raw materials were evaluated for China, Europe, and the United States, with the primary variable being the regional electricity mix. These mixes were weighted based on the current distribution of battery manufacturing capacity in each region. An independent cradle-to-grave system boundary extension was implemented for the closed-loop hydrometallurgical recycling of NMC811 cells. The main study conclusions are:

1. **Nordic battery raw materials may offer exceptionally lower carbon footprints by 51-85% compared to average global production routes.**

The study found advantageous potential of Terrafame's nickel and cobalt sulfates, Keliber's lithium hydroxide, and Vianode's synthetic graphite stemming from energy- and material-efficient processes coupled with low-carbon Nordic electricity. This mitigates hotspots linked to dominant global production routes which are typically material and energy intensive while also rely on carbon-intensive high-carbon electricity grids.

2. **Swedish NMC811 and Norwegian LFP prismatic cells may achieve lower manufacturing carbon footprints, 13-17% lower for NMC811 and 25-33% lower for LFP, compared to the electricity mixes of China, Europe, and the US when assuming global average raw materials.**

Swedish NMC811 cells produced using global average raw materials exhibited a climate change impact of 110.2 compared to 126.6-133.1 kg CO_2 eq. per kWh in other regions. However, the uncertainty analysis showed this reduction was discernible in only 37-49% of cases, indicating limited confidence due to variability in data quality and modelling assumptions. Norwegian LFP cells using global average raw materials showed a climate change impact of 71.1 compared to 94.9-106.2 kg CO_2 eq. per kWh in regional counterparts. In this case, uncertainty analysis found the reduction to be discernible in 74-92% of simulations, suggesting greater reliability than NMC811 in achieving sufficiently lower impacts.

3. **Utilising Nordic raw materials may offer further carbon footprint reductions compared to global averages and other regions, by 53-55% for Swedish NMC811 and 49-55% for Norwegian LFP.**

For Swedish NMC811 cells, using Nordic raw materials reduced the carbon footprint to 60.1 kg CO_2 eq. per kWh, with 100% discernibility in the uncertainty assessment - demonstrating consistent advantages over other regions and global average materials. Similarly, Norwegian LFP cells achieved a further reduction to 48.8 kg CO_2 eq. per kWh, also with 100% discernibility, confirming the consistently lower climate impacts of Nordic sourcing.

4. **LFP prismatic cells may consistently deliver 19-36% lower manufacturing carbon footprints than NMC811 due to their avoidance of carbon-intensive cathode materials such as nickel and cobalt.**

The lower carbon footprint of LFP cells is largely due to the absence of nickel and cobalt - major contributors to NMC811. Although LFP requires more material for components like containers and separators due to its lower energy density, this is offset by the lack of carbon-intensive metals. When modelled with Nordic raw materials, the gap between LFP and NMC811 narrows but remains, as nickel continues to be a major emissions hotspot. Uncertainty analysis reinforces these findings: under global average scenarios, LFP has at least a 20% lower impact than NMC811 in 96% of simulations but dropping to 59% with Nordic materials. Both chemistries show 100% discernible improvements when Nordic-sourced, but LFP demonstrates more consistent climate benefits, making it a potentially stronger candidate for low-carbon battery production. These comparisons are limited to a cradle-to-gate scope and do not account for use-phase, end-of-life impacts, or differences in cycle life and recyclability.

5. **Closed-loop hydrometallurgical recycling of NMC811 cells in Finland may offer a net carbon footprint reduction of approximately 6%. However, further work using primary**

data is needed to address uncertainties associated with the use of proxy models and underlying assumptions.

The independent cradle-to-grave system boundary extension of NMC811 finds that the recycling process increases the Swedish NMC811 impacts using Nordic materials by 19%, from 60.1 to 71.6 kg CO_2 eq. per kWh - despite benefits of low-carbon Finnish electricity, the hotspots were primarily driven by dilutants and extractants used in metal solvent extraction steps, in addition to other reagents such as sodium hydroxide and heating demands from natural gas. However, the recycling credits from yielded battery-grade lithium, nickel, and cobalt metals that displace the original Nordic production routes (closed-loop assumptions) obtain a net benefit for the NMC811 battery from 72.1 to 56.2 kg CO_2 eq. per kWh. Nonetheless, the 6% benefit remains uncertain due to proxy processes used and should be later validated against Fortum's primary recovery and process data.

4.2. Key Limitations

Several study limitations are listed below which should be considered when interpreting the study outcomes:

- Comparative assertions are made for equivalent cradle-to-gate scopes as a partial CFP and the study is intended for public communications and stakeholder engagement. As outlined by ISO 14067:2018, it is recommended for decision-making purposes that a full all product life cycle stages be considered and expanded to other environmental indicators.
- The investigated supply-chains are explorative and while Morrow Batteries provided data for LFP cells, inventories for both prismatic chemistries remain generalised with simplified manufacturing steps. Broad uncertainty assessments address these limits, but results should not be applied to specific sites or other form factors (e.g. cylindrical or pouch) without detailed primary data. Since only the climate change impact category was investigated at midpoint level, conclusions do not apply to other environmental impacts or references to sustainability.
- Regional comparisons and global average raw materials only illustrate general trends. The findings should not be applied to specific provinces or production sites without further evidence of their specific electricity mixes and raw material sources. For example,

the sensitivity tests showed that production in France may also offer competitively low carbon footprints with the Nordics. Furthermore, global average values are informed estimates and are subject to annual updates in light of new data and insight. Lastly, average electricity mixes are likely to change over time in response to current and future trends in energy generation capacity.

- Additional impact hotspots such as NMP, aluminium, electrolyte, and separators were identified. However, these findings are tentative due to reliance on generic data and lower data quality that would require further investigation.
- The recycling results are intended for independent, non-comparative analysis to explore the potential impacts of the recycling route. However, they are dominantly based on Minviro's internal hydrometallurgical model, which provides a generalised representation of Fortum's process. Therefore, conclusions should not be applied to Fortum's directly without further primary data collection to address significant uncertainties.
- The recycling approach assumes a closed-loop system using original Nordic battery material routes. However, conclusions may vary with changes in material quality, open-loop scenarios, or upstream recycled content, highlighting the need for further analysis.
- Although the data quality of the selected battery raw materials in Minviro's database was considered good to very good - especially for Vianode's synthetic graphite, which was based on a direct LCA - some datasets would benefit from further development to strengthen future conclusions. Some inputs, such as Keliber's lithium hydroxide, are based on early feasibility studies, while others like Terrafame's nickel and cobalt rely on technical reports. Although uncertainty assessments account for these limitations, future work would benefit from updated operational data through direct collaboration. Minviro's global averages may also shift as technologies and market conditions evolve, potentially affecting future results.
- Lastly, the uncertainty assessment used a semi-quantitative approach that captured broad variability. However, future studies should prioritise quantitative and empirical data collection to enable more robust statistical analysis.

4.3. Recommendations

Minviro provides Battery Norway several recommendations for future study:

- To strengthen the basis for comparative assertions and stakeholder communication, the study is recommended to be expanded to a full cradle-to-grave LCA. Including additional environmental indicators would also support a more comprehensive sustainability assessment and better suit decision-making purposes.
- Future CFP improvements should focus on collecting site-specific primary data, particularly from Morrow Batteries, Terrafame, Keliber, and Fortum, to enhance data quality and accuracy. Future updates and projects should also investigate the potential effects of graphite recovery with the respect to the recent announcement of the collaboration between Vianode and Fortum.
- Nickel and lithium remain major contributors to cathode impacts, highlighting the need to investigate further strategies for reducing cathode-related emissions.
- Hotspots such as the aluminium can, NMP, electrolyte, and separators present opportunities for further mitigation. Exploring decarbonisation strategies such as recycled aluminium could support reductions in overall impacts.
- Future work could explore additional chemistries and form factors, such as varying nickel content in NMC622 or NMC532, to assess how conclusions may differ.
- Future studies using pre-existing recycled content should align the substitution approach with the displaced materials. Applying methods like the Circular Footprint Formula can provide a more robust framework for assessing recycled content impacts. Additionally, in-depth investigation of graphite recovery from hydrometallurgical processing and upgrading to battery-grade quality may reveal further opportunities for impact reduction.
- Future mitigation pathways for Nordic battery supply chains can be explored using additional Minviro services such as XYCLE Software, Life Cycle Costing, and Decarbonisation Roadmapping. These tools also enable evaluation of carbon abatement cost curves for different mitigation strategies.

4.4. Critical Review

Following internal review processes, a critical review was carried out by three independent external experts, and together they cover the required competencies relevant to the critical review.

1. **Mudit Chordia (Panel Chair)** is a doctoral candidate in the Division of Environmental Systems Analysis at Chalmers University of Technology, Sweden. His research focuses on evaluating the environmental impacts of large-scale lithium-ion battery production, with a particular emphasis on the upstream supply chains of critical raw materials. He also investigates the potential of recycling to mitigate environmental impacts from the battery life cycle.
2. **Dr. Eleonora Crenna** is a Senior Research Associate at the Institute of Energy and Environment at HES-SO, University of Applied Sciences of Western Switzerland, and LCA analyst in the CIRAIG International Consortium. Eleonora has 6 years of experience in managing and performing LCA of energy technologies, including lithium-ion batteries and hydrogen technologies, and more than 10-year experience in LCA in various fields (e.g. construction, food sector) gained in international institutions like the European Commission's JRC and Empa.
3. **Riina Aromaa-Stubb** has a M.Sc. (Tech) with a major in sustainable metals processing and is currently a final year doctoral researcher at the School of Chemical Engineering at Aalto University. Her work involves life cycle assessment in combination with process simulation to study the environmental impacts of metal refining processes with a focus on cobalt recycling.

The critical review was performed at the end of the CFP study. The revisions implemented, reviewer comments and suggestions to improve the study are included in Appendix B.

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Appendix A – Additional Data and Results

A.1. Extended Methods

A.1.1. Description of Nickel and Cobalt Sulfates from Finnish Bioleaching

Two raw material routes were selected for $NiSO_4.6H_2O$ and $CoSO_4.7H_2O$ based in Terrafame in Finland[24,25]. At Kuusilampi, open-pit mining operations support an annual capacity of 18 million tonnes (Mt) of ore and 45 Mt of waste rock, extracting low-grade sulfide ore containing approximately 0.25% nickel, 0.02% cobalt, 0.52% zinc, and 0.14% copper. The ore undergoes crushing, screening, and agglomeration with a pregnant leach solution (PLS) before being stacked in designated leaching areas for primary and secondary bioleaching. Throughout these stages, primary inputs are explosives and fuels for operations. Bioleaching, which spans around five years, uses microbes to separate metals from the ore under conditions optimised by aeration and irrigation. The ore is initially placed in a primary heap for about 15 months, after which it is reclaimed and transferred to a secondary heap for further leaching. This process, modeled similarly to Terrafame's operations, results in around 90% lower energy consumption compared to conventional extraction methods.

Following bioleaching, metals are recovered from the PLS through sequential precipitation as sulfides at the metals extraction plant. Throughout these, chemical inputs such as sulfuric acid, caustic soda, hydrogen peroxide, sulphur, with energy supplied by low-carbon Finnish electricity and a significant share of renewable fuels. The main products extracted include nickel-cobalt sulfide intermediates and co-products of zinc and copper. In 2023, Kuusilampu operations yielded approximately 30 kilotonnes (kt) of nickel, 1.5 kt of cobalt, 5,000 kt of copper, and 80 kt of zinc. The nickel-cobalt sulfide is then refined in a battery chemicals plant using pressure leaching with oxygen at high temperature and pressure to create a metal-rich sulfate solution. After the removal of impurities via liquid-liquid extraction, cobalt and nickel are separately crystallised using energy-efficient Mechanical Vapor Recompression technology. This results in the production of high-purity nickel sulfate, cobalt sulfate, and ammonium sulfate as a by-product, with key reagents including ammonia, sulfuric acid, sodium hydroxide, light fuel oil, and renewable peat and wood fuels. The 2023 production was 170 kt of nickel sulfate hexahydrate and 7.4 kt of cobalt sulfate heptahydrate, and 115 kt of ammonium sulfate co-product that is sold as fertiliser.

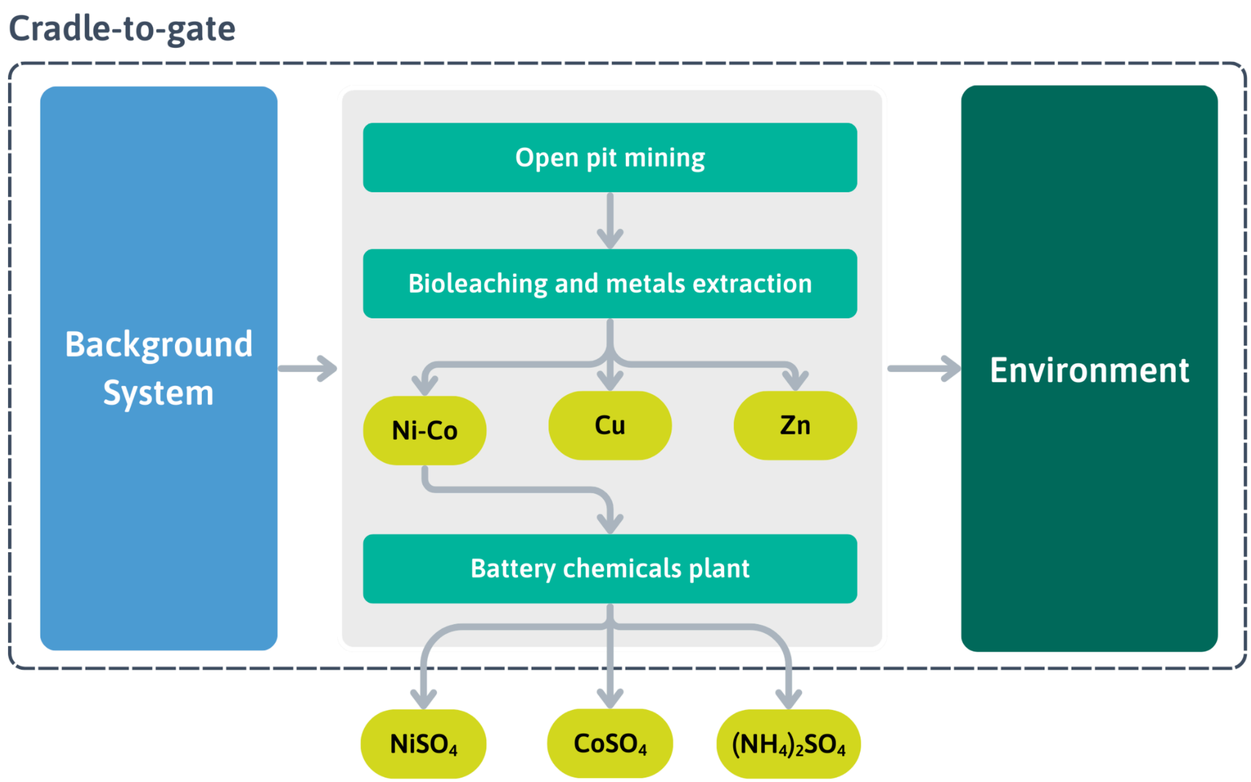

Figure A1: Process overview of Finnish nickel and cobalt sulfates from bioleaching.

A.1.2. Description of Lithium Hydroxide from Finnish Spodumene

Keliber Technology Oy plans to become Europe's first vertically integrated producer of battery-grade lithium hydroxide, sourcing lithium from its own ore reserves in Central Ostrobothnia, Finland, with operations expected to commence in 2026[26]. The project involves open-pit mining at the Syväjärvi and Rapasaari sites, targeting hard rock spodumene ore with an average lithium oxide grade of approximately 1.1%. Annually, about 650,000 tonnes of ore will be mined and processed into 165,000 tonnes of spodumene concentrate. Mineral processing, carried out at the concentration plant in Kaustinen, includes stone blasting, crushing, grinding, and flotation, utilising primary inputs such as electricity, explosives, fuels, and flotation chemicals. The resulting spodumene concentrate is transported to the lithium chemical plant at Kokkola Industrial Park. There, the concentrate undergoes high-temperature conversion in a natural gas-fired rotary kiln to transform spodumene into a more reactive β-phase.

This is followed by a hydrometallurgical process where the concentrate is pressure leached with soda to produce lithium carbonate, and subsequently converted by reacting with lime to form battery-grade lithium hydroxide monohydrate. Final purification stages include ion exchange and crystallisation, employing energy-efficient steam systems. Major chemical inputs across the process include quicklime, soda ash, sodium hydroxide, sulfuric acid, and hydrochloric acid, with energy requirements primarily met by electricity, natural gas, steam, and renewable fuels such as wood pellets.

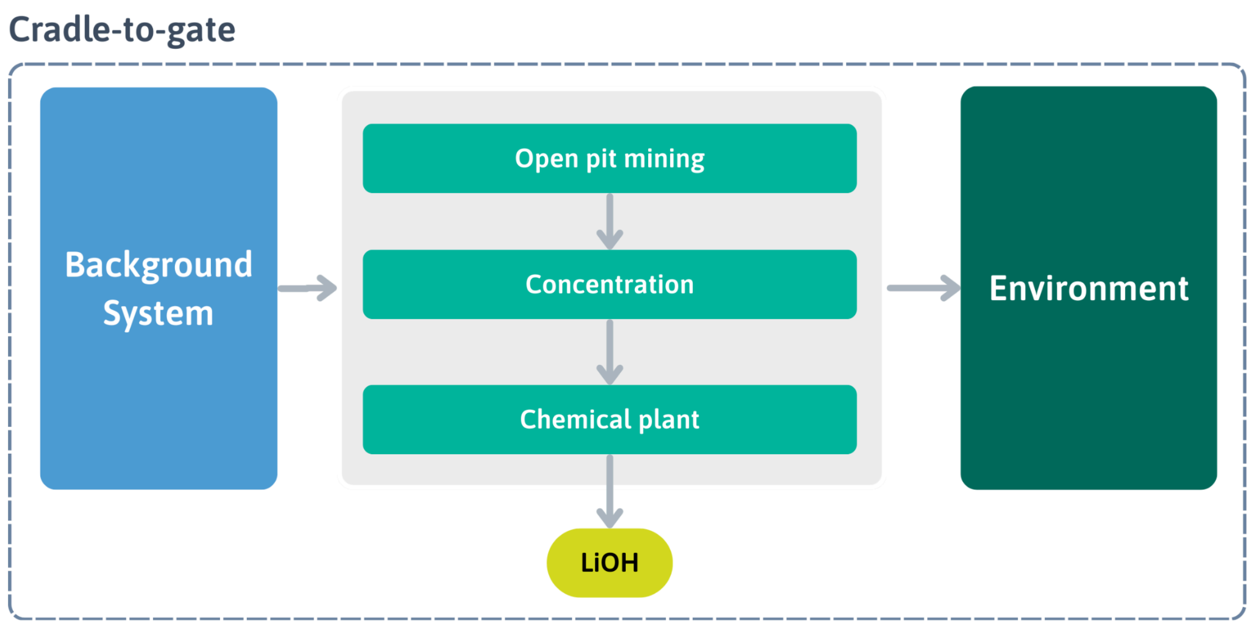

Figure A2: Process overview of Finnish lithium hydroxide from spodumene.

