CLIMATE CHANGE ANALYSIS OF MANUFACTURING AND USING LITHIUM ION BATTERIES

Prepared for Cobalt Institute

28 August 2024

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Reviewers: Kallitsis, E., Lander, L. and Tate, L.

Our Statement

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Life cycle assessment (LCA) is an environmental accounting method with an inherent level of uncertainty, and it should not be seen as having the same level of precision as financial accounting. LCA requires a very large amount of data on the life cycle inventory (LCI) flows for each stage of a product's or process' life cycle. Comprehensive datasets for lithium-ion (Li-ion) battery manufacturing and use have been developed by Minviro from a range of public sources. The ecoinvent 3.9.1 database has been used for the majority of background data collection 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.

Cobalt Institute commissioned LCA practitioner Minviro Ltd. in April 2023 to quantify and interpret the climate change impact of manufacturing and using Li-ion batteries of different chemistries. The batteries under study are designed to be similar to those currently found in upper medium size (class D) electric vehicles (EVs).[3] The chemistries studied are lithium nickel manganese cobalt (NMC; 8:1:1 Ni:Mn:Co), lithium nickel cobalt aluminium (NCA; 8:1.5:0.5 Ni:Co:Al), and lithium iron phosphate (LFP).

Table 1: Document Details.

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Date	28 August 2024
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Table 2: Report Revision Details.

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Version 1.1	1	Bridges, L., Shah, R., and Tijsseling, L.	Shah, R.
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Version 2.1	1	Bridges, L., Shah, R., and Tijsseling, L.	Cobalt Institute
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Version 5.2	0	Bridges, L., Shah, R., and Tijsseling, L.	Kallitsis, E.

Executive Summary

Cobalt Institute commissioned life cycle assessment (LCA) practitioner Minviro Ltd. ('Minviro') in April 2023 to quantify and interpret the climate change impact of manufacturing and using lithium-ion (Li-ion) batteries of different chemistries. The batteries under study are designed to be similar to those currently found in upper medium size (class D) electric vehicles (EVs).[3] The methodology applied was the Environmental Footprint (EU-EF) method[17] following the ISO-14067 standard.[4] The chemistries studied are lithium nickel manganese cobalt (NMC; 8:1:1 Ni:Mn:Co), lithium nickel cobalt aluminium (NCA; 8:1.5:0.5 Ni:Co:Al), and lithium iron phosphate (LFP) using foreground data adapted from a range of publicly available sources[12-14] and background data primarily from ecoinvent 3.9.1.[16]

The goals of the study are to:

- Quantify, interpret, and compare the climate change impact and hot spots of manufacturing NMC, NCA, and LFP battery packs, similar to those found in current Class D EVs, using public data that is best representative of current battery manufacturing supply chains, processes, and locations.
- Perform sensitivity analysis on the climate change impacts of battery manufacturing to demonstrate the significance of low carbon raw material and energy sourcing.
- Extend the system boundary to include a European EV use-phase scenario allowing quantification, interpretation, and comparison of the lifetime climate change impacts of NMC, NCA, and LFP battery packs similar to those currently used in Class D EVs.
- Perform use-phase sensitivity analysis on different electricity mixes to demonstrate the significance of grid decarbonisation.

The intended application of this LCA is to encourage discourse among industry stakeholders on:

- low carbon material sourcing in Li-ion battery supply chains;
- efficient use of critical raw materials (e.g. cobalt, natural graphite, phosphorus, and lithium)[29] in lightweight high energy density batteries;
- and the importance of grid decarbonisation in both manufacturing and use locations.

The results will be used to communicate the importance of these areas going forward to members of Cobalt Institute and wider industry stakeholders.

The LCA was performed using a cradle-to-gate system boundary. The gate to assess the climate change impact of battery pack manufacturing was set to production of a battery pack in the manufacturing facility. The base case manufacturing location is Jiangsu Province, China. The gate to assess lifetime emissions was set to 160,000 km travelled in a class D EV. The base case use-phase scenario has been developed to be representative of battery pack use in a class D EV charged in the European Union (EU); the EU27 average grid intensity is used.[28]

The system boundary chosen represents battery manufacturing and use for a specific EV application with defined manufacturing and use assumptions (see Chapter 3). Readers should be aware that LCI (Appendix A) and LCIA results may look significantly different for an alternative application (e.g. in a stationary ESS). Study parameters are presented in Table 3.

Table 3: Summary of Study Parameters.

Parameter	Description or Value
Battery Chemistries	Nickel Manganese Cobalt (NMC) 8:1:1 Ni:Co:Mn
	Nickel Cobalt Aluminium (NCA) 8:1.5:0.5 Ni:Co:Al
	Lithium iron phosphate (LFP)
Cell Type	Cylindrical 21700
Pack Capacity	70.6 kWh
Base Case Manufacturing Scenario	All Manufacturing in Jiangsu, China, using Industry Representative Raw Material Supply Chains
Battery Manufacturing Sensitivity Analyses	Low and High Impact Material and Energy Supply Chains
	Isolation of Low and High Impact Cobalt Supply Chains
	US Manufacturing with Base Case Material Supply Chains
	Low and High Cell Manufacturing Electricity Consumption
Base Case Use-Phase	Charging on Average EU27 Grid[28]
Base Case End-Gate	160,000 km
Use-Phase Sensitivity Analyses	Charging on European Grid with Lower than Average Carbon Intensity
	Charging on European Grid with Higher than Average Carbon Intensity
	Energy Delivered Over Maximum Service Life (Charging on Average EU27 Grid[28])

Fixed capacity (70.6 kWh) packs are assessed to ensure the study goals were met and the aforementioned discourse around pack mass and energy density was highlighted. Pack parameters were chosen as they are representative of pack sizes currently available in Class D EVs.[9-11] The functional units used to present LCIA results are summarised in Table 4.

Table 4: Functional Units Used to Present LCIA Results.

Life Cycle Stage	Results Chapters	Functional Unit
Manufacturing	4.1.1.	**One 70.6 kWh capacity battery pack.**
	4.1.2.	**One kilowatt hour (kWh) of battery pack storage capacity.**
	4.1.3.	
	4.2.1.	
	4.2.2.	
	4.2.3.	
	4.2.4.	
Use-Phase	4.3.	**One kilometre driven in a class D vehicle powered by a 70.6 kWh battery pack.**
	4.4.1	**One kilowatt hour (kWh) of energy delivered over the maximum service life.*** * It should be noted that the maximum service life refers to the specific EV application under study and does not consider potential for a second use-phase.[27]

The LCIA category selected for detailed investigation in this study is climate change as required by the ISO14067 standard.[4] This is a midpoint indicator which focuses on a single environmental problem. Climate change is an essential consideration for Cobalt Institute and their members, particularly in the context of the recently enforced European battery regulations.[19]

Manufacturing Results

LCIA results for the manufacturing stage are presented at the pack level in Figure 1. The total climate change impact results for manufacturing fixed capacity packs were found to be similar for all chemistries in the base case scenario (within 10% uncertainty). Cell manufacturing electricity is the largest contributor for LFP making up 43% of the total climate change impact. This area is the second largest contributor for the nickel-based chemistries making up 33% of the total climate change impact for both NMC and NCA. The Jiangsu grid (CN-ECGC) modelled sources around 60% of its power from hard coal combustion resulting in a large climate change impact contribution from this area.

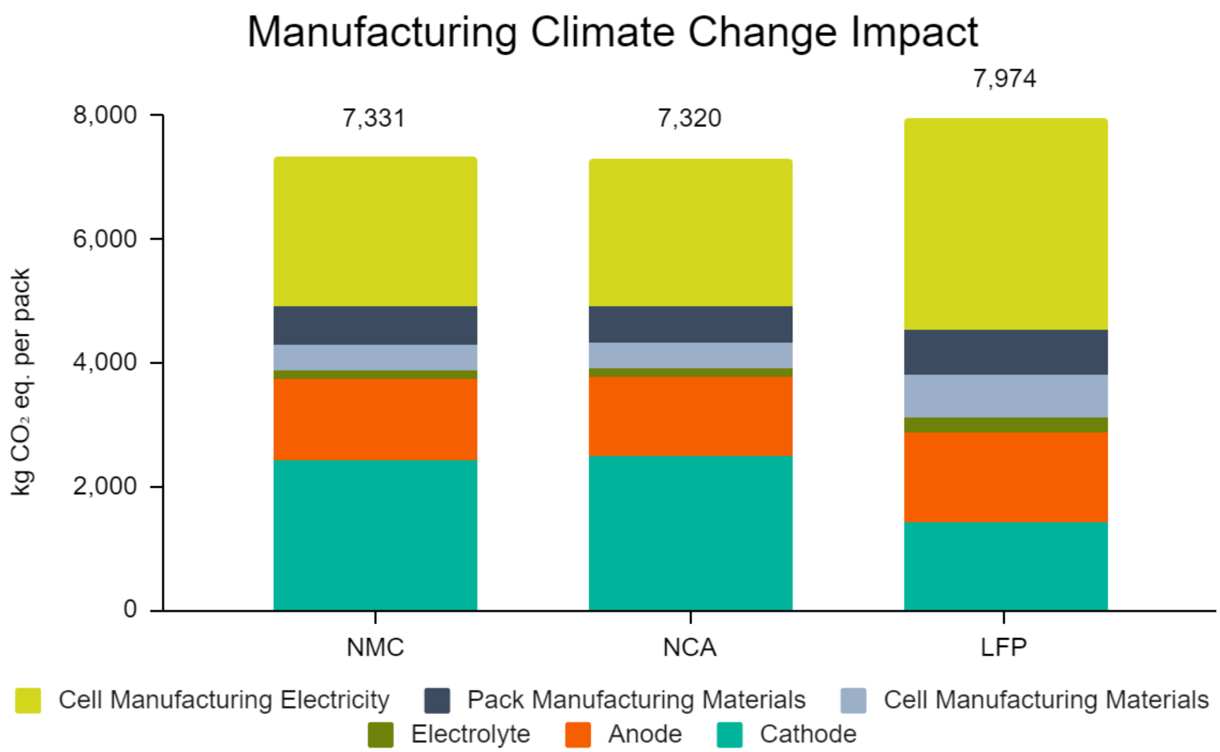

Figure 1: Summary of Manufacturing Climate Change Impacts at the Pack Level.

Cathode production is the largest contributor for NMC and NCA making up 33% and 34% of the total climate change impact, respectively. Anode production is the second largest contributing area for LFP and the third largest for NMC and NCA. It contributes 18% of the total climate change impact for NMC and LFP and 17% for NCA.

A summary of the manufacturing LCIA results per kWh pack capacity are presented in Figure 2 for the low impact, base case, and high impact scenarios. The calculated energy densities are 0.214 kWh per kg for NMC, 0.217 kWh per kg for NCA, and 0.154 kWh per kg for LFP.[12-14]

Contribution analyses per kWh pack capacity show that cell manufacturing electricity, CAM, and AAM are the top three contributors for all chemistries. Individual CAM contribution analyses highlight that nickel is a hotspot in both nickel-based chemistries contributing around 33% to the total CAM impact and around 10% to the total per kWh impact. This contribution is largely due to the mass required to achieve the NMC 8:1:1 and NCA 8:1.5:0.5 ratios.

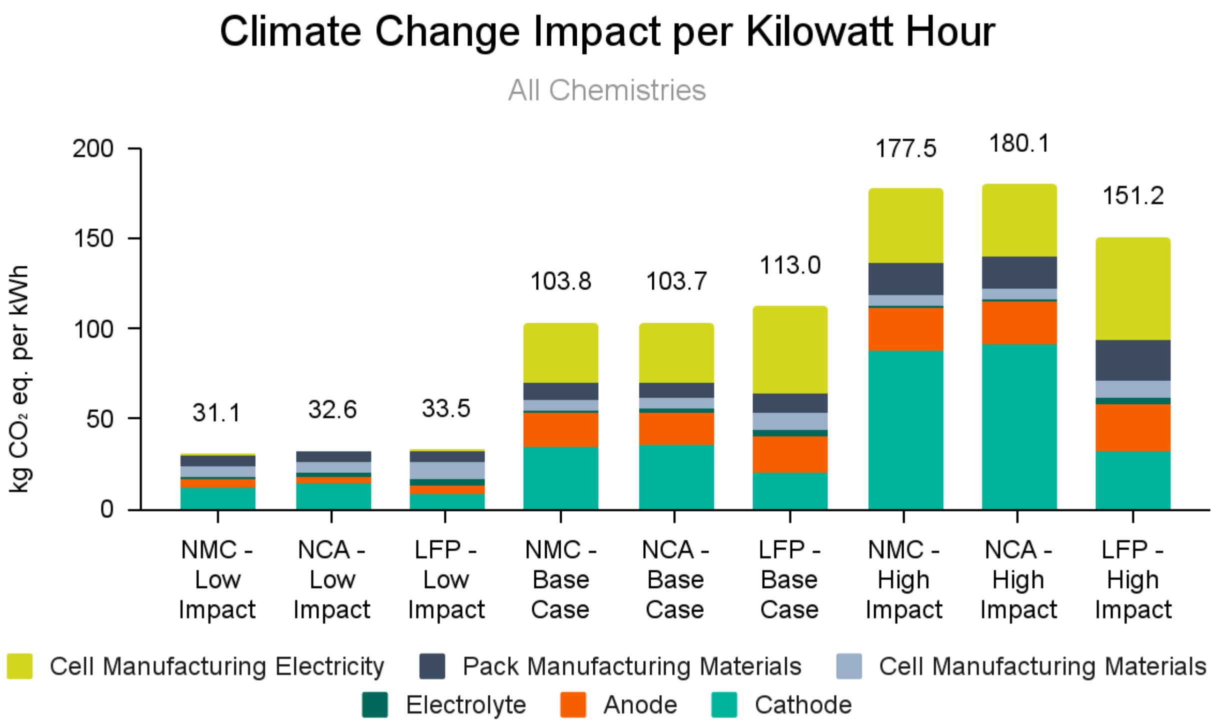

Figure 2: Manufacturing Climate Change Impact Results Summary.

Lithium carbonate is the most significant hotspot in LFP CAM making up around 40% of the CAM impact, and lithium hydroxide monohydrate is the third most significant contributor to the CAM impact in NMC and NCA after electricity. These lithium hotspots are largely driven by the embodied impact of lithium sourced from Australian spodumene that is refined in China.

AAM is a hotspot in all chemistries; it contributes around 15% to the total climate change impact for all chemistries. In the base case scenario, AAM is modelled as a combination of 60% anode-grade natural graphite produced in Heilongjiang, China, and 40% anode-grade synthetic graphite produced in Inner Mongolia, China. The embodied impact of the synthetic graphite is around 70% higher than that of the natural graphite meaning it is the largest single contributor to anode production.

The main drivers of differences between the low impact / base case / high impact scenarios are intrinsically linked to the climate change hotspots with sources of cell manufacturing electricity, nickel, lithium, and graphite being accountable for the majority of the variance. Variability in the embodied impact of key raw materials such as nickel, cobalt, lithium, graphite and aluminium highlights the dependence of manufacturing climate change impacts on supply chain choices. Details of the supply chains investigated can be found section 3.1.

A range of additional sensitivity analyses were performed on the manufacturing results to:

- isolate the influence of low and high impact cobalt supply chains;
- consider manufacturing in the Southeastern USA;
- and address the uncertainty of the cell manufacturing electricity data.

A summary of the sensitivity results is presented in Table 5.

Table 5: Summary of Manufacturing Sensitivity Results.

Cobalt Supply Chains			**Units**
	Low Impact Co Supply Chain	High Impact Co Supply Chain	kg CO_2 eq. per kWh Pack Capacity
NMC	103.0	104.9	
NCA	102.2	105.4	
Southeastern USA Manufacturing			
NMC	86.6		
NCA	86.3		
LFP	92.6		
Cell Manufacturing Electricity Consumption			
	Minus 13 kWh	Plus 13 kWh	
NMC	96.9	110.8	
NCA	96.8	110.5	
LFP	103.1	122.8	

Isolating the influence of high and low impact cobalt supply chains indicated that cobalt is not a hotspot in either NMC nor NCA when other base case supply chains are assumed, even when assuming a high impact Indonesian HPAL source.

Pack manufacturing (including production of pCAM and CAM) was also modelled on the Southeastern USA grid (US-SERC). As previously highlighted, the Jiangsu grid (CN-ECGC) modelled in the base case sources around 60% of its power from hard coal, but the dominant source of energy in the US-SERC mix is natural gas combustion (~45%). This results in an embodied impact around 45% lower than the Jiangsu grid of the base case scenario. Consequently, the contribution of cell manufacturing electricity decreases by 17.2 kg CO_2 eq. for NMC, 17.4 kg CO_2 eq. for NCA, and 20.3 kg CO_2 eq. for LFP.

Lifetime Climate Change Impact Results (Defined Service Life)

A summary of the lifetime climate change impact results are presented in Figure 3. Lifetime emissions for packs of a fixed 70.6 kWh capacity are similar for all three chemistries. Lifetime emissions vary between 58–62 g CO_2 eq. per km for the low impact grid scenario, 87–92 g CO_2 eq. per km for the average EU grid scenario, and 213–221 g CO_2 eq. per km for the high impact grid scenario.

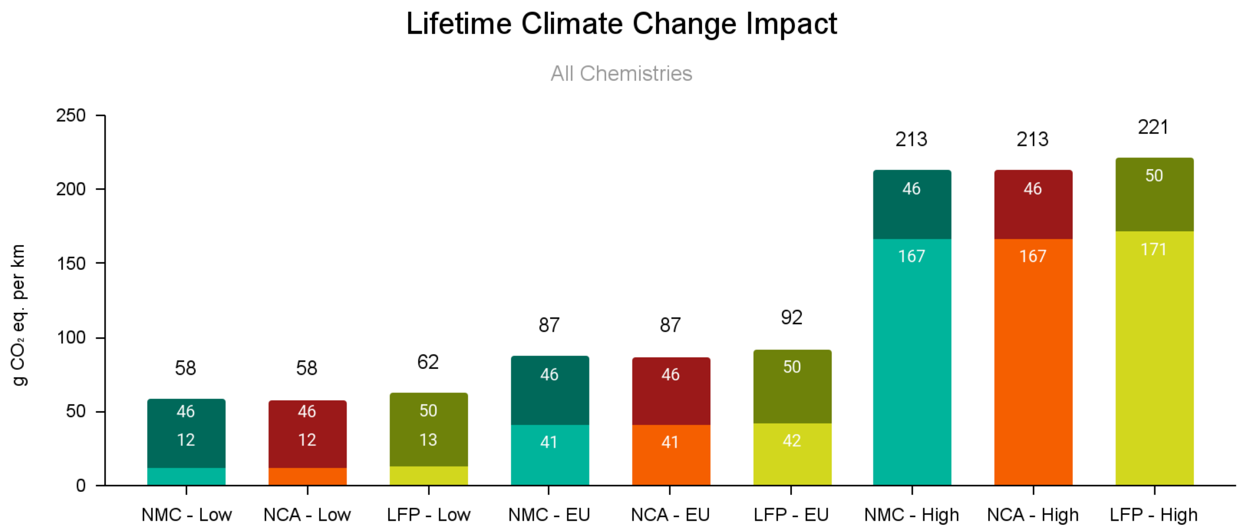

Figure 3: Lifetime Climate Change Impact Results Summary.

Minor differences can be seen between the chemistries with LFP pack manufacturing and use-phase typically contributing slightly more than NMC / NCA. This trend is seen because the overall impact of manufacturing a fixed capacity LFP pack is slightly more than NMC / NCA (see section 4.1.1) and the energy density is lower (see section 2.3.1). The latter results in a higher pack mass and lower efficiency (see section 3.2).

Significant differences in the relative contributions from each life stage are seen when assessing use on different electricity mixes. When charging occurs on a lower than average impact European grid, manufacturing contributes around 80% to the total lifetime emissions. When charging occurs on the average European grid, manufacturing contributes around 50% to the total lifetime emissions. When charging occurs on a higher than average impact European grid, manufacturing contributes around 20% to the total lifetime emissions.

Differences in the relative contributions from each life stage highlights that the effectiveness of mitigation strategies can change depending on use location. When considering base case manufacturing supply chains and a use location where the carbon intensity of the grid is above the European average, the results indicate that grid decarbonisation in the use location may be more effective at reducing lifetime emissions. In use locations where the grid intensity is similar to or less than the European average, mitigation strategies in the manufacturing stage may be more effective at reducing overall lifetime emissions.

Whilst the end-gate across the different use scenarios is fixed at 160,000 kilometres, differing energy densities, ranges, and efficiencies result in a slightly higher cycle number for LFP at this end-gate than NMC / NCA. However, as LFP degradation is typically lower than for nickel-based chemistries, LFP shows a lower utilisation percentage compared to NMC and NCA (14% vs. 28%; see Table 15). Whilst these additional results do not directly influence the lifetime climate change results of this LCA study, they should be considered alongside the LCIA results.

Readers should be aware that the results of the defined lifetime use-phase analyses represent the lifetime climate change impacts for a specific EV application with a fixed distance parameter. For all chemistries, this means the end-gate occurs before full utilisation is achieved (i.e. before the batteries reach 80% SoH). In a different application where the battery packs could be cycled until their true EoL, such as a stationary ESS, the different degradation rates and the lack of influence from efficiency / pack mass may generate significantly different climate change impact results.

In the context of the specific EV use-phase presented, these results highlight the importance of vehicle ecodesign and longevity. EV design strategy that considers required range and pack size, as well as prolonging the longevity of EV lifetime outside of the battery pack, could allow production of battery packs that use critical raw materials (e.g. cobalt, natural graphite, phosphorus, and lithium)[29] more efficiently. In theory this could allow all chemistries, particularly those with a longer maximum service life, to be utilised to a higher extent than in current standard EV applications assuming no second use-phase.[27]

Energy Delivered over Maximum Service Life

To assess the potential difference in longevity between the chemistries, a sensitivity analysis was performed to assess the lifetime climate change impact normalised to one kWh energy delivered over the maximum service life. Maximum service life parameters are presented in Table 16 (section 3.2.1) and were calculated assuming a cycle life of 1,500 for the nickel-based chemistries and 3,000 for LFP (to 80% state-of-health; SoH). Cycle lives are based on an 80% depth-of-discharge (DoD; i.e. how much energy has been drawn from a battery, expressed as a percentage of the battery's total capacity) per cycle. It should be noted that battery packs in an EV application will likely be cycled under much more aggressive conditions, potentially in a lower service life than laboratory estimates and therefore lower maximum service lives than calculated. The scenario assumes base case manufacturing routes and use on the average European grid.[28]

It is noted that EV batteries of all chemistries are underutilised with the life of the vehicle generally being the limiting factor, particularly when assuming usage of 20,000 km per year. When decoupling the battery pack life entirely from the vehicle life, results show that the lifetime climate change impact could be around 12% lower for LFP compared to nickel-based chemistries when the functional unit is one kWh of energy delivered over the maximum service life. It must be noted that this would result in an unrealistic vehicle life of 56 years.

The Product Environmental Footprint Category Rules (PEFCR) for High Specific Energy Rechargeable Batteries for Mobile Applications[27] assumes 20,000 km per year for light duty vehicles as standard, for which vehicle warranties in general do not exceed 8 years.[30] This makes it clear that appropriate battery sizing, chemistry longevity, and more holistic ecodesign will need to be applied to EVs as a whole in order to reap the benefits of long lasting batteries.

Data Quality

The primary limitation to this study is the LCI data uncertainty. As this is a hypothetical manufacturing and use scenario, the LCIs and use-phase parameters were developed by Minviro from a range of sources.[12-14] The data chosen was deemed the best publicly available at the time of LCI collection. Where possible, this uncertainty has been addressed by performing sensitivity analyses such as modelling high and low impact production routes and electricity consumption (see section 4.2). Sourcing of higher quality primary data - particularly for cell manufacturing electricity - would improve the quality of this study and reduce uncertainty within the results.

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List of Acronyms

Acronym	Meaning
AAM	Anode Active Material
BMS	Battery Management System
CAM	Cathode active material
CO_2	Carbon dioxide
EU-EF	Environmental Footprint method
EIA	Environmental Impact Assessment
EPD	Environmental product declaration
EoL	End-of-life
eq.	Equivalent
ESS	Energy storage system
EV	Electric vehicle
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies model
GVW	Gross vehicle weight
GWP	Global warming potential
HPAL	High-pressure acid leach
ICE	Internal combustion engine
ILCD	International life cycle data
IPCC	Intergovernmental Panel on Climate Change
kg	Kilograms
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LFP	Lithium iron phosphate
Li-ion	Lithium-ion
NCA	Nickel Cobalt Aluminium
NMC	Nickel Manganese Cobalt
pCAM	Precursor cathode active material
PEF	Product Environmental Footprint
RKEF	Rotary kiln-electric furnace
SoH	State-of-health

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 on which little to no influence may be exercised by the commissioner of the LCA
Class D Vehicle	Large cars (e.g. BMW 3-Series, Volkswagen Passat), correspondent with ‘Upper Medium’ classification by the European Automobile Manufacturers’ Association (ACEA).[3]
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	A partial product supply chain, from the extraction of raw materials (cradle) up to the manufacturer’s “gate”. The distribution, storage, use stage and end of life stages of the supply chain are omitted
Cradle to grave	A product’s life cycle that includes raw material extraction, processing, distribution, storage, use, and disposal or recycling stages. All relevant inputs and outputs are considered for all of the stages of the life cycle
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
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 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 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 state goal
System Boundary	Set of criteria specifying which unit processes are part of a product system

1. Goal

1.1. Goal of the Study

Cobalt Institute commissioned life cycle assessment (LCA) practitioner Minviro Ltd. ('Minviro') in April 2023 to quantify and interpret the climate change impact of manufacturing and using lithium-ion (Li-ion) batteries of different chemistries. The batteries under study are designed to be similar to those currently found in upper medium size (class D) electric vehicles (EVs).[3] The chemistries studied are lithium nickel manganese cobalt (NMC; 8:1:1 Ni:Mn:Co), lithium nickel cobalt aluminium (NCA; 8:1.5:0.5 Ni:Co:Al), and lithium iron phosphate (LFP).

The goals of the study are to:

- Quantify, interpret, and compare the climate change impact and hot spots of manufacturing NMC, NCA, and LFP battery packs, similar to those found in current Class D EVs, using public data that is best representative of current battery manufacturing supply chains, processes, and locations.
- Perform sensitivity analysis on the climate change impacts of battery manufacturing to demonstrate the significance of low carbon raw material and energy sourcing.
- Extend the system boundary to include a European EV use-phase scenario allowing quantification, interpretation, and comparison of the lifetime climate change impacts of NMC, NCA, and LFP battery packs similar to those currently used in Class D EVs.
- Perform use-phase sensitivity analysis on different electricity mixes to demonstrate the significance of grid decarbonisation.

The intended application of this LCA is to encourage discourse among industry stakeholders on:

- low carbon material sourcing in Li-ion battery supply chains;
- efficient use of critical raw materials (e.g. cobalt, natural graphite, phosphorus, and lithium)[29] in lightweight high energy density batteries;
- and the importance of grid decarbonisation in both manufacturing and use locations.

The results will be used to communicate the importance of these areas going forward to members of Cobalt Institute and wider industry stakeholders.

Fixed capacity (70.6 kWh) packs are assessed to ensure the study goals are met and the aforementioned discourse around energy density is highlighted. Pack parameters were chosen as they are representative of pack capacities currently available in Class D EVs.[9-11]

This LCA represents battery manufacturing and use for a specific EV application with defined manufacturing and use assumptions (see Chapter 3). Readers should be aware that life cycle inventory (LCI; Appendix A) and life cycle impact assessment (LCIA) results may look significantly different for an alternative application (e.g. stationary energy storage systems; ESS).

As the goals of this study include assessment of lifetime emissions the system boundary has been extended to include a use-phase. Inclusion of this use-phase also allows investigation on the influence of energy density and pack mass on efficiency. The use-phase parameters of this study have been designed to help indicate lifetime emissions directly associated with the battery packs and do not consider impacts associated with vehicle production, assembly, and maintenance. Differences in vehicle efficiency associated with pack mass, and subsequently energy density, are considered.

This document is the LCA report for the LCA study performed for Cobalt Institute and has been prepared in accordance with the ISO-14067:2018[4] standard. This report constitutes a reference document and should be made available to any third party to whom the results are communicated.

This report has been critically reviewed by a panel of experts and may be used to communicate comparative assertions in the public domain. It is recognised that the data provided by this LCA 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-14040/14044/14067 standards.[1,2,4]

1.2. ISO-Compliant LCA Methodology

LCA is a method to assess the environmental impacts associated with all life stages of a product, process, or activity.[5] Importantly, LCA makes it possible to evaluate indirect impacts that occur in the development of a product or process system over its entire life cycle, providing information that otherwise may not be considered. The holistic approach generates results on how decisions made at one stage of the life cycle might have consequences elsewhere, ensuring that a balance of potential trade-offs can be made, and the shifting of the environmental burdens can be avoided.[6,7] It should be noted that LCA is a suitable method for determining potential impacts on a global scale and is a complementary approach to local impact assessments such as environmental impact assessments (EIAs).

This LCA study was conducted according to the requirements of the ISO-14067 standard. In accordance with this standard, LCA has four fundamental steps: (i) goal and scope definition, (ii) LCI analysis, (iii) LCIA, and (iv) interpretation (Figure 4).

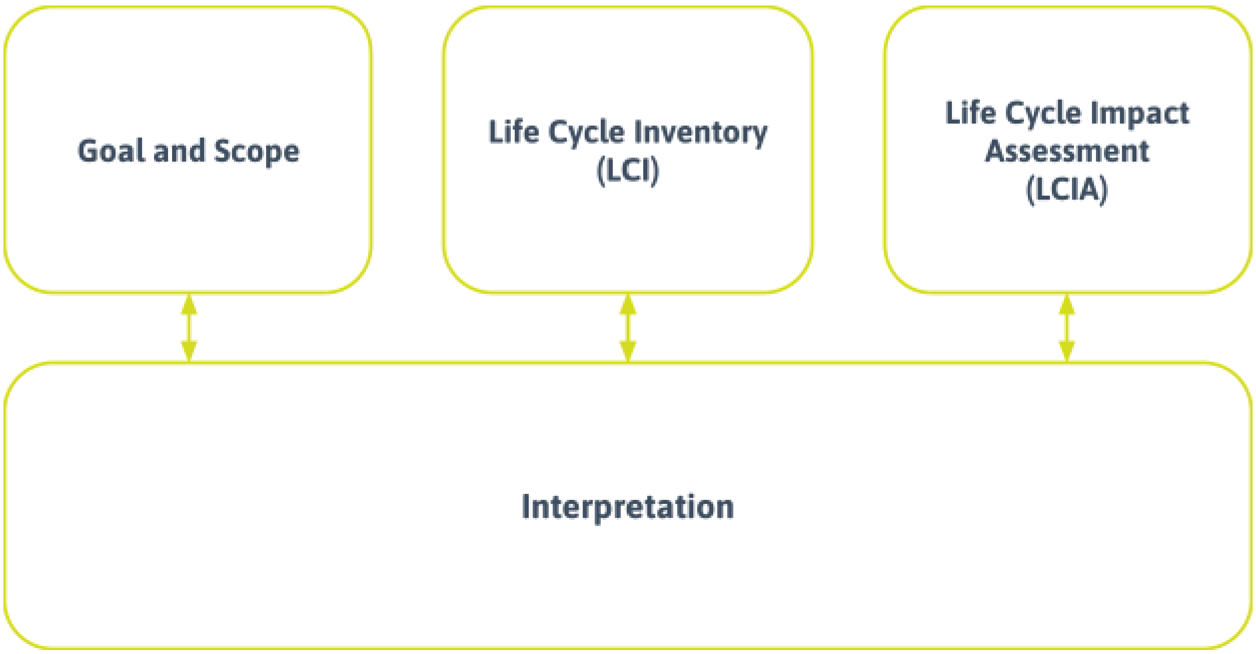

Figure 4: General Phases of a Life Cycle Assessment as Described by ISO-14067:2018.[1]

The goal and scope were 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.

2. Scope of Assessment

The following chapter describes the scope of the LCA study according to goals stated above. This includes a study description, battery functions, functional units, the system boundary, allocation procedures, cut-off criteria, LCIA methodology, and LCI analysis.

2.1. Study Description

This study assesses the climate change impacts and hotspots of manufacturing and using Li-ion batteries similar to those found in current class D EVs.[9-11] The chemistries assessed are NMC811, NCA, and LFP. Packs of a fixed capacity (70.6 kWh) are studied to ensure the study goals are met and the aforementioned discourse around pack mass and energy density is highlighted. Pack parameters were chosen as they are representative of pack sizes currently available in Class D EVs.[9-11] An overview of the study parameters is presented in Table 6.

