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How do residential lithium-ion batteries (LFP-C, LMO-C, NMC-C and NCA-C) perform in a cradle-to-gate life cycle assessment?

By

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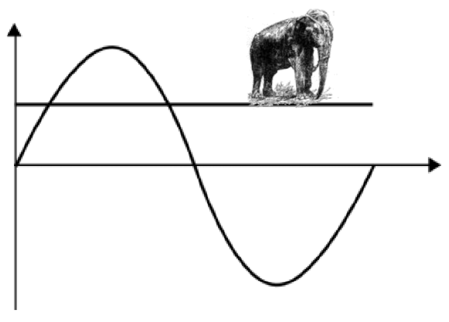
“Every effort should be made to stop the wanton, cruel slaughter of animals” – Nikola Tesla

“Until we stop harming all other living beings, we are still savages” – Thomas Edison



1 Abstract

The increasing presence of the lithium-ion battery technology for residential energy storage has triggered the need for comparison in terms of the environmental impact potential of the different chemistries which are currently in use. The LFP-C, LMO-C, NMC-C and NCA-C combinations of cathodes and anodes are privileged by manufacturers as their high power output, high energy density and long cyclability make them suitable for residential application. A cradle to gate life cycle assessment approach was used. In addition, some components were standardized across all battery chemistries. The end of life stage was also modelled. Two functional units where used: the environmental impact potential per kilogram of manufactured battery, as well as the environmental impact potential per lifetime kWh the batteries will be able to store. None of the batteries convincingly outperformed the others as statistical differentiability was not met. Nevertheless, all functional units considered, the LFP-C and NMC-C are showing a slight advantage. The findings of this study also suggest that increasing the recycling rate of the batteries would help offset the environmental footprint of their production significantly. In addition, it was found that different manufacturers using a same battery chemistry achieve very different performances. Therefore, benchmarking the batteries not by chemistry but by environmental impact potential per lifetime energy stored should be privileged by policy makers. A common methodology for all future life cycle assessments of lithium-ion chemistries is also suggested.

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3 Glossary

3.1 Abbreviations

Li-ion: Lithium-ion

LCO: Lithium Cobalt Oxide ($LiCoO_2$)

LMO: Lithium Manganese Oxide ($LiMn_2O_4$)

NMC: Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)

LFP: Lithium Iron Phosphate: ($LiFePO_4$)

C: Graphite

NCA: Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$)

LTO: Lithium titanate oxide ($Li_4Ti_5O_{12}$)

LCA: Life cycle assessment, with SimaPro being a common software for its modelling

GWP: Global warming potential

CED: Cumulative energy demand

MDP: Metal depletion potential

FDP: Fossil fuel depletion potential

ADP: Abiotic depletion potential

AP: Acidification potential

EP: Eutrophication potential

HTP: Human toxicity potential

ODP: Ozone depletion potential

PMF: Particulate matter formation

EDP: Ecosystem damage potential

LCI: life cycle inventory

BMS: Battery management system

FU: Functional unit

ESOI: Energy stored on energy invested

3.2 Battery terminology

Capacity: The amount of electric charge a battery can deliver at a given voltage

Electric power: Rate per unit of time at which electrical energy is transferred by an electrical circuit.

Electric current: Rate of flow of electric charge (electrons) past a point

Voltage: The difference in electric potential energy between two points per unit electric charge

Energy density: The amount of energy held in a given weight or volume

Specific energy: Energy per unit of mass

Lifetime specific energy: Energy stored during the battery's lifetime per unit of battery mass

Battery module: Cattery cell and battery module packaging together

Battery chemistry or technology: Type of cathode and anode used in the battery cell

3.3 Unit of measure

kWh: Kilowatt hour

kg: Kilogram

g: Gram

MJ: Megajoule

DALY: Disability adjusted life years

kg CO2 eq: Kilogram of CO_2-equivalent

PAF: Potentially affected fraction

Pt: Point

4 Background

4.1 The importance of batteries in residential energy storage

Batteries are essential to allow solar energy penetration. They allow to maximize the capture of solar energy by storing the excess of production that is not used directly. This stored energy can then be used during the evening, during the night and on cloudy days when there is less potential for solar power generation. Residential batteries also allow to store energy when there is less demand in the grid. In addition to alleviating the pressure from energy providers, it can have cost benefits for the consumer.

4.2 Favorable characteristics of battery technologies for residential application

The lithium-ion battery is the most promising technology currently available on the market for residential energy storage. Different cathodes and even anodes can be used. For example, the LCO positive electrode with a graphite negative electrode is used for portable consumer electronic devices, such as cell phones. Its low power output does not allow it to be used in very demanding applications. The high energy output permitted by the thermal stability of the NCA-C as well as its high capacity density will typically allow it to be placed in electric vehicles as well as in residential batteries with high power output requirement, such as hotels. However, the NCA-C battery cells typically have a relatively low cycle life. The LFP-C, LMO-C and NMC-C all have a good energy density, a power output that allows them to be used for residential application in homes and a very reasonable cycle life expectancy. In fact, most batteries on the market for residential application use the LFP-C technology, seconded by NMC-C, then LMO-C, and finally NCA-C. This study will be focusing on these 4 technologies.

4.3 Importance of making a life cycle assessment for each chemistry of li-ion battery

Lithium-ion batteries are prevailing on the residential energy storage market as they simply perform better than any other competing technology such as lead-acid batteries, which often also means lower costs on the long run. If a particular lithium-ion battery technology performs significantly better than the others from an environmental impact point of view and if its practicality is satisfactory enough, then it is important to start privileging this technology as we scale up our investments in residential energy storage. Moreover, the field of LCA for electric vehicle batteries has failed to find a common methodology for the modelling of their batteries. This makes most studies incomparable. It is important the nascent field of LCA for residential batteries finds a common methodology as soon as possible in order for all future studies to be comparable.

4.4 Present state of research

Most of the research has currently been focusing on lithium-ion batteries in electric vehicles, with few studies looking at li-ion batteries for residential application (Hiremath, Derendorf & Vogt, 2015). The debate among industrial ecologists on which li-ion battery performs the best in an LCA has started as early as 2000 (Gaines & Cuenca, 2000) and peaked around 2012. Many studies have been made, and they were often incomparable as different assumptions were set for components which should have proportionally weighed the same compared to the mass of the modules of the different battery chemistries. This is for example the case of the battery management system. Many studies don't even incorporate a cooling system in their model. It should be noted that some efforts of standardization have been done in the past few years to overcome these obstacles (Peters et al., 2017). Moreover, the studies often disregard the environmental impact of the batteries taking into account their performance in terms of the lifetime energy storage they will be able to carry. Finally, they often do not model an end of life stage and focus on a cradle to gate analysis, sometime adding the use stage. Enough primary data has been gathered over the years to standardize and compare the main technologies of batteries used for residential battery. This study will not bring new primary data from industry concerning manufacturing stages or processing. Finally, a statistical analysis of the significance of the differentiability of the different battery technologies' LCA results is clearly lacking in the current literature.

5 Aims and objectives

5.1 Standardized and comparable life cycle assessment results for each battery chemistry

It was fundamental for the purpose of this study to have comparable results for each modelled battery technology. One of the reasons why the current state of research has not drawn a definite conclusion on which battery technologies potentially might be the most environmentally friendly is because of the different assumptions made by the different LCAs in terms of the composition of the battery. This study will attempt to have the mass percentage, composition and manufacturing processes of some components standardized.

5.2 A comparison of batteries in terms of 2 functional units

There are at least two appropriate ways to analyze and compare batteries modelled in an LCA.

5.2.1 Environmental footprint potential per kg of manufactured battery

Comparing the battery technologies by looking at their environmental footprint potential per kg of manufactured battery means you only compare them on a cradle-to-gate and end of life basis, and disregard their performance in terms of cyclability and capacity density. The benefit of this functional unit is that it is independent from the uncertainty associated with the performance in terms of specific capacity of the batteries which can vary greatly among a same chemistry. Its disadvantage is that it disregards completely the performance of the batteries in terms of cyclability. Since they have many standardized components in their modelling this is what plays a major role in differentiating the chemistries.

5.2.2 Environmental footprint potential per kWh stored over the lifetime of the battery

The main advantage of looking at the environmental footprint potential of the battery technologies per kWh they will be able to store over their lifetime is that it looks at how different batteries using different chemistry technologies truly perform in the task they are meant to accomplish. It also better accounts for the capacity density of the batteries. The disadvantage of this functional unit is the uncertainty associated with the different performances within each chemistry technology as manufacturers put in a different amount of effort and have different objectives for their product. In addition, even if there are ways to standardize the batteries available on the market to compare them, it is difficult to make sure their power output and usable capacity are both standardized, as this requires putting a certain amount of battery cells in parallel and in series. The data in the manufacturers' data sheets and operating manual are very often lacking when it comes to those details.

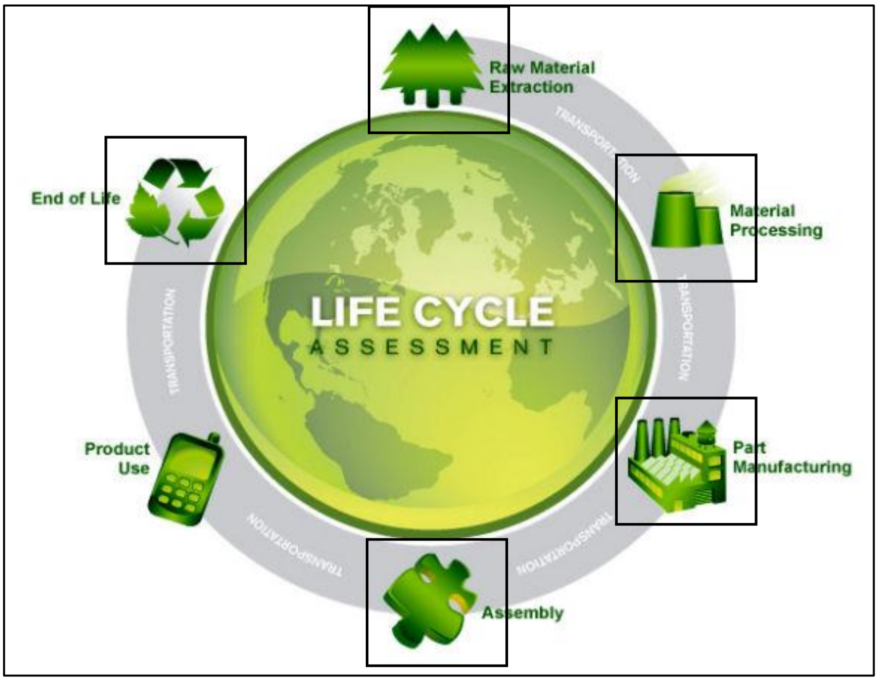
5.3 An assessment of the pollution with a variety of impact categories

Global warming potential is traditionally privileged by most LCAs (Peters et al., 2017) as the kg of CO2-equivalent is the most understandable unit for the public. However, this study will look across impact categories ranging from those related to human health, the health of ecosystems, resources depletion as well as single scores. Other studies usually only use one method to analyze the impact categories. This study will aim to use several different methods to be more critical about the results.

6 Methodology

6.1 Systems boundary: Cradle-to-gate and end of life

Figure 1: Encompassed stages of battery manufacturing

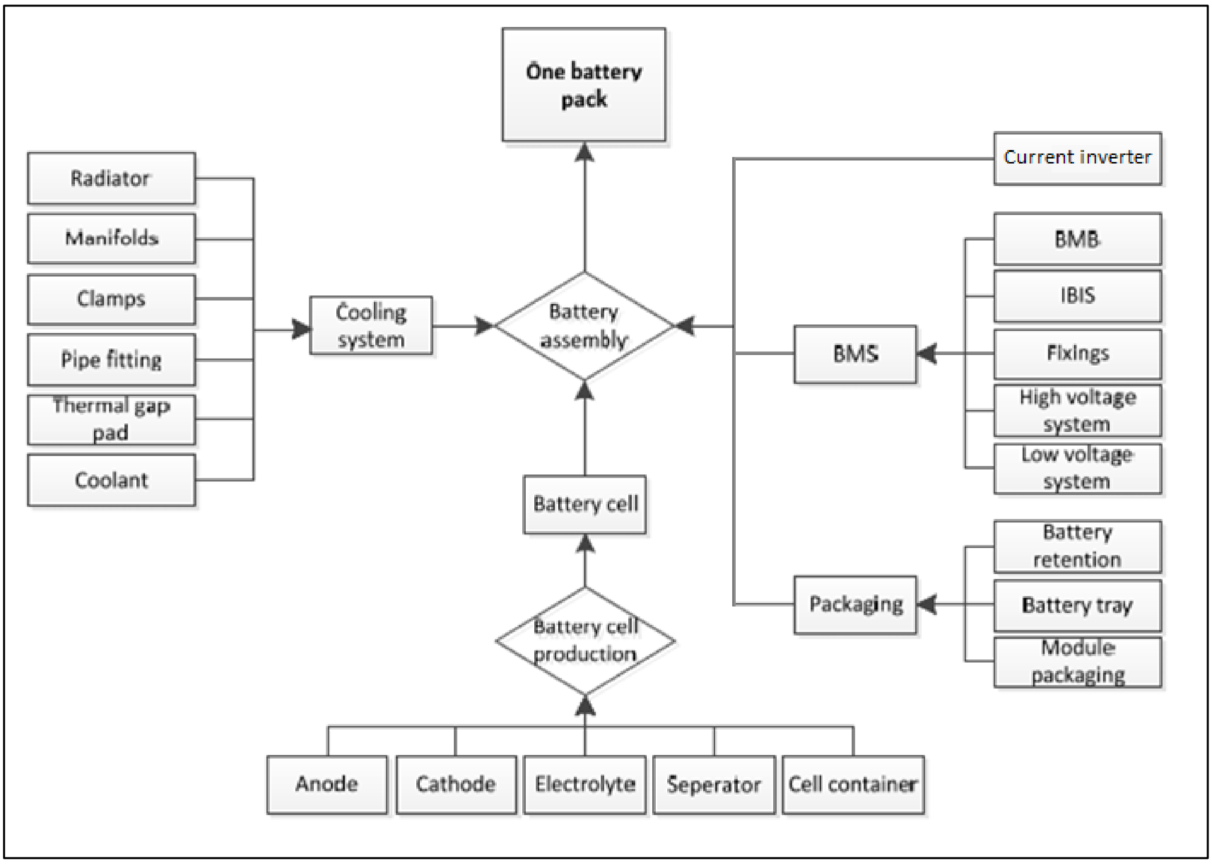


A cradle-to-gate approach was chosen, taking into account the materials input, energy input for processing, infrastructure requirements, transport and waste outputs. In addition, the end of life stage was modelled as this stage depends on the battery technology and must be taken care of whenever a battery is produced (Figure 1). However, even if some studies have deemed it useful to model the use stage, we believed it not to be appropriate. Indeed, they usually model this stage by looking at the environmental footprint of electricity production from the grid of different countries and then they calculate that a certain amount of energy will be stored during the whole battery's lifetime. This allows them to compare the environmental footprint of the production of the battery versus the environmental footprint of the production of the energy the battery will store. However, if anything, residential batteries should theoretically have a beneficial environmental footprint as they allow the maximization of renewable energies. Therefore, for this study, we have supposed the batteries will be used for storing mainly solar energy but the environmental footprint linked to the production of the energy the batteries will store was set aside.

6.2 System description and flowcharts

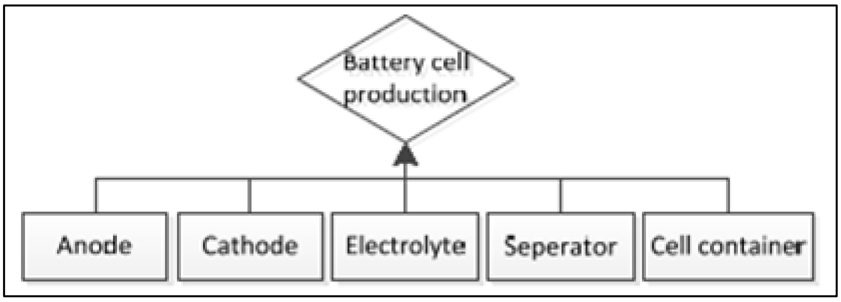
6.2.1 Residential battery packs

Figure 2: Flow chart for the production of the residential battery packs (Ellingsen et al., 2014)



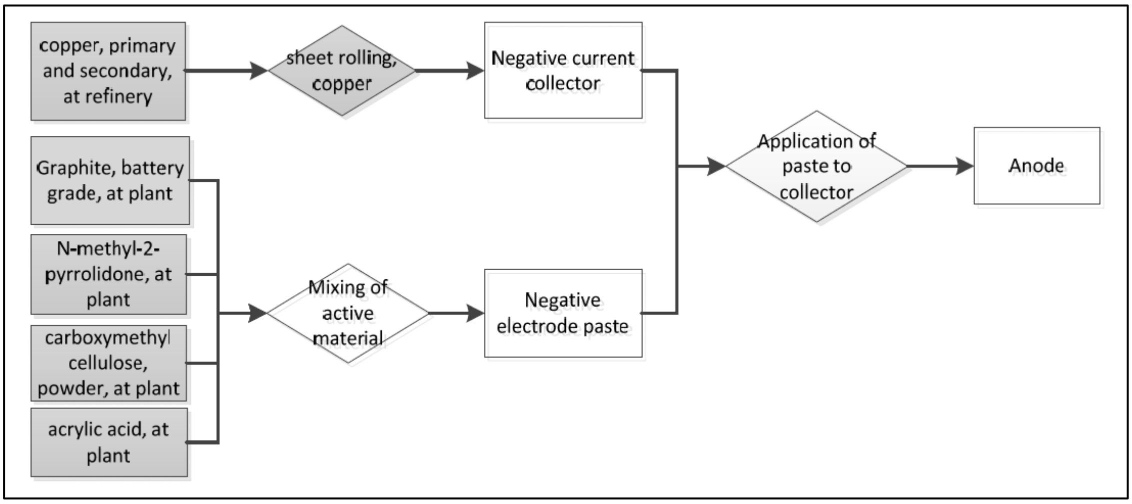
6.2.2 Battery cells

Figure 3: Flow chart for the production of the battery cell (Ellingsen et al., 2014)



6.2.2.1 Negative electrode

Figure 4: Flow chart for the production of the negative electrode (Ellingsen et al., 2014)



6.2.2.2 Positive electrodes

6.2.2.2.1 LFP-C positive electrode

Figure 5: Flow chart for the production of the active material of the LFP-C positive electrode (Majeau-Bettez, Hawkins & Strømman, 2011)

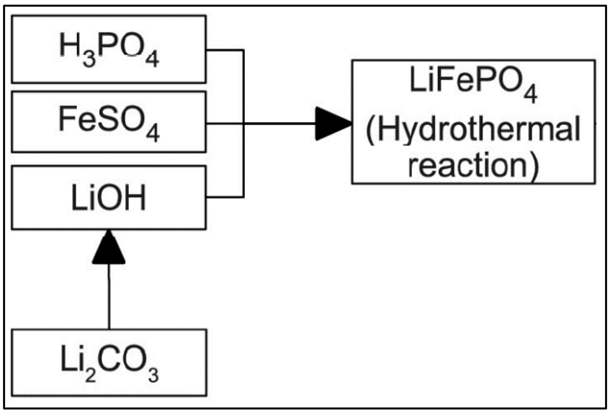
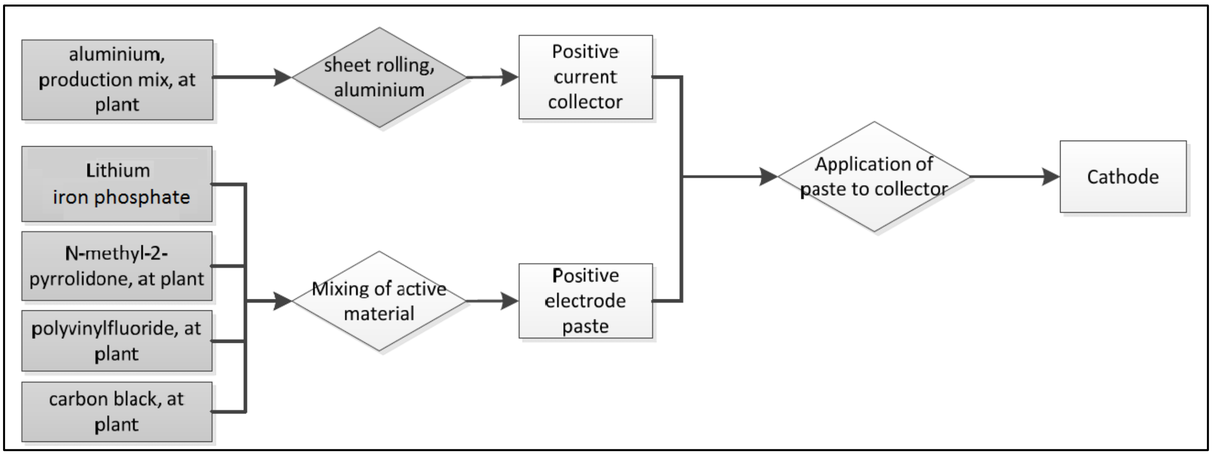


Figure 6: Flow chart for the production of the LFP-C positive electrode (Ellingsen et al., 2014)



6.2.2.2.2 LMO-C positive electrode

Figure 7: Flow chart for the production of the active material of the LMO-C positive electrode (A. Notter et al., 2010)

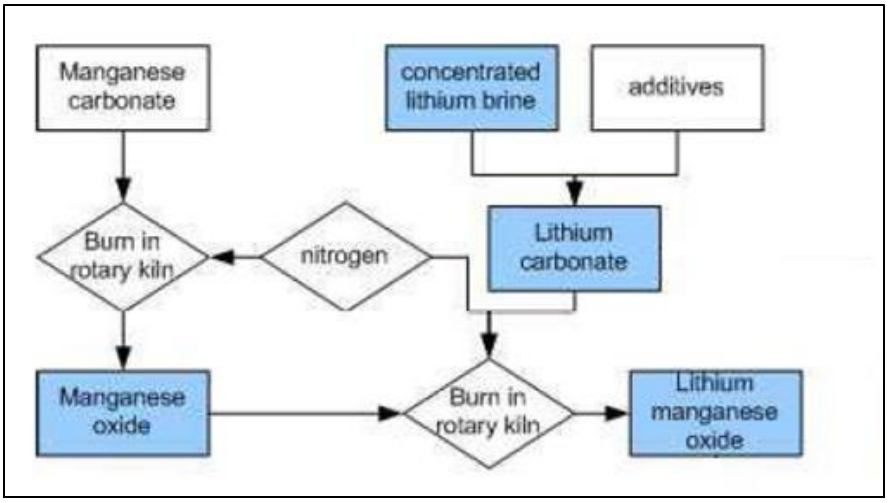
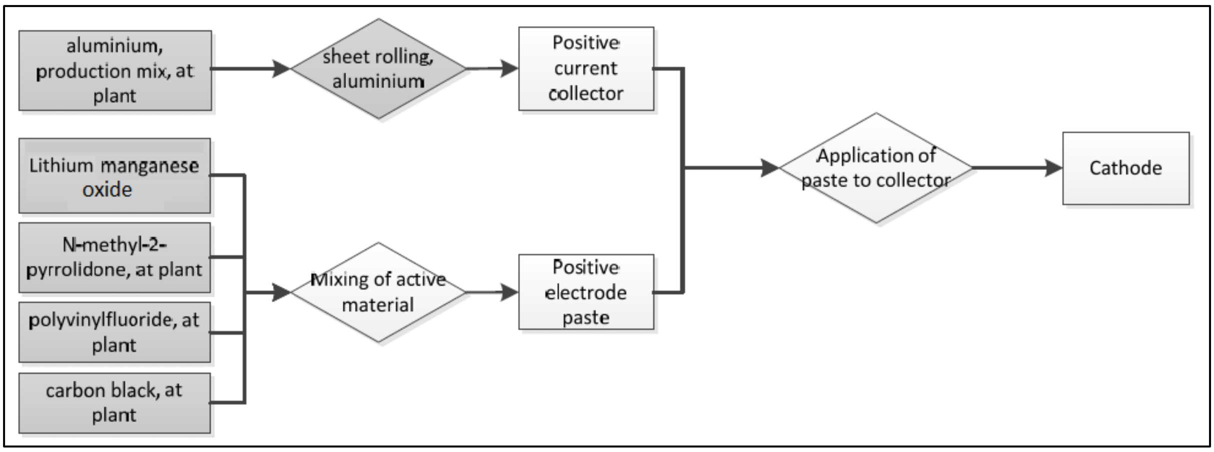


Figure 8: Flow chart for the production of the LMO-C positive electrode (Ellingsen et al., 2014)



6.2.2.2.3 NMC-C positive electrode

Figure 9: Flow chart for the production of the active material of the NMC-C positive electrode (Majeau-Bettez, Hawkins & Strømman, 2011)

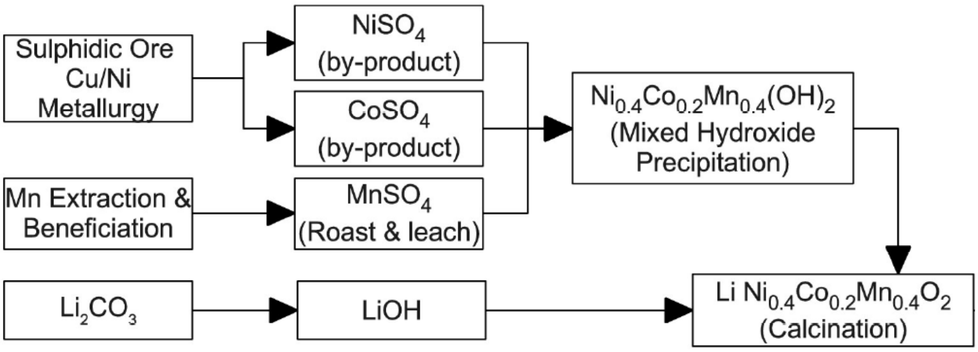
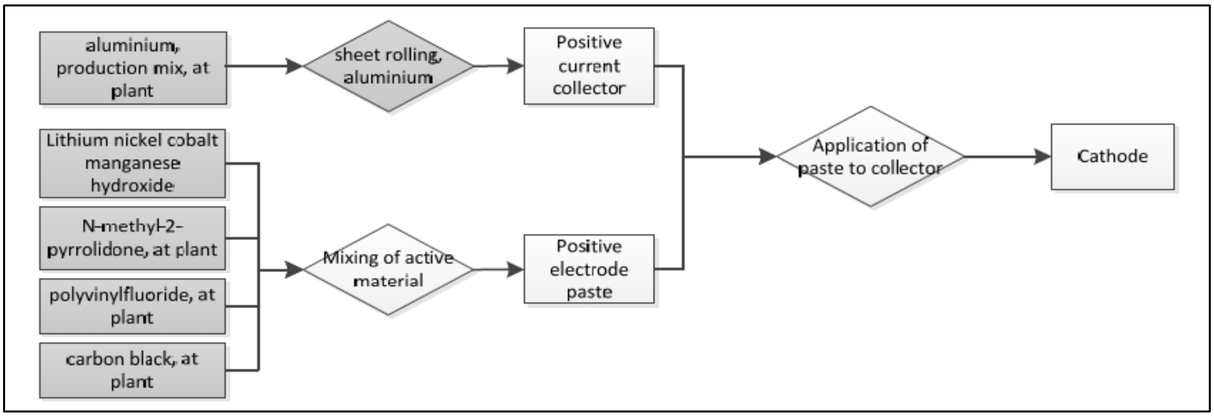


Figure 10: Flow chart for the production of the NMC-C positive electrode (Ellingsen et al., 2014)



6.2.2.2.4 NCA-C positive electrode

Figure 11: Flow chart for the production of the active material of the NCA-C positive electrode (Benavides et al., 2016)

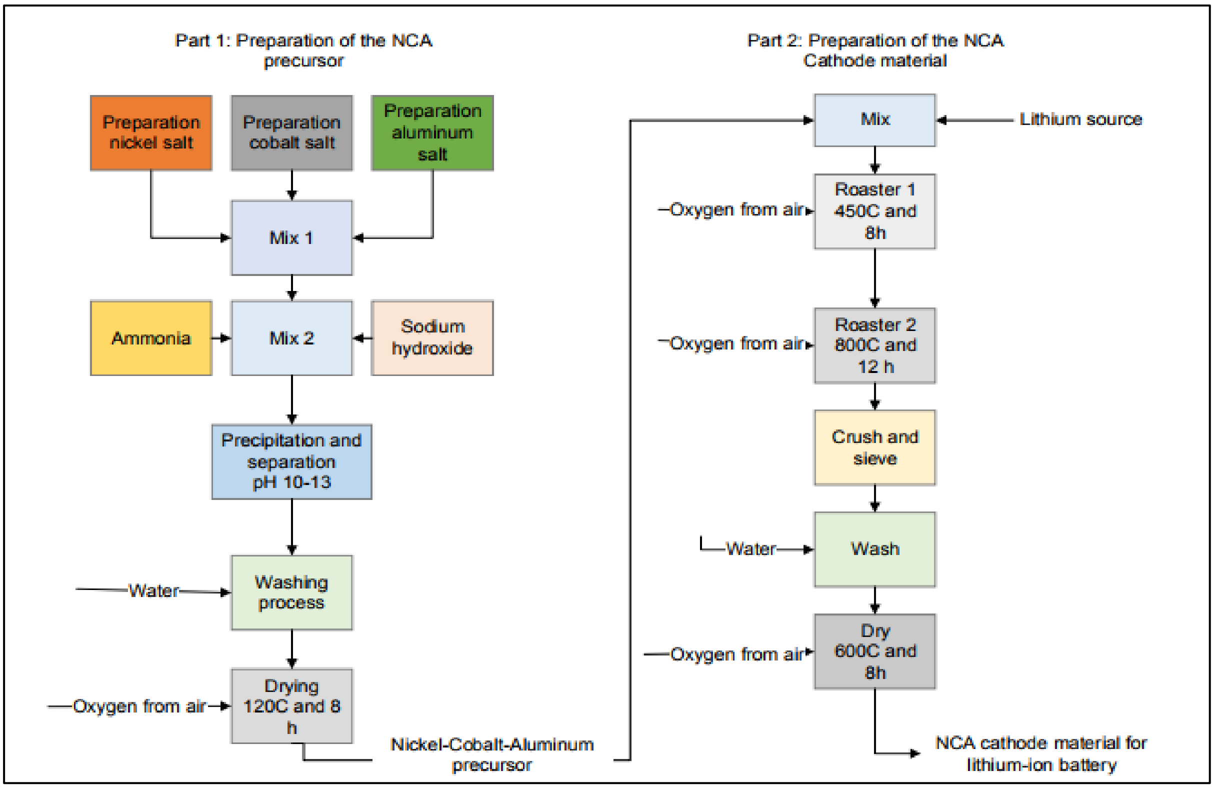
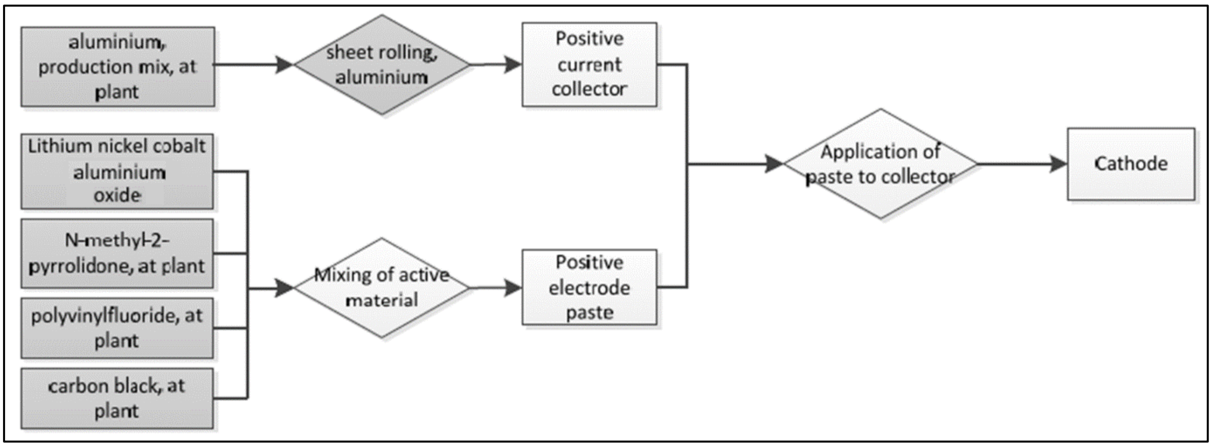


Figure 12: Flow chart for the production of the NCA-C positive electrode (Ellingsen et al., 2014)



6.2.2.3 Electrolyte

Figure 13: Flow chart for the production of lithium hexafluorophosphate and Ethylene carbonate (A. Notter et al., 2010)