A.1.3. Description of Synthetic Graphite from Norway

Vianode AS has inaugurated its first full-scale synthetic anode graphite production facility, Via ONE, located in Herøya, Norway. Operations commenced in 2024, with the plant designed to produce 2,000 tonnes of synthetic graphite annually[28]. The facility features four advanced full-scale furnaces dedicated to the high-temperature manufacturing of synthetic anode graphite. The production process at Via ONE employs a proprietary high-temperature method that differentiates it from traditional natural graphite extraction, which typically involves environmentally intensive mining activities. This innovative approach results in a significantly reduced carbon footprint. Further details regarding the production process and LCA are not publicly disclosed due to confidentiality.

A.1.4. Life Cycle Inventory Datasets

Table A1: Cradle-to-gate life cycle inventory for NMC811 and LFP prismatic cells.

Inventory Item	Background Activity	Regions	Database	Valid Period	Foreground Data type	Input, Output	NMC811	LFP	Units	Reference Unit
AAM Mixing										
Graphite	market for battery-grade graphite, production mix	GLO	Minviro	2023	Calculated	Input	1.089	[redacted]	kg	per kWh capacity
	market for battery-grade graphite, synthetic	NO	Minviro							
Binder	market for carboxymethyl cellulose, powder	RER, RoW	Ecoinvent 3.10	2023	Calculated	Input	0.028	[redacted]	kg	per kWh capacity
Carbon black	market for carbon black	GLO	Ecoinvent 3.10	2023	Calculated	Input	0.028	[redacted]	kg	per kWh capacity
Solvent	market for deionised water	RER, RoW	Ecoinvent 3.10	2020	Literature	Input	0.936	[redacted]	kg	per kWh capacity
AAM Paste	**AAM Paste**	**NO, SE**		**2023**	**Calculated**	**Output**	**1.146**	[redacted]	**kg**	**per kWh capacity**
Anode Production										
AAM Paste	AAM Paste	NO, SE		2023	Calculated	Input	1.146	[redacted]	kg	per kWh capacity
Collector	copper collector foil production, for Li-ion battery	GLO	Ecoinvent 3.10	2023	Calculated	Input	0.224	[redacted]	kg	per kWh capacity
Anode	**Anode**	NO, SE		**2023**	**Calculated**	**Output**	**1.371**	[redacted]	**kg**	**per kWh capacity**
pCAM Production										
CoSO4.7H2O	market for cobalt sulfate heptahydrate, production mix	GLO	Minviro	2023	Calculated	Input	0.493	[redacted]	kg	per kWh capacity
	market for cobalt sulfate heptahydrate, from sulfide bioleaching	FI								
NiSO4.6H2O	market for nickel sulfate hexahydrate, production mix	GLO	Minviro	2023	Calculated	Input	3.684	[redacted]	kg	per kWh capacity
	market for nickel sulfate hexahydrate, from sulfide bioleaching	FI								
MnSO4.H2O	market for cobalt sulfate hexahydrate, production mix	GLO	Minviro	2023	Calculated	Input	0.296	[redacted]	kg	per kWh capacity
Ammonium hydroxide	market for ammonium hydroxide	GLO	Carbon Minds	2020	Literature	Input	0.201	[redacted]	kg	per kWh capacity
Sodium hydroxide	market for sodium hydroxide, without water, in 50% solution state	RER, RoW	Ecoinvent 3.10	2020	Literature	Input	1.440	[redacted]	kg	per kWh capacity
Water	market for deionised water	RER, RoW	Ecoinvent 3.10	2020	Literature	Input	1.132	[redacted]	kg	per kWh capacity
pCAM	**pCAM**	**SE**		**2023**	**Calculated**	**Output**	**1.602**	[redacted]	**kg**	**per kWh capacity**
CAM Production - NMC811										
pCAM	pCAM	NO, SE		2023	Calculated	Input	1.618	[redacted]	kg	per kWh capacity
LiOH.H2O	market for lithium hydroxide monohydrate, production mix	GLO	Minviro	2023	Calculated	Input	0.735	[redacted]	kg	per kWh capacity
	market for lithium hydroxide monohydrate, from spodumene	FI								
NMC811 CAM	**NMC811 CAM**	NO, SE		**2023**	**Calculated**	**Output**	**1.704**	[redacted]	**kg**	**per kWh capacity**

CAM Production - LFP										
Magnetite	ilmenite - magnetite mine operation	GLO	Ecoinvent 3.10	2023	Calculated	Input	n/a	[redacted]	kg	per kWh capacity
Diammonium phosphate	market for diammonium phosphate	RER, RoW	Ecoinvent 3.10	2023	Calculated	Input	n/a	[redacted]	kg	per kWh capacity
LiOH.H2O	market for lithium hydroxide monohydrate, production mix	GLO	Minviro	2023	Calculated	Input	n/a	[redacted]	kg	per kWh capacity
	market for lithium hydroxide monohydrate, from spodumene	FI								
Nitrogen	market for nitrogen, liquid	RER, RoW	Ecoinvent 3.10	2020	Assumption	Input	n/a	[redacted]	kg	per kWh capacity
LFP CAM				**2023**	**Calculated**	**Output**	**n/a**	[redacted]	**kg**	**per kWh capacity**
CAM Mixing										
NMC811/LFP CAM	NMC811/LFP CAM	SE, NO		2023	Calculated	Input	1.704	[redacted]	kg	per kWh capacity
Binder	market for polyvinyldene fluoride	SE, NO, US, RER, US	Carbon Minds	2023	Calculated	Input	0.095	[redacted]	kg	per kWh capacity
	market for carboxymethyl cellulose, powder	GLO	Ecoinvent 3.10	2023	Calculated	Input	n/a	[redacted]	kg	per kWh capacity
Solvent	market for N-methyl-2-pyrrolidone	GLO	Ecoinvent 3.10	2020	Literature	Input	0.632	[redacted]	kg	per kWh capacity
	market for deionised water	RER, RoW	Ecoinvent 3.10	2020	Literature	Input	n/a	[redacted]	kg	per kWh capacity
Carbon black	market for carbon black	GLO	Ecoinvent 3.10	2023	Calculated	Input	0.095	[redacted]	kg	per kWh capacity
Solvent emission	N-methyl-2-pyrrolidone, Emissions to air, unspecified	GLO		2020	Literature	Input	0.632	[redacted]	kg	per kWh capacity
NMC811/LFP CAM Paste	**NMC811/LFP CAM Paste**	**SE, NO**		**2023**	**Calculated**	**Output**	**1.894**	[redacted]	**kg**	**per kWh capacity**
Cathode Production										
NMC811/LFP CAM Paste	NMC811/LFP CAM Paste	SE, NO		2023	Calculated	Input	1.894	[redacted]	kg	per kWh capacity
Aluminium Collector	aluminium collector foil production, for Li-ion battery	GLO	Ecoinvent 3.10	2023	Calculated	Input	0.127	[redacted]	kg	per kWh capacity
Cathode				**2023**	**Calculated**	**Output**	**2.021**	[redacted]	**kg**	**per kWh capacity**
Cell Container										
Copper tab	market for copper, anode	GLO	Ecoinvent 3.10	2014	Literature	Input	0.125	[redacted]	kg	per kWh capacity
Sheet rolling	sheet rolling, copper	RER, RoW	Ecoinvent 3.10	2014	Literature	Input	0.125	[redacted]	kg	per kWh capacity
Aluminum tab	market for aluminium, wrought alloy	GLO	Ecoinvent 3.10	2014	Literature	Input	0.083	[redacted]	kg	per kWh capacity
Can	market for aluminium, wrought alloy	GLO	Ecoinvent 3.10	2014	Literature	Input	0.500	[redacted]	kg	per kWh capacity
Sheet rolling	sheet rolling, aluminium	RER, RoW	Ecoinvent 3.10	2014	Literature	Input	0.583	[redacted]	kg	per kWh capacity
Nylon	market for nylon 6	RER, RoW	Ecoinvent 3.10	2014	Literature	Input	0.016	[redacted]	kg	per kWh capacity
LDPE	market for polyethylene, low density, granulate	GLO	Ecoinvent 3.10	2014	Literature	Input	0.008	[redacted]	kg	per kWh capacity
PET	market for polyethylene terephthalate, granulate, amorphous	GLO	Ecoinvent 3.10	2014	Literature	Input	0.025	[redacted]	kg	per kWh capacity
PP	market for polypropylene, granulate	GLO	Ecoinvent 3.10	2014	Literature	Input	0.049	[redacted]	kg	per kWh capacity

Injection moulding	injection moulding	RER, RoW	Ecoinvent 3.10	2014	Literature	Input	0.100	[redacted]	kg	per kWh capacity
Cell Container	**Cell Container**	**NO, SE**		**2014**	**Calculated**	**Output**	**0.808**	[redacted]	**kg**	**per kWh capacity**
Electrolyte										
EC	market for ethylene carbonate	GLO	Ecoinvent 3.10	2015	Literature	Input	0.245	[redacted]	kg	per kWh capacity
DMC	market for dimethyl carbonate	GLO	Ecoinvent 3.10	2015	Literature	Input	0.245	[redacted]	kg	per kWh capacity
LiPF6	market for lithium hexafluorophosphate	GLO	Ecoinvent 3.10	2015	Literature	Input	0.086	[redacted]	kg	per kWh capacity
Electrolyte	**Electrolyte**	**NO, SE**		**2023**	**Calculated**	**Output**	**0.577**	[redacted]	**kg**	**per kWh capacity**
Energy and Utilities										
Natural gas	market for heat, district or industrial, natural gas	RER, RoW	Ecoinvent 3.10	2020	Literature	Input	65.933	[redacted]	MJ	per kWh capacity
Electricity	market for electricity, medium voltage, battery production mix	SE, NO, EU, US, CN	Ecoinvent 3.10	2023	Literature, Estimated	Input	35.259	[redacted]	kWh	per kWh capacity
Nitrogen	market for nitrogen, liquid	RER, RoW	Ecoinvent 3.10	2023	Assumption	Input	3.203	[redacted]	kg	per kWh capacity
Energy	**Energy**	**SE, NO**		**2023**	**Literature, Estimated**	**Output**	**53.570**	[redacted]	**kWh**	**per kWh capacity**
Cell Assembly										
Cathode	Cathode	NO, SE		2023	Calculated	Input	2.020	[redacted]	kg	per kWh capacity
Anode	Anode	NO, SE		2023	Calculated	Input	1.374	[redacted]	kg	per kWh capacity
Electrolyte	Electrolyte	NO, SE		2023	Calculated	Input	0.577	[redacted]	kg	per kWh capacity
Cell container	Cell Container	NO, SE		2023	Calculated	Input	0.808	[redacted]	kg	per kWh capacity
Separator	market for battery separator	GLO	Ecoinvent 3.10	2023	Calculated	Input	0.106	[redacted]	kg	per kWh capacity
Energy	Energy	NO, SE		2023	Calculated	Input	53.571	[redacted]	kWh	per kWh capacity
Scrap waste	market for used Li-ion battery	GLO	Ecoinvent 3.10	2023	Estimated	Output	0.048	[redacted]	kg	per kWh capacity
Battery cell	Battery cell	NO, SE		2023	Calculated	**Output**	**4.830**	[redacted]	**kg**	**per kWh capacity**

Table A2: Transport distance and inventory assumptions for selected battery raw materials

Destination	Material	Mode	Background Activity	Region	Distance - km	Valid Period	Foreground data type	NMC811 and LFP	Unit	Reference Unit
Sweden and Norway	$NiSO_4.6H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	18,000	2023	Estimated	66.321	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	2,000	2023	Estimated	7.369	tkm	per kWh capacity
	$NiSO_4.6H_2O$ - FI	Ship	market for transport, freight, sea, container ship	GLO	600	2023	Estimated	2.211	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	300	2023	Estimated	1.105	tkm	per kWh capacity
	$CoSO_4.7H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	21,000	2023	Estimated	10.350	tkm	per kWh capacity

		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	2,000	2023	Estimated	0.986	tkm	per kWh capacity
	$CoSO_4.7H_2O$ - FI	Ship	market for transport, freight, sea, container ship	GLO	600	2023	Estimated	0.296	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	300	2023	Estimated	0.148	tkm	per kWh capacity
	$LiOH.H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	20,000	2023	Estimated	14.706	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	1,500	2023	Estimated	1.103	tkm	per kWh capacity
	$LiOH.H_2O$ - FI	Ship	market for transport, freight, sea, container ship	GLO	600	2023	Estimated	0.441	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	300	2023	Estimated	0.221	tkm	per kWh capacity
	C-Gr - GLO	Ship	market for transport, freight, sea, container ship	GLO	21,000	2023	Estimated	22.864	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	2,000	2023	Estimated	2.178	tkm	per kWh capacity
	C-Gr - NO	Ship	market for transport, freight, sea, container ship	GLO	600	2023	Estimated	0.653	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	300	2023	Estimated	0.327	tkm	per kWh capacity
EU	$NiSO_4.6H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	18,000	2023	Estimated	66.321	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	2,000	2023	Estimated	7.369	tkm	per kWh capacity
	$CoSO_4.7H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	21,000	2023	Estimated	10.350	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	2,000	2023	Estimated	0.986	tkm	per kWh capacity
	$LiOH.H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	20,000	2023	Estimated	14.706	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	1,500	2023	Estimated	1.103	tkm	per kWh capacity
	C-Gr - GLO	Ship	market for transport, freight, sea, container ship	GLO	21,000	2023	Estimated	22.864	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	2,000	2023	Estimated	2.178	tkm	per kWh capacity
US	$NiSO_4.6H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	18,000	2023	Estimated	66.321	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	2,000	2023	Estimated	7.369	tkm	per kWh capacity
	$CoSO_4.7H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	21,000	2023	Estimated	10.350	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	2,000	2023	Estimated	0.986	tkm	per kWh capacity
	$LiOH.H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	18,000	2023	Estimated	13.235	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	1,500	2023	Estimated	1.103	tkm	per kWh capacity
	C-Gr - GLO	Ship	market for transport, freight, sea, container ship	GLO	21,000	2023	Estimated	22.864	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	2,000	2023	Estimated	2.178	tkm	per kWh capacity
CN	$NiSO_4.6H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	1,100	2023	Estimated	4.053	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	2,000	2023	Estimated	7.369	tkm	per kWh capacity
	$CoSO_4.7H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	0	2023	Estimated	0.000	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	1,500	2023	Estimated	0.739	tkm	per kWh capacity

	$LiOH.H_2O$ - GLO	Ship	market for transport, freight, sea, container ship	GLO	5,500	2023	Estimated	4.044	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	1,500	2023	Estimated	1.103	tkm	per kWh capacity
	C-Gr - GLO	Ship	market for transport, freight, sea, container ship	GLO	0	2023	Estimated	0.000	tkm	per kWh capacity
		Lorry	market for transport, freight, lorry 16-32 metric ton, EURO6	RoW	1,500	2023	Estimated	1.633	tkm	per kWh capacity

Table A3: NMC811 Hydrometallurgical recycling life cycle inventory.

Inventory Item	Background Activity	Region	Database	Valid Period	Foreground Data type	Input, Output	Value	Units	Reference Unit
Pretreatment									
Waste battery input		SE		2023	Literature	Input	4.929	kg	per kWh capacity
Nitrogen	market for nitrogen, liquid	RER	Ecoinvent 3.10	2023	Literature	Input	0.051	kg	per kWh capacity
Lime	market for lime	RER	Ecoinvent 3.10	2023	Literature	Input	0.040	kg	per kWh capacity
Process water	market for water, deionised	Europe without Switzerland	Ecoinvent 3.10	2023	Literature	Input	0.384	kg	per kWh capacity
Diesel	diesel, burned in building machine	GLO	Ecoinvent 3.10	2023	Literature	Input	0.606	MJ	per kWh capacity
Natural gas	market for heat, district or industrial, natural gas	Europe without Switzerland	Ecoinvent 3.10	2023	Literature	Input	2.020	MJ	per kWh capacity
Electricity	market for electricity, medium voltage	FI	Ecoinvent 3.10	2023	Literature	Input	2.020	kWh	per kWh capacity
Aluminium scrap	Burden free under cut-off	GLO	Ecoinvent 3.10	2023	Literature	Output	0.646	kg	per kWh capacity
Copper scrap	Burden free under cut-off	GLO	Ecoinvent 3.10	2023	Literature	Output	0.313	kg	per kWh capacity
Solid waste	treatment of inert waste, sanitary landfill	RER	Ecoinvent 3.10	2023	Literature	Output	0.374	kg	per kWh capacity
Wastewater	treatment of wastewater, average, wastewater treatment	Europe without Switzerland	Ecoinvent 3.10	2023	Literature	Output	0.384	kg	per kWh capacity
Shredded Material		**FI**	**Ecoinvent 3.10**	**2023**	**Literature**	**Output**	**2.858**	**kg**	**per kWh capacity**
Leaching									
Cathodic black mass	Shredded Material	FI		2024	Calculated	Input	2.858	kg	per kWh capacity
Sulfuric acid	market for sulfuric acid	RER	Ecoinvent 3.10	2024	Calculated	Input	2.919	kg	per kWh capacity
Hydrogen peroxide	market for hydrogen peroxide, without water, in 50% solution state	RER	Ecoinvent 3.10	2024	Calculated	Input	0.394	kg	per kWh capacity
Heat	market for heat, district or industrial, natural gas	Europe without Switzerland	Ecoinvent 3.10	2024	Calculated	Input	6.161	MJ	per kWh capacity
Hydrogen gas	100-year GWP estimated of 11 kg CO_2 eq. per kg	GLO	Literature	2024	Calculated	Output	0.004	kg	per kWh capacity
Purification									