The LCA is a cradle-to-gate study meaning the climate change impact has been assessed from the point of raw material extraction to a defined gate. The gate to assess the climate change impact of battery manufacturing has been set to production of a battery pack in the manufacturing facility. The gate to assess lifetime emissions has been set to 160,000 km travelled in a class D EV. A sensitivity analysis is performed for maximum service life in section 4.4.1.

The 'base case' manufacturing scenario has been developed to be representative of current Li-ion battery raw material supply chains and manufacturing parameters. In this scenario battery manufacturing occurs in Jiangsu Province, China. The electricity source is the Jiangsu Province grid. Details of representative raw material supply routes are presented in Chapter 3.1. A range of sensitivity analyses are performed on the manufacturing results to:

- assess the influence of low and high impact raw material and energy supply chains;
- isolate the influence of low and high impact cobalt supply chains;
- consider manufacturing in the Southeastern USA;
- and address the uncertainty of the cell manufacturing electricity data.

The 'base case' use-phase scenario has been developed to be representative of battery pack use in a class D EV charged in the European Union (EU); the EU27 average grid intensity is used.[28] Sensitivity analyses are performed to assess the influence of EV charging on alternative European electricity mixes with lower and higher carbon intensities than the average (see section 3.2). A sensitivity analysis is performed for maximum service life in section 4.4.1 with an alternative functional unit.

It should be noted that only the impact of battery manufacturing and use are accounted for, meaning impacts associated with vehicle production, assembly, and maintenance are excluded (see section 2.3). The influence of pack mass on vehicle efficiency is considered (see section 3.2). Best efforts have been made to ensure information and assumptions on battery performance represent uniform operating conditions but this cannot be guaranteed and assessing the particular influence of operating conditions on lifetime emissions is not a goal of this study.

Table 6: Study Parameter Overview.

Parameter	Description or Value
Battery Chemistries	Nickel Manganese Cobalt (NMC) 8:1:1 Ni:Co:Mn
	Nickel Cobalt Aluminium (NCA) 8:1.5:0.5 Ni:Co:Al
	Lithium iron phosphate (LFP)
Cell Type	Cylindrical 21700
Pack Capacity	70.6 kWh
Base Case Manufacturing Scenario	All Manufacturing in Jiangsu, China, using Industry Representative Raw Material Supply Chains
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Use-Phase Sensitivity Analyses	Charging on European Grid with Lower than Average Carbon Intensity
	Charging on European Grid with Higher than Average Carbon Intensity
	Energy Delivered Over Maximum Service Life (Charging on Average EU27 Grid[28])

2.2. Battery Descriptions and Functions

Li-ion batteries are a type of rechargeable battery that use the reversible reduction of Li-ions to store energy. The technology is becoming increasingly popular in automotive engineering as a way of replacing internal combustion engines (ICE). Demand for Li-ion batteries is predicted to reach 4,700 GWh by 2030, and with the majority of this demand required for mobility applications,[8] research and development in the sector is thriving and has led to the evolution of multiple Li-ion battery chemistries.

Chemistry variations in commercial scale Li-ion battery technologies generally relate to the composition of the positive electrode called the cathode. The cathode chemistries assessed in this study are NMC811 (8:1:1 Ni:Mn:Co), NCA (8:1.5:0.5 Ni:Co:Al), and LFP. These compositions have been chosen as they are all currently produced at a commercial scale and used to power class D EVs.[9-11]

The main differences between the chemistries relate to energy density (i.e. the amount of energy stored in a given system or region of space per unit volume) and/or degradation (the irreversible loss of the ability of a battery to store charge or energy). NMC and NCA chemistries have very similar energy densities which are greater than LFP, but degrade at a considerably quicker rate (see Tables 10 and 16). Energy densities were calculated using the LCI data sources (see section 2.7).[12-13] Average degradation rates (e.g. cycle life) are based on recommendation from industry experts at About:Energy. Readers should be aware that operating conditions can influence cycle life significantly but assessing the particular influence of operating conditions on lifetime emissions is not a goal of this study.

Despite the differences highlighted, all chemistries are capable of performing the same function in this specific EV application scenario (see below).

2.2.1. Functional Unit and Reference Flow

LCA uses a functional unit as a reference to evaluate the components within a single system or among multiple systems on a common basis. The **functional unit** is the quantitative reference used for all inventory calculations and impact evaluations.

In accordance with the goals of this study, the functional units for quantifying the climate change impacts of battery **manufacturing** are presented in Table 7.

Table 7: Functional Units Used to Present Manufacturing Stage Climate Change Impact.

Results Chapters	Functional Unit
4.1.1.	**One 70.6 kWh capacity battery pack.**
4.1.2.	**One kilowatt hour (kWh) of battery pack storage capacity.**
4.1.3.	
4.2.1.	
4.2.2.	
4.2.3.	
4.2.4.	

In accordance with the goals of this study, the functional unit for quantifying **lifetime climate change impacts** (e.g. manufacturing + use-phase emissions) is presented in Table 8.

Table 8: Functional Units Used to Present LCIA Results for Lifetime Climate Change Impact.

Results Chapters	Functional Unit
4.3.	**One kilometre driven in a class D vehicle powered by a 70.6 kWh battery pack.**
4.4.1	**One kilowatt hour (kWh) of energy delivered over the maximum service life.*** * It should be noted that the maximum service life refers to the specific EV application under study and does not consider potential for a second use-phase.[27]

The functional units chosen are specific to application in an EV. They are influenced by defined manufacturing and use parameters and assumptions specific to the application as outlined in Chapter 3. Alternative functional units and reference flows may be suitable for assessing battery manufacturing and use in different applications or under alternative application parameters.

2.3. System Boundary

This LCA is a cradle-to-gate study, meaning the batteries' climate change impacts have been assessed from the point of resource extraction (cradle) to an end-gate. The gate to assess the climate change impact of battery manufacturing has been set to production of a battery pack in the manufacturing facility. The end-gate to assess lifetime emissions has been set to 160,000 km (100,000 miles) travelled in a class D EV. In this hypothetical scenario, potential secondary use-phases (e.g. ESS) and end-of-life treatment (EoL; e.g. landfill versus recycling) are not defined and have been excluded from the system boundary.

As this is a hypothetical LCA scenario based on adaptation of public datasets,[12-14] some foreground LCI data have been omitted from the system boundary. This includes capital goods and infrastructure, emergency energy and materials, packaging materials, and foreground transport (see Table 9). Background data from ecoinvent may not apply the same exclusions. For further information on the influence of these exclusions, see the cut-off criteria described in section 2.5.

The system boundary for the LCA study is presented in Table 9 and Figure 5. Energy, material, and emissions flow summaries (grouped by area) for manufacturing of each chemistry are included in Appendix A.

Table 9: Inclusions and Omissions From the System Boundary of This LCA Study.

Included in System Boundary	Omitted from System Boundary
• Background production of all major raw materials and energy inputs required to produce NMC / NCA / LFP battery packs, including all upstream chains. • Electrode manufacturing including precursory cathode active material (pCAM), CAM, and anode active material (AAM) manufacturing. • Electrolyte production. • Cell assembly and finishing including separation, stacking and packing, vacuum drying, electrolyte filling, formation, ageing and drying. • Module and pack assembly including the battery management system (BMS), inverter, and pack casing. • Use of grid electricity for EV charging, accounting for cell degradation, charging efficiency, and round trip efficiency.	• Capital goods and infrastructure such as production of machinery and construction of buildings. • Employee amenities. • Production and use of emergency materials and energy such as fire water and emergency generator power. • Packaging materials and dunnage for raw materials, reagents and products. • Foreground transport of reagents and raw materials to manufacturing locations and transport of battery packs to market. • Vehicle production, assembly and maintenance. • Secondary use-phase applications and EoL treatment.

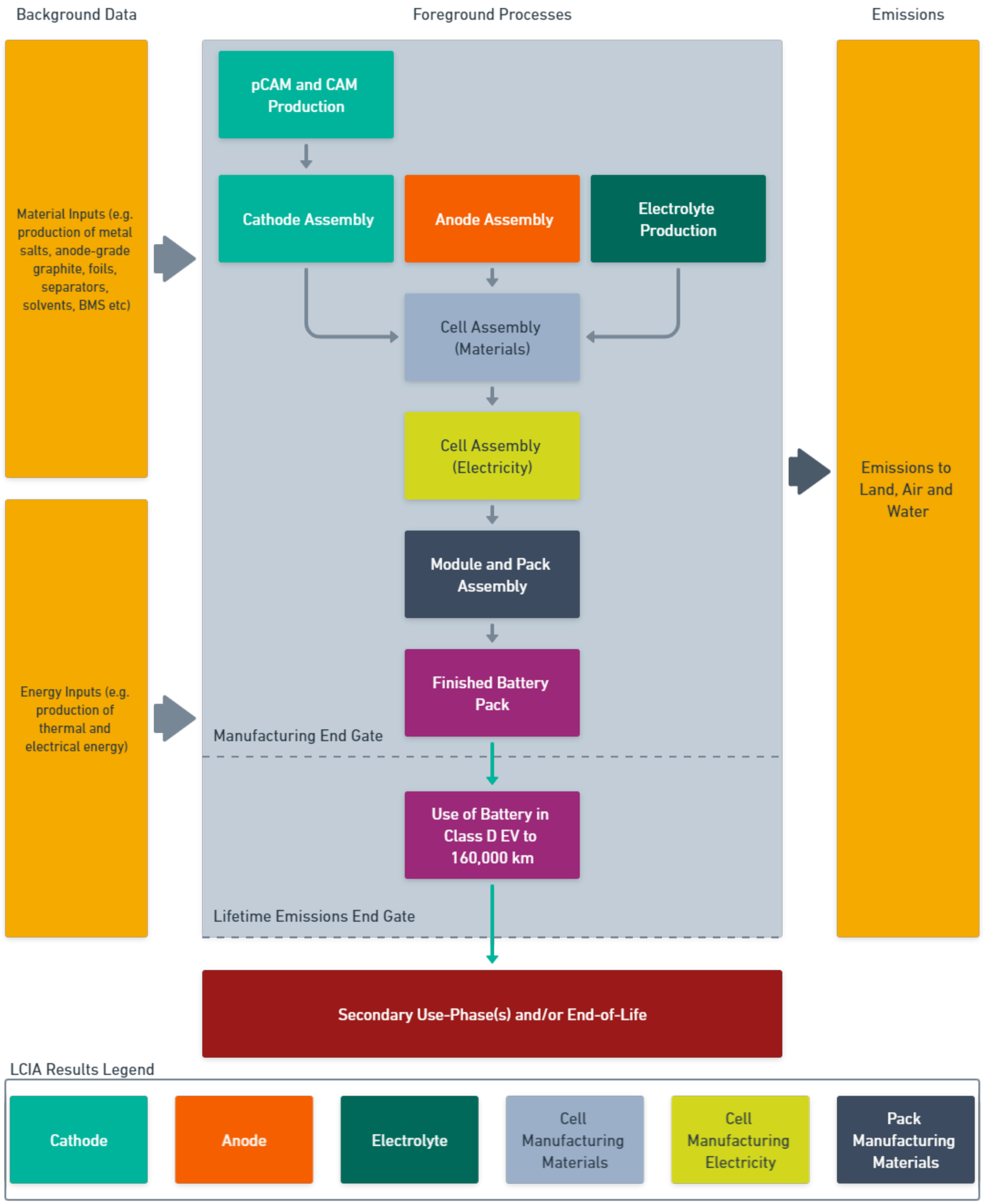

Figure 5: System Boundary Applied to this Life Cycle Assessment Study. The legend links unit processes to LCIA result groupings. Acronyms include pCAM: precursor cathode active material, CAM: cathode active material, BMS: battery management system.

2.3.1. System Boundary Description

This section describes the foreground unit processes presented in Figure 5, including production of battery cathodes, anodes, and electrolyte, assembly into cells and packs, and use in Class D EVs. Battery cell and pack parameters are presented in Table 10 for all chemistries. All manufacturing in the base case scenario occurs in Jiangsu, China.

Table 10: Battery Cell and Pack Parameters for all Chemistries.[9-13] SoH: State-of-health.

Parameter	NMC	NCA	LFP
Cell Specifications (21700)			
Mass (g)	84.3	83.4	71.4
Capacity (kWh)	0.0219	0.0220	0.0131
Specific Energy Density (kWh/kg)	0.2603	0.2634	0.1829
Cycle Life to 80% SoH (n)	1500	1500	3000
Pack Specifications			
Number of Cells	3219	3214	5409
Capacity (kWh)	70.6	70.6	70.6
Mass (kg)	330	326	460
Specific Energy Density (kWh/kg)	0.214	0.217	0.154

** Average degradation rates (e.g. cycle life) are based on recommendations from industry experts at About:Energy and account for an 80% depth-of-discharge (DoD) per cycle.*

Assumptions on raw material supply chains, energy sources, and use parameters are described in Chapter 3.

Precursor Production (pCAM / CAM / AAM)

NMC and NCA cathodes are produced in a similar way due to their similar chemical makeup. The required metal salts and reagents (e.g. nickel sulphate hexahydrate, cobalt sulphate heptahydrate, manganese sulphate monohydrate and/or aluminium sulphate monohydrate; see Appendix A) are mixed together to co-precipitate precursor cathode active material (pCAM). This precursor product is dried before being combined with lithium hydroxide monohydrate. The combined material is calcined to produce (Li)NMC / (Li)NCA cathode active material (CAM) powder.

The LFP cathode production process starts by processing iron sulphate and industrial grade phosphoric acid into iron phosphate pCAM using sodium hydroxide, thermal energy from natural gas, electricity, and water. In the base case scenario, phosphoric acid is produced using the 'wet-process' in which phosphate rock is ground and acidified with sulphuric acid. In the reaction, the tricalcium phosphate in the phosphate rock is converted to phosphoric acid and to the insoluble salt calcium sulphate ($CaSO_4$), also known as gypsum. Phosphoric acid produced using the 'thermal-process' is included in the high impact supply chain sensitivity analysis (see sections 3.1 and 4.2.1).

Iron phosphate pCAM is reacted with lithium carbonate, glucose, nitrogen, and deionised water to produce LFP CAM. Processing pCAM into CAM again requires thermal energy and electrical energy.

Anode active material (AAM) for all three chemistries is made from a mixture of anode-grade natural graphite and anode-grade synthetic graphite (see section 3.1). LFP chemistries typically require thicker anodes for the same cell capacity compared to nickel-based chemistries meaning a higher requirement of these materials for this chemistry.

In the base case scenario, all thermal energy is assumed to be sourced from natural gas and all electrical energy from the Jiangsu Province grid. Energy consumption for pCAM / CAM production is accounted for in the 'cathode' area when presenting LCIA results.

Electrode Assembly (Cathode / Anode)

Final electrode assembly requires mixing of CAM/AAM with binders (e.g. polyvinylidene fluoride and styrene-butadiene rubber) and solvents (e.g. N-methyl-2-pyrrolidone). The resulting compound is then pasted onto aluminium (cathode) or copper (anode) foil to form coated electrodes. The electrical energy required for this stage is accounted for in 'cell manufacturing electricity' when presenting LCIA results.

Electrolyte Production

Electrolyte composition for all chemistries is assumed to be a mixture of lithium hexafluorophosphate, ethylene carbonate, and dimethyl carbonate.

Cell Assembly (Materials and Electricity)

The coated electrodes are then dried, calendered, stacked, and packed into layers according to the particular design for the cell. Electricity consumption for these processes is accounted for in 'cell manufacturing electricity' when presenting LCIA results.

This study assumes all packs will be assembled from cylindrical 21700 cells. This assumption has been made to try and maintain fair comparisons between chemistries but may not be accurate to all real world manufacturers, with LFP often manufactured as pouch cells. It should be recognised that cell choice may influence the LCIA results. Additional cell materials required include separators, a range of plastics (polypropylene, polyethylene, and polyethylene terephthalate), and steel cans.

One of the last assembly steps is filling the cells with liquid electrolyte. This step is completed toward the end of the production process due to the flammable nature of the electrolyte. Filled cells are subjected to electrical formation (initial charging and discharging), degassing, and ageing to ensure performance. Again, electricity consumption for these processes is accounted for in 'cell manufacturing electricity' when presenting LCIA results.

Module and Pack Assembly

The final unit process of the manufacturing stage is assembling cells into battery packs. The materials required to assemble an operating battery pack include copper wiring, structural plastic, aluminium and steel, insulation and coolant for thermoregulation, and electrical battery management systems (BMS) including inverters. Pack assembly electricity is not accounted for due to lack of available data but is expected to fall within cut-off criteria (see section 2.5).

For the purposes of this study, it is assumed that all manufacturing processes occur in the same facility. It is recognised that in a more realistic scenario, it is likely that pCAM / CAM and AAM production would occur in a separate facility to cell and pack manufacturing and would not necessarily be under the direct control of the battery manufacturer. Furthermore, it should be noted that whilst the majority of Li-ion battery manufacturing does occur in China,[8] production of the chemistries studied does not necessarily occur in the same province. These assumptions have been made on the basis of data quality and do not inhibit the goals of the study.

Use-phase

As the goals of this study include assessment of lifetime emissions the system boundary has been extended to include a use-phase. The use scenario assesses use of NMC / NCA / LFP battery packs to power a class D EV 160,000 km (100,000 miles) in the EU. As foreground transport is excluded (see Table 9), transport of battery packs to vehicle manufacturing facilities is excluded.

Inclusion of this use-phase also allows investigation on the influence of energy density and pack mass on efficiency. The use-phase parameters of this study have been designed to help indicate lifetime emissions directly associated with the battery packs and do not consider impacts associated with vehicle production, assembly, and maintenance. Should the goals of this LCA be updated in the future to assess an entire vehicle, the excluded areas should be accounted for. The influence of pack mass on vehicle efficiency is considered.

Whilst the aim of the study relates to lifetime emissions directly associated with the battery packs and not the overall vehicle, chassis weight was considered when calculating efficiencies and other associated parameters (e.g. range; see section 3.2). To ensure fair comparison, the chassis weight is kept the same for all chemistries and all pack sizes investigated.

The 'base case' use scenario assumes charging on the EU27 average grid intensity.[28] Detailed use-phase parameters are presented in section 3.2.

2.4. Allocation

In LCA, it is critical to ensure that environmental impacts are divided among the different products of a multi-output system in a way that is scientifically valid and best practice. Following the guidance provided in ISO-14044 standard,[2] system expansion is the preferred approach when subdivision is not possible or still leads to multifunctionality. System expansion eliminates the co-products' impact by subtracting it from the overall impact of the multi-output system. The co-product's impact is calculated by assessing the impact of producing a functionally equivalent product produced by a mono-output process. Unfortunately this is not always suitable due to data quality, or because a mono-output process does not exist or may not produce a functionally equivalent product.

An alternative approach is to use allocation. Allocation refers to the process of distributing the environmental impacts of the multi-output system across the different products based on physical or non-physical relationships (i.e. mass or economics, respectively). Allocation by mass is generally preferred when the economic value per unit of output between co-products is similar. This is due to the fact that mass remains relatively constant over time, while market value is subject to market fluctuations.[7] As guidance, EN15804[15] defines 'small' as less than a 25% difference in value. It should be noted that any allocation can introduce uncertainty into the LCA results, as different allocation methods can yield varying outcomes.

In this LCA study, no system expansion or allocation is applied to battery manufacturing or use-phase as no co-products are produced. Background datasets on raw material production produced internally by Minviro follow the best practices outlined above (see section 3.1). Background data sourced from ecoinvent 3.9.1 follows the 'allocation, cut-off by classification' system model which categorises outputs as allocatable products, recyclable materials, or wastes. Allocation procedures for individual background datasets are detailed in ecoinvent 3.9.1 documentation.[16]

2.5. Cut-Off Criteria

Cut-off criteria are used in LCA to decide which inputs should be included in the assessment based on mass, energy, or environmental significance.[1] The cut-off criteria for this study is based on the latter; LCI exclusions are only applied if they are expected to individually contribute less than 1% to the overall climate change impact, and the sum of the exclusions is expected to total no more than 3% of the overall climate change impact.

As highlighted in section 2.3, capital goods and infrastructure, transport, and certain ancillary materials such as emergency energy/materials and packaging materials have not been included in the foreground LCI. Pack assembly electricity is also excluded. These exclusions are largely on the basis of data quality and availability, but it should be noted that when spread over the production capacity and operating life of a gigafactory, these areas are expected to have a very low contribution (< 1%) to the climate change impact.

It is possible that cut-off effects have been applied to the background flows from ecoinvent 3.9.1 due to missing flows in the background dataset.[16]

2.6. Selection of LCIA Methodology

The impact assessment methodology applied to this LCA is Environmental Footprint (EF v3.1).[17] The EF characterisation methodology was originally based on the International life cycle data (ILCD) system's recommended methods, but several methods have since been modified and updated by the European Commission as part of the ongoing development of the Product Environmental Footprint (PEF) initiative. EF 3.1 characterisation factors are considered to be the most robust and up-to-date available for the European context, are widely used and respected within the wider international LCA community. They are required for PEF studies and Environmental Product Declarations (EPDs) under ISO-14025:2006.[18]

2.6.1. Selection of the Climate Change Impact Category

The LCIA category selected for detailed investigation in this study is climate change as required by the ISO14067 standard.[4] This is a midpoint indicator which focuses on a single environmental problem. Climate change is an essential consideration for Cobalt Institute and their members, particularly in the context of the recently enforced European battery regulations.[19] These start to apply from February 2024 and state that all rechargeable batteries sold in the EU with a capacity > 2kWh must have a compulsory carbon footprint declaration.

Whilst the selection of this impact category satisfies the goal of the study, it should be noted that it results in limited consideration of environmental burden shifting and circularity benefits with respect to the other EF 3.1 impact categories. Furthermore, LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

Climate Change

Baseline model of 100 years based on Intergovernmental Panel on Climate Change (IPCC) 2021.[20]

Climate change can be defined as the change in global temperature caused by the greenhouse effect of "greenhouse gases" (GHGs) released by human activity. There is now scientific consensus that the increase in these emissions is having a noticeable effect on climate. Climate change is one of the major environmental effects of economic activity, and one of the most difficult to control because of its global scale.[20] The environmental profiles characterization model is based on factors developed by the United Nations' IPCC. Factors are expressed as

Global Warming Potential (GWP) over the time horizon of different years, the most common historically being 100 years, measured in the reference unit kg CO_2 eq.

The 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 LCA. The GHG Protocol defines scopes of emissions as:

Scope 1: Direct GHG emissions (e.g. from direct process emissions or combustion of carbon-based fuels).

Scope 2: Indirect GHG emissions from consumption of purchased energy (e.g. electricity, heat, or steam).

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 LCA, "upstream" scope 3 must be included.

2.7. Life Cycle Inventory (LCI) Analysis

2.7.1. Data Collection and Calculation

As this is a hypothetical manufacturing and use scenario, all foreground LCI were adapted by Minviro from publicly available datasets.[12-14] LCI flows and LCIA results are grouped into cell components and life cycle stages based upon the system boundary described in section 2.3 and depicted in Figure 5. Background data are sourced from both the ecoinvent 3.9.1 database, released in 2022, and Minviro's internal database.[16] The consistency and cohesion of these datasets increase the credibility and acceptance of the LCA. The baseline of the ecoinvent database is LCI datasets that consider human activities and their interactions with the environment. It must be noted that although ecoinvent's database is extensive, it is critical to understand the uncertainty, technological and geographical relevance of the data points.[21]

Assumptions and limitations for this study are discussed in Chapter 3. An energy, material, and emissions flow summary for each chemistry is included in Appendix A.

2.7.2. Data Quality Review

The key data criteria used to evaluate the quality of the LCI used for this LCA study were:

- **Technological, time, and geographical representativeness**: data is representative if it matches geographical, temporal, and technological aspects of the goal and scope of the study. By utilising representative data for all foreground processes, the study can be made as representative as possible. When primary data are not available, best-available proxy data is used, ideally from databases or academic LCA literature.

- **Completeness**: a dataset is judged based on the completeness of inputs and outputs per unit processes and the completeness of the unit processes. The goal is to capture all relevant data in terms of unit processes.

- **Precision**: measured primary data is of the highest precision, followed by calculated data, data from the literature, and estimated data. It must be noted that measured data can be precise but inaccurate. Accuracy can be obtained by cross-validation of measured data.

- **Methodological appropriateness and consistency**: data is considered appropriate and consistent if the differences between data reflect actual differences between distinct product systems and are not due to inconsistencies in data collection or modelling.

Table 11 presents the grading system of data quality indicators.[22] An evaluation of the data quality for this LCA can be found in section 5.1.

Table 11: Grading Guidelines for Data Quality Assessment as Environmental Footprint 2.0 Pedigree Matrix[22] (PEF = Product Environmental Footprint).

Data Quality Indicator	Very Poor	Poor	Fair	Good	Very Good
Technological Representativeness	Old to dissimilar technology used	Technology dissimilar to what is used	Generic technology average	From technology specific to the application	All technology aspects of data have been modelled
Time Representativeness	The time period for which the dataset is valid is more than 8 years old	The time period for which the dataset is valid is less than 8 years old	The time period for which the dataset is valid is less than 6 years old	The time period for which the dataset is valid is less than 4 years old	The time period for which the dataset is valid is less than 2 years old
Geographical Representatives	Data represented is from a distinctly dissimilar region of project location	Similar regions are represented in data	Global average is represented in data	Country of interest is represented in the data	Region of interest is fully represented in data
Completeness	Representativeness unknown or data from a small number of sites and from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations
Precision	Rough estimate with known deficits	Estimates based on calculations not checked by the reviewer	Estimates based on expert judgement	Estimates based on measured and prior values	Measured and verified values with <7% uncertainty
Methodological Appropriateness and Consistency	Attribution process-based approach and following none of the three method requirements of the PEF guide: dealing with multi functionality, end of life modelling, and system boundary	Attribution process-based approach and following one out of three method requirements of the PEF guide: dealing with multi functionality, end of life modelling, and system boundary	Attribution process based approach and following two out of three method requirements of the PEF guide: dealing with multi functionality, end of life modelling, and system boundary	Attribution process based approach and following three method requirements of the PEF guide: dealing with multi functionality, end of life modelling, and system boundary	Full compliance with all requirements of the PEF guide

3. Assumptions and Limitations

3.1. Manufacturing Assumptions

- The battery chemistries assessed are NMC (8:1:1 Ni:Co:Mn), NCA (8:1.5:0.5 Ni:Co:Al), and LFP. It is assumed that the compositional differences apply to the cathode only. All chemistries are modelled using graphite anodes and an electrolyte containing lithium hexafluorophosphate, ethylene carbonate, and dimethyl carbonate (see Appendix A).

- Packs of a fixed 70.6 kWh capacity are assessed. Pack parameters were chosen to be representative of pack sizes currently available in Class D EVs.[9-11]

- As this is a hypothetical manufacturing and use scenario, it is assumed that all manufacturing, inclusive of pCAM / CAM and AAM production, occurs in the same location in Jiangsu Province. This province has been chosen based on the large capacity for battery manufacturing in this area.[23] It is recognised that different production stages can often occur in separate facilities and would not necessarily all be under the direct control of the battery manufacturer. Furthermore, it should be noted that production volumes of different battery chemistries and cell types may vary according to geography. These assumptions have been made on the basis of data quality and availability and do not inhibit the goals of the study.

- Sodium sulphate is often produced as either a waste or saleable co-product in the production of NMC / NCA pCAM. In the data source used, all materials and energy consumptions for the production of sodium sulphate are ascribed to the pCAM on the premise of this being a non-saleable waste (i.e. non-allocatable).[12]

- Cell manufacturing electricity is taken from a publicly available data source and is based on a total of 37.43 ± 7.59 MJ per kg.[14] This is converted to kWh in the LCI assuming 3.6 MJ per kWh. Due to the uncertainty, a sensitivity analysis is performed on lower and higher cell manufacturing electricity consumption (see section 4.2.4).

- The base case scenario raw material supply chain assumptions have been developed to best match current global average and/or industry representative production routes. A summary of supply routes and data sources are presented in Table 13. Industry average values for nickel, cobalt, and aluminium are used. Internal raw material production models based on publicly available LCI data have been developed by Minviro for manganese, lithium chemicals, and graphite supply chains in the base case scenario.

- The high and low impact scenario raw material supply chains have been developed to demonstrate the influence of low carbon raw material sourcing on battery manufacturing emissions. The production routes modelled for these scenarios are presented in Table 14 and have been curated to represent a realistic range of raw material sourcing options. Supply routes chosen are based on industrial scale processes. Whilst it may be possible to produce higher and lower impact materials at the laboratory scale or through recycling processes, these have been excluded as are unlikely to meet battery material demand within the next decade.[8] Unless specified in Table 14, other material supply chains remain the same as the base case scenario (see Appendix A).

- Battery manufacturing LCIs have been adapted by Minviro from a range of publicly available sources.[12-14] LCI pertaining to cylindrical 21700 cells are used for all chemistries to ensure consistency and simplicity. Whilst this assumption does not inhibit the goal of the study, it should be noted that other cell types are available (e.g. pouch and prismatic) and may be used preferentially to cylindrical calls based on chemistry and application.

- Energy sources used for manufacturing scenarios are summarised in Table 12.

Table 12: Summary of Manufacturing Stage Energy Source Assumptions.

Scenario	Thermal Energy	Electrical Energy*	Dominant Energy Source for Electrical Energy
Base Case	Natural Gas (heat production only).	Market for medium voltage electricity in the east-central region of China (ECGC).**	Combustion of hard coal makes up around 60% of the high voltage electricity supply.
Low Impact	Biomass (woodchips; heat and power cogeneration).	Market for medium voltage electricity in Norway (NO).	Hydropower from reservoirs in alpine regions makes up around 85% of the high voltage electricity supply.
High Impact	Hard Coal (heat generation only).	Market for medium voltage electricity in the north-western region of China (NWG).	Combustion of hard coal makes up around 75% of the high voltage electricity supply.
Southeastern USA	Natural Gas (heat production only).	Market for medium voltage electricity in the Southeastern USA (US-SERC).	Combustion of natural gas makes up around 45% of the high voltage electricity supply.

** 'Market for' background electricity data includes transmission and distribution losses.*

*** The ECGC dataset includes Jiangsu Province.*

Table 13: Base Case Raw Material Supply Routes and Data Sources.

Electrode	Material	Raw Material Extraction	Refining	Source
Cathode	Nickel	Industry Average Value		Nickel Institute
	Manganese	South Africa	Hunan, China	Internal Minviro Model
	Cobalt	Industry Average Value		Cobalt Institute
	Lithium Chemicals	42% Chilean Brine	Sichuan, China	Internal Minviro Models
		58% Australian Spodumene	Sichuan, China	
	Iron phosphate	Iron Sulphate From Steel Industry, China	China	ecoinvent 3.9.1
		Phosphoric Acid Refined From Fertiliser Grade Phosphoric Acid, USA		
	Aluminium	Industry Average Value		ecoinvent 3.9.1
Anode	Graphite	60% Natural Flake Graphite, Heilongjiang	Heilongjiang, China	Internal Minviro Models
		40% Synthetic Graphite With Petroleum Coke Feedstock, Inner Mongolia	Inner Mongolia, China	

Table 14: High and Low Impact Raw Material Supply Routes. Unless specified, other supply chain assumptions remain the same as the base case scenario.

