COMPARATIVE LIFE CYCLE ASSESSMENT STUDY OF SOLID STATE AND LITHIUM-ION BATTERIES FOR ELECTRIC VEHICLE APPLICATION IN EUROPE

Prepared for The European Federation for Transport and Environment
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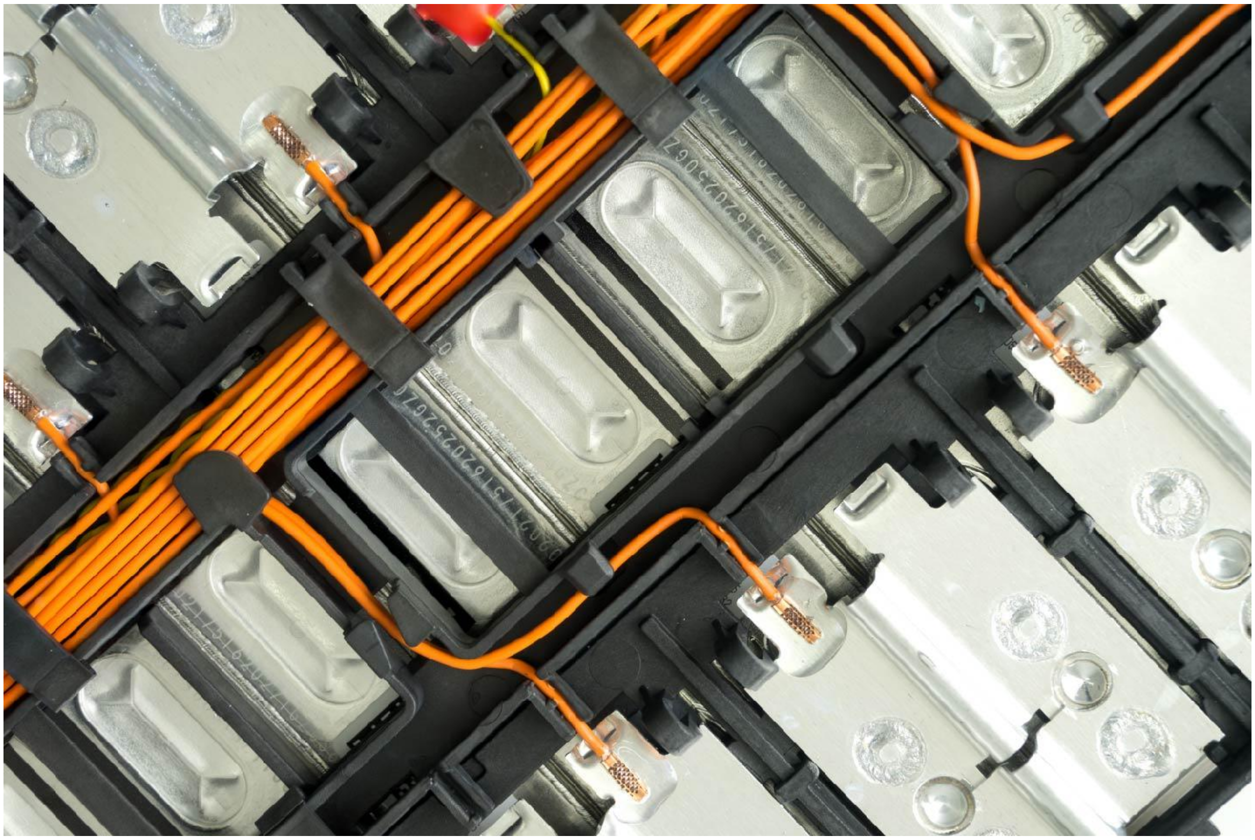

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2. Executive Summary

Minviro was appointed by The European Federation for Transport and Environment (T&E) to conduct a cradle-to-gate life cycle assessment (LCA) on the production of advanced batteries, including solid-state batteries (SSB) in Europe. The global warming potential (GWP) impact category is quantified for SSB production and compared to two commercial lithium-ion battery (LIB) chemistries - NMC-811 and LFP - and a third currently in development, LFMP. The LCA results for producing one kWh within a final battery pack are presented in Table 1. Other impacts are calculated and included as an annex to the main report.

*Table 1: Results Summary of LCA Study. * - defined by best-estimate academic studies - see Section 3.3.4.1 and Appendix B for a list of modelling assumptions, including battery parameters.*

Impact Category	Product	Pack kWh/kg*	Impact Value	Impact Units
Global Warming Potential	Sulfide SSB (LFP Cathode)	0.250	67.3	kg CO_2 eq. per kWh
	Sulfide SSB (NMC Cathode)	0.400	60.0	
	Oxide SSB (LFP Cathode)	0.250	64.1	
	Oxide SSB (NMC Cathode)	0.400	58.0	
	NMC-811 Li-ion Battery	0.250	76.7	
	LFP Li-ion Battery	0.174	77.9	
	LFMP Li-ion Battery	0.220	66.0	

The study's goal is to quantify the potential environmental impact of producing SSB in Europe. This emerging technology is proposed to have almost double the energy density of the highest-performing LIB chemistry, is safer due to the lack of flammable liquid electrolytes, and is more compact and lighter as a complete pack.[1,2] However, the environmental impact of mass-production is currently poorly understood, and no SSB set-up has been produced at a commercial scale as of 2021. Using best available academic and industrial data for the solid-state battery manufacturing process, this LCA identifies impactful SSB raw material components and energy-intensive production processes, and compares results to NMC-811, LFP and LFMP LIB chemistries. The aim is to provide an early insight into the environmental performance of SSB production, and to determine which battery set-up is the least impactful per kWh in the final battery. This LCA does not include the relative impact during the use-phase or end-of-life of the batteries.

From the results of this LCA, the main drivers of global warming potential in SSBs are lithium metal used in the anode, the cathode active material, and electricity consumption during certain manufacturing processes. The main drivers of global warming potential in NMC-811 batteries are nickel sulfate production used in the cathode, graphite production used in the anode and energy for drying processes. The main drivers of global warming potential in LFP batteries are lithium carbonate production used in cathode active material manufacturing, graphite production used in the anode (given the higher mass required per pack compared to NMC-811), and energy for drying processes. The addition of manganese oxide to the LFP bill of materials to produce LFMP results in a higher impact per kilogram. There are significant opportunities to reduce the total battery impact by selecting battery raw materials with lower embodied impacts.

When considering (i) the masses of the final battery packs and (ii) the specific energy (kWh/kg) of the final batteries, the comparative results vary. Although LFP has the lowest impact per kilogram of the battery chemistries analysed, its relatively low energy density means that it performs similarly to NMC-811 per kWh, the chosen functional unit. The improved energy density of LFMP batteries results in a significant reduction in impact per kWh compared to the other two LIBs. The optimised energy density of SSBs means that they outperform all three LIB chemistries analysed in terms of impact per kWh. However, this depends on the true energy density of the final, industrially-viable products, as can be seen when comparing LCA results for SSBs using NMC and LFP cathodes with differing kWh/kg performances. ***This LCA study has taken a conservative approach to SSB battery parameters, and assumed high pack mass, low specific energies (with respect to hypothetical maximums), common or average material input impacts and comparable manufacturing intensities and battery pack structure to LIBs***.

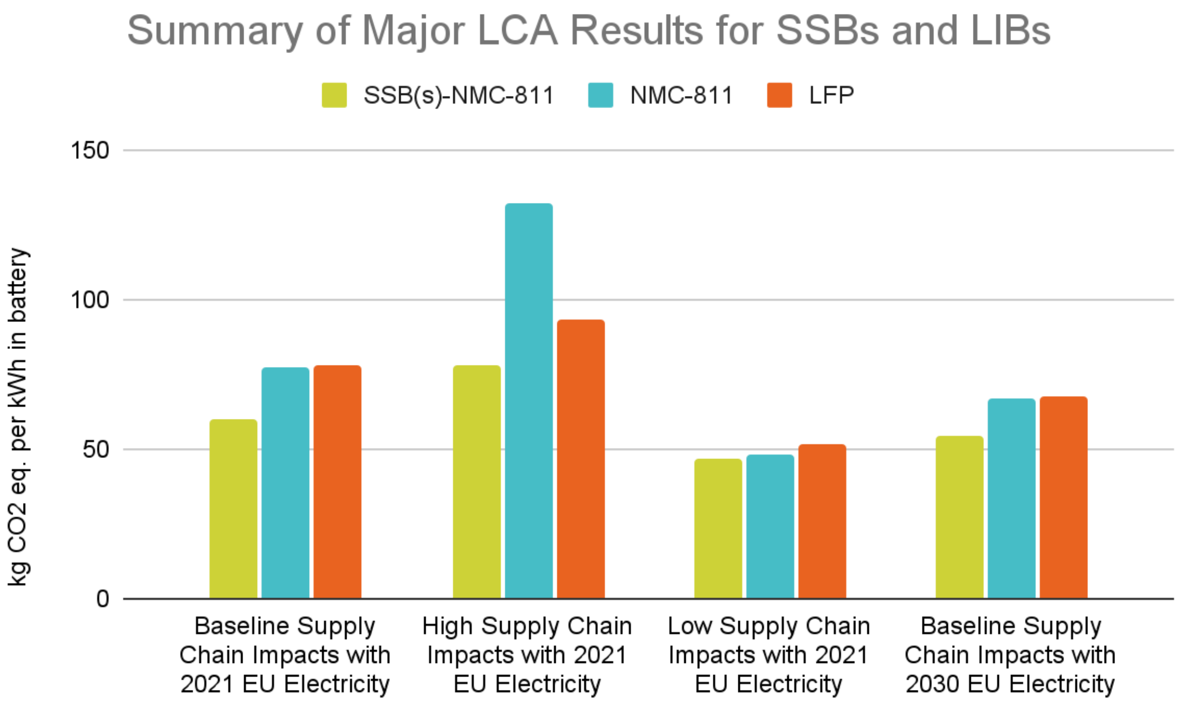
Scenario analysis conducted for this study explores the variability in individual battery material supply chain impacts and the cumulative effects on results from the main LCA.

This includes lithium chemicals, graphite, nickel sulfate, manganese sulfate and iron oxide supply chains:

- Lithium hydroxide, used in NMC cathode active material manufacturing, can have a large range of embodied impacts depending on extraction and processing methodologies - production from spodumene or sedimentary ore is significantly more impactful than from brines or from geothermal systems. Lithium from brines or geothermal systems can be processed via evaporative pond systems or direct lithium extraction (DLE).
- Likewise, lithium carbonate used in LFP cathode active material and SSB lithium metal anode manufacturing, varies with a similar magnitude for the same reasons.
- Nickel sulfate is required in large quantities in high-performance LIB chemistries, and combined with moderate to high impact extraction and processing steps for most production methods, the impact of nickel sulfate drives the overall material NMC-811 LIB or SSB cathode results per kWh.
- Manganese sulfate is used in smaller amounts than nickel sulfate in current NMC chemistries, but this may increase as political and social pressure restricts cobalt supply chains. Primary and secondary manganese sulfate production can be similar to or less than nickel sulfate but is used in far lower quantities; the general understanding is poor in a LCA context due to supply chain data opacity.
- Production impacts associated with natural and synthetic graphite, which is refined via highly energy-intensive processes for LIB anodes, depend strongly on the electricity grid mixes in the production regions and the consumption of fossil fuels within them.
- Despite the overall high environmental footprint of high-volume, high-grade iron ore mining, iron oxide impacts per kilogram are very low, particularly in the relatively small amounts required for LFP cathode production. For this reason, different supply chain routes have minimal impact on a final battery impact per kWh.

A key finding from this study is the sensitivity of the climate change impact of battery production to the raw material supply chain. Opportunities exist within the bill of materials supply chain for each battery type explored herein to reduce impacts alongside changing electricity grid mixes.

A summary of LCA results for the manufacturing of representative batteries from this report is shown below, taking into account current baseline, plus high and low supply chain impacts for materials explored in the model for the 2021 European grid mix, and a prospective baseline supply chain impact for the projected 2030 European grid mix. These scenarios are discussed extensively herein and the differences and similarities between the analysed battery configurations are interpreted using life cycle thinking.



Summary Figure - LCA results for global warming potential for three representative battery chemistries investigated in this report, for current (2021) baseline, high and low supply chain impacts and a projected 2030 European grid mix scenario. Please note - calculated high and low supply chain impacts represent the values used in this report only and not global achievable range of impacts for all commodities.

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List of Acronyms

Acronym	Meaning
CO_2	Carbon dioxide
DFS	Definitive feasibility study
DLE	Direct lithium extraction
eq.	Equivalent
GWP	Global warming potential
H_2SO_4	Sulphuric acid
HCl	Hydrochloric acid
IPCC	Intergovernmental Panel on Climate Change
kg	Kilograms
L	Litres
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
Li_2CO_3	Lithium carbonate
$LiOH \cdot H_2O$	Lithium hydroxide monohydrate
LiCl	Lithium chloride
Li_2O	Lithium oxide
Li_3PO_4	Lithium phosphate
Li_2SO_4	Lithium sulphate
m^2	Metres squared
m^3	Metres cubed
MJ	Megajoules
mol H^+	Moles of protons equivalent (units of acidification potential)
NaOH	Sodium hydroxide (caustic)
Na_2CO_3	Sodium carbonate (soda ash)
N	Nitrogen
NO_x	Nitrogen oxides (NO, NO_2)
PEA	Preliminary economic assessment
PFS	Pre-feasibility study
P	Phosphorous
SC	Spodumene concentrate (% Li_2O)
SO_x	Sulfur oxides (SO, SO_2, SO_3)
t	Metric tonne(s)

3. Introduction

The European Federation for Transport and Environment (Transport & Environment; T&E) has retained Minviro to model the environmental performance of manufacturing solid-state batteries (SSB) in Europe. This study uses life cycle assessment (LCA) to investigate the impact of producing new all-solid technologies in comparison to incumbent lithium-ion battery (LIB) technologies. This chapter is a summary of the methodology applied by Minviro in the LCA.

3.1. Project Description

The project encompasses the hypothetical production of SSB in Europe using the best available data for material inputs, energy inputs, and manufacturing processes for this emerging technology. Since no commercial-scale production is underway, this is primarily based on academic research. Europe has the opportunity to become a world leader in battery manufacturing, given its relatively competitive, low impact electricity grid mix compared to other continents and strong technology infrastructure. However, Europe is reliant and will continue to rely on high amounts of raw material imports for production. It is imperative that whilst creating products to drive decarbonisation (prominently batteries for electric vehicles), low-impact raw materials are selected through the entire bill of materials to ensure that the environmental cost of the creation of these products aligns with their use phase purpose.

In the first half of the study, environmental impacts associated with manufacturing batteries with solid sulfide and oxide electrolyte SSBs, two different existing cathode chemistries and solid lithium metal anodes are quantified using LCA. The results are compared to lithium-iron-phosphate (LFP) and nickel-manganese-cobalt-lithium (NMC-811) LIB production, using the same modelling and parameters, based upon each battery configuration's final specific energy performance (e.g. kWh per kg). Common ('baseline') supply chains for main cathode and anode materials are used for all calculations. An in-development lithium-iron-manganese-phosphate (LFMP) LIB configuration, identical to LFP but with a proportion of iron oxide in the cathode is swapped with manganese oxide to produce a battery with higher theoretical specific energy, is also investigated.

In the second half of the study, various supply chains for six common battery components are explored (lithium carbonate, lithium hydroxide, nickel sulfate, manganese sulfate, graphite and iron oxide), and the relative impacts of producing batteries via different global routes are compared and contrasted. These variations include different extraction methods, alternative ore bodies or region-specific production to make the same final product(s). The baseline LCA models in each instance are kept static, excluding the material being explored, to isolate the effects that raw material supply chains from around the world can have on overall battery impacts. Furthermore, future electricity scenarios for Europe are assessed to investigate the potential impact reduction from grid decarbonisation.

The key sensitivities, data quality and modelling uncertainty within the battery LCAs are quantitatively assessed before conclusions are drawn regarding the relative environmental performance of SSB and LIB production. Recommendations are given for (i) refining the LCA model and its various assumptions as more data on SSB production becomes available and (ii) sourcing the lowest-impact imported or regional raw materials for battery production. The SSB LCA model is the first of its kind and serves as a robust benchmark onto which all relevant future research into the products can be added to refine the results.

3.2. Scope of Assessment

The goal of this LCA is to determine the major project and process parameters contributing to the environmental life cycle impact of the production of emerging SSB configurations for use in electric vehicles (EVs). Additionally, the environmental impact of three chemistries of LIBs - nickel-manganese-cobalt (NMC-811), lithium iron phosphate (LFP) and lithium iron manganese phosphate (LFMP) - are evaluated and compared to results from the SSB study to contextualise their relative environmental performances against their respective energy densities.

LCA is a tool to assess the environmental impacts associated with all stages of a product, process or activity. [3] An important aspect is that it allows the evaluation of indirect impacts that occur in the development of a product or process system over the entire life cycle, providing information that otherwise may not be considered. A wide range of environmental impacts can be captured into a single integrated framework in a scientific and quantitative way. 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 avoiding shifting of the environmental burden [4,5]. It must be noted that LCA is a suitable tool for determining impacts on a global scale, however the tool should be complementary to approaches assessing local impacts such as environmental impact assessments.

3.3. Life Cycle Assessment Methodology

This LCA study has been conducted according to the requirements of the ISO-14040:2006 and ISO-14044:2006 standards.[6] LCA has four fundamental steps: goal and scope definition, inventory analysis, impact assessment, and interpretation, as presented in Figure 1.

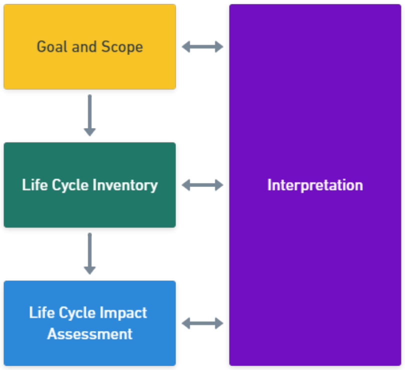


Figure 1: General Phases of a Life Cycle Assessment as Described by ISO 14040, Extracted from ISO 14040.

The life cycle impact assessment (LCIA) was carried out with data from Minviro's internal database and Ecoinvent. Ecoinvent version 3.8.0 provides a well-documented process for products supporting the understanding of their environmental impacts.[7] The Ecoinvent database comprises inventory data for many economic activities.

3.3.1. Goal and Scope

This study assesses the life cycle impact of the production of 1 kWh contained within a SSB from industry average or representative production routes (see assumptions in Section 3.3.4.1). The total production chain includes extraction of raw materials, processing of battery components and manufacturing of battery cells for a complete pack suitable for use in an electric vehicle.

This is a cradle-to-gate study, meaning the product life cycle impact is being assessed from the point of resource extraction to the end gate. The end gate has been set to the output of the battery facility. The use of the product and end-of-life is outside the scope of this LCA study. To understand the full life cycle impact of SSBs from cradle-to-grave requires the extension of the system boundary into the use-phase and the end-of-life phases.

The data generated during these studies provides estimates on the technical parameters for extraction, concentrating and refining associated with the production of SSBs. The primary objective for carrying out this study is to quantify the environmental impacts of the proposed production routes and to identify the environmental "hotspots" for the production of SSB. The second objective of this study is to assist strategic supply chain planning as new battery technologies become available, which involves comparing all results for SSB production to current LIB production. The third objective is to look at a variety of individual raw material supply chains for five key battery components (lithium chemicals, nickel sulfate, manganese sulfate, graphite and iron oxide) to identify opportunities for impact reduction in SSB or LIB production routes.

This study has been conducted according to the requirements of the ISO-14040:2006 and ISO-14044:2006 to ensure that the LCA study is scientifically robust. It is recognized that, in the absence of a third-party review, the results from this study are indicative and for educational purposes.

3.3.2. Functional Unit

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. The **functional unit** for this study is defined as: ***one kilowatt hour contained within a complete (SSB/Li-ion) battery pack, produced from comparable raw material supply chains*.**

3.3.3. System Boundary

This LCA models production of SSB in Europe from primary raw materials sourced from mines, processing and refining facilities from different geographical locations. The life cycle impact of eight distinct stages of the process are modelled: cathode, anode and electrolyte manufacturing, electrode assembly, cell assembly, module assembly, pack assembly, and battery activation. The system boundary for the LCA study covering these stages is presented in Figure 2. The stages are described in the following sections, and a manufacturing flow is presented in Figure 3.

3.3.3.1. Stage 1 - Cathode Active Material Production

Academic and industrial studies suggest that SSBs can use a multitude of existing cathode active material chemistries from Li-ion batteries, and some combinations of cathodes, anodes and solid electrolytes perform better than others. For this study, we analyse production routes for LFP and NMC-811 cathodes for use in SSB packs, given that an entire life cycle inventory for both are already calculated for the scenario analysis in later stages (Section 5), and studies suggest that they will be likely candidates for commercialisation alongside solid electrolytes and anodes. [8,9] Energy inputs for this stage include: mixing, coating and calendaring. These process steps essentially prepare and shape the cathode active material into layers suitable for cell manufacturing.

In this study production of NMC-811 cathodes involves extracting nickel, manganese and cobalt ores from primary sources and refining each into base metal sulfates. The sulfates are then mixed together with lithium hydroxide, sodium hydroxide and ammonium hydroxide, and water, electricity and natural gas are consumed during processing. See Section 5.1 for finer details of NMC-811 production in the context of LIB applications. See Section 6 for production details for each of these material components.