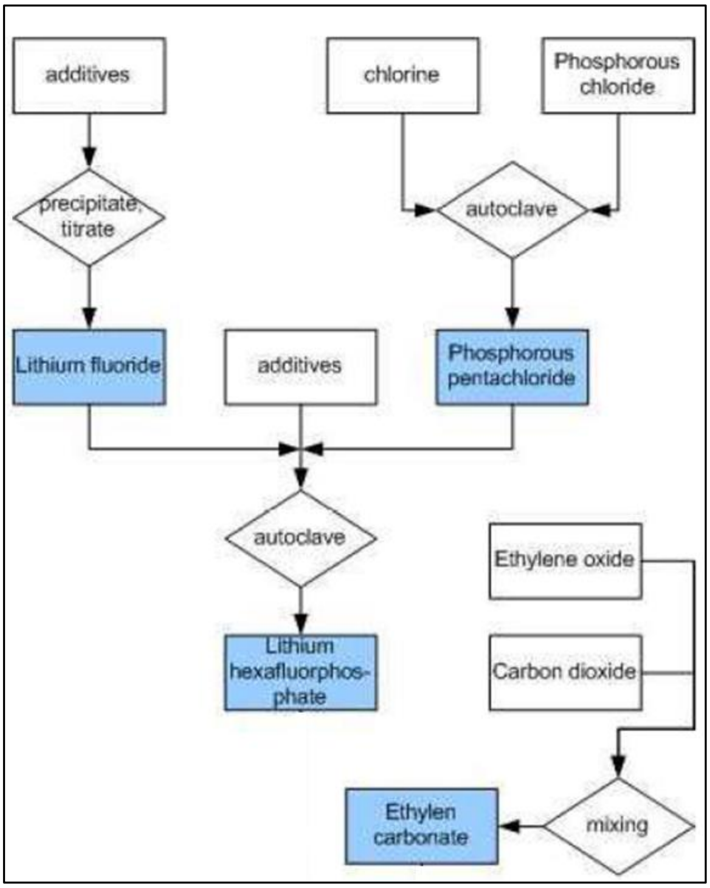
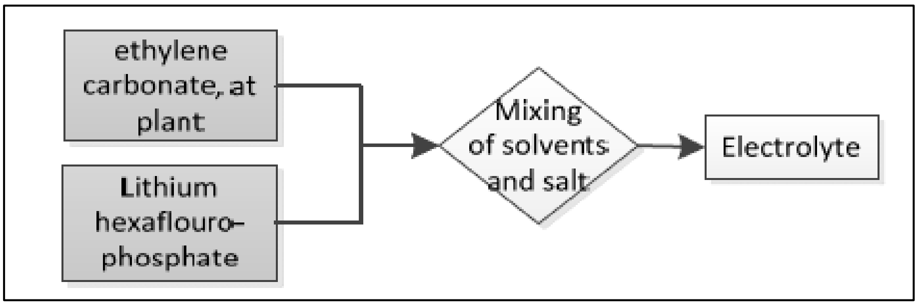
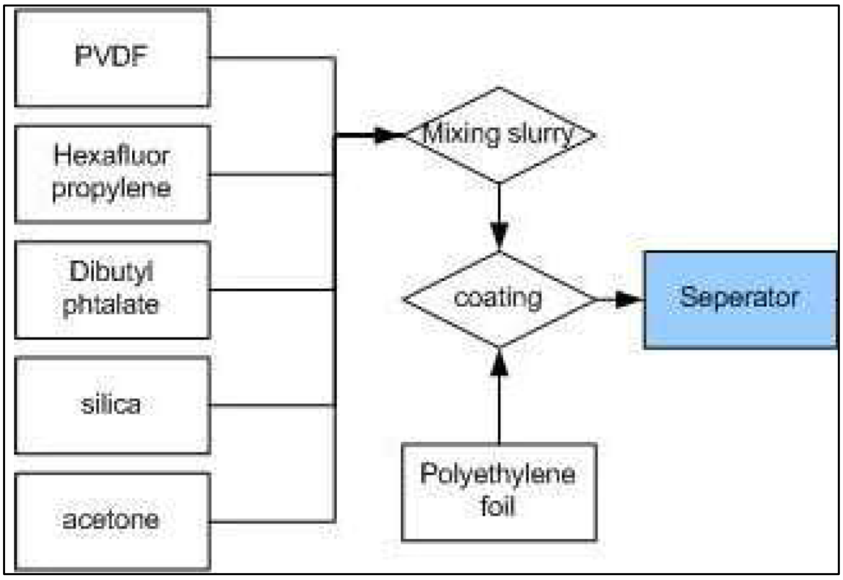


Figure 14: Flow chart for the production of the electrolyte (Ellingsen et al., 2014)



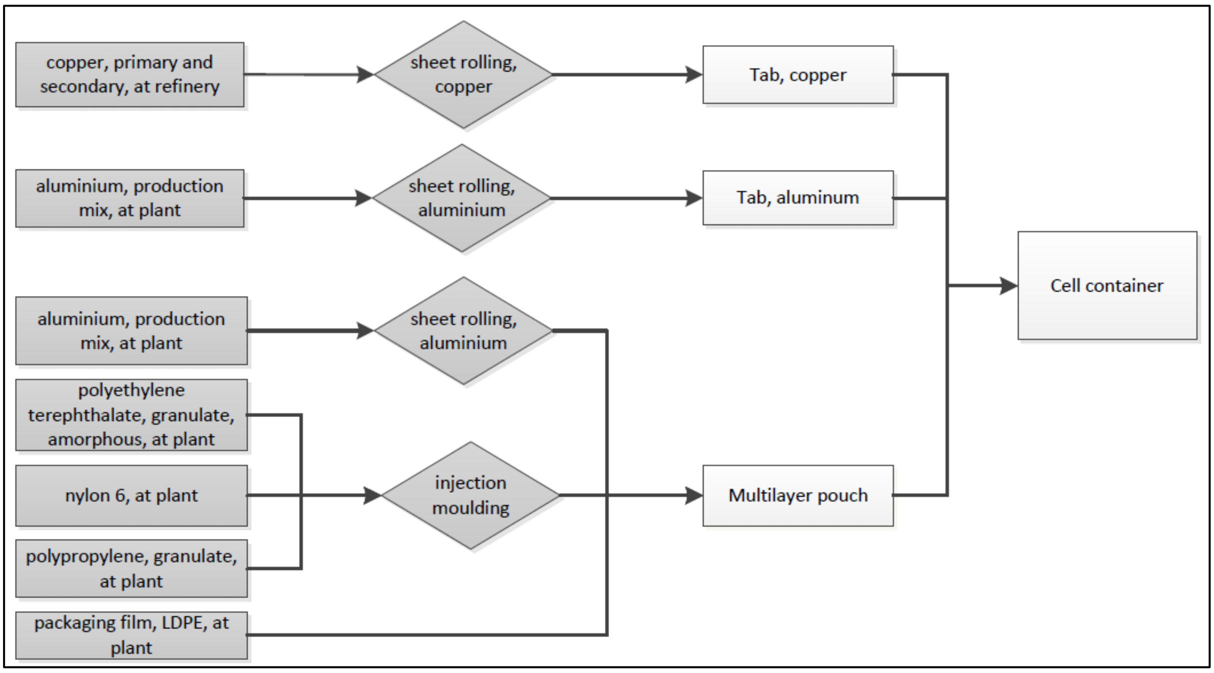
6.2.2.4 Separator

Figure 15: Flow chart for the production of the separator (A. Notter et al., 2010)



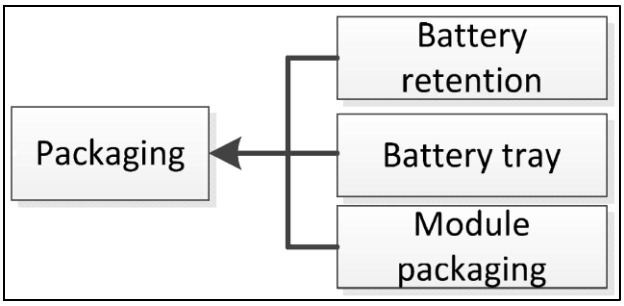
6.2.2.5 Cell container

Figure 16: Flow chart for the production of cell containers (Ellingsen et al., 2014)



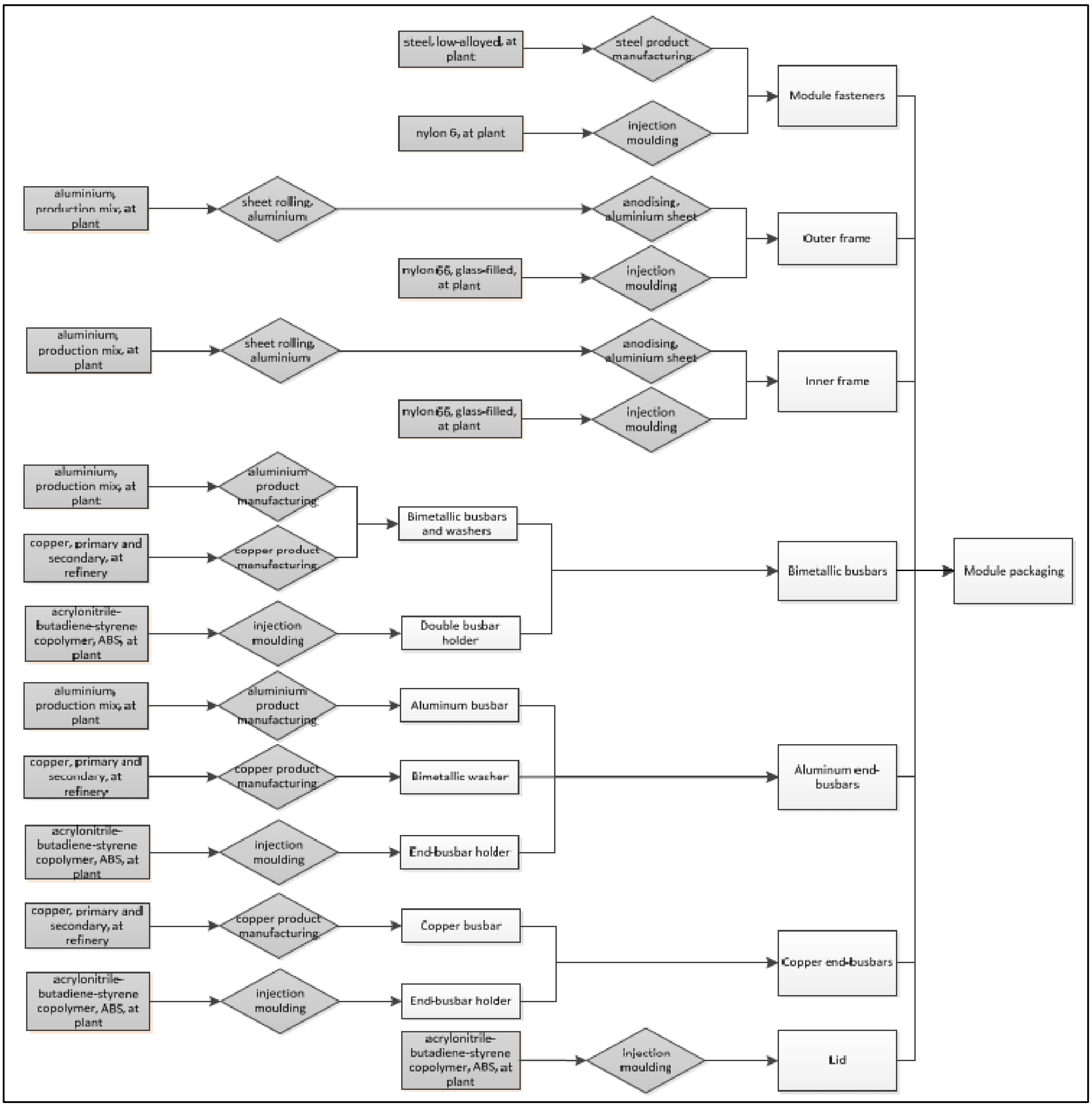
6.2.2.6 Battery pack casing

Figure 17: Flow chart for the production of the battery pack casing (Ellingsen et al., 2014)



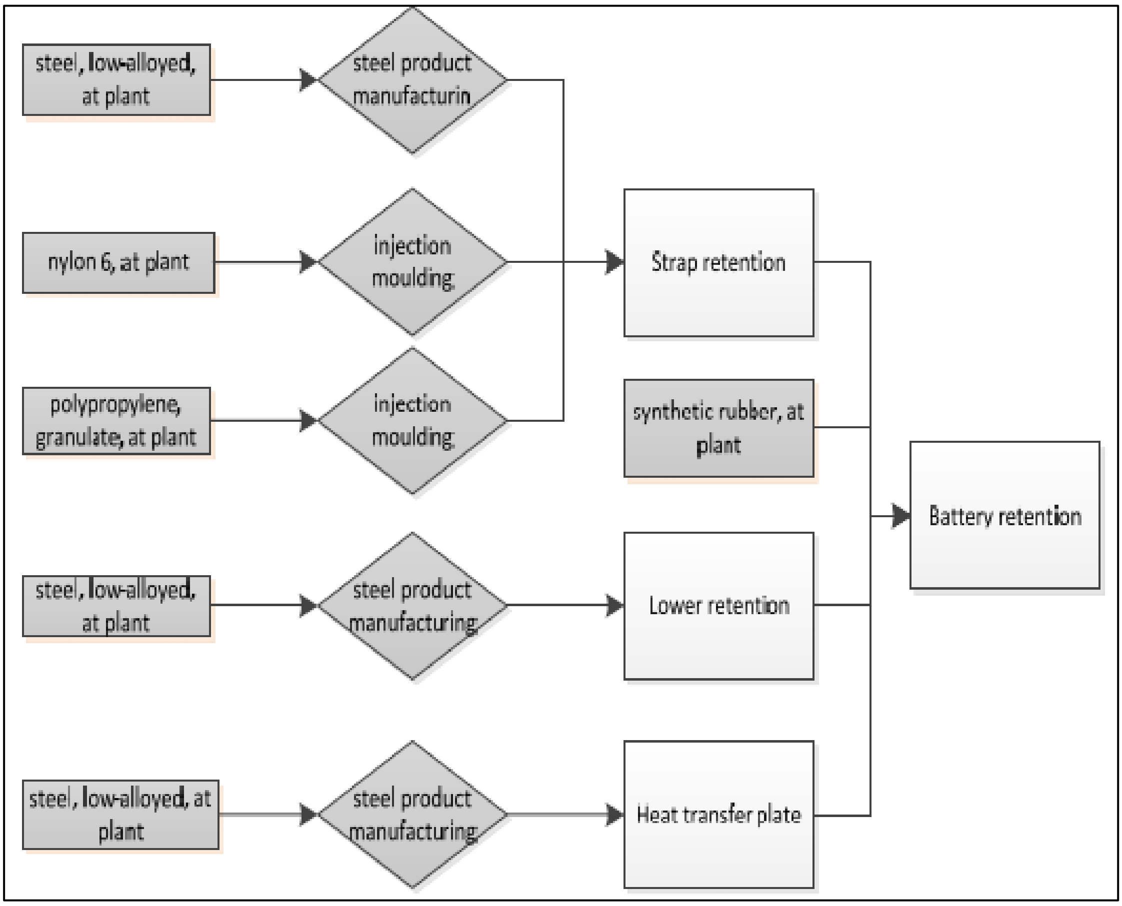
6.2.2.6.1 Module packaging

Figure 18: Flow chart for the production of the module packaging (Ellingsen et al., 2014)



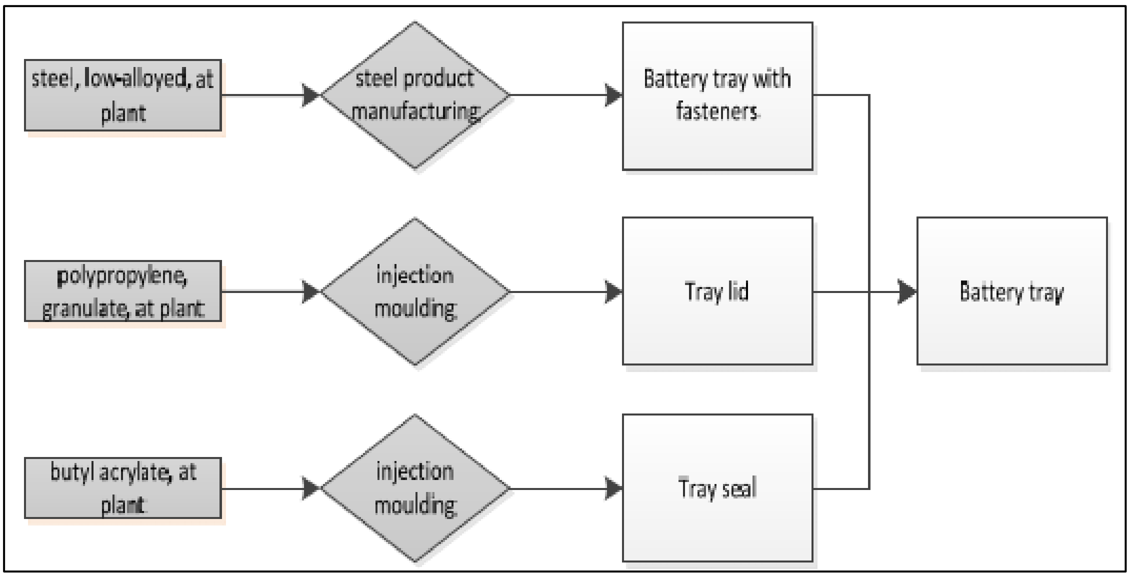
6.2.2.6.2 Battery retention

Figure 19: Flow chart for the production of the battery retention (Ellingsen et al., 2014)



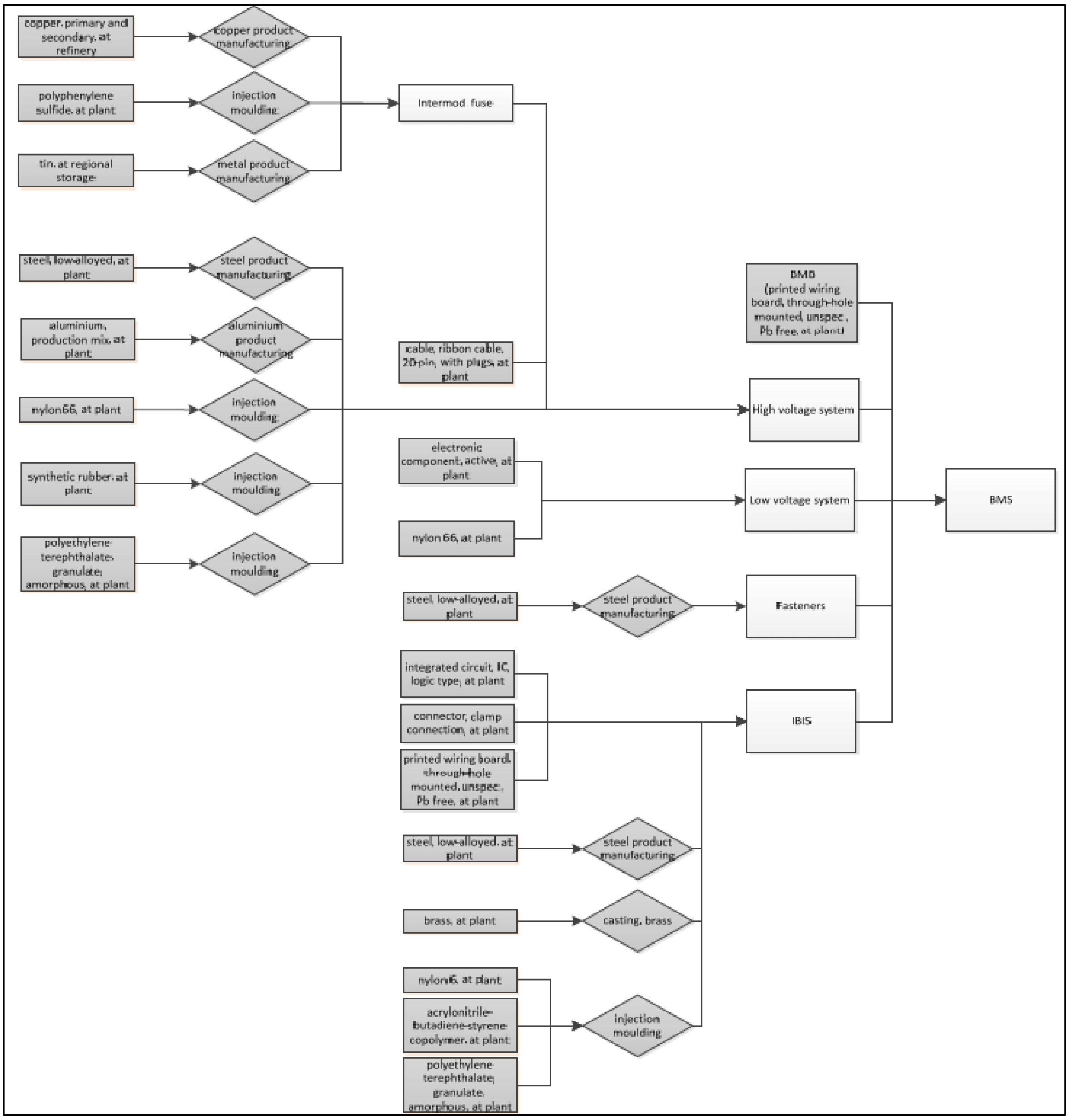
6.2.2.6.3 Battery tray

Figure 20: Flow chart for the production of the battery tray (Ellingsen et al., 2014)



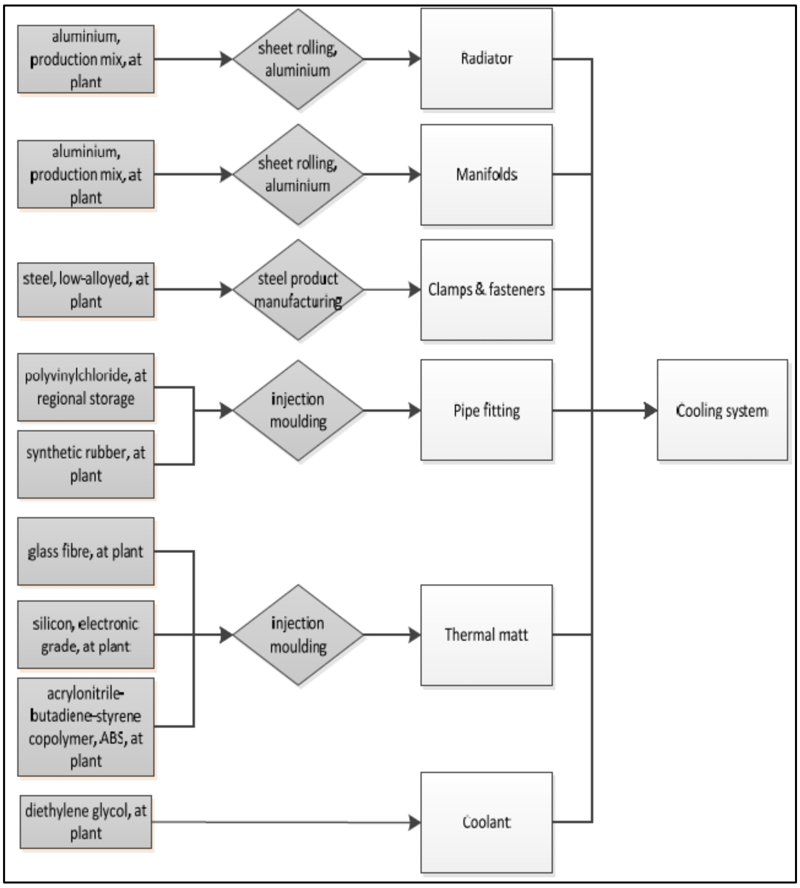
6.2.2.7 Battery management system

Figure 21: Flow chart for the production of the BMS (Ellingsen et al., 2014)



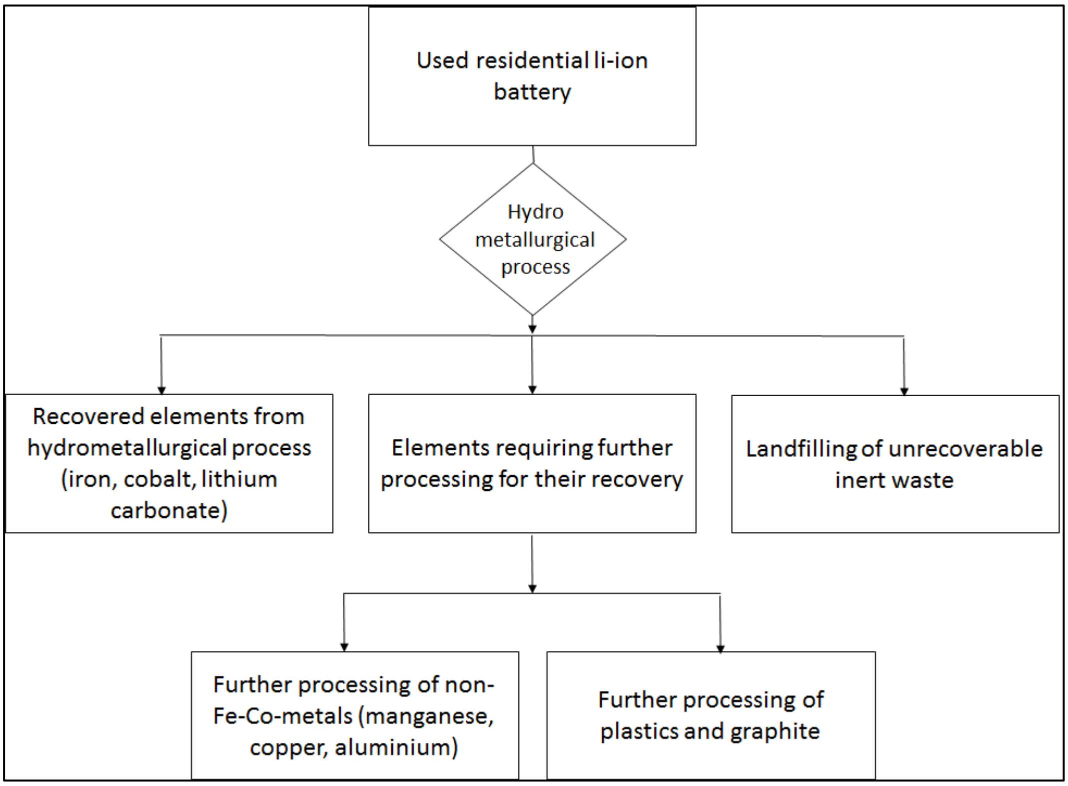
6.2.2.8 Cooling system

Figure 22: Flow chart for the production of the cooling system (Ellingsen et al., 2014)



6.2.2.9 End of life

Figure 23: Flow chart for the end of life stage



6.3 Mass composition inventory

6.3.1 Standardization of the current literature's li-ion battery mass composition

Some components of the batteries needed to have their materials and manufacturing standardized over all modelled batteries in order to obtain comparable results for their LCA. This is most notably the case of the positive electrode's binders, the negative electrode's binders, the positive electrode's current collectors, the negative electrode's current collector, the carbonate solvent and the lithium ions in the electrolyte, the separator, the cell container, the module and battery packaging, the BMS and the cooling system.

Other components, like the cell container, the module and battery packaging, BMS and cooling system also needed to have their mass ratio equal in all batteries in order for them to be truly comparable on the basis of their nature and performance and not biased by the different engineerings different manufacturers will be able to achieve.

In this preliminary step, Ellingsen's study (Ellingsen et al., 2014) is the only one which modelled a cooling system. Therefore, their value for the mass ratio of this component was chosen. For the other components, an average of each research group's value for only one of the batteries they analyzed, to avoid redundancy, was made and the mass ratios were adapted to the presence of a cooling system. The research groups analyzed for the battery mass composition are the following:

- LFP-C: (Majeau-Bettez, Hawkins & Strømman, 2011; Zackrisson, Avellán & Orlenius, 2010) and (Majeau-Bettez, Hawkins & Strømman, 2011);
- LMO-C: (A. Notter et al., 2010);
- NMC-C: (Majeau-Bettez, Hawkins & Strømman, 2011) and (Ellingsen et al., 2014);
- NCA-C: (Bauer, 2010).

Finally, for the battery cell, the mass ratios of its components specific to each battery chemistry were distributed among the 67.56%. It should be noted these studies were all made for electric vehicle battery packs.

Table 1: Standardization of battery cell, cell container, module and battery packaging, BMS and cooling system components

	Average mass ratio of research groups (Zackrisson: LFP-C; Notter: LMO-C; M-B: NMC-C; Ellingsen: NMC-C; Bauer: NCA-C)	Preliminary fixed values of cell casing, module and battery pack casing, BMS and cooling system
	% mass	% mass
Negative electrode	**24.10**	67.56
Anode material	12.81	
Binder	0.79	
Current collector (copper foil)	10.50	
Positive electrode	**29.72**	
Active material	22.93	
Binder	1.19	
Conductive carbon	0.99	
Current collector (aluminium foil)	4.61	
Electrolyte	**13.25**	
Carbonate solvent	11.59	
Lithium ions	1.65	
Separator	**3.38**	
Cell container	**5.91**	**5.67**
Module and battery packing	**18.92**	**18.15**
BMS	**4.72**	**4.52**

Cooling system	**0**	**4.1**

6.3.1.1 Preliminary standardized LFP-C

Table 2: Preliminary standardization of the mass composition of an LFP-C battery pack

LFP-C Battery components	Source: Majeau-Bettez	Source: Zackrisson	Preliminary standardized value
	% mass	% mass	% mass
Negative electrode	**16.30**	**21.61**	**17.91**
Anode material	7.60	15.49	10.91
Binder	0.40	1.92	1.10
Current collector (copper foil)	8.30	4.21	5.91
Positive electrode	**28.40**	**42.57**	**33.53**
Active material	21.58	36.41	27.40
Binder	1.98	2.22	1.98
Conductive carbon	1.24	2.20	1.63
Current collector (aluminium foil)	3.60	1.74	2.52
Electrolyte	**12.00**	**16.91**	**13.66**
Carbonate solvent	10.56	14.34	11.77
Lithium ions	1.44	2.57	1.89
Separator	**3.30**	**1.90**	**2.46**
Cell container	**20.00**	**1.13**	**5.67**
Module and battery packing	**17.00**	**9.73**	**18.15**
BMS	**3.00**	**6.15**	**4.52**
Cooling system	**0**	**0**	**4.10**
Total (%)	100.00	100.00	100.00

6.3.1.2 Preliminary standardized LMO-C

Table 3: Preliminary standardization of the mass composition of an LMO-C battery pack

LMO-C Battery components	Source: Notter	Preliminary standardized value
	% mass	% mass
Negative electrode	**30.79**	**28.43**
Anode material	14.97	13.82
Binder	0.86	0.79
Current collector (copper foil)	14.97	13.82
Positive electrode	**24.72**	**22.83**
Active material	14.32	13.22
Binder	0.52	0.48
Conductive carbon	0.65	0.60
Current collector (aluminium foil)	9.23	8.52
Electrolyte	**13.57**	**12.53**
Carbonate solvent	12.13	11.20
Lithium ions	1.44	1.33
Separator	**4.08**	**3.77**
Cell container	**6.79**	**5.67**
Module and battery packing	**14.47**	**18.15**
BMS	**5.59**	**4.52**
Cooling system	**0**	**4.10**
Total (%)	100.01	100.00

6.3.1.3 Preliminary standardized NMC-C

Table 4: Preliminary standardization of the mass composition of an NMC-C battery pack

NMC-C Battery components	Source: Majeau-Bettez	Source: Ellingson	Preliminary standardized value
	% mass	% mass	% mass
Negative electrode	**17.72**	**24.19**	**23.19**
Anode material	8.94	9.91	10.43
Binder	0.47	0.42	0.49
Current collector (copper foil)	8.31	13.87	12.27
Positive electrode	**26.83**	**26.8**	**29.67**
Active material	20.21	22.36	23.55
Binder	1.86	0.94	1.55
Conductive carbon	1.16	0.48	0.91

Current collector (aluminium foil)	3.60	3.02	3.66
Electrolyte	**12.01**	**9.91**	**12.13**
Carbonate solvent	10.57	8.72	10.67
Lithium ions	1.44	1.19	1.46
Separator	**3.30**	**1.36**	**2.58**
Cell container	**20.12**	**0.42**	**5.67**
Module and battery packing	**17.02**	**33.47**	**18.15**
BMS	**3.00**	**3.86**	**4.52**
Cooling system	**0**	**0**	**4.10**
Total (%)	100.00	100.01	100.00

6.3.1.4 Preliminary standardized NCA-C

Table 5: Preliminary standardization of the mass composition of an NCA-C battery pack

NCA-C Battery components	Source: Bauer	Preliminary standardized value
	% mass	% mass
Negative electrode	**26.2**	**23.92**
Anode material	14.74	13.46
Binder	0.3	0.27
Current collector (copper foil)	11.16	10.19
Positive electrode	**27.69**	**25.28**
Active material	21.37	19.51
Binder	0.4	0.37
Conductive carbon	0.44	0.40
Current collector (aluminium foil)	5.48	5.00
Electrolyte	**13.84**	**12.64**
Carbonate solvent	12.21	11.15
Lithium ions	1.63	1.49
Separator	**6.27**	**5.72**
Cell container	**1.1**	**5.67**
Module and battery packing	**19.92**	**18.15**
BMS	**4.98**	**4.52**
Cooling system	**0**	**4.10**
Total (%)	100.00	100.00

6.3.2 Composition and performance of residential lithium-ion batteries available on the market

As many available residential lithium-ion batteries as possible were found online and their data sheets and installation manuals analysed to determine the chemistry technology they use for their cathode and anode, their mass ratios for each components and their performance. Some batteries were sold as an "all-in-one" package, often including a hybrid current inverter. When batteries were sold without a current inverter, the hybrid current inverter brand the battery manufacturer recommends was used and the model was adapted to the battery's power output. When the mass of each component composing the battery was not specified in detail, it was estimated as closely as possible. In total, 10 LMO-C, 2 LMO-C, 9 NMC-C and only 1 NCA-C residential batteries were identified and analysed. Tables with all the residential batteries available on the market decomposed in terms of their mass and performance can be found in the appendix.