Sodium hydroxide	market for neutralising agent, sodium hydroxide-equivalent	RER	Ecoinvent 3.10	2024	Calculated	Input	0.172	kg	per kWh capacity
Iron chips	market for pig iron	RoW	Ecoinvent 3.10	2024	Calculated	Input	0.014	kg	per kWh capacity
Heat	market for heat, district or industrial, natural gas	Europe without Switzerland	Ecoinvent 3.10	2024	Calculated	Input	1.990	MJ	per kWh capacity
Electricity	market for electricity, medium voltage	FI	Ecoinvent 3.10	2024	Calculated	Input	0.343	kWh	per kWh capacity
Aluminium hydroxide	treatment of inert waste, sanitary landfill	RER	Ecoinvent 3.10	2024	Calculated	Output	0.091	kg	per kWh capacity
Iron hydroxide	treatment of inert waste, sanitary landfill	RER	Ecoinvent 3.10	2024	Calculated	Output	0.022	kg	per kWh capacity
Cu sponge	treatment of inert waste, sanitary landfill	RER	Ecoinvent 3.10	2024	Calculated	Output	0.016	kg	per kWh capacity
Solvent Extraction, Ni-Co with Cyanex 301GN									
Sodium hydroxide	market for neutralising agent, sodium hydroxide-equivalent	RER	Ecoinvent 3.10	2024	Calculated	Input	1.202	kg	per kWh capacity
Extractant	market for cyanex	RER	Minviro	2024	Calculated	Input	0.505	kg	per kWh capacity
Dilutant	market for kerosene	Europe without Switzerland	Ecoinvent 3.10	2024	Calculated	Input	2.111	kg	per kWh capacity
Electricity	market for electricity, medium voltage	FI	Ecoinvent 3.10	2024	Calculated	Input	0.081	kWh	per kWh capacity
Stripping Ni-Co									
Sulfuric acid	market for sulfuric acid	RER	Ecoinvent 3.10	2024	Calculated	Input	1.465	kg	per kWh capacity
Electricity	market for electricity, medium voltage	FI	Ecoinvent 3.10	2024	Calculated	Input	0.061	kWh	per kWh capacity
Solvent Extraction, Co with Cyanex 272									
Sodium hydroxide	market for neutralising agent, sodium hydroxide-equivalent	RER	Ecoinvent 3.10	2024	Calculated	Input	0.131	kg	per kWh capacity
Extractant	market for cyanex	RER	Minviro	2024	Calculated	Input	0.051	kg	per kWh capacity
Dilutant	market for kerosene	Europe without Switzerland	Ecoinvent 3.10	2024	Calculated	Input	0.798	kg	per kWh capacity
Electricity	market for electricity, medium voltage	FI	Ecoinvent 3.10	2024	Calculated	Input	0.030	kWh	per kWh capacity
Stripping Co									
Sulfuric acid	market for sulfuric acid	RER	Ecoinvent 3.10	2024	Calculated	Input	0.162	kg	per kWh capacity
Electricity	market for electricity, medium voltage	FI	Ecoinvent 3.10	2024	Calculated	Input	0.000	kWh	per kWh capacity
Solvent Extraction, Mn with D2EHPA									
Sodium hydroxide	market for neutralising agent, sodium hydroxide-equivalent	RER	Ecoinvent 3.10	2024	Calculated	Input	0.101	kg	per kWh capacity
Extractant	market for organophosphorus-compound production, unspecified	RER	Ecoinvent 3.10	2024	Calculated	Input	0.040	kg	per kWh capacity

Dilutant	market for kerosene	Europe without Switzerland	Ecoinvent 3.10	2024	Calculated	Input	0.323	kg	per kWh capacity
Electricity	market for electricity, medium voltage	FI	Ecoinvent 3.10	2024	Calculated	Input	0.111	kWh	per kWh capacity
Stripping Mn									
Sulfuric acid	market for sulfuric acid	RER	Ecoinvent 3.10	2024	Calculated	Input	0.111	kg	per kWh capacity
Electricity	market for electricity, medium voltage	FI	Ecoinvent 3.10	2024	Calculated	Input	0.017	kWh	per kWh capacity
Lithium Precipitation									
Sodium carbonate	market for soda ash, dense	GLO	Ecoinvent 3.10	2024	Calculated	Input	0.929	kg	per kWh capacity
Heat	market for heat, district or industrial, natural gas	Europe without Switzerland	Ecoinvent 3.10	2024	Calculated	Input	1.899	MJ	per kWh capacity
Electricity	market for electricity, medium voltage	FI	Ecoinvent 3.10	2024	Calculated	Input	0.061	kWh	per kWh capacity
Lithium carbonate			**Ecoinvent 3.10**	**2024**	**Calculated**	**Output**	**0.616**	**kg**	**per kWh capacity**
Lithium Conversion									
Lithium carbonate				2021	Calculated	Input	0.616	kg	per kWh capacity
Calcium hydroxide	market for lime, hydrated, packed	RER	Ecoinvent 3.10	2021	Literature	Input	0.618	MJ	per kWh capacity
Deionised water	market for water, deionised	Europe without Switzerland	Ecoinvent 3.10	2021	Literature	Input	3.089	kWh	per kWh capacity
Electricity	market for electricity, medium voltage	FI	Ecoinvent 3.10	2021	Literature	Input	0.060	kg	per kWh capacity
Lithium hydroxide	**lithium hydroxide monohydrate production, spodumene (Keliber)**	**FI**	**Minviro**	**2021**	**Literature**	**Product**	**0.379**	**kg**	**per kWh capacity**
Calcium carbonate	**market for calcium carbonate, precipitated**	**RER**	**Ecoinvent 3.10**	**2021**	**Literature**	**Product**	**0.793**	**kg**	**per kWh capacity**
Nickel Crystallisation									
Heat	market for heat, district or industrial, natural gas	Europe without Switzerland	Ecoinvent 3.10	2024	Calculated	Input	3.171	MJ	per kWh capacity
Nickel sulfate hexahydrate	**nickel sulfate hexahydrate production, bioleaching**	**FI**	**Minviro**	**2024**	**Calculated**	**Product**	**3.414**	**kg**	**per kWh capacity**
Cobalt Crystallisation									
Heat	market for heat, district or industrial, natural gas	Europe without Switzerland	Ecoinvent 3.10	2024	Calculated	Input	0.455	MJ	per kWh capacity
Cobalt sulfate heptahydrate	**nickel sulfate hexahydrate production, bioleaching**	**FI**	**Minviro**	**2024**	**Calculated**	**Product**	**0.444**	**kg**	**per kWh capacity**
Manganese Crystallisation									
Heat	market for heat, district or industrial, natural gas	Europe without Switzerland	Ecoinvent 3.10	2024	Calculated	Input	0.040	MJ	per kWh capacity

Manganese sulfate monohydrate	**market for manganese sulfate monohydrate, from global average**	**FI**	**Minviro**	**2024**	**Calculated**	**Product**	**0.192**	**kg**	**per kWh capacity**
Wastewater Treatment									
Wastewater	treatment of wastewater, average, wastewater treatment	Europe without Switzerland	Ecoinvent 3.10	2024	Calculated	Input	0.012	m3	per kWh
Sodium sulfate	treatment of inert waste, sanitary landfill	RER	Ecoinvent 3.10	2023	Calculated	Output	2.555	kg	per kWh
Heat	market for heat, district or industrial, natural gas	Europe without Switzerland	Ecoinvent 3.10	2024	Calculated	Input	10.363	MJ	per kWh
Electricity	market for electricity, medium voltage	FI	Ecoinvent 3.10	2024	Literature	Output	0.667	kWh	per kWh

A.1.5. Description of Minviro Global Average Production Routes

The global average production routes were generated utilising Minviro's previously critically reviewed LCIs and linked to estimated market shares for refined products based on International Energy Agency (IEA) data[23] and literature[22]. Due to limited data availability for market shares of specific metal products (e.g. cobalt sulfate), market shares for refined metals are used as proxy (e.g. inclusive of cobalt oxides, cobalt sulfate, hydroxides etc.). Therefore, the global average market shares are sensitive to future updates to data availability on refined products. The exception to these proxies is graphite, where battery-grade shares were used. Nonetheless, each product has a route that is dominantly responsible for the carbon intensity. Since further data on "other" were not available, the percentages of declared routes were scaled to 100%.

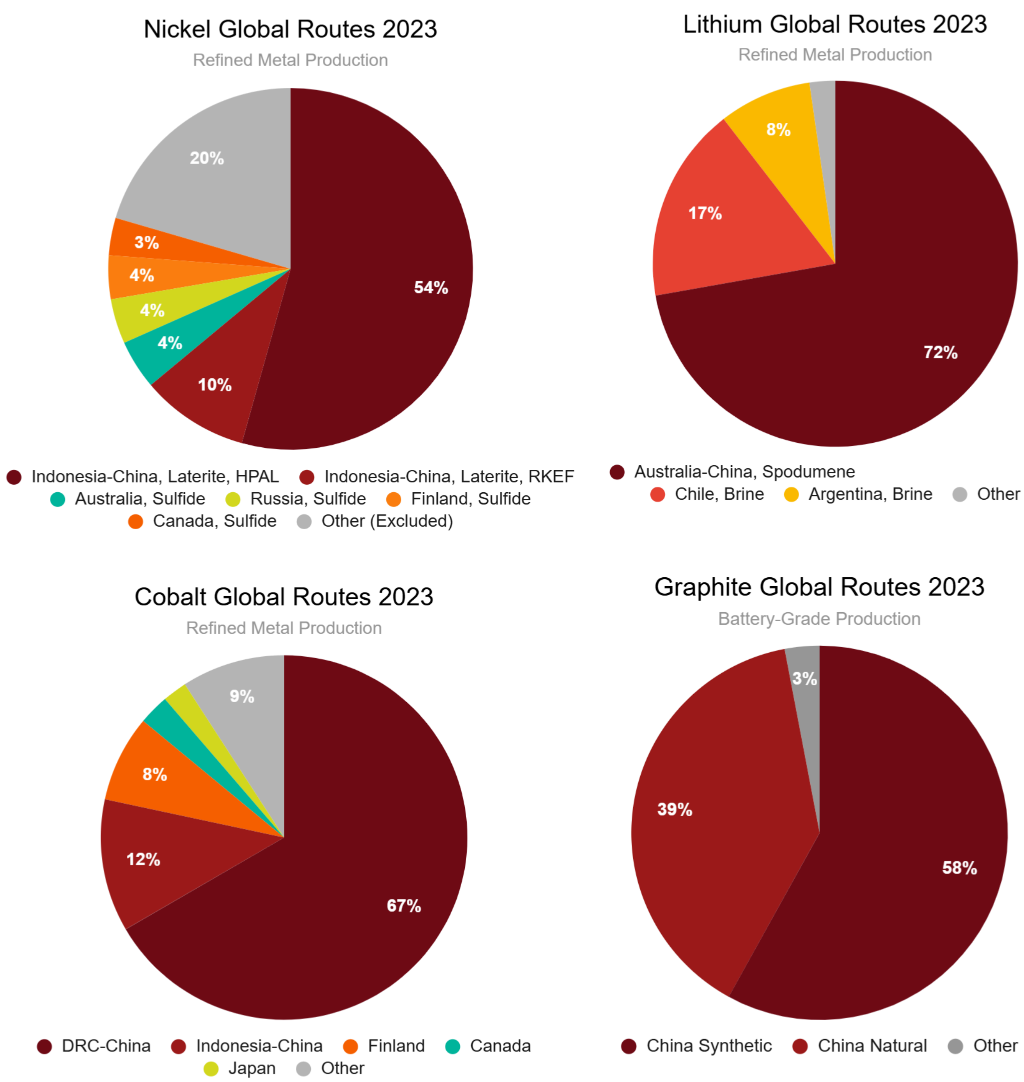

Figure A3: Minviro estimated global market shares of refined metals and products.

A.1.5.1 Nickel Sulfates

The dominant route (54%) involves Indonesian laterite ores processed via HPAL[37,38]. This hydrometallurgical method extracts nickel and cobalt from low-grade ores (~1.2% Ni, ~0.2% Co) by converting them into slurry and leaching (~270 kg sulfuric acid per tonne) in titanium-lined autoclaves at 260°C and 4300 kPa for 60 minutes. Nickel and cobalt are dissolved and the resulting solution is clarified via counter-current decantation and purified. Mixed hydroxide precipitate (MHP, ~39% Ni, ~4% Co) is then recovered with magnesia and quicklime, and typically shipped to China for re-leaching, solvent extraction, and crystallisation into nickel sulfate hexahydrate. This supply chain is energy- and reagent-intensive, with HPAL and purification as key carbon hotspots, largely driven by electricity and chemical use. In particular, the dependence on coal electricity drives the impact.

Additionally, a considerable portion (10%) is also assigned to the RKEF pyrometallurgical route based on rising projects in producing nickel sulfate from nickel matte[22,37]. The route starts with Indonesian open-pit mined saprolite ore (~1.8% Ni, ~0.1% Co) processed without upgrading. The ore is dried, calcined with bituminous coal and anthracite, then smelted in electric furnaces to form nickel pig iron (NPI). Then NPI converted to nickel matte using sulfur injection and silica flux, then cooled into granules and shipped to China. There, it undergoes hydrometallurgical processing with sulfuric acid and oxygen, producing a purified nickel solution that is crystallised into nickel sulfate. Indonesian stages use coal-based electricity; Chinese refining uses the Jiangsu grid. Again, due to the high dependence on coal reductants and electricity, this leads to a substantial carbon-intensity.

Smaller shares are attributed to Canada, Australia, Russia, and Finland, which rely on a mix of pyrometallurgical processing, carbonyl refining, ammonia refining, and bioleaching[37]. Data gaps are supplemented using the Nickel Institute's LCI. These regions have significantly lower carbon intensities, primarily due to the absence of coal-based energy and reductants used in Indonesia, but their overall influence remains limited. Other minor regions grouped under "Other" are excluded from the carbon calculations, and percentage distributions are scaled to the declared routes. For reference, the resulting global average carbon intensity is comparable to the HPAL route.

A.1.5.2. Cobalt Sulfates

The dominant route (67%) for all cobalt products is well-established as the DRC to China route[39].

Cobalt production follows a hydrometallurgical route co-processing copper-cobalt oxide ores with average grades of ~2.4% Cu and ~0.5% Co Open-pit mining is conducted using diesel-powered equipment, after which the ore is crushed and milled. Sulfide ores are pretreated via roasting, while oxide ores are leached directly using sulfuric acid and sulfur dioxide, both produced on-site in acid plants. The leach slurry is processed through solvent extraction and precipitation steps, recovering cobalt as crude cobalt hydroxide. This intermediate is exported to China for further refinement. It is treated with sulfuric acid among other chemicals, and purified through multiple solvent extraction steps, before being crystallised and dried into battery-grade cobalt sulfate. Though mining operations are powered by low-carbon hydropower, there are still considerable emissions from diesel use, explosives and materials such as lime. Furthermore, reagent use (e.g. sodium hydroxide) in refining and China's high-carbon electricity intensity, leads to considerable carbon footprints.

A substantial share (12%) is also derived from the Indonesian-China HPAL route as co-product from the same nickel-cobalt MHP processing as described in Section A.1.5.1. The remaining share of Finland is assumed as the bioleaching process, and all declared routes are scaled up to represent the cobalt average. Though Canada and Japan do have minor cobalt capacity, these are omitted due to unavailability of appropriate LCIs. Nonetheless, the final carbon footprint primarily reflects the DRC-China route. This approach disproportionately allocates impacts to copper which significantly understates cobalt's carbon intensity of cobalt. To better reflect cobalt as the primary economic driver, Minviro adopts economic allocation which also aligns to ecoinvent. This method more accurately attributes impacts to cobalt in line with its higher market value and its critical importance in driving mining operations.

A.1.5.3. Lithium Hydroxides

The dominant global production route (72%) for battery-grade lithium hydroxide begins with spodumene ore mined in Western Australia, which is extracted via open-pit mining using diesel-powered machinery[40]. The ore (~1% Li_2O) is crushed, milled, and subjected to flotation to produce a spodumene concentrate (~5% Li_2O). This concentrate is then shipped to China, where it undergoes a series of high-temperature chemical transformations: calcination at 1070–1100 °C (using natural gas) converts α- to β-spodumene; sulfuric acid roasting at 250 °C renders lithium soluble. The roasted material is leached at 60 °C and purified through sequential precipitation, NaOH addition, and ion-exchange with HCl to remove Fe, Al, Mg, and other impurities. Lithium is first recovered as lithium carbonate, which is then dissolved, reacted with calcium hydroxide at

95 °C, filtered, and crystallised to yield lithium hydroxide with calcium carbonate and sodium sulfate as co-products.

The other significant production routes are from Chilean and Argentine brines[41]. In the Chilean route, lithium-rich brine is extracted and concentrated through solar evaporation ponds, where sunlight and natural evaporation increase lithium content. Once concentrated, the brine is transported to a chemical processing facility where impurities such as boron and magnesium are removed using acids, alcohols, lime, and soda ash. Lithium carbonate is then precipitated using soda ash, followed by drying and compaction into a battery-grade product. In the Argentine route, Direct Lithium Extraction (DLE) is applied, using selective adsorption resins to efficiently recover lithium from brine. This is followed by reverse osmosis, multi-stage ion exchange, mechanical evaporation, and chemical precipitation to further purify the solution. Lithium carbonate is precipitated, then neutralised, dried, and micronised. In both cases, the resulting lithium carbonate can be further converted to lithium hydroxide via a conversion step: lithium carbonate is dissolved in deionised water and reacted with calcium hydroxide at elevated temperatures (~95°C), producing lithium hydroxide in solution and calcium carbonate as a byproduct. The solution is then filtered and evaporated to yield crystalline lithium hydroxide. These brine-based pathways, particularly those relying on solar evaporation, typically exhibit lower energy and water intensities per unit of lithium produced.

A.1.5.4. Graphites

The major anode-grade graphite is synthetic *via* the Acheson furnace route in Inner Mongolia, China. The process begins with calcination of green petroleum coke (~91% C) in electric furnaces at 700-1000 °C, removing volatiles and increasing carbon content to ~98%, with direct emissions of CO_2. This is followed by mixing and milling, where calcined coke is blended with carbon black and ground to reduce particle size for graphitisation. During graphitisation, the material is packed into graphite crucibles surrounded by conductive packing media and heated to ~3000 °C over a 4–5 week cycle. Partial oxidation of the packing media results in direct emissions of CO_2 with quicklime used to reduce sulfur emissions. Used crucibles are sold as low-value co-products. The spheronisation stage shapes the graphite into uniform particles (10–20 μm) using mills, with fines also recovered as co-products. In the coating phase, the graphite is kneaded with coal tar pitch, loaded into furnaces, and carbonised under nitrogen atmosphere, emitting CO_2 from volatilised pitch (assumed 35 wt%).