Area	Component	Low Impact	High Impact
Cathode	Nickel	Pyrometallurgy, Canada	Rotary Kiln-Electric Furnace (RKEF), Indonesia
	Cobalt	Co-product from Ni-sulphide, Canada	High-Pressure Acid Leach (HPAL), Indonesia
	Lithium Chemicals	100% Brine, Chile	100% Spodumene, Australia
	Iron Phosphate	Iron Sulphate Produced in Europe	Iron Oxide Produced in the USA
		Phosphoric Acid Refined From Fertiliser Grade Phosphoric Acid, USA	Phosphoric Acid Produced in China via the Thermal-process
	Thermal Energy	Biomass (Woodchips)	Hard Coal
Anode	Graphite	100% Anode-Grade Natural Graphite (Thermal Purification), Canada	100% Anode-Grade Synthetic Graphite, Inner Mongolia
Assembly	Aluminium (pack materials)	Recycled Aluminium, Norway	Primary Produced Aluminium, China
	Manufacturing location	Northern European (Norway)	Northwestern China

3.2. Use-Phase Assumptions

- The use-phase parameters of this study have been designed to help indicate lifetime emissions directly associated with the battery packs and do not consider impacts associated with vehicle production, assembly, and maintenance. Impacts associated with vehicle disassembly, EoL treatments and secondary use-phases are also excluded. Should the goals of this LCA study be updated in the future to include assessment of the entire vehicle, the system boundary should be revised and these areas should be considered.
- Parameters for battery use are presented in Table 15. It is assumed that the batteries are no longer fit for purpose in a class D EV when they reach 80% capacity (state-of-health; SoH).
- The assumed number of cycles to reach 80% SoH is 1,500 for NMC / NCA and 3,000 for LFP. Calendar ageing – ageing processes that lead to a degradation of a battery cell independent of charge-discharge cycling – is not considered.
- Average degradation rates (e.g. cycle life) are based on recommendations from industry experts at About:Energy and account for an 80% DoD per cycle. In reality, it is likely that battery packs in an EV application will be cycled under much more aggressive conditions, resulting in a lower service life than laboratory estimates. Readers should be aware that operating conditions (e.g. temperature) can influence cycle life significantly but assessing the particular influence of operating conditions on lifetime emissions is not a goal of this study.
- The end-gate for all chemistries studied is 160,000 kilometres (100,000 miles). This is based on:
    - the Product Environmental Footprint Category Rules (PEFCR) for High Specific Energy Rechargeable Batteries for Mobile Applications[27] where the assumed usage for light duty vehicles is 20,000 km per year, with the total life defined by the vehicle warranty;
    - and United Nations Economic Commission for Europe (UNECE) Global Technical Regulations (GTR) No. 22 which requires a minimum warranty of 8 years.[30]
- The resulting use phase reflects the expected service life of the entire vehicle, not just the battery pack.[27]

  - It should be noted that 160,000 km is reached before 80% SoH for all chemistries in the use-phase calculations of this study. The end-gate was chosen to represent a realistic class D EV lifetime. A sensitivity analysis on climate change impact per kWh delivered over the maximum service life is presented in section 4.4.1.

- Charging efficiency represents any difference in the amount of energy taken from the grid and the amount of energy delivered to the battery. It is assumed to be 90%.

- Round trip efficiency represents any difference in the amount of energy taken from the battery and the amount of energy used to power movement of the vehicle. It is assumed to be 90%.

- Three use locations are assessed to highlight the importance of grid decarbonisation. The electricity sources assumed for the **use-phase** are:

  - **European average (EU27 average)**.[28]

  - **Low impact grid mix (French high voltage residual mix**; ecoinvent 3.9.1).

  - **High impact grid mix (Polish high voltage residual mix**; ecoinvent 3.9.1).

- Efficiencies (kWh/km) were calculated from real NMC/NCA/LFP EV data[9-11] but were not available individually for each chemistry at the 70.6 kWh pack size..

- Whilst the aim of the study relates to lifetime emissions directly associated with the battery packs and not the overall vehicle, chassis weight is considered when calculating efficiencies and other related parameters (e.g. range). To ensure fair comparison, the chassis weight is kept the same for all chemistries and all pack sizes investigated.

- Available data were taken and scaled linearly with pack mass considering gross vehicle weight according to the following equation:

$$Efficiency_N = Efficiency_O \times \frac{GVM_N}{GVM_O}$$

- Where:
  - $Efficiency_N$ is the new scaled efficiency (kWh/km)
  - $Efficiency_O$ is the original efficiency (kWh/km)
  - GVM_N is the new gross vehicle mass (kg)
  - GVM_O is the original gross vehicle mass (kg)

Table 15: Use-Phase Parameters.

Parameter	NMC	NCA	LFP
Capacity (kWh)	70.6	70.6	70.6
Mass (kg/pack)	330	326	460
Range (km)	452	454	440
Efficiency (kWh/km)	0.156	0.156	0.160
Loss Per Cycle (kWh)	0.009	0.009	0.005
Cycles Until EoL	1500	1500	3000
Cycles to 160,000 km at 80% DoD	386	386	391
Maximum Lifetime Throughput (kWh)	72,441	72,441	144,877
Actual Lifetime Throughput (kWh)	24,913	24,913	25,564
Battery Lifetime Utilisation (%)	28%	28%	14%
SoH at EoL (%)	80		
Charging Efficiency (%)	90		
Round Trip Efficiency (%)	90		
Actual Lifetime Distance (km)	160000		

** Range = Capacity / Efficiency*

*** Calculated using equations and references in text above.*

† Average degradation rates (e.g. cycle life) are based on recommendations from industry experts at About:Energy and account for 80% DoD per cycle.

3.2.1. Maximum Service Life Assumptions

- To assess differences in longevity between the chemistries, a sensitivity analysis has been performed to assess the lifetime climate change impact normalised to one kWh energy delivered over the maximum service life. Maximum service life parameters are presented in Table 16 and were calculated assuming a cycle life of 1,500 for the nickel-based chemistries and 3,000 for LFP (to 80% SoH). Cycle lives are based on an 80% DoD per cycle. It must be noted that according to the sources referenced in this report,[27,30] the resulting maximum service in years (i.e. 29 / 56 years) is wholly unrealistic considering warranted vehicle lifetimes (8 years).[30]

- As highlighted above, it is likely that battery packs in an EV application will be cycled under much more aggressive conditions, resulting in a lower service life than laboratory estimates and therefore lower maximum service lives than calculated below. With that in mind, a 50% decrease in maximum service life would still result in battery lives significantly longer than vehicle warranties for all chemistries.

Table 16: Maximum Service Life Parameters.

Results	NMC	NCA	LFP
Cycles to 80% SoH at 80% DoD (n)	1500	1500	3000
Total Energy Delivered Over Maximum Service Life (kWh)	72,441	72,441	144,877
Energy Usage from Grid Over Maximum Service Life (kWh)	89,433	89,433	178,860
Maximum Service Life (kms)*	572,810	574,610	1,115,288
Maximum Service Life (Years)**	29	29	56

** Calculated using use-phase parameters (e.g. efficiency) in Table 15 (section 3.2).*

*** Assuming 20,000 km per year as per the PEFCR guidelines.[27] It must be noted that the results for maximum service life in years are unrealistically long, especially when considering the 8 year warranty specified in the UNECE GTR No.22.[30]*

- The scenario assumed base case manufacturing routes and use on the average European Grid.[28]
- It should be noted that, whilst use of average degradation rates satisfies the goal of this study, the conditions under which batteries are cycled can greatly influence service life. In reality, battery packs are likely to be cycled under much more aggressive conditions, resulting in a lower maximum service life than estimated above in Table 16.

- The calculation method of climate change impact per kWh delivered over maximum service life is presented below:

$$\frac{((Energy_{Grid} \times Impact_{Grid}) + Impact_{Pack})}{Battery\ Throughput}$$

- Where:
  - $Energy_{Grid}$ is the energy required from grid over the maximum service life (kWh)
  - $Impact_{Grid}$ is the embodied climate change impact of grid electricity (kg CO_2 eq. per kWh)
  - $Impact_{Pack}$ is the climate change impact of pack manufacturing (kg CO_2 eq. per pack)
  - $Battery\ Throughput$ is the energy delivered to the wheels over the maximum service life (kWh)

3.3. Limitations

The primary limitation to this study is the uncertainty associated with the LCI data. As this is a hypothetical manufacturing and use scenario, the LCIs and use-phase parameters were developed by Minviro from a range of public sources.[12-14] The data chosen was deemed the best publicly available at the time of LCI collection and LCIA calculation. Where possible this uncertainty has been addressed by performing sensitivity analyses such as modelling high and low impact production routes and high and low cell manufacturing electricity consumption (see section 4.2).

Uncertainty is also present in the use-phase as there are a large number of variable parameters dependent on user behaviour and operating conditions (e.g. degradation rate). To address this uncertainty, both manufacturing and use-phase climate change impact results have been assigned a 10% uncertainty (see section 5.2).

Another limitation is that not all geographies are covered in the industry average LCAs produced on behalf of the Nickel and Cobalt Institutes. The geographical coverage of Nickel Institute LCA (reference year 2017) is: Africa (4%), Oceania (11%), Europe (11%), Americas (15%), and Asia (59%).[24] Due to lack of available data and/or changes in supply since the reference year, it should be noted that this excludes significant nickel production in Africa, China, and Indonesia which would likely increase the average.

The geographical coverage of Cobalt Institute LCA (reference year 2019) for cobalt mining is as follows: Americas (5%), Oceania (7%), Asia (9%), Africa (75%), and others (4%). The coverage for cobalt refining is: Oceania (3%), Africa (5%), Americas (5%), Europe (17%), and Asia (70%).[25] Again, due to lack of available data and/or changes in supply since the reference year, it should be noted that this excludes significant cobalt mining and refining in China and Indonesia which would likely increase the average. These limitations should be considered when interpreting LCIA results.

Secondary use applications and EoL treatment are excluded from the system boundary of this LCA study. Whilst this is acceptable for a cradle-to-gate LCA and does not inhibit the specific goals of this study, these exclusions inhibit interpretation of recyclability for different battery chemistries. Extending the system boundary to include these life cycle stages (i.e. a cradle-to-grave LCA) may change lifetime climate change results significantly.

The LCIA results for a defined service life represent the climate change impacts for a specific EV application scenario with a fixed distance parameter. For all chemistries, this means the end-gate occurs before full utilisation is achieved (i.e. before the batteries reach 80% SoH). In a different application where the battery packs could be cycled until their true EoL, such as a stationary ESS), the different degradation rates and the lack of influence from pack mass may generate significantly different lifetime climate change impact results than those presented here. A functional unit sensitivity analysis is presented in section 4.4.1 and assesses lifetime climate change impacts when normalised to one kWh energy delivered over the maximum service life.

LCA is a suitable method for determining potential impacts on a global scale and is a complementary approach to local impact assessments such as EIAs. In addition, whilst the selection of the climate change impact category satisfies the goal of the study, it does result in limited consideration of environmental burden shifting and circularity benefits with respect to the other EF impact categories. Furthermore, LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

4. Results

Results for the climate change impact category are presented below for both manufacturing and lifetime emissions. Manufacturing LCIA results are presented by area according to the system boundary presented in section 2.3. Section 2.2.1 outlines the functional units used.

Contribution analysis figures aggregate the contributors worth less than 1% of the total impact as 'other' for aesthetic purposes (i.e. cut-off criteria). These small contributors are still included in the overall result. To aid in identifying climate change hotspots, contribution analyses are also presented for the cathode.

Graphical depictions of LCIA results should not be used for implicit comparisons and conclusions outside of the goal and scope of this study. Furthermore, the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

4.1. Base Case Battery Manufacturing

4.1.1. Climate Change by Area (per pack)

The results per 70.6 kWh pack for all chemistries are presented in Figure 6. Using base case raw material supply chains and energy sources, the total climate change impact for manufacturing battery packs of a fixed 70.6 kWh capacity are:

- 7,331 kg CO_2 eq. per fixed 70.6 kWh capacity NMC pack.
- 7,320 kg CO_2 eq. per fixed 70.6 kWh capacity NCA pack.
- 7,974 kg CO_2 eq. per fixed 70.6 kWh capacity LFP pack.

Total climate change impacts for manufacturing fixed capacity packs are relatively close for all chemistries in the base case scenario (within 10% uncertainty). Cell manufacturing is the largest contributor for LFP at 3,439 kg CO_2 eq. per pack. It is the second largest contributor after cathode for NMC and NCA at 2,417 and 2,387 kg CO_2 eq. per pack, respectively.

For nickel-based chemistries, cathode production is the largest contributor. Cathode production contributes 2,431 kg CO_2 eq. per fixed capacity pack for NMC and 2,504 kg CO_2 eq. per fixed capacity pack for NCA. Cathode production is significantly lower for LFP at 1,422 kg CO_2 eq. per fixed capacity pack. CAM contribution analyses are presented in section 4.1.3.

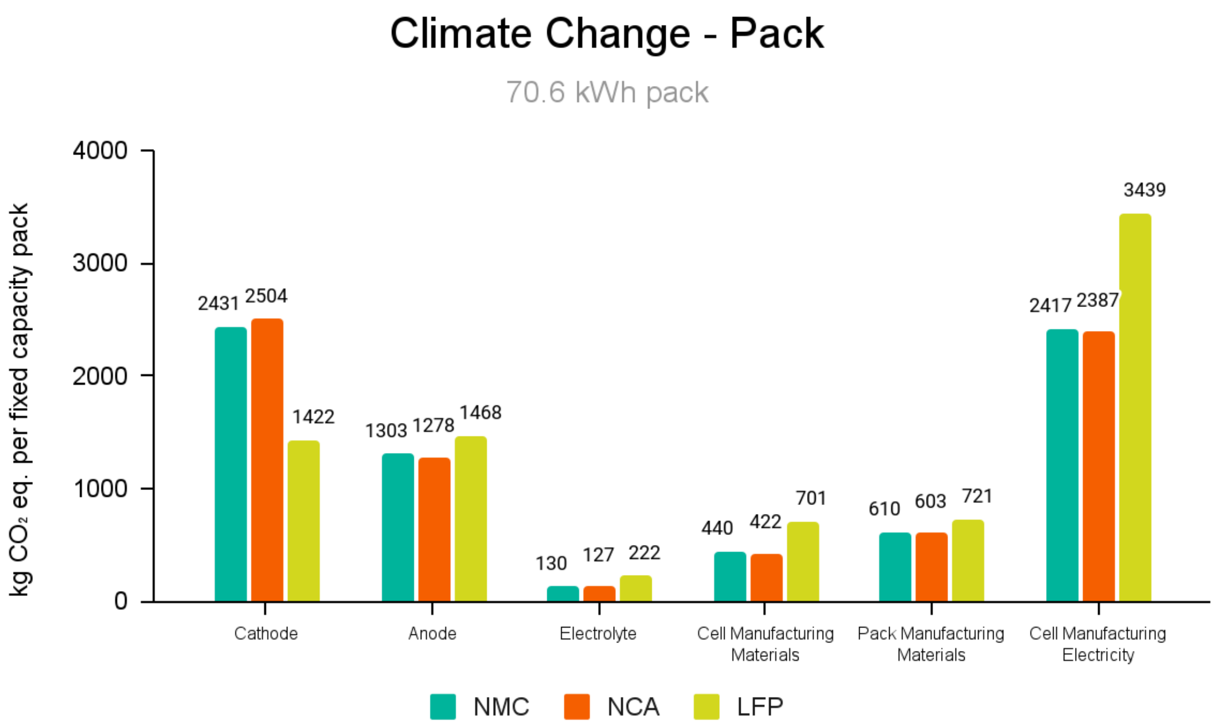

Figure 6: Base Case Climate Change Results for Manufacturing Packs of a Fixed 70.6 kWh Capacity.

Anode production is the second largest contributor for LFP contributing 1,468 kg CO_2 eq. per fixed capacity pack. Anode production contributes 1,303 and 1,278 kg CO_2 eq. per fixed capacity pack for NMC and NCA, respectively.

Contributions from electrolyte production, cell manufacturing materials, and pack manufacturing materials are higher for LFP than for the nickel-based chemistries as more cells are required to reach the fixed 70.6 kWh capacity due to LFP's lower energy density.

The results presented at the pack level highlight the question of efficient raw material use in lightweight high energy density batteries. Whilst the climate change contribution from the cathode is less impactful for LFP, its lower energy density results in higher contributions from electrolyte, and cell and pack manufacturing materials. Furthermore, as a higher volume of material needs to be processed to reach a set capacity compared to NMC / NCA, the contribution from cell manufacturing electricity is significantly higher.

4.1.2. Climate Change by Area (per kWh pack)

Climate change results for all chemistries are summarised in Figure 7.

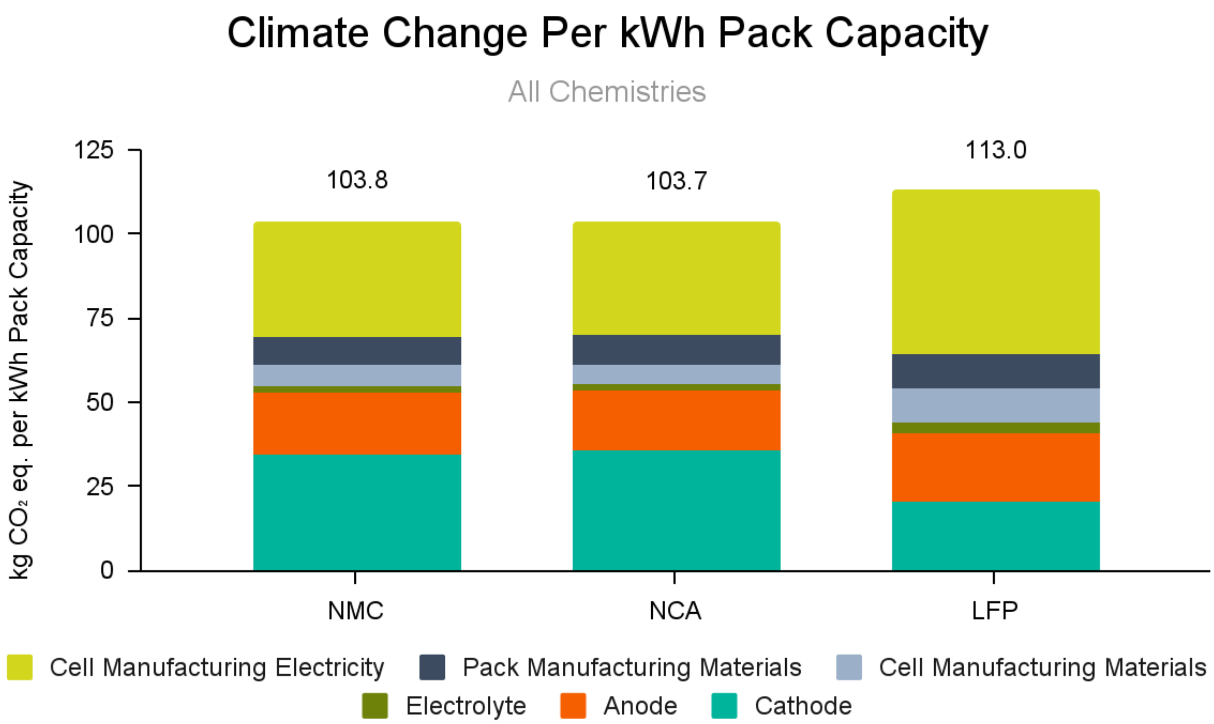

Figure 7: Summary of Manufacturing Climate Change Impact Per kWh Pack Capacity for All Chemistries.

NMC

The climate change impact for NMC assuming base case supply chains and energy sources is 103.8 kg CO_2 eq. per kWh NMC pack (Figure 8). The top three contributors are:

- 34.4 kg CO_2 eq. per kWh NMC pack (33%) associated with cathode production.
- 34.2 kg CO_2 eq. per kWh NMC pack (33%) associated with cell manufacturing electricity.
- 18.5 kg CO_2 eq. per kWh NMC pack (18%) associated with anode production.

The contribution of cathode production is highest at 34.4 kg CO_2 eq. per kWh for NMC. Nickel sulphate hexahydrate is the largest contributor to cathode production; CAM contribution analyses are presented in section 4.1.3.

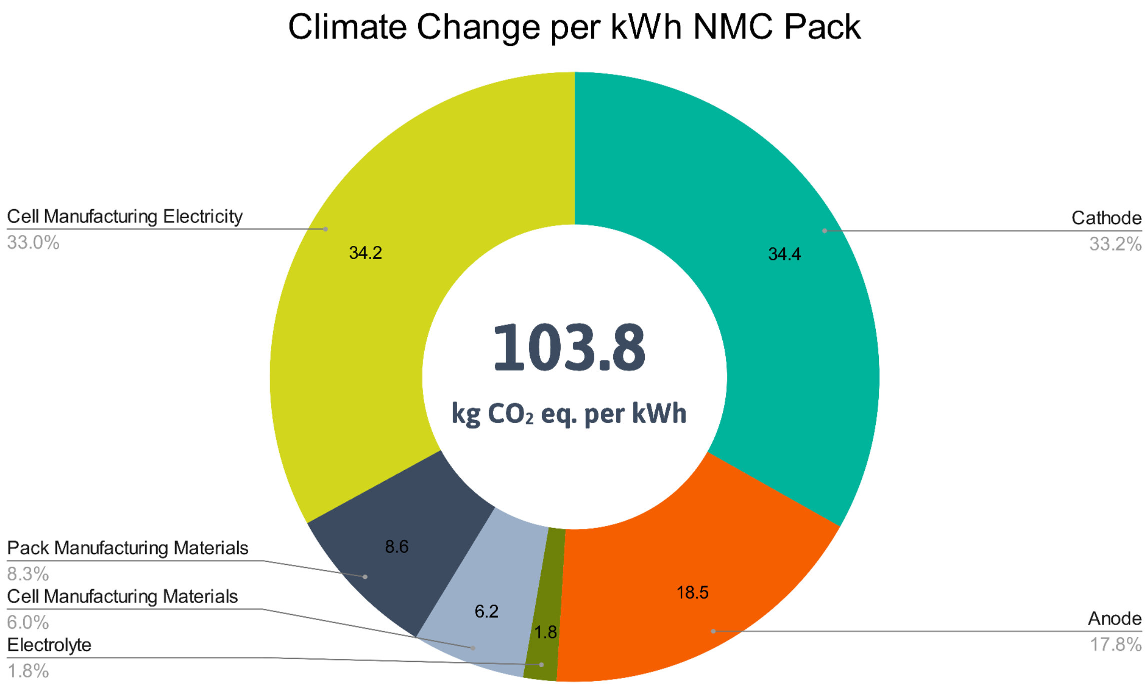

Figure 8: Base Case Manufacturing Climate Change Results per kWh NMC Pack Capacity.

Cell manufacturing electricity is the second largest contributor. The LCI source for this area calculates an average requirement of 37.43 ± 7.59 MJ per kg.[14] The Jiangsu grid (CN-ECGC) modelled sources around 60% of its power from hard coal combustion resulting in a relatively high embodied impact of 0.86 kg CO_2 eq. per kWh electricity. The combination of this embodied impact and the foreground electricity usage result in a large climate change impact contribution from this area.

The contribution of anode production is less than that of cathode production for two reasons: firstly, around 25% less AAM is needed per NMC cell than CAM (see material flow summary in Appendix A for mass inputs). Secondly, cathode metal salts go through extensive processing to produce pCAM and CAM as described in section 2.3; anode-grade graphite does not have to undergo these process steps.

In the base case scenario, AAM is modelled as a combination of 60% anode-grade natural graphite produced in Heilongjiang, China, and 40% anode-grade synthetic graphite produced in Inner Mongolia, China. The embodied impact of the synthetic graphite is around 70% higher than that of the natural graphite meaning it is the largest single contributor to anode production.

NCA

The climate change impact for NCA assuming base case supply chains and energy sources is lowest at 103.7 kg CO_2 eq. per kWh NCA pack (Figure 9). The top three contributors are:

- 35.5 kg CO_2 eq. per kWh NCA pack (34%) associated with cathode production.
- 33.8 kg CO_2 eq. per kWh NCA pack (33%) associated with cell manufacturing electricity.
- 18.1 kg CO_2 eq. per kWh NCA pack (17%) associated with anode production.

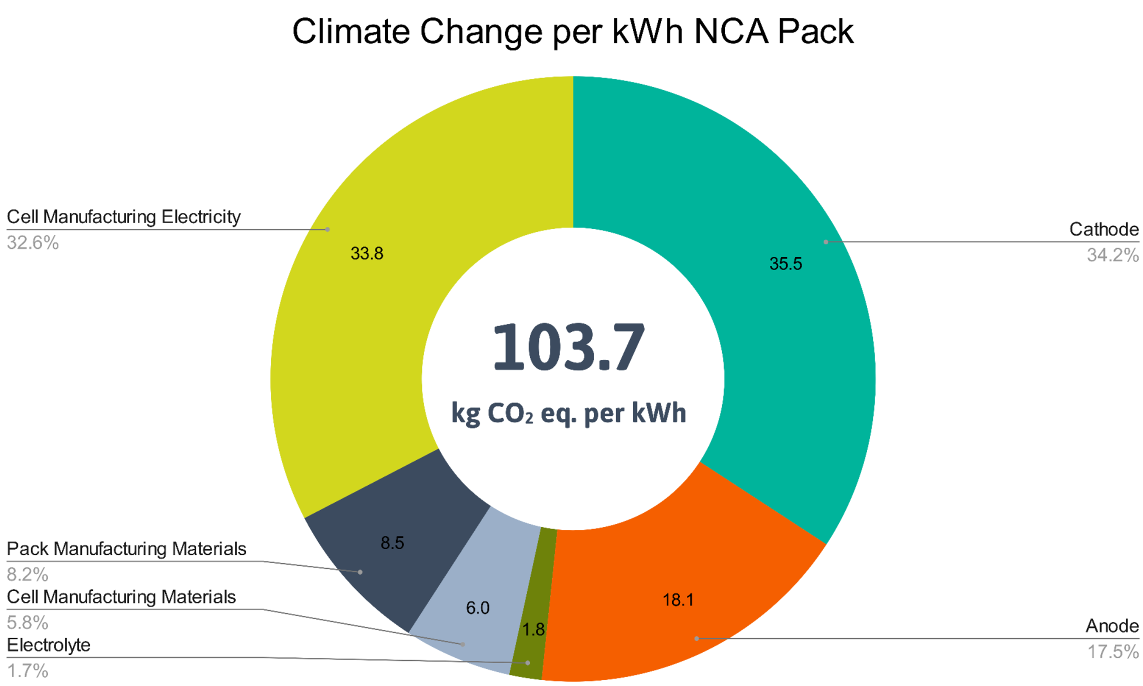

Figure 9: Base Case Manufacturing Climate Change Results per kWh NCA Pack Capacity.

The contribution of cathode production is 1.1 kg CO_2 eq. higher than NMC due to a slightly higher demand for nickel in this chemistry (2.31 vs. 2.28 kg nickel sulphate hexahydrate per kg pCAM). Contribution analyses are presented in section 4.1.3. The contribution from anode production is also lower than that of cathode production in this chemistry for the same reasons as previously described for NMC.

LFP

The climate change impact for LFP assuming base case supply chains and energy sources is the highest at 113.0 kg CO_2 eq. per kWh LFP pack (Figure 10). The top three contributors are:

- 48.7 kg CO_2 eq. per kWh LFP pack (43%) associated with cell manufacturing electricity.
- 20.8 kg CO_2 eq. per kWh LFP pack (18%) associated with anode production.
- 20.1 kg CO_2 eq. per kWh LFP pack (18%) associated with cathode production.

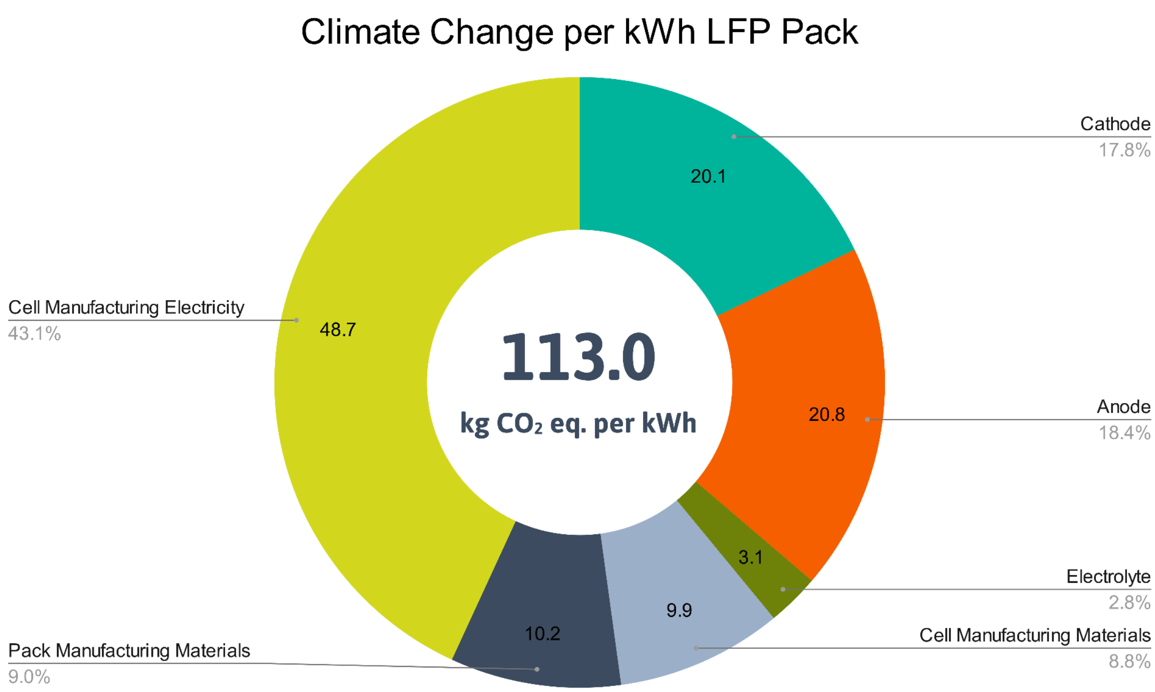

Figure 10: Base Case Manufacturing Climate Change Results per kWh LFP Pack Capacity.

The contribution from cathode production is 14.3 kg CO_2 eq. lower than NMC and 15.3 kg CO_2 eq. lower than NCA making it the lowest of all chemistries. Whilst slightly less CAM is required per LFP cell (0.024 kg) than per NMC cell (0.026 kg) or per NCA cell (0.028 kg), the majority of the impact difference is associated with the lower embodied impact of LFP cathode materials compared to NMC and NCA. Contribution analyses are presented in section 4.1.3.

Whilst the amount of AAM required per LFP cell is around 65% that required per NMC cell or NCA cell (see material flow summary in Appendix A for mass inputs), LFP cell capacity is significantly less due to its lower energy density. This means that the anode contribution is higher for LFP when normalised on the basis of capacity (i.e. to per kWh). As the AAM composition is the same for all chemistries, anode-grade synthetic graphite in AAM remains the largest contributor to anode production.

4.1.3. Contribution Analyses

Contribution analyses have been performed at the kWh pack level. It should be noted that CAM contribution analyses include the electricity required for production of pCAM and its transformation into CAM. Figures aggregate small contributors as 'other' for aesthetic purposes. Aggregation is set to < 1% for kWh pack analyses and < 5% for CAM analyses. These small contributors are still included in the overall result.

NMC

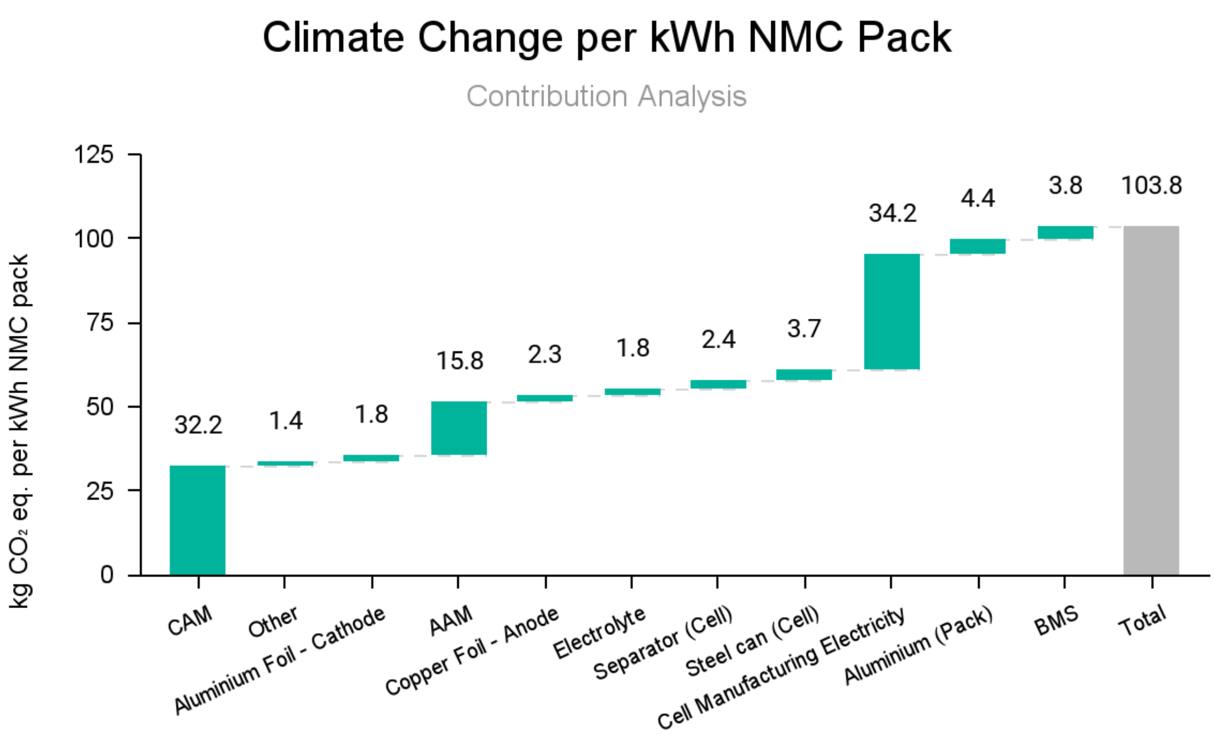

Figure 11: Base Case Climate Change Contribution Analysis per kWh NMC Pack.