In this study production of LFP cathodes involves extracting lithium carbonate from spodumene ores or brine and combining with iron oxide and diammonium phosphate to form lithium iron phosphate. This process uses water, electricity and natural gas for heating. See Section 5.2 for finer details of LFP production in the context of LIB applications.

3.3.3.2. Stage 2 - Lithium Metal Anode Production

In this study SSB anode production involves manufacturing lithium metal from lithium carbonate, which is extracted and refined from spodumene or brines. This is a material and energy intensive process, and is defined by the following chemical equation:

$$Li_2CO_3 + CaCl_2 \rightarrow CaCO_3 + 2LiCl$$

Lithium chloride is then converted into lithium metal and chlorine gas via electrolysis. This process requires 5.32 kg of lithium carbonate for every 1 kg of lithium metal produced. Lithium metal works particularly well in SSB set-ups and battery structure is designed around accommodating metal swelling and minimising dendroid formation, a limiting factor in LIB development. Energy inputs for this stage include: mixing, calendaring, lamination and slitting. These process steps essentially prepare and shape the anode material into layers suitable for cell manufacturing.

3.3.3.3. Stage 3 - Solid Electrolyte Production

The key differentiator between LIB and SSB technology lies in the electrolyte - in the former, this is a liquid and in the latter, this is a solid. As with SSB cathodes, a wide range of material options have been explored in the literature alongside predominantly lithium metal anodes, and can broadly be classified as sulfide, oxide or, more recently, polymer solid electrolytes. The production method varies for each category of electrolyte, as do the stages at which each component is mixed or stacked with the other components. For this study, data availability for sulfide and oxide manufacturing processes are sufficient, whilst polymer is still very much an emerging technology and data in sparse and unsuitable for LCA calculations. Once companies or institutions can make manufacturing data public, these electrolyte varieties can be explored, but the data resolution is currently too low compared to sulfides and oxides. Hence, the production flows for sulfide and oxide bearing SSB configurations are explored herein. Energy inputs for this stage include: mixing, coating, extrusion, calendaring and slitting. As with Stage 1 and 2, these process steps essentially prepare and shape the solid electrolyte material into layers suitable for cell manufacturing.

3.3.3.4. Stage 4 - Electrode Assembly

Once the cathode, anode and solid electrolyte have been made separately, they are combined depending on the electrolyte material. This normally involves individual processes for each component, before the cathode and electrolyte are affixed to each other and then to the anode. This varies slightly from sulfide to oxide configurations. In sulfide configurations, the “catholyte” is attached to the anode immediately before cell assembly. In oxide configurations, the catholyte must be tempered before it is then affixed to the anode prior to cell assembly. Energy inputs for this stage are variable and generally attributed to production of each of the electrodes or electrolytes in this study. This includes sintering and tempering of oxide catholytes, which are steps that prepare the oxide material for electrical applications, as in general oxide minerals are more technically difficult to embed in cells than sulfides.[10]

3.3.3.5. Stages 5, 6 and 7 - Cell, Module and Pack Assembly

Most manufacturing companies aim to apply SSB technology to existing pouch cell and battery pack structures, to enable reuse of existing infrastructure and technology for production; this is primary being developed for sulfide electrolytes [9,11] but the same methodology can be extended to oxide electrolytes.[12] Hence, in this model, we assume that assembly processes are identical to LIB routes, and all will use pouch configurations. Aluminium, copper and plastics are used for various structural applications to create cell, module and pack casings and architecture. Multiple cells are merged into a single module, and multiple modules are merged into a single pack. Energy inputs for these stages include: cutting, stacking, pressing, welding, packaging, sealing and formation, essentially forming the separate components and affixing them to each other as conductive cells, ready for assembly into modules and packs depending on battery model specifications.

3.3.3.6. Stage 8 - Conditioning

To finish the production process, the entire pack has to be conditioned, activating the electrical properties of the battery. This exclusively involves energy inputs for ageing and dry room generation for SSB chemistries; the former subjects batteries to a sustained temperature for days to weeks to ensure proper functionality, and the latter ensures no moisture or reactive gases impede manufacturing.[13,14]

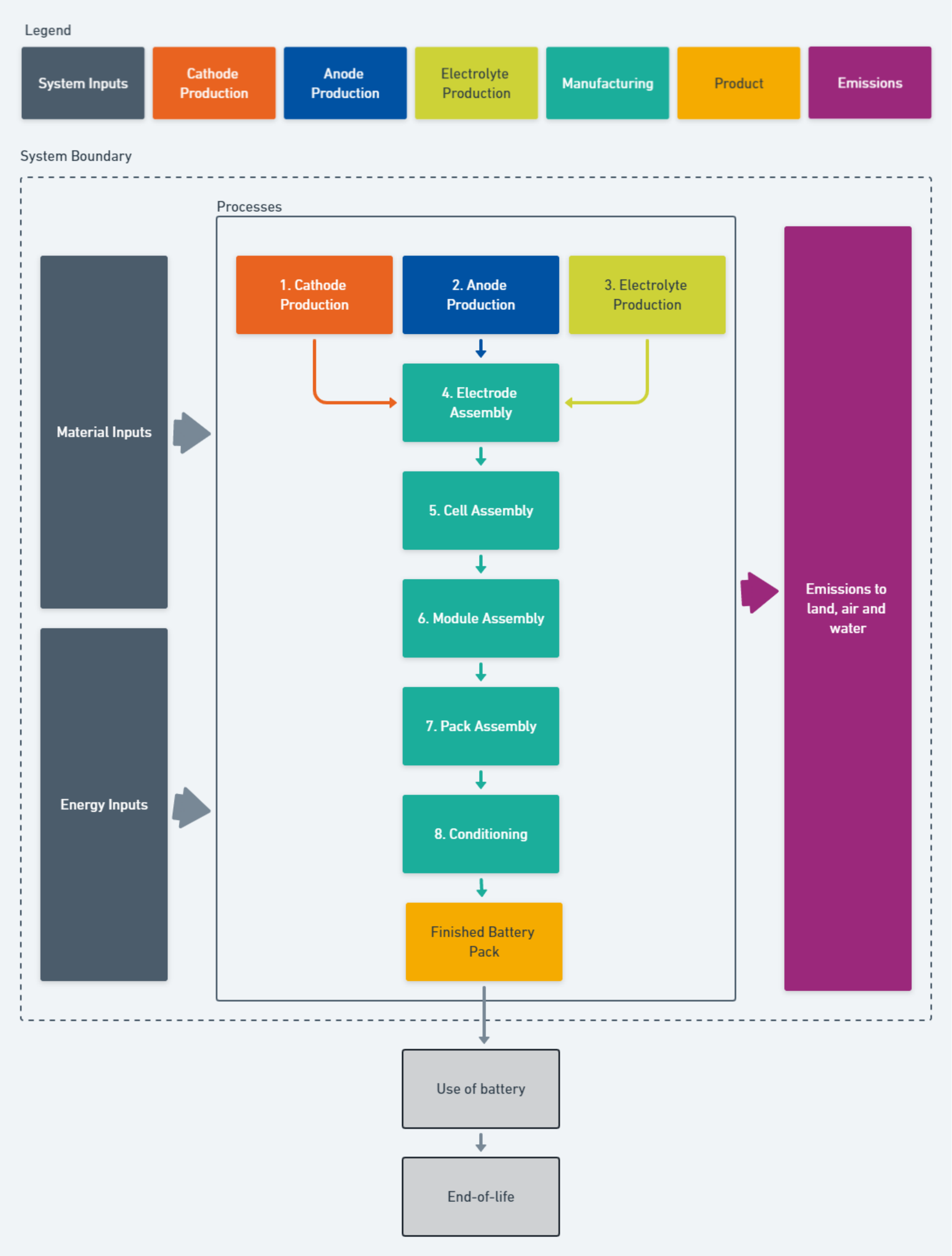


Figure 2: System Boundary Applied to the SSB LCA Study

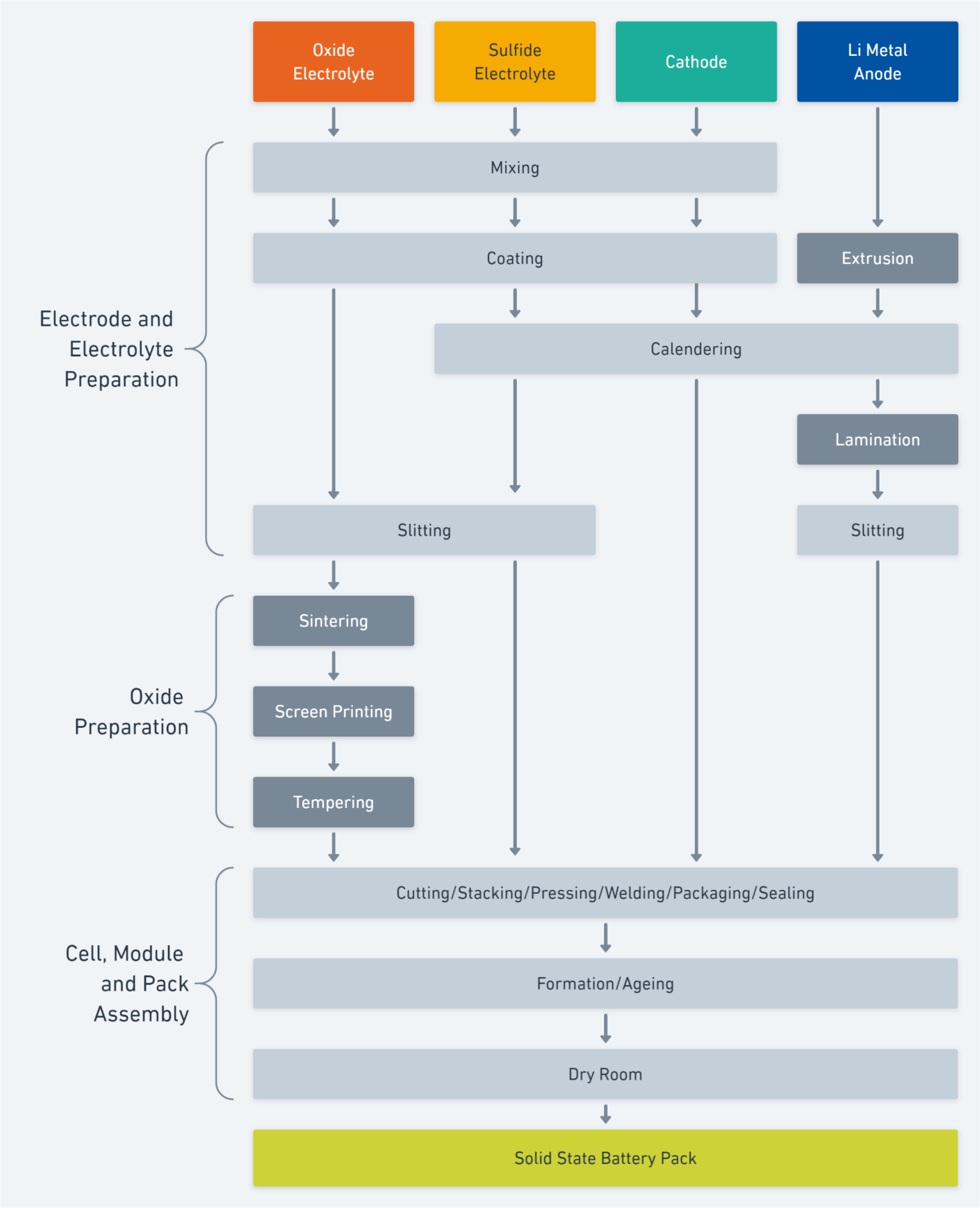


Figure 3: Manufacturing energy input stages for SSB assembly. Processes are either common to multiple components or unique to each, and all energy used for all processes in this flowsheet is taken into account in the LCA model.

3.3.4. Life Cycle Inventory

3.3.4.1. Solid-state Battery Production Route

This study was desk-based, meaning that all data was collected from public sources, or assembled from public and private databases. Background data was taken from Ecoinvent 3.8.0. A LCI summary is included in Appendix A. Battery model specifications used in the LCA are shown in Appendix B. An analysis of all material and energy flows within the system boundary were made and all material and energy flows related to the extraction and refining of the raw materials used to produce SSBs have been included in the LCI and included in the life cycle impact assessment, to the best of current data availability. This includes materials and energy consumed at each stage of the production process.

As SSBs are not currently in production, there is a large degree of uncertainty in the life cycle inventory, and a number of assumptions have been made in order to produce a functioning LCA model. Assumptions for the SSB production route in this LCA are as follows:

1. The total mass of the final SSB battery pack in the model is assumed to be 300 kg, the maximum proposed mass by companies seeking to commercialise their batteries. [15] This mass is used to calculate the impact per kg of battery, before conversion to impact per kWh in said battery.
2. The input mass of the SSB cathode, anode and solid electrolyte are based upon the total battery mass (300 kg for this model), the proportion of this total not occupied by aluminium, copper and other cell/module/pack structures, the idealised relative thickness of each component in a finished battery cell [16], and the density of each material, to give an approximate, workable bill of materials for pack manufacturing; this will vary as a function of the cathode and electrolyte selection(s). Commercial proportions for SSB cells are not currently available, so this calculation serves as an estimated bill of materials only, based on the required amount of cathode active material, anode and electrolyte to secure optimum battery performance.
3. The model assumes pouch battery cell design and all material inputs for SSB and LIB chemistries explored in the study reflect this - pouches are currently seen to be the most viable SSB configuration [9] and for a fair comparison, the model sets all

batteries to this set-up. Cylindrical and prismatic structures may have different impacts, although data resolution for these configurations is low.

4. The model assumes 8 cells per module and 18 modules per final battery pack; this predominantly affects energy inputs as most data availability is for kWh input per cell produced.
5. Since cathode/anode/electrolyte combinations are expansive, the model has assumed the most industrially-viable options that also have reasonable data quality for electrode impacts (e.g. NMC-811 or LFP cathode, lithium metal anode, and simple solid oxide or sulfide electrolytes).
6. Electricity values for ***all*** battery manufacturing processes are based in Europe (EU27 regional grid mix average for 2021)[17]; this does not include energy inputs to make cathode or anode precursor materials, as those are specific to the country of original for each raw material supply chain route (see Section 6.1-6.5). Different energy scenarios for future European manufacturing are considered in Section 6.7.
7. Given that SSB energy density is modelled to be between 250 and 500 Wh/kg [18], depending on a multitude of factors, a single value does not describe the full story and is a large factor in final impact per kWh, so variability must be addressed.
8. SSB using LFP cathodes are modelled at 250 Wh/kg and SSB using NMC-811 cathodes are modelled at 400 Wh/kg in this study, as per QuantumScape manufacturing predictions. [8]
9. For components common to multiple chemistries across the SSB and LIB LCAs (e.g. graphite in LIB anodes) the model assumes the same supply chain route for all calculations for a fair comparison (see Section 6 for different supply routes). The baseline for common battery components used in SSB and LIB configurations in this LCA are as follows:

*Table 2: Baseline supply chains for common battery materials used in all SSB/LIB models. * lithium chemical averages generated assuming a broad 70:30 split between global spodumene and brine sources, and calculating a new impact based on this proportion. † supply chains not included in investigation.*

Battery Material	**Supply Chain**	**Region**	**Used In**
Lithium hydroxide	Global average*	Australia/Chile	NMC Cathodes
Lithium carbonate	Global average*	Australia/Chile	LF(M)P cathodes; Li metal
Graphite	Natural and synthetic	China	LIB Anodes

Nickel sulfate	Nickel Institute average[19]	Global	NMC Cathodes
Manganese sulfate	Primary ore extraction	Global	NMC Cathodes
Cobalt sulfate †	Primary ore extraction	Global	NMC Cathodes
Iron Oxide	Primary ore extraction	Global	LF(M)P Cathodes

10. Transportation impacts are not included in this model, as the supply chain is too variable to accurately calculate without confirmed supplier locations; this can be enhanced once supply chain routes are identified. However, as a qualitative statement, climate change impacts are less sensitive to transport impacts compared to raw material production impacts.
11. Many data sources are laboratory-scale or commercial forecasted demands, but the efficiency of pilots may not be reflective of final gigafactory performances. Academic data is likely to differ from operational demand figures, and assumptions are made in all current studies to arrive at quantitative data until full production commences.
12. No data is available for solid electrolyte energy inputs for precursor material (e.g. preparing oxide and sulfides for use in SSB cells), only material inputs and manufacturing energy inputs once the oxide/sulfide has been produced. Certain impacts related to solid state electrolytes may be underestimated.
13. Some energy inputs for SSB are not available - namely for ageing and dry rooms; in this absence, the model assumes identical input values per final battery as LIB calculations, as it is likely to be very similar given the application.
14. Energy inputs for creating the argon atmosphere required for early SSB electrode/electrolyte assembly are not included in the model due to data unavailability.
15. Lithium metal SSB anode life cycle inventory is based upon the lithium carbonate to lithium metal chemical reaction; this is not verified for an industrial scale, and is currently based upon best knowledge from Minviro lithium experts.
16. The model uses the same pack configuration for all batteries included in this study - 8 cells per module and 18 modules per final pack, which produces a final energy capacity of between 25 and 60 kWh for all set-ups (including LIB comparisons), which is within the range desirable for an electric car (see Appendix B). In reality pack configurations will change and adapt to individual cell chemistry specific

energy performance and can be adjusted for each chemistry when data is available. For this current study, modelling requires robust values to begin with, and we acknowledge the limitations on calculating based on a fixed pack structure (see Section 10 for final comments on the effects of battery specifications on environmental impact quantification).

17. Typical LCA studies will allocate impacts for co-products produced alongside a final product (e.g. a battery), but without a real production setting and process flow, this is not possible to add into this study. In reality, saleable scrap metal, black mass or chemical co-products can be included in LCA models and impacts can be assigned as appropriate for realistic production facilities. Furthermore, material losses and inefficiencies in manufacturing steps, and recycled input streams can be incorporated in a similar manner. These aspects are of low data quality in the scientific literature, and without an industrial case study from which data can be taken from, are excluded in this study, but should be explored in further updates or associated studies.

3.3.4.2. LFMP Production Route

As part of the comparison of SSB against LIB configurations, this project involved calculating the impact of manufacturing a third emerging LIB chemistry, LFMP. This model is less established than NMC-811 and LFP, and thus assumptions are as follows:

1. The bill of materials and energy inputs for all stages of LFMP manufacturing are assumed to be identical to LFP used elsewhere in the study, excluding the iron oxide and manganese oxide; as with SSB models, this may not reflect production reality but due to lack of commercial data this will be as robust of possible at the time of writing.
2. Given that experimental studies into LFMP performance provide a list of potential Fe:Mn ratios [20], all of which do not affect the overall chemical formula of the compound ($LiFePO_4$, $LiFe_{08}Mn_{02}PO_4$, $LiFe_{02}Mn_{08}PO_4$ etc.), the model uses iron(III) oxide and manganese(III) oxide as material inputs, and assumes the chemicals are mixed within the regular lithium-iron-phosphate production route to produce the same amount of precursor material per kg of cathode as the LFP model.

3. Manufacturers suggest that LFMP has 25% higher specific energy than LFP, and thus the LCA model assumes 125% of 0.174 kWh/kg[21], resulting in 0.22 kWh/kg.

3.3.4.3. Alternative Supply Chain Scenarios

To understand the decarbonization opportunities available to lower the impacts of producing key raw materials for battery production, a number of scenarios were evaluated. This was done by switching a single input within a standard LCA model (i.e., that belonging to the material in question) to alternative supply chains or production processes. The system boundary does not change in these scenarios. All impacts are calculated using values from Minviro's internal database or Ecoinvent 3.8.0, although the latter is avoided unless necessary. The following scenarios were modelled:

- Lithium chemicals from various global supply chains;
- Nickel sulfate from various global supply chains;
- Manganese sulfate from various global supply chains;
- Graphite from various global supply chains;
- Iron oxide from various global supply chains.

The environmental impacts of each raw material are investigated adjacent to alternative routes to identify the most sustainable sources for European battery manufacturing. This does not include a quantitative transportation impact for delivering raw materials and intermediate products to Europe for battery manufacturing, but a qualitative impact will be indicated based upon proximity to Europe.

3.3.5. 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. In this study, no cut-off criteria were applied to the flows entering or leaving the system. All flows listed in the GREET model[21] and academic LCAs used as a basis for this study were considered. It is possible that cut-off effects have been applied to the background flows from Ecoinvent 3.8.0, for example, due to missing flows in the background dataset.

Flows related to the manufacturing of equipment, maintenance, packaging, or infrastructure have been excluded in this LCA. The reason for excluding these flows is that they are usually very small compared to flows of reagents or energy consumed in the process over decades of production, and are often challenging to model. These flows can be included in the LCI at a later date if T&E has information on them and if they are deemed to be significant.

3.3.6. Life Cycle Impact Assessment

The main LCIA category selected for this study is global warming potential (GWP). This impact category was chosen for this project because its focus is to perform a high-level climate change potential assessment of various battery supply chains and is not based on a specific project development. Other impacts and descriptions are given in Appendix A. The LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

3.3.6.1. Global Warming Potential

Baseline model of 100 years of the IPCC (based on IPCC 2013)

Climate change can be defined as the change in global temperature caused by the greenhouse effect of “greenhouse gases” 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 [22]. The environmental profiles characterization model is based on factors developed by the UN’s Intergovernmental Panel on Climate Change (IPCC). [23] Factors are expressed as GWP over the time horizon of different years, the most common historically being 100 years (GWP100), measured in the reference unit, **kg CO_2 eq.**

3.3.7. Interpretation

The results were interpreted with reference to the goal and scope, comparing the impacts associated with the identified process routes, geographic regions, and technology implemented. Contribution analysis, sensitivity analysis, and uncertainty analysis were carried out to support the interpretation of the LCA.