Natural graphite is also significant, mainly based in Heilongjiang, China. Mining is performed via open-pit methods, using ANFO explosives and diesel haul trucks to deliver ore (~11% C) to a nearby flotation facility[42]. The ore is then crushed, milled, and processed via multi-step flotation to yield a 98% carbon concentrate, which is dried using coal combustion. Spheronisation shapes the graphite into spherical particles using classifier mills, though only 45% of the material proceeds to purification, with the remainder leaving as co-product fines. Purification employs acid leaching (HF, HNO_3, HCl) to achieve >99.95% carbon purity, followed by neutralisation with quicklime and waste treatment. The purified spherical graphite is transported 1,780 km by truck for coating, where it is mixed with coal tar pitch, carbonised at up to 1300 °C in a nitrogen atmosphere, and finalised through deagglomeration, sieving, magnetic separation, and homogenisation. For both graphite routes, these rely on the Northeastern China Grid (CN-NECG) which is the dominant hotspot in driving carbon-intensity.

Appendix B – Critical Review

Comments by Eleonora Crenna

Initials	Index	Page No.	Section/ Figure /Table	Type of comment	Reviewer comments	Reviewer recommendation	Practitioner response
EC	EC1	1	Title (and along the text)	Ed	Major Prospective means "possible or expected in the future"; however, in my understanding, the study presented does not apply any projection into future scenarios (e.g. exploring emerging technologies/processes or using background scenarios like PREMISE) or upscale to higher TRL (as it is already a high TRL technology), as usually done in prospective LCA. For instance, the last sentence of the 3rd paragraph in the executive summary shows that there is no prospective/ future assessment by mentioning the representativeness of data for 2023, i.e. current/past time.	I would suggest replacing the term “prospective” with something else, e.g. explorative	[Revision] Agree, we will also take this onboard for our how we title similar future reports. Changed to “explorative”
EC	EC2	5	Figure ES-1 and ES-2	Ed	Minor Few questions to these figures: - ES-1; Since recycling is analyzed separately and not included in the comparison, it would be helpful to specify the system boundary in the caption - Typo in “Seperator” - Does “Energy” refers to assembly electricity? As I assume downstream energy/electricity is included in the material (anode, etc.)	I would suggest: - adding “cradle-to-gate” in the caption - correcting the typo into “Separator” - specify in the legend “Assembly energy”, “cell manufacturing energy” or something similar	[Revision] Added “cradle-to-gate” to both ES-1 and ES-2. Correct to “separator” throughout the report. Energy is kept for the legend for brevity; however we add the following to the figure caption. This has also been added to other relevant figures throughout the report. “Energy refers to the total electricity and natural gas consumption for precursor, active material, and cell production stages.”

EC	EC3	6	First paragraph in the page	Ed	Minor The sentence "Relying on the Swedish or Norwegian electricity mix alone in cell manufacturing did not consistently deliver this benefit." is a little generic.	I would recommend including some percentage values to give an indication of the magnitude of the impacts/ benefits, to better explain (and quantify) that this mean that the extraction of raw material is a relevant hotspot too, and that to have more env. sustainable supply chain the focus should be put on moving the upstream processes to Europe	[Revision] Text has been clarified "The uncertainty assessment, which accounted for a wide range of variability, demonstrated that using the Swedish or Norwegian electricity mix alone in cell manufacturing resulted in discernably lower carbon footprints in 37-49% instances for NMC811 and 74-92% cases for LFP compared to other regions. However, when Nordic-sourced raw materials were also incorporated, lower carbon footprints were discernable in 100% of cases. This highlights the considerable decarbonisation potential of combining both low-carbon Nordic electricity and raw materials."
EC	EC4	12	List of acronyms (and along the text)	Ed	Minor In my understanding, the abbreviation EU is used to refer to the European continent, while generally EU is used for European Union, thus with a different country coverage (e.g. Switzerland included in the former, but not in the latter). This can be misleading	I would suggest one of the following options: - writing Europe extensively (no abbreviation) - finding another more appropriate abbreviation - clearly explaining in the list of abbreviations and in the report, e.g. the first time this geographic region is mentioned, that the reference is to the continental area	[Revision] Changed to "Europe" throughout and other country names are spelled out for clarity; please also refer to comment RAS1.
EC	EC5	13	Glossary	Ed	Minor The definition of the system boundaries (SB) "cradle-to-gate" and "cradle-to-grave" could be better aligned. Indeed, the definitions are clear, but could be more harmonized, as one is the extension of the other in terms of system boundaries . Also	I would suggest harmonizing the definitions, using a similar structure of the description to make them consistent and more "connected"	[Revision] Definitions have been expanded and more harmonised. "Refers to a partial life cycle, encompassing all processes from the extraction of raw materials (the "cradle") through material processing, manufacturing, and up to the point the product leaves the

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					the term SB could be introduced here, as typical LCA term.		manufacturer's facility (the "gate"). This boundary excludes downstream activities such as product distribution, storage, use, and end-of-life treatment." "Defines a complete life cycle, covering all stages from raw material extraction and production to distribution, storage, product use, and final disposal or recycling. This approach accounts for all relevant inputs and outputs throughout the product's entire life span."
EC	EC6	14	1. Life Cycle Assessment	Ed	Minor LCA quantifies POTENTIAL environmental impacts	Please add the word "potential" in the first line before environmental impacts and in point 3 referred to LCIA	[Revision] Added "Potential"
EC	EC7	14	1. Life Cycle Assessment	Ed	Minor The sentence "all life cycle stages of a product" can be misleading, because the number/type of LC stages depends on the definition of the system boundaries	I would suggest removing the word "all"	[Revision] Removed "all"
EC	EC8	14	1. Life Cycle Assessment	Ed	Minor The sentence "offering insights that may otherwise be overlooked" is vague, not clear which insights are meant	Please, rephrase or remove	[Revision] Removed "offering insights that may otherwise be overlooked"
EC	EC9	14	1. Life Cycle Assessment	Ed	Minor In general, in the definition of LCA at the beginning of this section, there is no reference to the comparative aim / use of LCA	I would recommend adding a brief sentence about the comparative nature of LCA, also being this study a comparative one	[Revision] Text amended. "This holistic approach helps identify how decisions at one life cycle stage affect others, supporting balanced trade-offs, avoiding burden shifting, and can facilitate comparisons between product systems and mitigation options."

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EC	EC10	14	1. Life Cycle Assessment	Ed	The sentence "this LCA was conducted" is not clear: does it refer to your CF in this report? if so, it is not stated here (but only later) that it was conducted also according to ISO 14067 specifically for CF. Otherwise, if you only state to follow ISO 14040/44, you incur in the problem of not being complete, not accounting for "burden shifting".	I would suggest rephrasing as something like "this LCA follows the guidelines of ISO 14040 and ISO 14044, and specifically the requirements in ISO 14067 "	[Revision] Text amended. "This LCA follows ISO-14040:2006 and ISO-14044:2006, and specifically the Carbon Footprint of Product (CFP) requirements of ISO-14067:2018"
EC	EC11	14	1. Life Cycle Assessment	Ed	Minor In point 2 about LCI, it is not clear why specifically chemicals and not more generically "intermediary products" is stated; also, if intermediary products like chemicals are included, then why not mentioning waste and by-products too among the outputs?	I would suggest: - replacing chemicals with "intermediary products" - adding waste and by-products/ co-products alongside emissions as outputs	[Revision] Text amended. "Collects and quantifies input and output data on energy, materials, intermediary products, natural resources, by-products, waste, and emissions throughout the product life cycle stages."
EC	EC12	15	Section 2.1	Ge	All aspects of the goal according to ISO 14067 are included in the section: intended application; reason(s), intended communication, intended audience, statement about comparative purpose of this study	No modifications to do, since the comment is a statement for completeness check	N/A
EC	EC13	15	Section 2.1	Ge	Major Concerning the external communication: Ideally according to ISO 14067, if the CF is meant to be publicly available, the SB must be cradle-to-grave. However, if I understand correctly here, the study will be made available under NDA to the stakeholders, so it could be considered as not really-totally public available. In this case, ISO 14067 says that the SB must be at least cradle-to-gate ("partial CF"), which is the case here indeed. My only concern is if the study is shared	Please, verify (and state clearly) that the type of external communication, meant for this report is indeed in line with ISO 14067, especially that the partial CF presented in the report is not meant for decision making by e.g. governmental entities.	[Revisions] Indeed, Annex A suggests that for decision-making purposes it should be expanded to a full LCA - though not mandated. Throughout the report, in addition to the limitations and recommendations we have added these recommendations such as below "Comparative assertions are made for equivalent cradle-to-gate scopes as a partial CFP and the study is intended for public communications

					with the government, that it might be meant for decision making and in this case ISO 14067 mandates that the CF is complete, full LCA, not just a CF.		and stakeholder engagement. As outlined by ISO 14067:2018, it is recommended for decision-making purposes that a full all product life cycle stages be considered and expanded to other environmental indicators." "To strengthen the basis for comparative assertions and stakeholder communication, the study is recommended to be expanded to a full cradle-to-grave LCA. Including additional environmental indicators would also support a more comprehensive sustainability assessment and better suit decision-making purposes." We have made more explicit clarifications that the study results will be publicly communicated and is meant for stakeholder engagement - not for decision-making purposes. Such as: *"Due to the exploratory nature of the study it is not intended for decision-making purposes since a full LCA considering broad environmental impacts and other life-cycle stages is recommended"* We also made clarifications that it indeed is a partial CFP, though we do closely follow the requirements of Annex B regarding equivalence for comparative assertions e.g. *"Since goals (1) and (2) focus on cradle-to-gate and goal (3) on*

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							*cradle-to-grave, with certain stages such as use not considered, this study is classified as a **partial CFP**.”* ISO 14067 communication guidelines are not within standards scope; however, refer to ISO14026 and ISO14044. For these, we have closely followed comparative/public comms guidelines, and clearly indicated the limitations and applications of the study as much as possible, and followed the critical review guidelines. In case further clarification is needed, we can also outline this key limitation/application of the study in the critical review report and recommendation by reviewers.
EC	EC14	15	Section 2.1, Line 9	Ed	Minor “Among others” is a repetition with "primarily" , which in my interpretation implies already other stakeholders beside the mentioned ones	Please, remove either “among others” or “primarily”	**[Revision]** Text removed.
EC	EC15	15	Section 2.1 , Point 1	Ed	Minor When mentioning “raw material routes”, at least the first time, it would be useful to refer to it as "raw material extraction & processing/ refining routes" (or something like this) and explain that for simplicity from then on you refer to it as “raw material routes”	Please, rephrase according to comment or similarly	**[Revision]** Added the following “....inclusive of extraction, processing, and refining stages.”
EC	EC16	16	Section 2.2	Ge	The elements required by ISO 14067 for the scope are all available in the report; however some of them are reported in other sections, which I	No modifications to do, since the comment is a statement for completeness check	N/A

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					find being OK and understandable. For instance, data & data quality requirements are explained in section 2.3.6, main assumptions in section 2.3.5, allocation in 2.3.3 on multi-functionality, which all fall under the LCI related section.		
EC	EC17	16	Table 1	Ed	Minor The definition of the first two "Production Routes" of NMC811 are exactly the same, however, one should have "Nordic raw materials" as in the case of LFP. Furthermore, this sentence is not very clear. It is regional but GLO avg is mentioned? I guess the first part refers to cell manufacturing which is regional, and the second part refers to materials.	Please, correct and rephrase	[Revision] This was an error, now fixed.
EC	EC18	17	Section 2.2.2, lines 3-5	Ed	Minor Grammar check, the sentence "Morrow Batteries contributed assumptions used to derive the prismatic Norwegian LFP cells" is likely missing a verb…?	Please, check and correct/ rephrase	[Revision] Amended. "Morrow Batteries provided key assumptions, including cell capacity and gravimetric energy density, for deriving the Norwegian prismatic LFP cell model."
EC	EC19	17	Section 2.2.2, lines 5	Ed	Minor When mentioning representative estimate, what does representative actually mean? Representative of the prismatic battery in general, or the Nordic battery on the market…? a little bit more of precision would be better.	Please add a specification about the representativeness in the sentence	[Revision] Text was removed as these were not necessary.
EC	EC20	17	Table 2	Ed	Minor Using only "Location" can be misleading	Please specify for instance as "location of cell manufacturing facilities"	[Revision] Used "location of cell manufacturing facilities"
EC	EC21	17 + 24	Table 2 + Table 5	Ed	Minor Is there a specific reason why the LFP related column is presented in red?.	Unless there is a specific unmentioned reason, please change	[Revision] This was red since it was confidential data from Morrow. The red will be removed on sign-off but

						in black. Otherwise, please state the reason	for now we just need to have this as a reminder. For other report reviewers, this data will be made available on permission/NDA agreements in place.
EC	EC22	17	Section 2.2.3, first line	Ed	Minor "To evaluate the components" sounds incorrect	Please, rephrase e.g. to evaluate/ quantify the potential impacts associated to the production of the components	[Revision] Text amended "potential impacts associated with the production of components"
EC	EC23	18	Section 2.2.3.	Ge	Major It is not clearly stated the reason of reporting Supplementary results in Appendix A which consider the influence of the use-phase using a secondary FU of per 1 kWh of the total energy provided by the battery over its service life measured in kWh (A.2.2). Indeed, these results are not used anywhere in the report and it is clearly stated that cannot be used for the comparative purpose because out of the scope of the LCA presented in the report.	Please, clarify why these results were calculated and how should they be used / interpreted in the context of the overall report	[Revision] These sections of the report have been removed please refer to response to RAS12
EC	EC24	19	Table 3	Ed	Minor "omitted from system boundaries" – see recommendation	Please, specify here too that omissions refer to foreground only, not to ecoinvent/background datasets used	[Revision] Caption amended "…These only apply to the foreground system and may not be reflected in the background datasets used."
EC	EC25	19	Section 2.2.4.1 , point 1	Ed	It is mentioned that pCAM "is not applicable to LFP", but LFP cathode has precursors too, made of iron phosphate and lithium hydroxide through solid state or hydro process. Or do you mean that the specific type of process with sulfates does not apply to LFP?	Please, clarify the sentence	[Revision] This has been clarified with the following "…This process is specific to production NMC811 precursor hydroxides and is not applicable to LFP since the CAM is directly synthesised."

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EC	EC26	20	Section 2.2.4.1 , point 2	Ed	A "nearly 100% material conversion" is reported. This is too generic.	Please report the value assumed in the calculations for the sake of transparency and completeness	[Revision] Clarified "...The process assumes a 100% material conversion rate (near 100% is reported)..."
EC	EC27	20	Section 2.2.4.1 , point 2	Te	Major This means that no emissions/loss of NMP is reported? Indeed I see there is no emissions/waste flow referred to it in the LCI in the appendix. However, NMP is actually dried up during the production of the cathode, therefore ideally it should be accounted as waste / emissions	Please, verify this aspect and clarify your choice/ assumptions if you are not counting this in as emission or waste	[Revision] Amended text and added to LCI for completeness sake. "Although NMP solvent recovery is technically feasible, this assessment conservatively assumes total NMP use, evaporation, and emission. While NMP emissions are reported and may cause other environmental impacts, NMP is not a greenhouse gas and does not affect the carbon footprint"
EC	EC28	20	Section 2.2.4.1 , point 4	Ed	Minor Not clear from here if graphite is natural or synthetic. From the LCI in the appendix, I understand it is synthetic. It is a relevant point, there is a big difference in their CF depending on the origin	Please, mention in the text that the graphite you use in your LCI is synthetic	[Revision] This has been amended, please see RAS15 for full response.
EC	EC29	21	Figure 2	Ed	Minor Typo in "Seperator"	Correct typo	[Revision] Fixed.
EC	EC30	21	Figure 2	Ed	Minor Not clear why separator is a level above the electrolyte, and also levels above the cathode and anode. These are different components at the "same level"/ tier within a cell. Is it a choice for compactness?	Please, clarify and if needed adjust the figure	[Revision] This is for illustrative and compactness purposes and does not depict tiers. Clarified in the caption. "...The figure provides a conceptual overview of the CFP system and does not represent detailed bill-of-materials or the full hierarchy of components and sub-tiers.."
EC	EC31	22	Point 7 on Energy	Ed	Minor The estimate for NMC811 are reported, but not for LFP.	For consistency and completeness, I would suggest adding the values for LFP too	[Revision] This has been revised, please see RAS17 for complete justification.
EC	EC32	22	Section 2.2.4.2.	Ed	Minor	Please refer to my very first comment about the use of the word	[No changes] Prospective terminology has been now changed

					It is stated that "Graphite recovery was not considered as it is not offered by Fortum at present, though it is important to mention this will be a future offering due to the recently announced collaboration with Vianode and Fortum." If the study is meant to be "perspective", as mentioned in the title, shouldn't this "future offering" be considered in the study?	"perspective". It needs to be clarified that the study is more "exploratory" than perspective.	to explorative. Hence, the current statement does not impact the main goals of the study.
EC	EC33	24	Section 2.3	Ge	The elements required by ISO 14067 for the LCI are almost all available in the report; however, the calculations are not really reported and the time of data collection either. Indeed, only the validity period which might coincide with collection is reported but need to be clarified. It is mentioned in the intro, though, when the study has been commissioned.	Calculations could be made available by sharing the excel with the stakeholders; additionally, please state in the text the year of data collection.	[Revision] Added the following "Data for this study was collected in 2025; however, individual data points originate from various reference years spanning 2014 to 2025. The complete LCI is presented in Table A1, and detailed spreadsheet-based calculations are available upon request under a NDA."
EC	EC34	24	2.3.1.1	Ed	Minor Typo, space missing in "LCIbased"	Please correct the typo	[Revision] Fixed
EC	EC35	24	Table 5	Ed	Minor Clarification on % reported for BoM	Please specify that the % are % in weight of the overall cell, and that it refers to 1kg cell not to the FU	[Revision] Amended figure caption "Cell bill-of-materials based on percentage contributions to total cell mass."
EC	EC36	27	Section 2.3.1.2, line 3	Ed	Minor Inputs are mentioned; outputs are missing. Indeed, metal scrap and wastewater are reported in table in Appendix)	Please, add outputs to the sentence	[Revision] Amended, please see RAS24 for full response.
EC	EC37	28	Table 9	Ed/Te	Minor How is the significance assessed? It would be helpful to explicit the	Please, clarify	[Revision] Amended, please see RAS26 for full response.