CAM is the second largest contributor for this chemistry and a CAM contribution analysis is presented in Figure 12. Nickel sulphate hexahydrate is the largest climate change hotspot in NMC CAM making up 32% of the CAM impact. As the Nickel Institute average embodied impact is only 4.0 kg CO_2 eq. per kg, this contribution is largely due to the mass required to achieve the 8:1:1 ratio (2.28 kg per kg pCAM).

Electricity required for processing of pCAM into CAM is the second largest contributor to the CAM impact making up 25%. As described previously, the assumed source in the base case scenario is the coal-dominated Jiangsu grid (CN-ECGC).

In the base case scenario, the lithium hydroxide monohydrate source is modelled as 42% Chilean brine and 58% Australian spodumene, both refined in China. The embodied impact of the latter is around 300% higher than that of the Chilean source.

Cobalt sulphate heptahydrate only contributes 4% of the CAM impact (< 1% of the total impact per kWh) making it the fifth largest contributor to the CAM impact.

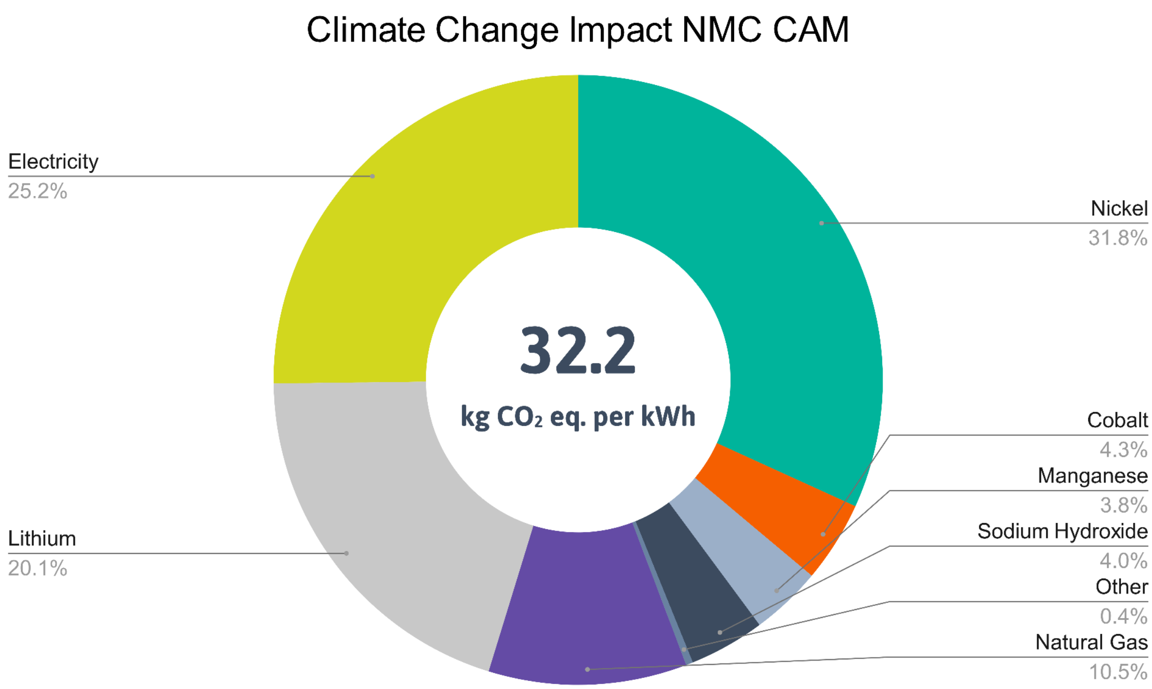

Figure 12: Base Case Climate Change CAM Contribution Analysis per kWh NMC Pack.

NCA

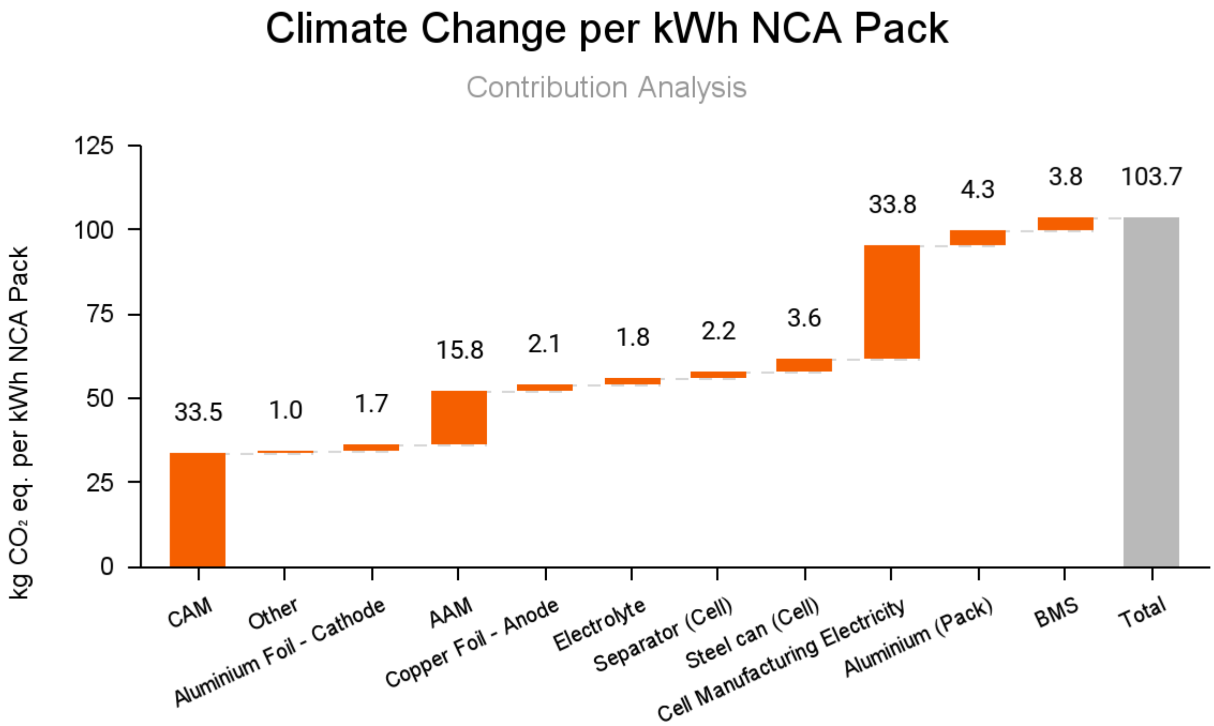

Figure 13: Base Case Climate Change Contribution Analysis per kWh NCA Pack.

CAM is also the second largest contributor for NCA and a CAM contribution analysis is presented in Figure 14. Nickel sulphate hexahydrate is the largest climate change hotspot in NMC CAM making up 34% of the CAM impact. Again, as the Nickel Institute average embodied impact is only 4.0 kg CO_2 eq. per kg, this contribution is largely due to the mass required to achieve the 8:1.5:0.5 ratio (2.31 kg per kg pCAM).

The amount of electricity required for processing of pCAM into CAM is similar to that required for NMC and is also the second largest contributor to the NCA CAM impact (26%).

The amount of lithium hydroxide required by the nickel-based chemistries is also very similar and the base came supply chain assumptions are the same. Lithium hydroxide contributes 21% to the CAM impact for NCA.

Cobalt sulphate heptahydrate only contributes 7% of the CAM impact (still < 1% of the total impact per kWh) making it the fifth largest contributor to the CAM impact.

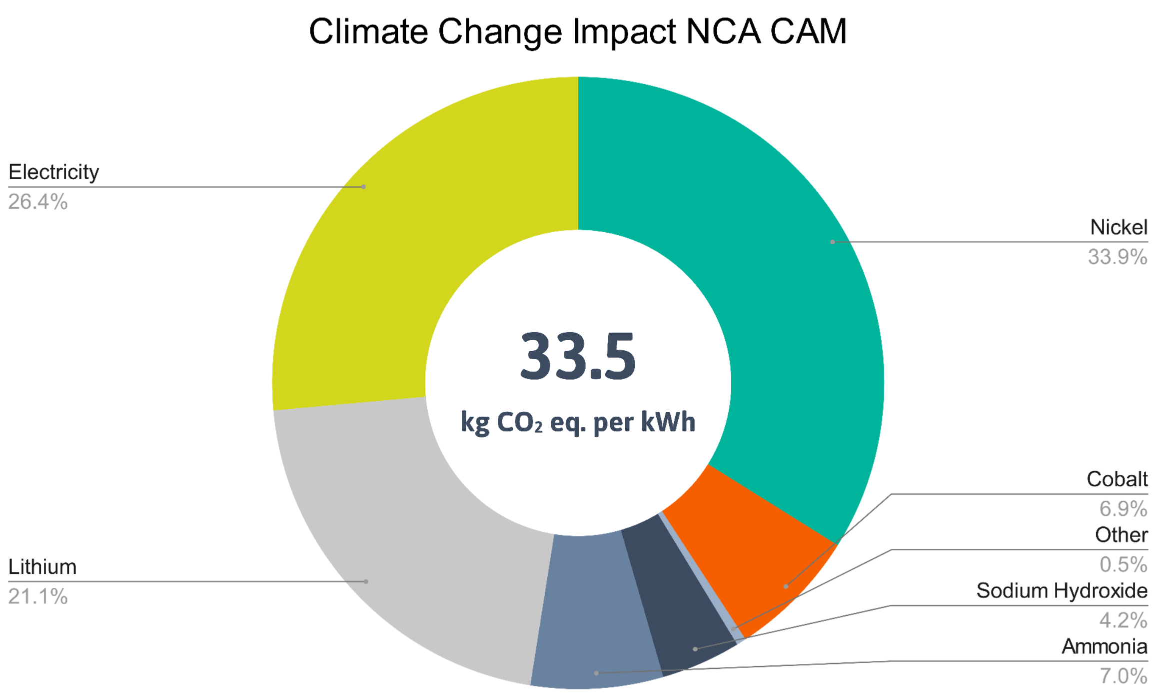

Figure 14: Base Case Climate Change CAM Contribution Analysis per kWh NCA Pack.

LFP

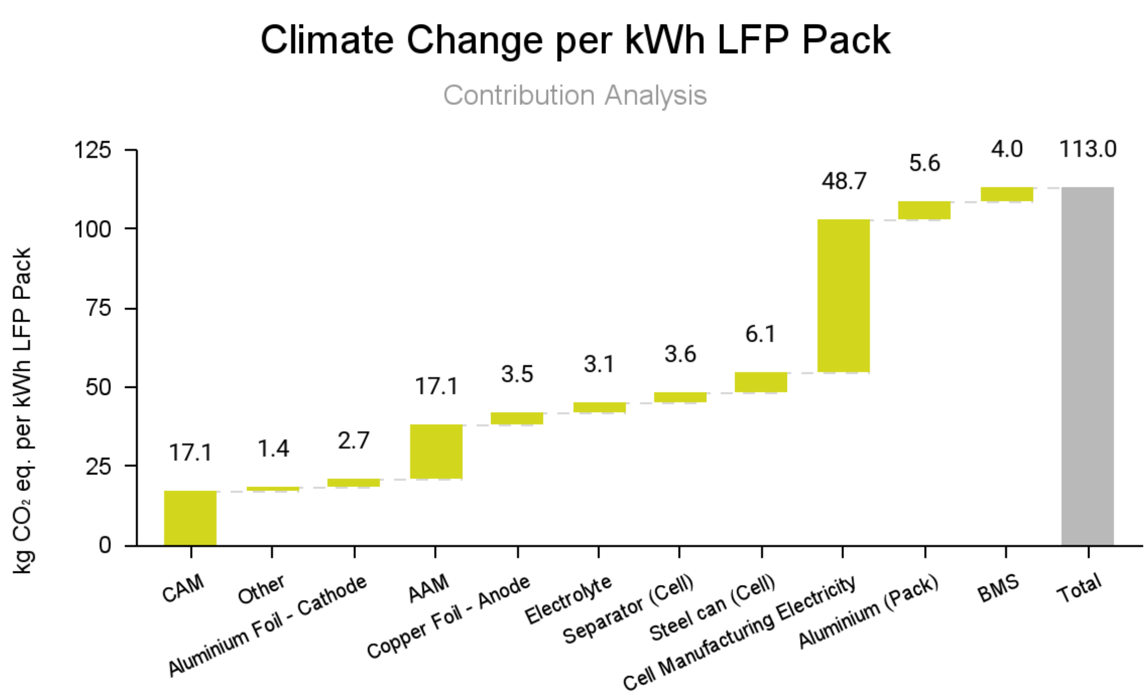

Figure 15: Base Case Climate Change Contribution Analysis per kWh LFP Pack.

CAM is the joint second largest contributor for this chemistry alongside AAM; a CAM contribution analysis is presented in Figure 16. Lithium carbonate is the largest climate change hotspot in LFP CAM making up 43% of the CAM impact. The supply chains remain the same as for lithium hydroxide production so lithium carbonate from an Australian spodumene source remains a hotspot here.

Natural gas required for pCAM anc CAM processing (totalling 21% of the CAM impact) make this the second largest contributor to the CAM impact for LFP. Electricity requirement is the third largest contributor making up 13% of the CAM impact. As described previously, the assumed source in the base case scenario is the coal-dominated Jiangsu grid (CN-ECGC).

The base case phosphoric acid supply route is industrial grade phosphoric acid refined from fertiliser grade acid in China. This input contributes 9% of the LFP CAM impact making it the fourth largest contributor.

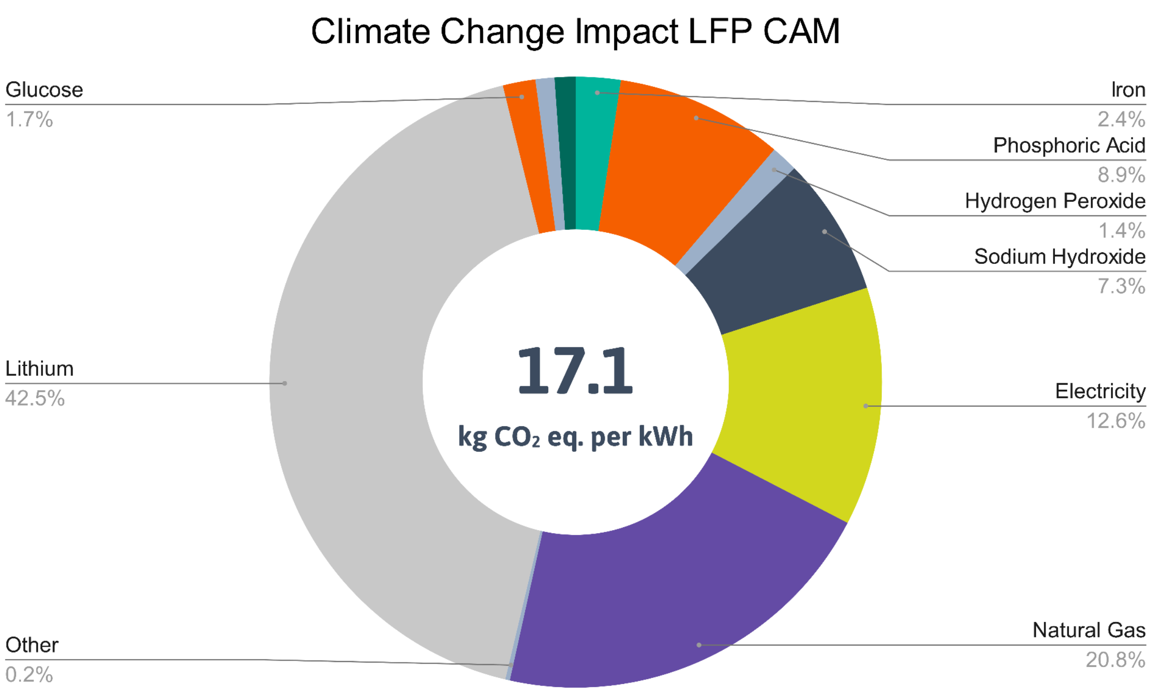

Figure 16: Base Case Climate Change CAM Contribution Analysis per kWh LFP Pack.

4.2. Battery Manufacturing Sensitivity Analyses

4.2.1. Low and High Impact Supply Chains

To assess the variability in manufacturing climate change impacts depending on raw material supply chains and energy sources, low and high impact scenarios have been assessed for each battery chemistry. The low and high impact scenario results for each chemistry are broken down by area and compared to the base case scenario in Figures 17-19. Raw material and energy assumptions for each scenario are detailed in section 3.1.

NMC

- 31.1 kg CO_2 eq. per kWh NMC pack in the low impact scenario.
- 103.8 kg CO_2 eq. per kWh NMC pack in the base case scenario.
- 177.5 kg CO_2 eq. per kWh NMC pack in the high impact scenario.

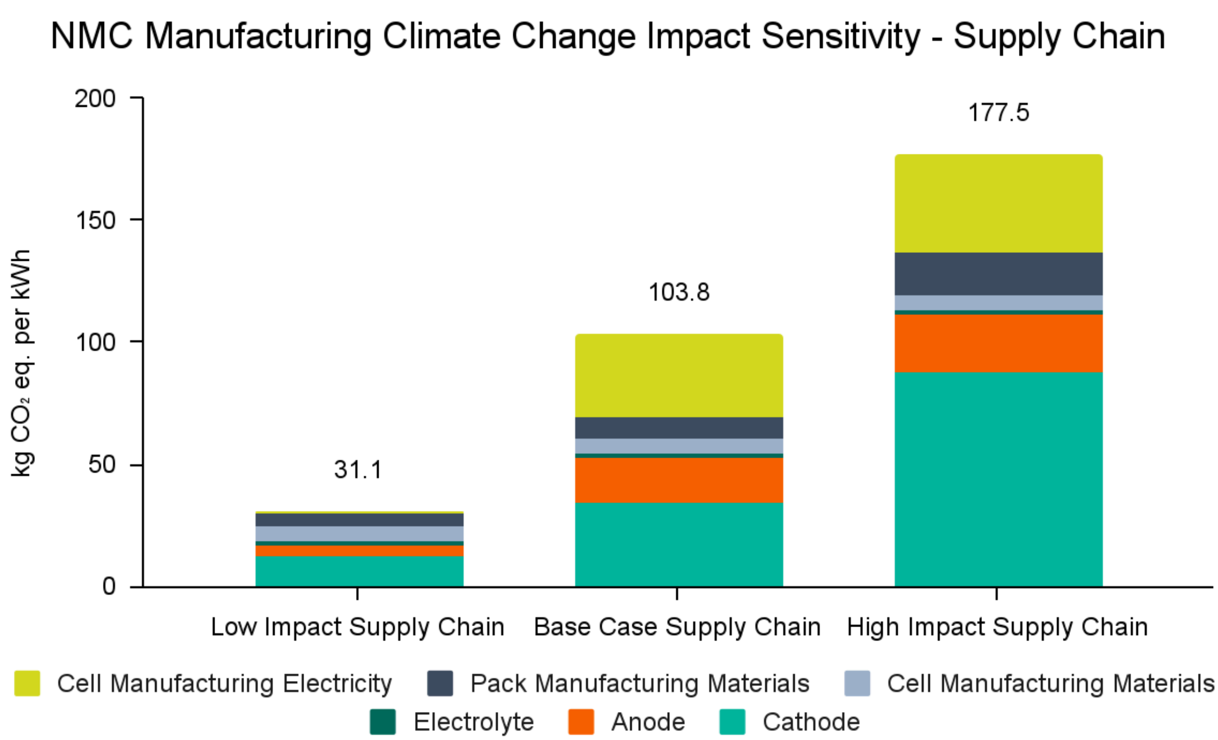

Figure 17: Climate Change Variation per kWh NMC Pack.

The climate change impact per kWh NMC pack varies by 146.5 kg CO_2 eq. between the low impact scenario at 31.1 kg CO_2 eq. per kWh NMC pack and 177.5 kg CO_2 eq. per kWh NMC pack in the high impact scenario (Figure 17). The low impact scenario represents a 70% decrease from the base case scenario. The high impact scenario represents a 71% increase on the base case scenario.

The majority of the variation is related to cathode production which varies by 75.0 kg CO_2 eq. between 12.4 kg CO_2 eq. per kWh NMC pack for the low impact scenario and 87.4 kg CO_2 eq. per kWh NMC pack for the high impact scenario. The largest driver of this variation is the difference between the embodied impacts of different nickel supply chains. The high impact supply chain (RKEF, Indonesia) has a climate change impact per kg nickel sulphate hexahydrate around 14 times that of the low impact supply chain (pyrometallurgy, Canada).

Cell manufacturing electricity is also a significant area of variation between the scenarios. This varies by 39.5 kg CO_2 eq. between 1.1 kg CO_2 eq. per kWh NMC pack for the low impact scenario and 40.6 kg CO_2 eq. per kWh NMC pack for the high impact scenario. The embodied impact of the high impact grid (CN-NWG) is only an 18% increase on the base case, hence why the contribution from this area in the base case and high impact scenarios is similar. The embodied impact of the low impact grid (NO) is a 97% decrease on the base case electricity source so the difference in this area's contribution between the base case and low impact scenarios is more significant.

NCA

- 32.6 kg CO_2 eq. per kWh NCA pack in the low impact scenario.
- 103.7 kg CO_2 eq. per kWh NCA pack in the base case scenario.
- 180.1 kg CO_2 eq. per kWh NCA pack in the high impact scenario.

The climate change impact per kWh NCA pack varies by 147.5 kg CO_2 eq. between the low impact scenario at 32.6 kg CO_2 eq. per kWh NCA pack and 180.1 kg CO_2 eq. per kWh NCA pack in the high impact scenario (Figure 18). The low impact scenario represents a 69% decrease from the base case scenario. The high impact scenario represents a 74% increase on the base case scenario.

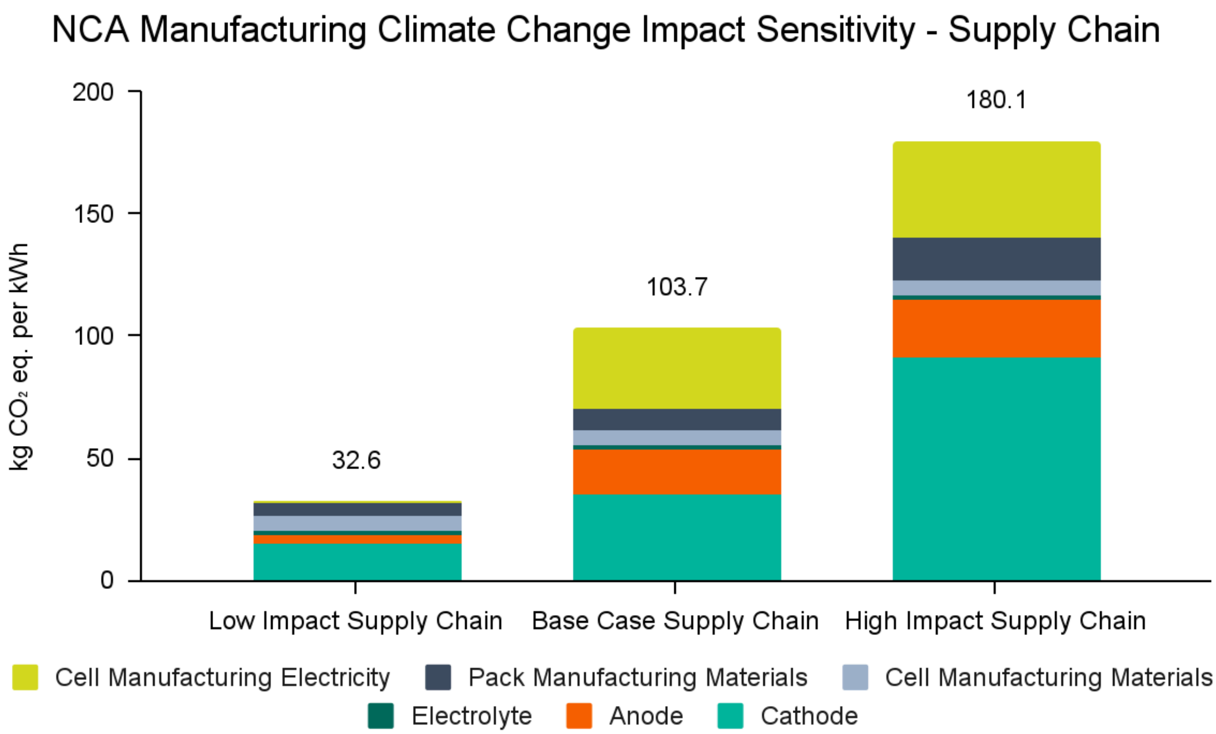

Figure 18: Climate Change Variation per kWh NCA Pack.

As the nickel-based chemistries are similar, the main drivers of variation between the scenarios are the same as for NMC. The majority of the variation is again related to cathode production which varies by 76.8 kg CO_2 eq. between 14.6 kg CO_2 eq. per kWh NCA pack for the low impact scenario and 91.5 kg CO_2 eq. per kWh NCA pack for the high impact scenario. The largest driver of this variation is also the embodied impacts of different nickel supply chains.

Cell manufacturing electricity varies by 39.0 kg CO_2 eq. between 1.1 kg CO_2 eq. per kWh NCA pack for the low impact scenario and 40.1 kg CO_2 eq. per kWh NCA pack for the high impact scenario. The variation is slightly less than seen in NMC as cell manufacturing electricity is linked to energy density (i.e. MJ per kg) and NCA has a slightly higher energy density than NMC (0.217 vs. 0.214 kWh per kg pack).

LFP

The climate change impact per kWh LFP pack varies by 117.7 kg CO_2 eq. between the low impact scenario at 33.5 kg CO_2 eq. per kWh LFP pack and 151.2 kg CO_2 eq. per kWh LFP pack in the high impact scenario (Figure 19). The low impact scenario represents a 70% decrease from the base case scenario and the high impact scenario represents a 34% increase.

- 33.5 kg CO_2 eq. per kWh LFP pack in the low impact scenario.
- 113.0 kg CO_2 eq. per kWh LFP pack in the base case scenario.
- 151.2 kg CO_2 eq. per kWh LFP pack in the high impact scenario.

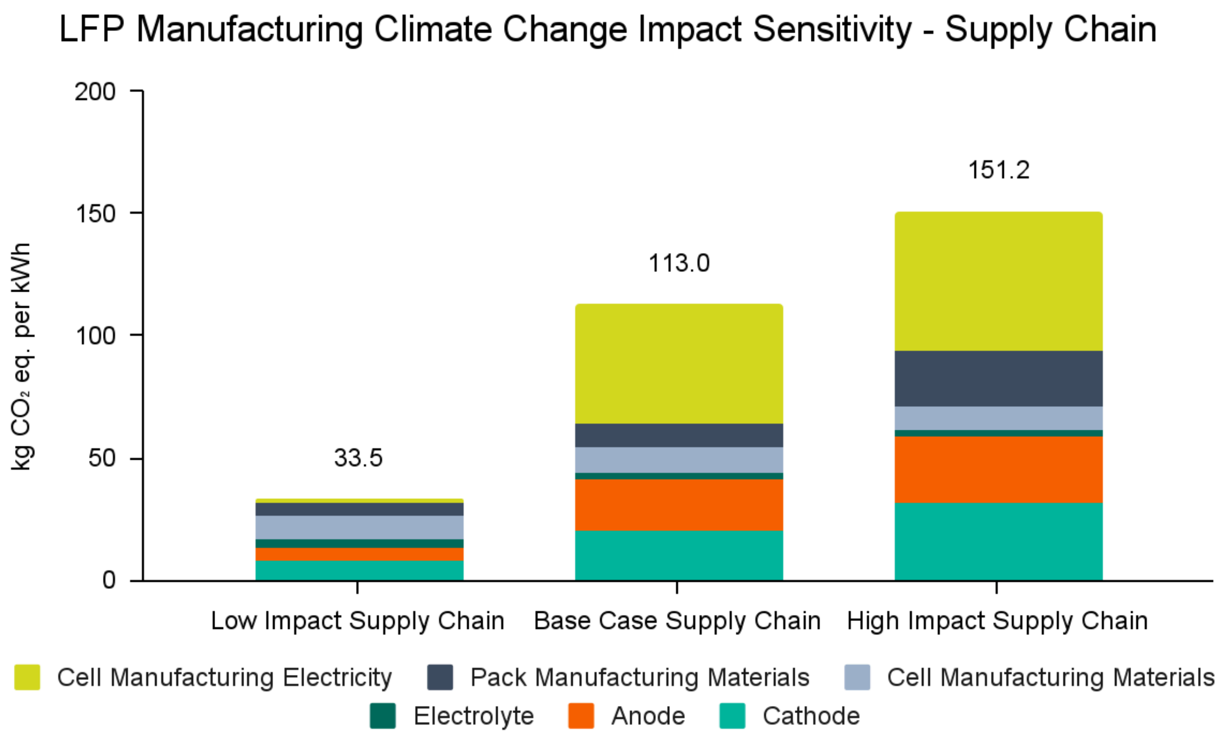

Figure 19: Climate Change Variation per kWh LFP Pack.

The majority of the variation is related to cell manufacturing electricity which varies by 56.2 kg CO_2 eq. between 1.6 kg CO_2 eq. per kWh LFP pack for the low impact scenario and 57.8 kg CO_2 eq. per kWh LFP pack for the high impact scenario. The variation here is significantly higher than seen for the nickel-based chemistries due to the link between electricity requirement and energy density. As LFP's energy density is significantly lower than NMC / NCA (0.154 kWh per kg pack), a higher volume of material is processed to achieve the same pack capacity. This higher requirement for electricity exaggerates the influence of lower and higher impact electricity supply chains.

Cathode production is the second largest driver of variation. Cathode production varies by 23.8 kg CO_2 eq. between 8.2 kg CO_2 eq. per kWh LFP pack for the low impact scenario and 32.0 kg CO_2 eq. per kWh LFP pack for the high impact scenario. For cathode production, lithium carbonate is the largest driver of variation between the scenarios. This is due to the difference between the embodied impacts of different lithium supply chains as discussed in section 4.1.3.

Anode production varies by 21.3 kg CO_2 eq. between 5.1 kg CO_2 eq. per kWh LFP pack for the low impact scenario and 26.4 kg CO_2 eq. per kWh LFP pack for the high impact scenario. The largest driver of this variation is the difference between the embodied impacts of different anode-grade graphite supply chains. As previously highlighted, the high impact supply chain (anode-grade synthetic graphite produced in Inner Mongolia, China) has a climate change impact around 16 times that of the low impact supply chain (anode-grade natural graphite produced in Canada).

The results highlight the importance of low carbon raw material and energy sourcing when considering the climate change impacts of battery pack manufacturing. The absolute amount of raw materials required to reach a specific capacity is lower for the nickel-based chemistries due to their higher energy densities, but the raw materials used typically have higher embodied climate change impacts. Conversely, the raw materials used for LFP typically have lower embodied climate change impacts than for NMC/NCA but the absolute amount required is higher and thus requires more energy for processing. The sensitivity analysis shows the variation - and therefore the opportunities for decarbonisation - that exist in battery manufacturing supply chains.

4.2.2. Low and High Impact Cobalt Supply Chains

To isolate variation in manufacturing climate change impact associated with cobalt, base case scenarios were created with variation in the cobalt supply chain only. These scenario results for each cobalt-containing chemistry (i.e. NMC and NCA) are broken down by area and compared to the base case scenario in Figures 20 and 21. The high impact supply chain considers cobalt production via HPAL in Indonesia and the low impact supply chain considers cobalt produced via pyrometallurgy in Canada (Table 13 in section 3.1).