3.3.8. Data Quality Requirements

The key data criteria used to create the LCI 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 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 considered to be of the highest precision, followed by calculated data, data from literature, and estimated data. This study is carried out with public academic and industrial data. It must be noted that measured data can be precise but inaccurate. Accuracy can be obtained by cross-validation of measured data with other standards.
- 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 3 presents the grading system of data quality indicators. An evaluation of the data quality for this LCA on SSB can be found in later chapters of this report.

Table 3: Grading Guidelines for Data Quality Assessment as Environmental Footprint 2.0 Pedigree Matrix [24]

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 dataset is older than 8 years	The dataset is less than 8 years old	The dataset is less than 6 years old	The dataset is less than 4 years old	The dataset is less than 2 years old
Geographical Representatives	Data represented is from a distinctly dissimilar region	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

	of project location				
Completeness	Unknown coverage	Data is from small parts of the target region	Data is less than 50% from the target region	Data is more than 50% from the target region	Data is representative of the entire target region
Precision	Rough estimate with known deficits	Estimates based on calculations not checked by the reviewer	Estimates based on expert judgment	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

3.3.9. Critical Review

A critical review has not been carried out by independent experts, and thus all results should be considered as indicative and for educational purposes only.

4. Results

4.1. Global Warming Potential

kg CO_2 equivalent

The overall global warming potential of the four SSB configurations explored in this LCA are presented in the following sections per kWh in the final battery pack, divided into the major production stages. All other impact categories are provided in Appendix A. Results are briefly discussed in the following sections and expanded upon in detail in Sections 5, 6 and 10.

4.1.1. Global Warming Potential - Sulfide SSB with LFP Cathode

The total GWP for producing SSB with a sulfide electrolyte and a LFP cathode is around 16.8 kg CO_2 eq. per kg SSB according to the LCA model produced by Minviro (Figure 4). This equates to 67.3 kg CO_2 eq. per kWh in the battery if assuming an energy density of 0.25 kWh/kg at pack level. The cathode and anode contribute to roughly a third of the total impact, each.

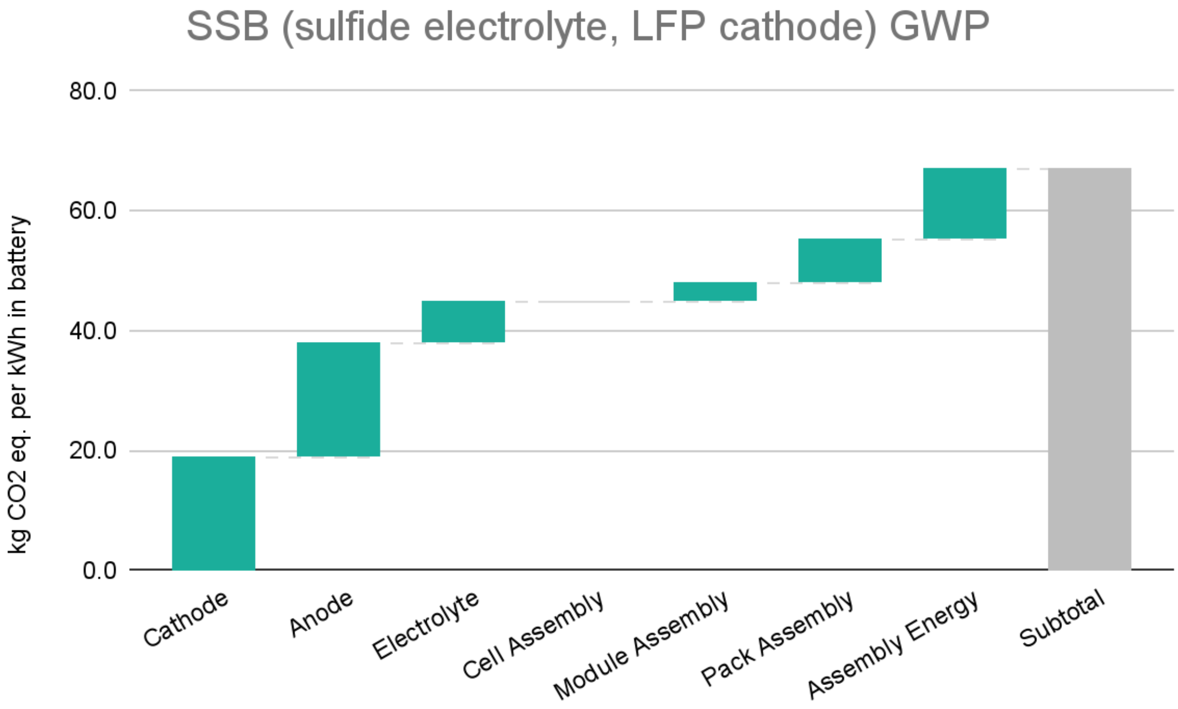


Figure 4: Total Global Warming Potential for the Production of sulfide SSBs with LFP cathodes.

4.1.2. Global Warming Potential - Sulfide SSB with NMC-811 Cathode

The total global warming potential for producing SSB with a sulfide electrolyte and a NMC-811 cathode is around 24.0 kg CO_2 eq. per kg SSB according to the LCA model produced by Minviro. This equates to 60.0 kg CO_2 eq. per kWh in the battery if assuming an energy density of 0.40 kWh/kg at pack level (Figure 5). Cathode production contributes more than half of the total impact, whilst anode production is less than a quarter.

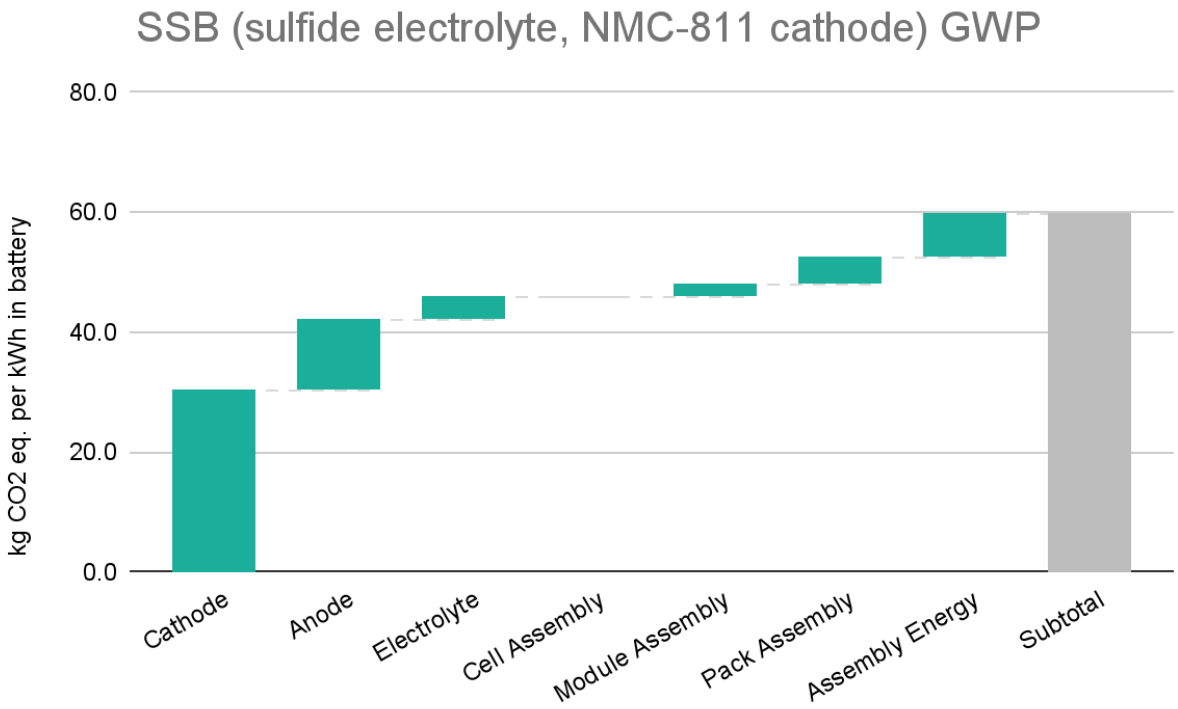


Figure 5: Total Global Warming Potential for the Production of sulfide SSBs with NMC-811 cathodes.

NMC-811 cathodes are more impactful to manufacture than LFP cathodes according to baseline supply chains (Section 3.3.4.1). Meanwhile the higher specific energy of NMC-811 SSBs will *relatively* reduce impacts through the full model per kWh compared to a LFP SSB.

4.1.3. Global Warming Potential - Oxide SSB with LFP Cathode

The total global warming potential for producing SSB with an oxide electrolyte and a LFP cathode is around 16.0 kg CO_2 eq. per kg SSB according to the LCA model produced by Minviro. This equates to 64.1 kg CO_2 eq. per kWh in the battery if assuming an energy density of 0.25 kWh/kg at pack level (Figure 6). Anode production contributes more than a third of the total impact, and cathode production is slightly less than this.

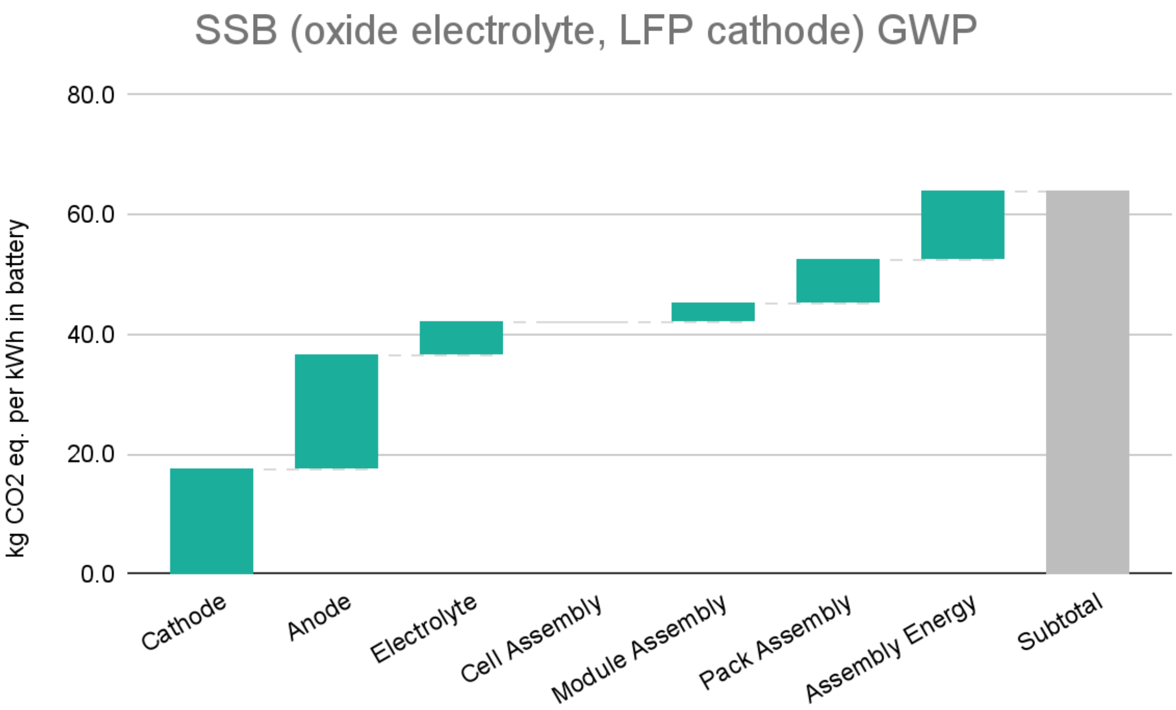


Figure 6: Total Global Warming Potential for the production of oxide SSBs with LFP cathodes.

4.1.4. Global Warming Potential - Oxide SSB with NMC-811 Cathode

The total global warming potential for producing SSB with an oxide electrolyte and a NMC-811 cathode is around 23.2 kg CO_2 eq. per kg SSB according to the LCA model produced by Minviro. This equates to 58.0 kg CO_2 eq. per kWh in the battery if assuming an energy density of 0.40 kWh/kg at pack level (Figure 7). Cathode production contributes around half of the total impact, whilst anode production is less around a quarter.

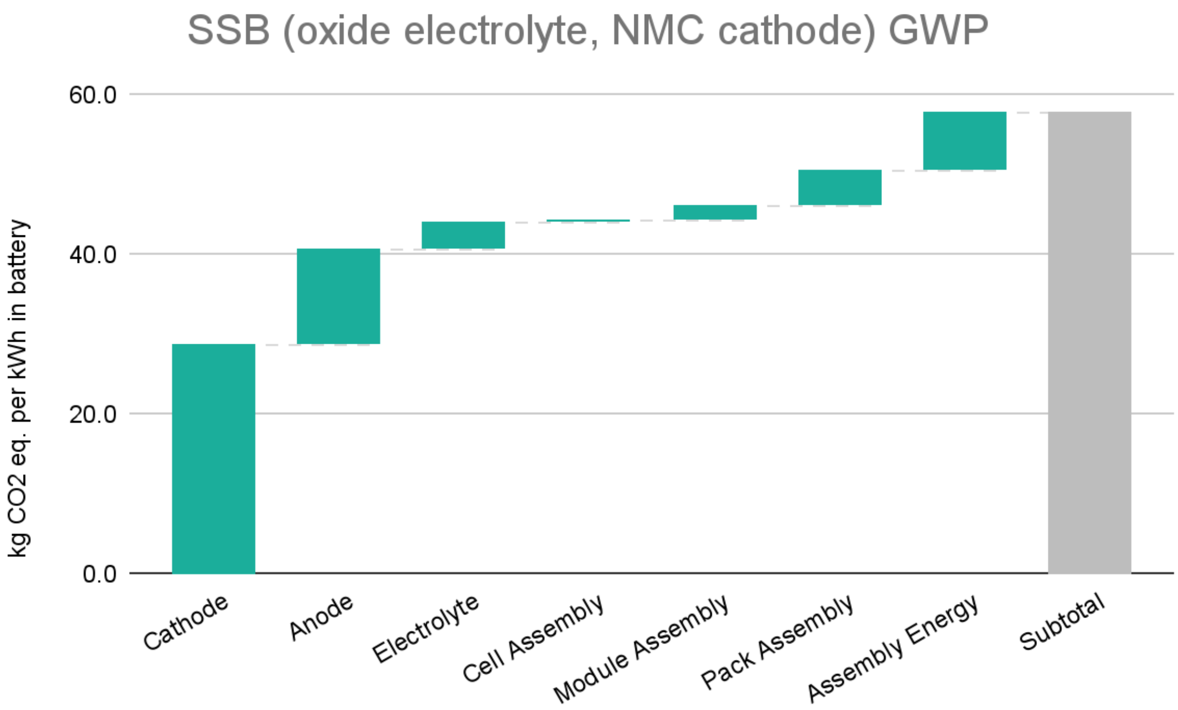


Figure 7: Total Global Warming Potential for the production of oxide SSBs with NMC-811 cathodes.

Oxide electrolytes are slightly less impactful than sulfides to manufacture than LFP cathodes according to baseline supply chains (Section 3.3.4.1), despite requiring extra manufacturing steps (Figure 3). Oxide minerals are often mined and processed in high grade, high volume scenarios, meaning that supplies used in small quantities will have a relatively lower contribution to total environmental impacts in products.

5. Comparison with Lithium-Ion Battery impacts

Minviro has developed generic process route data for making comparisons between battery pathways, either currently in production or in development. These comparison scenarios for LIBs (NMC-811, LFP and LFMP chemistries) are included below. The LCA models for each pathway are constructed identically to the SSB model, and when a material or energy input is the same in each pathway, the same characterisation factor is used in all instances. For example, lithium carbonate is used in both SSB (to make Li metal anodes) and LFP (to make lithium iron phosphate), and thus the model uses the same production route (the global average for spodumene and brines calculated for Table 2) in both scenarios to ensure a fair comparison of results. Different supply chain impacts for individual battery components, including lithium carbonate, are explored in Section 6. Baseline production for major LIB components used are stated in Section 3.3.4.1.

The following sections present life cycle impact results for the GWP impact category for the production of NMC-811, LFP and LFMP, and compare impacts to SSB results from Section 4. All other impact categories are provided in Appendix A.

5.1. NMC-811

NMC batteries have high specific energy performance compared to other LIB set-ups.[25] The NMC-811 bill of materials is based on the 2020 GREET model.[21] Energy inputs for each stage of battery manufacturing are based on a 2019 study by Thomitzek et al.[26] and reviewed by Erakca et al. in 2021[27], exploring energy demand in cell manufacturing. Results from the NMC-811 LCA for GWP are displayed in Figure 8.

The total global warming potential for producing NMC-811 batteries with graphite anodes is around 19.0 kg CO_2 eq. per kg battery according to the LCA model produced by Minviro. This equates to 76.7 kg CO_2 eq. per kWh in the battery if assuming an energy density of 0.25 kWh/kg at pack level. Cathode production contributes almost half of the total impact, and anode production and manufacturing energy contribute less than a quarter of the total impact each. Figure 9 gives a contribution analysis of the production of NMC-811 cathode active material. Nickel sulfate is a large contributor to overall impact, as is natural gas.

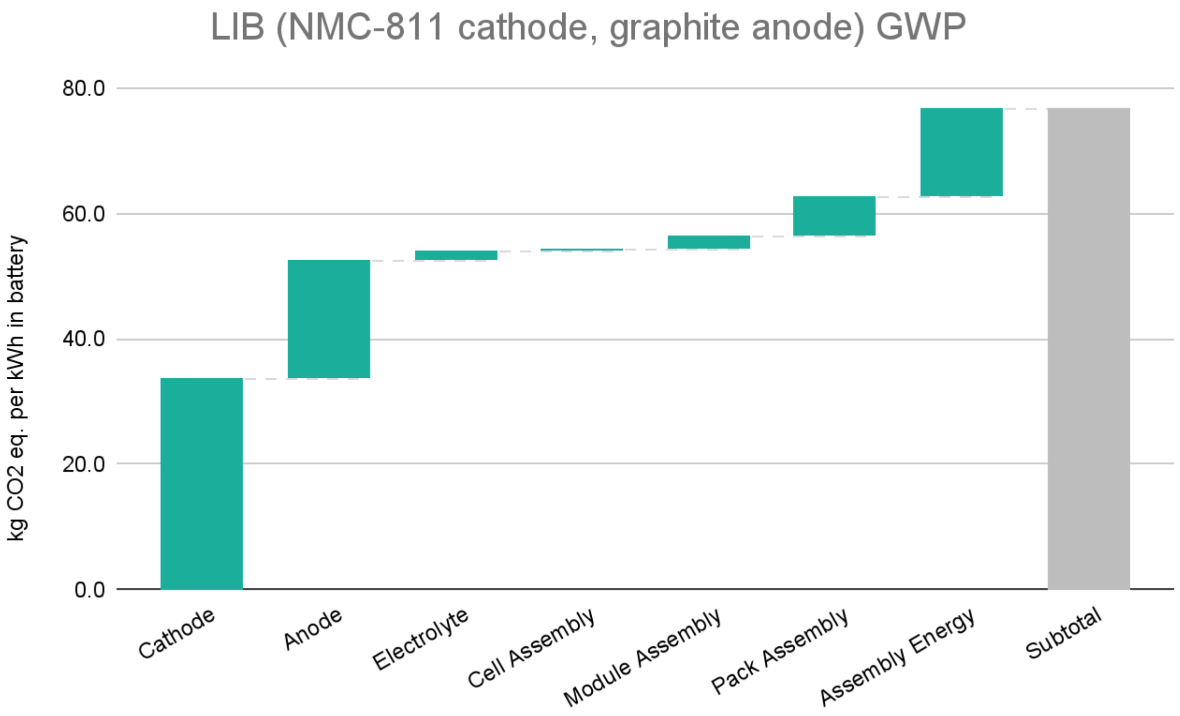


Figure 8: Total Global Warming Potential for the production of LIBs with NMC-811 cathodes.