6.3.3 Standardization of the battery mass composition using a 10 kWh battery module reference

The standardization of the usable capacity was important to make as otherwise some batteries have a disproportionately high ratio of hybrid inverter or of all the other components compared to the mass and the performance of the battery module. In order to achieve this standardization of the usable capacity, the usable capacity was brought to 10 kWh and the mass of the battery module was increased or decreased proportionately. The mass of the hybrid current inverter and of the rest of the components was not modified as battery modules were only put in parallel to increase the capacity, something that does not require a more sophisticated current inverter, BMS, cooling system, etc. The NCA-C Tesla Powerpack's cycle life was determined to be at least 3000 cycles. The estimate was made by analysing the cyclability of Panasonic's NCA-C 18650 cells (Watanabe et al., 2011) which are the ones used in the Tesla Powerpack. Tables with all the market's residential lithium-ion batteries standardized can be found in the appendix.

6.3.4 Standardization of the battery mass composition to build the residential batteries of this study

The average mass of a 10 kWh battery module was found by averaging all 22 data points for this value (Table 6**: *Mass decomposition of an average residential lithium-ion battery***. The same averaging process was used for the average mass of non-battery-module-non-inverter components (BMS, etc.) as well as for the hybrid current inverter which would suit a 10 kWh battery module. The hybrid current inverter's mass and other non-battery module components were assumed to be proportional to the mass of the battery module. Therefore, a ratio was constituted for the mass of non-battery module components per kg of battery module as well as the mass of current inverter per kg of battery module.

Variables:

- Mass of hybrid current inverter: b
- Mass of non-battery-module-non-current-inverter: c
- Mass of battery module: a
- Ratio of hybrid current inverter mass per mass of battery module: A
- Ratio of non-battery-module-non-hybrid-current-inverter mass per mass of battery module: B

$$A = \frac{b}{a} = \frac{29.2}{127.4} = 0.23$$

$$B = \frac{c}{a} = \frac{35.2}{127.4} = 0.28$$

Table 6: Mass decomposition of an average residential lithium-ion battery

	Value	Standard deviation		Standard error of the mean	
		Value	Sign	Value	Sign
Total average 10 kWh battery mass	191.72				
Average mass of 10 kWh battery module	127.36	43.93	σ_a	9.37	$\sigma_{\bar{x}a}$
Average mass of inverter for a 10 kWh battery module	29.2	4.63	σ_b	0.99	$\sigma_{\bar{x}b}$
Average mass ratio inverter/battery module	0.23	0.09	σ_A	0.02	$\sigma_{\bar{x}A}$
Inverter mass % in battery	15.23%				
Average mass of non-battery module and non-inverter components for a 10 kWh battery module	35.18	27.98	σ_c	5.96	$\sigma_{\bar{x}c}$
Average mass ratio of non-battery module and non-inverter components per 10 kWh battery module	0.28	0.24	σ_B	0.05	$\sigma_{\bar{x}B}$

non-battery module and non-inverter mass % in battery	18.35%				
battery module's module packaging mass (14.6% of battery module mass)	18.6				
Percentage of battery that is module packaging	9.70%				
Battery module without its module packaging	108.76				
Percentage of battery that is cell and cell container	56.73%				
Percentage of battery that is BMS and Cooling system and module packaging and battery packaging	28.05%				

It was thereby estimated that on average, using the batteries across all chemistries, the hybrid current inverter's mass in the battery was 15.23%, the cell without its container was 52.33% and the rest was 32.44%. The values previously found for the current literature of mass composition of electric vehicle batteries were adapted proportionately to fit the new data found by decomposing the market's available residential lithium-ion batteries. The mass ratio values in the table below are the ones that have been modelled in SimaPro.

Table 7: Mass composition of the LFP-C, LMO-C, NMC-C and NCA-C residential batteries modelled in this study

Battery components	Standardized LFP-C	Standardized LMO-C	Standardized NCA-C	Standardized NMC-C
	% mass	% mass	% mass	% mass
Negative electrode	**13.87**	**22.02**	**18.53**	**17.96**
Anode material	8.45	10.71	10.42	8.08
Binder	0.85	0.62	0.21	0.38
Current collector (copper foil)	4.58	10.71	7.89	9.50
Positive electrode	**25.97**	**17.68**	**19.58**	**22.98**
Active material	21.22	10.24	15.11	18.24
Binder	1.54	0.37	0.28	1.20
Conductive carbon	1.26	0.46	0.31	0.70
Current collector (aluminium foil)	1.95	6.60	3.88	2.84
Electrolyte	**10.58**	**9.71**	**9.79**	**9.39**
Carbonate solvent	9.11	8.68	8.63	8.27
Lithium ions	1.47	1.03	1.15	1.13
Separator	**1.90**	**2.92**	**4.43**	**2.00**

Cell container	**4.39**	**4.39**	**4.39**	**4.39**
Module and battery packing	**19.01**	**19.01**	**19.01**	**19.01**
BMS	**4.74**	**4.74**	**4.74**	**4.74**
Cooling system	**4.30**	**4.30**	**4.30**	**4.30**
Hybrid current converter	**15.23**	**15.23**	**15.23**	**15.23**
Total (%)	100.00	100.00	100.00	100.00

6.4 Lifecycle inventory

The materials and energy inputs and outputs were categorized according to different types:

- materials input;
- energy and manufacturing processes;
- transportation;
- infrastructure;
- materials output.

The detailed inputs and outputs for each stage and their inventory source can be found in the appendix.

6.5 End of life stage

It was assumed the residential li-ion batteries modelled will not be reused for another less demanding application. Nissan has a range of residential batteries which uses the used batteries from the Nissan Leaf electric vehicle. These LMO-C batteries offered by Nissan were not modelled in our study as their performance in terms of cycle life is significantly reduced. Instead, Nissan's LMO-C battery using new LMO-C cells was used. Since it was decided that a second life for the batteries was not appropriate to model for this study, the batteries were directly sent for hydrometallurgical processing after completing their last cycle.

It was estimated that the recovery rate of lithium carbonate and cobalt were overestimated in the Ecoinvent 3 model. In our study, cobalt was estimated to have an 80% recovery rate (Amarakoon, Smith & Segal, 2013). Lithium had an 85% recovery rate and then had to be enriched with carbon and oxygen to give the lithium carbonate recovery rate value modelled for this study as Ecoinvent 3 sets lithium carbonate and not pure lithium as an output. Nickel and phosphorus were not recovered as many hydrometallurgical processing plants rarely manage to focus on the recovery of all materials (Romare & Dahllöf, 2017). In addition, the Ecoinvent 3 hydrometallurgical model did not mention the recovery of nickel. The recovery rate of aluminium, plastics and graphite were also kept unchanged compared to the Ecoinvent 3 database.

The treatment of non-Fe-Co-metals from used li-ion batteries after hydrometallurgical process already existed in Ecoinvent 3 but it seems that it was applied to NMC-C batteries. The values for manganese which is absent in LFP-C and NCA-C batteries and copper which is present in different ratios in each technology had to be adapted depending on the battery chemistry.

The modelled recycling rate of this study varies between 48 and 50% of the total mass of the battery depending on the technology, making it realistically comply with the EU's legislation which requires a 50% recycling rate of the total mass of lithium-ion batteries (*Batteries directive*, 2006). The detailed inputs and outputs for each stage of the end of life can be found in the appendix.

6.6 Functional units

6.6.1 Environmental footprint potential per kg of manufactured battery

The environmental footprint potential per kg of manufactured battery functional unit only required the environmental pollution impact category scores from different methods for a kg of each battery chemistry modelled on SimaPro. This functional unit also allowed to compare the energy stored on energy invested of the different chemistries.

6.6.2 Environmental footprint potential per kWh stored over the lifetime of the battery

The second functional unit of our study involves the lifetime energy stored in the batteries. It should be reminded that the warranty of the battery manufacturers usually specifies that a battery will only be replaced if its capacity has gone beneath 80%, sometimes 70%, of the initial usable capacity before the expiry date of the warranty. Assuming a linear loss of usable capacity from 100% to 80% due to the deterioration of the components inside of the battery cell, we obtain an average capacity use of 90% compared to the one announced for the depth of discharge.

Variables:

- Energy stored during any battery module's lifetime (kWh): q

- Nominal capacity of the battery module (kWh): ε
- Cycle depth of discharge of the battery module (%): δ
- Cycle life expectancy of the battery module (number of cycles): γ
- Round trip efficiency of the battery module (%): η
- Average nominal capacity use representing the usable capacity loss due to the deterioration of the battery components (%): 90%

$$q = (\varepsilon\delta\gamma\eta)0.9$$

This calculation for q is done for each model of residential battery of a same chemistry. This lifetime energy storage is then divided by the battery module mass from the same battery model.

Variables:

- Lifetime energy storage per mass of battery module (kWh/kg): H
- Energy stored during battery module's lifetime: q
- Battery module weight: m

$$\tau = \frac{q}{\mathrm{m}}$$

For the standardized 10 kWh Sonnenbatterie Eco 8.2/16 Single phase, for example:

Variables:

- q = 77 400 kWh
- m = 145 kg

$$\mathrm{H}_{(Sonnenbatterie)} = \frac{q}{\mathrm{m}} = \frac{77400}{145} = 534$$

So for the Sonnenbatterie Eco 8.2/16 Single phase, τ = 534 kWh/kg

H is then averaged within each chemistry to give the average of the ratios, τ. For the LFP-C battery pack, for example:

Variables:

- $H_{\mathrm{model(1)}}$: Energy stored during the lifetime of a standardized 10 kWh Sonnenbatterie Eco 8.2/16 Single phase per mass of its battery module.

- H $_{\text{model(2)}}$: Energy stored during the lifetime of a standardized 10 kWh Alpha-ESS Storion ECO S5 per mass of its battery module.
- H $_{\text{model(3)}}$: …
- n = 10

$$\tau_{(LFP-C)} = \frac{\mathrm{H}_{model(1)} + \mathrm{H}_{model(2)} + \ldots + \mathrm{H}_{model(10)}}{n} = \frac{3899}{10} = 389.9$$

So τ_{LFP-C} is equal to 390 kWh/kg

τ which is different for each battery technology is then multiplied by the average module mass of the chemistry to which it belongs.

Variables:

- Total lifetime energy storage for the technology's module with a 10 kWh capacity: Q
- Lifetime energy storage per weight of battery module (kWh/kg): τ
- Average module mass within a chemistry: M

$$Q = \tau M$$

For the LFP-C battery pack, for example:

Variables:

- M=149.7 kg
- τ =389.9 kWh/kg

$$Q_{(LFP-C)} = \tau M = 149.73 \times 389.9 = 58378$$

This means our modelled 10 kWh LFP-C battery module will be able to store 58 378 kWh of energy during its lifetime. Our functional unit for this study requires to have the environmental pollution potential per kg given by SimaPro divided by a value in the form of "kWh/kg" in order to obtain the functional unit "pollution potential per kWh of lifetime stored energy". Q must therefore be divided by the total mass of each chemistry's battery pack which includes the battery module as well as the hybrid current inverter and all the other components.

First, the total mass of the battery for each chemistry is required. As seen in the previous section, the inverter's mass and the non-battery-module-non-hybrid-current-inverter's mass in a battery's chemistry is calculated as follows:

Variables:

- Average battery module's mass in a specific chemistry: M
- Ratio of hybrid current inverter mass per mass of battery module: A
- Ratio of non-battery-module-non-hybrid-current-inverter mass per mass of battery module: B
- Hybrid current inverter mass in a specific chemistry: α
- Non-battery-module-non-hybrid-current-inverter mass in a specific battery chemistry: β

$$\alpha = \mathrm{MA}$$

$$\beta = \mathrm{MB}$$

For the LFP-C chemistry, for example:

Variables:

- M = 149.7
- A = 0.23
- B = 0.28

$$\alpha_{(LFP-C)} = \mathrm{MA} = 149.7\mathrm{x}0.23 = 34.3$$

$$\beta_{(LFP-C)} = \mathrm{MB} = 149.7\mathrm{x}0.28 = 41.4$$

The masses of the battery module, the hybrid current inverter and the non-battery-module-non-hybrid-current-inverter must then be added together.

Variables:

- Total battery pack mass: ψ
- Average battery module's mass in a specific chemistry: M
- Hybrid current inverter mass in a specific chemistry: α
- Non-battery-module-non-hybrid-current-inverter in a specific battery chemistry: β

$$\psi = \mathrm{M} + \alpha + \beta$$

For the LFP-C battery, ψ is equal to 225.41 kg. We can now divide the energy stored during the lifetime of the battery by its total mass.

Variables:

- Lifetime energy storage per weight of total battery mass (kWh/kg): T
- Total lifetime energy storage for a module with a 10 kWh capacity: Q
- Total battery pack mass: ψ

$$T = \frac{Q}{\psi}$$

For the LFP-C, for example:

Variables:

- Q = 58378 kWh
- Ψ = 225.41 kg

$$T_{(LFP-C)} = \frac{Q}{\psi} = \frac{58378}{225.41} = 258.99$$

So for the LFP-C battery pack, T = 258.99 kWh/kg. This means a kilogram of the LFP-C battery pack we have modelled will be able to store 258.99 kWh over its lifetime.

Finally, the environmental pollution score of a given impact category given by SimaPro for the manufacturing of 1 kg of battery of a specific chemistry must be divided by T.

Variables:

- Lifetime energy storage per weight of total battery mass (kWh/kg): T
- Pollution score (pollution potential/kg): P
- Final score (pollution potential/kWh): S

$$S = \frac{P}{\mathrm{T}}$$

So for the LFP-C battery, for the global warming potential category, for example:

Variables:

- T = 258.99
- P = 7.960 (kg of CO2-eq)

$$S_{LFP-C} = \frac{P}{\mathrm{T}} = \frac{7.960}{258.99} = 0.03073$$

6.7 Sensitivity analysis: Integrating uncertainty

6.7.1 Standard deviation

The first step is to look at the error propagation from the standard deviations of a, b and c which are translated into A and B.

Variables:

- STDEV of the average mass of hybrid current inverter for all 22 data points: σ_b
- STDEV of the average mass of non-battery-module-non-current-inverter for all 22 data points: σ_c
- STDEV of the average mass of battery module for all 22 data points: σ_a
- STDEV of the ratio of hybrid current inverter mass per mass of battery module: σ_A
- STDEV of the ratio of non-battery-module-non-hybrid-current-inverter mass per mass of battery module: σ_B

$$\sigma_A = \frac{\sigma_b}{\sigma_a} = \left(\sqrt{\left(\left(\frac{\sigma_b}{b}\right)^2\right) + \left(\left(\frac{\sigma_a}{a}\right)^2\right)}\right) A$$

$$\sigma_B = \frac{\sigma_c}{\sigma_a} = \left(\sqrt{\left(\left(\frac{\sigma_c}{c}\right)^2\right) + \left(\left(\frac{\sigma_a}{a}\right)^2\right)}\right) B$$

Now, looking at the propagation of error transferred to the inverter's mass in a specific chemistry's standardized battery and to the non-battery-module-non-hybrid-inverter's mass:

$$\sigma_\alpha = \sigma_M \, \sigma_A = \left(\sqrt{\left(\left(\frac{\sigma_M}{M}\right)^2\right) + \left(\left(\frac{\sigma_A}{A}\right)^2\right)}\right) \alpha$$

$$\sigma_\beta = \sigma_M \, \sigma_B = \left(\sqrt{\left(\left(\frac{\sigma_M}{M}\right)^2\right) + \left(\left(\frac{\sigma_B}{B}\right)^2\right)}\right) \beta$$

The error is then propagated when we addition all the different components in a battery pack:

$$\sigma_\psi = \sigma_M + \sigma_\alpha + \sigma_\beta = \sqrt{(\sigma_M{}^2) + (\sigma_\alpha{}^2) + (\sigma_\beta{}^2)}$$

The next stage involves calculating the amount of kWh which will be stored during our chemistry-specific battery module's lifetime.

$$\sigma_Q = \sigma_\tau \sigma_M = \left(\sqrt{\left(\left(\frac{\sigma_\tau}{\tau}\right)^2\right) + \left(\left(\frac{\sigma_M}{M}\right)^2\right)}\right) Q$$

Error propagation continues for the division of the lifetime energy storage of the chemistry-specific battery by its total mass.

$$\sigma_T = \frac{\sigma_Q}{\sigma_\psi} = \left(\sqrt{\left(\left(\frac{\sigma_Q}{Q}\right)^2\right) + \left(\left(\frac{\sigma_\psi}{\psi}\right)^2\right)}\right) T$$

Finally, SimaPro gives environmental scores per kg of manufactured battery which will be divided by T to give the environmental pollution score per kWh of lifetime stored energy. Uncertainty has not been modelled in the SimaPro model, therefore the environmental pollution score per kg will be viewed as a constant.

$$\sigma_S = \frac{\sigma_P}{\sigma_T} = \left(\sqrt{\left(\left(\frac{0}{P}\right)^2\right) + \left(\left(\frac{\sigma_T}{T}\right)^2\right)}\right) S$$

6.7.2 Standard error of the mean

The first step is to turn the standard deviation into the standard error for a, b, and c.

- Standard error of average mass of hybrid current inverter for all 22 data points= $\sigma_{\bar{x}(b)}$
- Standard error of average mass of non-battery-module-non-current-inverter for all 22 data points= $\sigma_{\bar{x}(c)}$
- Standard error of average mass of battery module for all 22 data points: $\sigma_{\bar{x}(a)}$

$$\sigma_{\bar{x}(a)} = \frac{\sigma_a}{\sqrt{n}}$$

$$\sigma_{\bar{x}(b)} = \frac{\sigma_b}{\sqrt{n}}$$

$$\sigma_{\bar{x}(c)} = \frac{\sigma_c}{\sqrt{n}}$$

Next, we have to look at the error propagation from the standard errors of a, b and c which are translated into A and B.

$$\sigma_{\bar{x}(A)} = \frac{\sigma_{\bar{x}(b)}}{\sigma_{\bar{x}(a)}} = \left(\sqrt{\left(\left(\frac{\sigma_{\bar{x}(b)}}{b}\right)^2\right) + \left(\left(\frac{\sigma_{\bar{x}(a)}}{a}\right)^2\right)}\right) A$$

$$\sigma_{\bar{x}(B)} = \frac{\sigma_{\bar{x}(c)}}{\sigma_{\bar{x}(a)}} = \left(\sqrt{\left(\left(\frac{\sigma_{\bar{x}(c)}}{c}\right)^2\right) + \left(\left(\frac{\sigma_{\bar{x}(a)}}{a}\right)^2\right)}\right) B$$

Now, we must look at the propagation of error transferred to the inverter's mass in a specific chemistry's standardized battery and to the non-battery-module-non-hybrid-inverter's mass:

$$\sigma_{\bar{x}(\alpha)} = \sigma_{\bar{x}(M)}\ \sigma_{\bar{x}(A)} = \left(\sqrt{\left(\left(\frac{\sigma_{\bar{x}(M)}}{M}\right)^2\right) + \left(\left(\frac{\sigma_{\bar{x}(A)}}{A}\right)^2\right)}\right) \alpha$$

$$\sigma_{\bar{x}(\beta)} = \sigma_{\bar{x}(M)}\ \sigma_{\bar{x}(B)} = \left(\sqrt{\left(\left(\frac{\sigma_{\bar{x}(M)}}{M}\right)^2\right) + \left(\left(\frac{\sigma_{\bar{x}(B)}}{B}\right)^2\right)}\right) \alpha$$

The error is then propagated when we addition all the different components in a battery pack:

$$\sigma_{\bar{x}(\psi)} = \sigma_{\bar{x}(M)} + \sigma_{\bar{x}(\alpha)} + \sigma_{\bar{x}(\beta)} = \sqrt{\left(\sigma_{\bar{x}(M)}{}^2\right) + \left(\sigma_{\bar{x}(\alpha)}{}^2\right) + \left(\sigma_{\bar{x}(\beta)}{}^2\right)}$$

The next stage involves calculating the amount of kWh which will be stored during our chemistry-specific, battery module's lifetime.

$$\sigma_{\bar{x}(\mathrm{Q})} = \sigma_{\bar{x}(\tau)}\sigma_{\bar{x}(\mathrm{M})} = \left(\sqrt{\left(\left(\frac{\sigma_{\bar{x}(\tau)}}{\tau}\right)^2\right) + \left(\left(\frac{\sigma_{\bar{x}(\mathrm{M})}}{M}\right)^2\right)}\right) \mathrm{Q}$$

Error propagation continues for the division of the lifetime energy storage of the chemistry-specific battery by its total mass.

$$\sigma_{\bar{x}(\mathrm{T})} = \frac{\sigma_{\bar{x}(\mathrm{Q})}}{\sigma_{\bar{x}(\psi)}} = \left(\sqrt{\left(\left(\frac{\sigma_{\bar{x}(\mathrm{Q})}}{\mathrm{Q}}\right)^2\right) + \left(\left(\frac{\sigma_{\bar{x}(\psi)}}{\psi}\right)^2\right)}\right) \mathrm{T}$$

Finally, SimaPro gives environmental scores per kg of manufactured battery which will be divided by T to give the environmental pollution score per kWh of lifetime stored energy. Uncertainty has not been modelled in the SimaPro model, therefore, just like for the error propagation calculated for the standard deviation, the environmental pollution score per kg will be viewed as a constant.

$$\sigma_{\bar{x}(S)} = \frac{\sigma_{\bar{x}(P)}}{\sigma_{\bar{x}(T)}} = \left(\sqrt{\left(\left(\frac{0}{P}\right)^2\right) + \left(\left(\frac{\sigma_{\bar{x}(T)}}{T}\right)^2\right)}\right) S$$

The standard error of the mean will be priviledged over the standard deviation and shown with error bars when analysing the charts with the functional unit looking at the environmental footprint potential per kWh stored over the lifetime of the battery.

6.8 Life cycle assessment pollution category methods

Different methods were chosen for different impact categories (Table 8: ***Relevant and interpreted impact categories***. This is to be able to compare different sources for a same impact category, but also to have a broad idea of the environmental impact arising from the production of the batteries. Only a selection of the impact categories were interpreted as in some impact categories, the batteries modelled in this study have an irrelevantly small pollution potential compared to other impact categories where the impact is significant.

Table 8: Relevant and interpreted impact categories

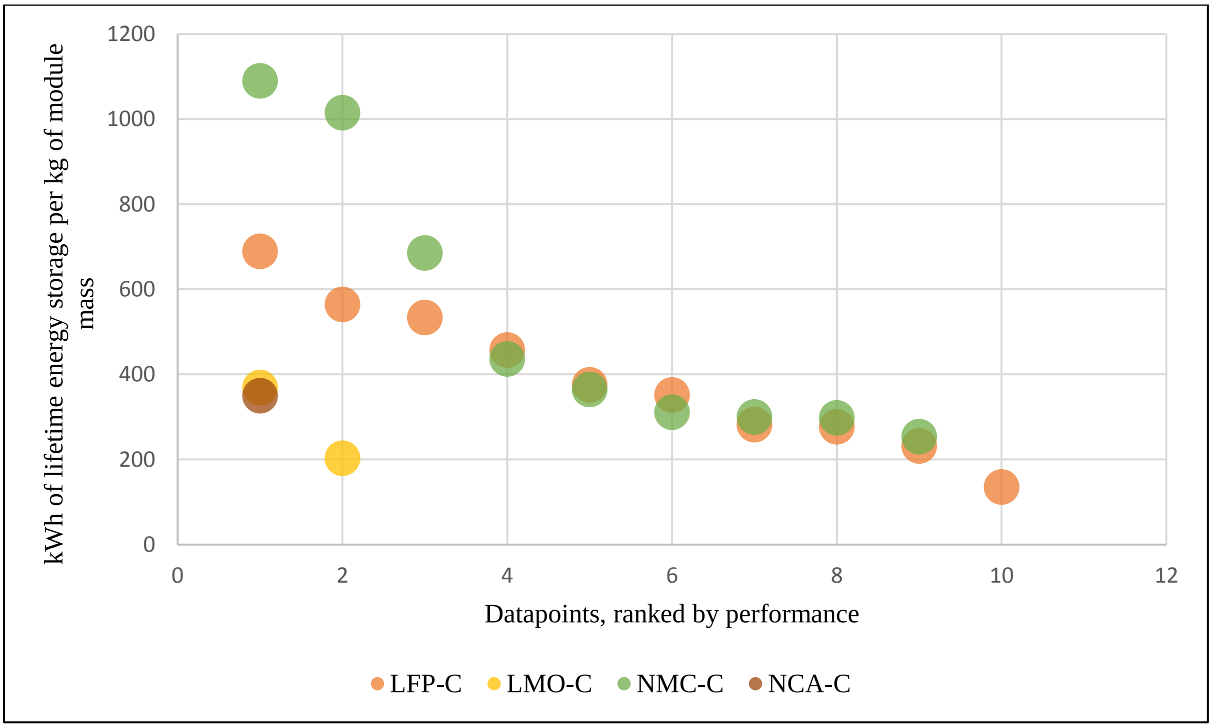
Environmental impact category	**Method**
Global warming depletion (GWP)	ILCD 2011 Midpoint+ V1.09 / EC-JRC global, equal weighting
Cumulative energy demand (CED)	Cumulative energy demand V1.09
Metal depletion potential (MDP)	ReCiPe Endpoint (H) V1.13 / World ReCiPe H/A
Human toxicity potential (HTP)	ReCiPe Endpoint (H) V1.13 / World ReCiPe H/A
Ecotoxicity (terrestrial, freshwater, marine)	Ecoindicator 99 (H) V2.10 / Europe EI99 H/A
Ecosystem damage potential (land occupation & transformation) (EDP)	Ecosystem damage potential V1.00
Single score (human health, Ecosystems, Resources)	ReCiPe Endpoint (H) V1.13 / World ReCiPe H/A

7 Results and analysis

7.1 Performance of the different battery technologies in their lifetime specific capacity

The lifetime energy storage per mass of total battery of LFP-C was estimated to be 259 kWh/kg on average over the 10 available batteries of this technology analysed (Figure 24). LMO-C performed less well, with 190 kWh/kg on average for the 2 models analysed. The 9 NMC-C analysed are the best performers, with 351 kWh/kg on average. Finally, the NCA-C or Tesla Powerpack performed at 232 kWh/kg. Despite the NCA-C's low cyclability, its lifetime specific energy stays interesting as its performance is boosted by its high specific capacity. It should be noted that it seems that the LFP-C and NMC-C perform very similarly except for the few very well performing NMC-C outliers like the Tesla Powerwall 2, the Senec Home Li 10.0 and to a lesser extent the LG Resu 6.5. In fact, an LFP-C battery can very well outperform an NMC-C battery, and this is also the case for an LMO-C battery or the NCA-C battery. A lot of the performance of the batteries depends not only on the chemistry used for the cathode but on the manufacturer's ability to engineer a long-lasting and capacity dense product.

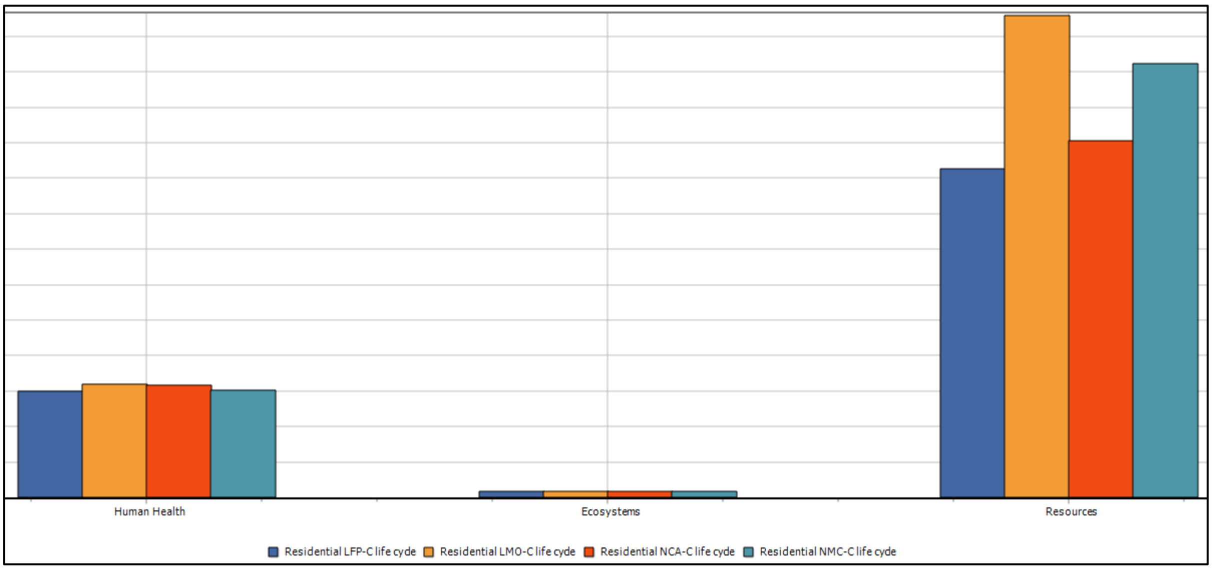
Figure 24: Performance of the lifetime specific capacity of different battery technologies



7.2 Comparison of the battery technologies by impact category

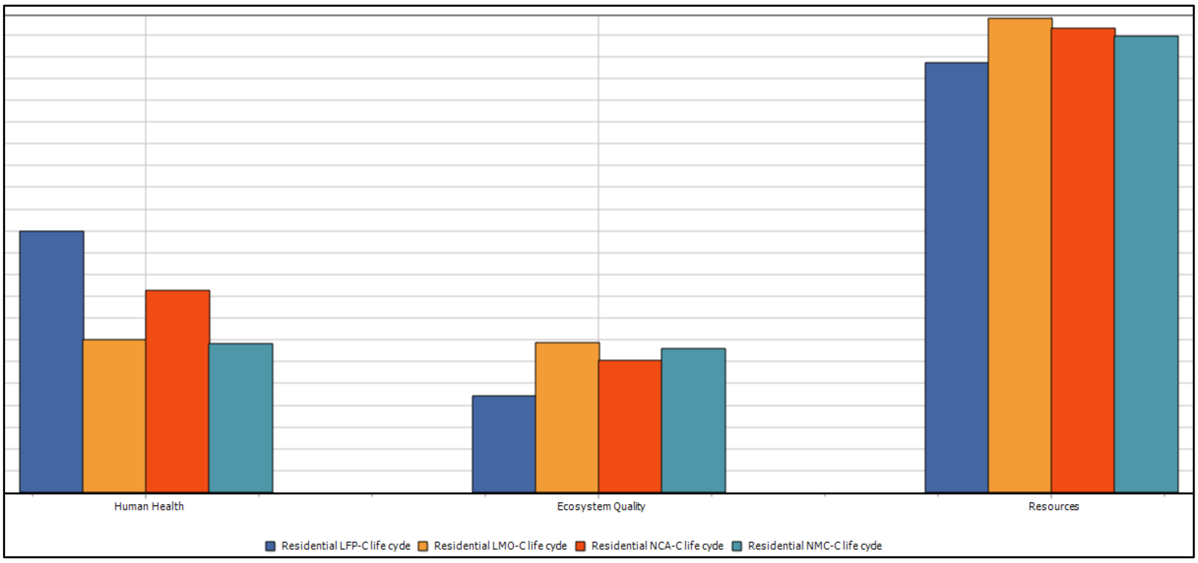
By normalising the scores assessed by the ReCiPe Endpoint (H) V1.13 / World ReCiPe H/A method (*Figure 25*), it clearly appeared resources depletion is the main issue regarding the production of the batteries. Climate change and human health issues come second.

Figure 25: ReCiPe's normalised single score assessment by broad category



Finally, it does not appear that the damage made to ecosystems is very important when analysed by the ReCiPe method but the Ecoindicator 99 (H) V2.10 / Europe EI99 H/A method's normalised assessment (*Figure 26*) proved it was still relevant to analyse the pollution potential of the batteries on the health of ecosystems.

Figure 26: Ecoindicator 99's normalised single score assessment by broad category



The values for the functional units' scores of each battery technology for each impact category can be found in the appendix.