NMC

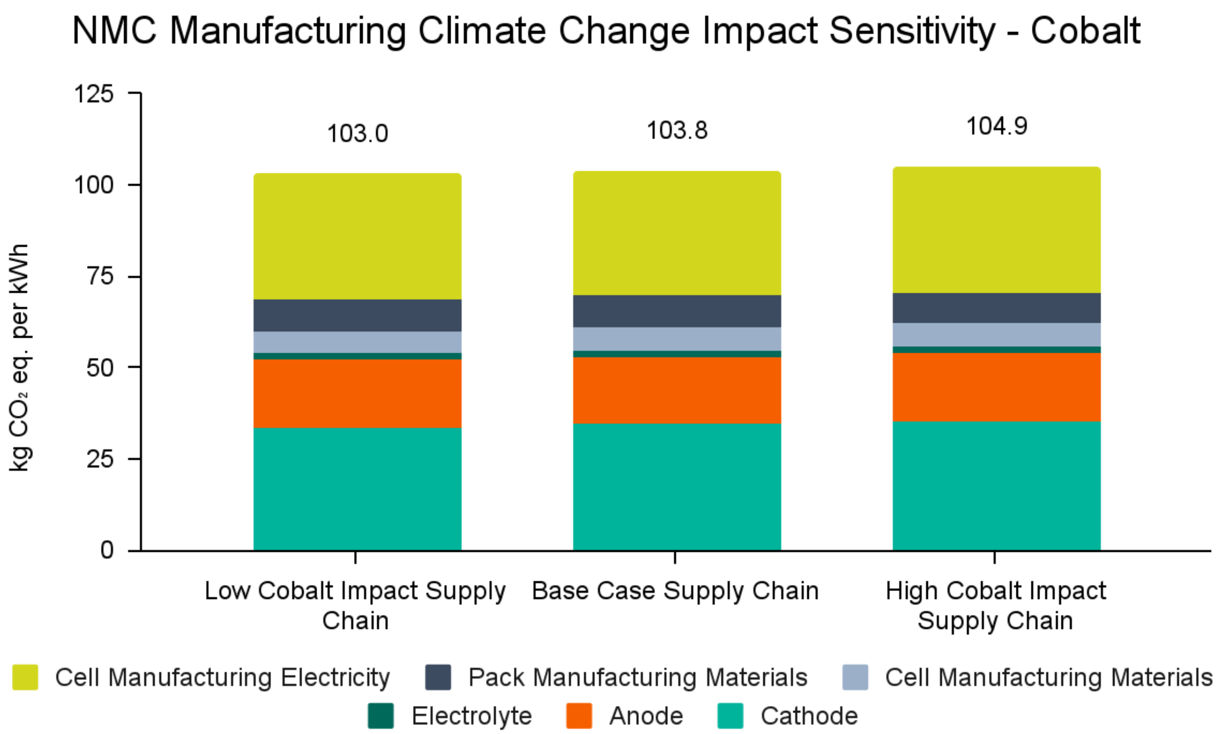

Figure 20: Climate Change Variation Depending on Low and High Impact Cobalt per kWh NMC Pack.

- 103.0 kg CO_2 eq. per kWh NMC pack for the low impact cobalt scenario.
- 104.9 kg CO_2 eq. per kWh NMC pack for the high impact cobalt scenario.

This variation of 1.9 kg CO_2 eq. between the low impact cobalt scenario (103.0 kg CO_2 eq.) and the high impact cobalt scenario (104.9 kg CO_2 eq.) equates to approximately 2% of the total impact. This demonstrates that cobalt is not a climate change hotspot in this chemistry.

NCA

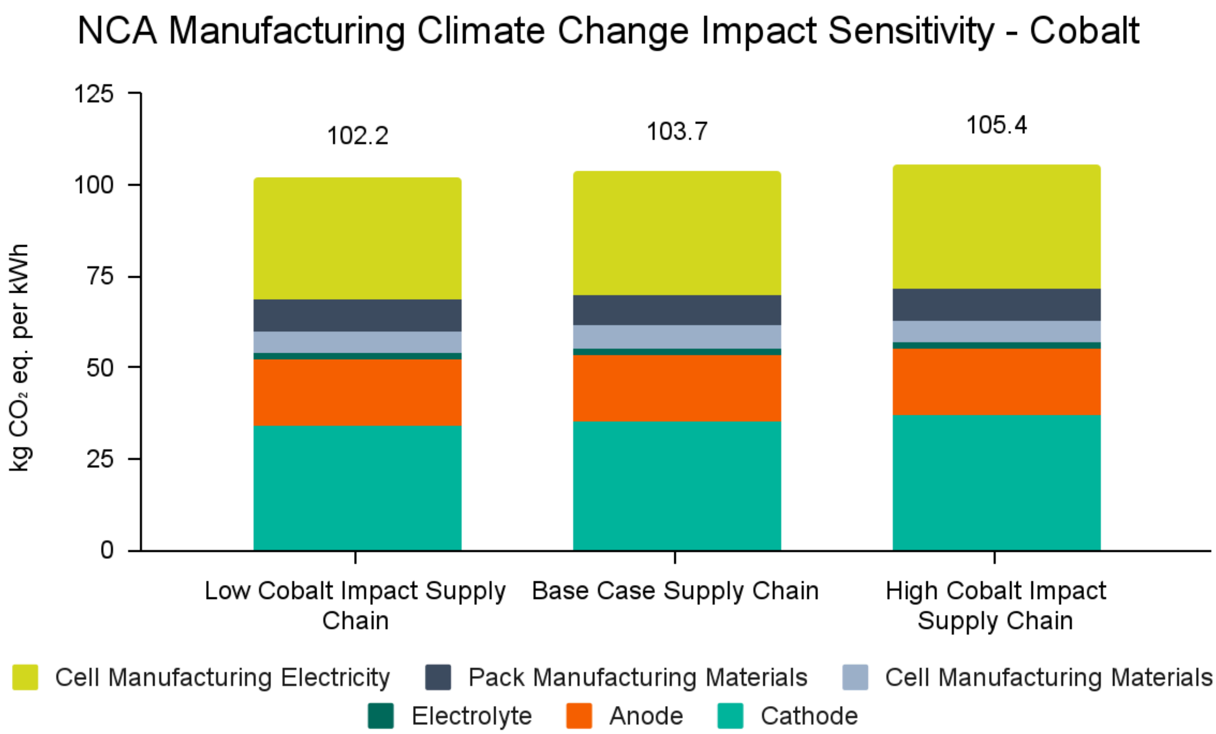

Figure 21: Climate Change Variation Depending on Low and High Impact Cobalt per kWh NCA Pack.

- 102.2 kg CO_2 eq. per kWh NCA pack for the low impact cobalt scenario.
- 105.4 kg CO_2 eq. per kWh NCA pack for the high impact cobalt scenario.

This variation of 3.2 kg CO_2 eq. between the low impact cobalt scenario (102.2 kg CO_2 eq.) and the high impact cobalt scenario (105.4 kg CO_2 eq.) equates to approximately 3% of the total impact. This demonstrates that cobalt is not a significant climate change hotspot in either nickel-based chemistry.

4.2.3. Southeastern USA Manufacturing Location

To assess the variability in manufacturing climate change results depending on manufacturing location alone, base case raw materials were modelled with all manufacturing (inclusive of pCAM / CAM) occurring in the Southeastern USA. Note that foreground transport is excluded in all scenarios. Results for each chemistry are broken down by area in Figure 22. Raw material and energy assumptions for each scenario are detailed in section 3.1.

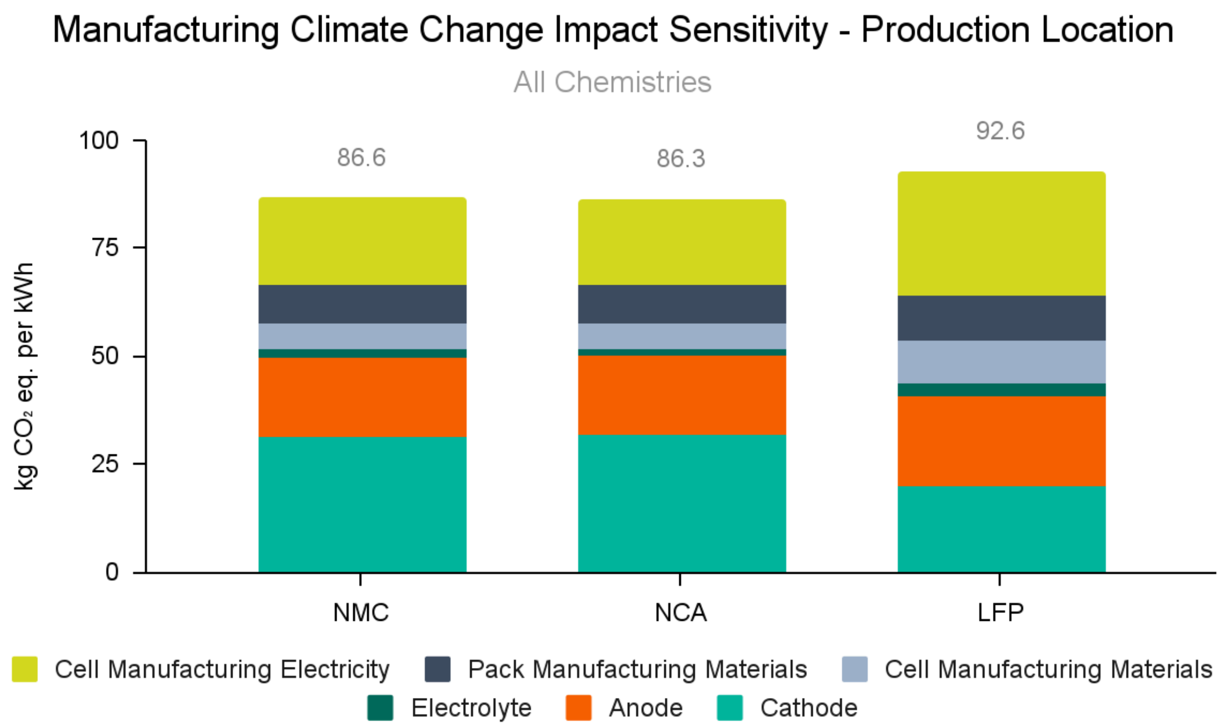

Figure 22: Climate Change Impact for Base Case Raw Materials and a Southeastern USA Manufacturing Location.

- 86.6 kg CO_2 eq. per kWh NMC pack manufactured in the southeastern USA.
- 86.3 kg CO_2 eq. per kWh NCA pack manufactured in the southeastern USA.
- 92.6 kg CO_2 eq. per kWh LFP pack manufactured in the southeastern USA.

Compared to the base case scenario (manufacturing in Jiangsu Province, China), the contribution of cell manufacturing electricity decreases by 17.2 kg CO_2 eq. for NMC, 17.4 kg CO_2 eq. for NCA, and 20.3 kg CO_2 eq. for LFP.

Reductions in climate change impact have also occurred for cathode production due to less impactful electricity consumption. This is most significant for NCA in which the cathode contribution has reduced by 3.6 to 31.9 kg CO_2 eq. per kWh NCA pack.

The southeastern USA grid (US-SERC) modelled sources around 45% of its power from natural gas combustion resulting in an embodied impact around 45% lower than the Jiangsu grid of the base case scenario.

4.2.4. Cell Manufacturing Electricity

The LCI source used for cell manufacturing calculates an average requirement of 37.43 ± 7.59 MJ per kg.[14] Due to the large uncertainty, sensitivity analysis has been performed to assess the influence of more and less energy intensive manufacturing on the base case manufacturing scenario. The results for all chemistries are presented in Figure 23.

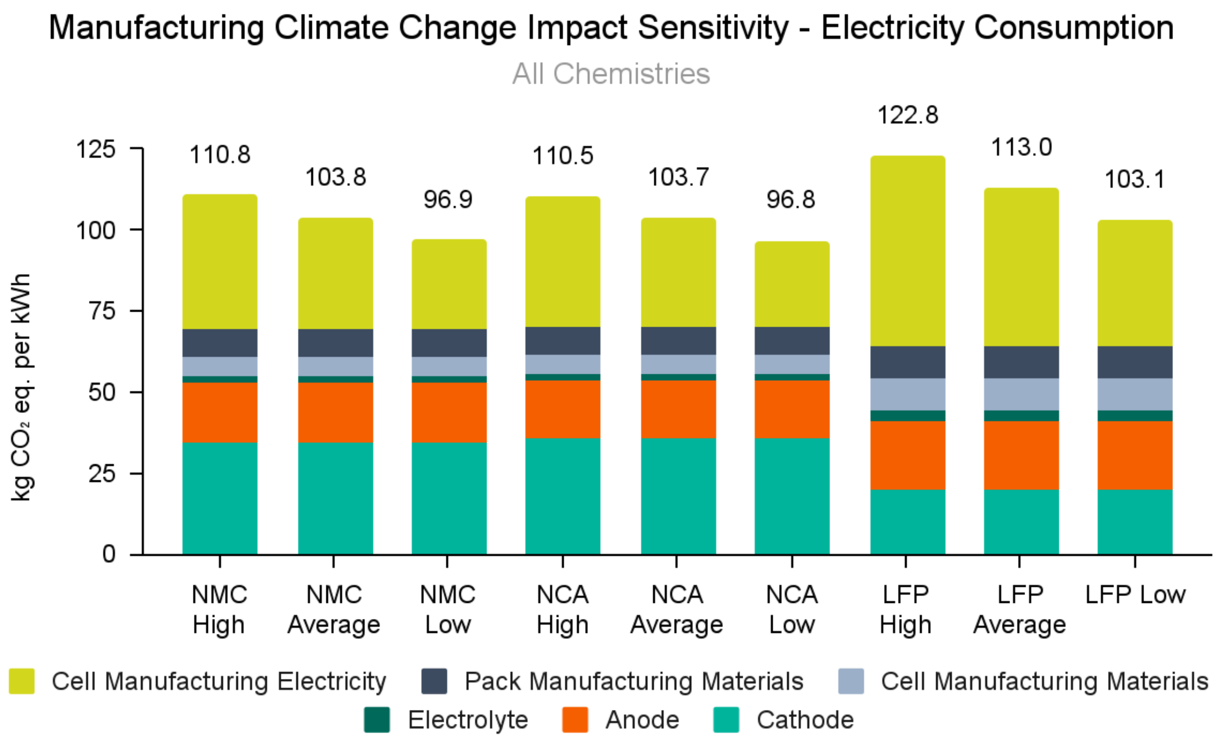

Figure 23: Climate Change Sensitivity Analyses for Cell Manufacturing Electricity Consumption.

When all other parameters are kept the same as the base case manufacturing scenario, increasing and decreasing cell manufacturing electricity consumption by ±7.59 MJ per kg changes the climate change contribution of this area by ±6.9 kg CO_2 eq. for NMC and NCA, and ±9.9 kg CO_2 eq. for LFP.

4.3. Lifetime Emissions Results

Lifetime climate change impacts are presented for fixed capacity battery pack use in Figure 24.

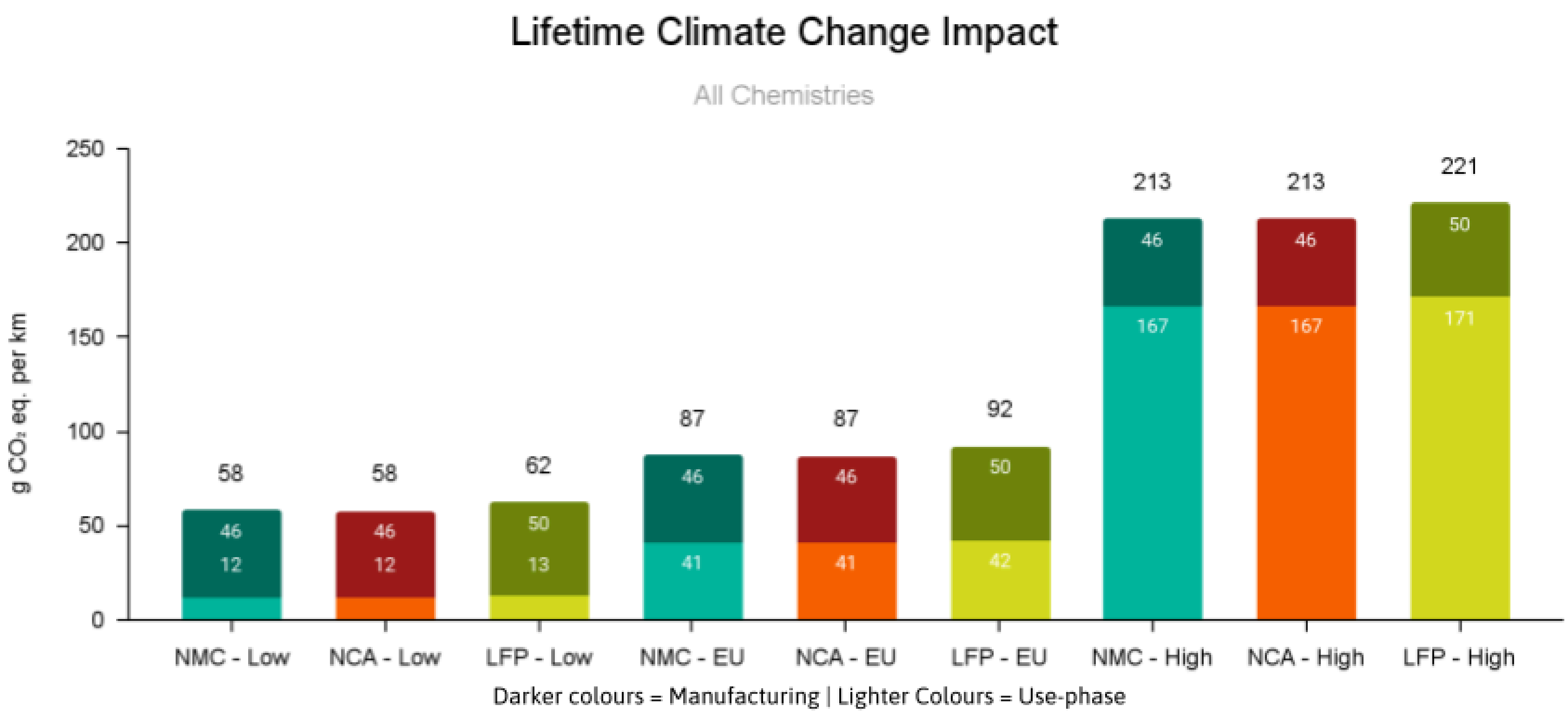

Figure 24: Lifetime Climate Change Impact for Fixed Capacity Battery Packs Broken Down by Life Cycle Stage.

Lifetime emissions for packs of a fixed 70.6 kWh capacity are similar for all three chemistries. Lifetime emissions vary between 58–62 g CO_2 eq. per km for the low impact grid scenario, 87–92 g CO_2 eq. per km for the average EU grid scenario, and 213–221 g CO_2 eq. per km for the high impact grid scenario.

Minor differences can be seen between the chemistries with LFP pack manufacturing and use-phase typically contributing slightly more than NMC / NCA. This trend is seen because the overall impact of manufacturing a fixed capacity LFP pack is slightly more than NMC / NCA (see section 4.1.1) and the energy density is lower (see section 2.3.1). The latter results in a higher pack mass and lower efficiency (see section 3.2). It should be noted that the lifetime emissions results in Figure 24 are within the 10% uncertainty assigned to the LCA study.

Significant differences in the relative contributions from each life cycle (i.e. manufacturing and use-phase) are seen when assessing use on different electricity mixes. When charging occurs on a lower than average impact European grid, manufacturing emissions contribute around 80% to the total lifetime emissions. When charging occurs on the average European grid, manufacturing emissions contribute around 50% to the total lifetime emissions. When charging occurs on a higher than average impact European grid, manufacturing emissions contribute around 20% to the total lifetime emissions.

Differences in the relative contributions from each life cycle stage highlights that the effectiveness of mitigation strategies can change depending on use location. When considering base case manufacturing supply chains and a use location where the carbon intensity of the grid is above the European average, the results indicate that grid decarbonisation in the use location may be more effective at reducing overall lifetime emissions. In use locations where the grid intensity is similar to or less than the European average, mitigation strategies in the manufacturing stage (e.g. low carbon raw material and energy sourcing) may be more effective at reducing overall lifetime emissions.

Whilst the end-gate across the different use scenarios is fixed at 160,000 kilometres, differing energy densities, ranges, and efficiencies result in slightly different actual cycle numbers. Assuming 80% DoD per cycle, LFP is cycled 391 times to achieve 160,000 km whereas NMC and NCA are cycled 386 times (Table 15). When coupled with different rates of degradation (i.e. loss per cycle) this also leads to different percentages of battery utilisation at the end of the assumed

160,000 kilometre lifetime. As LFP degradation is typically lower than for nickel-based chemistries, LFP shows a lower utilisation percentage at this gate compared to NMC and NCA (14% vs. 28%; see Table 15). Whilst these additional results do not directly influence the lifetime climate change results of this LCA study, they should be considered alongside the LCIA results.

Readers should be aware that the results of the defined lifetime use-phase analyses represent the lifetime climate change impacts for a specific EV application with a fixed distance parameter. For all chemistries, this means the end-gate occurs before full utilisation is achieved (i.e. before the batteries reach 80% SoH). In a different application where the battery packs could be cycled until their true EoL, such as a stationary ESS, the different degradation rates and the lack of influence from efficiency / pack mass may generate significantly different lifetime climate change impact results.

In the context of the specific EV use-phase presented, these results highlight the importance of vehicle ecodesign and longevity. EV design strategy that considers required range and pack size, as well as prolonging the longevity of EV lifetime outside of the battery pack, could allow production of battery packs that use critical raw materials (e.g. cobalt, natural graphite, phosphorus, and lithium)[29] more efficiently. In theory this could allow all chemistries, particularly those with a longer maximum service life, to be utilised to a higher extent than in current standard EV applications assuming no second use-phase.[27]

4.4. Use Phase Scenario Analysis

4.4.1. Energy Delivered over Maximum Service Life

Different battery chemistries have different rates of degradation with LFP typically having a significantly longer cycle life than NMC and NCA. Average degradation rates (e.g. cycle life) are based on recommendation from industry experts at About:Energy. Whilst the energy density is lower for LFP, slower degradation results in a longer maximum lifetime when assuming the end-gate is 80% SoH. Note that assuming set parameters for service life (i.e. 160,000 km) can occur before 80% SoH and can therefore negate longevity benefits.

To assess the difference in longevity between the chemistries, a sensitivity analysis has been performed to assess the climate change impact normalised to one kWh energy delivered over the maximum service life. Maximum service life parameters are presented in Table 16 (section 3.2.1) and were calculated assuming a cycle life of 1,500 for the nickel-based chemistries and

3,000 for LFP (to 80% SoH). Cycle lives are based on an 80% DoD per cycle. The results are presented in Figure 25 assuming base case manufacturing routes and use on the average European grid.[28]

It should be noted that, whilst use of average cycle degradation rates satisfies the goal of this study, the conditions under which batteries are cycled can greatly influence service life. In reality, battery packs in this application are likely to be cycled under much more aggressive conditions, resulting in lower maximum service lives than presented here.

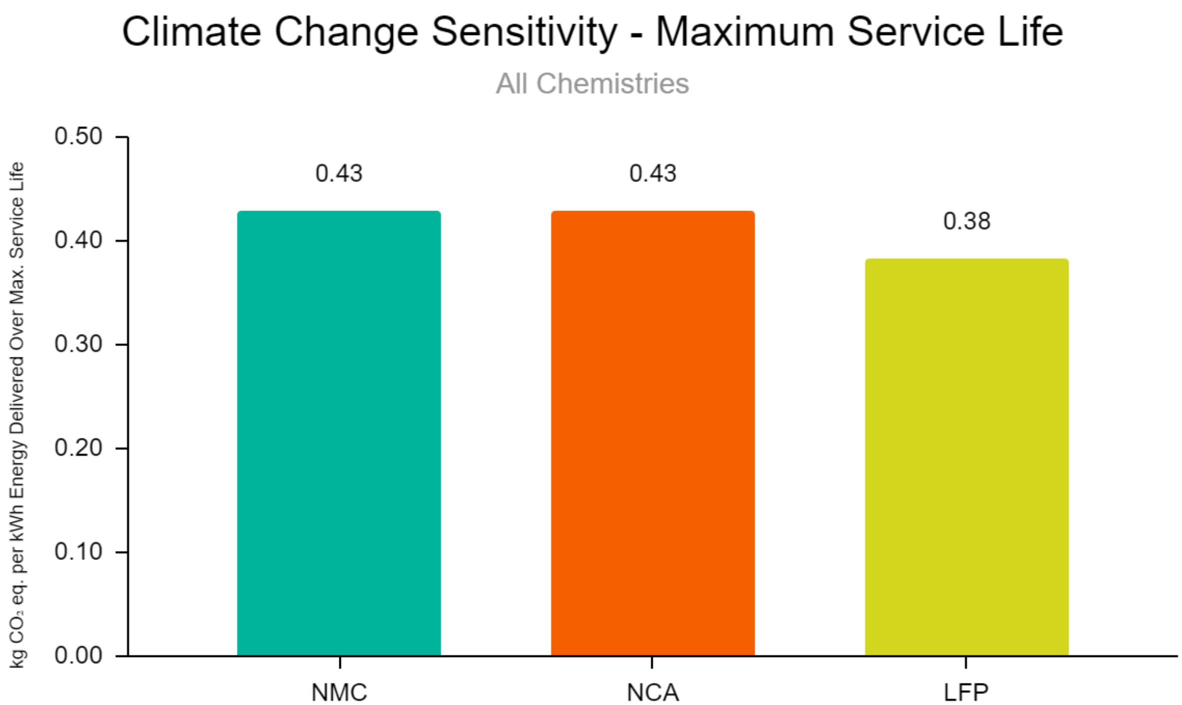

Figure 25: Lifetime Climate Change Impact per kWh Energy Delivered Over Maximum Service Life.

- 0.43 kg CO_2 eq. per kWh energy delivered by a 70.6 kWh NMC pack over the maximum service life.
- 0.43 kg CO_2 eq. per kWh energy delivered by a 70.6 kWh NCA pack over the maximum service life.
- 0.38 kg CO_2 eq. per kWh energy delivered by a 70.6 kWh LFP pack over the maximum service life.

The results show that the lifetime climate change impact is around 12% lower for LFP compared to nickel-based chemistries when the functional unit is one kWh of energy delivered over the maximum service life (i.e. when decoupling the battery pack life from the life of the vehicle). Although the absolute lifetime impact is higher for LFP packs, the longer cycle life means it is spread over a longer maximum service life, which in a use case of 20,000 km per year would require an unrealistic service life from a light duty vehicle of 56 years.

As presented in section 4.1.1, the climate change impact per pack for LFP is around 9% higher than NMC and NCA for fixed 70.6 kWh capacity packs. When considering the influence of longevity, LFP has a longer cycle life resulting in LFP having a considerably longer maximum service life than NMC / NCA and delivering significantly more energy. The climate change impact of pack manufacturing and use per unit of energy delivered is therefore lower for LFP compared to the nickel-based chemistries. Whilst this sensitivity analysis highlights significant differences in longevity between the battery chemistries, it should be noted that - assuming no second use-phase - the longevity of EVs as a whole must be improved to actualise these benefits. Assuming usage to 80% SoH resulted in service lives of 572,810–1,115,288 km over 29–56 years (see Table 16 in section 3.2.1). For all chemistries, full utilisation of the battery pack does not represent a realistic prospect for the service life of today's light duty vehicles.

Under the maximum service life assumptions that look at the battery pack life in isolation from the vehicle, the results indicate that an LFP battery could be around 12% less impactful in terms of climate change. However, given that the PEFCR for high specific energy rechargeable batteries for mobile applications assumes 20,000 km per year for a light duty vehicle,[27] it is clear that appropriate battery sizing, chemistry longevity, and more holistic ecodesign will need to be applied to EVs as a whole in order to reap the benefits of long lasting batteries.

5. Life Cycle Interpretation

5.1. Data Quality Assessment

The foreground and background data of the LCI were judged on technological and time representativeness, geographical coverage, completeness, precision, and consistency. Data collection and calculation procedures are documented in Chapter 2.7. Summaries of the data quality assessment are presented in Tables 17 and 18.

Table 17: Summary of Foreground Data Quality Assessment - Completeness, Precision and Methodology.

Data Quality Indicator	Grading	Reasoning
Completeness	Good	The foreground data have been developed to reflect industry representative battery manufacturing from production of precursory materials through to pack assembly. No data have been knowingly omitted. The foreground data has been graded as good.
Precision	Fair to Good	Foreground data for battery manufacturing of NMC, NCA, and LFP cells has been adapted from a number of publicly available sources.[12-14] These sources are based on a combination of measured, estimated, and expertly judged values. For these reasons the data has been graded as fair to good for this indicator.
Methodology Appropriateness and Consistency	Fair	Two out of three method requirements of the PEF guide have been met as secondary and tertiary use-phases, and EoL treatments are not covered within the system boundary. This corresponds to a fair data grade. Although there is no multifunctionality to be dealt with in the foreground, multifunctionality is dealt with using system expansion and/or allocation in background data. A detailed system boundary is considered throughout the study, as presented in section 2.3.

Table 18: Summary of Foreground and Background Data Quality Assessment - Representativeness.

Data Quality Indicator	Foreground Data		Background Data	
	Grading	**Reasoning**	**Grading**	**Reasoning**
Technological Representativeness	Fair	Foreground data for battery manufacturing of NMC, NCA, and LFP cells has been adapted from a number of publicly available sources. The Greenhouse gases, Regulated Emissions, and Energy use in Technologies model (GREET) 2020 bill-of-materials update forms the basis of the LCIs.[12] As these datasets are not specific to an operational facility producing 21700 cells of the studied chemistries, these data are graded as fair.	Fair to good	Background data internally developed by Minviro (e.g., for manganese, lithium chemicals, and anode grade graphite) have all been produced from publicly available data sources and private internal datasets within the last four years. They represent a number of operational and prospective production technologies that are specific to the application. These data are graded as good. 'Market' background data were selected from ecoinvent 3.9.1 where available. These data points represent the consumption mix of a product for a given region and account for variations in production technologies. These data are graded as fair.
Time-Related Representativeness	Good to very good	The GREET bill-of-materials update that forms the basis of the LCIs was published within four years of this study (2020) and is graded as good. Cell manufacturing electricity information is sourced from publicly available academic studies published in 2021 and 2022. These data are classified as very good.	Fair to good	Background data internally developed by Minviro have all been produced within the last four years. ecoinvent 3.9.1, the source for the majority of other background data, was updated in 2022 with all data points used valid until the end of 2023. This means the majority of background data used can be graded as good. Cobalt Institute and Nickel Institute LCAs are for reference years 2019 and 2017, respectively. These are between four and six years from this study, meaning they are graded as fair.
Geographical Representativeness	Fair to good	Again, the data sources used[12-14] do not represent actual operations occurring in Jiangsu, China. Whilst China is where the majority of battery manufacturing occurs,[8] the base case scenario has been developed to be industry representative and relies heavily on global averages. As previously highlighted, production of all three chemistries studied does not necessarily occur in the same province. For this reason, foreground data are graded as fair to good for this indicator.	Fair to very good	Custom Minviro models represent operational and prospective operations for specific countries. These data are graded as good. The energy source used for manufacturing in the base case scenario (CN-ECGC) is region specific and is graded as very good. As the base case scenario has been developed to be industry representative, many background data points from ecoinvent 3.9.1 represent global averages. These data are graded as fair.

5.2. Uncertainty Analysis

Whilst the alternative manufacturing and use-phase scenarios presented throughout sections 4.2 and 4.3 address supply chain and electricity source impact sensitivities, uncertainty remains in the LCI data itself (i.e. the actual amount of mass and energy consumed). Where operational data is available, each foreground LCI flow and its corresponding background data should be assigned a specific uncertainty and probability distribution. A Monte Carlo simulation - a computational method that uses random sampling to simulate complex systems and processes - can then be used to generate a distribution of possible outcomes for the climate change impact of the product or service.

Unfortunately due to reliance on publicly available data sources, details of uncertainty and probability distributions for individual LCI flows are not available. As a result, all LCI flows have been assigned an uncertainty of 10% and a normal probability distribution. When simulated using the Monte Carlo method, the results generated are equivalent to calculating LCIA results ± 10%. The results of these calculations assuming base case manufacturing and average EU grid usage are presented in Figure 26.