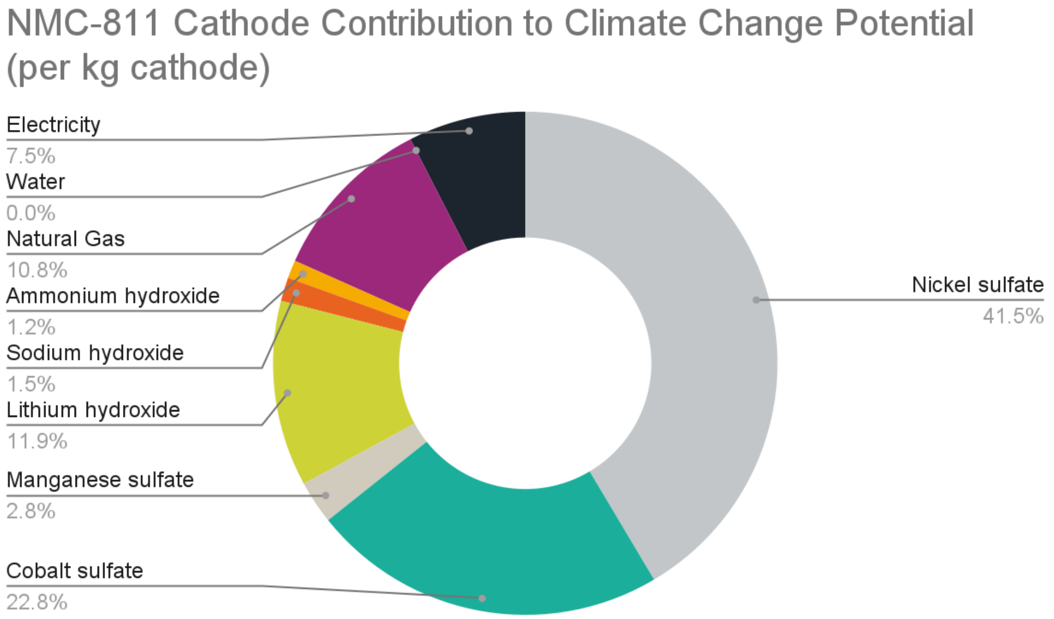


Figure 9: Global Warming Potential Contribution for NMC-811 cathode only, including energy, per kg cathode.

5.2. LFP

LFP batteries have low specific energy performance compared to other LIB set-ups, but superior longevity and safety.[25] The LFP bill of materials is based on the 2020 GREET model.[21] Energy inputs for each stage of battery manufacturing are based on data from the same study as NMC-811.[26] Results of the LFP LCA for GWP are shown in Figure 10.

The total global warming potential for producing LFP batteries with graphite anodes is around 13.6 kg CO_2 eq. per kg battery according to the LCA model produced by Minviro. This equates to 77.9 kg CO_2 eq. per kWh in the battery if assuming an energy density of 0.174 kWh/kg at pack level. See Section 10.1.1 for a discussion on LFP specific energy performance. Cathode production contributes just under a third of the total impact, and anode production is slightly less than this - this contrasts with NMC-811 where impacts associated with cathode production are more than double that of the anode. Figure 11 gives a contribution analysis of the production of LFP cathode active material. Lithium carbonate production is by far the largest contributor to overall impact, followed by diammonium phosphate.

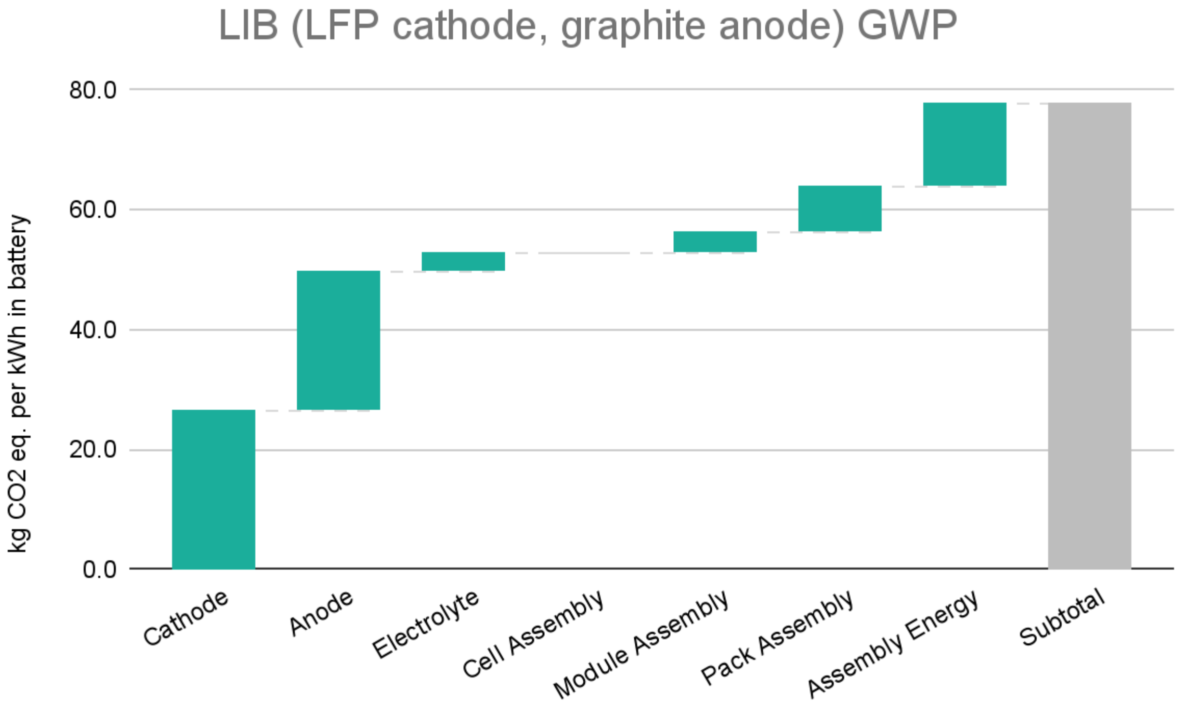


Figure 10: Total Global Warming Potential for the production of LIBs with LFP cathodes.

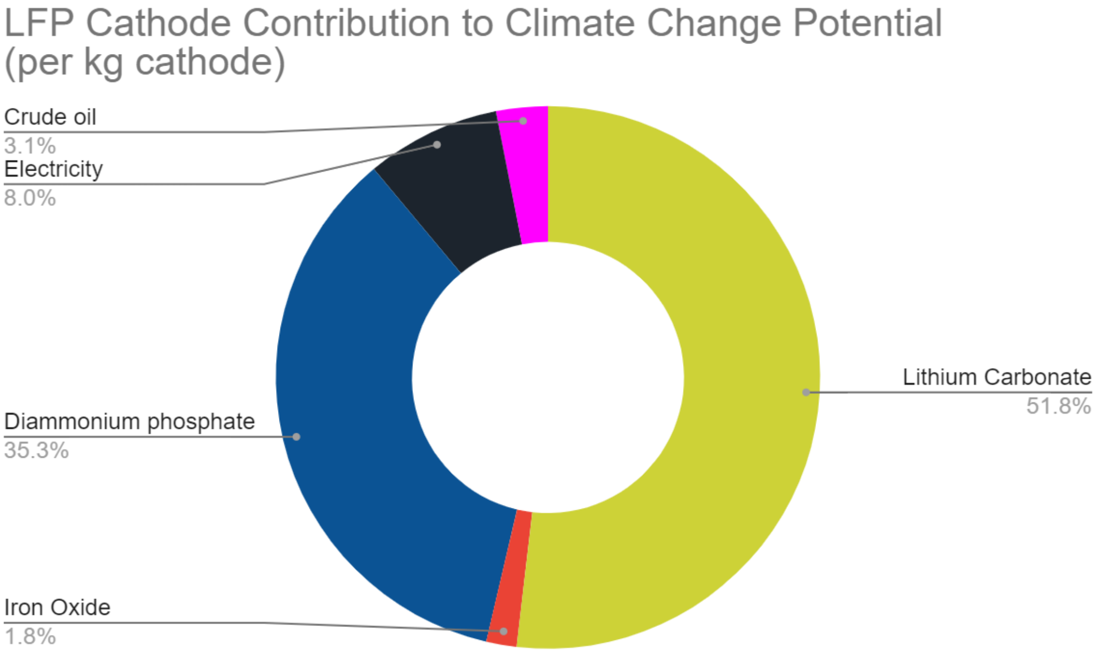


Figure 11: Global Warming Potential Contribution for LFP cathode only, including energy, per kg cathode.

5.2.1. LFMP

The LFMP bill of materials is based on the 2020 GREET model for LFP with adjustments to the cathode active material only.[21] A ratio of 4:1 (Mn:Fe) ferrous oxide in the precursor has been selected as it is most different from LFP.[20] This battery configuration is being developed with the intention to increase the specific energy of LFP batteries by 25% whilst maintaining their superior long-term performance (i.e. battery life, power, safety).[28] Early studies show that although there are significant benefits of including manganese oxide within the iron oxide precursor material, LFMP batteries see a performance drop-out at 50% charge not observed in LFP, which is the main detractor from this set-up and will require a specifically-developed battery management system.[29] Energy inputs for each stage of battery manufacturing are based on the same Thomitzek et al. study on energy demand as NMC-811.[26] Results from the LFMP LCA for GWP are displayed in Figures 12, 13.

The total global warming potential for producing LFMP batteries with graphite anodes is around 14.4 kg CO_2 eq. per kg battery according to the LCA model produced by Minviro, which is higher than LFP. However, this equates to 66.0 kg CO_2 eq. per kWh in the battery if assuming an energy density of 0.219 kWh/kg at pack level (125% of LFP energy density).

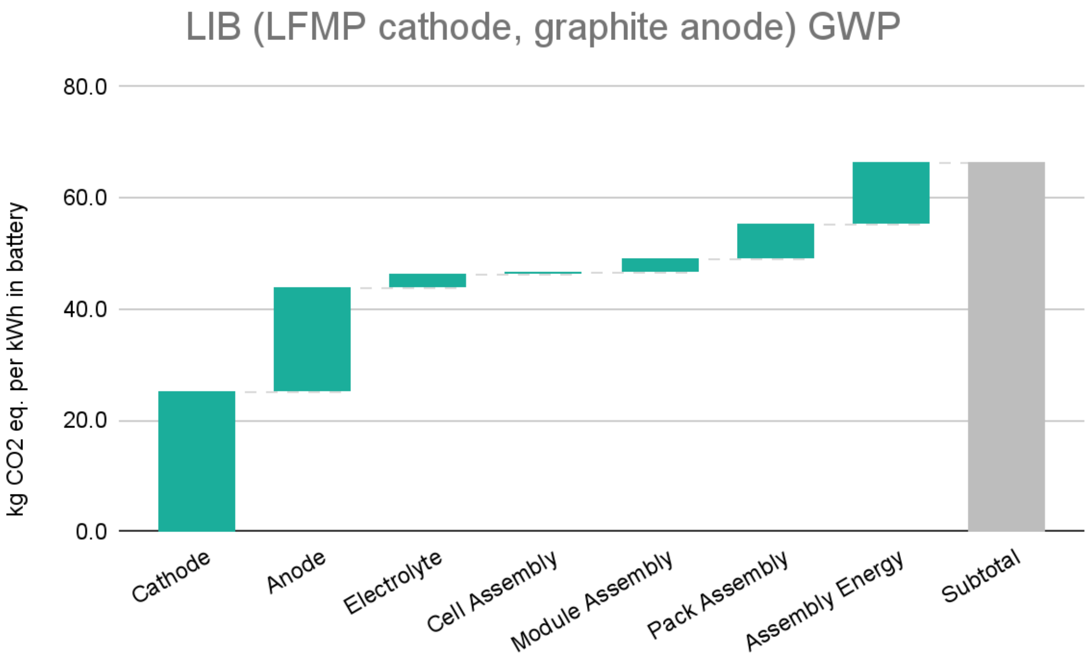


Figure 12: Total Global Warming Potential for the production of LIBs with LFMP cathodes.

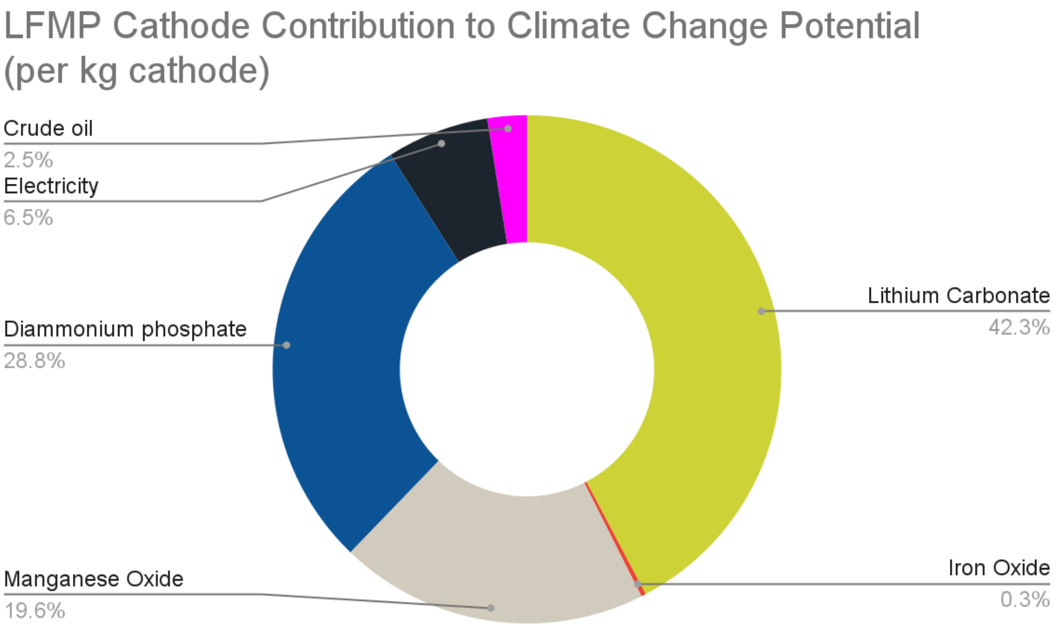


Figure 13: Global Warming Potential Contribution for LFMP cathode only, including energy, per kg cathode.

5.3. Comparison

Figures 14 and 15 compare the four baseline SSB global warming potential results from Section 4 against NMC-811, LFP and LFMP LIB results, per kWh and per kg, respectively. When considering battery impacts as a function of their mass, those associated with NMC-based cathode chemistries, either SSB or LIB, are notably higher than their LFP/LFMP counterparts (Figure 15). However, given that NMC cathode batteries are better performing in terms of pack specific energy, the relative impacts even out when comparing results per kWh in the final battery products. Generally, SSB are also less impactful per kWh compared to LIB, again due to higher energy density. LIBs with LFMP cathodes see a significantly better per kWh performance than those with LFP cathodes. In higher resolution, oxide electrolytes in SSBs contribute to a slightly lower total impact per kWh in the final battery compared to sulfide electrolytes, as sulfide minerals can be more intensive to process than oxides. See Section 6.5 for more details regarding oxide material production.

For a more in-depth discussion of how specific energy affects final LCA results of both SSBs and LIBs, see conclusions and insights in Section 10.

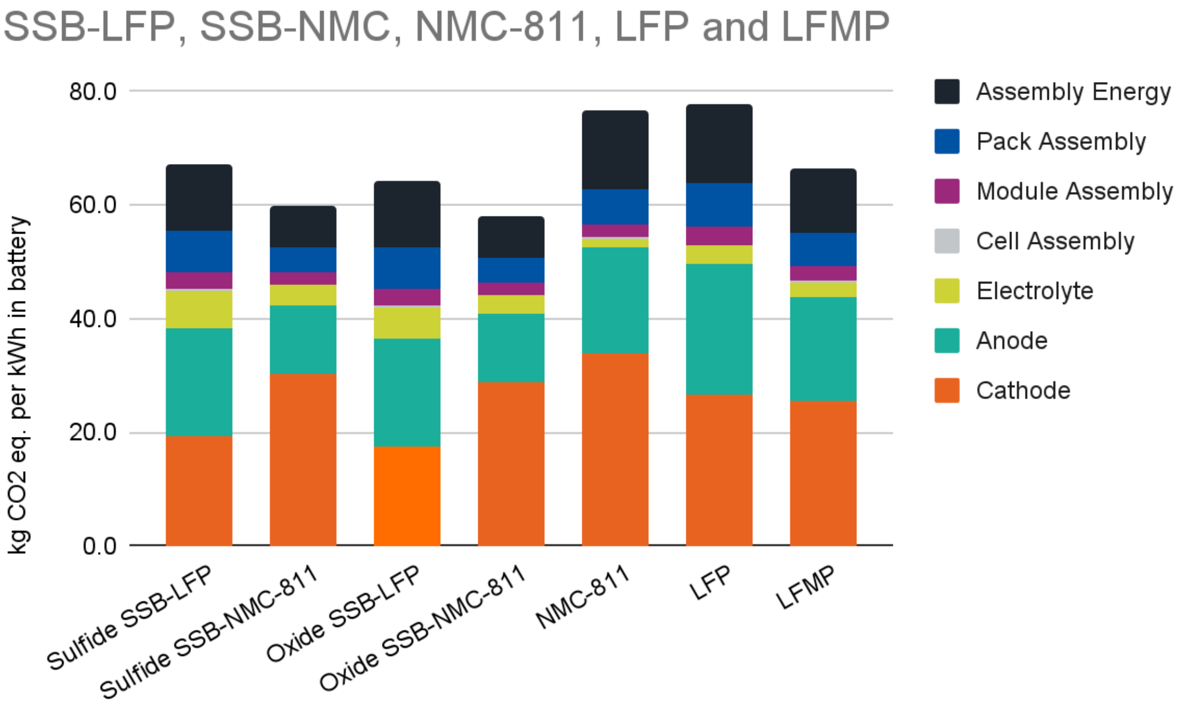


Figure 14: Global Warming Potential of all SSB and LIB chemistries investigated, per kWh.

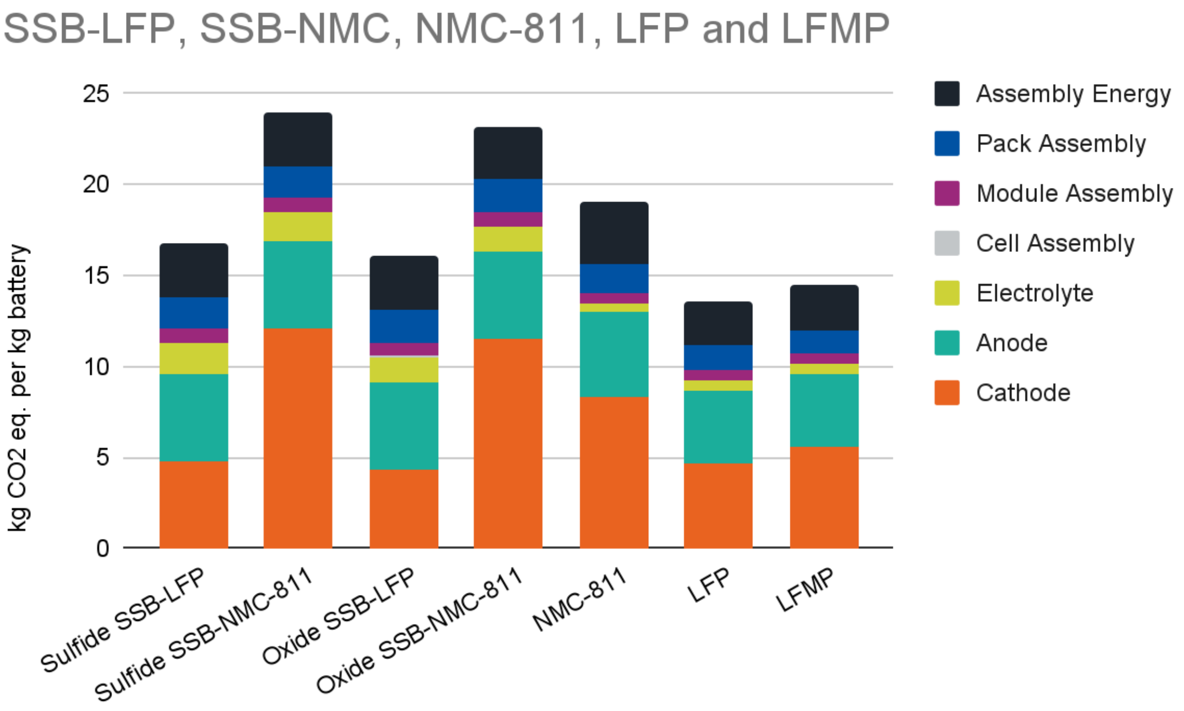


Figure 15: Global Warming Potential of all SSB and LIB chemistries investigated, per kg battery.

6. Scenario Modelling - Battery Raw Material Supply Chains

The second objective of this LCA is to investigate different raw material supply chain impacts for key battery components. As shown in Sections 4 and 5, individual material supply chains have huge impacts on the overall environmental footprint of a final battery product, and the embodied impacts of these components are highly variable depending on the production process, region of creation and resources used in manufacturing.

This scenario analysis of supply chains included in this study are as follows:

1. Lithium chemicals
2. Nickel sulfate
3. Manganese sulfate
4. Graphite
5. Iron oxide

For this scenario analysis exercise, each component is matched with a LCA model for either NMC-811, LFP or a SSB configuration (whichever one uses the highest mass of each material to emphasise impact variability) from Sections 4 and 5, and all material and energy inputs are kept identical to the base scenario except the component in question. For example, nickel sulfate is used in large quantities in NMC-811 batteries, so results for variable nickel sulfate production routes are displayed alongside a static NMC-811 LCA model. The most appropriate model to most clearly demonstrate variable component impacts are chosen in each case. We have excluded LFMP LIBs in this section due to the higher degree of uncertainty in their commercialisation compared to LFP. The following sections compare global warming potential results for supply chains for each material. Other impact categories are presented in Appendix A, for all baseline scenarios.