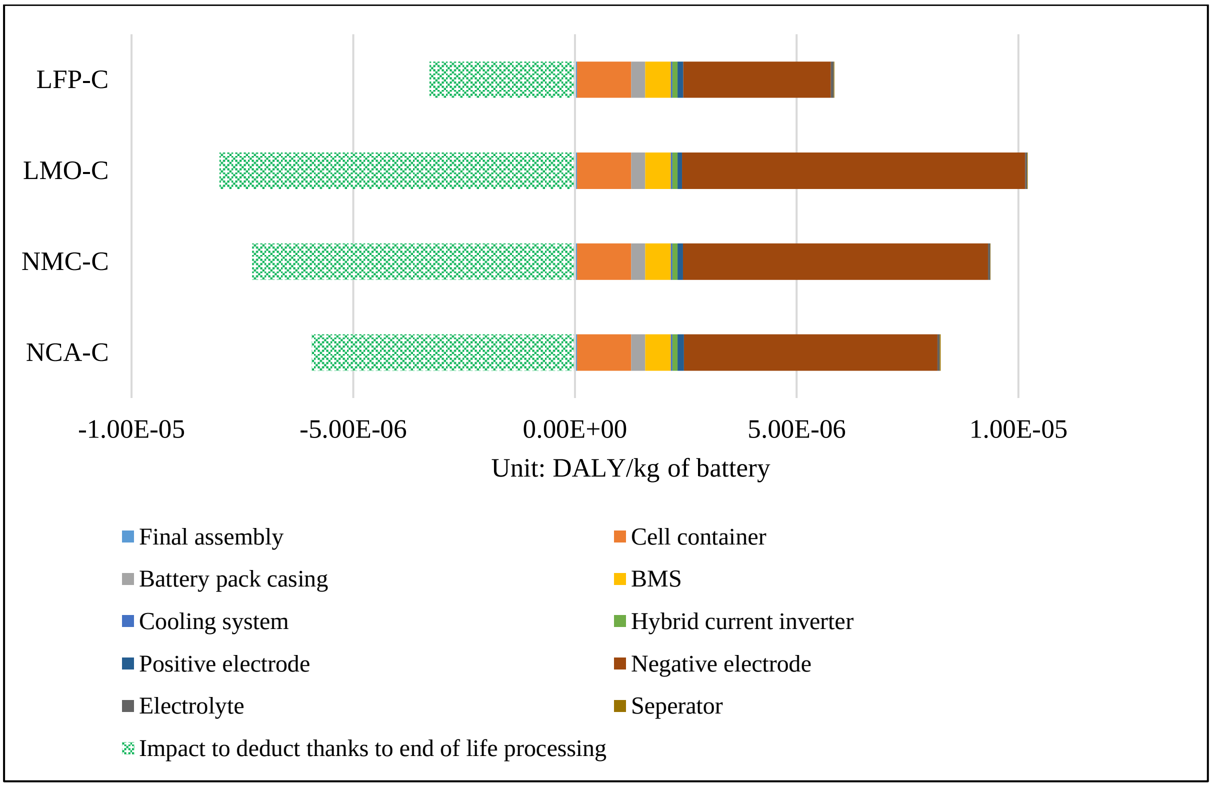
7.2.1 Human health-related impact categories

7.2.1.1 Human toxicity potential

7.2.1.1.1 Contribution of the batteries' components to the total environmental footprint

The negative electrode is the main source of pollution potential in the human toxicity impact category. This is driven by the copper present in the cell containers and in the negative electrode. The LFP-C battery performs better in this regard as it contains less copper in its negative electrode, compared to the other batteries. The cathodes and standardized components do not contribute much in this impact category.

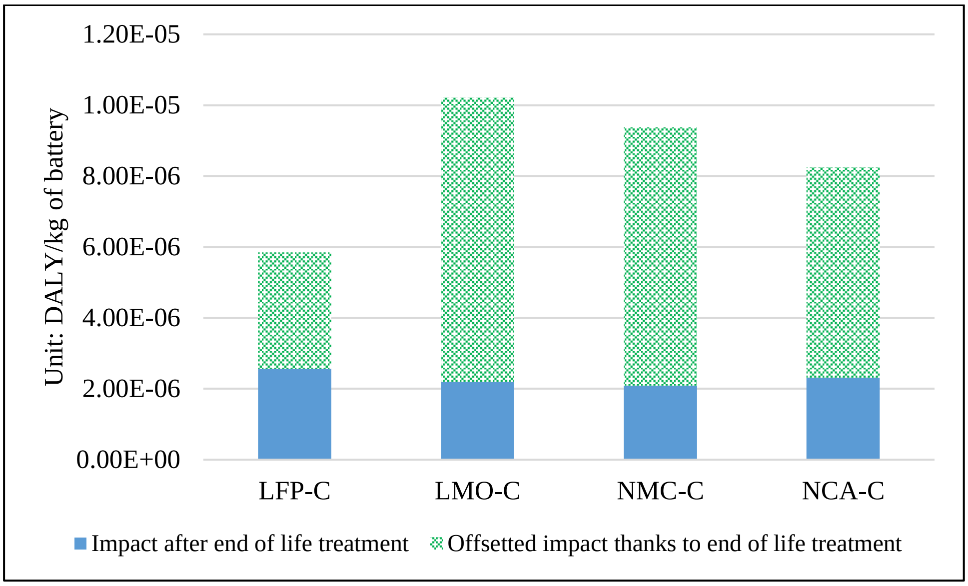
Figure 27: Human toxicity, component contribution, per kg FU



7.2.1.1.2 Benefits of recycling

Recycling the batteries offsets the human toxicity potential significantly and allows them to ultimately perform very similarly as a battery containing more copper will have more of it recovered after hydrometallurgical treatment.

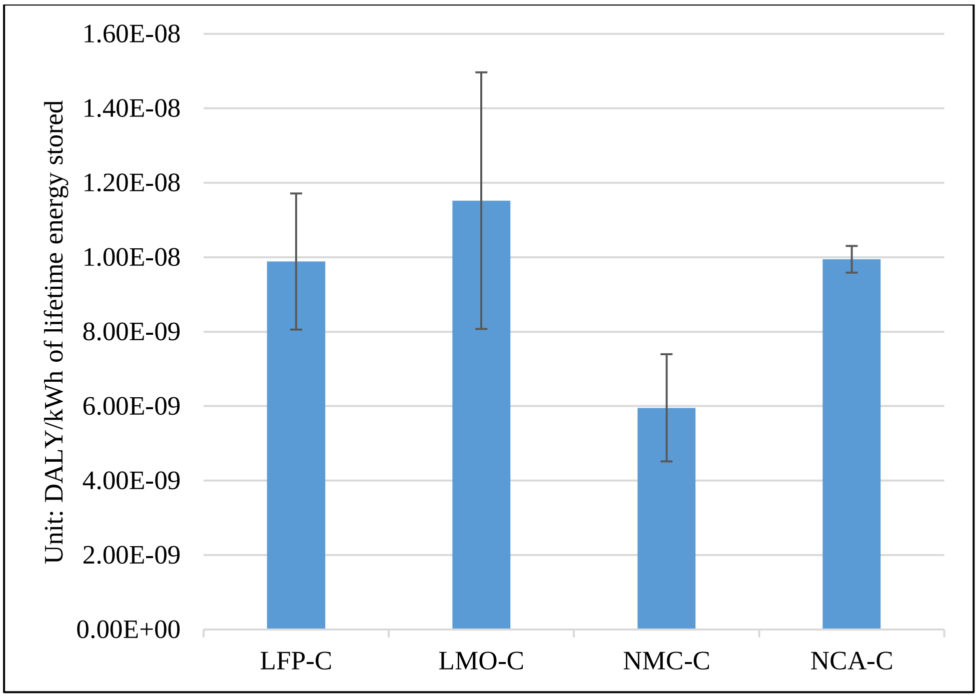
Figure 28: Human toxicity potential, benefits of recycling, per kg FU



7.2.1.1.3 Impact per kWh

When brought to a kWh basis, the NMC-C seems to be performing better. LFP-C and LMO-C and NCA-C perform similarly. The smaller error bar of the NCA-C should not be taken very formally as only a single battery was found for the NCA-C battery technology. Its error comes from the propagation of the standardization of components. For the LMO-C, the large error bar comes from the fact only 2 batteries of this chemistry were analysed in this study.

Figure 29: Human toxicity potential, per kWh of lifetime energy storage FU



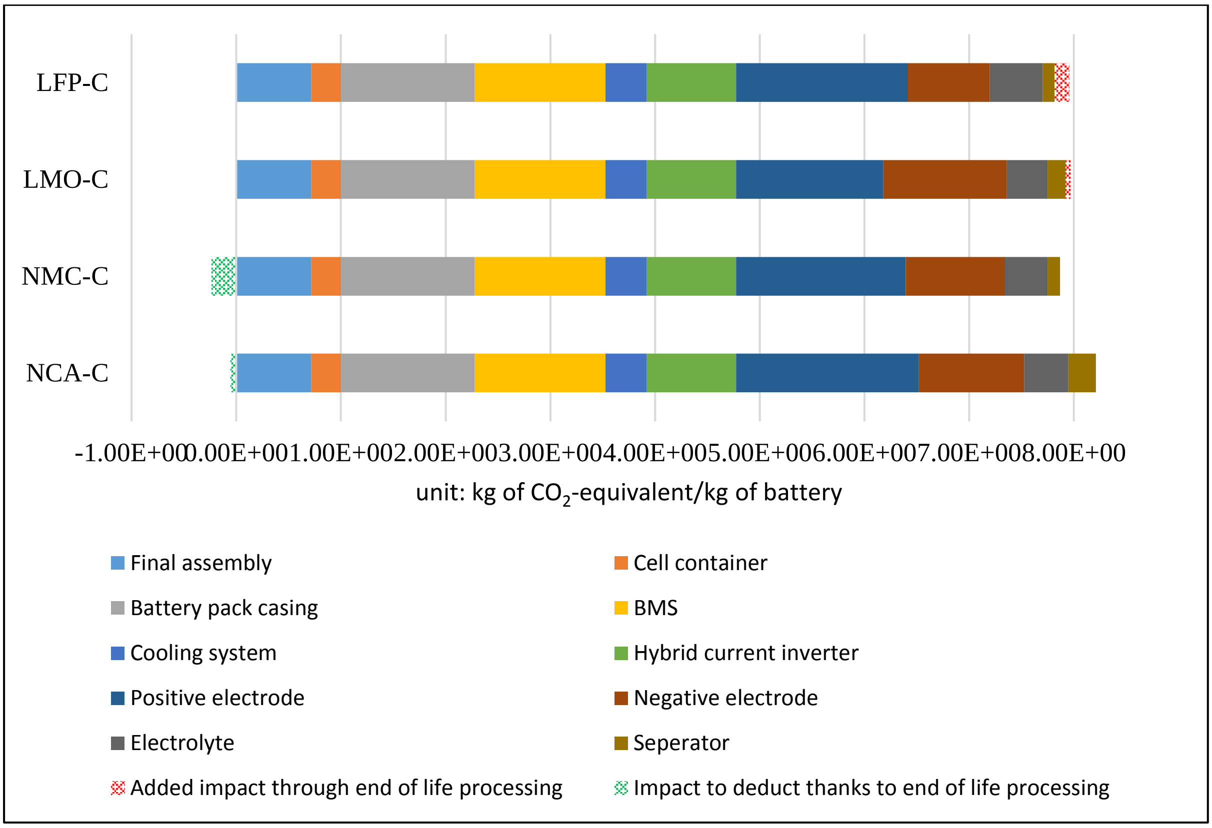
7.2.2 Ecosystems-related impact categories

7.2.2.1 Global warming potential

7.2.2.1.1 Contribution of the batteries' components to the total environmental footprint

There is no real difference in terms of global warming potential between the batteries on a kg FU. They are all around 8 kg of CO_2-equivalent per kg manufactured. The standardized components are responsible for a great part of this footprint, followed by the positive electrode and the negative electrode. This makes sense as producing the cathodes requires many manufacturing steps. The LFP-C, NMC-C and NCA-C positive electrodes seem to be very slightly more harmful than the LMO-C cathodes in this impact category. This is due to the presence of nickel in the NMC-C and NCA-C.

Figure 30: Global warming potential, component contribution, per kg FU

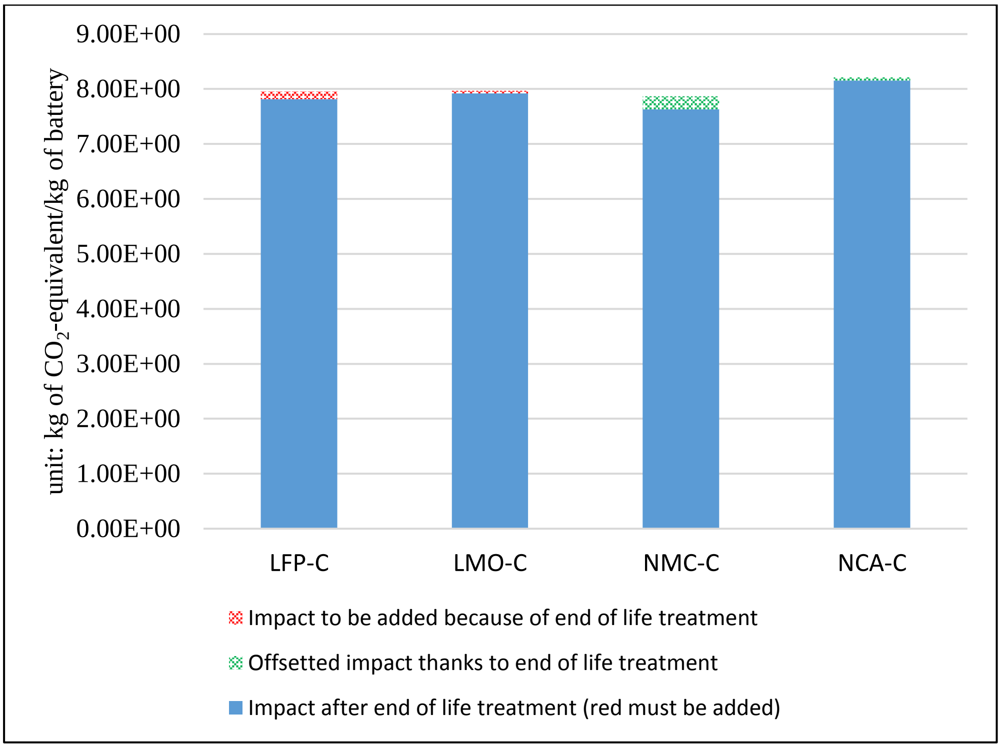


7.2.2.1.2 Benefits of recycling

The batteries perform very similarly even after being recycled in their end of life. Recycling the batteries has almost no impact on their global warming potential. In fact, it even increases it for the LFP-C and LMO-C due to the energy requirements of the hydrometallurgical process.

It is slightly offset for NMC-C and NCA-C due to the presence of rarer elements such as cobalt as well as due to the presence of more copper.

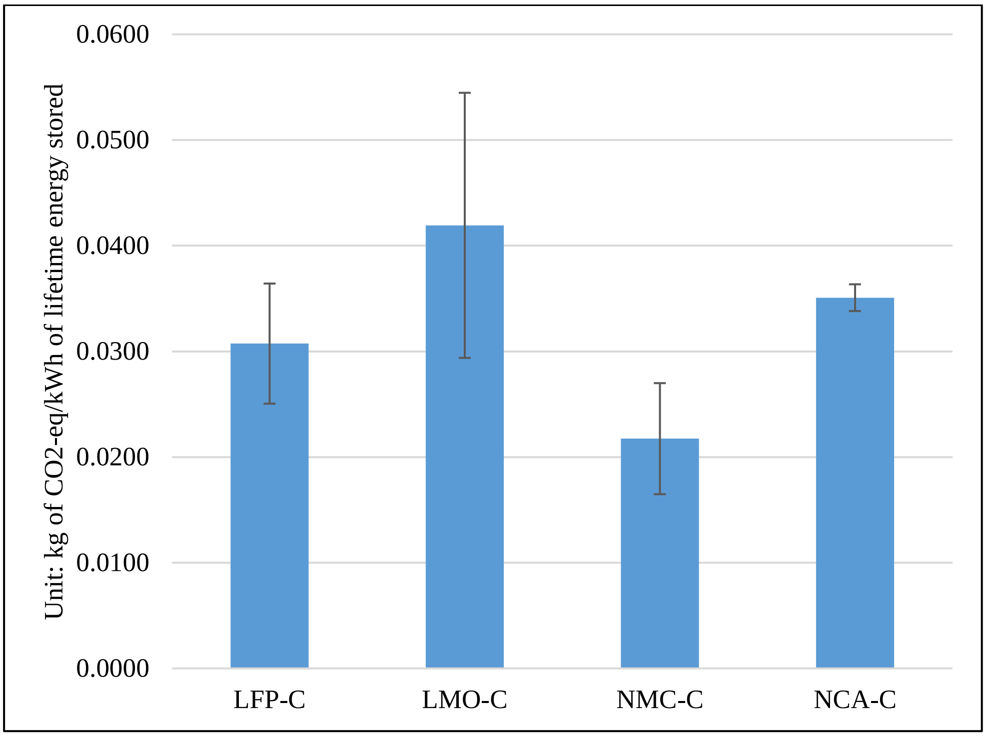
Figure 31: Global warming potential, benefits of recycling, per kg FU



7.2.2.1.3 Impact per kWh

When looking at the kWh functional unit, the NMC-C battery seems to be performing better (22 g of CO2-eq/kWh), seconded by the LFP-C (31 g of CO2-eq/kWh). In the third position comes the NCA-C (35 g of CO2-eq/kWh) and finally the LMO-C (42 g of CO2-eq/kWh).

Figure 32: Global warming potential, per lifetime kWh FU

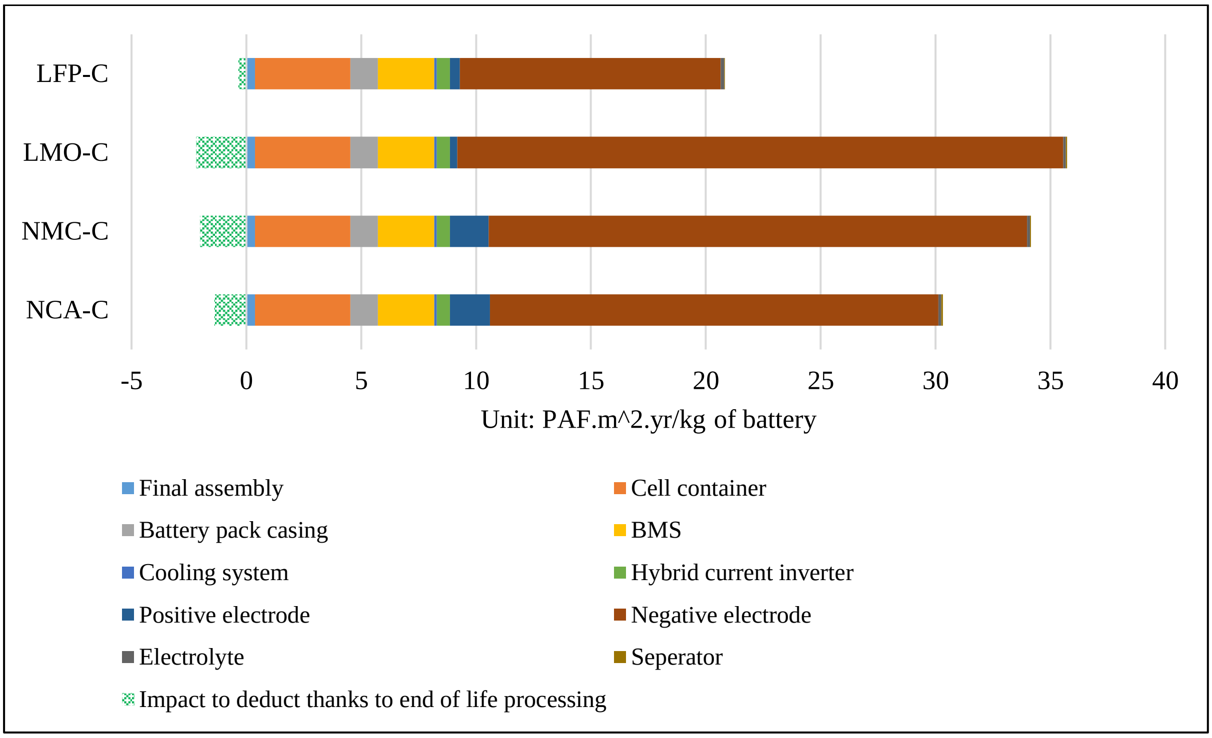


7.2.2.2 Ecotoxicity

7.2.2.2.1 Contribution of the batteries' components to the total environmental footprint

The negative electrode and its copper current collector are the main drivers of pollution potential in terms of ecotoxicity. Therefore, the LFP-C battery seems to be performing better than the others in terms of ecotoxicity as its negative electrode contains less copper. Only the cobalt and nickel present in the NMC-C and NCA-C positive electrodes seem to contribute to ecotoxicity. For the LFP-C and LMO-C, the impact of the positive electrode is almost inexistent. The standardized components have a contribution in terms of ecotoxicity, mainly driven by the cell container and the BMS.

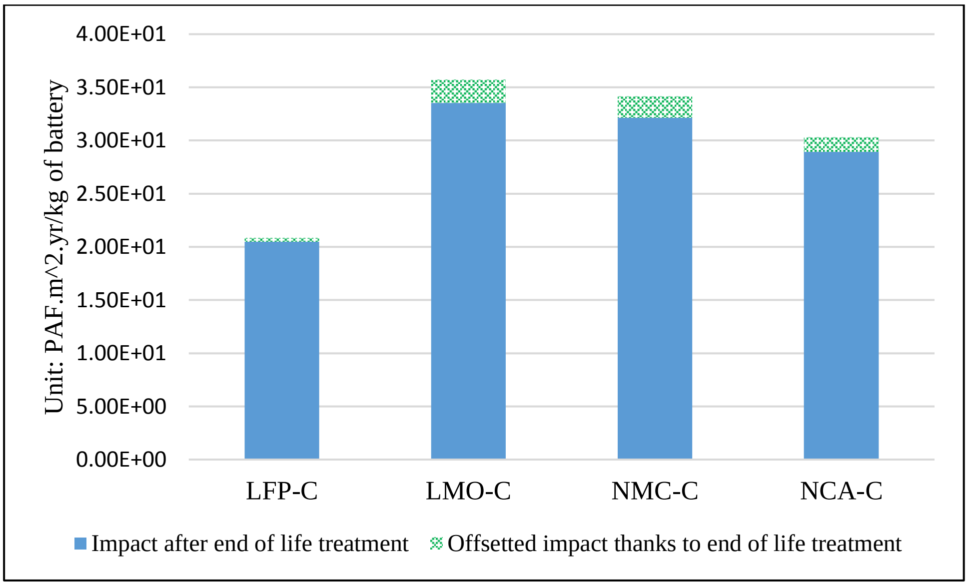
Figure 33: Ecotoxicity, component contribution, per kg FU



7.2.2.2.2 Benefits of recycling

Recycling does help a bit to offset the ecotoxicity of the LMO-C, NMC-C and NCA-C as copper is recovered but not enough for these battery technologies to perform anywhere close to the LFP-C in this impact category. Increasing the recovery rate of copper would allow to offset more significantly the ecotoxicity of these battery technologies.

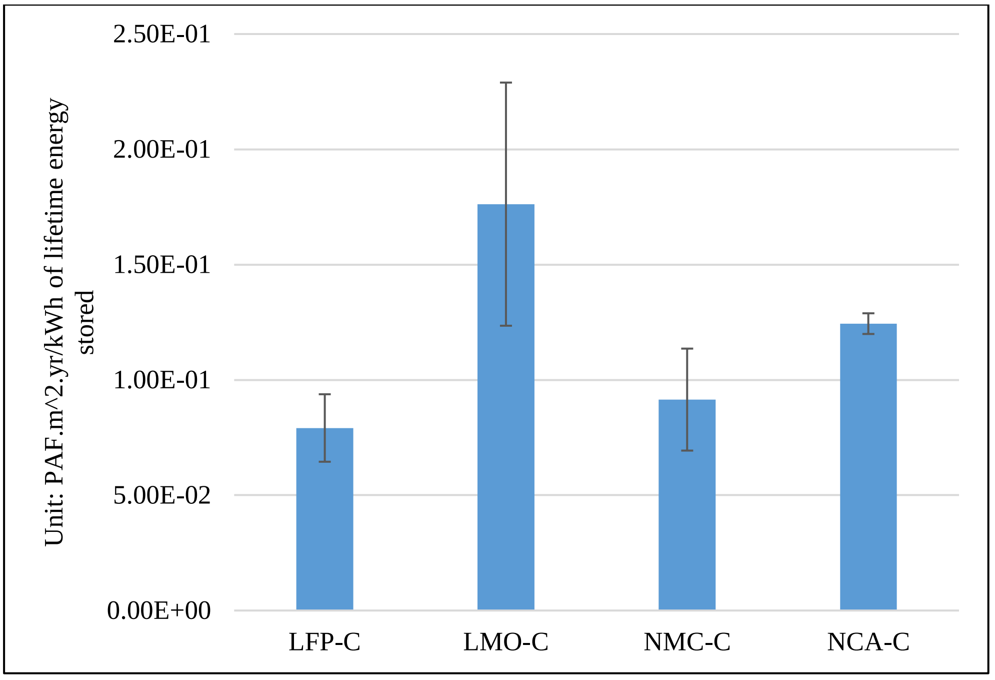
Figure 34: Ecotoxicity, benefits of recycling, per kg FU



7.2.2.2.3 Impact per kWh

This better environmental performance of LFP-C in the manufacturing is translated on a kWh basis where it performs very similarly to the NMC-C, perhaps even better. The NCA-C battery comes in third position, followed by the LMO-C.

Figure 35: Ecotoxicity, per lifetime kWh FU

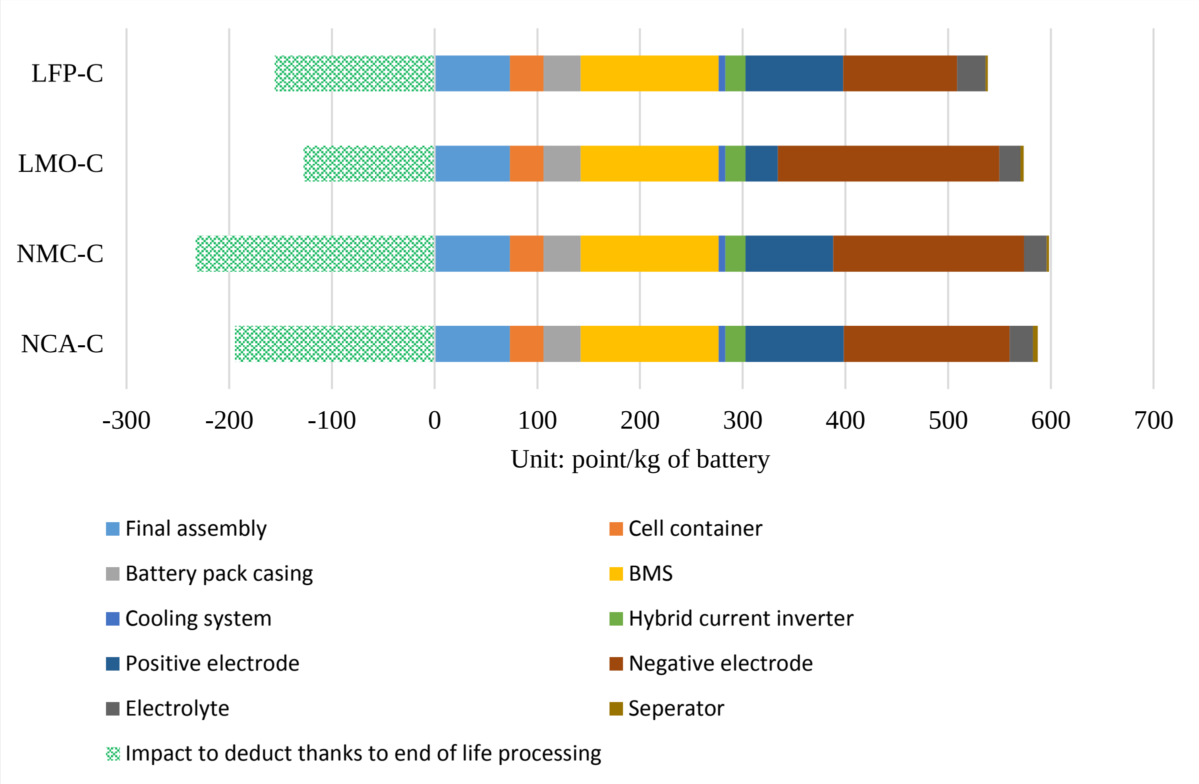


7.2.2.3 Ecosystem damage potential (land occupation and transformation)

7.2.2.3.1 Contribution of the batteries' components to the total environmental footprint

The standardized components have an important contribution to the ecosystem damage potential impact category, especially the BMS. The copper in the negative electrodes play an equally significant role, especially for the LMO-C which sees its good score for its positive electrodes compensated by its negative electrode. The positive electrodes come third. Overall, the battery technologies all seem to have a similar ecosystem damage potential. Deforestation and the disposal of sulfidic tailings are the main drivers of ecosystem damage potential.

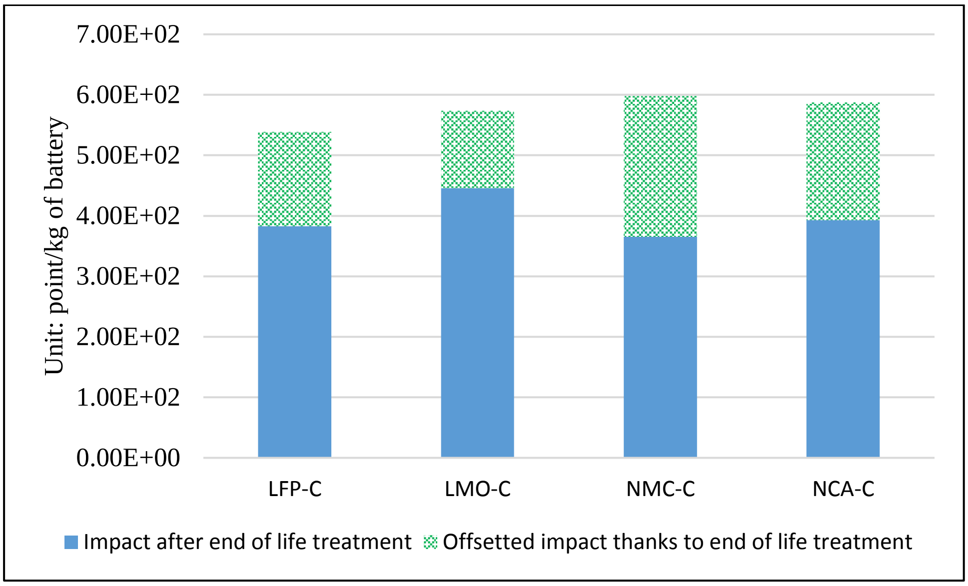
Figure 36: Ecosystem damage potential, component contribution, per kg FU



7.2.2.3.2 Benefits of recycling

Recycling the batteries does have a significant impact to reduce land occupation and transformation. All the batteries still seem to perform equally after this step but they all had their footprint significantly decreased. The recovery of lithium carbonate drives most of the offsetting.

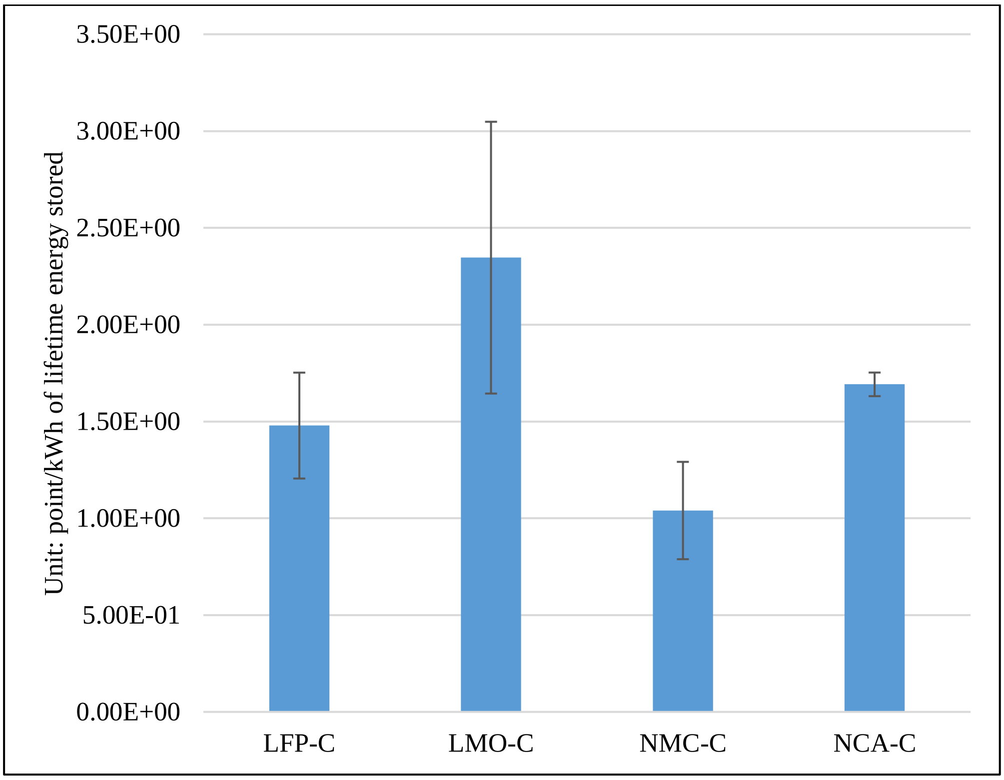
Figure 37: Ecosystem damage potential, benefits of recycling, per kg FU



7.2.2.3.3 Impact per kWh

The NMC-C seems to be performing better on a kWh basis for this impact category, followed by the LFP-C, the NCA-C and finally the LMO-C.