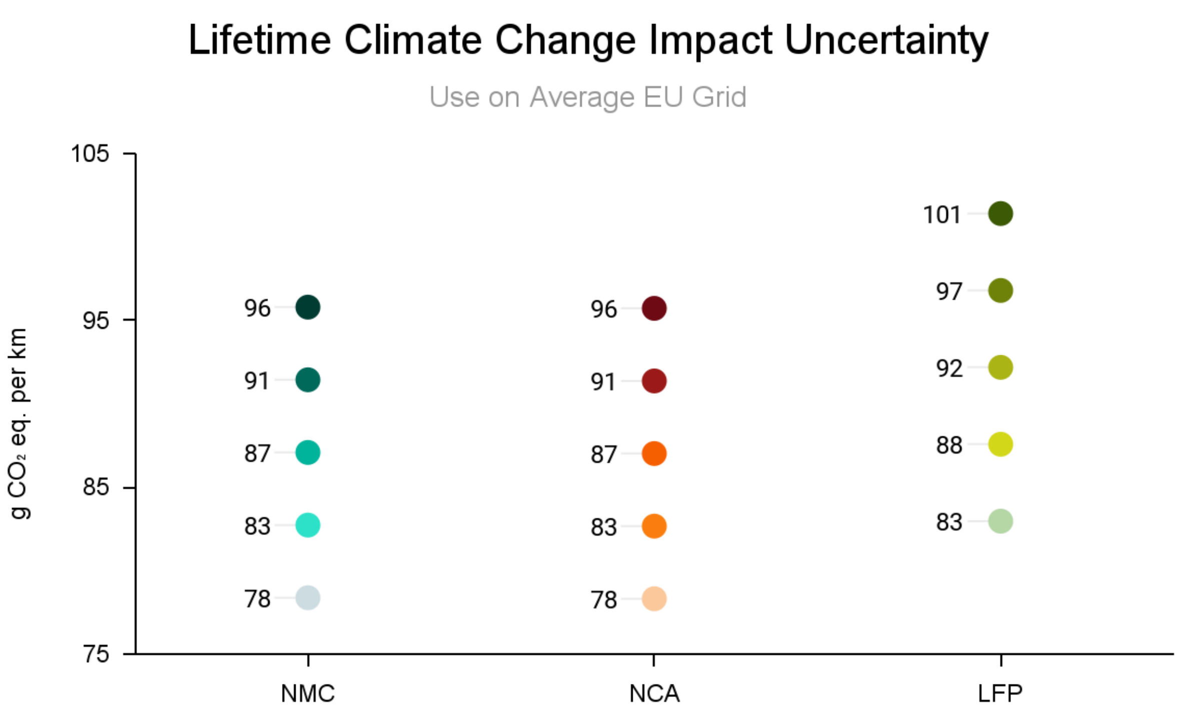

Figure 26: Climate Change Uncertainty for Lifetime Emissions. Lightest colours represent -10% and darkest represent +10%.

The results show considerable overlap between the lifetime emissions of all chemistries. For fixed 70.6 kWh capacity packs, results are similar for all chemistries. The difference between the highest and lowest lifetime climate change impact is 23 g CO_2 eq. per km. NMC and NCA display the lowest result with -10% producing a result of 78 g CO_2 eq. per km each. The result for LFP at -10% is 83 g CO_2 eq. per km. LFP displays the highest result with +10% producing a result of 101 g CO_2 eq. per km. The results for NMC and NCA at +10% are 96 g CO_2 eq. per km each.

5.3. Critical Review

Following internal review processes, a critical review was carried out by a panel of independent external experts, and together they cover the required competencies relevant to the critical review. The critical review was performed at the end of the LCA study. Details of the study review are included in Appendix B.

6. Conclusions and Recommendations

6.1. Conclusions

6.1.1. Manufacturing Climate Change Impact

Using base case raw material supply chains and energy sources, the total climate change impact for manufacturing battery packs of a fixed 70.6 kWh capacity are:

- 7,331 kg CO_2 eq. per fixed 70.6 kWh capacity NMC pack.
- 7,320 kg CO_2 eq. per fixed 70.6 kWh capacity NCA pack.
- 7,974 kg CO_2 eq. per fixed 70.6 kWh capacity LFP pack.

The total climate change impact results for manufacturing fixed capacity packs were found to be similar for all chemistries in the base case scenario (within 10% uncertainty). Cathode production is the largest contributor for NMC and NCA making up 33% and 34% of the total climate change impact, respectively. The high requirement for nickel sulphate hexahydrate is a climate change hotspot for these nickel-based chemistries.

Cell manufacturing electricity is the largest contributor for LFP making up 43% of the total climate change impact. This area is the second largest contributor for the nickel-based chemistries making up 33% of the total climate change impact for both NMC and NCA. The Jiangsu grid (CN-ECGC) modelled sources around 60% of its power from hard coal combustion resulting in a large climate change impact contribution from this area.

Anode production is the second largest contributing area for LFP and the third largest for NMC and NCA. It contributes 18% of the total climate change impact for NMC and LFP and 17% for NCA.

Per kWh Pack Capacity

The results per kWh pack capacity are presented in Figure 27.

Contribution analyses per kWh pack capacity show that cell manufacturing electricity, CAM, and AAM are the top three contributors for all chemistries. Individual CAM contribution analyses highlight that nickel is a hotspot in both nickel-based chemistries contributing around 33% to the total CAM impact and around 10% to the total per kWh impact. This contribution is largely due to the mass required to achieve the NMC 8:1:1 and NCA 8:1.5:0.5 ratios.

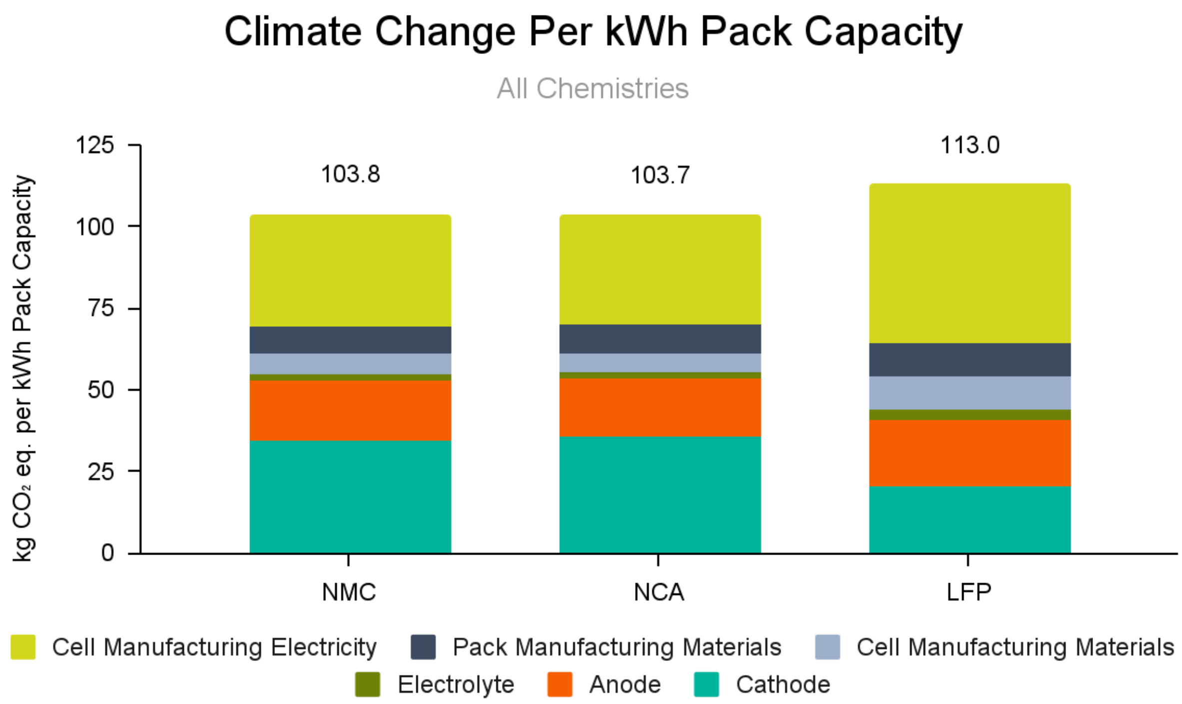

Figure 27: Climate Change Results for All Chemistries per kWh Pack Capacity.

Lithium carbonate is the most significant hotspot in LFP CAM making up around 40% of the CAM impact, and lithium hydroxide monohydrate is the third most significant contributor to the CAM impact in NMC and NCA after electricity. These lithium hotspots are largely driven by the embodied impact of lithium sourced from Australian spodumene that is refined in China.

AAM is a hotspot in all chemistries; it contributes around 15% to the total climate change impact for all chemistries. In the base case scenario, AAM is modelled as a combination of 60% anode-grade natural graphite produced in Heilongjiang, China, and 40% anode-grade synthetic graphite produced in Inner Mongolia, China. The embodied impact of the synthetic graphite is around 70% higher than that of the natural graphite meaning it is the largest single contributor to anode production.

Battery Manufacturing Sensitivity Analyses

A range of sensitivity analyses were performed on the manufacturing results to:

- assess the influence of low and high impact raw material and energy supply chains;
- isolate the influence of low and high impact cobalt supply chains;

- consider manufacturing in the Southeastern USA;
- and address the uncertainty of the cell manufacturing electricity data.

Variability in the embodied impact of key raw materials such as nickel, cobalt, lithium, graphite and aluminium highlights the dependence of manufacturing climate change impacts on supply chain choices. Details of the supply chains investigated can be found in Table 14 in section 3.1. The results of the sensitivity analyses are presented in Table 19.

Table 19: Summary of High and Low Impact Supply Chain Sensitivity Analysis for All Chemistries.

Chemistry	Low Impact Scenario	Base Case Result	High Impact Scenario	Percentage Change from Base Case
	kg CO_2 eq. per kWh pack capacity			
NMC	31.1	103.8	177.5	-70% to +71%
NCA	32.6	103.7	180.1	-69% to +74%
LFP	33.5	113.0	151.4	-70% to +34%

The main drivers of differences between the low / base case / high scenarios are intrinsically linked to the hotspots described previously with sources of cell manufacturing electricity, nickel, lithium, and graphite being accountable for the majority of the variance. Isolating the influence of high and low impact cobalt supply chains indicated that cobalt is not a hotspot in either NMC nor NCA, even when assuming a high impact Indonesian HPAL source.

Pack manufacturing (including production of pCAM and CAM) was also modelled on the Southeastern USA grid (US-SERC). As previously highlighted, the Jiangsu grid (CN-ECGC) modelled in the base case sources around 60% of its power from hard coal, but the dominant source of energy in the US-SERC mix is natural gas combustion (~45%). This results in an embodied impact around 45% lower than the Jiangsu grid of the base case scenario. Consequently, the contribution of cell manufacturing electricity decreases by 17.2 kg CO_2 eq. for NMC, 17.4 kg CO_2 eq. for NCA, and 20.3 kg CO_2 eq. for LFP.

A significant limitation of the LCA study is reliance on public data. The LCI source used for cell manufacturing calculates an average consumption of 37.43 ± 7.59 MJ per kg.[14] Due to the large uncertainty, sensitivity analysis was performed to assess the influence of more and less energy intensive manufacturing on the base case manufacturing scenario. When all other parameters are kept the same as the base case manufacturing scenario, increasing and decreasing cell manufacturing electricity consumption by ±7.59 MJ per kg changes the total climate change impact by ±7% for NMC and NCA, and ±9% for LFP.

6.2.2. Lifetime Climate Change Impact

Lifetime emissions for packs of a fixed 70.6 kWh capacity are similar for all three chemistries. Lifetime emissions vary between 58–62 g CO_2 eq. per km for the low impact grid scenario, 87–92 g CO_2 eq. per km for the average EU grid scenario, and 213–221 g CO_2 eq. per km for the high impact grid scenario.

Minor differences can be seen between the chemistries with LFP pack manufacturing and use-phase typically contributing slightly more than NMC / NCA. This trend is seen because the overall impact of manufacturing a fixed capacity LFP pack is slightly more than NMC / NCA (see section 4.1.1) and the energy density is lower (see section 2.3.1). The latter results in a higher pack mass and lower efficiency (see section 3.2). It should be noted that the lifetime emissions results in section 4.3 are within the 10% uncertainty assigned to the LCA study.

Significant differences in the relative contributions from each life cycle (i.e. manufacturing and use-phase) are seen when assessing use on different electricity mixes. When charging occurs on a lower than average impact European grid, manufacturing emissions contribute around 80% to the total lifetime emissions. When charging occurs on the average European grid, manufacturing emissions contribute around 50% to the total lifetime emissions. When charging occurs on a higher than average impact European grid, manufacturing emissions contribute around 20% to the total lifetime emissions.

Differences in the relative contributions from each life cycle stage highlights that the effectiveness of mitigation strategies can change depending on use location. When considering base case manufacturing supply chains and a use location where the carbon intensity of the grid is above the European average, the results indicate that grid decarbonisation in the use location may be more effective at reducing overall lifetime emissions. In use locations where the grid intensity is similar to or less than the European average, mitigation strategies in the manufacturing stage (e.g. low carbon raw material and energy sourcing) may be more effective at reducing overall lifetime emissions.

Whilst the end-gate across the different use scenarios is fixed at 160,000 kilometres, differing energy densities, ranges, and efficiencies result in a slightly higher cycle number for LFP at this end-gate than NMC / NCA. However, as LFP degradation is typically lower than for nickel-based chemistries, LFP shows a lower utilisation percentage compared to NMC and NCA (14% vs. 28%;

see Table 15). Whilst these additional results do not directly influence the lifetime climate change results of this LCA study, they should be considered alongside the LCIA results.

Readers should be aware that the results of the defined lifetime use-phase analyses represent the lifetime climate change impacts for a specific EV application with a fixed distance parameter. For all chemistries, this means the end-gate occurs before full utilisation is achieved (i.e. before the batteries reach 80% SoH). In a different application where the battery packs could be cycled until their true EoL, such as a stationary ESS, the different degradation rates and the lack of influence from efficiency / pack mass may generate significantly different lifetime climate change impact results.

In the context of the specific EV use-phase presented, these results highlight the importance of vehicle ecodesign and longevity. EV design strategy that considers required range and pack size, as well as prolonging the longevity of EV lifetime outside of the battery pack, could allow production of battery packs that use critical raw materials (e.g. cobalt, natural graphite, phosphorus, and lithium)[29] more efficiently. In theory this could allow all chemistries, particularly those with a longer maximum service life, to be utilised to a higher extent than in current standard EV applications assuming no second use-phase.[27]

To assess the potential difference in longevity between the chemistries, a sensitivity analysis was performed to assess the lifetime climate change impact normalised to one kWh energy delivered over the maximum service life. Maximum service life parameters are presented in Table 16 (section 3.2.1) and were calculated assuming a cycle life of 1,500 for the nickel-based chemistries and 3,000 for LFP (to 80% SoH). Cycle lives are based on an 80% DoD per cycle. It is likely that battery packs in an EV application will be cycled under much more aggressive conditions, resulting in a lower service life than laboratory estimates and therefore lower maximum service lives than calculated. The scenario assumes base case manufacturing routes and use on the average European grid.[28]

The results show that the lifetime climate change impact is around 12% lower for LFP compared to nickel-based chemistries when the functional unit is one kWh of energy delivered over the maximum service life (i.e. when decoupling the battery pack life from the life of the vehicle). Although the absolute lifetime impact is higher for LFP packs, the longer cycle life means it is spread over a longer maximum service life, which in a use case of 20,000 km per year[27] would require an unrealistic service life from a light duty vehicle of 56 years. The PEFCR for High Specific Energy Rechargeable Batteries for Mobile Applications[27] assumes 20,000 km per year for light duty vehicles as standard, for which vehicle warranties in general do not exceed 8 years.[30] This makes it clear that appropriate battery sizing, chemistry longevity, and more holistic ecodesign will need to be applied to EVs as a whole in order to reap the benefits of long lasting batteries.

6.2. Recommendations

Minviro has several recommendations to improve the quality of this LCA.

- The primary limitation to this study is the uncertainty associated with the LCI data. As this is a hypothetical manufacturing and use scenario, the LCIs and use-phase parameters were developed by Minviro from a range of public sources.[12-14] Where possible, this has been addressed by assessing alternative material and energy scenarios and performing uncertainty analysis on LCIA results. Operational data from manufacturers of each chemistry would greatly improve the quality of this LCA. This is particularly relevant for cell manufacturing electricity consumption where an average consumption proportional to mass was assumed.

- More specific background data would also enhance the quality of this study. A base case scenario was developed from available data but it is noted that not all geographies were covered in some of the sources used. This is particularly significant for nickel as it was found to be a hotspot for both NMC and NCA. Updated industry average nickel and cobalt LCAs would improve the accuracy of the results.

- Secondary use applications and EoL treatment were excluded from the system boundary of this LCA study. Whilst this was acceptable for a cradle-to-gate LCA and did not inhibit the specific goals of this study, these exclusions inhibit interpretation of recyclability for different battery chemistries. Extending the system boundary to include these life cycle stages (i.e. a cradle-to-grave LCA) may change lifetime climate change results significantly.

- The results of the analyses represent the lifetime climate change impacts for a specific EV application scenario with a fixed distance parameter. For all chemistries, this means the end-gate occurs before full utilisation is achieved (i.e. before the batteries reach 80%

SoH). In a different application where the battery packs could be cycled until their true EoL, such as a stationary ESS), the different degradation rates and the lack of influence from pack mass may generate significantly different lifetime climate change impact results than those presented here. This may require assessment of alternative functional units.

- LCA is a suitable method for determining potential impacts on a global scale and it is recommended to be used in conjunction with local impact assessments for specific operations. In addition, whilst the selection of the climate change impact category satisfied the goal of the study, it does result in limited consideration of environmental burden shifting and circularity benefits with respect to the other EF impact categories.

- It is recommended that stakeholders in the battery value chain consider the results of this assessment in future design decisions. The results highlight the significance of low carbon material and energy sources. The potential to decarbonise EV production and use is great but will depend on more efficient use of low carbon raw materials and energy sources in the manufacturing of more efficient, higher energy density battery packs. Considering ecodesign and longevity when making these decisions can also ensure better utilisation of all battery chemistries, particularly those with longer cycle lives.

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Appendix A - Energy, Material, and Emissions Flow Summaries

NMC

Inventory Item	Background Data / Description	Data Source	Country Code	Inventory Value	Unit	Reference Unit
Cathode						
Nickel Sulphate Hexahydrate	Industry Average	Nickel Institute	[GLO]	2.2767	kg	per kg pCAM
Cobalt Sulphate Heptahydrate	Industry Average	Cobalt Institute	[GLO]	0.3077	kg	per kg pCAM
Manganese Sulphate Monohydrate	Mining in South Africa. Refining in China.	Internal Minviro Model	[GLO]	0.1792	kg	per kg pCAM
Sodium Hydroxide	market for sodium hydroxide, without water, in 50% solution state	Ecoinvent 3.9.1	[GLO]	0.8900	kg	per kg pCAM
Ammonium Hydroxide	ammonium hydroxide (Carbon Minds)	Carbon Minds	[GLO]	0.1240	kg	per kg pCAM
Natural Gas - pCAM	heat production, natural gas, at industrial furnace >100kW	Ecoinvent 3.9.1	[RoW]	40.7000	MJ	per kg pCAM
Water	market group for tap water	Ecoinvent 3.9.1	[GLO]	0.6400	kg	per kg pCAM
Lithium Hydroxide Monohydrate	58% Australian Spodumene. 42% Chilean Brine.	Internal Minviro Models	[GLO]	0.4375	kg	per kg CAM
Electricity - CAM	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	8.0000	kWh	per kg CAM
Cathode Active Material (CAM)	-	-	-	0.0260	kg	cell
Carbon Black - Cathode	market for carbon black	Ecoinvent 3.9.1	[GLO]	0.0007	kg	cell
PVDF Binder - Cathode	polyvinylidene fluoride (CarbonMinds)	Carbon Minds	[GLO]	0.0013	kg	cell
CMC Binder - Cathode	market for carboxymethyl cellulose, powder	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
SBR Binder - Cathode	market for acrylonitrile-butadiene-styrene copolymer	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
NMP Solvent - Cathode	market for N-methyl-2-pyrrolidone	Ecoinvent 3.9.1	[GLO]	0.0002	kg	cell
Aluminium Foil - Cathode	aluminium collector foil production, for Li-ion battery	Ecoinvent 3.9.1	[GLO]	0.0025	kg	cell
Anode						
Anode Active Material (AAM)	60% Natural, Heilongjiang. 40% Synthetic, Inner Mongolia.	Internal Minviro Models	[GLO]	0.0197	kg	cell
Carbon Black - Anode	market for carbon black	Ecoinvent 3.9.1	[GLO]	0.0005	kg	cell
PVDF Binder - Anode	polyvinylidene fluoride (CarbonMinds)	Carbon Minds	[GLO]	0.0013	kg	cell
CMC Binder - Anode	market for carboxymethyl cellulose, powder	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
SBR Binder - Anode	market for acrylonitrile-butadiene-styrene copolymer	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
NMP Solvent - Anode	market for N-methyl-2-pyrrolidone	Ecoinvent 3.9.1	[GLO]	0.0001	kg	cell
Copper Foil - Anode	copper collector foil production, for Li-ion battery	Ecoinvent 3.9.1	[GLO]	0.0057	kg	cell
Cell Materials						
Separator (Cell)	battery separator production	Ecoinvent 3.9.1	[CN]	0.0013	kg	cell
Polypropylene (Cell)	market for polypropylene, granulate	Ecoinvent 3.9.1	[GLO]	0.0011	kg	cell
Polyethylene (Cell)	market for polyethylene, high density, granulate	Ecoinvent 3.9.1	[GLO]	0.0003	kg	cell

Polyethylene Terephthalate (Cell)	market for polyethylene terephthalate, granulate, amorphous	Ecoinvent 3.9.1	[GLO]	0.0003	kg	cell
Steel can (Cell)	market for steel, chromium steel 18/8	Ecoinvent 3.9.1	[GLO]	0.0163	kg	cell
Pack Materials						
Copper (Pack)	market for metal part of electronics scrap, in copper, anode	Ecoinvent 3.9.1	[GLO]	0.5200	kg	pack
Aluminium (Pack)	market for aluminium alloy, AlMg3	Ecoinvent 3.9.1	[GLO]	40.9800	kg	pack
Steel (Pack)	market for steel, chromium steel 18/8	Ecoinvent 3.9.1	[GLO]	1.7800	kg	pack
Plastic (Pack)	market for polyethylene, high density, granulate	Ecoinvent 3.9.1	[GLO]	0.1300	kg	pack
Insulation (Pack)	market for polypropylene, granulate	Ecoinvent 3.9.1	[GLO]	1.0500	kg	pack
Coolant (Pack)	market for ethylene glycol	Ecoinvent 3.9.1	[GLO]	8.4700	kg	pack
Battery Management System (Pack)	market for battery management system, for Li-ion battery	Ecoinvent 3.9.1	[GLO]	5.3400	kg	pack
Cell Manufacturing Electricity						
Electricity - Anode Mixing	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0360	kWh	kWh in cell
Electricity - Cathode Mixing	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0660	kWh	kWh in cell
Electricity - Anode Coating	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0080	kWh	kWh in cell
Electricity - Cathode Coating	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0080	kWh	kWh in cell
Electricity - Anode Drying	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	5.2460	kWh	kWh in cell
Electricity - Cathode Drying	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	16.3370	kWh	kWh in cell
Electricity - Anode Calendering	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0010	kWh	kWh in cell
Electricity - Cathode Calendering	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0010	kWh	kWh in cell
Electricity - Separation	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.1600	kWh	kWh in cell
Electricity - Stacking and Packing	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.2500	kWh	kWh in cell
Electricity - Vacuum Drying	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	1.5700	kWh	kWh in cell
Electricity - Electrolyte Filling	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0010	kWh	kWh in cell
Electricity - Formation	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	1.4730	kWh	kWh in cell
Electricity - Aging	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.4000	kWh	kWh in cell
Electricity - Dry Room	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	21.3050	kWh	kWh in cell
Electricity - Auxiliaries	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.6000	kWh	kWh in cell
Electrolyte						
Electrolyte - $LiPF_6$	market for lithium hexafluorophosphate	Ecoinvent 3.9.1	[GLO]	0.0013	kg	cell
Electrolyte - Ethylene Carbonate	market for ethylene carbonate	Ecoinvent 3.9.1	[GLO]	0.0032	kg	cell
Electrolyte - Dimethyl Carbonate	market for dimethyl carbonate	Ecoinvent 3.9.1	[GLO]	0.0025	kg	cell

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NCA

Inventory Item	Background Data / Description	Data Source	Country Code	Inventory Value	Unit	Reference Unit
Cathode						
Nickel Sulphate Hexahydrate	Industry Average	Nickel Institute	[GLO]	2.3120	kg	per kg pCAM
Cobalt sulphate Heptahydrate	Industry Average	Cobalt Institute	[GLO]	0.4706	kg	per kg pCAM
Aluminium Sulphate Monohydrate	market for aluminium sulfate, powder	Ecoinvent 3.9.1	[RoW]	0.0900	kg	per kg pCAM
Sodium Hydroxide	market for sodium hydroxide, without water, in 50% solution state	Ecoinvent 3.9.1	[GLO]	0.8900	kg	per kg pCAM
Electricity - pCAM	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0100	kWh	per kg pCAM
Natural Gas - pCAM	heat production, natural gas, at industrial furnace >100kW	Ecoinvent 3.9.1	[RoW]	0.1300	MJ	per kg pCAM
Ammonia	market for ammonia, anhydrous, liquid	Ecoinvent 3.9.1	[CN]	0.3700	kg	per kg pCAM
Lithium Hydroxide Monohydrate	58% Australian Spodumene. 42% Chilean Brine.	Internal Minviro Models	[GLO]	0.4375	kg	per kg CAM
Oxygen	market for oxygen, liquid	Ecoinvent 3.9.1	[RoW]	0.0400	kg	per kg CAM
Electricity - CAM	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	8.0000	kWh	per kg CAM
Cathode Active Material (CAM)	-	-	-	0.0284	kg	cell
Carbon Black - Cathode	market for carbon black	Ecoinvent 3.9.1	[GLO]	0.0003	kg	cell
PVDF Binder - Cathode	polyvinylidene fluoride (CarbonMinds)	Carbon Minds	[GLO]	0.0007	kg	cell
CMC Binder - Cathode	market for carboxymethyl cellulose, powder	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
SBR Binder - Cathode	market for acrylonitrile-butadiene-styrene copolymer	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
NMP Solvent - Cathode	market for N-methyl-2-pyrrolidone	Ecoinvent 3.9.1	[GLO]	0.0002	kg	cell
Aluminium Foil - Cathode	aluminium collector foil production, for Li-ion battery	Ecoinvent 3.9.1	[GLO]	0.0024	kg	cell
Anode						
Anode Active Material (AAM)	60% Natural, Heilongjiang. 40% Synthetic, Inner Mongolia.	Internal Minviro Models	[GLO]	0.0197	kg	cell
Carbon Black - Anode	market for carbon black	Ecoinvent 3.9.1	[GLO]	0.0002	kg	cell
PVDF Binder - Anode	polyvinylidene fluoride (CarbonMinds)	Carbon Minds	[GLO]	0.0007	kg	cell
CMC Binder - Anode	market for carboxymethyl cellulose, powder	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
SBR Binder - Anode	market for acrylonitrile-butadiene-styrene copolymer	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
NMP Solvent - Anode	market for N-methyl-2-pyrrolidone	Ecoinvent 3.9.1	[GLO]	0.0001	kg	cell
Copper Foil - Anode	copper collector foil production, for Li-ion battery	Ecoinvent 3.9.1	[GLO]	0.0054	kg	cell
Cell Materials						
Separator (Cell)	battery separator production	Ecoinvent 3.9.1	[CN]	0.0012	kg	cell
Polypropylene (Cell)	market for polypropylene, granulate	Ecoinvent 3.9.1	[GLO]	0.0009	kg	cell
Polyethylene (Cell)	market for polyethylene, high density, granulate	Ecoinvent 3.9.1	[GLO]	0.0002	kg	cell

Polyethylene Terephthalate (Cell)	market for polyethylene terephthalate, granulate, amorphous	Ecoinvent 3.9.1	[GLO]	0.0003	kg	cell
Steel can (Cell)	market for steel, chromium steel 18/8	Ecoinvent 3.9.1	[GLO]	0.0160	kg	cell
Pack Materials						
Copper (Pack)	market for metal part of electronics scrap, in copper, anode	Ecoinvent 3.9.1	[GLO]	0.5200	kg	pack
Aluminium (Pack)	market for aluminium alloy, AlMg3	Ecoinvent 3.9.1	[GLO]	39.9400	kg	pack
Plastic (Pack)	market for polyethylene, high density, granulate	Ecoinvent 3.9.1	[GLO]	0.1300	kg	pack
Insulation (Pack)	market for polypropylene, granulate	Ecoinvent 3.9.1	[GLO]	1.0400	kg	pack
Battery Management System (Pack)	market for battery management system, for Li-ion battery	Ecoinvent 3.9.1	[GLO]	5.3500	kg	pack
Steel (Pack)	market for steel, chromium steel 18/8	Ecoinvent 3.9.1	[GLO]	1.6900	kg	pack
Coolant (Pack)	market for ethylene glycol	Ecoinvent 3.9.1	[GLO]	8.9700	kg	pack
Cell Manufacturing Electricity						
Electricity - Anode Mixing	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0360	kWh	kWh in cell
Electricity - Cathode Mixing	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0660	kWh	kWh in cell
Electricity - Anode Coating	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0080	kWh	kWh in cell
Electricity - Cathode Coating	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0080	kWh	kWh in cell
Electricity - Anode Drying	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	5.2460	kWh	kWh in cell
Electricity - Cathode Drying	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	16.3370	kWh	kWh in cell
Electricity - Anode Calendering	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0010	kWh	kWh in cell
Electricity - Cathode Calendering	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0010	kWh	kWh in cell
Electricity - Separation	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.1600	kWh	kWh in cell
Electricity - Stacking and Packing	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.2500	kWh	kWh in cell
Electricity - Vacuum Drying	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	1.5700	kWh	kWh in cell
Electricity - Electrolyte Filling	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0010	kWh	kWh in cell
Electricity - Formation	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	1.4730	kWh	kWh in cell
Electricity - Aging	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.4000	kWh	kWh in cell
Electricity - Dry Room	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	21.3050	kWh	kWh in cell
Electricity - Auxiliaries	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.6000	kWh	kWh in cell
Electrolyte						
Electrolyte - $LiPF_6$	market for lithium hexafluorophosphate	Ecoinvent 3.9.1	[GLO]	0.0012	kg	cell
Electrolyte - Ethylene Carbonate	market for ethylene carbonate	Ecoinvent 3.9.1	[GLO]	0.0031	kg	cell
Electrolyte - Dimethyl Carbonate	market for dimethyl carbonate	Ecoinvent 3.9.1	[GLO]	0.0025	kg	cell

LFP

Inventory Item	Background Data / Description	Data Source	Country Code	Inventory Value	Unit	Reference Unit
		Cathode				
Iron Sulphate	market for iron sulfate	Ecoinvent 3.9.1	[RoW]	0.8080	kg	per kg pCAM
Phosphoric Acid	Adjusted for 35% concentration	Ecoinvent 3.9.1	[GLO]	1.8000	kg	per kg pCAM
Hydrogen Peroxide	Adjusted for 27.5% concentration	Ecoinvent 3.9.1	[RoW]	0.3310	kg	per kg pCAM
Sodium Hydroxide	Adjusted for 30% concentration	Ecoinvent 3.9.1	[GLO]	1.8500	kg	per kg pCAM
Electricity - pCAM	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.9270	kWh	per kg pCAM
Natural Gas - pCAM	heat production, natural gas, at industrial furnace >100kW	Ecoinvent 3.9.1	[RoW]	7.6220	MJ	per kg pCAM
Water	market for water, deionised	Ecoinvent 3.9.1	[RoW]	50.0000	kg	per kg pCAM
Lithium Carbonate	58% Australian Spodumene. 42% Chilean Brine.	Internal Minviro Models	[GLO]	0.2380	kg	per kg CAM
Glucose	market for glucose	Ecoinvent 3.9.1	[GLO]	0.0968	kg	per kg CAM
Nitrogen	market for nitrogen, liquid	Ecoinvent 3.9.1	[RoW]	0.2170	kg	per kg CAM
De-ionised Water	market for water, deionised	Ecoinvent 3.9.1	[RoW]	0.0031	kg	per kg CAM
Electricity - CAM	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.4960	kWh	per kg CAM
Natural Gas - CAM	heat production, natural gas, at industrial furnace >100kW	Ecoinvent 3.9.1	[RoW]	19.2400	MJ	per kg CAM
Direct Emissions	Carbon Dioxide Emissions	EU Emissions Database	[GLO]	0.1047	kg	per kg CAM
Cathode Active Material (CAM)	-	-	-	0.0235	kg	cell
Carbon Black - Cathode	market for carbon black	Ecoinvent 3.9.1	[GLO]	0.0006	kg	cell
PVDF Binder - Cathode	polyvinylidene fluoride (CarbonMinds)	Carbon Minds	[GLO]	0.0003	kg	cell
CMC Binder - Cathode	market for carboxymethyl cellulose, powder	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
SBR Binder - Cathode	market for acrylonitrile-butadiene-styrene copolymer	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
NMP Solvent - Cathode	market for N-methyl-2-pyrrolidone	Ecoinvent 3.9.1	[GLO]	0.0002	kg	cell
Aluminium Foil - Cathode	aluminium collector foil production, for Li-ion battery	Ecoinvent 3.9.1	[GLO]	0.0023	kg	cell
		Anode				
Anode Active Material (AAM)	60% Natural, Heilongjiang. 40% Synthetic, Inner Mongolia.	Internal Minviro Models	[GLO]	0.0127	kg	cell
Carbon Black - Anode	market for carbon black	Ecoinvent 3.9.1	[GLO]	0.0006	kg	cell
PVDF Binder - Anode	polyvinylidene fluoride (CarbonMinds)	Carbon Minds	[GLO]	0.0002	kg	cell
CMC Binder - Anode	market for carboxymethyl cellulose, powder	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
SBR Binder - Anode	market for acrylonitrile-butadiene-styrene copolymer	Ecoinvent 3.9.1	[GLO]	0.0000	kg	cell
NMP Solvent - Anode	market for N-methyl-2-pyrrolidone	Ecoinvent 3.9.1	[GLO]	0.0001	kg	cell
Copper Foil - Anode	copper collector foil production, for Li-ion battery	Ecoinvent 3.9.1	[GLO]	0.0052	kg	cell