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					scale, or explicit that it is a qualitative scale based on expert judgment if this is the case		
EC	EC38	30	Section 2.3.6, Table 12	Te	Major Do I understand correctly that the pedigree matrix of ecoinvent datasets is re-assessed according to the PEF system? However, ecoinvent datasets already have values for quality in 5 areas. Is the re-evaluation consistent with the original one? is the original one taken into consideration?	Please, clarify	[Revision] Clarification added. "While background databases like ecoinvent have independent data quality ratings, these were reviewed and aligned with the PEF DQR to assess the representativeness of the LCI items used in this study."
EC	EC39	32	Table 13	Te	Not clear how the "overall" value is calculated, whether still with the formula or as kind of average between foreground and background	Please, clarify	[Revision] Caption updated "The overall weighted DQR is an average of the foreground and background scores."
EC	EC40	33	Line 12 from the beginning of the page	Ed	Minor In the sentence, four type of climate change emissions type are mentioned, below in the list only 3 are reported. Soil carbon change is missing from the list, however if I understand correctly, this is not mandatory to account for in the CF according to ISO 14067. Indeed, the ISO says "should" and not "shall".	Please, adapt for consistency between the sentence and the list	[Revision] Fixed to three, this was an error.
EC	EC41	36	Section 2.5.3	Te	Minor Not clear why transport has higher uncertainty associated compared to other flows/ processes	Please, clarify	[Revision] This has been amended, please see RAS30 for full changes.
EC	EC42	38	Section 3, point 3	Ed/Te	Minor To double check: the uncertainty analysis was run only on the foreground?	Please, clarify	**[No changes]** The uncertainty assessment was run for both the foreground data points and the background data points. This has been indicated in the points.
EC	EC43	39	Section 3.1	Ge/Te	Major	Please, clarify and if needed add few sentences accordingly	[Revision] We have added a short paragraph

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					The analysis is presented per scope 1,2,3; shouldn't the contribution of the different emissions sources (i.e. biogenic, fossil, LULUC) be analyzed and discussed too, even briefly, as a fundamental point of the ISO 14067?		"It should be noted that the vast majority of the climate impact falls under the fossil category, which forms the primary focus of the analysis. LULUC and biogenic emissions are not examined in detail, as their contributions are minimal. However, in general, their dominant contributor is electricity generation related to upstream land occupation and transformation, and linked biogenic emissions required for power production."
EC	EC44	39	Section 3.1, point 1	Ed	Minor Typo – missing space in "includedIndonesian"	Please, correct the typo	[Revision] Typo has been fixed.
EC	EC45	39	Section 3.1	Te	Major Concerning the Terrafame cobalt sulfate: here more impact are associated to scope 1 and 3, while above in the nickel sulfate the impacts are from scope 1 and 2. If I understand correctly, the responsible is the same process (+ Finland energy mix in the case of nickel sulfate). What's also responsible, to make scope 3 higher here?	Please clarify	[Revision] The scope distributions between the two are actually identical (ratio between 1,2,3). The reason for different percentage difference is because it is relative to their global average route. We have made this clearer in the caption. "For each Nordic raw material, the percentage difference is normalized relative to its corresponding global average production route."
EC	EC46	40	Section 3.2.1, line 12 from the beginning	Ed	Minor In some cases, % of contribution are presented, in some other cases it is possible to back-calculate them, in other cases these are not at all reported. Here, when presenting the	I would suggest adding % of contribution of impact into brackets	[Revision] These have been added. "*NMP solvent and aluminium foil also contribute notably at 5.6 (9%) and 2.7 kg CO_2 eq per kWh (4%), respectively.*".

			of the section		impacts of NMP solvent and aluminium foil, it would be useful to have % in brackets, as done for container		
EC	EC47	41 + 45	Figure 5 + 11	Ed	Minor Type - "Seperator"	Please, correct the typo	[**Revision**] Fixed
EC	EC48	41-42	Figure 6-7	Ed/Te	Major It is not very clear what contribution analysis by input means, because Ni, Co and Li are not inputs of the system as elements but mostly as sulfate or hydroxide. So what Ni, Co and Li represent here in the figures? the sulfates/ hydroxide for the precursor or an additional steps accounting for the % of element in the final electrode (and electrolyte in case of lithium as usually it is in form of LiPF6)?	Please, clarify in the caption and/or in the text	[**Revision**] Caption now clarifies this. "*For nickel, cobalt, and lithium, this corresponds to their sulfate and hydroxide precursor forms.*".
EC	EC49	43	Figure 9	Ed	Minor Also here, contribution analysis by input can be misleading here, because what is represented here on the X axis are processes or production steps, which I guess include both inputs of energy and material, and outputs like waste and emissions.	Please, modify the caption or clarify the choice of wording	[**Revision**] Caption now clarifies this. "*This is inclusive of all energy and material inputs and outputs of waste and emissions.*"
EC	EC50	44	3.2.4	Ed	The sentence "Specific data was collected for nickel, graphite, and lithium" is not clear. Are specific data collected from which (additional) source? Other data, different from the original sources? Do you refer to the local routes	Please, clarify this sentence	[**Revision**] Sentence has been amended since "specific" was not required. "*Data collected for nickel, graphite, and lithium, achieved good to very good DQRs (Table 17), appropriately reflecting their importance in the sensitivity analysis.*"

EC	EC51	49 + 51	Figure 15 + 18	Ed	Minor Type - “Seperator”	Please, correct the typo	[Revision] Fixed
EC	EC52	49	Section 3.3.1	Te	Major It is stated that “the cell container is the single largest contributor, accounting; however, the cathode follows -I'd say- closely with 24% after the 37% of cell container.	Please, clarify and if needed rephrase	[Revision] The sentence has been rephrased to remove “single”. *“However, the cell container is the largest contributor,”*
EC	EC53	52	Section 3.3.4	Ed	Concerning the sentence “Specific data was collected for graphite and lithium” – please see comment EC50	Please, clarify this sentence	[Revision] Sentence has been amended since “specific” was not required. *“Data collected for graphite and lithium achieved good to very good DQRs (Table 17),”*
EC	EC54	54	Section 3.4	Te/Ed	Major A limitation should be stated here, with reference to the extra analysis in Appendix on including the use phase (so to give this analysis a more added value) : different use scenarios due to different applications and cell properties like life lifetime might lead to different results on a cradle-to-grave than on a cradle-to-gate boundary.	Please, adjust the text accordingly	[Revision] Additional text was added, please see RAS39 for full response.
EC	EC55	55	Figure 22	Ed	Minor Type - “Seperator”	Please, correct the typo	[Revision] Fixed
EC	EC56	55	Section 3.4	Ed/Te	Major The sentence “Therefore, LFP and NMC811 have more competitive impacts in this case”, should probably be about LFP having more competitive impacts. Additionally, this sentence is valid if the technologies are used in the same applications, over the same lifetime. Differences in the EoL e.g. possibility	Please, double check the sentence and correct it accordingly. Consider including the additional limitation.	[Revision] This has been amended, please see RAS40 for full response/change.

					of recycling/reusing more or less materials, might change the scenario results. This could be stated as limitation		

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Comments by Riina Aromaa-Stubb

Initials	Index	Page No.	Section/ Figure /Table	Type of comment	Reviewer comments	Reviewer recommendation	Practitioner response
RAS	RAS1	4	Second paragraph	Ed	Minor - Does "Europe (EU)" refer to the European continent or the European Union?	Please clarify	[**Revision**] We acknowledge this was not clear labelling since the abbreviation indicates the European Union. This is meant to be major locations across the European continent. We have not defined this in the text as Europe; saying: *Pg 4 "...major battery production locations in China, the United States, and across the European continent ("Europe")."*
RAS	RAS2	5	Figures ES-1 and ES-2	Ed	Minor - "Seperator" should be Separator	Please fix typo	[**Revision**] Fixed here and in other figures.
RAS	RAS3	6	Third paragraph	Ed	Minor – An assessment of how uncertainty affects this conclusion (as in the previous paragraph) would be beneficial here for the reader	Please add	[**Revision**] Thank you for your suggestion; I believe this was relating to the recycling paragraph? *Pg 6 "Hence, a net carbon benefit of 5% was achieved, suggesting potential value in circular approaches when integrated with low-carbon supply chains. However, this benefit is modest and the conclusion is subject to several underlying assumptions and uncertainties that require further*

							investigation before definitive conclusions can be drawn."
RAS	RAS4	7	First paragraph, first full sentence	Ed	Minor – Should cobalt be included in this sentence? On the previous page it was stated that: "LFP cells also showed more consistently lower carbon footprints than NMC811, as they do not use nickel or cobalt which remained key NMC811 hotspots even when Nordic raw materials are used."	Please check	[**Revision**] Changed to only nickel as that indeed is the most critical hotspot, while cobalt is much more minor - to help keep the focus. *Pg 6 "as they do not use nickel, which still remained a critical NMC811 hotspots even when Nordic raw materials are used"*
RAS	RAS5	12	Acronym "DRC"	Ed	Minor – Should be Democratic Republic of the Congo	Please add "the"	[**Revision**] Fixed.
RAS	RAS6	12	Acronym "EU"	Ed	Minor - Does "Europe (EU)" refer to the European continent or the European Union?	Please clarify	[**Revision**] EU acronyms have been completely removed from the report to avoid any confusion; all references are to "Europe".
RAS	RAS7	13	Glossary	Ed	Minor – Alphabetically "Interpretation" should be before "Life cycle"	Please check	[**Revision**] Fixed.
RAS	RAS8	15	2.1	Ed	On the previous page, the study was referred to as a LCA study conducted according to the requirements of ISO 14040 and 14044 whereas here it is referred to as a CFP study prepared in accordance with ISO 14067. A clear limitation of a CFP study is the focus on a single environmental issue which can hide burden shifting effects.	Please clarify	[**Revision**] Page 14 clarified the text. *"This LCA study was conducted according to the requirements of ISO-14067:2018 which is also based on ISO-14040:2006 and ISO-14044:2006"* The limitations are single impact category are discussed in section 4.2. and table
RAS	RAS9	16	2.2.1	Ed	Minor - Does "Europe (EU)" refer to the European continent or the European Union?	Please clarify	[**Revision**] See RAS1
RAS	RAS10	16	Table 1	Ed	Minor – Both scenarios for Sweden are said to be using global average	Please check	[**Revision**] Fixed

					raw materials when one should likely be using Nordic raw materials		
RAS	RAS11	17	Table 2	Ed	Minor – Is there a reason for the LFP column to be in red?	Please check	[Revision] This was red since it was confidential data from Morrow. The red will be removed on sign-off but for now we just need to have this as a reminder. For other report reviewers, this data will be made available on permission/NDA agreements in place.
RAS	RAS12	18	2.2.3	Ge	Major - The stated goals of the study are all related to the cell manufacturing and recycling. How are the supplementary results in Appendix A related to the use phase relevant to the goal?	Please clarify either the inclusion of the results in the report or the goal	[Revision] We have now removed the use phase results and all mentions and sections of it. For context, we were interested in how we could represent and estimate the longer lifespans of LFP vs. NMC. However, we decided this detracts from the main purposes of the study and there are many more variables to consider that warrant a separate study. This is also in agreement with comments made by other reviewers. **Changes are as following:** 1. Table 2 amended to remove use-based characterisation parameters that are no longer relevant to the study. 2. Removed in section 2.2.2. "~~Although the results focus on cradle-to-gate, Table 2 also includes cycle life parameters used to evaluate additional use-phase~~

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							~~results in Appendix A (A.1.6 and A.2.2).”~~ 3. Removed in section 2.2.3. ~~“Supplementary results in Appendix A also considered the influence of the use-phase using a secondary FU of per 1 kWh of the total energy provided by the battery over its service life measured in kWh (A.2.2). This provided insight into the life cycle impacts relative to the total service life provided by the battery, allowing for the representation of differences between LFP and NMC811 lifespans.”~~ 4. Removed in Table 3 “~~Use-phase results are only considered as supplementary material in Appendix A.1.6. And A.2.2.~~” 5. Relevant appendix sections removed from A.1.6. And A.2.2
RAS	RAS13	19	2.2.4.1, Point 1	Ed	Minor – Does the total metals in “0.33 mol NH_3 per mol of total metals” refer to metal sulphates as in later in the paragraph or the metal content of the sulphates?	Please clarify	[**Revision**] Clarified. *“Ammonium hydroxide complexing agent and sodium hydroxide base are added at rates of 0.33 mol NH_3 eq. and 1.03 mol NaOH eq. per mol of metal contained in sulfate precursors.”*
RAS	RAS14	20	2.2.4.1, Point 2	Ed	Minor – The conversion rate is stated as “near 100%”. Was the conversion rate used in the calculations 100% or something else?	Please clarify	[**Revision**] Clarified. *“The process assumes a 100% material conversion rate (near 100% is reported)…”*

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RAS	RAS15	20	2.2.4.1, Point 4	Ed	Minor – Is the graphite used in the study synthetic or natural?	Please specify	[Revision] Referenced relevant section where it is declared since these sections do not discuss sources but the general process descriptions. *"For both NMC811 and LFP cells, battery-grade graphite (sources discussed in Table 6) is mixed in a water-based solvent with conductive carbon and CMC binder"*
RAS	RAS16	21	Figure 2	Ed	Minor – "Seperator" should be Separator	Please fix typo	[Revision] See RAS2
RAS	RAS17	22	2.2.4.1, Point 7	Ed	Minor – Estimates are provided for NMC but not for LFP	Please add used estimates for LFP as well	[Revision] Text revised in point 7. Red is confidential data from Morrow. *"Morrow Batteries reports a total energy consumption of [redacted] powered by electricity. This figure encompasses the entire production chain - from CAM synthesis to final cell assembly. For NMC811 cells, direct comparison is more complex due to differences in the manufacturing processes, specifically the additional pCAM step and different CAM synthesis. These contributions are detailed in points (1) and (2). However, to enable comparability where possible, it is assumed that the entire NMC811 cell assembly process is powered by 100% electricity. Under this assumption, cell assembly alone is estimated to consume 23 kWh per kWh of cell capacity,. When including the upstream pCAM and CAM production stages, the total estimated energy demand for*

							NMC811 cells also approximates 50 kWh per kWh of cell capacity. *"*
RAS	RAS18	22	2.2.4.2	Ed	Minor – Is the 95% metal recovery rate accurate for each of the metals or only the total recovery?	If the rate is for total metal recovery, please specify the recoveries for each of the metals	[**Revision**] Fortum has a general declaration without further specifics; this has been clarified accordingly. The subsequent text within section further clarifies and expands on this. *"95% recovery rate for metals from black mass (individual metals or more specifications are not given),"*
RAS	RAS19	22-23	2.2.4.2 and Figure 3	Ed	Major - The text and the figure don't seem to match when it comes to the solvent extraction. In the description the first solvent extraction is said to extract cobalt and manganese while in the figure the streams after the first solvent extraction are Co-Ni rich solution and Li-Mn rick solution.	Please fix	[**Revision**] This is a great spot, thank you for flagging this. This was an error using a process description from a variant process instead of the correct one. All text has now been revised to the correct process used in this report. To help readability, overall metal recovery rates are used.
RAS	RAS20	22	2.2.4.2	Ed/Te	As the solvent extraction chemicals are found to contribute substantially to the recycling impact, it would be beneficial to state how much of the solvent extraction chemicals are assumed to require replacing, e.g., as a % annually	Please clarify	[**Revision**] Clarified *"Extractant regeneration rates were conservatively assumed to be 95% meaning a 5% annual replacement."*
RAS	RAS21	23	2.2.4.2	Ed	A description of the approach to treat wastewater and solid waste would be beneficial. Particularly in hydrometallurgical processes, the	Please provide more details on the waste treatment approaches	[**Revision**] This has now been provided.

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					contribution of wastewater treatment may be substantial.		*"The wastewater generated is treated by applying an evaporation-crystallisation process [REF]. The wastewater is firstly agitated and mixed at 48°C and then fed into a series of evaporators. Once the wastewater has been evaporated and condensed, the remaining stream is a concentrated sodium sulfate solution, which is fed into a crystalliser to recover the anhydrous sodium sulfate from the solution while remaining wastewater is discharged. Although sodium sulfate is a low-value co-product in some cases, a conservative assumption is applied in this study whereby it is landfilled along with other solid waste outputs. However, this assumption has a negligible impact on the overall study results. This process consumes both heat and electricity."*
RAS	RAS22	24	2.3.1.1	Ed	Minor – Space missing in "LCIbased"	Please fix typo	[**Revision**] Fixed
RAS	RAS23	24	Table 5	Ed	Minor – Is there a reason for the LFP column to be in red?	Please check	[**Revision**] See RAS11
RAS	RAS24	27	2.3.1.2	Ed	Minor – The modelling of inputs to the recycling process is described but the modelling of outputs, e.g., wastes is missing	Please add description	[**Revision**] Clarified *"Remaining wastewater and solid waste outputs are linked to waste treatment activities, while metal scrap co-products are typically used as secondary feedstock in industrial operations and are therefore assigned a burden-free status under the end-of-life cut-off approach (Section 2.3.4)."*

RAS	RAS25	28	2.3.4/Table 9	Ed/Te	What is the motivation for choosing only primary production processes when e.g., aluminium is expected to be a key hotspot	Please clarify	[Revision] Below text has expanded on this on page 29. *"To avoid double counting of recycling benefits, this approach excludes pre-existing recycled content in input materials; thus, only virgin metal production was considered including for aluminium. This was applied across both cradle-to-gate and cradle-to-grave scopes to maintain consistency. This is a conservative approach and aluminium hotspots for example could be overestimated but this was not directly relevant to the primary study goals"*
RAS	RAS26	28	Table 9	Ed/Te	Minor - What is the determination of significance based on and how are they considered? What are the criteria for Low/Medium/High and what is the actual expected effect of determined significance in e.g., ±X% or other description?	Please add description	[Revision] Below text has expanded on this in Table 9 caption. *"The significance is qualitatively judged by the LCA practitioner based on study goals and is revisited as results are generated, in line with the iterative nature of LCAs"*
RAS	RAS27	29	2.3.6	Ed/Te	Minor – Data quality assessment method and results are described but a description of data quality requirements is missing	Please add description	[Revision] Relevant sections have now been readded for completeness; though these do not have influence over the main study purposes and explorative nature.
RAS	RAS28	31	2.3.6.1, Line 4	Ed	Minor – "Tables 13" should likely be Table 13	Please fix typo	[Revision] Fixed
RAS	RAS29	33	2.4	Ed	Minor – It is stated that climate change impact is categorized into four distinct types but only three (or four if land use and land use change are considered separate but they are	Please align	[Revision] Fixed to "three"

					referred to as one, "this subcategory") are listed.		
RAS	RAS30	36	2.5.3	Ed/Te	Minor – How were the base uncertainty factors of 1.05 and 2.00 chosen?	Please clarify	[**Revision**] Clarified. "Firstly, base uncertainty factors were assigned to all data points to account that even "perfect" data (e.g. unanimously scored as ones in Table 18) would expect some variation. A minimum base uncertainty factor of 1.05 is applied to exchanges like energy, materials, and waste services, reflecting moderate variability and high data reliability. Transport services (e.g. tonne-kilometres by road or rail) carry a higher factor of 2.00, accounting for greater uncertainty in vehicle type, load factors, and distance assumptions. These default values are based on expert judgment within ecoinvent's pedigree matrix framework."
RAS	RAS31	36	Table 17	Ed/Te	Minor – How were the base uncertainty factors for Ni, Co, Li, graphite determined?	Please clarify	[**Revision**] Clarified. "Battery-specific raw materials were assigned quality indicators based on detailed, context-specific data and used tailored uncertainty factors from the Minviro Database. These pre-calculated values, based on prior pedigree matrix assessments, better capture variability than generic defaults and support a more robust and representative uncertainty analysis that aligns with the broad, exploratory nature of the study and applies conservative assumptions where appropriate (Table 18)"