Figure 38: Ecosystem damage potential, per lifetime kWh FU



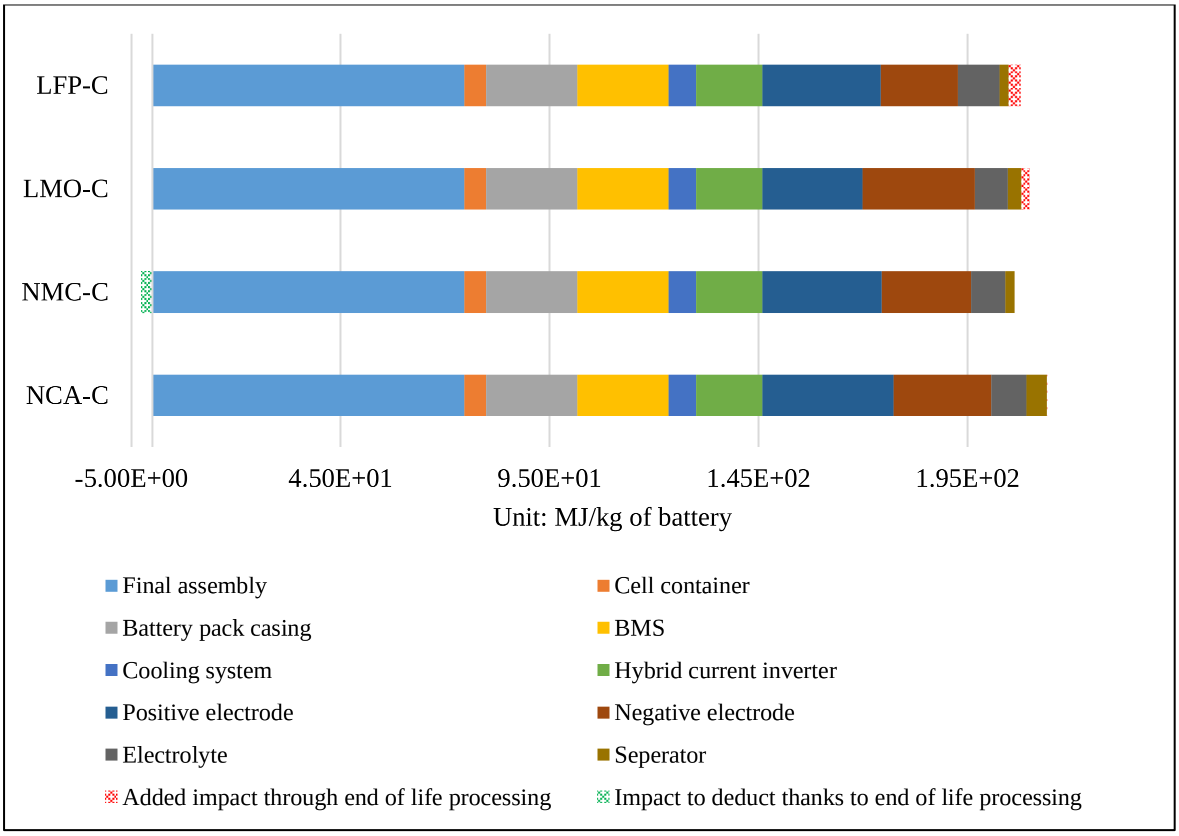
7.2.3 Resources-related impacted categories

7.2.3.1 Cumulative energy demand

7.2.3.1.1 Contribution of the batteries' components to the total environmental footprint

The standardized components play the biggest role in terms of cumulative energy demand, especially the final assembly step of the components. This is mainly due to the electricity used for welding. The negative electrode has a small role, and surprisingly, the positive electrode does not contribute very much. In fact, its aluminium current collector contributes relatively significantly to the cumulative energy demand.

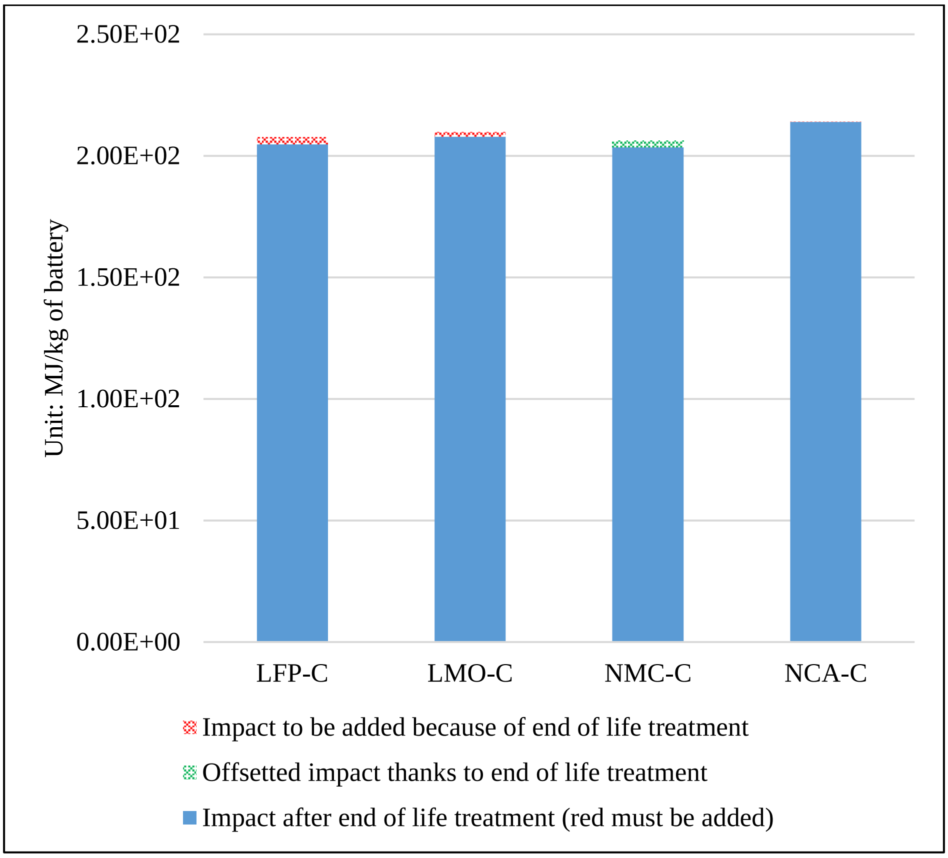
Figure 39: Cumulative energy demand, component contribution, per kg FU



7.2.3.1.2 Benefits of recycling

Recycling the batteries does not help much in terms of cumulative energy demand. In fact, the energy used to run the hydrometallurgical process can worsen the footprint of the LFP-C, LMO-C and NCA-C battery technologies. The more important amounts of recovered cobalt in the NMC-C allows it to improve its footprint slightly.

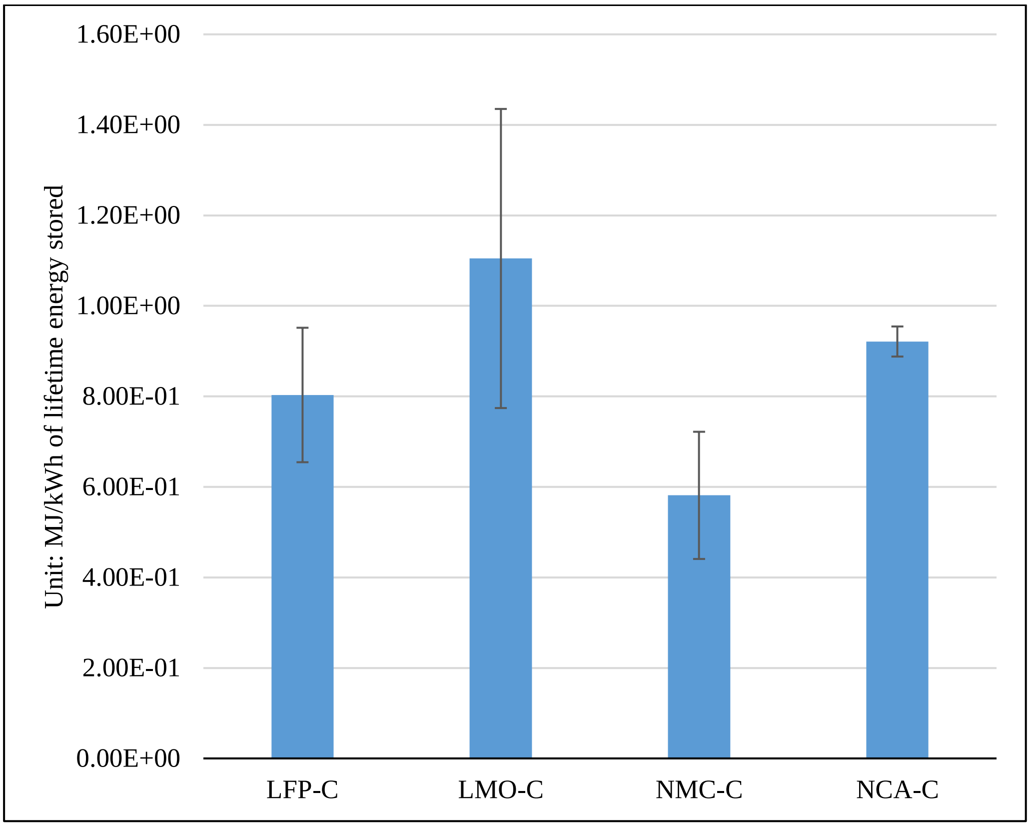
Figure 40: Cumulative energy demand, benefits of recycling, per kg FU



7.2.3.1.3 Impact per kWh

The better performance of the NMC-C on a kWh basis only arises from its apparent better lifetime energy storage density per kilogram. LFP-C comes second, NCA-C third and LMO-C last.

Figure 41: Cumulative energy demand, per lifetime kWh FU

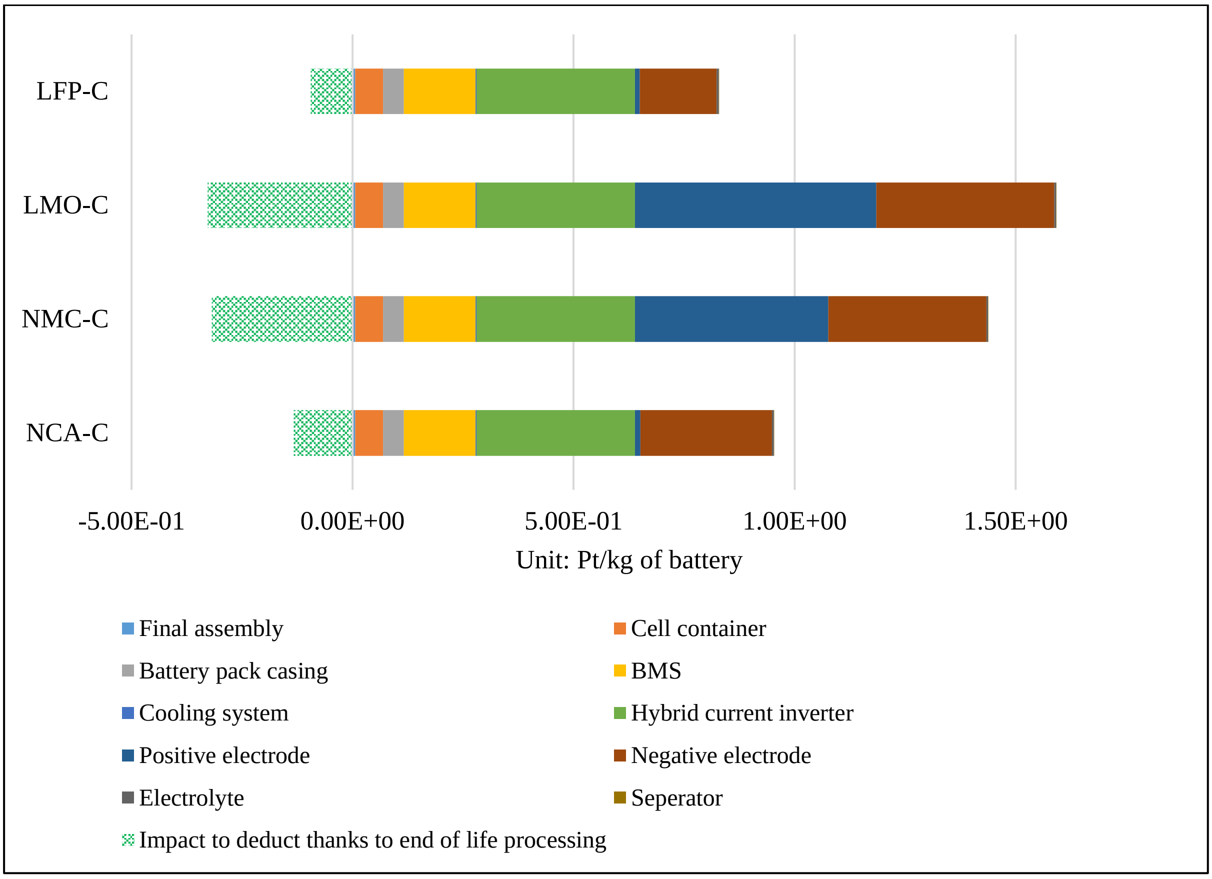


7.2.3.2 Metal depletion potential

7.2.3.2.1 Contribution of the batteries' components to the total environmental footprint

Most of the metal depletion potential of the LFP-C and NCA-C battery technologies comes from the standardized components, mainly the hybrid current converter. For the LMO-C and NMC-C which perform worse, the positive electrodes play a major role, as well as the negative electrodes. Manganese and copper are the main drivers in terms of metal depletion potential. The hybrid current inverter also requires some manganese in its production.

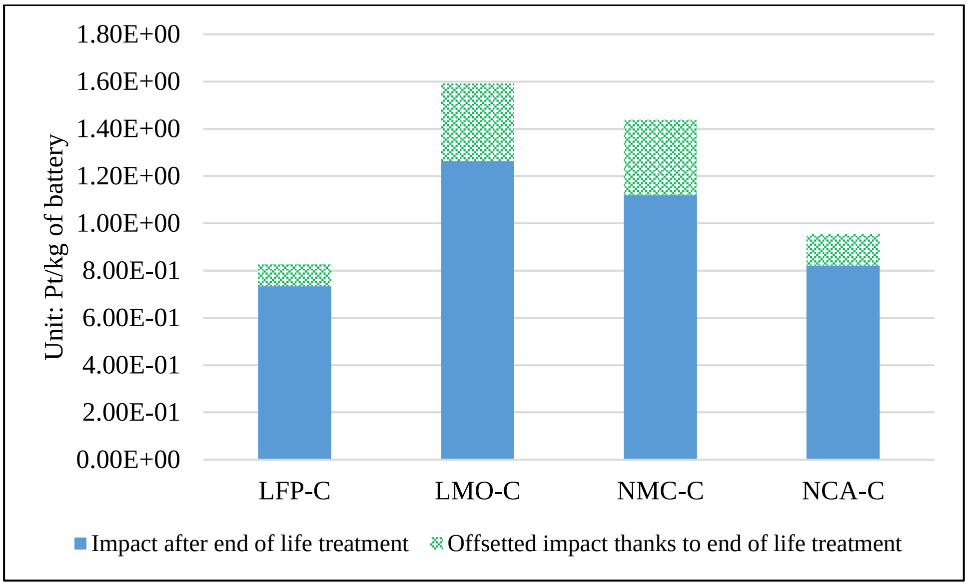
Figure 42: Metal depletion potential, component contribution, per kg FU



7.2.3.2.2 Benefits of recycling

The recovered manganese allows some offsetting for the LMO-C and NMC-C. As for the LFP-C and NCA-C, the end of life treatment of the batteries also helps improve their metal depletion potential as copper is recovered.

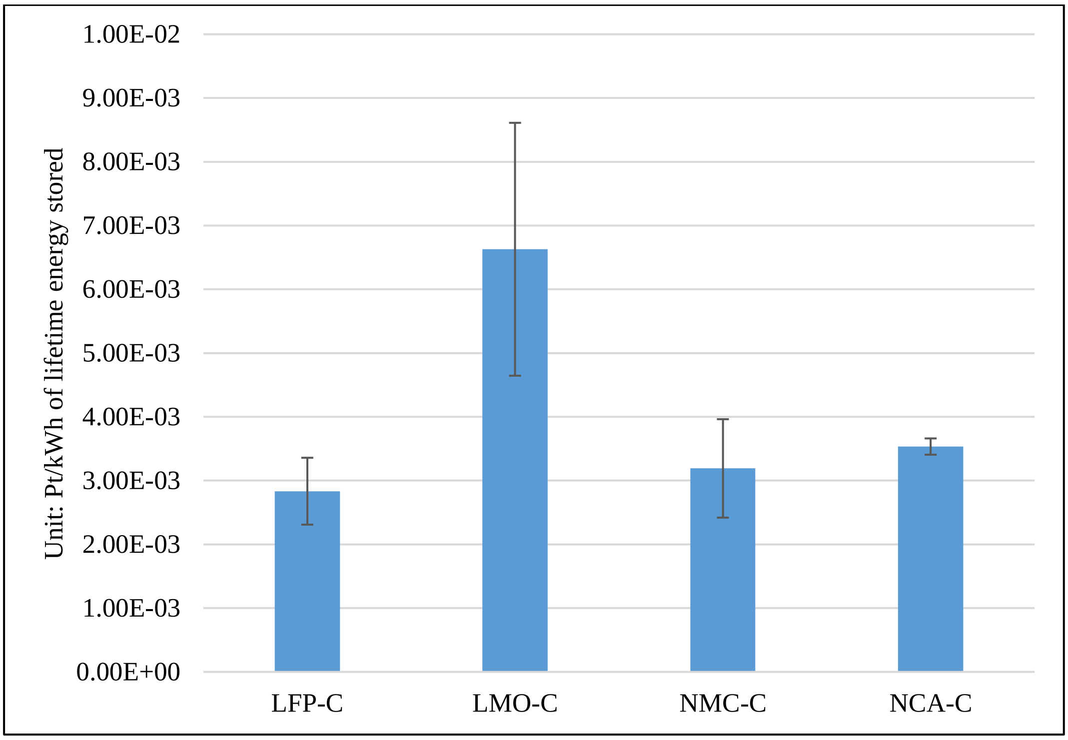
Figure 43: Metal depletion potential, benefits of recycling, per kg FU



7.2.3.2.3 Impact per kWh

When brought to a kWh basis, LFP-C, NMC-C and NCA-C seem to be performing equally well. LMO-C is significantly behind.

Figure 44: Metal depletion potential, per lifetime kWh FU

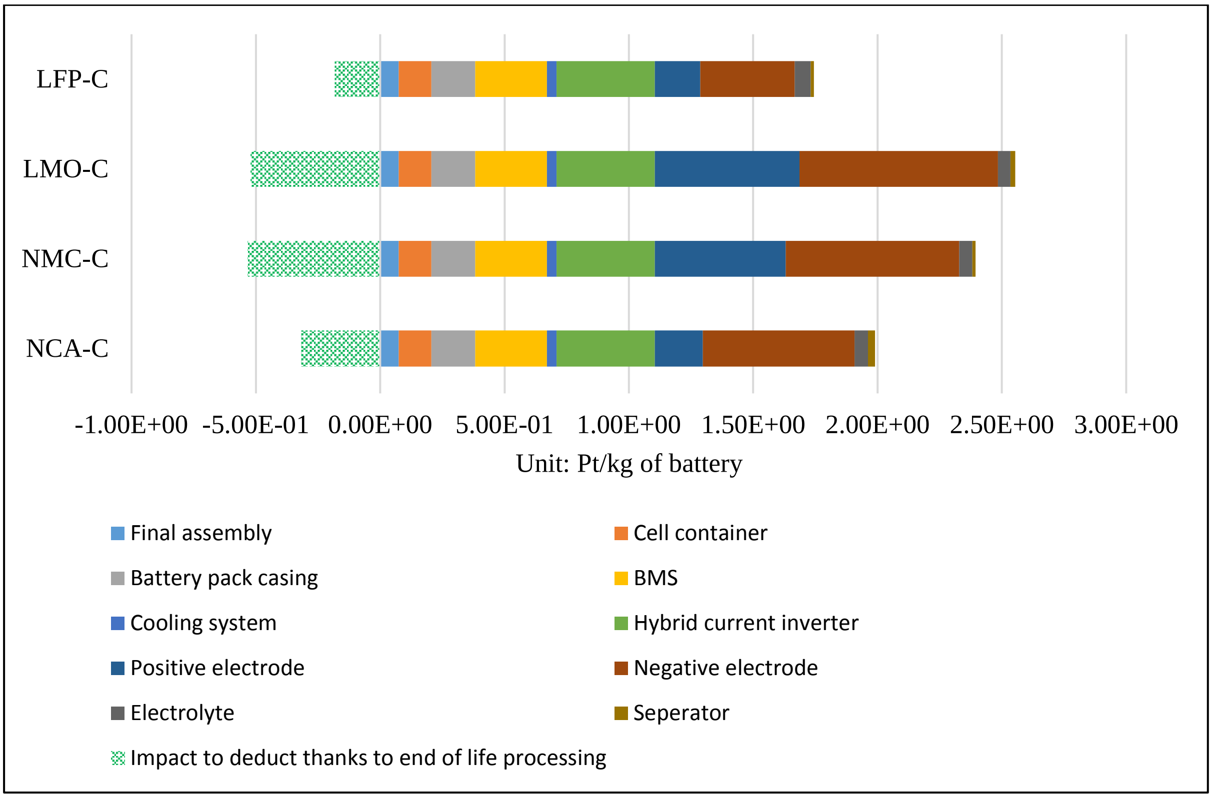


7.2.4 Single scores

7.2.4.1 Contribution of the batteries' components to the total environmental footprint

The metal depletion potential is the main contributor to the single score impact category of the ReCiPe method for our model. The anode and the copper in it have an unexpectedly high contribution to the total environmental footprint. The presence of manganese in the cathodes and current converter and the high ratios of copper are responsible for the high environmental pollution score of the NMC-C and LMO-C. The hybrid current inverter has about the footprint of the cathodes. The BMS also has a significant contribution. Unsurprisingly, components like the electrolyte and the separator have a far less important footprint as they are present in much smaller quantities. Overall, the standardized components are responsible for about half of the total impact potential. When only looking at the components that have not been standardized, The NMC-C and LMO-C are actually performing quite badly when it comes to comparing them to LFP-C and NCA-C. LFP-C performs slightly better in the manufacturing process mainly thanks to its negative electrode which contains less copper and to its absence of manganese in its cathode.

Figure 45: Single score, component contribution, per kg FU

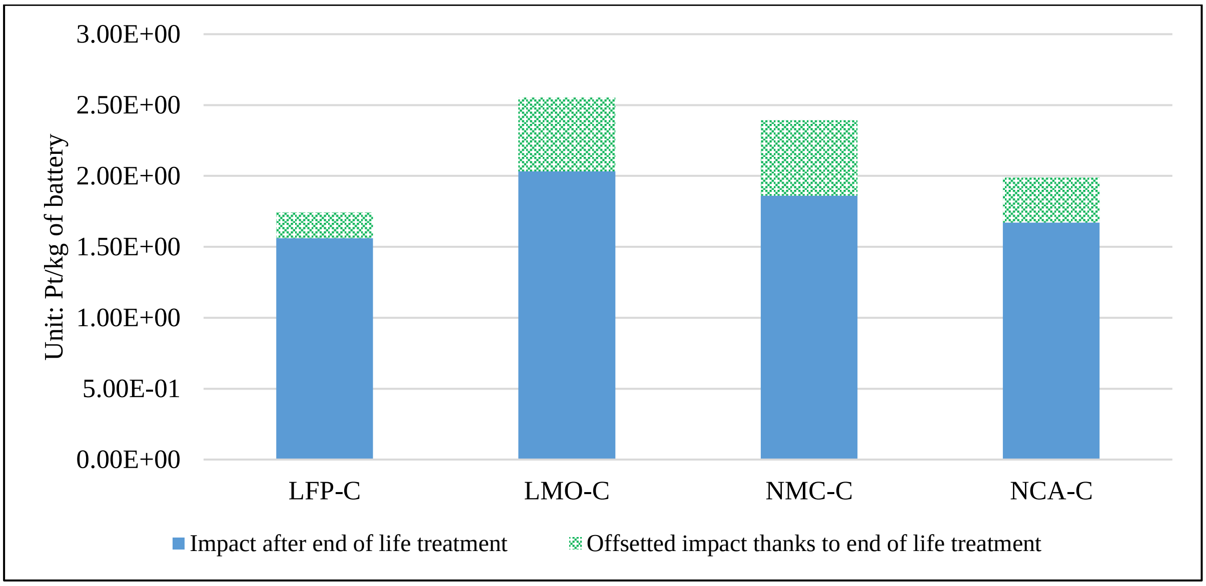


7.2.4.2 Benefits of recycling

Recycling allows to reduce the single score environmental footprint by 10% for the LFP-C, 20% for the LMO-C, 22% for the NMC-C and 16% for the NCA-C, mainly in the metal depletion potential category. Even if the LFP-C performs better without the end of life-stage, when the recycling is included for every battery, this is slightly less so. The other chemistry technologies offset the pollution potential of their production quite significantly by having their important amounts of cobalt, manganese and copper recovered.

The LFP-C battery has less rare elements in it and therefore will have a lower recovery rate and incentive for recyclers. If a recycling facility is interested in recovering one part of a battery they will end up recycling at least some of the rest once the hydrometallurgical process has been done. In addition, the advantage of Li-ion batteries is that they produce inert waste after hydrometallurgical processing. Contrary to lead batteries, they can be landfilled. This is potentially negative as the European Union legislation is less stringent towards li-ion batteries, requiring only a 50% recycling rate versus 75% for nickel-cadmium batteries and 65% for lead-acid (*Batteries directive*, 2006). The NCA-C battery seems to be the second best performing technology, NMC-C third, and LMO-C fourth. As producing the batteries is mainly a resource depletion problem, recycling can counter that as it is seen particularly with the LMO-C and NMC-C battery technologies.

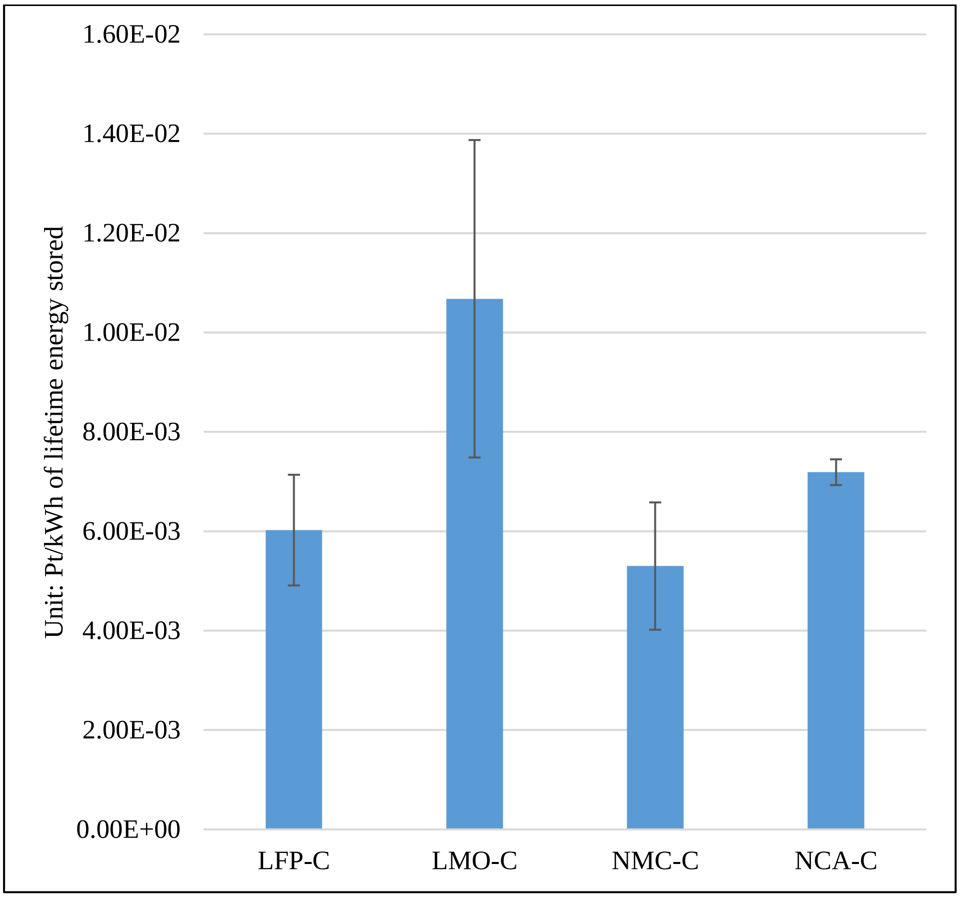
Figure 46: Single score, benefits of recycling, per kg FU



7.2.4.3 Impact per kWh

Globally, NMC-C seems to be performing very slightly better than LFP-C on a per kWh functional unit. NCA-C seems to be taking the third place, and LMO-C the fourth. The reason why manufacturers preferably choose the LFP-C, NMC-C battery technologies is in part because they have long cycle lives and thermal stabilities which allow high power outputs and longevity, meaning they do not degrade as quickly as the LMO-C or NCA-C. This might be why there is a correlation between the amount of data points this study has managed to find for LFP-C (n=10) and NMC-C (n=9) compared to LMO-C (n=2) and NCA-C (n=1). LFP-C and NMC-C simply perform better in terms of their longevity and thereby in terms of their practicality for the consumer, lifelong cost and environmental footprint per kWh. The high capacity density of the NCA-C is interesting in electric vehicles where mass is an issue, but for residential batteries, cyclability is far more important for a consumer. However, for larger scale operations where many battery packs are required, the capacity density of the NCA-C and its high power output can become interesting again as reducing the area and volume taken by the many batteries is interesting, hence perhaps the motivation of Tesla to use NCA-C for its Powerpack model.

Figure 47: Single score, per lifetime kWh FU



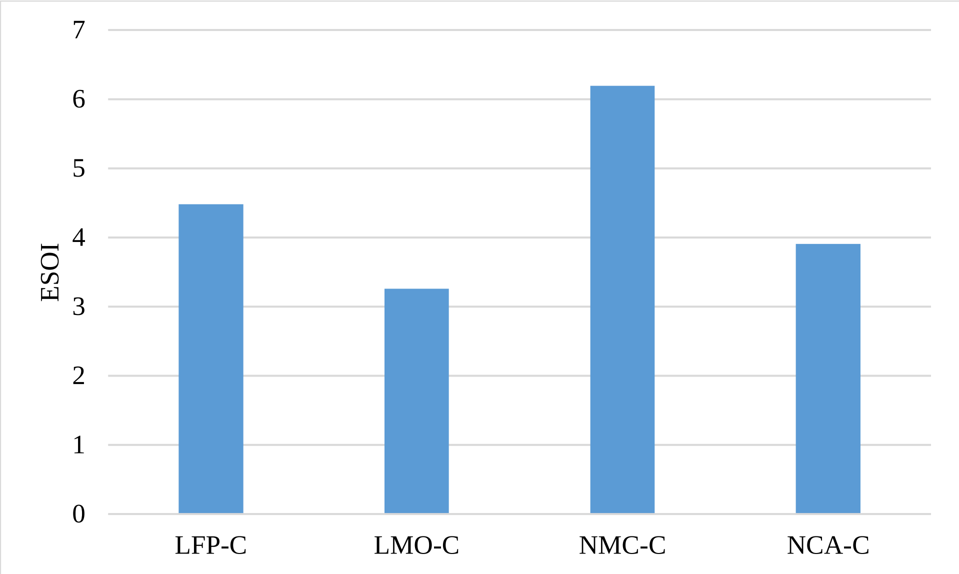
7.3 Energy stored on energy invested

The lifetime energy stored on energy invested is calculated in the following way:

$$ESOI = \frac{Lifetime\ energy\ stored}{Embodied\ energy}$$

The values of the CED impact category were used to calculate the embodied energy. The ESOI looks at the ratio between the amount of energy the battery will be able to store during its whole lifetime and the amount of energy required to produce the battery. The NMC-C appears to be the best performer in ESOI with a score of 6.2 (Figure 48), meaning it will be able to store a bit more than 6 times the amount of energy necessary for its production. In second place comes the LFP-C with 4.5, then NCA-C with 3.9 and finally the LMO-C with 3.3. These figures seem very low but they are actually fairly common for batteries. The scenario of usage of the batteries assumed that the batteries were going to be used quite intensively. If there are not used much, their ESOI could very well go below 1, meaning more energy will have been required to produce them than they would have stored. In the case where the ESOI approaches 1 or even goes bellow, the relevance of using the batteries can be heavily argued. The consumer would then be better off using the grid to supply all of his electricity, and if he has solar panels, he would be better off simply reselling to the grid all his excess of production. Using batteries for second lives in less demanding applications can improve their ESOI.