Cell Materials						
Separator (Cell)	battery separator production	Ecoinvent 3.9.1	[CN]	0.0012	kg	cell
Polypropylene (Cell)	market for polypropylene, granulate	Ecoinvent 3.9.1	[GLO]	0.0009	kg	cell
Polyethylene (Cell)	market for polyethylene, high density, granulate	Ecoinvent 3.9.1	[GLO]	0.0002	kg	cell
Polyethylene Terephthalate (Cell)	market for polyethylene terephthalate, granulate, amorphous	Ecoinvent 3.9.1	[GLO]	0.0002	kg	cell
Steel can (Cell)	market for steel, chromium steel 18/8	Ecoinvent 3.9.1	[GLO]	0.0160	kg	cell
Pack Materials						
Copper (Pack)	market for metal part of electronics scrap, in copper, anode	Ecoinvent 3.9.1	[GLO]	0.5700	kg	pack
Aluminium (Pack)	market for aluminium alloy, AlMg3	Ecoinvent 3.9.1	[GLO]	52.5000	kg	pack
Steel (Pack)	market for steel, chromium steel 18/8	Ecoinvent 3.9.1	[GLO]	2.7100	kg	pack
Plastic (Pack)	market for polyethylene, high density, granulate	Ecoinvent 3.9.1	[GLO]	0.1300	kg	pack
Insulation (Pack)	market for polypropylene, granulate	Ecoinvent 3.9.1	[GLO]	1.0500	kg	pack
Coolant (Pack)	market for ethylene glycol	Ecoinvent 3.9.1	[GLO]	10.9400	kg	pack
Battery Management System (Pack)	market for battery management system, for Li-ion battery	Ecoinvent 3.9.1	[GLO]	5.6200	kg	pack
Cell Manufacturing Electricity						
Electricity - Anode Mixing	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0360	kWh	kWh in cell
Electricity - Cathode Mixing	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0660	kWh	kWh in cell
Electricity - Anode Coating	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0080	kWh	kWh in cell
Electricity - Cathode Coating	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0080	kWh	kWh in cell
Electricity - Anode Drying	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	5.2460	kWh	kWh in cell
Electricity - Cathode Drying	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	16.3370	kWh	kWh in cell
Electricity - Anode Calendering	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0010	kWh	kWh in cell
Electricity - Cathode Calendering	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0010	kWh	kWh in cell
Electricity - Separation	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.1600	kWh	kWh in cell
Electricity - Stacking and Packing	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.2500	kWh	kWh in cell
Electricity - Vacuum Drying	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	1.5700	kWh	kWh in cell
Electricity - Electrolyte Filling	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.0010	kWh	kWh in cell
Electricity - Formation	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	1.4730	kWh	kWh in cell
Electricity - Aging	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.4000	kWh	kWh in cell
Electricity - Dry Room	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	21.3050	kWh	kWh in cell
Electricity - Auxiliaries	market for electricity, medium voltage	Ecoinvent 3.9.1	[CN-ECGC]	0.6000	kWh	kWh in cell
Electrolyte						
Electrolyte - $LiPF_6$	market for lithium hexafluorophosphate	Ecoinvent 3.9.1	[GLO]	0.0013	kg	cell
Electrolyte - Ethylene Carbonate	market for ethylene carbonate	Ecoinvent 3.9.1	[GLO]	0.0032	kg	cell
Electrolyte - Dimethyl Carbonate	market for dimethyl carbonate	Ecoinvent 3.9.1	[GLO]	0.0026	kg	cell

Appendix B - Critical Review Summary

CRITICAL REVIEW STATEMENT

Study Name	**CLIMATE CHANGE ANALYSIS OF MANUFACTURING AND USING LITHIUM ION BATTERIES** **Dated**: 29 May 2024 **Version**: 5.0
Commissioner of LCA Study	Cobalt Institute 3rd floor, 45 Albemarle St, London W1S 4JL
Practitioners of LCA Study	Minviro Ltd Metal Box Factory, 101 30 Great Guildford St, London SE1 0HS
Critical Review Panel Members	**Chairperson**: Evangelos Kallitsis Evangelos Kallitsis, Research Associate, Imperial College London, United Kingdom **Panelist**: Laura Lander (Lecturer, King's College London, United Kingdom) **Panelist**: Lyle Trytten (President, Trytten Consulting Services)

Scope of the Critical Panel Review

The critical panel review process has been carried out following international standards for life cycle assessment (LCA) 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, Genève, Switzerland.
  - ISO-14067:2018 Greenhouse Gases — Carbon Footprint of Products — Requirements and Guidelines for Quantification. International Standard Organization (ISO), Genève, Switzerland.
- 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 (LCI), impact assessment methodologies, characterisation factors, calculated LCI and LCI analysis results, and interpretation.

Critical (Panel) Review Process

In December 2023, Evangelos Kallitsis, Laura Lander, and Lyle Trytten were engaged by the practitioner of the LCA study, 'Minviro Ltd', to perform an independent expert critical panel review on the CLIMATE CHANGE ANALYSIS OF MANUFACTURING AND USING LITHIUM ION BATTERIES. The LCA study was commissioned to Minviro by Cobalt Institute, and it investigates the life cycle impacts of the production and use of NMC811, NCA, and LFP battery packs.

The critical review was carried out at the end of the study and was performed on v2 – v5 of the report. As part of the review, the LCA models and use of foreground and background datasets were evaluated. The critical review consisted of three rounds of comments with v5 sent back to the panel on Wednesday 29 May 2024. This version was reviewed and sign-off from all three reviewers was received on Monday 10 June 2024. The comments and responses for all three rounds of the critical review are in 'Appendix B - Critical Review Summary'.

Study Evaluation

The LCA study has certain strengths, limitations and potential improvements as described throughout. 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 and ISO-14067. This is the critical review statement prepared on 12 June 2024 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 and ISO-14067:2018. The report is considered an appropriate summary of the study's goal, scope, methodology, assumptions, LCI, 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):

Evangelos Kallitsis Review Chairperson Imperial College London June 14th, 2024	Laura Lander Review Panelist King's College London 18th June, 2024	Lyle Trytten Review Panelist Trytten Consulting Services June 12, 2024

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ADDENDUM TO CRITICAL REVIEW STATEMENT

Study Name	**CLIMATE CHANGE ANALYSIS OF MANUFACTURING AND USING LITHIUM ION BATTERIES** **Dated**: 28 August 2024 **Version**: 5.2
Commissioner of LCA Study	Cobalt Institute 3rd floor, 45 Albemarle St, London W1S 4JL
Practitioners of LCA Study	Minviro Ltd Metal Box Factory, 005 30 Great Guildford St, London SE1 0HS
Critical Review Panel Members	**Chairperson**: Evangelos Kallitsis, Research Associate, Imperial College London, United Kingdom **Panelist**: Laura Lander (Lecturer, King's College London, United Kingdom) **Panelist**: Lyle Trytten (President, Trytten Consulting Services)

An additional round of review on version 5.1 of the report was conducted by the review chairperson on 23 August 2024. The additional round of review was to assess minor textual changes and enhancement of figure quality at the request of the LCA study commissioner. The changes totalled < 1,000 words and are confirmed not to have affected the results, conclusions, or ISO-compliance of the study.

This is the critical review addendum prepared on 28 August 2024 and, after being submitted to Minviro Ltd, shall be part of the final LCA report.

Conclusions

The critically reviewed LCA study, inclusive of minor textual changes, complies with ISO-14040:2006 and ISO-14067:2018. The report is considered an appropriate summary of the study's goal, scope, methodology, assumptions, LCI, quality of foreground and background data, results, and interpretation of sensitivities.

[signature]	Evangelos Kallitsis Review Chairperson Imperial College London 03 September 2024

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 and ISO 14044

☒ 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: June 14th, 2024

Name (print): Evangelos Kallitsis

Signature:

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 and ISO 14044

☒ 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: 18th June, 2024

Name (print): Laura Lander

Signature: 

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 and ISO 14044

☒ 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: June 12, 2024

Name (print): Lyle Trytten

Signature:

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Critical Review Comments - Round 1

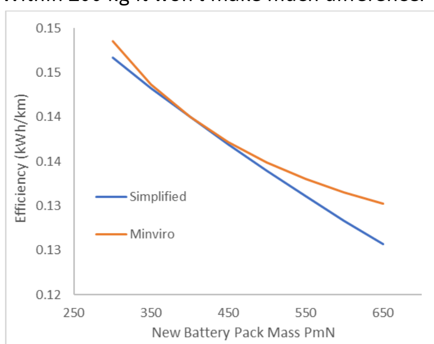
Initials	Index	Pg.	Section/ Figure /Table	Type of comment	Reviewer comments	Reviewer recommendation	Practitioner response
LL	1	5	Executive Summary	te	"Due to uncertainty in the LCI data source for cell manufacturing electricity, a sensitivity analysis was performed which showed variation of ±9.1 kg CO2 eq. per kWh pack for all chemistries" The values for the chemistries in low impact and industry scenarios for all chemistries are relatively close – a difference in 9.1 kg CO2eq would be able to change the trend in both cases. How reliable are the conclusions then in terms of trend?		Statements and conclusions throughout have been revised to highlight the closeness of results in the low impact and base case scenarios.
LL	2	8	Executive Summary	te	"With the aforementioned in mind, the results highlight that consumers could obtain the same EV range using less critical raw materials when the battery packs are higher energy density NMC / NCA chemistries." It is stated in that sentence that using NMC/NCA materials in a pack can reduce the use of critical materials compared to LFP. Has this been proven? NMC/NCA batteries use more critical elements (nickel, cobalt, lithium, graphite) than LFP batteries (lithium, graphite, phosphate rock). It would depend on the mass ratios and used mass of critical materials to be able to state that less critical materials are used in NMC/NCA batteries. Similarly written also on page 68 in Results section. On page 44 it is phrased as "lesser volume of more impactful materials" – this might be a better way of phrasing.	To be more prudent, it could be stated that "less material is used" instead of "less critical material".	Where critical raw materials are mentioned, examples of cobalt, natural graphite and lithium have been added as well as a reference to the EU critical raw material list published in 2020. Statements around critical raw material use in specific chemistries have been removed.
LL	3		Executive summary		A more detailed discussion of the choice of assessed life cycle impact category is missing. This should be at least clearly mentioned that only GWP is assessed. I saw it has been mentioned on page 26 in 2.3.1. in detail. If just a sentence on this could	Please add a sentence specifying which LCI category is assessed and that others have been excluded. If there is a specific reason for this (e.g. GWP is the most important impact etc.) please state so.	Sentences added specifying quantification of climate change only in accordance with ISO14067 and the importance of this to the members of the CI given incoming battery regs.

					be added in the executive summary that would be useful.		
LL	4	10	List of Tables		Table 2 in List of Tables has a different name than the caption of Table 2 in the text. Also, Table 2 and Table 4 (page 18) have very similar captions.	Please modify either the caption of Table 2 or the name of Table 2 in the "List of Tables" to be consistent.	All tables revised.
LL	5	17	2.1.	ed	"point of raw material extraction (e.g. raw material extraction)" ... Repetition of "raw material extraction". Maybe more useful to add one of the raw materials.	Please revise sentence and either remove parenthesis or modify it.	Sentence revised.
LL	6	18	2.1.	ed	"impact of battery use is accounted for" ... The sentence might be misleading as it mentions only battery use. Maybe it would be more complete to write "impact of battery manufacturing and use are accounted for"	Please revise sentence and modify is required	Sentence revised.
LL	7	18	2.22	ed	"With demand predicted to reach 4,700 GWh by 2030,"... Does this refer to global demand? Does this refer to demand in the EV sector or also including other applications?	Please specify if the demand is global and if it includes other applications or refers to EVs only	Updated to: Demand for Li-ion batteries is predicted to reach 4,700 GWh by 2030, and with the majority of this demand required for mobility applications,[8] research and development in the sector is thriving and has led to the evolution of multiple Li-ion battery chemistries.
LL	8	23	2.3.1. Table 6		Would it be possible to add the references used for the data to the table caption, please?	Please add references	Caption updated to include references and footnote added on cycle life.
LL	9	31	3.1.	ed	"It is recognised that in a more realistic scenario, it is likely that different production stages would occur in separate facilities and would not necessarily all be under the direct control of the battery manufacturer. Furthermore, it should be noted that whilst the majority of Li-ion battery manufacturing does occur in China,8 production of the chemistries studied does not necessarily occur in the same province." The same has been written on page 24 "Pack Assembly". It makes sense in both spots, but maybe it can be rephrased so it doesn't seem just copied.	Please rephrase in one of the sections or delete paragraph on page 24.	Rephrased in section 3.1 so not to be an exact repeat of page 24.
LL	10	31	3.1.	ed	It is written sodium sulphate, in the rest of report is written sulfate (BE vs AE).	Please be consistent across report on how to write sulphate/sulfate	Updated to sulphate.

LL	11	33	Figure 5	te	In the low impact electricity mix, 5.4 % are noted as imported. Is it known what the electricity source is?	Please specify electricity source if known	Figure removed. Main energy sources for mixed are given in table 12. Details for ecoinvent mixes can be found in ecoinvent files (background data descriptions given in report for electricity and in Appendix A).
LL	12	35	Table 10	ed	Row – Cobalt, high impact: HPAL, Indonesian Should be written Indonesia Row - Iron phosphate, high impact: "Phosphoric acid refined from fertiliser grade phosphoric acid, China". It is the same as in the industry representative scenario (Table 9). Is there any difference e.g. location? If so please specify	Please change Indonesian to Indonesia Please specify the difference to industry representative scenario.	Updated to Indonesia. Specified it is the same background data as the industry representative scenario.
LL	13	41	4.1. Fixed capacity	te	Would it be possible to add a section outlining the mass for each component/material for the three battery chemistries in the various scenarios (fixed capacity, fixed volume). It would facilitate the understanding of the differences in materials requirements and the outcomes of the LCA	Please add a table specifying the mass ratios/materials requirements for the battery chemistries for the scenarios fixed capacity/fixed volume	I agree this information is useful but I fear the report would become too lengthy and the results may be lost. More references to the BOMs in Appendix A have been included throughout - they contain all the required mass information.
LL	14	52	4.2.1.	ed	"The climate change impact per kWh NMC pack varies by 149.9 kg CO2 eq. between the low impact scenario at 30.7 kg CO2 eq. per kWh NMC pack and 180.6 kg CO2 eq. per kWh NMC pack (Figure 17)." "High impact scenario" is missing in this sentence	Please add "high impact scenario" "The climate change impact per kWh NMC pack varies by 149.9 kg CO2 eq. between the low impact scenario at 30.7 kg CO2 eq. per kWh NMC pack and 180.6 kg CO2 eq. per kWh NMC pack in the high impact scenario (Figure 17)." Same on page 54 for NCA and page 55 for LFP. Please add "high impact scenario"	Updated for all chemistries.
LL	15	74	5.3.	ed	"For fixed 4,41 cell packs,"... 4,416 cell packs is meant?	Please revise and modify	Corrected.
LL	16	Ove rall		te	In the model it is assumed that cell manufacturing electricity consumption scales with capacity. Whilst a caveat has been added (page 34) and a sensitivity analysis, intuitively I would have expected that the cell manufacturing electricity scales more with the	No action needed	Please see response to other comments on this topic.

					size of the cell/amount of material used etc. than it does with capacity.		
	1			GE	Overall, I don't think the Fixed Volume case adds value. EVs are specified with a total kWh basis to deliver a certain outcome. I would have no problem eliminating this portion, but ok to keep it in as well.		The fixed volume case was added at the request of the CI. It does become significant for energy delivered over max service life and lifetime emissions.
LCT	2	5	Figure 1	GE	Figure 1 doesn't show higher per cell, that is the interpretation derived from similar per kWh values. The sensitivity analysis suggest that at Industry Average, you can't really say that NMC/NCA are higher than LFP, they are the same within the accuracy of the study. Probably the same at Low Impact case, but accept that the High Impact case is different. May change wording of conclusion. Always be careful about stating a number is higher or lower when within the bounds of typical accuracy. The impacts do not APPEAR closer, they ARE closer. Appear makes it seem interpretative vs simple results-based.	Move per kWh statements to front, move per cell statements to end. Consider whether you can conclude that 99 or 100 is actually different than 97. Eliminate language that suggests things are other than as shown.	Per cell statements removed throughout. Descriptions revised through to highlight results are very close in both the low impact supply chain and industry representative scenarios. The high impact supply chain scenario is the only one where a real difference is seen. Language update throughout to be definitive.
LCT	3	4	Table 3	GE	The use phase is set as 160,000 km, not 8 years. The 8 years may be typical but is not directly related.	Revise to remove 8 years. Correct other similar references (i.e. 3.2, 3.4 reference to distance AND time, 4.2.5, etc)	8 years removed throughout other than in reference to PEF assumptions.
LCT		23	Table 6	TE	Something seems off here – need to check models. For FV, NMC/NCA go 4.7 km/kWh while LFP goes 6.24. 32% more efficient seems very odd considering that vehicle is 73 kg lighter which is ~3% of total vehicle weight. Similar issue on FC with LFP 13% less efficient. Specific energy densities don't agree with kWh and kg for FC cases (0.201 vs 0.248, 0.203 vs 0.251, 0.158 vs 0.174). Specific energy densities do match for FC cases.	Check efficiency calculations.	Range removed from this table as not relevant. See further efficiency comments below. Specific energy density calculations checked and updated. Following sentence added to text: Note that specific energy density does not differ between fixed capacity and fixed volume packs as the model assumes a linear relationship between pack mass and capacity.
LCT	4	24	2.3.1 – Electrode Manufacturin g	ED	I would not describe pCAM as compounding sulfates. The process includes at a minimum dissolution and re-precipitation as hydroxides with controlled chemical and physical properties.	Revise process description.	Revised to: NMC and NCA cathodes are produced in a similar way due to their similar chemical makeup. The required metal salts and reagents (e.g. nickel sulphate hexahydrate, cobalt sulphate heptahydrate, manganese sulphate monohydrate and/or aluminium sulphate monohydrate; see Appendix A) are mixed together to co-precipitate precursor

							cathode active material (pCAM). This precursor product is dried before being combined with lithium hydroxide monohydrate. The combined material is calcined to produce (Li)NMC / (Li)NCA cathode active material (CAM) powder.
LCT	5	25	2.3.1 – Pack Assembly	ED	The commentary about potentially different facilities raises the spectre of transportation impacts. A statement is required. Is the transportation negligible compared to other impacts? This could also impact the USA case if some parts are still done in China then shipped to USA for assembly. Is transportation included equally in all upstream studies?	Note the exclusion (and expected magnitude) of transportation emissions. Ensure that transportation is considered equally across all upstream studies and provide commentary on how much is included.	Now clearly highlighted in sections 2.3 and 2.5 that foreground transport is excluded but that this is expected to be within cut-off criteria. Highlighted that background data may not make the same assumptions and exclusions. E.g.: This includes capital goods and infrastructure, emergency energy and materials, packaging materials, and foreground transport (see Table 9). Background data from ecoinvent may not apply the same exclusions.
LCT	6	mul tipl e	multiple	ED	Inconsistent use of Ecoinvent/ecoinvent	Standardize	Standardized throughout to ‘ecoinvent’.
LCT	7	32	3.1	GE	Is the assumption of 21700 cells for LFP relevant? I know there has been a lot of talk of other form factors, which give higher capacity and lower unit mass. Is a reasonable proportion of LFP cell production still 21700, or is this skewing the study away from where industry is?	Validate the industry usage of 21700 cells for LFP.	Added: This study assumes all packs will be assembled from cylindrical 21700 cells. This assumption has been made to try and maintain fair comparisons between chemistries but may not be accurate to the real world, with LFP often manufactured as pouch cells. It should be recognised that cell choice may influence the results. This section also states: ‘…it should be noted that production volumes of different battery chemistries and cell types may vary according to geography. These assumptions have been made on the basis of data quality and availability and do not inhibit the goals of the study.’
LCT	8	35	Table 9	GE	The phosphate source looks to be the wet process, which is one route. The thermal process probably has a higher impact. Is there any weighting of different production methods? Thermal may have a higher proportion of LIB use since wet process largely used for fertilizer.	Consider using an industry average for Chinese production of wet process and thermal.	Added: This is known as the ‘wet process’ but other potentially more impactful production routes are also used. We do not currently have sufficient data to model the thermal process.
LCT	9	36	3.2	GE	Is there a reference for the use cycles? A bald assumption is problematic.		Updated throughout to specify that degradation at 80% DoD (e.g. cycle life) are based on expert recommendation from industry experts at About:Energy. We have

							spoke with them and they are happy to be referenced in this way. Also added the following (or similar) sentence(s) throughout: Best eorts have been made to ensure information and assumptions on battery performance represent uniform operating conditions but this cannot be guaranteed and assessing the particular influence of operating conditions on lifetime emissions is not a goal of this study.
LCT	10	37		TE	The efficiency equation seems odd, and is certainly non-linear. Is there a source? A simpler form is *EffN = EffO*GVM/(GVM-PmO+PmN)* *EffN = EffO*GVMO/GVMN* Which is more linear. Chart below shows hypothetical difference for GVM = 2200 kg, PmO = 400 kg, EffO = 0.14. Within 100 kg it won't make much difference. 	Consider efficiency correlation and revise if warranted.	Efficiency calculations updated (see vehicle_efficiency_calcs) sheet in new model. I assume there is an error in the equation given and that it should be: *EffN = EffO*GVMN/GVMO* Using the equation suggested (where GVMO is divided by GVMN) results in higher Wh/mi (i.e. lower efficiencies) for lighter vehicles.
LCT	11	38	Table 11	ED	Missing digit on 160,000 km What is Round-trip Efficiency and how does that figure in to the calculations? I note that your Use models appear to use 90%*90% (i.e. Charging*RoundTrip) but not clear why. Grid CFs should be for power delivered at point of use, so using a charging efficiency makes sense, but the other = ??	Revise Provide commentary/rationale around this.	Revised. Added to section 3.2: Round trip efficiency represents any difference in the amount of energy taken from the battery and the amount of energy used to power movement of the vehicle. It is assumed to be 95%.
LCT	12	39	3.4	ED	Multiple uses of Oceana, should probably be Oceania.	Check and revise if necessary.	Updated throughout.

LCT	13	39	3.4	GE	The data shortage on Ni deserves further commentary – the missing data is likely to be higher emissions, especially if any NPI matte to batteries is considered. This difference might be smaller for cobalt, but needs consideration of included vs excluded routes and geography.	Consider expansion of commentary.	Further comments have been added noting that the missing geographies would likely increase the impacts. Also noted this in recommendations.
LCT	14	41	4.1.1	ED	The results for LFP cathode are 1410, not 1494. Figure 6 is correct.	Revise	All results and descriptions updated throughout.
LCT	15	4.1.1	Model	TE	The models have different cell LCIA #s, which seems incorrect. Difference is in CAM. NMC: 1.9954 FC vs 1.9908 FV NCA: 2.0169 FC vs 2.0169 FV LFP: 1.1329 FC vs 1.1301 FV	Check discrepancies and revise if necessary. This could affect multiple sections of the report depending on whether the FC or FV values were used.	New combined model created meaning cell impact is same in FC and FV scenarios.
LCT	16	43	4.1.1	GE	The cell manufacturing electricity consumption data seems inappropriate, Perhaps it would be relevant to quote the Wh/cell instead of per Wh in cell. The list of activities appears more consistent to quantity of materials than to efficiency of materials.	Consider a sensitivity case where the Wh/Wh in cell is normalized to Wh/cell based on a given cell chemistry.	An additional excel file has been shared to look at taking 37.43 MJ per kg from the source paper. Calculating on a energy density basis (e.g. MJ per kg) is counteracted by a figure from that same source which shows NMC and LFP having a similar energy consumption per kWh, despite having quite different energy densities. This is why the average (47 kWh) was taken for all chemistries and a sensitivity was performed. It is highlighted throughout that this is an average and this data is a major limitation of the study.
LCT	17	44	4.1.1	ED	The language below could be strengthened to note that the energy basis makes the impact differential minor to non-existent comparing between chemistries. Simply stating a lesser volume of raw materials does not confer any information about the outcome. *When comparing packs of a fixed capacity, it appears a lesser volume of more impactful raw materials can be used to reach a defined capacity for nickel-based chemistries*	Consider strengthening language	Language updated to: The results presented at the pack level highlight the question of efficient raw material use in lightweight high energy density batteries. different energy densities make the climate change impact differential minor to non-existent comparing between chemistries on a fixed capacity pack basis. When comparing chemistries through the lens of fixed volume, LFP has a lower total climate change impact per pack than NMC and NCA but also a significantly lower capacity.
LCT	18	44	4.1.2	GE	As noted above, there is a per kWh differential in NMC or LFP between the two cases. NMC is	Ensure that calculations are consistent in model.	New combined model created meaning impact per kWh is same for FC and FV scenarios.

					99.4 or 99.6, depending which case. LFP is 97.0 or 97.3.		
LCT	19	48	4.1.3	GE	The statement referring to the high embodied impact of Ni is misleading. The embodied impact of Ni is 17.9 kg/kg Ni vs 18.4 for Mn and 19.1 for Co. Ni has the **lowest** embodied impact of these cathode metals.		Statement revised: As the nickel institute average embodied impact is only 4.0 kg CO2 eq. per kg, this contribution is largely due to the mass required to achieve the 8:1:1 ratio (2.28 kg per kg pCAM).
LCT	20	Mo del	NMC, NCA	TE	When I review the materials list and the metal:salt ratio, I get NMC at 0.509 kg Ni, 0.065 Co, 0.058 Mn per kg PCAM. This is close to 811, but actual molar ratios are Ni:Co ~7.9; Ni:Mn ~8.2 For NCA, similar issue. I calculate molar ratios as Ni:Co = 5.25 vs 5.33 specified (80/15) and Ni:Al as 16.7 vs 16 specified (80/5).	Confirm that the quantities are correct, and that the 811 is a nominal recipe, not an exact one. Also confirm the hydrate state of aluminum sulphate specified in the quantities list and ensure that the CF is for the right material. Likewise confirm that the form of phosphoric acid and iron sulfate used in the CF are the same form used in the mass requirement (% H3PO4, ferrous vs ferric, hydrate quantity)	Quantities checked with source material and LCI inputs are correct. Incorrect references to iron sulphate monohydrate updated to iron sulphate. Phosphoric acid % checked in source material and adjustment applied to CF in model. CF is iron (2+) sulphate (i.e. ferrous sulphate as specified in source material).
LCT	21	52	4.2.1	GE	This section could use some elaboration on what elements were not varied to examine impact and what % of the total they make up. I note MnSO4, Al2(SO4)3, NaOH, NH3 and NH4OH, H2O2 many miscellaneous cathode and anode elements, electrolyte, cell materials, and all pack materials except aluminum. For NMC, about 19% of base case. There may be information available for some materials (i.e. steel, copper) but acknowledge not available for most.	Expand commentary to include the level of exclusions, the impact, and supporting information as to why for each chemistry case.	Added text in description and caption to state that all material and energy supply chains outside of those highlighted in Table 10 remain the same as the industry representative scenario.
LCT	22	55	4.2.1	GE	For LFP it is important to note that the biggest driver on the CAM side is the lithium. For NMC/NCA, the biggest driver on CAM is the Ni.	Add commentary.	This is now reflected in text: The majority of the variation is related to cathode production which varies by 75.0 kg CO2 eq. between 12.4 kg CO2 eq. per kWh NMC pack for the low impact scenario and 87.4 kg CO2 eq. per kWh NMC pack for the high impact scenario. The largest driver of this variation is the dierence between the embodied impacts of dierent nickel supply chains. The high impact supply chain (RKEF, Indonesia) has a climate change impact per kg nickel sulphate hexahydrate around 14 times that of the low impact supply chain (pyrometallurgy, Canada).

							As the nickel-based chemistries are similar, the main drivers of variation between the scenarios are the same as for NMC. Anode production is the second largest driver of variation. Anode production varies by 21.3 kg CO2 eq. between 5.1 kg CO2 eq. per kWh LFP pack for the low impact scenario and 26.4 kg CO2 eq. per kWh LFP pack for the high impact scenario. The largest driver of this variation is the difference between the embodied impacts of different anode-grade graphite supply chains. As previously highlighted, the high impact supply chain (anode-grade synthetic graphite produced in Inner Mongolia, China) has a climate change impact around 16 times that of the low impact supply chain (anode-grade natural graphite produced in Canada). For cathode production, lithium carbonate is the largest driver of variation between the scenarios. This is due to the difference between the embodied impacts of different lithium supply chains as discussed in section 4.1.3.
LCT	23	56	4.2.2	GE	Figures 20 and 21 do not compare the high and low cobalt figures to the industry standard.	Revise commentary or add industry standard to the figures.	Industry representative scenario added to figures.
LCT	24	57	4.2.3	GE	The text describes SE USA. The model describes Texas, using electricity for US-TRE which appears to be Texas grid. Texas is not SE USA.	Confirm power source and make text and model consistent. Describe in the section that power source is the only change.	Source updated to US-SERC grid.
LCT	25	59	4.2.4	ED	The reference is missing at end of line 1. Does the reference provide this accuracy value?		Reference added - yes it does provide the referenced uncertainty information.
LCT	26	61	4.2.5	GE	The statement that the balance of the EV must last to the max cycle life is not correct. A second-life use could also be valid.	Revise statement to include potential second life (post-EV).	Updated to: Whilst this sensitivity analysis highlights significant differences in longevity between the battery chemistries, it should be noted that - assuming no second use-phase - the longevity of EV hardware as a whole must be improved to actualise these benefits.
LCT	27		Model	GE	In general, when there are more than a dozen spreadsheet models in play, it would be helpful to the review phase if the data/figures in the report were referenced to a specific workbook or worksheet page, at least in the draft for review stage.	Note for future	Models rebuilt with summary tabs.