RAS	RAS32	37	2.5.3	Ed/Te	Minor – How was the minimum threshold value selected?	Please clarify	[Revision] Clarified. "A 20% threshold ensures that only meaningful differences are considered, avoiding decisions based on statistically significant but practically negligible variations [34]"
RAS	RAS33	39	3.1	Ed	Minor – Space missing in "includesIndonesian-China"	Please fix typo	[Revision] Fixed.
RAS	RAS34	40	3.2.1	Ed	Minor – The cathode hotspot is stated to be halved by the greatly lower impact of nickel and cobalt when the decrease in lithium is larger than the decrease in cobalt	Please clarify	[Revision] Clarified by adjusting the bullet point. The reason nickel/cobalt are grouped together is because they are both from Terrafame. Now it should be clearer that all three simultaneously produce impact reductions. "*Cathode hotspot is halved from 61.1 to 30.2 kg CO2 eq. per kWh due to greatly lower impacts in nickel (from 31.9 to 10.1 kg CO2 eq. per kWh) and cobalt (from 4.9 to 2.3 kg CO2 eq. per kWh) provided by Terrafame's route; and meaningfully lower impacts in lithium through the Keliber project (from 13.6 to 7.0 kg CO2 eq. per kWh).*"
RAS	RAS35	40	3.2.1	Ed	Minor – A % of contribution is given to the cathode and container but not to the NMP solvent and aluminium foil which are also named as considerable contributors	Please add the % of contribution to NMP solvent and aluminium foil	[Revision] Added "*NMP solvent and aluminium foil also contribute notably at 5.6 (9%) and 2.7 kg CO_2 eq per kWh (4%), respectively*.".
RAS	RAS36	41-42	Figures 5, 6 and 7	Ed	Minor – "Seperator" should be Separator	Please fix typo	[Revision] See RAS2
RAS	RAS37	43	3.2.2	Ed/Te	Major - If I understand correctly, the recycling was not included in the uncertainty analysis, but some	Please add at minimum a qualitative assessment based on expert judgement of the uncertainty related	[Revision] Thank you for flagging this and totally agree. In addition to changing some language that was

					acknowledgment and assessment of uncertainty would be beneficial, particularly considering that the difference between the recycling impact and recycling credits is quite small	to the result somewhere in the report	too definitive, we have also added the following paragraph in addition to the section added in the executive summary. *Pg 47 "However, the potential 6% benefit is modest, and it must be acknowledged that Minviro's hydrometallurgical model was used as a proxy due to the absence of primary operational data from Fortum. As such, the overall conclusions are subject to several key assumptions and significant uncertainties that require further validation. Critical parameters - including actual metal recovery rates, reagent and energy consumption, graphite recovery potential, and variations across different processing stages - should be examined in detail and compared against Fortum's primary data once available to strengthen the robustness of the findings."* As such we also refine point 5 of the conclusion (pg 62) and the limitation sections (pg 63)
RAS	RAS38	45-46, 49, 51, 55	Figures 11, 12, 15, 18 and 22	Ed	Minor – "Seperator" should be Separator	Please fix typo	[**Revision**] See RAS2
RAS	RAS39	54-56	3.4	Ed/Te	Major - Comparison of the battery chemistries based only on the cradle-to-gate results should be accompanied by a description of the limitations of such an approach even	Please add description	[**Revision**] The following paragraph has been added. *Pg 60 "It should be noted that these comparisons are limited to a*

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					though the functional unit is the same as the use and end-of-life phases might change the results		*cradle-to-gate scope, and results may change when use-phase and end-of-life stages are considered. For instance, while NMC811 offers higher energy density, LFP batteries typically exhibit significantly longer cycle life and may deliver greater lifetime energy [REF]. Additional differences could also arise from comparing recycling processes between the two chemistries, but such comparisons are beyond the scope and goals of this study."*
RAS	RAS40	55	3.4	Ed	Minor – "LFP and NMC811 have more competitive impacts" Should this be that LFP has more competitive impacts?	Please check	[**Revision**] This was referring to the gap between the batteries being smaller in the Nordic case but it was not clearer. This has been rephrased. *Pg 59 "Therefore, while LFP still retains lower impacts compared to NMC811, the margin and significance is lesser"*
RAS	RAS41	65	A1.1	Ed	Minor – "Kuusilampu" should likely be Kuusilampi	Please fix typo	[**Revision**] Fixed.
RAS	RAS42	81	Table A6	Ed	Minor – Is there a reason for the LFP column to be in red?	Please check	[**Revision**] See RAS11
RAS	RAS43	81	Figure A4	Ed	Minor – "Seperator" should be Separator	Please fix typo	[**Revision**] See RAS2

Comments by Mudit Chordia

Initials	Index	Page No.	Section/ Figure /Table	Type of comment	Reviewer comments	Reviewer recommendation	Practitioner response
MC	MC1	4	Executive summary	Ed	"Swedish NMC811 and Norwegian LFP"	I recommend just saying NMC811 and LFP and removing the reference to the country here.	[Revision] Removed.
MC	MC2	4	Executive summary	Ed	"four specific raw material routes based on global average and Nordic routes for nickel sulfate, cobalt sulfate, lithium hydroxide and graphite"	Paraphrase this a bit. It is not specific raw material route if its based on global average.	[Revision] Clarified *"It evaluated four Nordic raw material routes against global averages"*
MC	MC3	4	Executive summary	Ed	"Global average … by a single route"	Can you extend the sentence by adding which materials global supply routes were dominated by a single route.	[Revision] Clarified *"Global average commodity routes were also modelled for comparison, typically dominated by a single pathway such as the Indonesia–China HPAL route for nickel sulfate."*
MC	MC4	6	Table ES1	Ed	This is meant for public communication like you say in the first few sentences of the summary. Its hard enough to interpret what the study means adding biogenic, fossil and LULUC will confuse a lot of readers not aware of how climate impacts are reported.	For the summary I recommend just reporting the total. In the main report you can be explicit about the breakdown.	**[No changes]** This is a good point but for completeness sake we will retain the results. Overall results will be shared with main audiences in other formats (e.g. a public presentation) with this report being the technical basis.
MC	MC5	6	Executive summary	Ed	"The uncertainty assessment, accounting for wide variability.."	Clarify what is the variability in.	[Revision] We have removed this to keep it summary focussed. Later discussed in the main contents.
MC	MC6	6	Executive summary	Ed	"The uncertainty .. " [full para]	What i gather from this para is that using nordic materials are a good way to reduce CF, but not necessarily	[Revision] This is valid, the phrasing was not quite right. We revised this, see EC3 for full revisions/reasoning.

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						nordic energy. Plus, LFP is better than NMC. .. correct? if yes, i think you can paraphrase a bit, it was a bit hard to break this para down. Also, if you are saying something is better or worse its also needed to say "in comparison to what"? That information is missing in this context the way the para is written.	
MC	MC7	6	Executive summary	Ed		You need to write a sentence why LFP was not recycled. Was it cause of the specific case that the technology is not available in Finland, or the data, or is LFP generally not recycled because of low economic returns.. ?	[**Revision**] The project budget was only for an analysis of one recycling route; hence, NMC was selected. We have added the text below to be transparent about this. However, this is sufficient and valid since the NMC recycling analysis is an independent chapter and not meant for NMC vs. LFP comparisons. "*LFP recycling was not considered due to project constraints and is subject to future work.*"
MC	MC8	6	Executive summary	Ed	"The study evidenced … ". [full para]	In the first para on this page you said that the Nordic manufacturing did not deliver the benefit (of reducing CF). Need a clearer context here.	**[No changes]** This should now make more sense based on response to MC7 and EC3.
MC	MC9	7	Executive summary	Ed	"Key limitations.. " [first sentence of the para	What did you use the secondary data for? I ask this cause on the previous page you highlight where you have used the Minviro database. By clarifying what you have used secondary data you will also communicate how relevant is it in	**[No changes]** We appreciate the suggestion. On page 4 we clarify a bit further in types of data used but would like to still keep these limitations. We agree with your points, but we would like to keep the paragraph

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						the big picture that you did not use primary data for those products. Secondly, I dont think exploring general trends is necessarily a limitation. As you say this meant for the public general results are better for communication. Site specific information is best for a company trying to figure where to invest. Again, just a thought.	conservative so specific companies/sites do not take the study outcomes out of context since there could be variability in their manufacturing processes, BOMs etc.
	MC10	15	Section 2.1	Ed	Point 1: "Four nordic .. and graphite"	This sentence reads like there are 4 routes each for nickel, cobalt, lithium and graphite that were investigated. Whereas its one each. Can you please paraphrase this sentence?	[**Revision**] Paraphrased. "*Nordic raw material routes were selected for nickel, cobalt, lithium, and graphite, inclusive of extraction, processing, and refining stages.* "
	MC11	15	Section 2.1	Ed	Point 2: "This was selected as a non comparative analysis"	You are comparing it to not recycling, so i would take sentence out. Or at least elaborate it that way.	[**Revision**] Paraphrased. "*This was selected as a independent analysis and not to be compared with LFP recycling.*"
	MC12	16	Table 1	Ed	"Scenario" heading.	Split into Scenario and Chemistry/material	[**Revision**] Split and corrected.
	MC13	16	Table 1	Ed	Generic comment on Production routes heading	How about splitting production routes to Energy and materials or something else that you prefer so that that differentiation is very clear in each scenario?	[**No changes**] Thank you for your suggestion but we prefer the current descriptor column.
	MC14	17	Table 1	Ed	"Nordic raw materials"	I dont follow how Nordic raw materials is a scenario. You are not varying anything here, or am I missing something... ?	[**Revision**] Column heading changed to "*Routes / Scenarios.*"
	MC15	17	Table 1	Ed	"Nordic recycling"	This you can argue as a Recycling vs no recycling scenario but again that would be a weak argument since you	[**Revision**] Response to MC14 should encompass this now.

						are not exploring multiple options within recycling. The way I understand the report, only Cell Manufacturing are scenarios.	
	MC16	17	Section 2.2.2	Ed	“Table 2 also includes… “	Why was this done? Is it a part of the scope you were given or is it something you are doing on your own.? The reason I ask is cause before this point, there is no mention of the use phase in the summary as well.	[**Revision**] Sections related to use-phase and additional results have now been removed, please see response to RAS12 for full reasoning and changes.
	MC17	18	Section 2.2.3	Ed	“per 1 kWh”	Write as, 1 kWh or per kWh.	[**Revision**] Amended.
	MC18	18	Section 2.2.4	Ed	“3% climate impact, mass..”	Can you confirm if less than 3% of each climate, mass or energy input were excluded. or was it just climate impacts. The reason I ask this is cause something with low mass per functional unit could still have high impacts so its feels a bit counter intuitive to exclude based on mass or energy. Also you need to add a sentence why 3% was chosen as the cut off criteria?	[**Revision**] Thank you for flagging this and it is a very important point. This was actually an older statement from a previous version of our reporting template and this was not correct. We have revised this section to confirm that no cut-off criteria was applied to our foreground system; expect from typical system boundary exclusions. Also, we have revised our internal reporting template to make sure we don’t apply cut-off criteria as the baseline unless there’s a specific justification. “*Certain areas were excluded from the system boundaries such as capital goods and product*

							packaging. However, it is important to note that such exclusions only apply to the foreground, and may not be reflected in the background databases used such as in ecoinvent. *Cut-off criteria refers to the amount of material or energy flow, or the level of significance of environmental impacts, to be excluded from a LCA study. No cut-off criteria were applied to the foreground data. However, there is inherent uncertainty for some flows that may have not been captured (e.g. dust and particulate emissions from manufacturing activities) due to the limitations such as the use secondary data; but the practitioner deems that all major flows contributing to climate change impacts and the scope of this work have been captured."*
	MC19	19	Table 2	Ed	Generic	Can you break this down into background and foreground as well. it will make reading of this table easier. The reason i said this is because you are alternating between background and foreground system in the bullets.	**[No changes]** This could be better aesthetically but we think the bullet point descriptors suffice since it's not an extensive table.
	MC20	20	Bullet 4	Ed	"... same assumption applied in CAM ...'	What assumptions are you referring to here? I recommend stating the same thing here to be clear about what data or assumption is being used for the production of AAM.	[**Revision**] Clarified below. "*each comprising less than 5% of the final anode mass*"
	MC21	22	Bullet 7	Ed		This section is quite unclear. The Degen article you refer to here cites 20 kWh ish electricity and 20	[**Revision**] This section has been revised subject to RAS17 that addresses some of these points.

						kWh ish heating from natural gas. Did you include that in the calculations somehow? Also, Degen et al dont consider the production of the precursor CAM as far as i recollect from their article. So where is that value coming from. Lastly, what is the per kWh value used for LFP?	I think you are referring to an older Degen et al. study in 2022 while here we use a more recent study from them here - See Fig. 3, though we pulled the direct number from the supporting information. Firstly, indeed the number is just cell assembly, but we have combined with the pCAM and CAM energy numbers too which the text should now make clearer. The main assumption we used was to assume that all cell assembly demand was by electricity to try make the study as comparable to the LFP data provided by Morrow. We have declared some limitations and uncertainties surrounding these assumptions which could be debated; however, we have also conducted a sensitivity test for using the original natural gas value in Figure 13 (top 2 and bottom 2 bars) - and it has no influence on the primary goals/conclusions of the study. "*Energy: For simplification, all energy demands associated with pCAM, CAM, and cell production stages are consolidated into a single unit process supplying the cell assembly stage. Morrow Batteries reports a total energy consumption of 50 kWh per kWh of LFP cell capacity powered by electricity. This figure*

							encompasses the entire production chain - from CAM synthesis to final cell assembly. *For NMC811 cells, direct comparison is more challenging due to differences in the manufacturing processes, specifically the additional pCAM step and different CAM synthesis.* *These contributions are detailed in points (1) and (2). However, to enable comparability where possible, it is assumed that the entire NMC811 cell assembly process is powered by 100% electricity. Under this assumption, cell assembly alone is estimated to consume 23 kWh per kWh of cell capacity.* *It should be noted that the original estimate included some natural gas consumption; hence, this assumption was sensitivity tested (Table 9, 16, and 17). When including the upstream pCAM and CAM production stages, the total estimated energy demand for NMC811 cells approximated to 50 kWh per kWh of cell capacity.* "
	MC22	24	Table 4	Ed	Degen et al	I am a bit uncertain about what value you have used here	[**Revision**] This is now addressed in MC21
	MC23	24	Table 4	Ed	Ellingsen et al	Ellingsen et al 2014, provided data for pouch cells whereas you have stated prismatic cells. Similar construction but its internal details differ a bit. So	[**Revision**] Clarified below. "*Based on Ellingsen et al.17, the pouch cell composition has been adapted for a prismatic form factor.*

						you need to explain how Ellingsen et al was adapted to your study.	*80% of mass was assigned to aluminium and 20% to other materials such as tabs, insulation, and plastics based on expert judgement."*
	MC24	25	Table 6	Ed	"Non battery specific..."	Where do foils fall as per this definition?	[**Revision**] Added foils to Table 4 but they fall into the non-battery specific row in Table 6.
	MC25	26	Section 2.3.1.1	Ed	"While ecoinvent 3.10 ...battery manufacturing locations"	This needs to be expanded a bit. How is it that market for electricity mix is representative in Sweden, Norway etc and not in other locations. The reason i point this out is cause market mix in Sweden includes 40% nuclear and 40% hydro, whereas the NV facility was located to source electricity from hydro plant only. We need to come up with a better argument here. Not sure what that might be but likely saying there are multiple locations in US, China etc whereas in Sweden and Norway there is only one location ... ?	[**Revision**] Agree that it needs to expand for, nice suggestion. We have made it clearer now. *"While ecoinvent 3.10 average electricity mixes were used for Sweden, Norway, and Finland, the "market group for electricity" datasets were not applied for Europe, the United States, and China, as these broader regional mixes are not representative of current battery manufacturing activity. In the Nordic countries, national electricity mixes were considered appropriate because battery manufacturing is limited to a small number of locations with relatively homogeneous and low-carbon electricity profiles, resulting in minimal deviation from national averages. In contrast, battery production in Europe, the United States, and China occurs across numerous facilities situated in regions with widely varying grid compositions. As such, national or regional market mixes could significantly misrepresent actual electricity use. To better reflect the diversity of supply in these larger*

							regions, weighted electricity mixes were developed based on the locations of existing lithium-ion battery gigafactories (≥1 GWh annual capacity), which were mapped to their most representative ecoinvent 3.10 locations (see Table 7).”
	MC26	28	Table 9, Assumption	Ed	“This scales all inputs by 1% …”	I would like to confirm how this was done?	**[No changes]** Assuming we need to produce 1 kg of battery; if we assume 1% scrap, then we have produced 0.99 kg of battery and 0.01 kg that is scrapped. Therefore, we need an additional 1% of 0.01 kg of battery to meet the demand. Hence, net input is 1.01 kg of battery needed to meet 1 kg FU. So, the same was done for the kWh FU.
	MC27	38	Results	Ed	Bullet 1 and 2	I think these 2 bullets can be combined.	[**Revision**] Amended.
	MC28	38	Results	Ed	Bullet 3 and 4	I think these 2 bullets can be combined.	[**Revision**] Amended.
	MC29	38	Table 18	Ed	Generic	Since biogenic, fossil and LULUC are summed up in the first row, make them italic to differentiate from the total. Also, biogenic and LULUC hardly are 1% of the total, isnt it better to just show total and say that fossil emissions are responsible for all the climate impacts.	[**Revision**] We have adjusted the border and italics as suggested. You are right for brevity it would be better to focus on the fossil impacts though we need to include all the categories for compliance with ISO 14067.
	MC30	39	Section 3.1	Ed	Generic	I did not follow why scope 3 emissions are so different between global and nordic routes. I assumed the difference would be in scope 1 and 2. can you explain this?	[**Revision**] We have some small additions and references to which scopes are reduced in the bullet point explainers.