6.1. Lithium chemical supply chains

Lithium can be extracted from two major source types - spodumene hard rock or brines in salars. Spodumene is mined predominantly in Australia and processed in China, whereas brines are extracted and processed mainly in Chile. Furthermore, two lithium chemicals are used in SSBs and LIBs - lithium carbonate and lithium hydroxide monohydrate (lithium hydroxide for brevity). Both can be sourced from the same lithium deposit, but require different approaches to create the final chemical. The original source and final product combination thus determines the overall material and energy requirements for a given lithium chemical. In general, both products can be manufactured directly from spodumene, but lithium from brines must be converted into carbonate *then* hydroxide monohydrate.[30]

Lithium carbonate is formed by (i) conversion directly from spodumene concentrate via the sulfate chemical process or (ii) calcining and leaching brine evaporate solids, and combining with sodium carbonate. It can be used in cathode manufacturing, most prominently for creating the lithium iron phosphate active material in LFP cathodes by combining with iron oxide and diammonium phosphate (although LFP can be made in other ways). Furthermore, SSB lithium metal anodes can be created by removing lithium from lithium carbonate in the chemical reaction shown in Section 3.3.3.2. Modern production views lithium hydroxide as the higher quality option, but the carbonate form is still used extensively as an input for active material mixes.[31]

Lithium hydroxide monohydrate can be (i) converted directly from spodumene concentrate via the sulfate chemical process or (ii) converted from brine-derived lithium carbonate products; the latter entails a slightly higher energy requirement due to the extra steps beyond those in the carbonate route and thus, higher project cost. The compound's performance exceeds that of lithium carbonate, which degrades quicker, and thus presents a higher-cost but higher-efficiency component in cathode manufacturing. NMC-811 cathodes require lithium hydroxide in their active material alongside base metal sulfates, and other lithium-centric cathodes can also benefit from its higher performance provided the cost of production is viable. [32]

6.1.1. Lithium carbonate supply chains

The total GWP impact of lithium carbonate supply chains are displayed in the context of the sulfide SSB (LFP cathode) model in Figure 16. This model has been chosen to isolate the quantitative variability for a single model input and allow a fair comparison between supply routes. Lithium carbonate is used in both the LFP cathode and lithium metal anode; all other model inputs are fixed to the baseline values. Routes analysed include:

- Lithium carbonate from Chilean Brine

- Lithium carbonate From Australian Spodumene
- Lithium carbonate from Sedimentary Clay in the U.S.
- Lithium carbonate from geothermal sources

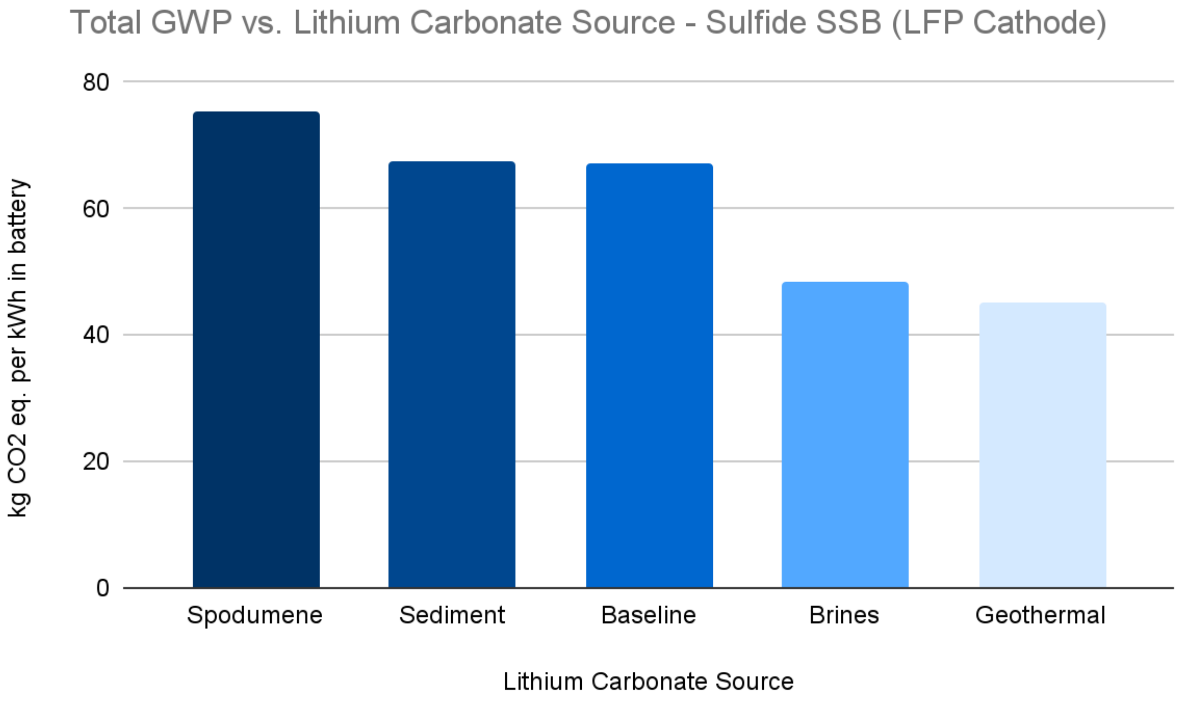


Figure 16: Global Warming Potential of sulfide SSBs with LFP cathodes, with various lithium carbonate supply chain impacts. "Baseline" refers to the 70:30 global spodumene:brine split from Section 3.3.4.1. All other input calculations are kept identical to the baseline from Section 4.1.

Spodumene and sedimentary clay-based lithium sources (predominantly mined in Australia and refined in China) result in higher impacts than the other sources given the amount of processing required to mine, prepare and refine to the final carbonate product. Spodumene concentrate chemical processing requires large amounts of coal for conversion stages, where a large proportion of the total impacts are derived from. [30] Sedimentary clay processing (emerging in the United States) can emit substantial direct CO_2 emissions as ore is treated with acids, sulfur and calcium oxide; this will vary depending on the host rock type.[33] The baseline value is a 70:30 split between spodumene and brines.

Brine-derived lithium carbonate (dominated by Chilean production) is comparatively simpler to produce, involving evaporation and sodium carbonate reactions as the key impact drivers.[30] Geothermal brine recovery provides environmental impact credits via secondary energy generation, and thus reduces overall impacts associated with a combined lithium carbonate and geothermal energy plant.[34] DLE is becoming a popular brine processing route (geothermal or otherwise) in the lithium sector where lithium-rich brines are extracted, selectively stripped of their metals and reinjected into the ground.[35] The method is gaining prominence given its perceived lesser water consumption impact compared to resource-intensive evaporation pond systems used in most brine projects.[36] However, the relatively small scale of DLE and the potential of seismic activity as a result of lithium-stripped brines being reinjected into the ground, merit careful consideration by project developers.

It should be concluded that if impacts related to lithium carbonate are near-zero (e.g. for geothermal sources), the battery impact will be based on the impact for the remaining materials.

6.1.2. Lithium hydroxide supply chains

Lithium hydroxide supply chains are displayed in the context of the NMC-811 battery model for LIBs in Figure 17. This model has been chosen to isolate the quantitative variability for a single model input and allow a fair comparison between supply routes for the cathode. Routes analysed include:

- Lithium hydroxide from Chilean Brine
- Lithium hydroxide from Australian spodumene
- Lithium hydroxide from sedimentary clays in the U.S.
- Lithium hydroxide from geothermal sources

The relative impact explanations are very similar to lithium carbonate (Section 6.1.1) but the overall impacts vary slightly between the two chemicals given the different process flows from source to final product (summarised in Section 6.1).

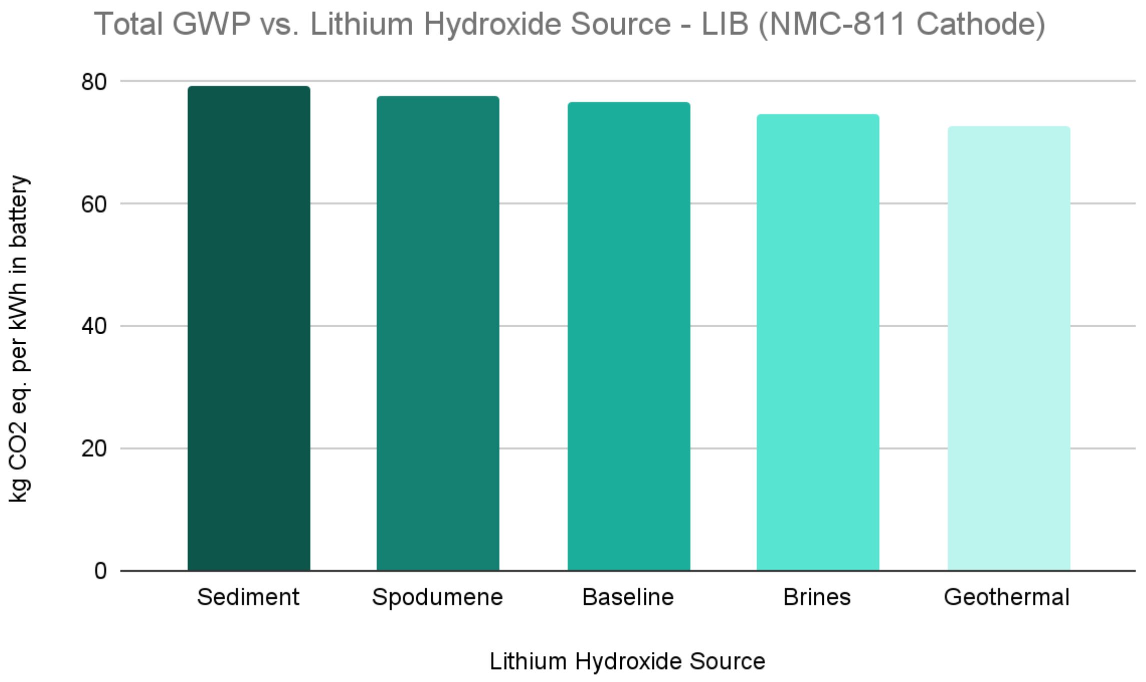


Figure 17: Global Warming Potential of NMC-811 LIBs, with various lithium hydroxide supply chain impacts. "Baseline" refers to the 70:30 global spodumene:brine split from Section 3.3.4.1. All other input calculations are kept identical to the baseline from Section 5.1.

Spodumene-derived and sedimentary clay-derived lithium hydroxide routes are again the highest impact supply chain scenarios for this component, although the smaller amount of lithium hydroxide per battery compared to lithium carbonate (sulfide SSB, LFP cathode) means that the absolute impact reduction is less as per Figures 16 and 17. Brine-derived and geothermal lithium hydroxide are the lowest-impact choices for this component, for the same reasons as for lithium carbonate.

6.2. Nickel sulfate supply chains

Nickel sulfate has been a prominent component of battery cathodes for decades, and is now under more demand than ever as research and development into high energy density performance in LIBs leads manufacturers to favour highly nickel-weighted cathode chemistries [37], including NMC-811 and the developing NMX configuration, which removes the need for cobalt completely.[38] Nickel ores include laterites and sulfides, which are often highly-concentrated with multiple base metals, but require substantial processing and refining to produce battery-grade sulfate salts. Environmental impacts associated with base metal sulfate production are thus very sensitive to process routes and energy demand.

Nickel sulfate supply chains are displayed in the context of the NMC-811 battery model for LIBs in Figure 18. This model has been chosen to isolate the quantitative variability for a single model input and allow a fair comparison between supply routes for the cathode. Routes analysed include:

- Nickel sulfate from industry average (Nickel Institute)
- Nickel sulfate from high pressure acid leach (HPAL)
- Nickel sulfate from sulfide ore
- Nickel sulfate from pig iron
- Nickel sulfate from bioleaching

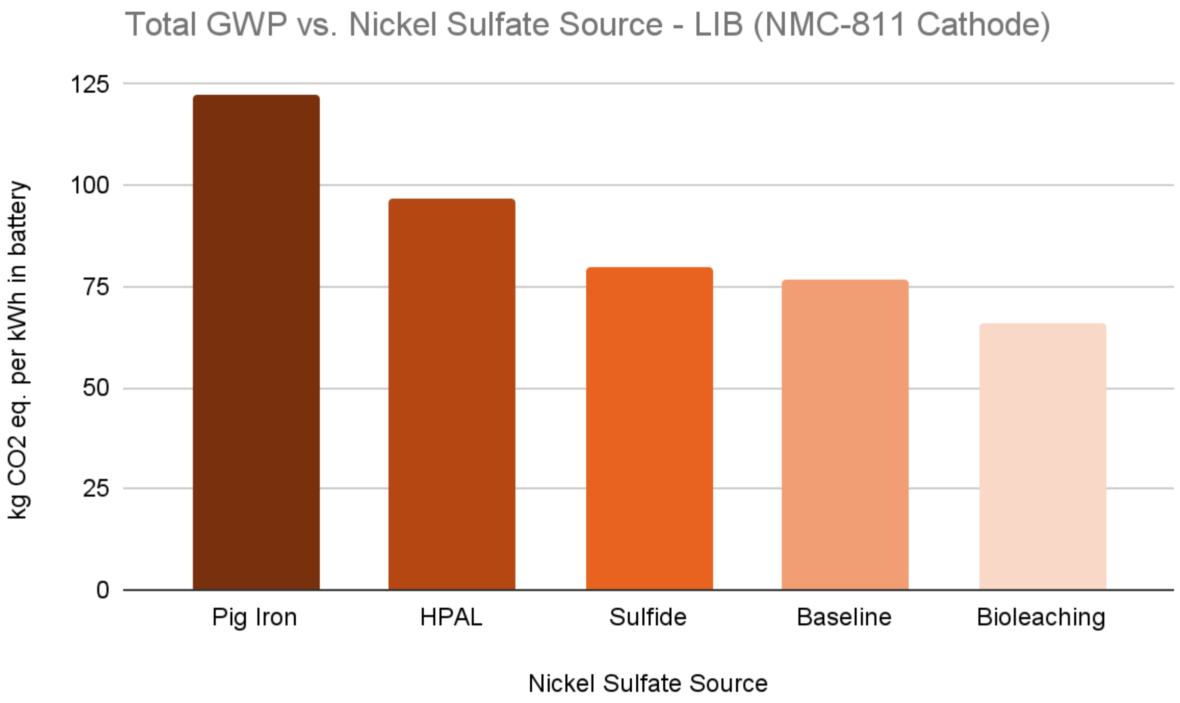


Figure 18: Global Warming Potential of NMC-811 LIBs, with various nickel sulfate supply chain impacts. "Baseline" refers to the Nickel Institute global average from Section 3.3.4.1. All other input calculations are kept identical to the baseline from Section 5.1.

Nickel pig iron is a cheap source of nickel created by mixing low-grade nickel ore with coking coal and has a large environmental burden due to the consumption of such fossil fuels; it is the highest-impact source in this study. HPAL is conducted in countries including Indonesia, where electricity grid mixes often contain fossil fuels. The HPAL process is also very chemically-intensive and the embodied impacts of creating such reagents can result in a high total impact for nickel sulfate derived from these sources. Sulfide ores, found in many countries, can be processed via conventional hydrometallurgy. The baseline route, used by the Nickel Institute as an average of their member projects, does not necessarily encompass all supply routes, only those in the consortium, and thus may be lower-impact than some potential sources. Bioleaching technology of large nickel ore bodies would remove the need for intense chemical processing, and presents the minimum-impact supply chain in this study, despite potentially high investment costs.

6.3. Manganese sulfate supply chains

Manganese sulfate has seen lowering demand in response to rising nickel sulfate demand as the industry aims for optimum energy densities in LIBs. Lithium manganese oxide (LMO) batteries have lower manufacturing rates given their relatively low specific energy, and NMC chemistries have moved from 5:3:2 to 6:2:2 to 8:1:1 ratios Ni:Mn:Co for the same reason. However, as cobalt acquisition presents socio-political issues, efforts are underway to move away from cobalt dependency, sparking a resurgence in manganese interest to fill the base metal sulfate gaps. Manganese ores can be oxide-based or carbonate based, and refining from the respective ores relies on variable chemical process flows. Unfortunately, manganese sulfate is one of the more opaque supply chains in popular LIB bills of materials, and if it is to replace a portion of the cobalt market, will require new LCAs to capture the breadth of supply chain variability.

Current and potential future manganese sulfate supply chains are displayed in the context of the NMC-811 battery model for LIBs in Figure 19. This model has been chosen to isolate the quantitative variability for a single model input and allow a fair comparison between supply routes for the cathode. Routes analysed include:

- Manganese sulfate from primary oxide ores
- Manganese sulfate from baseline industry average
- Manganese sulfate from secondary sources, such as carbonates

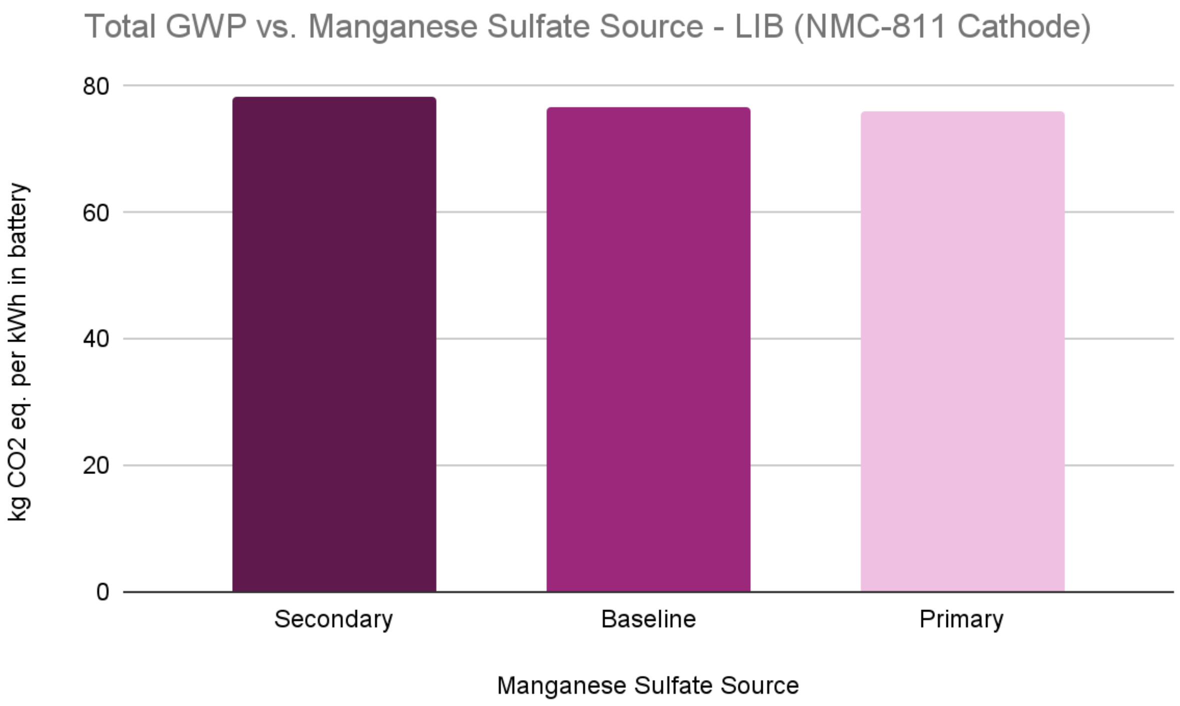


Figure 19: Global Warming Potential of NMC-811 LIBs, with various manganese sulfate supply chain impacts. "Baseline" refers to the global average from Section 3.3.4.1. All other input calculations are kept identical to the baseline from Section 5.1.

There is little difference in the variable supply chain but the issue lies in the move away from cobalt - manganese supply chains *can* be impactful per kg of intermediate material, and the less cobalt we use as a society, the more manganese we'll need to make up the difference, unless different LIB or SSB cathodes become the norm e.g. LFP.

6.4. Graphite supply chains

Graphite is a unique component in LIBs as it (a) can exist as a single-material anode without necessity for mixing (although some modern manufacturers choose to compound it with silicon [39] and (b) can be made synthetically. Natural graphite is mined, processed and refined via multiple complex and energy-intensive stages to create high-purity, suitably spheronized and coated anode precursor material. Battery-grade graphite is predominantly produced in China in 2021, and energy inputs are subject to the effects of potentially fossil fuel dominant grid mixes common in the country. Synthetic graphite is created via chemical processing of green coke, and refining stages similar to that of a natural graphite process flow - purification, spheronization and coating. This entails similar energy inputs, to create the initial intermediate material.