Figure 48: ESOI of the different battery chemistries



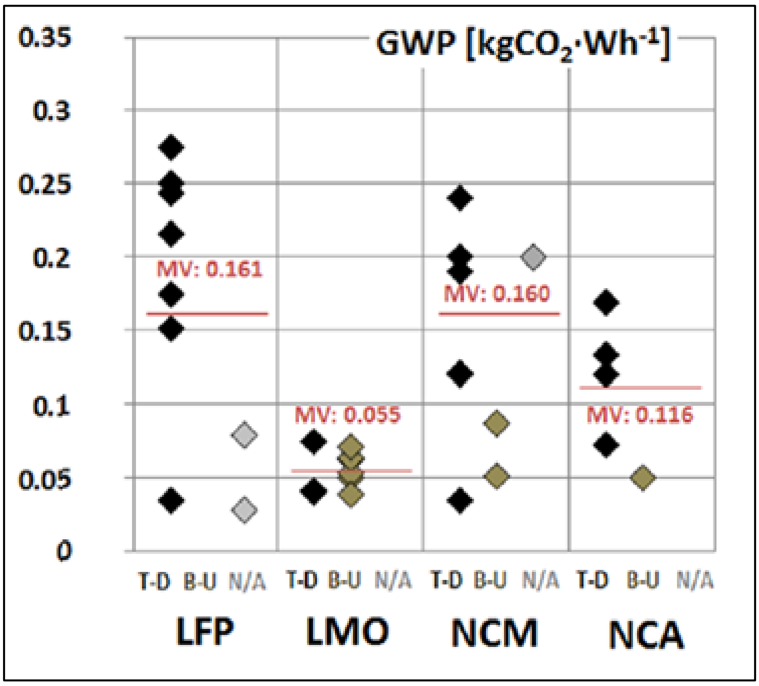
8 Discussion

8.1 Comparison of results with other studies

8.1.1 Global warming potential per usable capacity

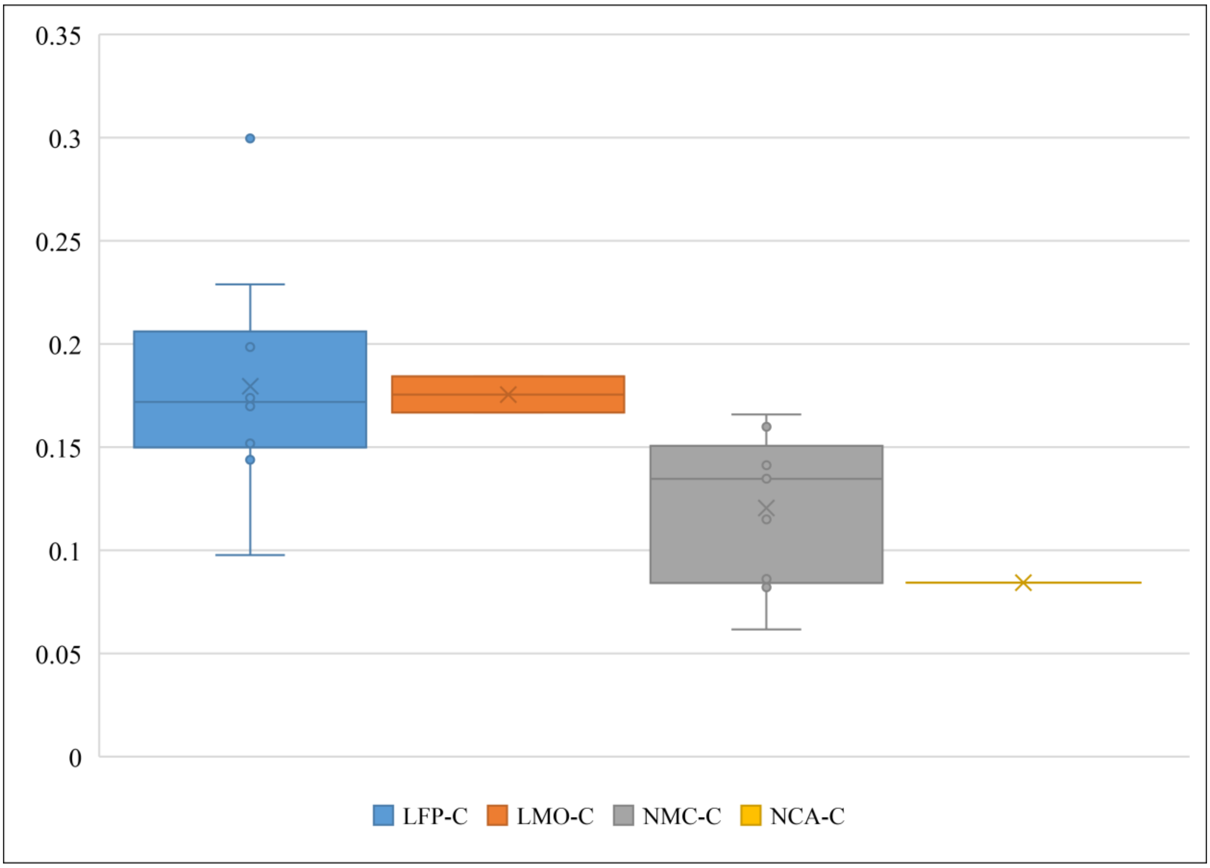
Jens F. Peters and his team (Peters et al., 2017) attempted to aggregate as many LCAs for li-ion batteries as possible (Figure 49). It does not seem like there is differentiability between any of the battery chemistries they reviewed. In addition, the unit "kg of CO2-eq per production of Wh of usable capacity" is debatable as a lot relies on the manufacturer's ability to make a very capacity dense battery or not, depending on the application of the battery. Moreover, it is problematic to compare the batteries of our study with the other studies as we modelled a hybrid current inverter, a cooling system and an end of life treatment while most other studies did not and were for electric vehicles' batteries.

Figure 49: Graphical representation of the LCA results from the review of different battery chemistries for the global warming potential impact category (Peters et al., 2017)



When comparing the results, it seem that the LFP-C modelled in our study (Figure 50) performs closely to that of the aggregated study, at 0.18 kg of CO2-eq/production of Wh of usable storage capacity, versus 0.16. Our NMC-C performed at 0.12 which is aligned with the NMC-C's high theoretical performance in terms of specific capacity, while theirs averaged 0.16. Both our NCA-C unsurprisingly performed well for this functional unit which advantages specific capacity, at 0.08 for our study and 0.116 for theirs. Finally, the biggest different is for the LMO-C. Theirs performed at 0.06 with many studies confirming this value, while the one of this study performs very closely to the LFP-C at 0.18 which is more aligned with the LMO-C's theoretical performance in terms of specific capacity.

Figure 50: global warming potential per production of Wh of usable capacity, values of our study arranged in a box-and-whisker chart

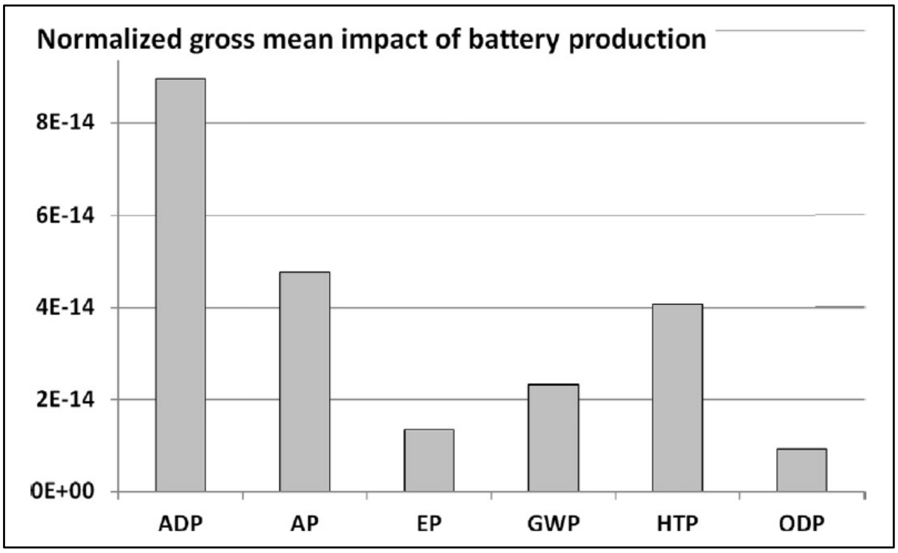


Globally, the amount of scattering in both the current literature and our study is significant enough to consider there might be little or no differentiability between battery chemistries.

8.1.2 Normalized gross mean impact of battery production

Peters' review (Peters et al., 2017) also noted that the main issue of batteries is resource depletion potential and cumulative energy demand, abiotic depletion potential or fossil fuel depletion, depending on the impact category chosen. It is usually followed by human toxicity potential and global warming potential. Finally, the impact on the ecosystems' health seems to be secondary according to the weighting of different methods such as ReCiPe, for example (Figure 51). Our study has found the same results (Figure 25).

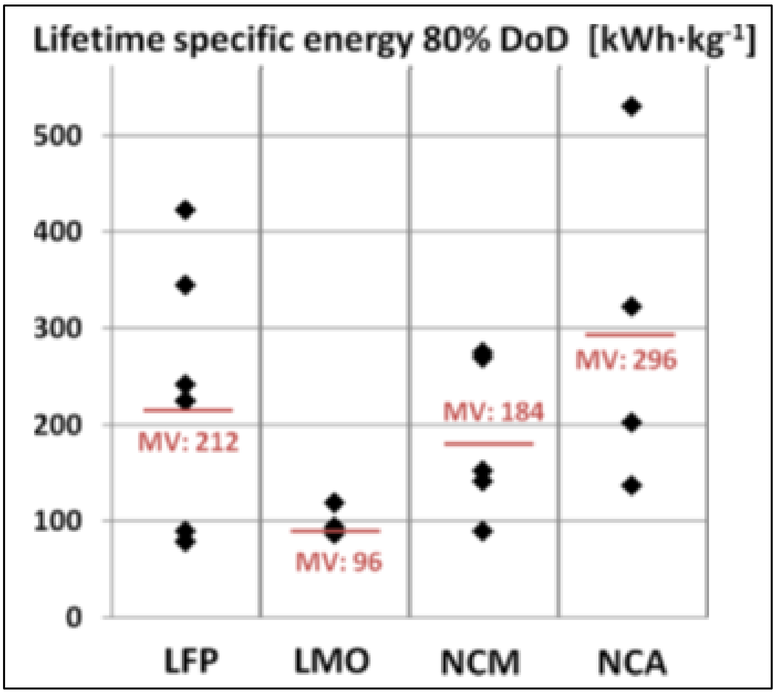
Figure 51: Normalized gross mean impact of battery production (Peters et al., 2017)



8.1.3 Lifetime specific energy

The literature has the NCA-C score well in terms of lifetime specific energy with 296 kWh/kg (Figure 52) versus 232 in our study (Figure 24), although the data points are extremely scattered. This could be due to its high specific energy from start. The LFP-C of the literature scores rather well but has a lot of scattering as well. The LFP-C, NMC-C and NCA-C of the literature seem to score rather similarly on average which is a common finding with our study which has the LFP-C score at 259 kWh/kg and the NMC-C 350 kWh/kg. As residential batteries traditionally require longer cyclability, it is understandable that the values of our studies are higher. Finally, the score of the literature's LMO-C (96 kWh/kg) scores badly compared to the one of our study, 190 kWh/kg, yet both the literature and our study have this battery chemistry score bellow the LFP-C, NMC-C and NCA-C.

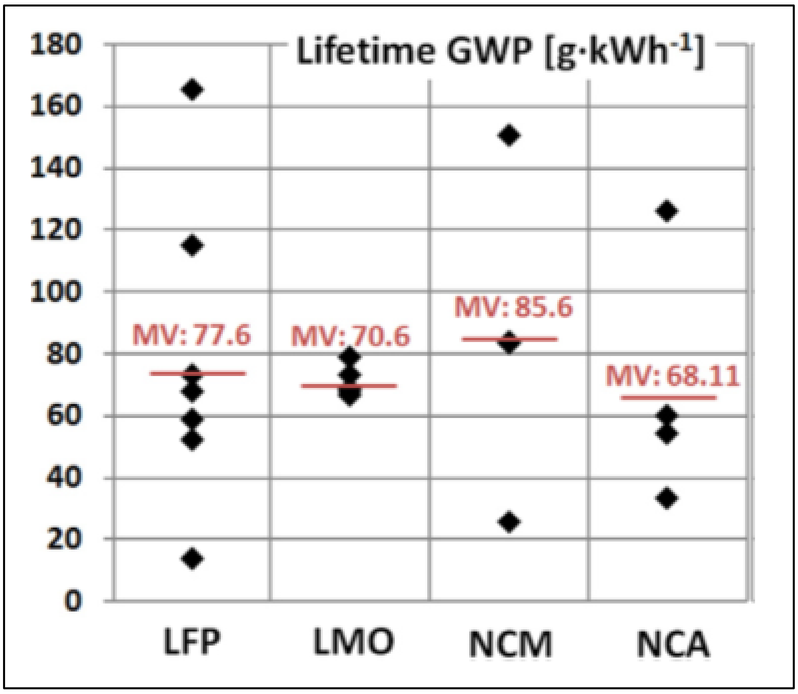
Figure 52: Lifetime specific energy of batteries in the literature (Peters et al., 2017)



8.1.4 Lifetime environmental impacts

The scattering for the literature's LFP-C, NMC-C and NCA-C is impressive (Figure 53), as results might come from very different assumptions and electric vehicles batteries as well as residential batteries. Overall, the literature's batteries perform very similarly which is a common finding with our study. While the LFP-C of the literature performs at 78 grams of CO2-eq per kWh of lifetime energy stored, our study has it perform at 31. The literature's NMC-C performs at 86 and is the least well performing on average compared to the other 3 technologies, while our NMC-C performed at 22 and is the best in this functional unit. The literature's LMO-C performed at 71 while ours at 42.

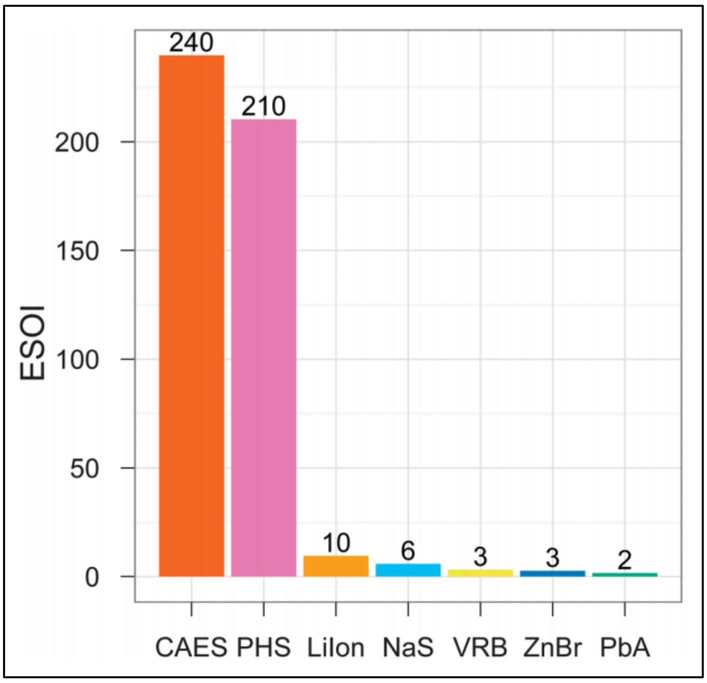
Figure 53: Lifetime global warming potential from literature (Peters et al., 2017)



8.1.5 Energy stored on energy invested

Barnhart and Benson (2013) estimated that lithium-ion batteries would be able to store 10 times the amount of energy required for their production (Figure 54). This is a better performance than for the batteries modelled in our model with at best perform at 6.2 for the NMC-C. This could be partly due to the fact that our study deemed necessary to include the hybrid current inverter's mass to the total mass of the battery packs analysed. The batteries modelled in this study still performed better than the lead-acid battery - another battery technology sometimes used for residential application - in terms of ESOI.

Figure 54: Energy stored on energy invested for different energy storage solutions (Barnhart & - Benson, 2013)



8.2 Statistical analysis of the differentiability of the battery chemistries concerning the impact per kWh functional unit

It must be noted that the p-values when comparing the kWh/kg of LMO-C and LFP-C, LMO-C and NMC-C, LFP-C and NMC-C, NCA-C and LFP-C, NCA-C and LMO-C, and NCA-C and NMC-C indicate that the difference between the groups of battery technologies is statistically not significant. This also occurs when comparing the environmental pollution score of these chemistries per kWh of lifetime energy stored. The p-value is constantly way above 0.05. For the single score impact category, with the kWh FU, with a 95% confidence interval, the p-values are as follows:

- LFP-C vs LMO-C: $p = 0.3909$
- LFP-C vs NMC-C: $p = 0.9741$
- LFP-C vs NCA-C: $p = 0.9903$
- LMO-C vs NMC-C: $p = 0.2808$
- LMO-C vs NCA-C: $p = 0.8668$
- NMC-C vs NCA-C: $p = 0.9621$

Even when only the battery modules are compared and the hybrid current inverter and other components are ignored, the p-value still does not indicate differentiation. This statistical analysis indicates that the battery chemistries cannot be differentiated with the current data sets, and that there is only a hint that the NMC-C and to a lesser extent the LFP-C battery technologies might be performing better from an environmental point of view using a kWh FU. There is too much uncertainty arising from the fact that each manufacturer will build a battery with a different specific capacity and cyclability performance even if they use the same cathode chemistry. In fact, the values for the environmental performances of all chemistries are globally close from one another. It is possible that a real differentiation exists between battery technologies and to prove it more residential battery models would need to be analysed. However, by looking at the 22 batteries analysed, this does not appear to be the case even if the Tesla Powerwall 2 and other NMC-C or LFP-C longevity and energy dense outliers seem to outperform the average LMO-C and NCA-C technologies in the kWh FU. This statistical test for the p-value does not apply for the kg FU as this functional unit was made independent from the performance of the batteries.

8.3 Limitations

Three main limitations rose. The first one concerns the modelling on SimaPro. The inventories for the materials and energy inputs were gathered mostly from studies which looked at electric vehicles. For example, they did not incorporate a current inverter. It is possible that the inventories for a residential li-ion battery would differ to a significant extent compared to an electric vehicle's. In fact, residential batteries often have LCD screens incorporated as well as other gadgets which were ignored in the modelling of this study. In addition, the recycling and hydrometallurgical end of life treatment adapted from the Ecoinvent 3 database and modelled in this study certainly needs more refining. Most notably, the production and recycling of the hybrid current inverter should be modelled with more precision.

The second limitation is more methodological. Finding the right way to standardize the mass ratio of batteries with different specific capacities across all chemistries but also among a same chemistry has become crucial to allow comparability between studies. This study was influenced by a trend of works like (Peters et al., 2017) and (Peters & Weil, 2016) which try to standardize the mass ratio of components. Their method is not recommendable to use for residential batteries as setting the hybrid current inverter at a same mass ratio across all chemistries (15% in this study) disregards the differences in specific capacity and leads to methodological inconsistencies when looking at different functional units. Indeed, in this study, the hybrid current inverter was estimated to have the same mass percentage in each battery, 15%, which was estimated by making the ratio for all chemistries together of the average current inverter mass over the module mass. This made its mass range from 16 kg in the modelled NCA-C battery which has a high specific capacity to 34 kg in the LFP-C battery with has a lower specific capacity. Perhaps a better approach would have consisted in giving it a fixed mass of 29 kg, which is the average mass of current inverters in all residential batteries analysed, and then use this value to look at the percentage mass it would represent in each modelled battery technology. Another problem is that each battery module has a different power output and the mass of the current inverter is assumed to be proportional to its performance in terms of its power input and output. This means modelling a 29 kg current inverter for the LFP-C which had a 3680 W power output on average as well as in the NMC-C which had a 4710 W power output on average might be a wrong approach, as the one in the NMC-C should have a higher mass. Another debate arises from this limitation: to what extent are the residential batteries analysed comparable since their power output varies significantly and therefore so will their application and use? The fact remains that a reason why maintaining the current inverter at a same mass ratio across all chemistries, around 15%, is that for the NCA-C, using the 29 kg current inverter approach mentioned above, the current inverter would have represented 25% of the mass of the battery, 18% for the NMC-C, 14% for the LMO-C and 13% for the LFP-C. However, this study used a current transformer already available on the Ecoinvent 3 database to model its current inverter. Even if current inverters and transformers are similar in many ways, the approach taken was that if a current transformer actually does not correspond at all to a current inverter in its manufacturing, at least the amount of error will be the same across all chemistries modelled and the results remain interpretable. This same critique could be made for most of the components which had their mass ratio standardized across all battery chemistries, such as the BMS or the cooling system which perhaps should have a higher mass for battery cells with lower thermal stability. This choice means the specific capacity of the battery modules across different chemistry was disregarded, but this might be a safer decision given the different performances of batteries within a same chemistry and given the insufficient LMO-C and NCA-C residential battery models analysed. The extent to which this choice influenced the results is more significant for the NCA-C which currently has a current inverter mass of 16 kg modelled and the NMC-C which currently has a current inverter mass of 24 kg. The NMC-C and NCA-C have lighter module masses and would have gotten their total mass increased by 3% for the NMC-C and 13% for the NCA-C, thereby reducing their lifetime specific energy and increasing their environmental impact potential per kWh of lifetime energy stored. The effect would have been the opposite for the LMO-C and

LFP-C as they currently have a hybrid current inverter of around 34 kg. Setting it to 29 kg would have seen their environmental impact potential per kWh of lifetime energy stored improved, although to a small extent. Setting new standardization methodologies which fully take into account the different specific capacities between chemistries would likely make the kg functional unit irrelevant, and require the use of the environmental impact potential per kWh of usable capacity. There has been a preference for the per kg functional unit in many studies (Peters & Weil, 2016), and this functional unit is tempting at first glance, but perhaps it is time life cycle assessments for batteries stop using it as it corresponds less to the real performance of the batteries.

The third main limitation arises from the quality of the data from the residential batteries available on the market. First of all, only a single NCA-C residential battery was identified, the Tesla Powerpack, and it is more suitable for large scale applications like hotels. In addition, some data sheets and installation manuals from the manufacturers required some estimates to be made for the mass composition of the battery. In addition, the manufacturers are often quite blurry about the performance of their batteries in terms of cycle life at different depths of discharge. This is understandable as the residential batteries are a relatively new product and are constantly improving. Manufacturers might not have the necessary perspective to predict the exact trend their batteries will follow, especially since sometimes they do not even manufacture the battery cells themselves. Indeed, some battery manufacturers of a same chemistry technology use the battery cells from companies like LG, Samsung or Panasonic which can also lead to redundancy in terms of comparing the performance of the different battery modules.

8.4 Potential for further research

In addition to the necessary readaptation of the methodology for the standardization of components like the hybrid current inverter and the use of more appropriate functional units, other points could be further improved in the near future, such as the uncertainty which was only modelled for the performance of the battery technologies. It should also be modelled on SimaPro in the materials and energy inputs to truly have a better idea of the wide range of mass ratios and manufacturing techniques that are used to produce battery cells from different technologies. A Monte Carlo analysis could then be conducted.

In terms of the kWh functional unit, more data should be collected for each chemistry in terms of the mass of the battery modules in residential batteries as well as their performance, especially for the LMO-C and NCA-C technologies. Some manufacturers do not specify the type of cathode used by their battery cells which did not allow their residential batteries to be analysed in this study. Some more precise data concerning the weight decomposition of some batteries have to be found by, perhaps, contacting the manufacturers which unfortunately rarely answer these kind of concerns as it flirts with industrial secrecy. An analysis of which residential batteries have the highest sales could help put the focus on these as they will be the most relevant ones to look at to estimate how the batteries the most used by consumers are impacting our environment. Moreover, modelling a more precise depth of discharge as applied to the lifetime energy storage instead of assuming it is linear would add precision to the study. Finally, a more precise life cycle inventory for the production of the hybrid current inverter and a more accurate recycling stage would allow the models to better suit reality for all the functional units.

Finally, the LFP-LTO, LMO-LTO or NCA-LTO battery technologies with a lithium titanate oxide negative electrode active material seem promising. It is possible they might start appearing on the market in the upcoming years. Their cyclability is supposed to be superior to a graphite negative electrode. Therefore, more transparent inventories must start being built for this battery technology. Mainly, inventories for the mass composition of the battery, especially the LTO negative electrode, as well as the manufacturing of lithium titanate oxide must be compiled.

8.5 Business and policy implications

The LMO-C has been the worst performer in both our functional units but the lack of statistical differentiability does not allow us to discourage its use. According to the data collected, it seems relatively safe to say that the LFP-C and NMC-C battery technologies should be encouraged for residential application, and this is the trend the industry and different manufacturers are already following. More residential batteries using the NCA-C chemistry must be analysed before any potential policy recommendations can be made on them.

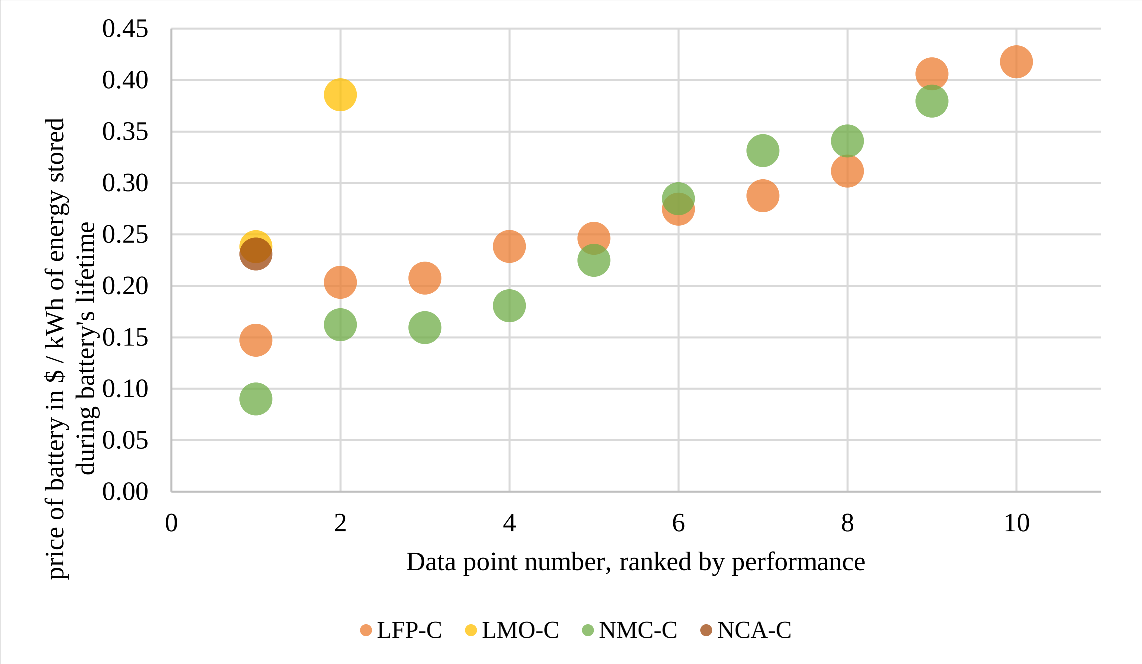
With the field of residential batteries only emerging and the research and development still going on, it would be highly inappropriate to discourage the use of any cathode or anode chemistry on the market, especially since the findings of this study suggests the different battery technologies actually perform rather similarly and none has a definite advantage. Rather than banning a specific cathode, research towards increasing the longevity and energy density of the batteries should be continued. Perhaps a performance directive leading towards at least a 250 kWh of lifetime energy stored per kilogram of battery mass could be implemented, as this would force manufacturers to make efforts to build better and lighter residential batteries, regardless of which battery technology they wish to use.

Consumers who buy residential batteries are usually environmentally-cautious and they could be buying a battery that performs three times better environmentally by buying a Tesla Powerwall 2 over an E-KwBe from the Chinese manufacturer GCL, even if they both use the NMC-C chemistry. Perhaps residential battery manufacturers should include the environmental performance of their product very openly on their battery data sheets. The global warming potential per kWh of lifetime energy stored seems to be the best option as this unit is the easiest to understand for the consumer. If given the environmental footprint information, this consumer could be tempted to get a battery that will last longer, cost less in the long run and have a lower impact on our environment

Perhaps a good way to encourage the consumer who is not that concerned about the protection of our environment is to show him the cost of the battery per kWh stored. Indeed, the cost of the battery per stored kWh is supposed to follow the trend of the environmental score per kWh as they are both mostly driven by the amount of life cycles of the battery (Figure 55). The findings of this research could therefore allow consumers interested in buying a residential battery to make a better informed purchase choice and thereby better protect our environment all the while making cost savings.

The rarity of the components in the cathode does not seem to affect significantly the overall price of the battery. It was estimated that the average purchase price of a 10 kWh of usable storage LFP-C battery is 14351 USD, LMO-C is 12121 USD, and NMC-C is 10557 USD. The cost per kWh between the 4 technologies is rather similar, just like the environmental impact potential. The LFP-C and NMC-C, however, seem to have some better performing outliers. It should be noted that a fairly cost efficient and well-built LMO-C battery can perform just as well as an average LFP-C or NMC-C from a financial point of view. This all means that should one technology outperform the other from an environmental pollution potential point of view or resource depletion point of view, the shift could be made without too much pain for the consumers and manufacturers.

Figure 55: Price per kWh of lifetime energy stored



Finally, encouraging the recycling of lithium-ion batteries could help offset many of the impacts of its production, especially since the resources depletion potential is the main issue. Incentivizing hydrometallurgical process recycling plants to start accepting li-ion batteries is necessary. Manufacturers also need to make their batteries easier to disassemble and the chemistry used easier to identify. In addition to resources availability, environmental impact potential and policy incentives, future progress in the fields of specific capacity and cyclability of batteries will have an important impact on the future batteries used for residential application.

9 Conclusion and key recommendations

It is safe to say increasing the recycling rate of lithium-ion batteries will help them improve from an environmental impact potential point of view. Policy makers can incentivize the recycling.

Industrial ecologists and life cycle analysts investigating and comparing the environmental footprint of batteries must start making more statistical analysis looking at the true differentiability of the set of battery chemistries they have assessed, and not simply look at the means. In addition, a new, more realistic way of standardizing some components' mass ratios across all chemistries which would take into account the specific capacity of the different chemistries' battery cells must be defined in order for future comparative LCAs to be comparable. To improve comparability between future studies, the "Topsy the elephant" guideline, described below, could be cited as the methodology chosen to model and analyse future life cycle assessment studies for residential batteries:

1. Use the best available life cycle inventories.
2. If more than one battery chemistry is analysed, the standardization of components must attempt to take into account the different specific capacities inherent to each chemistry.
3. Model a hybrid current inverter.
4. Model an end of life stage which complies with legislation recycling rates and best available recycling techniques.
5. Use the three following functional units "energy stored on energy invested", "environmental impact potential per usable capacity" and "environmental impact potential per lifetime stored energy".
6. Analyse at least the following impact categories: global warming potential, resources depletion potential and cumulative energy demand.
7. Run a p-value statistical analysis focusing on differentiability if there is more than one battery model analysed per chemistry.

As no lithium-ion battery chemistry seems to outperform the other, benchmarking the batteries not by technology or chemistry but by environmental impact potential per lifetime energy stored should be privileged by policy makers. Performance requirements could be imposed.

Battery manufacturers need to become more transparent concerning the cost and environmental impact potential per kWh of lifetime energy storable in their batteries to help the customer choose a battery model as aligned as possible with his needs and values. The new norms to compare residential battery models could be established jointly by battery manufacturers and policy makers backed up by academics.