							The main stark differences are for the nickel and graphite that you are referencing. In brief, HPAL for nickel (the dominant global route) is known to be exceptionally energy-intensive which leads to the disproportionate scope 2 emissions; compared to terrafame bioleaching process is much less energy-intensive and is known for its efficiency. Likewise for graphite, Vianode have developed an innovative process that substantially reduces process energy demands.
	MC31	39	Section 3.1	Ed	Generic	Is Ni from terrafame included in global average? This point needs to be addressed. if yes, then how much is terrafame;s share. Or if not, then you need to make a point about what the terrafame;s output looks like as compared to global production of Ni in terms of ton of Ni per year. Something ti include in the discussion section.	[**Revision**] Clarified. "*It should also be noted that Terrafame's nickel and cobalt is included within the global average estimates as Finnish output proxies in the Minviro Database (Section A.1.5); though other routes have the dominant influence. As such, if Terrafame's products were isolated from the global average, the global average would expect a minor increase in impact.*"
	MC32	40	Section 3.2.1	Ed	"… climate change impacts by area.."	what does climate change impact by area mean here? shouldnt it be per kWh?	[**Revision**] Adjusted to "Cell Component" for clarity. Y-axis provides the functional unit.
	MC33	40	Section 3.2.1	Ed	Anode (graphite)	earlier in the report you mentioned that you have used the ratio of 60:40. I am not sure if you have a reference for it. As i understand its more like 90:10.	[**Revision**] The 60:40 value is currently in the Minviro Database provided by our graphite specialist and informed by our industry contacts. Added "*informed by industry experts*" since there is not a

							direct citations under proprietary constraints, Indeed, there are sources for higher synthetic shares and we have seen claims ranging from 60-90% for synthetic. That said, we are awaiting an incoming update soon to the Minviro Database; and our value is subject to change. We have added this as a general limitation of using Minviro Database (same as ecoinvent etc.); but for the main goals of this study remain in tact. "...global average values are informed estimates and are subject to annual updates in light of new data and insight."
	MC34	42	Figure 7	Ed	Comment on the figure	Between figure 6 and 7, there are a lot of material inputs whose Co2 values are the same. So to make this crystal clear just highlight in the nordic routes what are different from the global average route.	[**Revision**] This has now been implemented.
	MC35	42	Figure 7	Ed	Comment on figure caption	its not nordic average, right? There is one nordic route for each material.	[**Revision**] Corrected.
	MC36	43	Section 3.2.2	Ed	".. outweighs the recycling ..."	I dont agree that we can argue with 5% reduction as a outweighing the impacts from primary production. Just state as 5% reduction.	[**Revision**] Amended to "offer recycling credits of 15.4 kg CO2 eq. per kWh yielding a reduced cell net impact by 6% relative to production."

	MC37	45	Figure 11	Ed	Generic	Why are some of these total values different from what is reported in figure 13?	[Revision] Figure 13 is sensitivity testing of different background datapoints for the regions from ecoinvent and not the weighted averages we created. Table 17 in the sensitivity testing declared that different tests are done using different background datapoints to test our energy assumptions. We have also added the below: "These were separate selections from the weighted averages used in Table 7 for sensitivity testing declared in Table 17."
	MC38	45	Figure 11	Ed	Generic	Can you please verify the emission factor for China and EU. Seems like Chinese average is almost the same as EU average. Since that is the only differentiator in the figure i just want to be doubly sure.	**[No changes]** That is correct, this is because manufacturing in Poland drive up the coal in the EU mix and inclusion of more hydro in China drives down the carbon intensity. Hence, these and the US one end up being very similar all round.
	MC39	45	Section 3.2.4	Ed	Generic	I have struggled with understanding this section. I dont know if its adding much value to the analysis or the learnings.	**[No changes]** That is true that this does not add too much value to the primary study goals and is mainly an added formality and another uncertainty perspective. However, some stakeholders will find it useful to understand how impacts increase/decrease across the ranges; so the section will remain. We will however, consider how in future we could reframe these

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							analyses and take on board your comment.
	MC39	45	Section 3.2.4	Ed	Nickel	Can you add a sentence clarifying what is major contributor to nickel supply emissions if its not the energy mix as you are suggesting.	[**Revision**] Added the following to reference the sections where this is discussed. "due to remaining hotspots discussed in Sections 3.1. and 3.2.1."
	MC40	46	Figure 12	Ed	Generic	I cannot see what the figure is trying to communicate. Is it really needed after your have already summarized in the text on the previous page?	**[No changes]** Responded to MC39.
	MC41	47	Figure 13	Ed	Generic	What is the difference in CN and CN-CCG? Is it referring to China average and the latter for a specific region? I am not following why FR was used here? If i understand correctly, the difference in this and the above US Ecoinvent electricity is that half the energy consumption is Natural gas? If so, it seems a bit odd that the difference in results is so low. A bit odd that the Scope 1 emissions of SE are higher than that of US? Can you explain that? The way the assumptions or the scenarios are described in the figure are very inconsistent. hard to follow a narrative here. How were these scenarios established?	[**Revision**] Section 2.5.2. sensitivity analysis declares and defines the testing various different assumptions. This was to test some uncertainties in our battery-production weighted mixes for different regions and ecoinvent averages. We have also added the below to the caption to help clarify this. "The Swedish baseline cases (top two bars) are compared to various regional electricity mix assumptions from ecoinvent instead of the weighted battery production averages used. Furthermore, assumptions on 50% natural gas and 50% electricity use during cell assembly are also included (bottom two bars) compared to the 100% electricity used in the baseline." Minor differences in scope 1 is due to differences the background emission factors for natural gas

							between EU/RoW datasets used for EU/US "...differences in natural gas emission factors between European and Rest-of-World datasets."
	MC42	48	Section 3.2.5	Ed	Generic	I recommend writing a very short summary here of what you want the key message to be. Ex. Using Nordic raw materials and producing NMC811 cells is better than the global average. What is the hotspot. Scope 1, 2 and 3.. ? etc etc.	[No changes] To avoid too much repetition of key messages in section 3. Summary and the conclusion we won't include this for now.
	MC43	49	Section 3.3.1	Ed	Bullet on Cathode (nickel)	Nickel? That seems to be an error.	[Revision] Good catch!... Corrected to lithium.
	MC44	49	Section 3.3.1	Ed	Para below the figure 15	As per this para, everything is a hotspot except energy. i think you could be more strict about using the term hotspot. As I read the figure there are no hotspot, instead three major contributors in the global RM case (cathode, anode, and container). Hotspot as I have understood is a single largest dominant contributor in terms of the impacts in a product system and there isnt one here.	[Revision] We still refer to anode/cathode as hotpots and changed some text to contributors; though, the terminology is interpretable since I think it is justifiable to say there are several hotspots though I can see your perspective too. We will consider revisiting the terminology in our future work and reporting templates.
	MC45	50	Figure 16	Ed		Same comment as what I had for the NMC811 part. You can make Figure 16 and 17 easier to read by identifying what impacts are different between Global and Nordic routes. If magnetite is so low, isnt it better to include it in others... ? Wasnt this the part of the cut off criteria?	[Revision] This has now been implemented. Magnetite is included as separate for reference because it is a key precursor to LFP.
	MC46	51	Section 3.3.2	Ed	"resulting in a grid carbon..."	per kWh of electricity generated.	[Revision] Corrected

	MC47	51	Figure 18	Ed	Generic	I came across a report stating that China has added more renewable energy capacity than any other country last year. Obviously its possible only for a country that size. But this also means we need to check our assumptions about the grid mix once, just to make sure we are not completely off. The reason i bring this up now, is that I realize that the difference between China and EU is very minimal, and US is not too far off. So it could be that with latest additions to the grid, the outlier is no longer China.	[Revision] This is a great point, and our baseline estimate calculated was around 680 g CO2e per kWh based on the regional battery productions (instead of the ecoinvent national average which is closer to 1000 g CO2e I believe which is way off). Looking at the most latest intensities reported, I think our estimated value is also in the ballpark I have also added this as a general limitation below. "Lastly, average electricity mixes are likely to change over time in response to current and future trends in energy generation capacity."
	MC48	51	Section 3.3.4	Ed	Generic comment on sensitivity analysis	Here too, like the NMC811 case, I am not able to figure out how is this adding value. We need to discuss this a bit in our meeting next time.	**[No changes]** Responded in MC39
	MC49	53	Section 3.3.4	Ed	"... since no natural gas is used for ..."	Is it also correct to say, "... and no data for site related emissions is available.. ?"	**[No changes]** I can confirm that the original sentence is correct; no natural gas is used for manufacturing by Morrow.
	MC50	53	Figure 20	Ed	Comments on the final values reported in the figure.	120 - Why is this result for China different from the result in Figure 18, where it is 106? 95.1 - Almost the same value as it is in Figure 18, but shouldnt it be exactly the same? 86.6- Big difference here again. Am sure there is an explanation and I havent followed it in the text.	[Revision] This should be addressed and clarity provided in the following responses: - MC21: For energy value justificiations. - MC41: Explaining why the numbers are different since its alternative sensitivity assumptions.

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	MC51	55	Section 3.4	Ed	"Energy demand is also slightly ... gas heat"	Slight incorrect here. The energy demand is not lower, its the impacts from energy demand which is lower. As far as I recollect you used Degens article for calculating the energy demand in cell assembly, but the value you used was approx 23 kWh/kWh-cell, which is not accounting for the additional 21 kWh/kWh-cell heat requirements. Whereas here you state that natural gas is included. I just need some clarity on the scope and the data on this aspect as also pointed out earlier in the NMC811 section. Also note that Degen modeled NMC622 cell, whereas you are modeling a 811 cell.	[Revision] Revised for clarity below; rest of the points are addressed in MC50 and other comments. "The differences in energy contributions are due to factors such as Morrow Batteries' use of 100% low-carbon Norwegian electricity for production, whereas the NMC811 cell assumptions include partial reliance on natural gas for heat during CAM production; though both are minor contributors to total cell impacts."
	MC52	55	Section 3.4	Ed	"Therefore LFP and NMC811... in this case"	You need to bring into the discussion the differences in gravimetric density kWh/kg of the 2 cells. Also, point out the limitation that since you are not assessing the use phase there is another element from the analysis as NMC811 cells likely perform better than LFP given the kWh/kg. Your conclusion here might give the impression that LFP is an outright better chemistry to those who do not follow LCA and functional units that well.	[Revision] This should now be addressed based on response and changes to RAS39.
	MC53	58	Section 4.1	Ed	Bullet point 4	Include the caveat about the kWh/kg (performance).	[Revision] This should now be addressed based on MC52 and added the following caveat "These comparisons are limited to a cradle-to-gate scope and do not

							account for use-phase, end-of-life impacts, or differences in cycle life and recyclability."

Study Name	Explorative Carbon Footprint of Product Study for Nordic NMC811 and LFP Battery Cells Dated: 24/07/2025 Version: v1.2
Commissioner of LCA Study	Battery Norway Kystveien 2, 4841 Arendal, Norway
Practitioners of LCA Study	Minviro Ltd Metal Box Factory, Room GG.005, 30 Great Guildford St, London SE1 0HS
Critical Review Panel Members	Chairperson: Mudit Chordia, Doctoral candidate, Chalmers, Sweden Eleonora Crenna (Senior Scientific Associate, HES-SO Sion, Switzerland) Riina Aromaa-Stubb (Doctoral researcher, Aalto University, Finland)

Scope of the Critical (Panel) Review

The critical (panel) review process has been carried out following international standards for life cycle assessment as identified in Critical review processes and reviewer competencies ISO/TS 14071:2014.

- The methods used to carry out the study followed the international standards
  - ISO 14040:2006 International Organisation for Standardisation (ISO), Environmental management – Life cycle assessment – Principles and framework.
  - ISO 14044:2006 International Standard Organization (ISO), Environmental management — Life cycle assessment — Requirements and guidelines.
  - ISO 14067:2018 International Standard Organization (ISO), Greenhouse Gases — Carbon Footprint of Products — Requirements and Guidelines for Quantification.
- The methods used to carry out the LCA are scientifically and technically valid
- The data used are appropriate and reasonable in relation to the goal of the study

- The report is transparent and consistent with the aims of the study

The critical review covered all aspects of the LCA, including data appropriateness and reasonability, calculation procedures, life cycle inventory, impact assessment methodologies, characterisation factors, calculated life cycle inventory and life cycle inventory analysis results, and interpretation.

Critical (Panel) Review Process

In July 2025, Mudit Chordia, Eleonora Crenna, and Riina Aromaa-Stubb were engaged by the practitioner of the LCA study, 'Minviro Ltd', to perform an independent expert critical review on the "Explorative Carbon Footprint of Product Study for Nordic NMC811 and LFP Battery Cells". The LCA study was commissioned to Minviro by Battery Norway, and it explored the potential life cycle climate change impacts of Nordic NMC811 and LFP batteries using Nordic raw materials. The project consisted primarily of a cradle-to-gate analysis from raw materials, refining, and manufacture, but also an independent cradle-to-grave including recycling.

The critical review was carried out at the end of the study, and performed on the reports "Prospective Carbon Footprint of Product Study for Nordic NMC811 and LFP Battery Cells", 10/06/2025, and on the revised version of "Explorative Carbon Footprint of Product Study for Nordic NMC811 and LFP Battery Cells", 11/07/2025. As part of the review life cycle inventory model and use of foreground and background datasets were evaluated, as disclosed within the study reports.

The critical review report with the comments were sent to Minviro on 07/07/2025 and a revised version of the LCA report named "Explorative Carbon Footprint of Product Study for Nordic NMC811 and LFP Battery Cells" was returned to the reviewer on 11/07/2025. The responses to the comments are in the "Appendix B - Feedback from Reviewers of the same report".

Study Evaluation

The LCA study has certain strengths, limitations and potential improvements as described in section 4.2 and 4.3 of the last study. To the best of our knowledge and with the data we have in hand, this study has been found to be in conformance with ISO 14040, ISO 14044 and ISO 14067. This is the critical review statement prepared on 25/07/25 and, after being submitted to Minviro Ltd, shall be part of the final LCA report.

Conclusions

The critically reviewed LCA study complies with ISO 14040:2006, ISO 14044:2006 and ISO 14067:2018. The report is considered an appropriate summary of the study’s goal, scope, methodology, assumptions, life cycle inventory, quality of foreground and background data, results and interpretation of sensitivities.

Responsible for the critical review report and critical review statement have been the following reviewer(s):

Mudit Chordia Doctoral candidate Chalmers University of Technology 25.07.2025	Eleonora Crenna Senior Scientific Associate HES-SO Sion 28.07.2025	Riina Aromaa-Stubb Doctoral researcher Aalto University 29.07.2025

Self-declaration of reviewer independence and competencies

I, the signatory, hereby declare that:

- ☑ I am not a full-time or part-time employee of the commissioner or practitioner of the LCA study (external reviewers only)
- ☑ I have not been involved in defining the scope or carrying out any of the work to conduct the LCA study at hand, i.e. I have not been part of the commissioner's or practitioner's project team(s)
- ☑ I do not have vested financial, political or other interests in the outcome of the study

My competencies relevant to the critical review at hand include knowledge of and proficiency in:

- ☑ ISO 14040, ISO 14044, and ISO 14067
- ☑ LCA methodology and practice, particularly in the context of LCI (including data set generation and data set review, if applicable)
- ☑ Critical review practice
- ☑ The scientific disciplines relevant to the important impact categories of the study
- ☑ Environmental, technical and other relevant performance aspects of the product system(s) assessed
- ☑ Language used for the study

I attach a curriculum vitae and a list of relevant references.

I declare that the above statements are truthful and complete. I will immediately notify all parties involved (commissioner of the critical review, practitioner of the LCA study, reviewer(s)), as applicable, if the validity of any of these statements changes during the course of the review process.

Date: 25/07/2025

Name (print): MUDIT CHORDIA

Signature:

Signed by: Mudit Chordia

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Education

Doctoral student in Energy, Environment and Systems
Chalmers University of Technology, Sweden — *2020-*

Master of Science in Sustainable Technology (Industrial Ecology)
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Master of Engineering in Petroleum Engineering
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Jacobs, Canada — *2012-15*

Mechanical Engineer
Larsen & Toubro Valdel Engineering, India — *2006-09*

Research output

Licentiate thesis

Chordia, M. (2022). *Taking stock of large-scale lithium-ion battery production using life cycle assessment*. Chalmers Tekniska Hogskola (Sweden).

Journal articles

Kallitsis, E., Lindsay, J. J., **Chordia, M**., Wu, B., Offer, G. J., & Edge, J. S. (2024). Think global act local: The dependency of global lithium-ion battery emissions on production location and material sources. *Journal of cleaner production*, *449*, 141725.

Chordia, M., Wickerts, S., Nordelöf, A., & Arvidsson, R. (2022). Life cycle environmental impacts of current and future battery-grade lithium supply from brine and spodumene. *Resources, Conservation and Recycling*, *187*, 106634.

Arvidsson, R., **Chordia, M.**, & Nordelöf, A. (2022). Quantifying the life-cycle health impacts of a cobalt-containing lithium-ion battery. *The International Journal of Life Cycle Assessment*.

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Nordelöf, A., Poulikidou, S., **Chordia, M.**, Bitencourt de Oliveira, F., Tivander, J., & Arvidsson, R. (2019). Methodological Approaches to End-Of-Life Modelling in Life Cycle Assessments of Lithium-Ion Batteries. *Batteries*, *5*(3), 51.

Manuscript under review

Chordia, M., Wikner, E., Nordelöf A., Lacey, M., & Arvidsson, R. (2025). Parameterization methodology for assessing the influence of lithium-ion battery cell type on the environment. *Journal of Industrial Ecology*.

Manuscripts in preparation

Chordia, M., Nordelöf A, Istrate, R., Steubing, B., & Arvidsson R. (2025). Scenarios for prospective life cycle assessment of lithium-ion batteries.

Chordia, M., Nordelöf A, Petranikova, M., & Arvidsson R. (2025). Large-scale recycling of lithium-ion batteries.

Conference articles and posters

Chordia, M., Nordelöf, A., & Wikner, E. (2024) Large-scale lithium-ion battery pack recycling. SETAC LCA Symposium, Gothenburg, Sweden.

Chordia, M., Nordelöf, A., & Wikner, E. (2022) A model platform for solving lithium-ion battery cell data gaps in life cycle assessment. EVS35, Oslo, Norway.