Graphite anodes are replaced completely by lithium metal anodes in SSBs, thus supply chains are displayed in the context of the LFP LIB model in Figure 20. The GREET model [21] indicates that LFP batteries require significantly more graphite in the accompanying LIB anode, thus environmental impacts will be more clearly highlighted for this chemistry than for NMC-811. Routes analysed include:

- Natural graphite from China
- Synthetic graphite from China
- Natural graphite from Europe
- Synthetic graphite from Europe

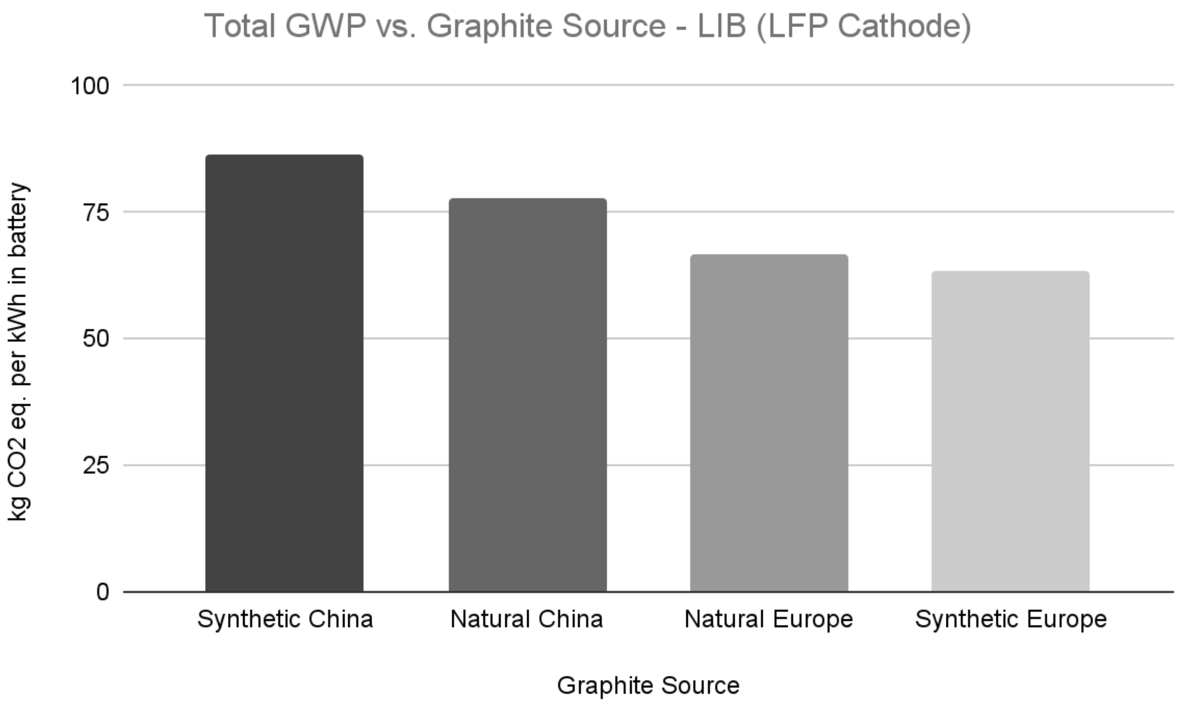


Figure 20: Global Warming Potential of LFP LIBs, with various graphite supply chain impacts. All other input calculations are kept identical to the baseline from Section 5.2.

Chinese graphite, both natural and synthetic, are highly impactful towards total battery impacts due to fossil fuel consumption in grid mixes combining with high electricity consumption in the processes. Comparatively, European options for both are substantially less impactful to produce, simply by harnessing more renewable energy.[40,41] This is a key discussion point featured in the discussion portions of Section 10, alongside lithium chemical supplies.

6.5. Iron oxide supply chains

Iron oxide is mined in large volumes at high grades, which means that any assigned impacts per kg are relatively low compared to nickel, for example. In this study, iron oxide is only consumed in the creation of LFP cathode active material, hence this battery's selection as the demonstration model for supply chain variability in Figure 21. Routes analysed include:

- Iron oxide from primary routes
- Iron oxide from secondary routes

The total impact of each of the scenarios modelled for LFP battery manufacturing are very similar. Given that iron oxide impacts are low per kg and the total mass required for the battery compared to e.g. lithium is low, this input is not a key model sensitivity. Ultimately, the combination of high-impact and high-volume materials (e.g. nickel sulfate) result in significant model controls, and components like iron oxide do not. Secondary sources may require extra processing steps than primary sources, and thus may be higher-impact.

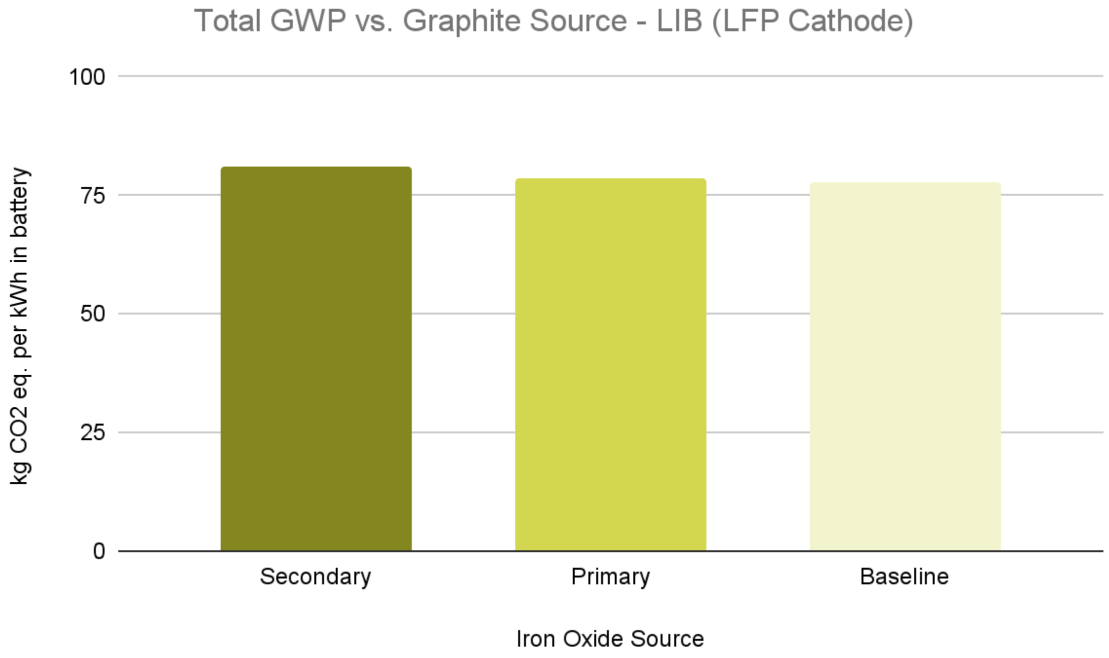


Figure 21: Global Warming Potential of LFP LIBs, with various iron oxide supply chain impacts. "Baseline" refers to the global average from Section 3.3.4.1. All other input calculations are kept identical to the baseline from Section 5.1.

6.6. Electricity scenarios for 2025 and 2030

As Europe adopts more renewable energy grid mixes, the environmental impact of electricity consumption for manufacturing processes will decrease. In this section, the LCA model is adjusted to account for these future changes. For these scenarios, all model components are kept the same except the EU27 grid mix for 2021, which is replaced in all instances of electricity consumption during the manufacturing stage (i.e. Figure 3) with the projected average European grid mix for 2025 and 2030. Figure 22 shows the total GWP results for a selection of batteries to demonstrate the impact reduction available for future European manufacturing compared to the original scenario. All batteries demonstrate a 10-15% decrease in total GWP (in kg CO_2 eq. per kWh) by 2030 from their current modelled values in baseline scenarios (Sections 4 and 5).

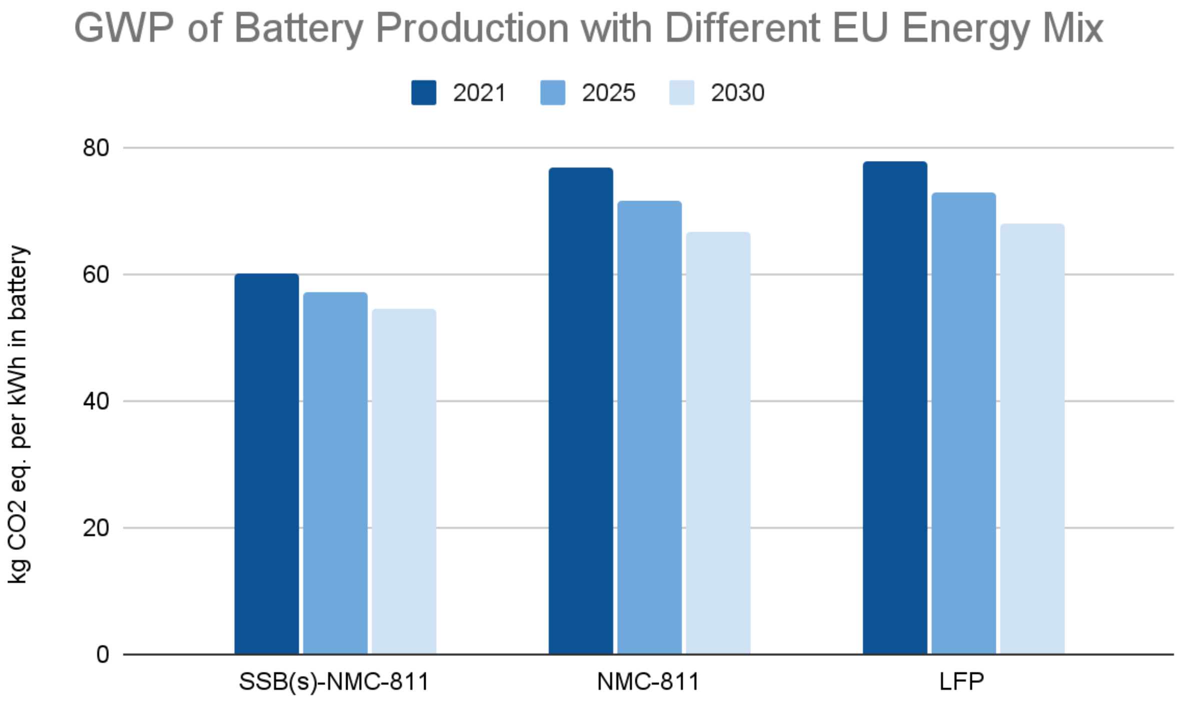


Figure 22: Scenario analysis for variable total Global Warming Potential of a representative SSB and two LIBs with different European energy grid mixes - current usage (2021; used throughout the rest of this LCA), 2025 and 2030, as proposed by the European Environment Agency. [17]

6.7. High & low material impact routes for batteries

As a conclusion to supply chain variability scenario analysis, Figure 23 presents two final battery GWP impact scenarios for a selection of batteries - one with the highest GWP impact supply chain options for the given battery, and one with the lowest GWP impact supply chain options. Model variation is restricted to the raw material inputs included in Sections 6.1-6.5 in this report; all other inputs are kept identical to the baseline scenario for each battery presented in Sections 4 and 5. ***Note that this does not suggest the absolute maximum and minimum impacts associated with global production of each battery, but simply the range from the values in this study alone***. This illustrates the cumulative effect combining impacts from supply chains for multiple major raw materials can have on a final product, and the opportunities that exist for manufacturers to reduce their environmental footprint by simply addressing material inputs.

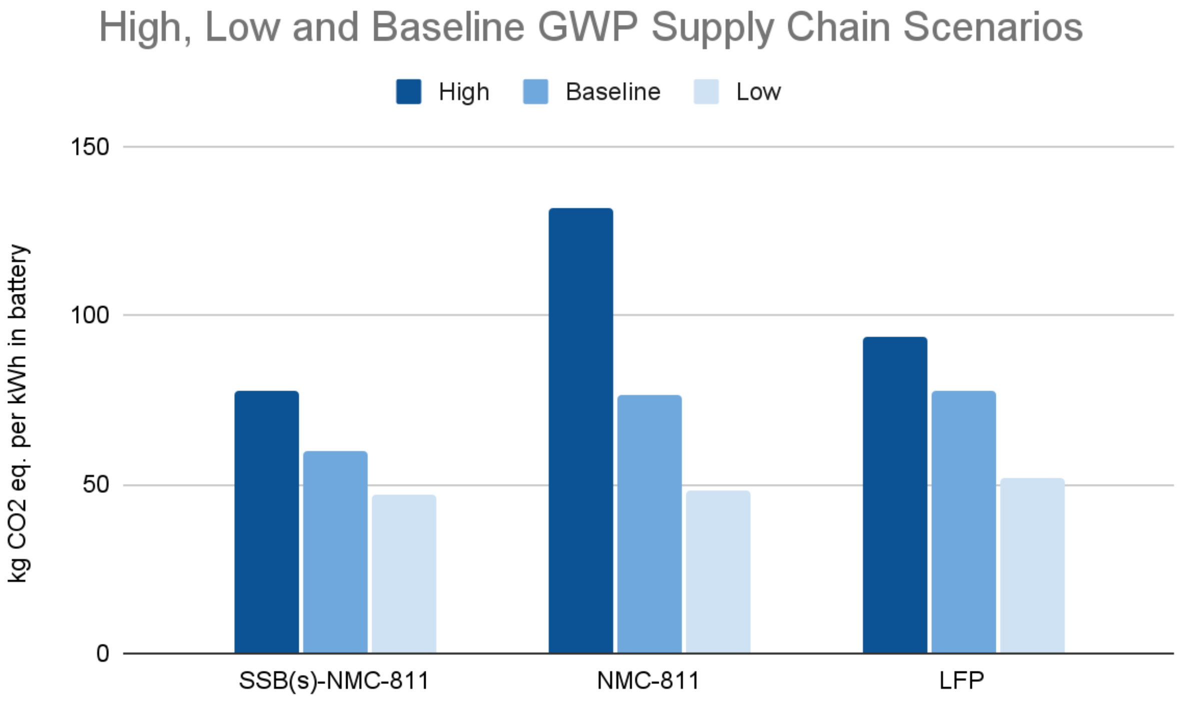


Figure 23: Scenario analysis for variable total Global Warming Potential of a representative SSB and two LIBs with the highest and lowest supply chain impact scenarios from Sections 6.1-6.5 for all relevant materials.

NMC-811 has the potential to be the highest-impact per kWh battery to produce (70% higher than its baseline), primarily due to high impact options associated with base metal sulfate production, and large amounts of nickel sulfate used to create cathode active material (Section 6.2). LFP has the second highest supply chain scenario (20% higher than its baseline), and the representative SSB configuration (sulfide electrolyte, NMC-811 cathode) has the lowest (30% higher than its baseline), most likely due to its higher specific energy.

The low impact scenarios for each of the three batteries in Figure 23 are similar - when the material impacts from the scenario analysis are minimised, the static LCA inputs drive the majority of the results (e.g. materials for cell, module and pack assembly and manufacturing energy). In this model, SSB can be 20% lower, NMC-811 can be 35% lower and LFP can also be 35% lower than their respective baseline impacts. Further reductions may lie in sourcing low-impact aluminium and copper, reducing energy requirements for manufacturing, or increasing battery specific energy.

Overall, modelled impacts for NMC LIBs are highly sensitive to supply chain variations, whilst LFP LIBs and SSB are less sensitive (i.e. a smaller percentage change to overall impact when increasing or decreasing individual raw material impacts).

7. Data Quality Assessment

The foreground and background data of the LCI were judged on technological and time representativeness, geographical coverage, completeness, precision, and consistency. Foreground data used in this study was generated from data from Minviro's internal LCA calculations. The background data used in this LCA was from Ecoinvent 3.8.0.[7] The study is in a scoping stage, with many SSB set-ups being hypothetical and in development for mass-production. The primary limitation to this study is the uncertainty associated with the level of definition of SSB products. This has been addressed by assigning a 50% uncertainty to the data.[42] The comparison scenario data was gathered from generic datasets developed by Minviro. Data quality for the baseline SSB LCA is presented in Table 4 and discussed below:

- Technological representativeness: This is the main area of uncertainty in the LCA - all modelling is conducted based on academic studies, data is taken from different sources, and beyond all else, SSB production is poorly understood as a whole. There is currently no consensus on best electrode combinations, assembly steps, specific energy ratings, industrial viability, economic viability or safety of SSBs. This will improve with further study, concrete pilot schemes and thorough material and energy input assessment. All background data was sourced from Ecoinvent 3.7.1. **The technological representativeness of SSB data is considered to be very poor.**
- Time representativeness: Although all data sources used for all calculations in this study have been published within the last four years, SSB research advances so quickly that prior findings can often become obsolete or out of date. **The time representativeness of SSB data is considered to be fair.** The data collected for the comparison scenarios were collected within 4 years of the reference year 2021. All background data was sourced from recent Minviro studies or Ecoinvent 3.7.1. **The time representativeness of the comparison scenarios is considered to be very good.**
- Geographical Coverage: All material and energy inputs are, whenever available, specific to the region of production. This includes regional cathode, anode and electrolyte precursor materials for all batteries investigated, appropriate local

energy supplies for individual supply chains (e.g. lithium metal in the USA) and European averages for hypothetical production. The main improvement to this aspect of the study is to identify specific countries or, better still, local energy grid mixes for energy supply to the European SSB production facilities. **The geographical representativeness of SSB data is considered to be good.**

- Completeness: Although the SSB LCA model is based on many assumptions and academic insights, it is relatively complete. No major material or energy inputs have been omitted for lack of data and all energy inputs for all production processes are included for all battery configurations. The completeness may, in reality, reflect differently once more certainty is applied for SSB routes, but the model is the best currently available for the scarcity of data surrounding the technology. **The completeness of SSB data was considered to be fair.**
- Precision: The majority of the model is based upon assumptions and various unconnected studies, and is the best available attempt at a unifying calculation in the current literature climate for SSB. We are confident in the results for the data we have available, but this may not reflect true impacts when more work is done to refine SSB manufacturing processes. **The precision of SSB data was considered to be poor.** For the comparison scenarios, the data was collected from public datasets. Datasets used were based on expert judgement values. All background data sources were sourced from internal Minviro studies or EcoInvent 3.7.1, of which the precision was well documented. **The precision of the comparison scenarios was considered to be very good.**
- Methodological appropriateness and consistency: Although the LCA model is hypothetical, it is consistent, robust, validated and reviewed by the Minviro team. In the absence of GREET models or concrete bills of materials, this represents the best source of LCA data for SSB in the industry, and uses the firmly established Minviro approach to modelling. All inputs have been verified for appropriateness by experienced LCA practitioners, calculations have been conducted for all inputs in a consistent manner for all batteries, and measures have been employed to ensure model integrity despite assumptions detailed in Section 3.3.4.1. **The methodological appropriateness of SSB data was considered to be very good.**

Table 4: Data Quality Assessment for SSB Life Cycle Inventory

Data Quality Indicator	Very Poor	Poor	Fair	Good	Very Good
Technological Representativeness	■				
Time Representativeness			■		
Geographical Representatives				■	
Completeness			■		
Precision		■			
Methodological Appropriateness and Consistency					■

8. Sensitivity Analysis

Sensitivity analysis was carried out to explore the effects that variations in reagent, material, and energy consumption may have on the final SSB product life cycle impact assessment results. The analysis studies the effect of variation of the top ten main contributors to GWP in the LCA: cathode active material; lithium metal anode; electricity for dry room, coating and ageing; aluminium for cell, module and pack assembly; copper for cell assembly; and the sulfide solid electrolyte . The results are presented in Figure 24.

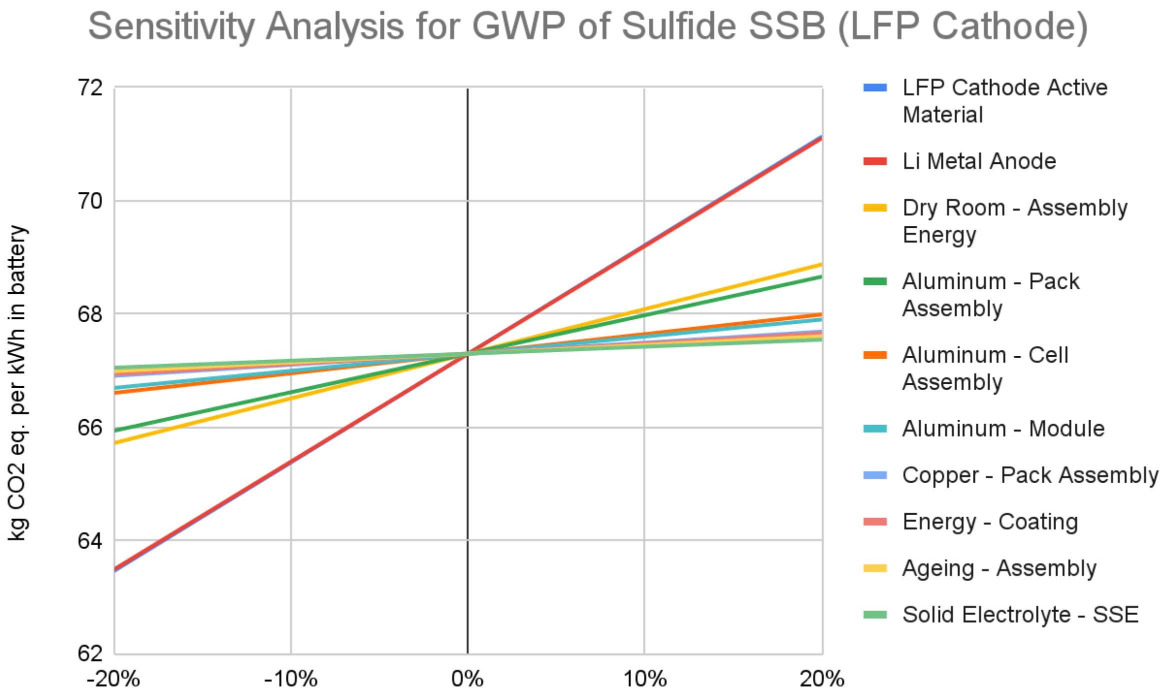


Figure 24: Sensitivity Analysis of Major Contributors to Global Warming Potential for SSB production

This analysis shows that the LCA model for GWP is most sensitive to the impact values of cathode active material and lithium metal anode production for use in the battery manufacturing process. The model is moderately sensitive to dry room electricity consumption and aluminium used in pack, module and cell assembly. Copper and solid electrolyte manufacturing, plus electricity used for coating and ageing processes are minor sensitivities in the model, but still have influence on the overall impact in the full life cycle inventory.