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12 Appendix

12.1 Life cycle inventory

12.1.1.1 Residential battery packs

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Assembly of residential battery packs (LFP-C; LMO-C; NMC-C; NCA-C)	*Ellingsen et al., adapted to the weight ratios of this study*	*Ellingsen et al., adapted to the weight ratios of this study*	*Ellingsen et al., adapted to the weight ratios of this study*	*Ellingsen et al., adapted to the weight ratios of this study*	*Ellingsen et al., adapted to the weight ratios of this study*	*Ellingsen et al., adapted to the weight ratios of this study*

12.1.1.1.1 Assembly of LFP-C residential battery pack

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Residential battery pack (LFP-C)		**1.0E+0**	kg		
Materials input					
Cooling system	0.043		kg	Cooling system	Ellingsen et al.
Battery cell (LFP-C)	0.5672		kg	Battery cell (LFP-C)	*Various*
Battery packaging	0.1901		kg	Battery packaging	*Ellingsen et al.*
BMS	0.0474		kg	BMS	*Ellingsen et al.*
Hybrid current inverter	0.1523		kg	Transformer, high voltage use, at plant/GLO U	*Ecoinvent Centre*
Energy and Processes					
Electricity for welding	4.0E-4		kWh	Electricity, medium voltage, at grid/NO U	*Ecoinvent Centre*
Transport					
Transport by ship	4.9		tkm	Transport, transoceanic freight ship/OCE U	*Ecoinvent Centre*

Transport by lorry	1.6E-1		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	1.9E-8		p	Facilities precious metal refinery/SE/I U	*Ecoinvent Centre*
Emissions to air					
Heat, waste	1.4E-3		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.1.2 Assembly of LMO-C residential battery pack

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Residential battery pack (LMO-C)		**1.0E+0**	kg		
Materials input					
Cooling system	0.043		kg	Cooling system	Ellingsen et al.
Battery cell (LMO-C)	0.5672		kg	Battery cell (LMO-C)	*Various*
Battery packaging	0.1901		kg	Battery packaging	*Ellingsen et al.*
BMS	0.0474		kg	BMS	*Ellingsen et al.*
Hybrid current inverter	0.1523		kg	Transformer, high voltage use, at plant/GLO U	*Ecoinvent Centre*
Energy and Processes					
Electricity for welding	4.0E-4		kWh	Electricity, medium voltage, at grid/NO U	*Ecoinvent Centre*
Transport					
Transport by ship	4.9		tkm	Transport, transoceanic freight ship/OCE U	*Ecoinvent Centre*
Transport by lorry	1.6E-1		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	1.9E-8		p	Facilities precious metal refinery/SE/I U	*Ecoinvent Centre*
Emissions to air					

Heat, waste	1.4E-3		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.1.3 Assembly of NMC-C residential battery pack

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Residential battery pack (NMC-C)		**1.0E+0**	kg		
Materials input					
Cooling system	0.043		kg	Cooling system	Ellingsen et al.
Battery cell (NMC-C)	0.5672		kg	Battery cell (NMC-C)	*Various*
Battery packaging	0.1901		kg	Battery packaging	*Ellingsen et al.*
BMS	0.0474		kg	BMS	*Ellingsen et al.*
Hybrid current inverter	0.1523		kg	Transformer, high voltage use, at plant/GLO U	*Ecoinvent Centre*
Energy and Processes					
Electricity for welding	4.0E-4		kWh	Electricity, medium voltage, at grid/NO U	*Ecoinvent Centre*
Transport					
Transport by ship	4.9		tkm	Transport, transoceanic freight ship/OCE U	*Ecoinvent Centre*
Transport by lorry	1.6E-1		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	1.9E-8		p	Facilities precious metal refinery/SE/I U	*Ecoinvent Centre*
Emissions to air					
Heat, waste	1.4E-3		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.1.4 Assembly of NCA-C residential battery pack

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Residential battery pack (NMC-C)		**1.0E+0**	kg		
Materials input					
Cooling system	0.043		kg	Cooling system	Ellingsen et al.
Battery cell (NMC-C)	0.5672		kg	Battery cell (NMC-C)	*Various*
Battery packaging	0.1901		kg	Battery packaging	*Ellingsen et al.*
BMS	0.0474		kg	BMS	*Ellingsen et al.*
Hybrid current inverter	0.1523		kg	Transformer, high voltage use, at plant/GLO U	*Ecoinvent Centre*
Energy and Processes					
Electricity for welding	4.0E-4		kWh	Electricity, medium voltage, at grid/NO U	*Ecoinvent Centre*
Transport					
Transport by ship	4.9		tkm	Transport, transoceanic freight ship/OCE U	*Ecoinvent Centre*
Transport by lorry	1.6E-1		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	1.9E-8		p	Facilities precious metal refinery/SE/I U	*Ecoinvent Centre*
Emissions to air					
Heat, waste	1.4E-3		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.2 Battery cells

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Assembly of single cell (LFP-C; LMO-	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*

C; NMC-C; NCA-C)						

12.1.1.2.1 Assembly of LFP-C battery cell

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Battery cell (LFP-C)		**1.0E+0**	kg		Various
Materials input					
Negative electrode (LFP-C)	0.245		kg	Negative electrode (LFP-C)	Notter et al. & Ellingsen et al.
Positive electrode (LFP-C)	0.458		kg	Positive electrode (LFP-C)	*Majeau-Bettez et al.* & Ellingsen et al
Electrolyte (LFP-C)	0.187		kg	Electrolyte (LFP-C)	Notter et al. & Ellingsen et al.
Separator	0.0336		kg	Separator	*Notter et al.*
Cell container	0.0774		kg	Cell container	*Ellingsen et al.*
Water, decarbonised, at plant/RER U	380		kg	Water, decarbonised, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
	2.8E1		kWh	Electricity, medium voltage, at grid/NO U	*Ecoinvent Centre*
Transport					
Transport by freight	2.6E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	1.9E-8		p	Facilities precious metal refinery/SE/I U	*Ecoinvent Centre*
Emissions to air					

Heat, waste	1.0E2		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.2.2 Assembly of LMO-C battery cell

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Battery cell (LMO-C)		**1.0E+0**	kg		
Materials input					
Negative electrode (LMO-C)	0.388		kg	Negative electrode (LMO-C)	Notter et al. & Ellingsen et al.
Positive electrode (LMO-C)	0.312		kg	Positive electrode (LMO-C)	Notter et al. & Ellingsen et al.
Electrolyte (LMO-C)	0.171		kg	Electrolyte (LMO-C)	Notter et al. & Ellingsen et al.
Separator	0.0515		kg	Separator	*Notter et al.*
Cell container	0.0774		kg	Cell container	*Ellingsen et al.*
Water, decarbonised, at plant/RER U	380		kg	Water, decarbonised, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
	2.8E1		kWh	Electricity, medium voltage, at grid/NO U	*Ecoinvent Centre*
Transport					
Transport by freight	2.6E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	1.9E-8		p	Facilities precious metal refinery/SE/I U	*Ecoinvent Centre*
Emissions to air					
Heat, waste	1.0E2		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.2.3 Assembly of NMC-C battery cell

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Battery cell (NMC-C)		**1.0E+0**	kg		
Materials input					
Negative electrode (NMC-C)	0.317		kg	Negative electrode (NMC-C)	Notter et al. & Ellingsen et al.
Positive electrode (NMC-C)	0.405		kg	Positive electrode (NMC-C)	*Majeau-Bettez et al.* & Ellingsen et al
Electrolyte (NMC-C)	0.166		kg	Electrolyte (NMC-C)	Notter et al. & Ellingsen et al.
Separator	0.0352		kg	Separator	*Notter et al.*
Cell container	0.0774		kg	Cell container	*Ellingsen et al.*
Water, decarbonised, at plant/RER U	380		kg	Water, decarbonised, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
	2.8E1		kWh	Electricity, medium voltage, at grid/NO U	*Ecoinvent Centre*
Transport					
Transport by freight	2.6E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	1.9E-8		p	Facilities precious metal refinery/SE/I U	*Ecoinvent Centre*
Emissions to air					
Heat, waste	1.0E2		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.2.4 Assembly of NCA-C battery cell

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Battery cell (NCA-C)		**1.0E+0**	kg		
Materials input					
Negative electrode (NCA-C)	0.327		kg	Negative electrode (NCA-C)	Notter et al. & Ellingsen et al.
Positive electrode (NCA-C)	0.345		kg	Positive electrode (NCA-C)	*P.T. Benavides et al., Majeau-Bettez et al, & Ellingsen et al.*
Electrolyte (NCA-C)	0.173		kg	Electrolyte (NCA-C)	Notter et al. & Ellingsen et al.
Separator	0.0781		kg	Separator	*Notter et al.*
Cell container	0.0774		kg	Cell container	*Ellingsen et al.*
Water, decarbonised, at plant/RER U	380		kg	Water, decarbonised, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
	2.8E1		kWh	Electricity, medium voltage, at grid/NO U	*Ecoinvent Centre*
Transport					
Transport by freight	2.6E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	1.9E-8		p	Facilities precious metal refinery/SE/I U	*Ecoinvent Centre*
Emissions to air					
Heat, waste	1.0E2		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.3 Negative electrodes

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of battery grade graphite	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*
Production of negative electrode current collector	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of negative electrode material/electrode pastes (LFP-C; LMO-C; NMC-C; NCA-C)	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*
Assembly of negative electrodes (LFP-C; LMO-C; NMC-C; NCA-C)	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*

12.1.1.3.1 LFP-C Negative electrode

12.1.1.3.1.1 Assembly of negative electrode (LFP-C)

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Negative electrode (LFP-C)		**1.0E+0**	kg		
Components					
Negative current collector	0.330		kg	Negative current collector	Ellingsen et al.
Negative electrode paste (LFP-C)	0.671		kg	Negative electrode paste (LFP-C)	Ellingsen et al. & Notter et al.
Transport					

Transport by freight	3.7E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.3.1.1.1 Negative electrode's current collector

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Negative current collector		**1.0E+0**	kg		
Components					
Current collector, primary copper	8.5E-1		kg	Copper, primary, at refinery/GLO U	*Ecoinvent Centre*
Current collector, secondary copper	1.5E-1		kg	Copper, secondary, at refinery/RER U	*Ecoinvent Centre*
Energy and Processes					
Production of current collector	1		kg	Sheet rolling, copper/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.6E-10		p	Metal working factory/RER/I U	*Ecoinvent Centre*

12.1.1.3.1.1.2 LFP-C negative electrode paste

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Negative electrode paste (LFP-C)		**1.0E+0**	kg		
Components					
Battery grade graphite	0.908		kg	Battery grade graphite	

CMC (binder)	0.0458			Carboxymethyl cellulose, powder, at plant/RER U	*Ecoinvent Centre*
PAA (binder)	0.0458			Acrylic acid, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
Solvent to give the mixture a slurry texture	9.4E-1		kg	N-methyl-2-pyrrolidone, at plant/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	1.2		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.9E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Evaporation of the solvent	9.4E-1		kg	1-Methyl-2-pyrrolidinone	*Ecoinvent Centre*

12.1.1.3.1.1.2.1 Battery grade graphite

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Battery grade graphite		**1.0E+0**	kg		
Components					
Water	2.93E-5		m^3	Water, well, in ground	*Ecoinvent Centre*
graphite containing rock	1.05		kg	Metamorphous rock, graphite containing	*Ecoinvent Centre*
Energy and Processes					
Blasting	7.73E-5		kg	Blasting/RER U	*Ecoinvent Centre*
Heat	8.92E-2		MJ	Heat, light fuel oil, at industrial furnace 1MW/RER U	*Ecoinvent Centre*
Light fuel oil	3.59E-3		MJ	Light fuel oil, burned in boiler 100kW, non-modulating/CH U	*Ecoinvent Centre*

Diesel	1.8E-2		MJ	Diesel, burned in building machine/GLO U	*Ecoinvent Centre*
Industrial machine	2.31E-4		kg	Industrial machine, heavy, unspecified, at plant/RER/I U	*Ecoinvent Centre*
Conveyor belt	2.78E-8		m	Conveyor belt, at plant/RER/I U	*Ecoinvent Centre*
Electricity	1.03		kWh	Electricity, medium voltage, at grid/CN U	*Ecoinvent Centre*
hard coal coke	4.00E1		MJ	Hard coal coke, at plant/GLO U	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Mine, limestone	5.25E-11		p	Mine, limestone/CH/I U	*Ecoinvent Centre*
Land use	8.48E-5		m2a	Occupation, mineral extraction site	*Ecoinvent Centre*
Land transformation	6.52E-6		m^2	Transformation, to mineral extraction site	*Ecoinvent Centre*
Land transformation	6.52E-6		m^2	Transformation, from forest, intensive, clear-cutting	*Ecoinvent Centre*
Recultivation, limestone mine	6.25E-6		m^2	Recultivation, limestone mine/CH U	*Ecoinvent Centre*
Emissions to air					
Particulates	8.87E-6		kg	Particulates, < 2.5 um	*Ecoinvent Centre*
Particulates	4.78E-5		kg	Particulates, > 10 um	*Ecoinvent Centre*
Particulates	1.21E-4		kg	Particulates, > 2.5 um, and < 10um	*Ecoinvent Centre*
Waste heat to air	3.72		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.3.2 LMO-C negative electrode

12.1.1.3.2.1 Assembly of negative electrode (LMO-C)

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Negative electrode (LMO-C)		**1.0E+0**	kg		
Components					
Negative current collector	0.486		kg	Negative current collector	Ellingsen et al.
Negative electrode paste (LMO-C)	0.514		kg	Negative electrode paste (LMO-C)	Ellingsen et al. & Notter et al.
Transport					
Transport by freight	3.7E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.3.2.1.1 LMO-C negative electrode paste

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Negative electrode paste (LMO-C)		**1.0E+0**	kg		
Components					
Battery grade graphite	0.946		kg	Battery grade graphite	
CMC (binder)	0.0270			Carboxymethyl cellulose, powder, at plant/RER U	*Ecoinvent Centre*
PAA (binder)	0.0270			Acrylic acid, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
Solvent to give the mixture a slurry texture	9.4E-1		kg	N-methyl-2-pyrrolidone, at plant/RER U	*Ecoinvent Centre*

Transport					
Transport by freight	1.2		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.9E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Evaporation of the solvent	9.4E-1		kg	1-Methyl-2-pyrrolidinone	*Ecoinvent Centre*

12.1.1.3.3 NMC-C negative electrode

12.1.1.3.3.1 Assembly of negative electrode (NMC-C)

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Negative electrode (NMC-C)		**1.0E+0**	kg		
Components					
Negative current collector	0.529		kg	Negative current collector	Ellingsen et al.
Negative electrode paste (NMC-C)	0.471		kg	Negative electrode paste (NMC-C)	Ellingsen et al. & Notter et al.
Transport					
Transport by freight	3.7E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.3.3.1.1 NMC-C negative electrode paste

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					

Negative electrode paste (NMC-C)		**1.0E+0**	kg		
Components					
Battery grade graphite	0.955		kg	Battery grade graphite	
CMC (binder)	0.0224			Carboxymethyl cellulose, powder, at plant/RER U	*Ecoinvent Centre*
PAA (binder)	0.0224			Acrylic acid, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
Solvent to give the mixture a slurry texture	9.4E-1		kg	N-methyl-2-pyrrolidone, at plant/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	1.2		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.9E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Evaporation of the solvent	9.4E-1		kg	1-Methyl-2-pyrrolidinone	*Ecoinvent Centre*

12.1.1.3.4 NCA-C negative electrode

12.1.1.3.4.1 Assembly of negative electrode (NCA-C)

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Negative electrode (NCA-C)		**1.0E+0**	kg		
Components					
Negative current collector	0.426		kg	Negative current collector	Ellingsen et al.
Negative electrode paste (NCA-C)	0.574		kg	Negative electrode paste (NCA-C)	Ellingsen et al. & Notter et al.
Transport					

Transport by freight	3.7E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.3.4.1.1 NCA-C negative electrode paste

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Negative electrode paste (NCA-C)		**1.0E+0**	kg		
Components					
Battery grade graphite	0.980		kg	Battery grade graphite	
CMC (binder)	9.83E-3			Carboxymethyl cellulose, powder, at plant/RER U	*Ecoinvent Centre*
PAA (binder)	9.83E-3			Acrylic acid, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
Solvent to give the mixture a slurry texture	9.4E-1		kg	N-methyl-2-pyrrolidone, at plant/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	1.2		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.9E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Evaporation of the solvent	9.4E-1		kg	1-Methyl-2-pyrrolidinone	*Ecoinvent Centre*

12.1.1.4 Positive electrodes

12.1.1.4.1 LFP Positive electrode

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of lithium iron phosphate (LiFePO4) (hydrothermal reaction)	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*
Production of positive electrode active material/electrode paste (Mixing)	*Majeau-Bettez et al.*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*
Production of positive electrode substrate	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Assembly of positive electrode	*Ellingsen et al.*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*

12.1.1.4.1.1 Assembly of LFP positive electrode

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Positive electrode (LFP-C)		**1.0E+0**	kg		
Components					
Positive current collector	0.0752		kg	Positive current collector (Al)	*Ellingsen et al.*

Positive electrode paste	0.925		kg	Positive electrode paste (LFP)	*Majeau-Bettez et al. & Ellingsen et al.*
Transport					
Transport by freight	5.5E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.4.1.1.1 Positive current collector

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Positive current collector (Al)		**1.0E+0**	kg		
Components					
Current collector made of aluminium	1		kg	Aluminium, production mix, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
Production of current collector	1		kg	Sheet rolling, aluminium/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	1.5E-10		p	Aluminium casting, plant/RER/I U	*Ecoinvent Centre*

12.1.1.4.1.1.2 Positive electrode paste

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					

Positive electrode paste (LFP)		**1.0E+0**	kg		
Components					
Active material	0.884		kg	Lithium iron phosphate (LiFePO4)	Majeau-Bettez et al.
Conductive material	0.0526		kg	Carbon black, at plant/GLO U	*Ecoinvent Centre*
Binder	0.0639		kg	Polyvinylfluoride, at plant/US U	*Ecoinvent Centre*
Energy and Processes					
Solvent	4.1E-1		kg	N-methyl-2-pyrrolidone, at plant/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	4.6E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.4E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Evaporation of solvent	4.1E-1		kg	1-Methyl-2-pyrrolidinone	*Ecoinvent Centre*

12.1.1.4.1.1.2.1 Lithium iron phosphate

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Lithium iron phosphate (LiFePO4)		**1.0E+0**	kg		
Components					
LiOH	0.46		kg	Lithium hydroxide, at plant/GLO U	*Ecoinvent Centre*
H3PO4	0.65		kg	Phosphoric acid, industrial grade, 85% in H2O, at plant/RER U	*Ecoinvent Centre*
FeSO4	1		kg	Iron sulphate, at plant/RER U	*Ecoinvent Centre*

H2O	46		kg	Water, deionised, at plant/CH U	*Ecoinvent Centre*
Energy and Processes					
Heating	15		MJ	Heat, unspecific, in chemical plant/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	1.3		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	0.21		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Heat, waste	1.5		MJ	Heat, waste	*Ecoinvent Centre*
Emissions to water					
Waste	0.1		kg	Lithium	*Ecoinvent Centre*
Waste	1.9E-2		kg	Iron	*Ecoinvent Centre*
Waste	3.2E-2		kg	Phosphate	*Ecoinvent Centre*

12.1.1.4.2 LMO Positive electrode

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of lithium carbonate	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*
Production of manganese oxide	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*
Production of lithium manganese oxide	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*
Production of positive electrode	*Adapted from*	*Ellingsen et al., using*	*Ellingsen et al., using*	*Ellingsen et al., using*	*Ellingsen et al., using*	*Ellingsen et al., using*

active material/electrode paste (Mixing)	*Ellingsen et al.*	*this study's mass ratios*	*this study's mass ratios*	*this study's mass ratios*	*this study's mass ratios*	*this study's mass ratios*
Production of positive electrode substrate	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Assembly of positive electrode	*Majeau-Bettez et al.*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*

12.1.1.4.2.1 Assembly of LMO positive electrode

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Positive electrode (LMO-C)		**1.0E+0**	kg		
Materials input					
Positive current collector	0.373		kg	Positive current collector (Al)	*Ellingsen et al.*
Positive electrode paste	0.626		kg	Positive electrode paste (LMO)	*Notter et al.*
Transport					
Transport by freight	5.5E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.4.2.1.1 Positive electrode paste

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Positive electrode paste (LMO)		**1.0E+0**	kg		

Materials input					
Conductive carbon	0.0420		kg	Carbon black, at plant/GLO U	*Ecoinvent Centre*
Binder	0.0336			Polyvinylfluoride, at plant/US U	*Ecoinvent Centre*
Active material	0.924			Lithium manganese oxide (LiMn2O4)	*Notter et al.*
Solvent	4.1E-1			N-methyl-2-pyrrolidone, at plant/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	4.6E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.4E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Evaporation of solvent	4.1E-1		kg	1-Methyl-2-pyrrolidinone	*Ecoinvent Centre*

12.1.1.4.2.1.1.1 Lithium Manganese oxide

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Lithium manganese oxide (LiMn2O4)		**1.0E+0**	kg		
Materials input					
Manganese oxide	9.18E-1		kg	Manganese oxide (Mn2O3)	Notter et al.
Lithium carbonate	2.15E-1		kg	Lithium carbonate	*Notter et al.*
liquid, for oxidising atmosphere	7.15E-1		kg	Oxygen, liquid, at plant/RER U	*Ecoinvent Centre*
liquid, for inert atmosphere	7.86E-1		kg	Nitrogen, liquid, at plant/RER U	*Ecoinvent Centre*
for suspension	3.4		kg	Water, deionised, at plant/CH U	*Ecoinvent Centre*
Energy and Processes					

mechanical drive of the rotary kiln	5.0E-3		kWh	Electricity, medium voltage, at grid/CN U	*Ecoinvent Centre*
furnace for rotary kiln	1.53E1		MJ	Heat, natural gas, at industrial furnace >100kW/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	3.23		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	5.64E-1		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Waste heat to air	1.8E-2		MJ	Heat, waste	*Ecoinvent Centre*
Evaporated water	3.4		kg	Water	*Ecoinvent Centre*
Amount of CO2 that result from the stoichiometry	1.28E-1		kg	Carbon dioxide, fossil	*Ecoinvent Centre*
Waste and emissions to treatment					
5% loss from manganese conversion (manganese oxide)	4.59E-2		kg	Disposal, inert waste, 5% water, to inert material landfill/CH U	*Ecoinvent Centre*
5% loss from manganese conversion (manganese oxide)	1.07E-2		kg	Disposal, inert waste, 5% water, to inert material landfill/CH U	*Ecoinvent Centre*

12.1.1.4.2.1.1.1.1 Lithium carbonate

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Lithium carbonate		**1.0E+0**	kg		
Materials input					

Concentrated lithium brine chloride	9.38		kg	Lithium brine, 6.7 % Li {GLO}| market for | Conseq, U	*Ecoinvent Centre*
Quicklime	1.76E-1		kg	Quicklime, milled, loose, at plant/CH U	*Ecoinvent Centre*
Sulphuric acid	3.57E-2		kg	Sulphuric acid, liquid, at plant/RER U	*Ecoinvent Centre*
Hydrochloric acid	5.71E-2		kg	Hydrochloric acid, 30% in H2O, at plant/RER U	*Ecoinvent Centre*
Filtering earth	1.44E-2		kg	Bentonite, at processing/DE U	*Ecoinvent Centre*
Alcohol	1.19E-3		kg	2-methyl-2-butanol, at plant/RER U	*Ecoinvent Centre*
Soda ash	3.73		kg	Soda, powder, at plant/RER U	*Ecoinvent Centre*
Organic solvent	4.75E-3		kg	Solvents, organic, unspecified, at plant/GLO U	*Ecoinvent Centre*
Sodium hydroxide	1.88E-4		kg	Sodium hydroxide, 50% in H2O, production mix, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
Electricity, Brazil used as a proxy for Chile	5.6E-4		kWh	Electricity, medium voltage, at grid/BR U	*Ecoinvent Centre*
Natural gas	6.09		MJ	Natural gas, burned in industrial furnace >100kW/RER U	*Ecoinvent Centre*
Credit: processing of natural gas substracted, equal to the value of liquefied gas	-2		MJ	Natural gas, high pressure, at consumer/RER U	*Ecoinvent Centre*
The plant uses liquid gas.	9.53E-5		m^3	Natural gas, liquefied, at freight ship/JP U	*Ecoinvent Centre*
diesel oil	2.84E-1		MJ	Diesel, burned in building machine/GLO U	*Ecoinvent Centre*
Transport					
Transport by lorry	2.59		tkm	Transport, lorry 16-32t, EURO3/RER U	*Ecoinvent Centre*
Transport by lorry	2.4E-3		tkm	Transport, lorry 7.5-16t, EURO3/RER U	*Ecoinvent Centre*

Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Waste heat to air	2.02E-3		MJ	Heat, waste	*Ecoinvent Centre*
Waste and emissions to treatment					
Hazardous waste, underground deposit	2.05E-4		kg	Disposal, hazardous waste, 0% water, to underground deposit/DE U	*Ecoinvent Centre*
Non-hazardous waste, residual material landfill	6.41		kg	Disposal, decarbonising waste, 30% water, to residual material landfill/CH U	*Ecoinvent Centre*

12.1.1.4.2.1.1.1.2 Manganese oxide

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Manganese oxide (Mn2O3)		**1.0E+0**	kg		
Materials input					
basic material, no special quality demand	1.71		kg	Manganese concentrate, at beneficiation/GLO U	*Ecoinvent Centre*
nitrogen	2.56		kg	Nitrogen, liquid, at plant/RER U	*Ecoinvent Centre*
Oxygen	5.37E-1		kg	Oxygen, liquid, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
Mechanical drive of the rotary kiln	5.0E-3		kWh	Electricity, medium voltage, at grid/CN U	*Ecoinvent Centre*
Process heat	4.13		MJ	Heat, natural gas, at industrial furnace >100kW/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	2.2		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*

Transport by lorry	4.81E-1		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
waste heat to air	1.8E-2		MJ	Heat, waste	*Ecoinvent Centre*
Amount of CO2 that results from the stoichiometry	2.79E-1		kg	Carbon dioxide, fossil	*Ecoinvent Centre*
Equal amount of CO as CO2 stoichiometrically, conversion of CO to CO2	2.79E-1		kg	Carbon dioxide, fossil	*Ecoinvent Centre*
CO	4.67E-5		kg	Carbon monoxide, fossil	*Ecoinvent Centre*
Waste and emissions to treatment					
85% manganese conversion from MnCO3 to Mn2O3, 15% loss	2.57E-1		kg	Disposal, inert waste, 5% water, to inert material landfill/CH U	*Ecoinvent Centre*

12.1.1.4.3 NMC positive electrode

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of MnSO4 (Roasting and leaching)	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*
Production of CoSO4	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*
Production of NiSO4	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*
Production of NiCoMn(OH)	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*

(mixed hyrdroxide precipitation)						
Production of LiNiCoMnO (calcination)	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*
Production of positive electrode active material/electrode paste (Mixing)	*Majeau-Bettez et al.*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*
Production of positive electrode substrate	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Assembly of positive electrode	*Ellingsen et al.*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*

12.1.1.4.3.1 Assembly of NMC positive electrode

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Positive electrode (NMC)		**1.0E+0**	kg		
Materials input					
Positive current collector	0.123		kg	Positive current collector (Al)	*Ellingsen et al.*
Positive electrode paste	0.877		kg	Positive electrode paste (NMC-C)	*Majeau-Bettez et al. & Ellingsen et al.*
Transport					
Transport by freight	5.5E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*

Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.4.3.1.1 Positive electrode paste

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Positive electrode paste (NMC-C)		**1.0E+0**	kg		
Materials input					
Binder	0.060		kg	Polyvinylfluoride, at plant/US U	*Ecoinvent Centre*
Conductive carbon	0.035		kg	Carbon black, at plant/GLO U	*Ecoinvent Centre*
Active material	0.91		kg	Lithium nickel cobalt manganese hydroxide (LiNi0.4Co0.2Mn0.4O2)	*Majeau-Bettez et al.*
Solvent	4.1E-1		kg	N-methyl-2-pyrrolidone, at plant/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	4.6E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.4E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Evaporation of solvent	4.1E-1		kg	1-Methyl-2-pyrrolidinone	*Ecoinvent Centre*

12.1.1.4.3.1.1.1 Lithium nickel cobalt manganese oxide

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					

Lithium nickel cobalt manganese hydroxide (LiNi0.4Co0.2Mn0.4O2)		**1.0E+0**	kg		
Materials input					
Lithium hydroxide, at plant/GLO U	0.25		kg		*Ecoinvent Centre*
Nickel cobalt manganese hydroxide (Ni0.4Co0.2Mn0.4(OH) 2)	0.95		kg		*Majeau-bettez et al.*
Energy and Processes					
	0.55		MJ	Heat, unspecific, in chemical plant/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	0.72		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	0.12		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.6E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Heat, waste	5.5		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.4.3.1.1.1.1 Nickel cobalt manganese hydroxide

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Nickel cobalt manganese hydroxide (Ni0.4Co0.2Mn0.4(OH) 2)		**1.0E+0**	kg		
Materials input					
Sodium hydroxide			kg		*Ecoinvent Centre*
Nickel sulfate (NiSO4)				Nickel sulfate (NiSO4)	*Majeau-Bettez et al.*

Cobalt sulphate (CoSO4)				Cobalt sulphate (CoSO4)	*Majeau-Bettez et al.*
Manganese sulphate (MnSO4)				Manganese sulphate (MnSO4)	*Majeau-Bettez et al.*
Transport					
Transport by freight	1.5		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	0.26		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.6E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Sodium sulfate	1.5		kg	Sodium sulfate	*Ecoinvent Centre*

12.1.1.4.3.1.1.1.2 Manganese sulphate

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Manganese sulphate (MnSO4)		**1.0E+0**	kg		
Materials input					
Manganese component	1.1		kg	Manganese concentrate, at beneficiation/GLO U	*Ecoinvent Centre*
Sulphuric acid	0.65		kg	Sulphuric acid, liquid, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
	0.036		MJ	Natural gas, high pressure, at consumer/RER U	*Ecoinvent Centre*
	1.43		MJ	Hard coal coke, at plant/RER U	*Ecoinvent Centre*
	0.077		MJ	Electricity, medium voltage, production UCTE, at grid/UCTE U	*Ecoinvent Centre*
Transport					
Transport by freight	0.39		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*

Transport by lorry	0.06		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	1.6E-14		p	Non-ferrous metal mine, underground/GLO/I U	*Ecoinvent Centre*
Facility	2.4E-10		p	Aluminium hydroxide, plant/RER/I U	*Ecoinvent Centre*
Emissions to air					
Heat, waste	1.5		MJ	Heat, waste	*Ecoinvent Centre*
Waste and emissions to treatment					
	0.71		kg	Disposal, non-sulfidic tailings, off-site/GLO U	*Ecoinvent Centre*

12.1.1.4.3.1.1.1.3 Cobalt sulphate

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Cobalt sulphate (CoSO4)		**1.0E+0**	kg		
Materials input					
	0.032		kg	Chemicals inorganic, at plant/GLO U	*Ecoinvent Centre*
	0.010		kg	Chemicals organic, at plant/GLO U	*Ecoinvent Centre*
	0.0015		kg	Hydrogen cyanide, at plant/RER U	*Ecoinvent Centre*
	0.019		kg	Limestone, milled, packed, at plant/CH U	*Ecoinvent Centre*
	1.4		kg	Portland calcareous cement, at plant/CH U	*Ecoinvent Centre*
	17		kg	Sand, at mine/CH U	*Ecoinvent Centre*
Energy and Processes					
	0.063		kg	Blasting/RER U	*Ecoinvent Centre*
	4.6		MJ	Diesel, burned in building machine/GLO U	*Ecoinvent Centre*

	6.4		MJ	Electricity, medium voltage, production UCTE, at grid/UCTE U	*Ecoinvent Centre*
Transport					
Transport by lorry	0.94		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	3.4E-10		p	Aluminium hydroxide, plant/RER/I U	*Ecoinvent Centre*
Facility	1.6E-6		m	Conveyor belt, at plant/RER/I U	*Ecoinvent Centre*
Facility	2.1E-9		p	Non-ferrous metal mine, underground/GLO/I U	*Ecoinvent Centre*
Waste and emissions to treatment					
	13		kg	Disposal, nickel smelter slag, 0% water, to residual material landfill/CH U	*Ecoinvent Centre*
	25		kg	Disposal, sulfidic tailings, off-site/GLO U	*Ecoinvent Centre*

12.1.1.4.3.1.1.1.4 Nickel sulfate

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
		1.0E+0	kg		
Materials input					
	0.032		kg	Ammonia, liquid, at regional storehouse/RER U	*Ecoinvent Centre*
	0.023		kg	Chemicals inorganic, at plant/GLO U	*Ecoinvent Centre*
	0.0068		kg	Chemicals organic, at plant/GLO U	*Ecoinvent Centre*
	0.0011		kg	Hydrogen cyanide, at plant/RER U	*Ecoinvent Centre*
	0.73		kg	Limestone, milled, packed, at plant/CH U	*Ecoinvent Centre*

	1		kg	Portland calcareous cement, at plant/CH U	*Ecoinvent Centre*
	13		kg	Sand, at mine/CH U	*Ecoinvent Centre*
	0.72		kg	Silica sand, at plant/DE U	*Ecoinvent Centre*
Energy and Processes					
	0.046		kg	Blasting/RER U	*Ecoinvent Centre*
	3.1		MJ	Diesel, burned in building machine/GLO U	*Ecoinvent Centre*
	4.1		MJ	Electricity, high voltage, production UCTE, at grid/UCTE U	*Ecoinvent Centre*
	10.5		MJ	Electricity, hydropower, at run-of-river power plant/RER U	*Ecoinvent Centre*
	1.7		MJ	Electricity, medium voltage, production UCTE, at grid/UCTE U	*Ecoinvent Centre*
	0.71		MJ	Heat, at hard coal industrial furnace 1-10MW/RER U	*Ecoinvent Centre*
	8.1		MJ	Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	*Ecoinvent Centre*
	3.5		MJ	Natural gas, burned in industrial furnace >100kW/RER U	*Ecoinvent Centre*
Transport					
Transport by lorry	0.68		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	1.5E-9		p	Non-ferrous metal mine, underground/GLO/I U	*Ecoinvent Centre*
Facility	1.3E-11		p	Non-ferrous metal smelter/GLO/I U	*Ecoinvent Centre*
Facility	2.5E-10		p	Aluminium hydroxide, plant/RER/I U	*Ecoinvent Centre*

Facility	1.2E-6		m	Conveyor belt, at plant/RER/I U	*Ecoinvent Centre*
Waste and emissions to treatment					
	3.6		kg	Disposal, nickel smelter slag, 0% water, to residual material landfill/CH U	*Ecoinvent Centre*
	27		kg	Disposal, sulfidic tailings, off-site/GLO U	*Ecoinvent Centre*

12.1.1.4.4 NCA positive electrode

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of NiSO4	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*
Production of CoSO4	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*
Production of NCA precursor	*P.T. Benavides et al.*	*P.T. Benavides et al.*	*P.T. Benavides et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*
Production of the NCA cathode material (LiNCA)	*P.T. Benavides et al.*	*P.T. Benavides et al.*	*P.T. Benavides et al.*	*Majeau-Bettez et al.*	*Majeau-Bettez et al.*	*P.T. Benavides et al.*
Production of positive electrode active material/electrode paste (Mixing)	*Majeau-Bettez et al.*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*	*Ellingsen et al., using this study's mass ratios*
Production of positive electrode substrate	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Assembly of positive electrode	*Ellingsen et al.*	*Ellingsen et al., using*	*Ellingsen et al., using*	*Ellingsen et al., using*	*Ellingsen et al., using*	*Ellingsen et al., using*

		this study's mass ratios	*this study's mass ratios*	*this study's mass ratios*	*this study's mass ratios*	*this study's mass ratios*