LCT	28		Model – LFP Use FC	TE	I note a number of invalid references on the Simulation page (rows 473-3002). Don't know if they are meaningful.	Check	New models created.
LCT	29	62	Fig 25	GE	Per earlier comment, the use phase seems to use a vehicle efficiency of 0.155 kWh/km for LFP and a net 81% efficiency of delivering power to the vehicle for a net grid consumption of 0.191 kWh/km. Table 11 provides Efficiencies that I expected to be for the vehicle, but may include the charging etc. It would be most clear to show vehicle efficiency assumption, then layer in the charging impacts. Grid effects only matter if CF is for power created, not power delivered.	Clarify.	See new efficiency description and use phase calculations.
LCT	30		Models		I don't see a clear reference to the EU grid intensity, but it appears to be based on 0.5265 kg/kWh. Is this valid? I note much lower numbers published by EU. (https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1)	Provide reference	Updated to EU27 average and reference added.
LCT	31	62	4.3.1	ED	The phrase "somewhat counteracted" seems weak. It is clear that the use phase difference dominates the minor difference in manufacturing phase. Fixed volume use case comparisons seem truly odd, as noted before. They deliver different outcomes and are not comparable.	Strengthen language	Language removed. Please review the revised use-phase section. FV comparison of chemistries was requested by CI. Emphasis added throughout that the pack capacities are significantly different e.g: With that being said, the capacity of a 4,416 cell LFP pack is also much lower than a NMC or NCA pack of the same cell volume due to LFP's lower energy density (~58 kWh for LFP vs ~97 kWh for NMC / NCA).
LCT	32	70	Table 12	GE	I don't understand why there is difference between FC and FV for a set range. If targeting 300 km, there is neither a FC nor an FV – there is a fixed range. This would require slightly more kWh for LFP due to heavier batteries for any given use case. It is probably an iterative calculation to derive the corresponding kWh required and the resulting mass and vehicle efficiency.	Check and revise if necessary.	Table removed as it did not draw particularly new / insightful conclusions. Per cell was not one of the functional units of the original report and I am hesitant to add more functional units at this time (see Evangelos' comments).
LCT	33	74	5.3	ED	Cell count is incorrect in last paragraph.	Revise.	Revised.
EK	1			GE	Consider mentioning the full chemical form when defining abbreviations for NMC, NCA, e.g. Lithium Nickel Manganese Cobalt Oxide	Edit	Full chemical form and ratios defined on first use.

					(NMC). Same when defining 8:1:1 ratios of NMC.		
EK	2	6		GE	Need to mention the functional units somewhere in the Exec Summary, before presenting the comparison between chemistries. Text discusses impacts per cell but figure 1 shows per kWh.	Modify text/figure1 for consistency.	References to 'per cell' removed. Functional units defined in exec summary before results.
EK	3	6	Figure 1	TE	Low scenario for LFP has a higher impact than NMC/NCA. This appears to come as a result of higher "cell manufacturing materials" contribution. The background values used for this comparison where not clear after reading the report.	Clarify background values for all sensitivity analyses throughout the report.	Updated results show the difference in low impact scenario is not significant (31.3 NMC vs. 32.9 NCA vs. 33.2 LFP). Other reviewers have discouraged drawing conclusions from such small differences. No sensitivity analyses were performed on cell manufacturing materials. This is now highlighted more explicitly in section 3.1 and in Appendix A. Section 2.3 has also been revised to try and clarify background vs. foreground data.
EK	4	6		GE	Sentence "Higher impact per cell results in higher climate change impact per pack for NMC and NCA compared to LFP for both fixed capacity and fixed volume packs." not very clear. The need to perform comparisons with both fixed capacity and volume is not very clear here? This highlights a general issue with using too many functional units in the report.	Modify	Per cell statements removed throughout. Fixed capacity & fixed volume packs were requested by the CI, and does become significant for lifetime emissions + maximum service life sensitivities. Text now relates the selection more clearly to the intended applications e.g: Fixed capacity (70.6 kWh) and fixed volume (4,416 cells) packs are assessed at the request of the CI to ensure the study goals were met and the aforementioned discourse around pack mass and energy density was highlighted. These capacity and volume parameters were chosen as they are representative of pack sizes currently available in Class D EVs.[9-11] Functional unit section updated to aid readers.
EK	4	7	Par. 1	TE	Comparative climate impact per kWh for NMC/NCA vs LFP are quite close to each other. Would be good to mention assumed energy density for each chemistry here so the reader knows exactly what you are talking about.	Mention energy densities in text, source and how they where calculated.	Revised to: A summary of the manufacturing LCIA results per kWh pack capacity are presented in Figure 2 for the low impact, base case, and high impact scenarios. The calculated energy densities are 0.214 kWh per kg for NMC, 0.217 kWh per kg for NCA, and 0.154 kWh per kg for LFP.[12-14]
EK	5	7		GE	"Cobalt was not found to be a hotspot in either NMC nor NCA". This is expected given that	Consider modifications in text and/or further analysis.	Text revised: Isolating the influence of high and low impact cobalt supply chains indicated that

					those are high nickel chemistries. However, source of nickel would impact the results. This is essential to support the claims of manufacturing electricity impacts vs material supply chains.		cobalt is not a hotspot in either NMC nor NCA when other base case supply chains are assumed, even when assuming a high impact Indonesian HPAL source.
EK	6	8	Par. 2	TE	Not sure that fixed 4,416 cell packs adds more information as a functional unit. Manufacturing impacts for fixed capacity pack are practically the same across chemistries, where is the effect of energy density? Again, in my opinion too many functional units are used which to not necessarily reflect the function of the product.	Consider.	See comment response above. Results are similar because LFP materials have lower embodied impact but a higher amount is required due to lower energy density. The contribution of cell and pack materials are higher for LFP fixed capacity packs because more cells are needed but these areas are not hotspots. See other comments responses for call manufacturing electricity.
EK	7	10	Par.2	GE	The sentence, "With the aforementioned in mind, the results highlight that consumers could obtain the same EV range using less critical raw materials when the battery packs are higher energy density NMC / NCA chemistries." is not very clear. A series of claims are made about lowering the consumption of critical raw materials, while no such assessment was performed in the study.	Make significant modifications in this paragraph given that critically assessment was beyond the scope of this report.	Where critical raw materials are mentioned, examples of cobalt, natural graphite and lithium have been added as well as a reference to the EU critical raw material list published in 2020. Statements around critical raw material use in specific chemistries have been removed.
EK	8	10	Par.3	GE	Explain how the results support this sentence "Considering all the results presented it was found that grid decarbonisation has great climate change mitigation potential for both battery manufacturers and users.". Material supply chain decarbonisation is also important wrt Figure 1	Explain or modify. To make such claim further sensitivity analyses should be performed.	Text revised to: Significant dierences in the relative contributions from each life cycle (i.e. manufacturing and use-phase) are seen when assessing use on dierent electricity mixes. A relationship is observed in which the relative contribution of the manufacturing life-cycle stage decreases as the carbon intensity of the charging grid increases. Dierences in the relative contributions from each life cycle stage highlights that the eectiveness of mitigation strategies can change depending on use location. When considering base case manufacturing supply chains and a use location where the carbon intensity of the grid is above the European average, the results indicate that grid decarbonisation in the use location may be more eective at reducing overall lifetime emissions. In use locations where the grid intensity is similar to or less than the European average, mitigation

							strategies in the manufacturing stage (e.g. low carbon raw material and energy sourcing) may be more eective at reducing overall lifetime emissions.
EK	9	24	Section 2.2.1	TE	Too many different functional units are shown here, may be very confusing to the reader without necessarily adding new information. In addition, kWh throughput functional unit might be relevant to the use phase here instead of km.	Consider modifications throughout the document.	Functional units were discussed and agreed upon with the CI. Section has been reformatted to aid readers. References to 'per cell' have been removed throughout.
EK	10	25	Section 2.3	TE	Sentence "As the end-of-life treatment for the battery packs is undefined, this life cycle stage has been excluded from the system boundary." What is meant by undefined?	Explain why EOL was excluded.	Updated to: In this hypothetical scenario, potential secondary use-phases (e.g. ESS) and end-of-life treatment (EoL; e.g. landfill versus recycling) are not defined and have been excluded from the system boundary.
EK	11	27	Table 5	TE	Capital goods and infrastructure were excluded from foreground inventory modelling. However, background datasets from Ecoinvent include such contributions. Same for transport requirements, some background datasets might include transport.	Comment in text.	Added: Background data from ecoinvent may not apply the same exclusions. Now explicit in sections 2.3 and 2.5 that foreground transport is not included.
EK	11	28	Figure 4	TE	1) Legend doesn't add much e.g. electrolyte production 2) Other processes e.g. separator production excluded? 3) Module/pack assembly has additional inputs, have they been excluded? E.g. TMS 4) Are cell assembly, module assembly, pack assembly and conditioning modelled through different foreground inventories? 5) Use of battery, show included /excluded inputs inputs.	Modify figure. It might be good to show exclusions from the system boundary here.	Figure reformatted to more clearly separate foreground and background processes, and show inputs + outputs to use-phase. Reader also directed to Appendix A in text. Subheadings of section 2.3 updated to match unit processes shown in Figure. Legend revised to help match unit processes to LCIA result groupings.
EK	12	29	Table 3	GE	What is the source of the data shown in Table 6? E.g. cycle life taken from where and at which conditions? Key car- related parameters are missing here. For example, the km range is shown but not the energy consumption of the car.	Add references and/or explain further	References added to caption. Footnote added on cycle life. Range removed from table as not relevant.

EK	13	29	Table 3	TE	On fixed capacity vs volume, I would expect the pack energy density for the same chemistry to be the same. It is not clear what changes here.	Explain	Model updated - now the same.
EK	14	31	Par.4	GE	The industry representative scenario is more of a base case scenario. Manufacturing in Guangxi Province is not exactly industry representative.	Phrase as base case	Manufacturing location revised - see updated model.
EK	15	31	Par.1	TE	Electrode manufacturing here refers to precursor manufacturing. Consider changing the title as electrode manufacturing typically refers to coating of CAM to foils etc.	Modify	Descriptions revised to better match system boundary figures and grouping of LCIA results.
EK	16	32		GE	Module assembly was shown in the system boundary but not discussed in text, same for conditioning.	Edit text or figure.	Updated figure and text.
EK	17	33	Par.1	TE	The inclusion of the use phase in this study should be further explained. Specifically, referring to a class D EV many key parameters have not been discussed and all vehicle production/maintenance processes have been excluded.	Explain in text or modify scenarios.	Added statements throughout such as: As the goals of this study include assessment of lifetime emissions the system boundary has been extended to include a use-phase. Inclusion of this use-phase also allows investigation on the influence of energy density and pack mass on efficiency. The use-phase parameters of this study have been designed to help indicate lifetime emissions directly associated with the battery packs and do not consider impacts associated with vehicle production, assembly, and maintenance. Differences in vehicle deficiency associated with pack mass, and subsequently energy density, are considered.
EK	18	34	Section 2.5	TE	The cut-off rules applied in this study should be further explained. Specifically, was there any systematic rule as e.g. % of mass contribution or % of total impact based on which the cut-off was applied?	Clarify	Revised cut-off description to be quantitative.
EK	19	39	Section 3.1	TE	It is mentioned that the Guangxi province was chosen due to increased battery manufacturing capacity in this area. A report from BYD is referenced to support that. However, other Chinese provinces (Anhui, Jiangsu, Hubei, Sichuan) are projected to produce much more GWh than Guangxi.	Explain why Guangxi was chosen as a baseline.	Model updated to manufacturing in Jiangsu. Terminology changed to 'base case'.
EK	20	48	Table 11	TE	Clarify how the cycle life for each chemistry was calculated. Cycles refer to full equivalent cycles? No mention to depth-of-discharge,	Clarify and/or double check numbers	Energy densities were calculated from LCI sources and this is now specified in the report.

					C-rate etc. LFP has double the cycle life of NMC/NCA, it is not clear how the production burden was allocated to the 160.000km. Actual Lifetime Throughput (kWh), Battery Utilisation at 160,00 km (%), are not very clear. The latter is based on the number of cycles required for 160,000 km divided by the cycles until end-of-life?		Added: Average degradation rates (e.g. cycle life) are based on recommendation from industry experts at About:Energy. Readers should be aware that operating conditions can influence cycle life significantly but assessing the particular influence of operating conditions on lifetime emissions is not a goal of this study. Depth of discharge (80%) added. Stated clearly through that secondary use phases are not considered. Table revised and descriptions added.
EK	21	47		GE	All efficiencies are assumed to be independent of battery chemistry.	Clarify	Efficiencies were taken from chemistry specific sources specified in references. See calculation methodology in section 3.2.
EK	22	52		GE	"Contribution analysis figures aggregate the contributors worth less than 1% of the total" This should be connected to the cut-off rules in a systematic way.	Edit	Now links to <1% cut-off criteria. <5% for CAM is for aesthetic purposes.
EK	23	52		GE	"Cell manufacturing electricity contributes 2,313 kg CO_2 eq. for all chemistries as these LCI inputs are proportional to pack capacity (see section 3.1)" This is not representative, see Jinasena et al. in refs. NCA has lower energy consumption per kWh than LFP. For fixed capacity one would expect the numbers to be different.	Modify calculations to account for that. Keep in mind that the energy consumption per kWh should be connected to energy density.	The reference does show NCA was modelled to have a lower energy consumption per kWh cell than LFP and NMC. With that being said, the critical review comments point towards a connection between energy density and energy consumption. An additional excel file has been shared to look at taking 37.43 MJ per kg from that paper. Calculating on a energy density basis (e.g. MJ per kg) is counteracted by that same figure in the reference which shows NMC and LFP having a similar energy consumption per kWh, despite having quite different energy densities. This is why the average (47 kWh) was taken for all chemistries and a sensitivity was performed.
EK	24	53		ED		Double-check label positioning in figure 6	All figures updated.
EK	25	53	Figure 6	GE	Not clear what is included in the terms "cell manufacturing materials", pack manufacturing materials"	Explain maybe in legend.	Revised system boundary description to say what is included so should be clear to the reader by this point. Have added more pointers to Appendix A (BOMs) which show how LCI flows and LCIA results are grouped.
EK	26	55		GE	"As described in section 3.1, there is no difference between packs of a fixed capacity	Comment further or clarify.	Section states: There is no distinction between packs of a fixed capacity and a fixed volume

					and a fixed volume when normalised on a per kWh basis due to linear scaling of pack manufacturing materials and cell manufacturing electricity with capacity." I would expect to see a difference as a result of energy density.		when normalised on a per kWh basis because pack materials are scaled linearly with pack size and cell manufacturing electricity is proportional to pack capacity.The limitations of these assumptions are discussed in section 3.4.
EK	27	55	Section 4.1.2	ED	The climate change impact for LFP is very similar to NCA NMC per kWh which is surprising. Consider adding a comparative graph with the impact for each chemistry per kWh as done in section above.	Clarify key inputs associated with the comparison of NMC/NCA vs LFP in text and consider adding comparative figure.	Unsure what the first part of the reviewer's suggestion refers to. Summary figure added (Figure 8).
EK	28	68	Section 4.2.2	TE	The carbon footprint of cobalt assumed in high/low scenarios is not clear. For example, cobalt can be mined and refined in China with very high impact, was that considered within the range? Given that the report includes high nickel chemistries , a sensitivity analysis on the source of nickel should be presented to support the claim that "As for the nickel-based chemistries, the majority of the variation is related to cell manufacturing electricity"	Edit here and throughout the report, all sensitivity analyses should show the range of values that were considered.	Revised: To isolate variation in manufacturing climate change impact associated with cobalt, base case scenarios were created with variation in the cobalt supply chain only. These scenario results for each cobalt-containing chemistry (i.e. NMC and NCA) are broken down by area and compared to the base case scenario in Figures 21 and 22. The high impact supply chain considers cobalt production via HPAL in Indonesia and the low impact supply chain considers cobalt produced via pyrometallurgy in Canada (Table 14 in section 3.1).
EK	29	70	Section 4.2.3.	TE		Clarify which electricity mix was used for southeastern USA.	Updated to US-SERC mix and clarified in report.
EK	30		Figure 25	TE	LFP has a lower impact per kWh and a much higher service life. How is the manufacturing contribution in figure 25 almost the same with NMC/NCA?	Explain further in text.	Please review the revised use-phase section. As presented in section 4.1.1, the impact of manufacturing fixed capacity packs is similar for all chemistries due to the interplay between material + energy embodied impact and energy density. LFP has a longer *maximum* service life but the end-gate is set to 160,000 km meaning that doesn't really make a difference here. The max service life is investigated in 4.2.5. It is clearly stated throughout that 160,00 km is reached before 80% SoH for all chemistries. Assumptions section states: It should be noted that 160,000 km is reached before 80% SoH for all chemistries in the use-phase calculations of this study. The end-gate was chosen to represent a realistic class D EV lifetime. A

							sensitivity analysis on manufacturing impact per kWh delivered over maximum service life is presented in section 4.2.5. Lifetime climate change impact sections states: When coupled with different rates of degradation (i.e. loss per cycle) this also leads to different percentages of battery utilisation at the end of the assumed 160,000 kilometre lifetime. As LFP degradation is typically lower than for nickel-based chemistried, LFP packs show a consistently lower utilisation percentage at this gate compared to NMC and NCA (see Table 16). Whilst these additional results do not directly influence the lifetime climate change results of this LCA study, they should be considered alongside the LCIA results.
EK	31			GE	Figure before section 4.3.2 looks a bit off, same for similar figures.	Double check such figures throughout the document.	Please review the revised use-phase section.
EK	32		Goal & scope definition	GE	Acknowledge the limitations of only studying carbon footprint. Especially given that claims are made regarding reducing resource use several times in the document.	Clarify throughout text	This is addressed in sections 2.6.1, 3.4 and 6.2.
EK	33			GE	Discuss temporal boundaries, foreground/background inventories representative for which year? Particularly relevant to electricity mix.	Clarify throughout text	Time-related representativeness is discussed in Table 18 (section 5.1)
EK	34			GE	Key background data such as the carbon footprint of electrode materials or the electricity mix should be discussed when presenting findings or performing sensitivity analyses.	Discuss background data when presenting results.	Comments on embodied impacts of energy and raw materials added throughout results descriptions.

MINVIRO

COBALT INSTITUTE

Critical Review Comments - Round 2

Initials	Index	Page number	Section/ Figure /Table	Type of comment	Reviewer comments	Reviewer recommendation	Practitioner response
LCT		6		ED	It is not immediately clear that the base case is Chinese-located manufacturing. Doesn't really come up until pg 10.	State base case location.	Added location on pg 5 paragraph 2.
LCT			Figure 1, 3, maybe others	ED	Figure is fuzzy.	Improve figure quality.	Increased size should be okay now.
LCT		9	Table 5	ED	What does the asterisk on Fixed Volume refer to? Do you need to refer to Table 13?	Clarify	Removed FV.
LCT		10		ED	The paragraph on +/- 13 kWh should refer to the base case.	Revise	Revised.
LCT		13		ED	Chemistried vs chemistries – occurs 3x	Revise all cases	Corrected.
LCT		43/44	3.2, also Table 16	TE	I note 95/95 charging and round-trip efficiency here, but the use phase models in New Models>New Use Phase Models use 90/90.	Clarify and use appropriate consistent value.	Corrected to 90/90 throughout the report.
LCT		30		GE	Per prior comment 8, it would be good to strengthen the comment on wet process vs other. Recognize you may not have data – I have not sourced any but the process flowsheet looks like higher energy impact. The reality is likely that if thermal P is used, LFP will be higher impact than NMC/NCA. The conclusions and recommendations need to reflect (https://en.cd1958.com/html/122.html, https://nepis.epa.gov/Exe/ZyPDF.cgi/91010OYY.PDF?Dockey=91010OYY.PDF This Belboom paper seems to compare thermal and wet process by LCA, giving results of 950 kg CO2e/t P2O5 wet and 7365 thermal. Your model looks to use 1373 kg for H3PO4. When I put these on a P basis, I get Minviro = 4.344 kg/kg P, Belboom = 2.177 kg/kg P wet, 16.877 kg/kg P thermal. I do not vouch for these numbers, nor have I checked the analysis to see if there is consistency amongst production areas re: CI study, but it is indicative at least.	Strengthen from "potentially more impactful".	Comment strengthened and thermal route added to sensitivity analysis.

<table>
<tr><td></td><td></td><td></td><td></td><td></td><td>For a sensitivity check, using 1373*(16.877/2.177) for phosphate pushes the LFP from 7045 to 8126 (FC) and 6046 to 6635 (FV), or +10 – 15%. You could perhaps reference that the use of thermal process P could push the LFP impact per kWh above the NMC/NCA.</td><td></td><td></td></tr>
<tr><td>LCT</td><td></td><td>50</td><td>NMC/NCA/LFP LCI</td><td>GE</td><td>Per prior comment 16, the electricity use seems flawed. I would be happier if it was done on the basis shown in the new file: ~40 kWh/kWh NMC/NCA and ~57 for LFP. At the very least, this should be shown as a sensitivity or alternative in 4.2.4 and disclosed better.</td><td></td><td>Updated - now uses MJ per kg.</td></tr>
<tr><td>LCT</td><td></td><td>56</td><td></td><td>ED</td><td>Capitalize Nickel Institute</td><td></td><td>Corrected.</td></tr>
<tr><td>LCT</td><td></td><td>68</td><td>4.2.5</td><td>GE</td><td>I find the language around maximum service life is challenging to interpret, and I don’t understand the results.

I would approach it this way using the results from your use case models: [(kWh from grid*grid intensity)+(kg CO2e manufacturing)] / (kWh to wheels). The result is that LFP is 13% better than NMC on a maximum service life use case.
<table>
<tr><th></th><th>LFP</th><th></th></tr>
<tr><td>Initial Capacity (kWh)</td><td>57.6</td><td></td></tr>
<tr><td>Cycles</td><td>3000</td><td></td></tr>
<tr><td>Energy Utilized (kWh to wheels)</td><td>118,200</td><td></td></tr>
<tr><td>Energy Consumed (kWh from grid)</td><td>145,925</td><td>1</td></tr>
<tr><td>Electricity Grid Intensity (kg/kWh)</td><td>0.265</td><td></td></tr>
<tr><td>kg CO2e Manufacture</td><td>6,046</td><td></td></tr>
<tr><td>kg CO2e Use</td><td>38,670</td><td></td></tr>
<tr><td>kg CO2 total</td><td>44,716</td><td></td></tr>
<tr><td>kg CO2e/kWh delivered</td><td>0.378</td><td></td></tr>
</table>
I would only do one case (FV or FC) since the results are the same either way.

If the max service life is considered as km (see note below about the calculation), I derive 47 and 58 g CO2e/km.

This calculation method does deliver the reported results for 160,000 km lifetime use – 79 and 110 g/km for FV and 89 and 90 for FC.</td><td></td><td>Assumptions and results updated according to your recommended method.</td></tr>
</table>

LCT		69			There is something that doesn't make sense about the lifetime vs maximum cases referring back to Table 13. For LFP FV we have 24,637 kWh (grid) used over 160,000 km lifetime (0.154 kWh/km) which makes sense. For the maximum service case, we have 145,925 kWh used, which should be about 948,000 km at same efficiency. T13 shows only 766,000 km, or about 81%. If we look at kWh used to wheels, 118200/19958*160,000 km = 948,000 km as well. Similarly for NMC, 26355 kWh (grid) for 160,000 km (0.165 kWh/km) and 122622 kWh maximum ⊠ 744,000 km vs 602,000 km = 81%. For the FC case, I get 1.12M km for LFP and 573k km for the NMC. It seems like the max service life case might be comparing grid power to wheel power: 118200 kWh (wheel) / 24637 kWh (grid)*160,000 km = 768,000 km, approximately what is in T13. All of this will change when the 95/95 is used.		Corrected - see new results.
LL	1				Some figures and tables are a bit blurry. • Figure 1 • Box on page 4 • Figure 3 • Box page 19 • Box page 35, 48, 52, 69 • Figures 9-11 • Figure 13, 15, 17, 26, 27	Please add high resolution figures/text boxes	Figures updated - should be improved.
LL	2			te	I am still having trouble with the statement that cell manufacturing	Please explain in more detail the statement "cell electricity	Updated - models now use MJ per kg so LFP has higher cell manufacturing electricity requirements.

					electricity scales with pack capacity. I am not sure if you mean for the same cell chemistry (that I think makes sense) or in general across chemistries. In case of the latter, I cannot imagine that say a 40 kWh pack using LFP has the same cell manufacturing electricity consumption than a 40 kWh pack using NMC since you would need more cell material for the LFP pack. So practically electricity consumption would scale differently across chemistries. So in this case, the statement might be misleading. I also found this paper (https://www.nature.com/articles/s41560-023-01355-z), which shows that cell manufacturing electricity consumption decreases with increasing cell energy. In the spreadsheet "Additional cell manufacturing electricity modelling (MJ per kg)" the cell manufacturing energy is given on a kWh energy per kg basis (Reference: Jinasena et al), which I understand as that it scales with weight of the cell. In the same spreadsheet, column C 14-16, I understand the lower manufacturing electricity for LFP being a consequence of the lower cell mass and not the lower capacity of LFP. I can see that in the LCI inputs the energy consumption is given in units kWh per kWh in cell. Where does this data come from and how does it relate to the data in the "Additional cell manufacturing electricity modelling (MJ per kg)" spreadsheet?	consumption scales with pack capacity" Please explain in more detail the relation between the two inputs and specify the origin of the input data. Please comment.	

					Also, in reference 12 (Winjobi, O et al) I have the impression that the higher energy consumption for cell manufacturing is more related to the processing steps a certain material needs and not necessarily the rule "the higher the capacity of a material, the more processing and hence energy it requires". Also, this study seems to focus on materials production and not cell production (electrode and cell assembly), which is associated to "cell manufacturing electricity" in the report (p. 30/31). I also could not find any explanation of this assumption in Section 3.1. as pointed out on page 48, where it is referred to section 3.1. "The impact is uniform across the three chemistries in a fixed capacity scenario because the LCI inputs for this area are proportional to pack capacity (see section 3.1)."	Please add a paragraph in Section 3.1.	
EK	1	n/a	Throughout	ge	My main concern with the current version of the report relates to the amount of functional units presented and I insist a bit on that as I believe it is important. Your response to my comments in this direction was that the CI suggested the fixed capacity and fixed volume functional units. However, I believe the choice of the most representative functional unit(s) for each product system ultimately rests with the practitioner. In this direction, the PEFCR for batteries defines the kWh of energy delivered over the service life as a representative functional unit, as correctly stated in the report when the use phase is included. When focusing on the production system, kWh	Please consider my feedback together with the other reviewers and happy to have a look at the updated version of the report.	Discussed with panel and LCA commissioner. Fixed volume removed.

					capacity is the widely accepted functional unit. In my view, fixed capacity and fixed volume might not add any further insight into the environmental impact. The PEFCR FU has received some criticism claiming that the calculation should be based on how long the battery will last, not the vehicle. You have mentioned this in the report, by saying that if you account for max service life of the battery, LFP will have much lower climate impact, showing the cycle life of LFP vs NMC, NCA. In case you want to include the FUs suggested by the CI, my suggestion would be to also include the kWh of energy delivered at max battery lifetime (80% capacity) as a functional unit, i.e. show figure 25 in the results instead of sensitivity analysis section.		

MINVIRO

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Critical Review Comments - Round 3

Initials	Index	Page number	Section/ Figure /Table	Type of comment	Reviewer comments	Reviewer recommendation	Practitioner response
LCT	1	N/A	Model	TE	I note the paper you referenced shows thermal process impact as 7.8x wet process – using BAT for the thermal process - where your calcs show ~3.2x. Is this because of different CFs used for the inputs for the thermal process? I note that you have judged water below cutoff criteria, but the math on the water consumption (process and cooling) is out by a factor of 10E6. 1 m3 = 1 tonne, so 40 m3 water/t P2O5 = 40 t water/t P2O5 and should be treated just like phosphate rock, clay, coke. It might well still be below the threshold, but I can't be sure the assumption is valid. That MIGHT be why your thermal:wet ratio is so different.	-	• Corrected water LCI (not sure what planet I originally calculated that on!) and included in LCIA using RoW market for tap water as background data. • Increased LCIA result from 1.52 to 1.58 kg CO_2 eq. per kg H_3PO_4 (35% conc) so this is not where the majority of difference comes from. I have updated the value in the main battery model but it has no influence on the results to 1 dp. • Result is ~7x higher in the paper because the wet process route in the paper is significantly lower than in ecoinvent (likely because the paper models production in Belgium). • I have added some additional information to the LCIA tab of the model showing that: ○ Minviro's thermal result is 1.58 kg CO_2 eq. per kg H_3PO_4 (35% conc). ○ Paper's thermal result is 1.92 kg CO_2 eq. per kg H_3PO_4 (35% conc). ■ Still -18% but this is likely due to background data.

							◦ Minviro's thermal result is 6.4x that of the wet process in the paper and 3.3x that of the wet process in ecoinvent. ◦ The paper's thermal result is 7.8x that of the wet process in the paper and 4.0x that of the wet process in ecoinvent. • Given the background updates that will have occurred since the paper was published in 2015, and given the inclusion of this result in only a sensitivity analysis, I believe no further changes are needed in the background model.
LCT	2	67	Energy Delivered over Maximum Service Life	Ed	I note on pg 67 you refer to the maximum service life scenario as related to manufacturing rather than manufacturing and use – the use phase is the dominant feature for the data. The results show that the climate change impact of EV battery pack manufacturing is around 12% lower for LFP.	-	• Language updated throughout to "Although the absolute lifetime impact is higher for LFP packs, the longer cycle life means it is spread over a longer maximum service life." • Maximum service life assessment has been moved to use-phase sections (both assumptions and results).
LCT	3	11 +	Throughout	Ed	Although this following paragraph is no doubt true, the actual ability to extend vehicle life to >20 yrs is limited by many features, including mechanical components, electronics and programming, and customer desire. To me, the paragraph implies a lot about the current battle over things like right to repair, planned obsolescence, marketing tactics, etc. It might deserve a broader comment than just "hardware". Actually achieving the goal requires a complete re-design of our current consumptive society – but I	-	I completely agree that the phrasing has limitations and that it arguably has a lot more to do with behaviour throughout the entire life cycle than hardware! Phrase updated to say 'EV lifetime' instead of 'EV hardware'.

					recognize fomenting revolution is beyond Minviro's scope! • "In the context of the specific EV use-phase presented... assuming no second use-phase.27"		
LCT	4	77	Lifetime Emissions	ed	Table 19 has a typo – LCP	-	Updated.
LCT	5	Pg 10, 38, 41, 78 +	Throughout	ed	Pg 10, 38, 41, 78 and others are a little confusing around 80% SoH and 80% DoD. I think you mean to refer to the lifetime cycles to get to 80% SoH – the remaining chargeability of the battery – not how much is discharged each cycle which is what is usually referred to as DoD. In the Use Phase Model you refer to a declining nameplate capacity which is what reaches 80% in your modeled end of life, but which is modelled with a **95% usable capacity** and an 80% utilized capacity. This doesn't quite reflect in the language in the report. Suggest you give those aspects a critical read to make sure the reader will understand you – the topic is not easy. Example: NMC cycle 1127 Initial Nameplate: 70.6 kWh Capacity Loss = 1126 cycles*0.009413 kWh/cycle = 10.6 kWh Remaining Nameplate: 70.6-10.6 = 60 kWh Usable Capacity = 60 kWh*0.95 = 57 kWh Utilized Capacity = 57 kWh*0.80 = 45.6 kWH	-	Language updated to more clearly explain meaning. For example: • "Maximum service life parameters are presented in Table 13 (section 3.1) and were calculated assuming a cycle life of 1,500 for the nickel-based chemistries and 3,000 for LFP (to 80% state-of-health; SoH). Cycle lives are based on an 80% depth-of-discharge (DoD; i.e. how much energy has been drawn from a battery, expressed as a percentage of the battery's total capacity) per cycle." • "Average degradation rates (e.g. cycle life) are based on recommendations from industry experts at About:Energy and account for 80% DoD per cycle."

LCT	6	-	-	Te	Related, I wonder if it would be more easily understandable to do the maximum service life on a g/km basis like the Lifetime Climate Change Impact? The calculations then become very similar, just for 160,000 km vs the 570,000 or more km of the maximum service life case. That would get rid of all the language around 1 kWh delivered over the maximum life which is – in my opinion – the most confusing part of the description.	-	The functional unit 'per kwh delivered over maximum service life' was specifically requested by CI members on the basis that it aligns with the battery PEFCR. I am therefore hesitant to change the functional unit to a unit of distance.
EK	1	Throughout	Throughout	Te/Ed	The calculations based on a 160,000 km basis are fine from my point of view as the guidelines recommend it. However, this assumption does not favour long-life battery packs and you have correctly included the calculations per kWh over max service life. The number of cycles for different chemistries to reach 80% SOH is accounted for from experimental data of About:Energy and are based on cycling at 80% DOD. In reality, the battery pack will be cycled under much more aggressive conditions, resulting in a lower service life than what is estimated in the lab. It is very hard to tell what would be the impact of real-world driving conditions and would not expect you to make any modifications. It might be good to acknowledge that the number of cycles for all chemistries is overestimated, resulting in 56 years of lifetime for LFP (Table 13). For comparison purposes, it is fine to say that LFP has double the lifetime of NMC/NCA, but when it comes to absolute numbers of cycles these will likely be much lower and will be impacted by different C-rates, operating temperatures in addition to DOD.	If you want to add some text related to those, together with addressing Lyle's comments we can do a quick iteration to finalise.	Revised version highlights issues of longevity.