As an example demonstrating sensitivities, if the input value of LFP cathode active material, the most significant contributor to GWP, increased or decreased by 20%, the total GWP would vary between 63 and 71 kg CO_2 eq. per kWh when all other model inputs are identical. This is a clear demonstration of the high sensitivity of the LCA model to a handful of major inputs to the process of manufacturing SSB. These top contributors should be the main targets of environmental impact mitigation strategies.

9. Uncertainty Analysis

The uncertainty in relation to the LCI and data quality has been explored in relation to the environmental impacts using Monte Carlo simulations. Monte Carlo simulations are used to assess the range and likelihood of different impacts. The results of the Monte Carlo simulations assist with understanding the impact of risk and uncertainty on the prediction and forecasting of models.

For the Monte Carlo simulations conducted on a representative SSB LCA (in this instance, sulfide electrolyte with LFP cathode), an uncertainty of 50% was assumed for all energy and material inputs. Monte Carlo simulations do not consider the uncertainty from background data. As the global effort to produce SSB progresses into more developed stages, the standard deviation will decrease, but for a study with many assumptions, the currently assigned uncertainty is reasonable. Monte Carlo simulations were also conducted on the LFP LIB results, for comparison. As the LFP model uses verified input data for a commercially viable battery from GREET and academic sources (but is nonetheless not a primary source), a lower uncertainty of 25% was assigned to this battery.

The Monte Carlo simulation was run through 1,000 iterations. The results of the Monte Carlo simulations for GWP for both battery configurations can be seen in Figure 25 and Table 5. SSB values range from 20.7 to 113.7 kg CO_2 eq. per kWh; LFP LIB values range from 52.0 to 106.7 kg CO_2 eq. per kWh. The mean values of the simulations are 67.5 kg CO_2 eq. per kWh for SSB and 77.7 kg CO_2 eq. per kWh for LFP. There is no difference between the results derived from the LCA study and the mean value from the Monte Carlo simulations. This is expected, as for all energy and material inputs, an equal uncertainty was assigned.

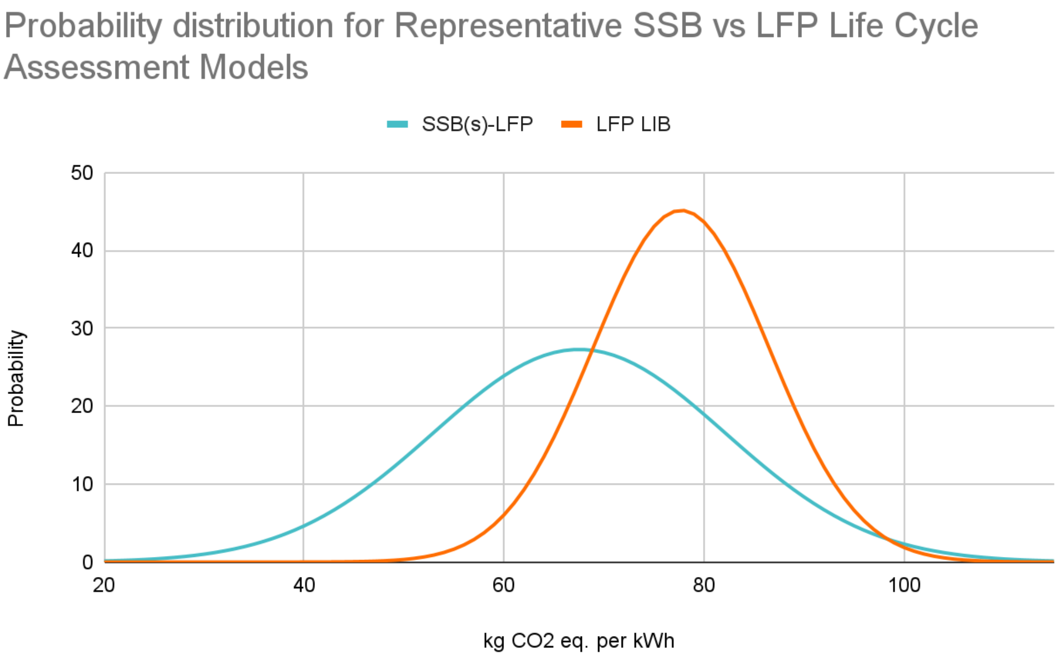


Figure 25: Monte Carlo Simulations for the GWP of the production of sulfide SSB with LFP cathode and LFP LIBs.

Table 5: Statistics Describing Results for the GWP as a Result of the Monte Carlo Simulations for a representative SSB configuration (sulfide electrolyte, LFP cathode).

Data Quality Indicator	**SSB (s) LFP - Global Warming Potential (kg CO_2 eq.)**	**LFP LIB - Global Warming Potential (kg CO_2 eq.)**
LCA Study Result	67.3	77.9
Mean	67.5	77.7
Minimum	113.7	106.7
Maximum	20.7	52.0
20th Percentile	80.2	85.4
80th Percentile	55.2	69.9
Standard Deviation	14.7	8.8

This uncertainty analysis shows that the higher data certainty for LIBs results in more consistent LCA results (narrower curve in Figure 25), and SSB final values could theoretically differ from those modelled as shown by the wider randomly generated probability spread.

10. Conclusions and Insights

10.1. Conclusions

10.1.1. Specific Energy

The specific energy of a final battery pack is the primary factor in determining its environmental impact in this study, given that the functional unit of the LCA is a kWh rather than a mass value, in order to allow a comparison between different battery chemistries or configurations. Comparing impacts related to a particular mass of battery is interesting for context, but does not present a level playing field for all batteries given the breadth of variable components in each, hence the extra stage of normalising by specific energy. For example, LFP cathodes are less impactful per kilogram of cathode active material than NMC-811, but the latter battery performs better (0.40 or 0.25 kWh/kg compared to 0.25 or 0.174 kWh/kg if in SSB or LIB, respectively), and thus per kWh has a lower impact. Figures 26 and 27 display this effect graphically across a theoretical range of specific energies for SSB and LIB, respectively.

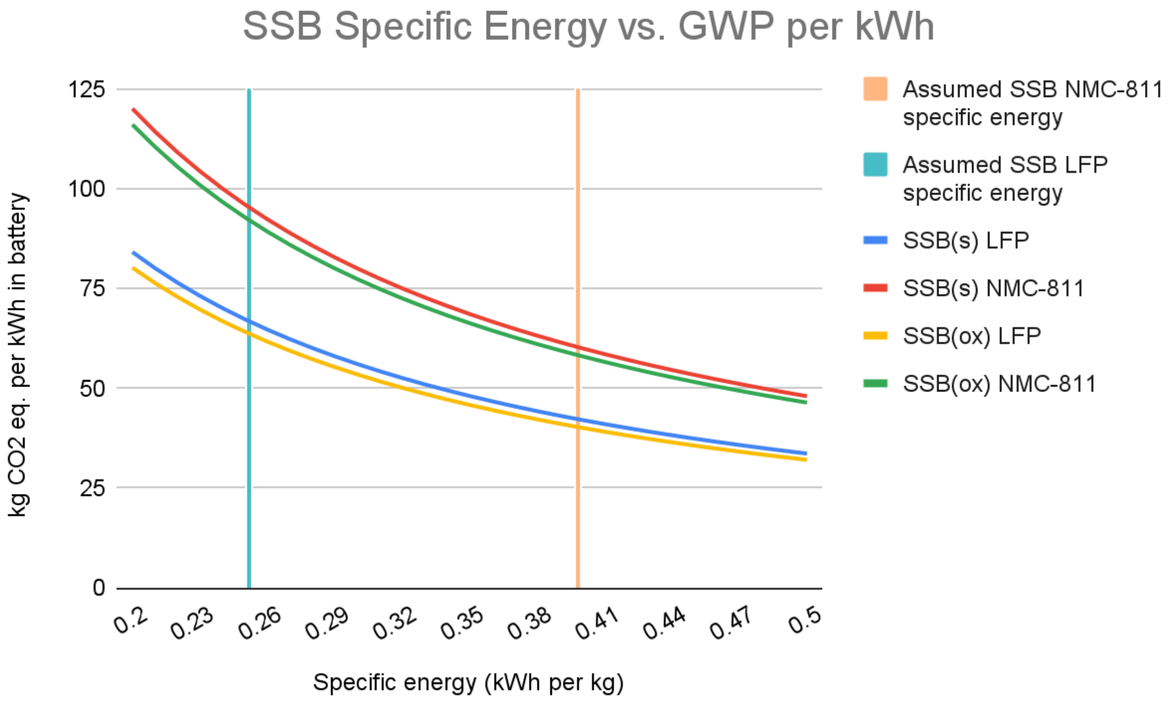


Figure 26: SSB pack specific energy vs. GWP impact per kWh. Solid vertical lines represent the static specific energies used in the LCA models from Section 4, 0.25 kWh/kg for LFP cathodes and 0.40 kWh/kg for NMC-811 cathodes. This distribution explains why, despite having a larger impact per battery mass, NMC-811 configurations are less impactful per kWh contained within the final pack.

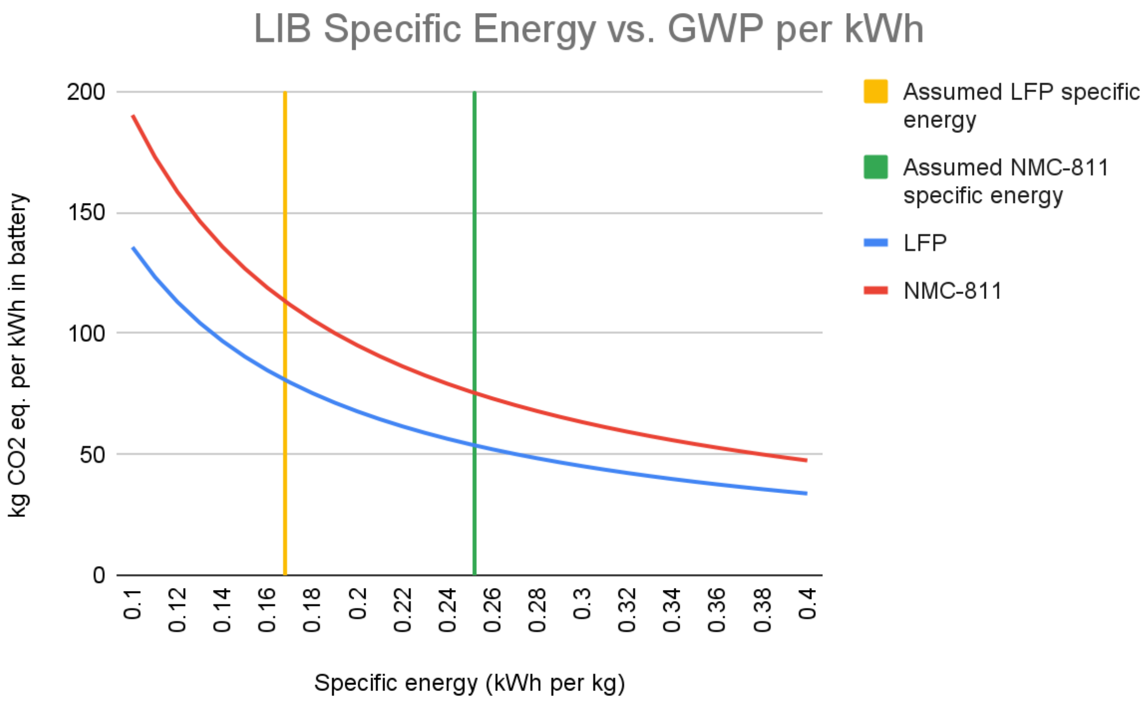


Figure 27: LIB pack specific energy vs. GWP impact per kWh. Solid vertical lines represent the static specific energies used in the LCA models from Section 4, 0.174 kWh/kg for LFP and 0.25 kWh/kg for NMC-811. This distribution explains why, despite having a larger impact per battery mass, NMC-811 configurations are similarly impactful as LFP per kWh contained within the final pack.

This issue of variable specific energy is particularly relevant for LFP batteries, given that they have been selected for future mass production by numerous high profile companies, including Tesla.[43,44] The currently accepted specific energy value for LFP packs used in this study means that even though their per kg impact is relatively low compared to other battery chemistries in the study, their per kWh impact is not necessarily low. Only a slight improvement (to perhaps 0.18 kWh/kg) would bring GWP results for LFP LIBs in the current model set-up to be lower than NMC-811 equivalents - even higher specific energies would ensure stronger environmental performance per kWh.

The development of LFMP batteries appears to be a direct response to this issue - maintaining the other favourable properties of LFP batteries whilst increasing their pack specific energy. Research has found that replacing a portion of iron oxide with manganese oxide in the manufacturing of lithium iron phosphate can achieve 25% higher specific energy. The Fe:Mn blend in the precursor is variable (in this report we have opted for the highest experimental Mn content [20], and given that manganese oxide bearing cathodes are ~20% more impactful per kg than pure iron oxide ones (on comparing cathode impacts in Figure 15), shifting away from pure LFP will increase the impact of producing a battery when only considering the mass. However, due to its higher energy density, LFMP configurations have a significantly lower impact per kWh in the final pack. It is apparent that the way forward for battery innovation is to adjust existing favoured configurations or chemistries slightly to improve desirable properties, whilst balancing the potential negative effects of such changes. For LFMP, the charge performance drop-off at 50% charge is a large burden that may not be worth the increased specific energy - the industry will have to compromise on enhancements to ensure safety for customers and product longevity.

10.1.2. Material and energy inputs

Major conclusions from the study regarding material and energy interpretations are as follows:

1. Environmental impact results for energy impacts are comparable between all different setups (four SSBs and two LIBs), which puts much more emphasis on the sustainable acquisition of raw materials for making (especially) cathodes, anodes and electrolytes.
2. The kWh performance is a key method for comparing battery impacts, but is not the only thing considered when selecting combinations, although it is very important. Other factors identified by academic studies (although mostly qualitative and inappropriate for LCA modelling) are shown in Appendix C. However, this said, if companies can manufacture a very high specific energy battery with less impactful raw material supply chains, this will be the most sustainable of all technologies/chemistries, quantitatively.
3. Manufacturing and raw material costs will always be a huge driver for all businesses, which is potentially why LFP has been adopted by large firms like Tesla as a key SSB component, alongside some of the other properties from Appendix C. Hesitance regarding base metal supply chains from unstable regions or economies, especially cobalt, will also greatly influence this. A potential side effect of cost-driven business decisions are that material bottlenecks and high material costs could force

manufacturers to favour cheap supply chains with high environmental impacts. Thus, early global investment in sustainable raw materials within the battery sector is key to avoid causing future problems.

4. Similarly to the last point, SSB cell and pack configurations are very unclear in the current literature and will likely differ from the values in Appendix B used in all model calculations. For this LCA model, all battery packs have the same pack structure, which creates a naturally higher total impact per kWh for the batteries with high kWh/kg (e.g. SSB). This means that the impacts presented for SSB are potentially overestimated, as manufacturers will always opt for lighter batteries with reduced cell consumption and an optimistic target kWh/kg performance. Thus, as data quality improves regarding cell requirements per pack and even pouch/cylindrical/prismatic performance, the model can be adjusted to better represent realistic SSB environmental impact per kWh.
5. SSBs, currently, are tied to existing cathode active material impacts, but there are many different experimental compounds being trialled as replacements [45,46], which may avoid the combined burden of base metal sulfate production, excess lithium and energy intensity for production. Equally, new high-technology solutions will carry their own production challenges, which should also be captured by LCA for comparative assertions.
6. Lithium metal is a key discussion point for SSBs. Moving to SSBs as the norm will put huge supply pressure on the lithium chain to produce even more than currently used for LIB applications. The difference between brine, geothermal, sedimentary clay and spodumene impacts is therefore hugely important to discuss for all battery manufacturers, and opportunities exist for low-impact products by engaging this supply chain.
7. Graphite demand may fall if SSBs are adopted globally as predicted by researchers into all-solid technology, as it is replaced by lithium metal or a synthetic anode in most cases for SSBs. This is a more prominent source of high impact for LIBs (if sourced from China) but also a potentially sustainable pursuit for European graphite producers, who can harness a wealth of advanced infrastructure and renewable energy options for the energy-intensive graphite process flow. If LFP continues as

the chosen LIB (e.g. by Tesla)[43,44], graphite demand will be substantial - a great economic and environmental opportunity for Europe.

8. Recycled material in battery supply chains will be a prominent feature in discussions over European battery manufacturing moving forward and although this is poorly understood in LCA terms at the moment, may provide an extra source of avoided burden in the production process. Base metal recycling in particular would reduce pressure on imported primary source supplies, and should certainly be explored in the context of NMC-811 (or other battery configurations) environmental performance.[47]
9. The LCA results for LIBs in this study are higher than some other public datasets [48], almost certainly due to underestimated raw material impacts in the latter. Graphite and lithium product impacts in particular are low in available literature, and these values have been found to be unrepresentative by factors of as much as ten in recent detailed studies.[40,41,49] The importance of accurately identifying raw material impacts in the context of battery supply chains cannot be overstated.

10.2. Insights

Minviro has several recommendations for T&E to improve the quality of this LCA moving forward and to further understand the environmental performance of SSBs, which, at the time of writing, are still highly conceptual and not yet fully suitable for mass production in their current research and development state.

Recommendations for improving data quality for SSB impact calculation:

- The major limitation for this LCA is the uncertainty surrounding SSB production processes, material requirements and energy inputs. Assumptions listed in Section 3.3.4.1 can be gradually removed once more concrete production processes are identified, and if industrially-viable cathode, anode and solid electrolyte combinations are accepted. This would most likely involve collaborations with battery producers for procuring an updated life cycle inventory. Acquiring such data would in turn reduce SSB model uncertainty (e.g. Section 9), with the eventual aim to produce results with similar confidence to LIB models (Figure 25).
- Energy inputs and bill of material masses in particular are poorly understood for battery manufacturing, and data availability is sparse. As more studies are conducted on optimising supply routes and process flows, the accuracy of the energy inputs per stage and the exact mass of each material used can be refined. Ideally, the model would require confirmation of cathode active material, anode and electrolyte masses per final battery pack, and measured commercial electricity demand for each process stage in Figure 3.
- A major assumption in our model is that of the relative thickness and mass of each electrode and electrolyte component. This is currently based on (i) experimental thicknesses of each required for sufficient electricity generation and (ii) the densities of each layer. When switching NMC and LFP cathodes or oxide and sulfide electrolytes, this equation becomes complex and can affect the overall battery pack mass, which has been targeted for ~300 kg. For this study, we calculated material inputs by subtracting all mass from the battery total not attributed to the three active components, and creating a ratio based on the thickness and density of each material. Even if the 300 kg total mass is reduced, the relative proportions of each material required will be similar, and impact differences will be minimal. However,

the life cycle inventory should ideally not require third-party calculated masses, but measured or predicted ones from manufacturers. As with energy inputs, when a viable single battery cell bill of materials is generated, as with recent efforts with LIBs in the Argonne Lab GREET model[21], the representativeness of the LCA will be enhanced.

- As an aside to SSB calculations, the impacts of the also in-development LFMP LIB configuration have been modelled using the LFP bill of materials and energy inputs, with the theoretical addition of manganese oxide in place of a portion of iron oxide (4:1, Mn:Fe), and with a calculated 25% higher specific energy (0.22 kWh/kg). All other input values remain unchanged from the GREET model for LFP, which may not be the final scenario in reality. Results are thus of lower data quality and higher uncertainty compared to LFP and can be improved with new data from further research or even commercialisation for this emerging chemistry.

Recommendations for minimising supply chain environmental impacts:

- Source lithium and lithium chemicals from brine or geothermal operations (via evaporative pond systems or DLE) instead of spodumene or sedimentary mines to significantly reduce overall impacts associated with the production of lithium metal. Given that over five kilograms of lithium carbonate is required to make one kilogram of lithium metal, impacts associated with the intermediate material are substantial.
- Source nickel from more sustainable leaching means (in the future, bioleaching) - pig iron will almost certainly be incredibly high-impact and although this may be cheap, will carry a huge environmental burden that will not fit with upcoming EU battery manufacturing legislations. If using NMC-811 cathodes for SSBs, the nickel supply chain will be under pressure to produce enough material and keep within sustainability objectives, and European battery manufacturers must adhere to sustainability goals simultaneously.
- Source manganese sulfate from low-impact primary resources, although given the direction of NMC cathode base metal relative proportions, as detailed in this LCA, manganese sulfate is not a high impactor in the grand scheme of battery production. The risk lies in the reduction of cobalt sulfate use in batteries, and the remaining proportion being accommodated by manganese sulfate. Manganese LCA

data is sparse and requires significant investment to uncover a wider range of potential impacts if the metal becomes an attractive battery option moving forward.

- Source graphite from low-impact energy regions. Graphite product manufacturing is not particularly resource intensive, but very energy intensive, especially to make battery-grade anode precursors, which requires graphitization and spheronization processes to aid in battery performance. Most graphite is currently imported from China, where grid mixes are still very fossil fuel dominant. Thus, securing production from, for example, hydropower rich regions like Scandinavia, a downstream battery manufacturer can significantly reduce their impacts.[40,41] There are many upcoming European graphite projects that will be ideal for further LIB manufacturing, but of course this will not be applicable to most SSB given the prominence of lithium metal anodes. This may be an extra step in the SSB vs. LIB supply chain debate, and a good discussion point going forward - graphite vs. lithium metal (environmentally, economically and performance-wise).
- Iron oxide, used in LFP cathode active material, is not a major impactor in battery manufacturing. However, as attention is brought to LFP as a future cornerstone of LIB and, potentially, SSB development, optimisation opportunities will always exist within mass-production. LFMP manufacturing will have a higher impact on a strictly supply chain basis based on the model created for this report, but manganese addition results in a battery with desirable higher specific energy.
- Increasing renewable energy utilisation in European electricity grid mixes will reduce battery manufacturing environmental impacts by 10-15%. This alone is not enough to drive low-impact battery production, and as demonstrated throughout this report, raw material supply chains truly drive impact mitigation opportunities.