Chordia, M., Wickerts, S., Nordelöf, A., & Arvidsson, R. (2022). Does the grade and source of lithium used in batteries matter? SETAC Europe 2022, Copenhagen, Denmark.

Chordia, M., & Nordelöf, A. (2021) Upscaling lithium-ion battery production. Roads to the future. Uppsala, Sweden.

Arvidsson, R., **Chordia, M.**, & Nordelöf, A. (2022) Blood cobalt? Life cycle human health impacts of a lithium-ion battery. 8^{th} International Conference on Social Life cycle assessment, Aachen, Germany.

Reports

Langeveld, J., **Chordia M.**, Oladosu, G., Brandão, M., Dale, V., Kline, K., & Cowie, A. (2022) Towards an improved assessment of land-use change - Evaluating common narratives, approaches, and tools. IEA Bioenergy.

Contributed to: Ekener, E. (2019). Developing an approach for systematic assessment of positive social impacts. f3 Centre.

Peer review

Journal of Cleaner Production

Environment, Development and Sustainability

Energy Technology

Environmental Science and Technology

Resources, Conservation and Recycling

Self-declaration of reviewer independence and competencies

I, the signatory, hereby declare that:

- ☑ I am not a full-time or part-time employee of the commissioner or practitioner of the LCA study (external reviewers only)
- ☑ I have not been involved in defining the scope or carrying out any of the work to conduct the LCA study at hand, i.e. I have not been part of the commissioner's or practitioner's project team(s)
- ☑ I do not have vested financial, political or other interests in the outcome of the study

My competencies relevant to the critical review at hand include knowledge of and proficiency in:

- ☑ ISO 14040, ISO 14044, and ISO 14067
- ☑ LCA methodology and practice, particularly in the context of LCI (including data set generation and data set review, if applicable)
- ☑ Critical review practice
- ☑ The scientific disciplines relevant to the important impact categories of the study
- ☑ Environmental, technical and other relevant performance aspects of the product system(s) assessed
- ☑ Language used for the study

I attach a curriculum vitae and a list of relevant references.

I declare that the above statements are truthful and complete. I will immediately notify all parties involved (commissioner of the critical review, practitioner of the LCA study, reviewer(s)), as applicable, if the validity of any of these statements changes during the course of the review process.

Date: 28/07/2025

Name (print): ELEONORA CRENNA

Signature:

Signed by: Eleonora Crenna

ELEONORA CRENNA, Ph.D

PERSONAL INFORMATION

Born on 18.01.1989
Nationality: Italian
Swiss Permit: C
LinkedIn | ResearchGate

Address: Nussbaumstr. 11, 8003 Zürich
Telephone: +41 78 957 60 74
Email: eleonora.crenna@gmail.com

LANGUAGE

Italian: mother tongue; English: C1; Spanish: B2; German: B1;

WORK EXPERIENCE

02/2024 – Today **Senior Scientific Associate,** *Institute of Sustainable Energy, HES-SO, Sion (CH)*

LCA Analyst, *CIRAIG International, Montreal (CA)*

- Leading the sustainability work packages of the Horizon EU projects ANEMEL, NOAH2, ASTERISK, ECOPEM and contributing to the tasks within SUSTAINCELL, focused on the **life cycle assessment (LCA)** and **eco-design** of clean hydrogen technologies, including **supervision** of students and junior collaborators, and coordination with international academic and industrial partners.
- **LCA coaching and technical support** for HES-SO and EPFL students, and industrial clients in Switzerland, Italy and within the CIRAIG consortium.
- **Project design and acquisition** at Swiss and European level

06/2019 - 1/2024 **Postdoc/ Scientist,** *Technology & Society Lab, Empa, St. Gallen (CH)*

Promoted within 2.5 year for exceeding goals and fostering collaborations

- Leading the activities focused on the **environmental impact and sustainability assessment** of the life cycle of new materials and technologies in various sectors, including **supervision** of students:
  - **batteries**: H2020 Si-DRIVE; FluoriBAT; Innosuisse Flagship CircuBAT; Innosuisse LIBREC;
  - **construction**: DEZA-funded CEELA.
  - **food:** PACKME; Coop-funded project;
- Performing LCA, from data collection to impact assessment and reporting, coordinating the exchanges of information with other Empa laboratories, Swiss/European research institutes and private companies.
- Contribution to publication of life cycle inventory datasets on ecoinvent database.
- Contribution to events as speaker and moderator (ABAA 2019, SETAC Europe 2020, E-MRS Fall Meeting 2021, Green Batteries Conference 2021, WRF 2021; LCE 2022; Interview with RSI- "Il giardino di Albert" program 2023; WRF 2023)
- **Lecturer** at ETH Material Science in the M.Sc. course on Sustainable Materials Management
- Active member in the "Global Guidance for Life Cycle Impact Assessment Indicators and Methods" (GLAM) project, normalisation subtask force.

09/2016 – 05/2019 **Environmental Sustainability Analyst**, *European Commission's JRC, Ispra (IT)*

- Contribution to the LCA research projects, mostly dealing with biodiversity and food systems, aiming at supporting the European Strategies towards meeting the Sustainable Development Goals.
- Responsible for the improvement and development of normalization references on global scale, within the context of the Product Environmental Footprint (PEF).

ADDITIONAL EXPERIENCE

03/2016 – 08/2016 **LCA trainee**, *European Commission's JRC, Ispra (IT)*
06/2014 – 11/2019 **Environmental volunteer | Local volunteers' coordinator,** *LIPU-BirdLife Italia, Varese area (IT)*
06/2014 – 12/2014 **Collaborator in Environmental Impact Assessment,** *Progetto Natura Onlus, Milan area (IT)*
12/2013 – 02/2017 **Environmental educator,** *Associazione Idea, Milan area (IT)*

EDUCATION

12/2014 – 03/2018 **Ph.D. in Environmental Science & Sustainability**, *University of Milano-Bicocca, Milan (IT)*
Thesis: Novel models and indicators for characterizing impacts on biodiversity in Life Cycle Impact Assessment
Erasmus+ Traineeship, Technical University of Denmark (DTU)

10/2011 – 12/2013 **M.Sc. Natural Science**, *University of Milano, Milan (IT)*
Erasmus, Universidad de Salamanca, Spain

10/2008 – 10/2011 **B.Sc. Natural Science**, *University of Milano, Milan (IT)*

ADDITIONAL ACTIVITIES

- **Review Editor** for Frontiers in Sustainable Food Systems journal, 2023-2024-2025
- Volunteer reviewer for various scientific journals in the field of cleaner production.
- **President** of the Staff Committee, 2023, Empa
- Mentee in the fem-LEAD (female Mentoring: Leadership for Equity And Diversity) program by ETH domain (2023-2024)
- Coachee in the Fix the Leaky Pipeline, peer mentoring program promoted by Empa for female researchers (2021-2022 and 2022-2023). Topics: assertiveness, interviewing, career planning and development, stress management, networking and social interactions
- Social Life Cycle Assessment course (8 hours, March 2023), Empa & WRF Association
- **Project Management** course (16 hours, December 2022), Empa

COMPUTER SKILLS

Office package:	proficient user
SimaPro, Activity Browser, OpenLCA (software for LCA):	proficient user
R (software for statistical analysis):	beginner user
ArcGis and Qgis (software for geospatial information analysis):	beginner user

MEMBERSHIPS

Society of Environmental Toxicology and Chemistry (SETAC):	2017, 2020
Lega Italiana Protezione Uccelli (LIPU) – BirdLife Italia:	2014 – 2025
Italian Society of Natural Sciences (SISN):	2018 – 2024

AWARDS

Best in-person presentation at World Resource Forum (WRF) 2023, “Planetary boundaries and the energy, climate change and materials nexus” session

HOBBIES

Power yoga practice; Kizomba dancing; Birdwatching

Scientific papers

Abdelbaky, M., Crenna, E., Hischier, R., Dewulf, W., Peeters, J. (2024) Balancing Environmental and Economic Impacts of the rapidly evolving European electric vehicle Battery Sector. Submitted to Technological Forecasting and Social Change.

Crenna, E., Gauch, M., Widmer, R., Wäger, P. Hischier, R. (2021). Towards more flexibility and transparency in life cycle inventories for Lithium-ion batteries. Resources, Conservation and Recycling, 170, 105619.

Crenna, E., Hischier, R., Defraeye, T., Onwude, D. (2024). Ecological hotspots of the journey of a South African citrus fruit. Submitted to Resources, Conservation and Recycling in November 2024.

Crenna, E., Jolliet, O., Collina, E., Sala, S., Fantke, P. (2020). Characterizing honey bee exposure and effects from pesticides for chemical prioritization and life cycle assessment. Environ Int, 138, 105642.

Crenna, E., Marques, A., La Notte, A., Sala, S. (2020). Biodiversity Assessment of Value Chains: State of the Art and Emerging Challenges. Environ Sci Technol, 54(16), 9715-9728.

Crenna E., Sala S., Polce C., Collina E. (2017). Pollinators in life cycle assessment: towards a framework for impact assessment. J Clean Prod, 140: 525-536.

Crenna, E., Secchi, M., Benini, L., Sala, S. (2019). Global environmental impacts: data sources and methodological choices for calculating normalization factors for LCA. Int J Life Cycle Ass, 24(10), 1851-1877.

Crenna, E., Sinkko, T., Sala, S. (2019). Biodiversity impacts due to food consumption in Europe. J Clean Prod, 227, 378-391.

Crenna E., Sozzo S., Sala S. (2018). Natural biotic resources in LCA: towards an impact assessment model for sustainable supply chain management. J Clean Prod, 172, 3669-3684.

Defraeye, T., Shrivastava, C., Motmans, T., Kingsley, U., Crenna, E., Shoji, K., Onwude, D. (2022). The charcoal cooling blanket: A scalable, simple, self-supporting evaporative cooling device for preserving fresh foods. Submitted to Frontiers in Sustainable Food Systems in November 2022.

Dou, X., Ulissi, U., Liu, H., Weil, M., Baumann, J., Peters, J., Crenna, E., Hischier, R., Wu, K., Ouyang, C. (2024). A Greener Lithium-ion Battery Ecosystem: Sustainability Perspective on Near-future Technologies. In preparation for submission to Nature Sustainability.

Karabulut A.A., Crenna E., Sala S., Udias, A. (2018). A proposal for the integration of the Ecosystem-Water-Food-Land-Energy (EWFLE) nexus concept into the life cycle assessment: A Synthesis Matrix for food security. J Clean Prod, 172, 3874-3889.

Liu, H, Baumann, M., Moon, H., Zhang, X., Zarrabeitia Ipina, M., Crenna, E., Hischier, R., Passerini, S., von der Assen, N., Weil, M. (2024). Life cycle assessment of bio-based hard carbon for sodium-ion batteries across different production scales. Chemical Engineering Journal, 153410.

Martines Tola, J. S., Barros Bermeo, E., Padron Flasher, K., Crenna, E., Matasci, C., Gauch, M., Sucozhanay Calle, D. C., Vanegas Pena, P. F. (2024). Environmental and social sustainability assessment of manufacturing traditional construction materials in Ecuador. Sustainability. Accepted for publication on 15.02.2025.

Onwude, D., Bahrami, F., Shrivastava, C., Berry, T., Cronje, P., North, J., Scudel, S., Crenna, E., Shoji, K., Defraeye, T. (2022). Physics-driven digital twins to quantify the impact of pre-and postharvest variability on the end quality evolution of orange fruit. Resources, Conservation and Recycling, 186, 106585.

Onwude, D., Crenna, E., Cronje, P., Berry, T., Hischier, R., Defraeye, T. (2024). Dynamic physics-driven life cycle model for a sustainable global maritime citrus supply chain. In preparation.

Saavedra-Rubio, K., Thonemann, N., Crenna, E., Lemoine, B., Caliandro, P., & Laurent, A. (2022). Stepwise guidance for data collection in the life cycle inventory (LCI) phase: Building technology-related LCI blocks. Journal of Cleaner Production, 132903.

Sala, S., Crenna, E., Secchi, M., Sanyé-Mengual, E. (2020). Environmental sustainability of European production and consumption assessed against planetary boundaries. J Environ Manage, 269, 110686.

Serra, M., Crenna, E., Bartolomè, N., Moysiadou, A., Battaglia, C., Hischier, R. (2023). Aqueous recovery of lithium salts from end-of-life lithium-ion batteries: a prospective ecological evaluation. Submitted to Resource, Conservation & Recycling, January 2024.

Serra, M., Crenna, E., Querel, E., Battaglia, C., Hischier, R. (2024). Dry-coated battery electrode – a more environmental friendly solution?. In preparation for submission to Battery & Supercaps.

Shrivastava, C., Crenna, E., Schudel, S., Shoji, K., Onwude, D., Hischier, R., Defraeye, T. (2021). To wrap or to not wrap cucumbers?. engrXiv..

Technical reports

Sala S., Benini L., Crenna E., Secchi M. (2016). Global environmental impacts and planetary boundaries in LCA. JRC technical report, EUR 28371 EN.

Sala S., Crenna E., Secchi M., Pant R. (2018). Global normalisation factors for the Environmental Footprint and Life Cycle Assessment. JRC technical report, EUR 28984 EN.

Conference communications (posters and presentations as first author or presenter)

Crenna, E., Gauch, M., Barros Bermeo, E., Martines Tola, J.S., Sucozhanay Calle, D. C., Vanegas Pena, P. F. (2023). Achieving sustainability in buildings: an interdisciplinary approach to the selection and use of building materials. WRF 2023, Geneva, Switzerland

Crenna, E. (2022). Batterie: sostenibilità ambientale e nuovi materiali. Oral presentation at the conference on sustainable electro-mobility organized by I Verdi del Ticino, June 11th 2022.

Crenna, E., Abdelbaky, M., Tommasi, A., Fallah, S.N., Fitzpatrick, C., Schwich, L., Friedrich, B., Hischier, R., Peeters, J. (2021). Sustainability challenges of the next generation Si-DRIVE Li-ion battery. Panel presentation at the European Materials Research Society Symposium B: Battery and energy storage devices: from materials to eco-design

Crenna, E., Gauch, M., Hischier, R. (2021). Environmental sustainability potentials of electric vehicles' batteries. Green Batteries Conference 2021.

Crenna E., Sala S. (2016). Pollinators in LCA: relevance and challenges. Poster for SETAC Europe 26th Annual Conference, Nantes.

Crenna E., Sala S. (2017). Making biotic resources count in Life Cycle Impact Assessment. Poster for SETAC Europe 27th Annual Conference, Brussels, Belgium.

Crenna E., Sala S., Polce C., Collina E. (2015). Pollinators in LCA: towards a framework for impact assessment. Proceedings of the International Conference LCA for feeding the Planet and energy for life. ENEA. ISBN 978-88-8286-321-0.

Crenna E., Saouter E., Sala, S. (2017). A trophic chain-based approach for ranking chemicals in LCA. SETAC Europe 27th Annual Conference, Brussels, Belgium.

Crenna E., Saouter E., Sala S. (2016). Pollinators in Life Cycle Impact Assessment. Proceeding of the 10th Conference of Associazione Rete Italiana LCA. ENEA. ISBN 978-88-8286-333-3.

Other outputs

Abdelbaky, M., Schwich, L., Crenna, E., Peeters, J. R., Hischier, R., Friedrich, B., & Dewulf, W. (2021). Comparing the environmental performance of industrial recycling routes for lithium nickel-cobalt-manganese oxide 111 vehicle batteries. Procedia CIRP, 98, 97-102.

Crenna, E. (2018). Novel models and indicators for characterizing impacts on biodiversity in Life Cycle Impact Assessment. PhD thesis.

Fazio S., Crenna E., Diaconu E., Sala S. (2017). Make Biotic Resources count in Life Cycle Assessment. European Commission, JRC 109912.

Sala S., Benini L., Beylot A., Castellani V., Cerutti A., Corrado S., Crenna E., Diaconu E., Sanyé-Mengual E, Secchi M., Sinkko T., Pant R. (2019) Consumption and Consumer Footprint: methodology and results. Indicators and Assessment of the environmental impact of EU consumption. Science for Policy report, doi:10.2760/98570, JRC 113607.

Sala S., Benini L., Crenna E., Secchi M. (2017). Searching for the right number: which are the most suitable reference values to be compared to the planetary boundaries? Poster for SETAC Europe 27th Annual Conference, Brussels, Belgium.

Sala S., Benini L., Crenna E., Secchi M. (2017). European and global consumption: to which extent are they surpassing planetary boundaries? Poster for Life Cycle Management (LCM) Conference, Luxembourg.

Sala S., Cerutti A., Castellani V., Secchi M., Beylot A., Crenna E., Corrado S, Sinkko T. (2018). Consumption and consumer footprint: LCA as pivotal methodology for assessing consumption patterns and eco-innovations. Panel presentation for SETAC Europe 28th Annual Conference, Rome, Italy.

Self-declaration of reviewer independence and competencies

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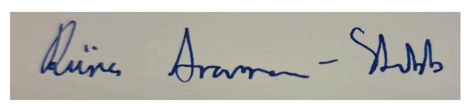
Date: 29/07/2025

Name (print): RIINA AROMAA-STUBB

Signature:



Signed by: Riina Aromaa-Stubb

Riina Aromaa-Stubb

https://orcid.org/0000-0002-9810-7521

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EXPERIENCE

Doctoral researcher, Aalto University School of Chemical Engineering, Group of Hydrometallurgy and Corrosion | Feb 2021–present

Life cycle assessment in combination with process simulation to study the environmental impacts of cobalt recycling. Data collection and analysis for simulation and LCA. Dissemination of results to various audiences, preparation of research articles and LCA reports.

Project Engineer at Neste Engineering Solutions, Academic Work | Nov.2019 – Nov 2020

Project control and cost engineering activities for multiple projects. Preparation of monthly cost reports, calculation and compilation of cost estimates.

Research Assistant, Aalto University School of Chemical Engineering, Group of Metallurgy | Feb-Jul 2019

Master's thesis project on the distribution kinetics of rare earth elements between copper matte and fayalite slag.

DEGREES

M.Sc. (Tech) | 2019 | Master's Programme in Chemical, Biochemical and Materials Engineering, Sustainable Metals Processing - Aalto University, Finland

Thesis title: *Rare earth elements distribution kinetics in copper matte-slag system*

B.Sc. (Tech) | 2018 | Bachelor's Programme in Chemical Engineering, Materials Science and Technology – Aalto University, Finland

Thesis title: *Use of secondary raw materials in high temperature processes (in Finnish)*

LANGUAGES

Finnish – Native

English – Full professional proficiency

Swedish – Professional working proficiency

German – Limited working proficiency

French – Elementary proficiency

Spanish – Elementary proficiency