Minviro has greatly enjoyed working with T&E on this interesting project on some cutting edge applications of LCA. We hope to continue our relationship with the goal of minimising the environmental impacts of manufacturing critical products in the green revolution.

Appendix A - Additional Impact Categories

*Table 6: Total life cycle impacts for all PEF impact categories [50] for baseline supply chain routes for all six battery configurations modelled in Sections 4 and 5. * Land use is unitless and only used as a multiplier factor for land transformation calculations (high factor = higher impact).*

Total Impacts per kWh in battery	**SSB (sul.) LFP**	**SSB (sul.) NMC-811**	**SSB (ox.) LFP**	**SSB (ox.) NMC-811**	**LIB NMC-811**	**LIB LFP**	**LIB LFMP**
Global Warming Potential ***kg CO_2 eq.***	67.3	60.0	64.2	58.0	76.7	77.9	66.0
Acidification Potential ***mol H^+ eq.***	0.36	1.48	0.34	1.41	1.65	0.53	0.44
Freshwater Eutroph. ***kg P eq.***	0.06	0.05	0.05	0.05	0.03	0.06	0.05
Terrestrial Eutroph. ***mol N eq.***	0.71	0.93	0.66	0.89	0.95	0.91	0.76
Freshwater Ecotoxicity ***CTU***	204	951	57	860	998	71	58
Marine Eutroph. ***kg N eq.***	0.07	0.09	0.07	0.09	0.09	0.09	0.07
Ionising Radiation ***kg U^{235} eq.***	8.04	14.94	7.75	14.32	13.84	8.13	7.59
Photochemical Ozone ***kg NMVOC***	0.18	0.33	0.17	0.31	0.32	0.22	0.18
Carcinogenic ***CTUh***	4.65E-6	6.96E-6	4.50E-6	6.71E-6	6.12E-6	3.67E-06	3.02E-6
Non- Carcinogenic ***CTUh***	8.50E-5	3.58E-5	1.10E-5	1.13E-5	9.93E-6	1.20E-5	9.84E-6
Respiratory ***disease incidence***	4.52E-6	4.05E-3	4.31E-6	3.85E-3	4.50E-3	3.83E-6	3.09E-6
Ozone Depletion ***kg CFC-11 eq.***	4.88E-6	1.08E-5	4.61E-6	1.03E-5	1.05E-5	4.27E-6	3.66E-6
Minerals + Metals ***kg Sb eq.***	0.00	0.26	0.00	0.25	0.29	0.00	0.00
Fossils ***MJ***	1042	1426	987	1366	1409	1312	1108
Water Use ***M^3 water***	167	73	154	70	75	218	179
Land Use ***n/a****	567	291	524	279	275	734	622

Table 7: *Description of all PEF impact categories quantified for this study.*[50]

Impact Category	Unit	Indicator/Method
Global Warming Potential	Kg CO2 eq	Radiative forcing as Global Warming Potential (GWP100)
Ozone depletion	Kg CFC-11 eq	Steady-state ozone depletion potential
Human toxicity cancer effects	CTUh	Comparative toxic unit for humans as provided in the USEtox 2.1. Factors have been applied on inorganics and metals to account for the fact that USEtox has been designed for organic substances
Human toxicity non-cancer effects	CTUh	Comparative toxic unit for humans as provided in the USEtox 2.1. model. Factors have been applied on inorganics and metals to account for the fact that USEtox has been designed for organic substances.
Particulate matter/ respiratory	Disease incidences	Human health effects associated with exposure to PM2.5 from the PM method recommended by UNEP
Ionising radiation, human health	kBq U	Human exposure efficiency relative to U235 using the Human health model as developed by Dreicer et al 1995
Photochemical ozone formation	kg NMVOC eq	Tropospheric ozone concentration increases from LOTOS-EUROS as applied in ReCiPe 2008
Acidification	Mol H+ eq	Accumulated Exceedance
Eutrophication, terrestrial	Mol N eq	Accumulated Exceedance
Eutrophication, aquatic freshwater	kg P eq	Fraction of nutrients reaching freshwater end compartment (P) using the EUTREND model as implemented in ReCiPe
Eutrophication aquatic marine	kg N eq	Fraction of nutrients reaching freshwater end compartment (N) using the EUTREND model as implemented in ReCiPe
Ecotoxicity freshwater	CTUe	Comparative toxic units for ecosystems derived from USEtox 2.1.derived from the HC20 instead of the HC50. In addition, factors have been applied on inorganics and metals to account for the fact that USEtox has been designed for organic substances.
Land use	Dimensionless,	Soil quality index (biotic production, erosion resistance, mechanical filtration and groundwater replenishment) used for further calculations in the LANCA method
Water use	kg world eq. deprived	User deprivation potential (deprivation-weighted water consumption) from the AWARE method
Resource use, minerals and metals	kg SB eq	Abiotic resource depletion from ultimate reserves using CML
Resource use, energy carriers	MJ	Abiotic resource depletion from fossil fuels using CML

Appendix B - Battery Model Specifications and Results

Table 8: Battery pack masses and specific energies used in all LCA calculations. NMC-811, LFP and LFMP specific energies either taken directly or calculated from GREET model [21], and SSB specific energies from QuantumScape predictions as per Section 3.3.4.1.[8]

	Sulfide SSB LFP	**Sulfide SSB NMC-811**	**Oxide SSB LFP**	**Oxide SSB NMC-811**	**NMC-811 LIB**	**LFP LIB**	**LFMP LIB**
Battery Pack Mass ***kg***	300	305	301	306	285	405	405
Pack Specific Energy ***kWh/kg***	0.25	0.40	0.25	0.40	0.25	0.174	0.22
Battery Performance ***kWh***	36	58	36	58	36	25	32
Cell and Module ***per pack***	8 Cells x 18 Modules						

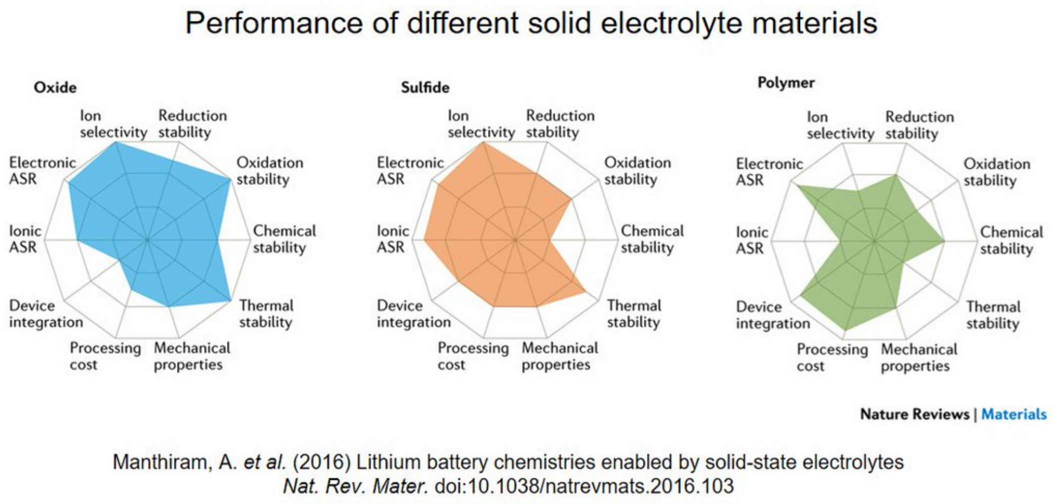
Table 9: *Calculated global warming potential impact for all battery types in this study, presented as kg CO_2 equivalent per kWh.*

kg CO_2 eq. per kWh	**Sulfide SSB LFP**	**Sulfide SSB NMC-811**	**Oxide SSB LFP**	**Oxide SSB NMC-811**	**NMC-811 LIB**	**LFP LIB**	**LFMP LIB**
Cathode	19.2	30.3	17.5	28.8	33.8	26.7	25.4
Anode	19.1	11.9	19.1	11.9	18.7	23.1	18.5
Electrolyte	6.8	3.9	5.6	3.5	1.7	3.1	2.5
Cell Assembly	0.2	0.1	0.2	0.1	0.1	0.2	0.1
Module Assembly	3.1	1.9	3.1	1.9	2.3	3.2	2.6
Pack Assembly	7.2	4.5	7.2	4.5	6.2	7.7	6.1
Assembly Energy	11.9	7.4	11.6	7.3	13.9	13.9	11.1
Total	67.3	60.0	64.2	58.0	76.7	77.9	66.4

Table 10: *Calculated global warming potential impact for all battery types in this study, presented as kg CO_2 equivalent per kg of battery.*

kg CO_2 eq. per kg	**Sulfide SSB LFP**	**Sulfide SSB NMC-811**	**Oxide SSB LFP**	**Oxide SSB NMC-811**	**NMC-811 LIB**	**LFP LIB**	**LFMP LIB**
Cathode	4.8	12.1	4.4	11.5	8.4	4.6	5.5
Anode	4.8	4.8	4.8	4.8	4.6	4.0	4.0
Electrolyte	1.7	1.5	1.4	1.4	0.4	0.5	0.5
Cell Assembly	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Module Assembly	0.8	0.8	0.8	0.8	0.6	0.6	0.6
Pack Assembly	1.8	1.8	1.8	1.8	1.5	1.3	1.3
Assembly Energy	3.0	3.0	2.9	2.9	3.4	2.4	2.4
Total	16.8	24.0	16.0	23.2	19.0	13.6	14.4

Appendix C - Battery Property References



Manthiram, A. *et al.* (2016) Lithium battery chemistries enabled by solid-state electrolytes *Nat. Rev. Mater.* doi:10.1038/natrevmats.2016.103

Figure 28: Battery property plots for selected SSBs.[51]

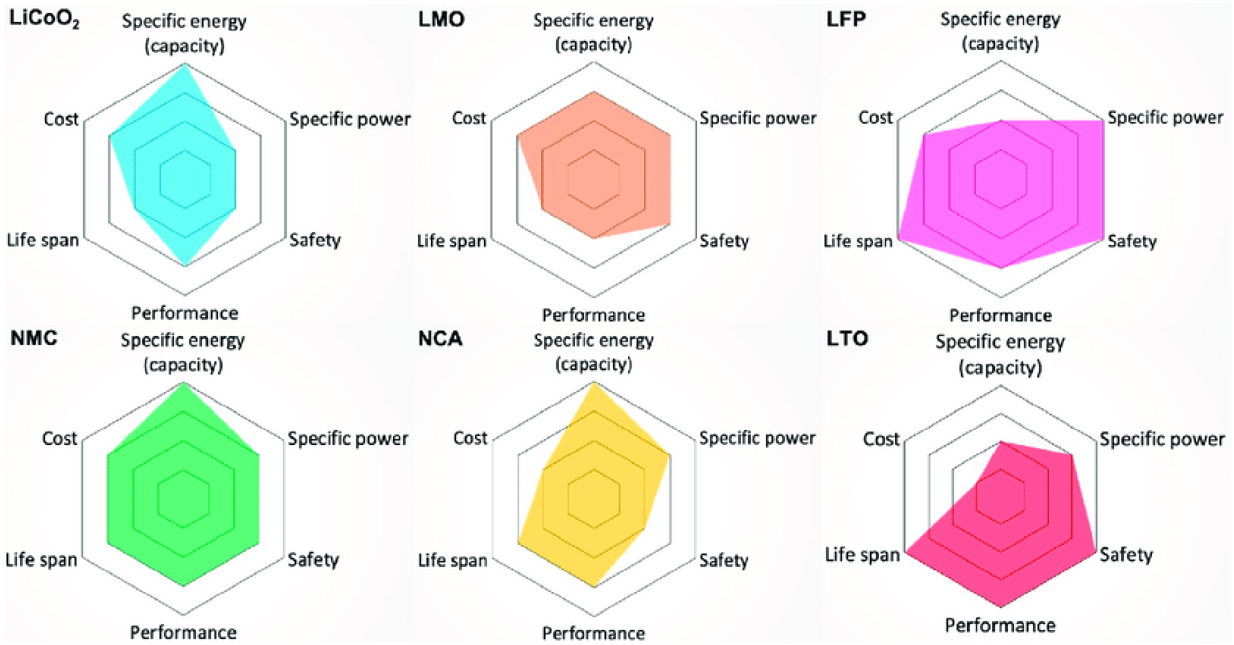


Figure 29: Battery property plots for selected LIBs.[25]

References

1. Explainer: How will solid-state batteries make electric vehicles better? *Reuters* (2021).
2. Sun, Y.-K. Promising All-Solid-State Batteries for Future Electric Vehicles. *ACS Energy Lett.* **5**, 3221–3223 (2020).
3. Finkbeiner, M., Tan, R. & Reginald, M. Life cycle assessment (ISO 14040/44) as basis for environmental declarations and carbon footprint of products. in *ISO Technical Committee 207 Workshop, Norway* (2011).
4. Horne, R. E., Grant, T. & Verghese, K. *Life Cycle Assessment: Principles, Practice and Prospects*. (Csiro Publishing, 2009).
5. Santero, N. & Hendry, J. Harmonization of LCA methodologies for the metal and mining industry. *Int. J. Life Cycle Assess.* **21**, 1543–1553 (2016).
6. Klöpffer, W. The critical review of life cycle assessment studies according to ISO 14040 and 14044. *Int. J. Life Cycle Assess.* **17**, 1087–1093 (2012).
7. Wernet, G. *et al.* The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* **21**, 1218–1230 (2016).
8. QuantumScape. Lithium iron phosphate on the QuantumScape solid-state lithium-metal platform. https://www.quantumscape.com/blog/lithium-iron-phosphate-on-the-quantumscape-solid-state-lithium-metal-platform/ (2021).
9. Addionics looks to the pouch cell. https://www.eenewspower.com/news/addionics-looks-pouch-cell (2021).
10. Wei, R., Chen, S., Gao, T. & Liu, W. Challenges, fabrications and horizons of oxide solid electrolytes for solid-state lithium batteries. *Nano Select* **2**, 2256–2274 (2021).
11. Erickson, C. Shift to solid-state batteries could be ‘seamless,’ experts say. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/shift-to-solid-state-batteries-could-be-seamless-experts-say-64837445 (2021).
12. Thieu, T. *et al.* Long cycle-life prototype lithium-metal all-solid-state pouch cells employing garnet-rich composite electrolyte. *Electrochim. Acta* **397**, 139249 (2021).
13. Liu, Y., Zhang, R., Wang, J. & Wang, Y. Current and future lithium-ion battery manufacturing. *iScience* **24**, 102332 (2021).
14. Pasta, M. *et al.* 2020 roadmap on solid-state batteries. *J. Phys. Energy* **2**, 032008 (2020).

15. Choi, C. Q. Solid-state batteries rev up electric cars, boost grid storage. *IEEE Spectrum* https://spectrum.ieee.org/solid-state-battery (2021).
16. Zhao, L., Lakraychi, A. E., Chen, Z., Liang, Y. & Yao, Y. Roadmap of Solid-State Lithium-Organic Batteries toward 500 Wh kg–1. *ACS Energy Lett.* **6**, 3287–3306 (2021).
17. Greenhouse gas emission intensity of electricity generation in Europe. https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment (2020).
18. Battery Whitepapers. https://www.battery.associates/battery-whitepapers.
19. Nickel life cycle assessments. https://nickelinstitute.org/policy/nickel-life-cycle-management/life-cycle-assessments/.
20. Battery Research and Quality Control Solutions. *Malvern Panalytical* https://www.malvernpanalytical.com/en/assets/PN12181_BR_BATTERY_RESEARCH_AND_QC_SOLUTIONS-FINAL-2_tcm50-63955.pdf.
21. Argonne GREET Publication : Update of Bill-of-Materials and Cathode chemistry addition for Lithium-ion Batteries in the GREET® Model. https://greet.es.anl.gov/publication-bom_lib_2020.
22. Intergovernmental Panel on Climate Change. *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2014).
23. Hiraishi, T. *et al.* 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands. *IPCC, Switzerland* (2014).
24. Committee, E. & E60 Committee. Guide for Environmental Life Cycle Assessment (LCA) of Building Materials/Products. doi:10.1520/e1991-05.
25. Miao, Y., Hynan, P., von Jouanne, A. & Yokochi, A. Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements. *Energies* **12**, 1074 (2019).
26. Thomitzek, M., von Drachenfels, N., Cerdas, F., Herrmann, C. & Thiede, S. Simulation-based assessment of the energy demand in battery cell manufacturing. *Procedia CIRP* **80**, 126–131 (2019).
27. Erakca, M. *et al.* Energy flow analysis of laboratory scale lithium-ion battery cell production. *iScience* **24**, 102437 (2021).
28. VSPC boosts energy density of LFP cells up to 25% by incorporating manganese; LMFP. *Green Car Congress*

https://www.greencarcongress.com/2020/12/20201207-vspc.html.

29. Lima, P. VSPC develops cobalt-free LFMP battery cell. 🔋*PushEVs - Push Electric Vehicles* https://pushevs.com/2020/12/11/vspc-develops-cobalt-free-lfmp-battery-cell/ (2020).
30. Kelly, J. C., Wang, M., Dai, Q. & Winjobi, O. Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. *Resour. Conserv. Recycl.* **174**, 105762 (2021).
31. namadmin. Lithium supply – hard rock vs. Brine. https://newagemetals.com/lithium-supply-hard-rock-vs-brine/ (2019).
32. Bisley International. Difference Between Lithium Carbonate & Lithium Hydroxide. https://bisleyinternational.com/what-is-the-difference-between-lithium-carbonate-lithium-hydroxide/ (2021).
33. A Look At The Lithium Clay Projects. https://seekingalpha.com/article/4205681-look-lithium-clay-projects.
34. Zero Carbon Lithium^{TM} - Vulcan Energy Resources. https://v-er.eu/zero-carbon-lithium/ (2020).
35. Direct Lithium Extraction. *Cornish Lithium Ltd.* https://cornishlithium.com/projects/lithium-in-geothermal-waters/direct-lithium-extraction/ (2021).
36. From Catamarca to Qinghai - the commercial scale DLE operations —. *Jade Cove Partners* https://www.jadecove.com/research/fromcatamarcatoqinghai.
37. Nickel in batteries. https://nickelinstitute.org/about-nickel/nickel-in-batteries/.
38. Kane, M. SVOLT reveals first NMx cobalt-free battery pack. *InsideEVs* https://insideevs.com/news/530037/svolt-first-nmx-cobaltfree-battery/ (2021).
39. Moyassari, E. *et al.* Impact of Silicon Content within Silicon-Graphite Anodes on Performance and Li Concentration Profiles of Li-Ion Cells using Neutron Depth Profiling. *J. Electrochem. Soc.* **168**, 020519 (2021).
40. Whattoff, P. *et al.* SHIFTING THE LENS. https://www.jadecove.com/s/Minviro-Shifting-the-Lens-October-2021.pdf (2021).
41. Goodbody, A. Minviro recalculates environmental impact of graphite production. https://www.miningmagazine.com/sustainability/news/1413495/minviro-recalculates-environmental-impact-of-graphite-production (2021).
42. Nethery, B. The role of feasibility studies in mining ventures. in *Conference Board of Canada, Structuring More Effective Mining Ventures, AMEC Mining and Metals, Vancouver* (2003).

43. Tesla Model 3 Standard Range Plus LFP. *EV Database* https://ev-database.uk/car/1320/Tesla-Model-3-Standard-Range-Plus-LFP.
44. Wayland, M. Tesla will change the type of battery cells it uses in all its standard-range cars. *CNBC* https://www.cnbc.com/2021/10/20/tesla-switching-to-lfp-batteries-in-all-standard-range-cars.html (2021).
45. Zhang, Z. *et al.* An advanced construction strategy of all-solid-state lithium batteries with excellent interfacial compatibility and ultralong cycle life. *J. Mater. Chem. A Mater. Energy Sustain.* **5**, 16984–16993 (2017).
46. Kim, A., Woo, S., Kang, M., Park, H. & Kang, B. Research Progresses of Garnet-Type Solid Electrolytes for Developing All-Solid-State Li Batteries. *Front Chem* **8**, 468 (2020).
47. Stuart, G., MacLeod, R. & Haque, A. Europe: EU Commission proposes new regulation for sustainable batteries. https://www.globalcompliancenews.com/2021/04/05/all-europeeu-commission-proposes-new-regulation-for-sustainable-batteries110321/ (2021).
48. Kelly, J. C., Dai, Q. & Wang, M. Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. *Mitigation and Adaptation Strategies for Global Change* **25**, 371–396 (2020).
49. The CO2 impact of the 2020s battery quality lithium hydroxide supply chain — Jade cove partners. https://www.jadecove.com/research/liohco2impact.
50. Impact assessment in the PEF initiative - PRé Sustainability. https://pre-sustainability.com/articles/pef-series-impact-assessment-in-the-pef-approach/ (2016).
51. Manthiram, A., Yu, X. & Wang, S. Lithium battery chemistries enabled by solid-state electrolytes. *Nature Reviews Materials* **2**, 1–16 (2017).