12.1.1.4.4.1 Assembly of NCA positive electrode

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Positive electrode (NCA)		**1.0E+0**	kg		
Materials input					
Positive current collector	0.198		kg	Positive current collector (Al)	Ellingsen et al.
Positive electrode paste	0.802		kg	Positive electrode paste (NCA)	*P.T. Benavides et al., Majeau-Bettez et al. & Ellingsen et al.*
Transport					
Transport by freight	5.5E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.4.4.1.1 Positive electrode paste

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Positive electrode paste (NCA)		**1.0E+0**	kg		
Materials input					
Binder	0.0182		kg	Polyvinylfluoride, at plant/US U	*Ecoinvent Centre*
Active material	0.962		kg	Lithium nickel cobalt aluminium	*P.T. Benavides et al. &*

					Majeau-Bettez
solvent	4.1E-1		kg	N-methyl-2-pyrrolidone, at plant/RER U	*Ecoinvent Centre*
Conductive carbon	0.0197		kg	Carbon black, at plant/GLO U	*Ecoinvent Centre*
Transport					
Transport by freight	4.6E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.4E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Evaporation of solvent	4.1E-1		kg	1-Methyl-2-pyrrolidinone	*Ecoinvent Centre*

12.1.1.4.4.1.1.1 Lithium nickel cobalt aluminium

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Lithium nickel cobalt aluminium		**1.0E+0**	kg		
Materials input					
	0.25		kg	Lithium hydroxide, at plant/GLO U	*Ecoinvent Centre*
	0.95			Nickel cobalt aluminium precursor	*P.T. Benavides et al. & Majeau-Bettez*
	0.04			Oxygen, liquid, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
	0.55		MJ	Heat, unspecific, in chemical plant/RER U	*Ecoinvent Centre*
Transport					

Transport by freight	0.72		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	0.12		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.6E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Heat, waste	5.5		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.4.4.1.1.1.1 Nickel Cobalt aluminium precursor

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Nickel cobalt aluminium precursor		**1.0E+0**	kg		
Materials input					
	0.88		kg	Sodium hydroxide, in ground	*Ecoinvent Centre*
	1.36			Nickel sulfate (NiSO4)	*Majeau-Bettez et al.*
	0.26			Cobalt sulphate (CoSO4)	*Majeau-Bettez et al.*
	0.09			Aluminium sulphate, powder, at plant/RER U	*Ecoinvent Centre*
	0.37			Ammonia, liquid, at regional storehouse/RER U	*Ecoinvent Centre*
Energy and Processes					
	0.042		MJ	Electricity, medium voltage, at grid/CN U	*Ecoinvent Centre*
	0.126		MJ	Heat, natural gas, at industrial furnace >100kW/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	1.5		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*

Transport by lorry	0.26		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.6E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Sodium sulfate	1.5		kg	Sodium sulfate	*Ecoinvent Centre*

12.1.1.5 Electrolytes

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of lithium fluoride	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*
Production of phosphorous pentachloride	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*
Production of lithium hexafluorophosphate	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*
Production of ethylene carbonate	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*
Assembly of LFP-C, LMO-C, NCA-C and NMC-C electrolytes (mixing of solvent and salts)	*Notter et al. (as referenced by Ellingsen) and using this study's mass ratios*	*Notter et al. (as referenced by Ellingsen) and using this study's mass ratios*	*Notter et al. (as referenced by Ellingsen) and using this study's mass ratios*	*Notter et al. (as referenced by Ellingsen) and using this study's mass ratios*	*Notter et al. (as referenced by Ellingsen) and using this study's mass ratios*	*Notter et al. (as referenced by Ellingsen) and using this study's mass ratios*

12.1.1.5.1 LFP-C electrolyte

12.1.1.5.1.1 Assembly of electrolyte (LFP-C)

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Electrolyte (LFP-C)		**1.0E+0**	kg		
Components					
Ethylene carbonate	0.862		kg	Ethylene carbonate	Notter et al.
LiPF6	0.138		kg	Lithium hexafluorophosphate (LiPF6)	Notter et al.
Transport					
Transport by freight	6.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Infrastructure, chemical plant	*Ecoinvent Centre*

12.1.1.5.1.1.1 Production of ethylene carbonate

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Ethylene carbonate		**1.0E+0**	kg		
Components					
Ethylene oxide	5.01E-1		kg	Ethylene oxide, at plant/RER U	*Ecoinvent Centre*
Carbon dioxide	5.05E-1			Carbon dioxide liquid, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
mechanical drive of labor mixer and pumps	2.0E-3		kWh	Electricity, medium voltage, at grid/CN U	*Ecoinvent Centre*
furnace of the reactor	1.43E-1		MJ	Heat, natural gas, at industrial furnace >100kW/RER U	*Ecoinvent Centre*
Transport					

Transport by freight	3.51E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.01E-1		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Ethylene oxide	2.5E-4		kg	Ethylene oxide	*Ecoinvent Centre*
Carbon dioxide	5.3E-3		kg	Carbon dioxide, fossil	*Ecoinvent Centre*
Waste heat to air	7.2E-3		MJ	Heat, waste	*Ecoinvent Centre*
Waste and emissions to treatment					
Catalyst	5.0E-3		kg	Disposal, catalyst base Eth.oxide prod., 0% water, to residual material landfill/CH U	*Ecoinvent Centre*

12.1.1.5.1.1.2 Lithium hexafluorophosphate

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Lithium hexafluorophosphate ($LiPF_6$)		**1.0E+0**	kg		
Components					
Lithium fluoride	1.97E-1		kg	Lithium fluoride	Notter et al.
Phosphorous pentachloride	1.98		kg	Phosphorous pentachloride	Notter et al.
Hydrogen fluoride	4.04		kg	Hydrogen fluoride, at plant/GLO U	*Ecoinvent Centre*
Nitrogen	1.25E-3		kg	Nitrogen, liquid, at plant/RER U	*Ecoinvent Centre*
Neutralisation and disposal of HF	7.44		kg	Nitrogen, liquid, at plant/RER U	*Ecoinvent Centre*

Energy and Processes					
Electricity	5.39E-1		kWh	Electricity, medium voltage, at grid/CN U	*Ecoinvent Centre*
For pumps, stirring, milling of LiPF6, etc.	2.0E-3		kWh	Electricity, medium voltage, at grid/CN U	*Ecoinvent Centre*
Transport					
Transport by freight	8.19		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.37		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Phosphorous trichloride	2.63E-1		kg	Phosphorus trichloride	*Ecoinvent Centre*
heat pump and laboratory apparatus	1.95		MJ	Heat, waste	*Ecoinvent Centre*
Waste and emissions to treatment					
disposal of KF and KCL	8.61		kg	Disposal, limestone residue, 5% water, to inert material landfill/CH U	*Ecoinvent Centre*
water from reaction for neutralisation of HF and HCl	3.61E-3		m^3	Treatment, sewage, to wastewater treatment, class 1/CH U	*Ecoinvent Centre*

12.1.1.5.1.1.2.1 Production of lithium fluoride

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Lithium fluoride		**1.0E+0**	kg		
Components					
lithium carbonate	1.49		kg	Lithium carbonate, at plant/GLO U	*Ecoinvent Centre*
Hydrogen fluoride	8.06E-1		kg	Hydrogen fluoride, at plant/GLO U	*Ecoinvent Centre*

Ammoniac	3.28E-2		kg	Ammonia, liquid, at regional storehouse/RER U	*Ecoinvent Centre*
Water	2.21		kg	Water, deionised, at plant/CH U	*Ecoinvent Centre*
Energy and Processes					
Process heat	1.21		MJ	Heat, natural gas, at industrial furnace >100kW/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	1.4		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	2.33E-1		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Hydrogen fluoride	3.63E-2		kg	Hydrogen fluoride	*Ecoinvent Centre*
Carbon dioxide from chemical reaction	8.86E-1		kg	Carbon dioxide, fossil	*Ecoinvent Centre*
Emissions to water					
Ammonium, ion	3.47E-2		kg	Ammonium, ion	*Ecoinvent Centre*
Waste and emissions to treatment					
Water from HF solution	2.21E-3		m^3	Treatment, sewage, to wastewater treatment, class 1/CH U	*Ecoinvent Centre*
Water from chemical reaction	3.63E-4		m^3	Treatment, sewage, to wastewater treatment, class 1/CH U	*Ecoinvent Centre*
from washing le LIF	1.0E-3		m^3	Treatment, sewage, to wastewater treatment, class 1/CH U	*Ecoinvent Centre*

12.1.1.5.1.1.2.2 Production of phosphorous pentachloride

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Phosphorous pentachloride		**1.0E+0**	kg		
Components					
Phosphorous trichloride	7.03E-1		kg	Phosphorous chloride, at plant/RER U	*Ecoinvent Centre*
Chlorine	3.63E-1		kg	Chlorine, liquid, production mix, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
Electricity, medium voltage, at grid/CN U	2.0E-3		kWh	Electricity, medium voltage, at grid/CN U	*Ecoinvent Centre*
Furnace of the reactor	8.67E-2		MJ	Heat, natural gas, at industrial furnace >100kW/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	4.58E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.07E-1		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
Waste heat to air	7.2E-3		MJ	Heat, waste	*Ecoinvent Centre*

12.1.1.5.2 LMO-C electrolyte

12.1.1.5.3 Assembly of electrolyte (LMO-C)

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Electrolyte (LMO-C)		**1.0E+0**	kg		
Components					

Ethylene carbonate	0.894		kg	Ethylene carbonate	Notter et al.
LiPF6	0.106		kg	Lithium hexafluorophosphate (LiPF6)	Notter et al.
Transport					
Transport by freight	6.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Infrastructure, chemical plant	*Ecoinvent Centre*

12.1.1.5.4 NMC-C electrolyte

12.1.1.5.5 Assembly of electrolyte (NMC-C)

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Electrolyte (NMC-C)		**1.0E+0**	kg		
Components					
Ethylene carbonate	0.880		kg	Ethylene carbonate	Notter et al.
LiPF6	0.120		kg	Lithium hexafluorophosphate (LiPF6)	Notter et al.
Transport					
Transport by freight	6.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Infrastructure, chemical plant	*Ecoinvent Centre*

12.1.1.5.6 NCA-C electrolyte

12.1.1.5.7 Assembly of electrolyte (NCA-C)

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Electrolyte (NCA-C)		**1.0E+0**	kg		
Components					
Ethylene carbonate	0.882		kg	Ethylene carbonate	Notter et al.
LiPF6	0.118		kg	Lithium hexafluorophosphate (LiPF6)	Notter et al.
Transport					
Transport by freight	6.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Infrastructure, chemical plant	*Ecoinvent Centre*

12.1.1.6 Separator

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of a separator	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*	*Notter et al.*

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Separator		**1.0E+0**	kg		
Components					
foil, carrier for slurry	3.51E-1		kg	Fleece, polyethylene, at plant/RER U	*Ecoinvent Centre*
PVDF	1.92E-1		kg	Polyvinylfluoride, at plant/US U	*Ecoinvent Centre*

Hexafluoroethane	2.62E-2		kg	Hexafluoroethane {GLO}| market for | Alloc Def, U	*Ecoinvent Centre*
Phthalyic anhydride	2.91E-1		kg	Phthalic anhydride, at plant/RER U	*Ecoinvent Centre*
Silica sand	2.18E-1		kg	Silica sand, at plant/DE U	*Ecoinvent Centre*
Acetone	1.44E-2		kg	Acetone, liquid, at plant/RER U	*Ecoinvent Centre*
Energy and Processes					
Mechanical drive for pumping slurry, coating, coiling, cutting	2.00E-3		kWh	Electricity, medium voltage, at grid/CN U	*Ecoinvent Centre*
Evaporating solvent, heating seperator base materials	1.93E-1		MJ	Heat, natural gas, at industrial furnace >100kW/RER U	*Ecoinvent Centre*
Transport					
Transport by freight	5.25E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	9.84E-2		tkm	Transport, lorry >16t, fleet average/RER U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical plant, organics/RER/I U	*Ecoinvent Centre*
Emissions to air					
evaporating solvent	1.44E-2		kg	Acetone	*Ecoinvent Centre*
Heat and electric power	7.2E-3		MJ	Heat, waste	*Ecoinvent Centre*
Waste and emissions to treatment					
5% loss, according to ecoinvent assumption for missing information, included waste from slitting the coils	5.39E-2		kg	Disposal, residues, shredder fraction from manual dismantling, in MSWI/CH U	*Ecoinvent Centre*

12.1.1.7 Cell container

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of copper tab	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of aluminum tab	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of multilayer pouch	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of cell container	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Cell container		**1.0E+0**	kg		
Components					
Tab Aluminium	2.2E-1		kg		Ellingsen et al.
Tab Copper	3.8E-1		kg		Ellingsen et al.
Multilayer pouch	4.0E-1		kg		Ellingsen et al.
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.7.1 Aluminium tab

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Tab, aluminum		**1.0E+0**	kg		

Components					
Tab, aluminium	1.0E+0		kg	aluminium, production mix, at plant/ RER	*Ecoinvent Centre*
Energy and Processes					
production of aluminium tab	1.0E+0		kg	sheet rolling, aluminium/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	1.5E-10		p	aluminium casting, plant/ RER/ unit	*Ecoinvent Centre*

12.1.1.7.2 Copper tab

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Tab, copper		**1.0E+0**	kg		
Components					
Tab, primary copper share	8.5E-1		kg	copper, primary, at refinery/ GLO/ kg	*Ecoinvent Centre*
Tab, secondary copper share	1.5E-1		kg	copper, secondary, at refinery/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of copper tab	1.0E+0		kg	sheet rolling, copper/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.6E-10		p	metal working factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.7.3 Multilayer pouch

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Multilayer pouch		**1.0E+0**	kg		
Components					
Aluminium	5.0E-1		kg	aluminium, production mix, at plant/ RER	*Ecoinvent Centre*
PETP	7.8E-2		kg	polyethylene terephthalate, granulate	*Ecoinvent Centre*
Oriented nylon	8.0E-2		kg	nylon 6, at plant/ RER/ kg	*Ecoinvent Centre*
PP	3.2E-1		kg	polypropylene, granulate, at plant/ RER/	*Ecoinvent Centre*
Dry lamination	2.5E-2		kg	packaging film, LDPE, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of nylon, PP and PETP	4.7E-1		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Production of aluminium material in pouch	5.0E-1		kg	sheet rolling, aluminium/ RER/ kg	*Ecoinvent Centre*
Infrastructure					
Facility	7.7E-11		p	aluminium casting, plant/ RER/ unit	*Ecoinvent Centre*
Facility	3.5E-10			plastics processing factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.8 Battery packaging

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of battery pack packaging (assembly)	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.

12.1.1.8.1 Assembly of battery packaging

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Battery packaging		**1.0E+0**	kg		
Components					
Module packaging	5.9E-1		kg	Module packaging	*Miljøbil*
Battery retention	1.1E-1		kg	Battery retention	*Miljøbil*
Battery tray	3.0E-1		kg	Battery tray	*Miljøbil*
Transport					
Transport by lorry	1.5E-1		tkm	transport, lorry >16t, fleet average/ RER/ tkm	*Ecoinvent Centre*
Shipping from Asia to Norway	4.8E+0		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.8.1.1Module packaging

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructu re LCI	Materials output LCI
Production of module fasteners	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of outer frame	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of inner frame	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Prodution of bimetalic busbars and washers	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of aluminum end-busbars	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of copper end-busbars	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*

Production of module lid	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of module packaging (assembly)	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*

12.1.1.8.1.1.1 Assembly of module packaging

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Module packaging		**1.0E+0**	kg		
Components					
Module fasteners	4.8E-2		kg		Ellingsen et al.
Outer frame	4.8E-1		kg		Ellingsen et al.
Inner frame	4.0E-1		kg		Ellingsen et al.
Bimetallic busbars and washers	3.4E-2		kg		Ellingsen et al.
End-busbar, aluminium	1.6E-3		kg		Ellingsen et al.
End-busbar, copper	4.9E-3		kg		Ellingsen et al.
Module lid	2.8E-2		kg		Ellingsen et al.
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	1.9E-8		p	facilities precious metal refinery/ SE/ unit	*Ecoinvent Centre*

12.1.1.8.1.1.1.1 Module fasteners

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Module fasteners		**1.0E+0**	kg		
Components					
Total fasteners, steel	9.6E-1		kg	steel, low-alloyed, at plant/ RER/ kg	*Ecoinvent Centre*
Washer, nylon	4.2E-2		kg	nylon 6, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of fasteners	9.6E-1		kg	steel product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Production of nylon washer	4.2E-2		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.4E-10		p	metal working factory/ RER/ unit	*Ecoinvent Centre*
Facility	3.1E-11		p	plastics processing factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.1.1.2 Outer frame

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Outer frame		**1.0E+0**	kg		
Components					
Cassette outside frame, zytel	3.0E-1		kg	nylon 66, glass-filled, at plant/ RER/ kg	*Ecoinvent Centre*
Heat transfer plate, anodized aluminium	7.0E-1			aluminium, production mix, at plant/ RER/ kg	

Energy and Processes					
Production of cassette outside frame	3.0E-1		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Anodizing heat transfer plate	3.0E-2		m2	anodising, aluminium sheet/ RER/ m2	*Ecoinvent Centre*
Production of heat transfer plate	7.0E-1		kg	sheet rolling, aluminium/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	2.2E-10		p	plastics processing factory/ RER/ unit	*Ecoinvent Centre*
Facility	1.1E-10		p	aluminium casting, plant/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.1.1.3 Inner frame

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Inner frame		**1.0E+0**	kg		
Components					
Cassette inside frame, zytel	3.5E-1		kg	nylon 66, glass-filled, at plant/ RER/ kg	*Ecoinvent Centre*
Heat transfer plate, anodized aluminum	6.5E-1		kg	aluminium, production mix, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of cassette outside frame	3.5E-1		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Anodizing heat fransfer plate	3.0E-2		m2	anodising, aluminium sheet/ RER/ m2	*Ecoinvent Centre*
Production of heat transfer plate	6.5E-1		kg	sheet rolling, aluminium/ RER/ kg	*Ecoinvent Centre*
Transport					

Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	2.6E-10		p	plastics processing factory/ RER/ unit	*Ecoinvent Centre*
Facility	1.0E-10		p	aluminium casting, plant/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.1.1.4 Bimetallic busbars and washers

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Bimetallic busbars and washers		**1.0E+0**	kg		
Components					
Busbar and washer, aluminium (30%)	2.5E-1		kg	aluminium, production mix, at plant/ RER/ kg	*Ecoinvent Centre*
Busbar and washer, copper (70%*85%, primary)	4.9E-1		kg	copper, primary, at refinery/ GLO/ kg	*Ecoinvent Centre*
Busbar and washer, copper (70%*15%, secondary)	8.6E-2		kg	copper, secondary, at refinery/ RER/ kg	*Ecoinvent Centre*
Double busbar holder	1.7E-1		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of Al part of busbar	2.5E-1		kg	aluminium product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Production of Cu part of busbar	5.7E-1		kg	copper product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Production of double busbar holder	1.7E-1		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Transport					

Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	3.8E-10		p	metal working factory/ RER/ unit	*Ecoinvent Centre*
Facility	1.3E-10		p	plastics processing factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.1.1.5 Aluminum end-busbars

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
End-busbar, aluminum		**1.0E+0**	kg		
Components					
Endbusbar, aluminum	9.1E-1		kg	aluminium, production mix, at plant/ RER/ kg	*Ecoinvent Centre*
Endbusbar holder, ABS	9.1E-2		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of aluminum parts	9.1E-1		kg	aluminium product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Production of endbusbar holder	9.1E-2		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	1.4E-10		p	aluminium casting, plant/ RER/ unit	*Ecoinvent Centre*
Facility	6.7E-11		p	plastics processing factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.1.6 Copper end-busbars

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
End-busbar, copper		**1.0E+0**	kg		
Components					
Endbusbar, primary copper	8.2E-1		kg	copper, primary, at refinery/ GLO/ kg	*Ecoinvent Centre*
Endbusbar, secondary copper	1.5E-1		kg	copper, secondary, at refinery/ RER/ kg	*Ecoinvent Centre*
Endbusbar holder, ABS	3.1E-2		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of Cu endbusbar	9.7E-1		kg	copper product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Production of endbusbar holder	3.1E-2		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.4E-10		p	metal working factory/ RER/ unit	*Ecoinvent Centre*
Facility	2.3E-11			plastics processing factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.1.7 Module lid

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Module lid		**1.0E+0**	kg		
Components					

Plastic lid	1.0E+0		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of lid	1.0E+0		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	7.4E-10		p	plastics processing factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.2 Battery retention

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of strap retention	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of lower retention	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of propagation plate	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Assembly of battery retention (assembly)	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*

12.1.1.8.1.2.1 Assembly of battery retention

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Battery retention		**1.0E+0**	kg		

Components					
Strap retention	8.7E-2		kg	Strap retention	Ellingsen et al.
Lower retention	3.5E-1		kg	Lower retention	Ellingsen et al.
Heat transfer plate	4.6E-1		kg	Heat transfer plate	Ellingsen et al.
Foam retention	1.0E-1		kg	synthetic rubber, at plant/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.8.1.2.1.1 Strap retention

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Strap retention		**1.0E+0**	kg		
Components					
Screws, bolts, and retainer plate	4.9E-1		kg	steel, low-alloyed, at plant/ RER/ kg	*Ecoinvent Centre*
Straps	1.3E-1		kg	nylon 6, at plant/ RER/ kg	*Ecoinvent Centre*
Bracket	3.8E-1		kg	polypropylene, granulate, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of steel products	4.9E-1		kg	steel product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Production of straps and bracket	5.1E-1		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*

Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	2.2E-10		p	metal working factory/ RER/ unit	*Ecoinvent Centre*
Facility	3.8E-10		p	plastics processing factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.2.1.2 Lower retention

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Lower retention		**1.0E+0**	kg		
Components					
Lower retention, steel	1.0E+0		kg	steel, low-alloyed, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of restraints and bolt	1.0E+0		kg	steel product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.6E-10		p	metal working factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.2.1.3 Heat transfer plate

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Heat transfer plate		**1.0E+0**	kg		
Components					

Heat transfer plate, steel	1.0E+0		kg	steel, low-alloyed, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of heat transfer plate	1.0E+0		kg	steel product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.6E-10		p	metal working factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.3Battery tray

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of tray with fasteners	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.
Production of tray lid	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.
Production of tray seal	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.
Production of battery tray (assembly)	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.	Ellingsen et al.

12.1.1.8.1.3.1 Assembly of battery tray

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Battery tray		**1.0E+0**	kg		

Components					
Tray with fasteners	7.9E-1		kg	Tray with fasteners	*Miljøbil*
Tray lid	2.1E-1		kg	Tray lid	*Miljøbil*
Tray seal	4.1E-4		kg	Tray seal	*Miljøbil*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.8.1.3.1.1 Tray with fasteners

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Tray with fasteners		**1.0E+0**	kg		
Components					
Battery tray and fixings, steel	1.0E+0		kg	steel, low-alloyed, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of tray and fixings	1.0E+0		kg	steel product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.6E-10		p	metal working factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.3.1.2 Tray lid

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Tray lid		**1.0E+0**	kg		

Components					
Tray lid, polyproylene	1.0E+0		kg	polypropylene, granulate, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of lid	1.0E+0		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	7.4E-10		p	plastics processing factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.8.1.3.1.3 Tray seal

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Tray seal		**1.0E+0**	kg		
Components					
Tray seal, butyl acrylate	1.0E+0		kg	butyl acrylate, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of seal	1.0E+0		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	7.4E-10		p	plastics processing factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.9 BMS

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of high-voltage system	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of low-voltage system	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of IBIS fasteners	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of IBIS	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of BMS (assembly)	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
BMS		**1.0E+0**	kg		
Components					
BMB	8.9E-2		kg	printed wiring board, through-hole mounted, unspec., Pb free, at plant/ GLO/ kg	*Ecoinvent Centre*
IBIS	4.8E-1		kg	IBIS	*Miljøbil*
IBIS fasteners	3.0E-3		kg	IBIS fasteners	*Miljøbil*
High Voltage system	3.0E-1		kg	High Voltage system	*Miljøbil*
Low Voltage system	1.3E-1		kg	Low Voltage system	*Miljøbil*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.9.1 IBIS

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
IBIS		**1.0E+0**	kg		
Components					
BMS_GLAND_O-RING	2.0E-4		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg	*Ecoinvent Centre*
BMS printed circuit board	1.1E-1		kg	printed wiring board, through-hole mounted, unspec., Pb free, at plant/ GLO/ kg	*Ecoinvent Centre*
BMS_FIRMWARE	1.7E-5		kg	integrated circuit, IC, logic type, at plant/ GLO/ kg	*Ecoinvent Centre*
Components, steel	8.5E-1		kg	steel, low-alloyed, at plant/ RER/ kg	*Ecoinvent Centre*
Connectors	2.1E-2		kg	connector, clamp connection, at plant/ GLO/ kg	*Ecoinvent Centre*
Crimp housing	6.8E-3		kg	polyethylene terephthalate, granulate, amorphous, at plant/ RER/ kg	*Ecoinvent Centre*
Standoffs, nylon part	1.9E-3		kg	nylon 6, at plant/ RER/ kg	*Ecoinvent Centre*
Standoffs, brasspart	5.7E-3		kg	brass, at plant/ CH/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of steel products	8.5E-1		kg	steel product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Production of nylon and plastics	8.8E-3		kg	injection moulding/ RER/ kg	
Production of bolt for micro stan	5.7E-3		kg	casting, brass/ CH/ kg	
Transport					
Transport by freight	1.7E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*

Transport by lorry	8.7E-2		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	2.0E-8		p	electronic component production plant/ GLO/ unit	*Ecoinvent Centre*

12.1.1.9.2 IBIS fasteners

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
IBIS fasteners		**1.0E+0**	kg		
Components					
Fixings	1.0E+0		kg	steel, low-alloyed, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of fixings	1.0E+0		kg	steel product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.6E-10		p	metal working factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.9.3 High voltage system

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
High Voltage system		**1.0E+0**	kg		
Components					
Steel products	1.4E-3		kg	steel, low-alloyed, at plant/ RER/ kg	*Ecoinvent Centre*

HVC and lid	1.2E-1		kg	aluminium, production mix, at plant/ RER/ kg	*Ecoinvent Centre*
Clips & fasteners	4.4E-2		kg	nylon 66, at plant/ RER/ kg	*Ecoinvent Centre*
Neoprene gasket	3.6E-3		kg	synthetic rubber, at plant/ RER/ kg	*Ecoinvent Centre*
Plastic	5.7E-2		kg	polyethylene terephthalate, granulate, amorphous, at plant/ RER/ kg	*Ecoinvent Centre*
Intermodule Fuse	2.3E-1		kg	copper, primary, at refinery/ GLO/ kg	*Ecoinvent Centre*
Intermodule Fuse	4.1E-2		kg	copper, secondary, at refinery/ RER/ kg	*Ecoinvent Centre*
Intermodule Fuse	3.2E-2		kg	polyphenylene sulfide, at plant/ GLO/ kg	*Ecoinvent Centre*
Intermodule Fuse	1.6E-2		kg	tin, at regional storage/ RER/ kg	*Ecoinvent Centre*
Cables	4.5E-1		kg	cable, ribbon cable, 20-pin, with plugs, at plant/ GLO/ kg	*Ecoinvent Centre*
Energy and Processes					
Production of steel products	1.4E-3		kg	steel product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Production of aluminum products	1.2E-1		kg	aluminium product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Production of plastic products	1.4E-1		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Production of copper for fuse	2.7E-1		kg	copper product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Production of tin product	1.6E-2		kg	metal product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	1.1E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	5.5E-2		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

Infrastructure					
Facility	2.0E-8		p	electronic component production plant/ GLO/ unit	*Ecoinvent Centre*

12.1.1.9.4 Low voltage system

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Low Voltage system		**1.0E+0**	kg		
Components					
Clips	2.9E-2		kg	nylon 66, at plant/ RER/ kg	*Ecoinvent Centre*
Harnesses	9.7E-1			electronic component, passive, unspecified, at plant/ GLO/ kg	
Energy and Processes					
Production of clips	2.9E-2		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	2.0E-8		p	electronic component production plant/ GLO/ unit	*Ecoinvent Centre*

12.1.1.10 Cooling system

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Production of radiator	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Prodution of manifolds	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*

Production of clamps and fasteners	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of pipe fitting	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of thermal pad	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*
Production of the cooling system (assembly)	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*	*Ellingsen et al.*

12.1.1.10.1 Cooling system

Description	**Input**	**Output**	**Unit**	**Process name in SimaPro libraries**	**Reference**
Functional Unit					
Cooling system		**1.0E+0**	kg		
Components					
Radiator	8.7E-1		kg	Radiator	*Miljøbil*
Manifolds	3.8E-2		kg	Manifolds	*Miljøbil*
Clamps & fasteners	2.3E-2		kg	Clamps & fasteners	*Miljøbil*
Pipe fitting	9.6E-4		kg	Pipe fitting	*Miljøbil*
Thermal pad	2.0E-2		kg	Thermal pad	*Miljøbil*
Coolant	4.8E-2		kg	ethylene glycol, at plant/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.2E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*

12.1.1.10.2 Radiator

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					

Radiator		**1.0E+0**	kg		
Components					
Insulation pad, top plate, matrix plate	1.0E+0		kg	aluminium, production mix, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
Proxy for production	1.0E+0		kg	sheet rolling, aluminium/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	1.5E-10		p	aluminium casting, plant/ RER/ unit	*Ecoinvent Centre*

12.1.1.10.3 Manifolds

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Manifolds		**1.0E+0**	kg		
Components					
Manifolds	1.0E+0		kg	aluminium, production mix, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
proxy for production	1.0E+0		kg	aluminium product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	1.5E-10		p	aluminium casting, plant/ RER/ unit	*Ecoinvent Centre*

12.1.1.10.4 Clamps and fasteners

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Clamps & fasteners		**1.0E+0**	kg		
Components					
Clamps & fasteners	1.0E+0		kg	steel, low-alloyed, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
proxy for production	1.0E+0		kg	steel product manufacturing, average metal working/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	4.6E-10		p	metal working factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.10.5 Pipe fitting

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Pipe fitting		**1.0E+0**	kg		
Components					
Pipe fitting plastic	7.5E-1		kg	polyvinylchloride, at regional storage/ RER/ kg	*Ecoinvent Centre*
Pipe Fitting rubber	2.5E-1		kg	synthetic rubber, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
proxy for production			kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*

Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	7.4E-10		p	plastics processing factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.10.6 Thermal pad

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Thermal pad		**1.0E+0**	kg		
Components					
Thermal pad, glass fibre	1.0E-1		kg	glass fibre, at plant/ RER/ kg	*Ecoinvent Centre*
Thermal pad, silicon	3.0E-1		kg	silicon, electronic grade, at plant/ DE/ kg	*Ecoinvent Centre*
Thermal pad, ABS	6.0E-1		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg	*Ecoinvent Centre*
Energy and Processes					
proxy for production	1.0E+0		kg	injection moulding/ RER/ kg	*Ecoinvent Centre*
Transport					
Transport by freight	2.0E-1		tkm	transport, freight, rail/ RER/ tkm	*Ecoinvent Centre*
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm	*Ecoinvent Centre*
Infrastructure					
Facility	7.4E-10		p	plastics processing factory/ RER/ unit	*Ecoinvent Centre*

12.1.1.11 Hybrid current inverter

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI

Production of battery grade graphite	*Ecoinvent 3*	*Ecoinvent 3*	*Ecoinvent 3*	*Ecoinvent 3*	*Ecoinvent 3*	*Ecoinvent 3*

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Hybrid current inverter		**1.0E+0**	kg		
Components					
Hybrid current inverter	1.0E+0		kg	Transformer, high voltage use, at plant/GLO U	*Ecoinvent Centre*

12.2 End of life stage

Process name	Process chain	Materials input LCI	Energy input LCI	Transport LCI	Infrastructure LCI	Materials output LCI
Treatment of non-Fe-Co-metals, from used residential Li-ion battery, hydrometallurgical processing (LFP-C; LMO-C; NMC-C; NCA-C)	Ecoinvent 3, adapted to this study	Ecoinvent 3, adapted to this study	Ecoinvent 3, adapted to this study	Ecoinvent 3, adapted to this study	Ecoinvent 3, adapted to this study	Ecoinvent 3, adapted to this study
Treatment of used residential li-ion battery, hydrometallurgical treatment (LFP-C; LMO-C; NMC-C; NCA-C)	Ecoinvent 3, adapted to this study	Ecoinvent 3, adapted to this study	Ecoinvent 3, adapted to this study	Ecoinvent 3, adapted to this study	Ecoinvent 3, adapted to this study	Ecoinvent 3, adapted to this study

12.2.1 Treatment of used li-ion residential battery, hydrometallurgical treatment

12.2.1.1 LFP-C

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Used Li-ion battery {GLO}| treatment of used Li-ion battery, hydrometallurgical treatment | Conseq, U (LFP-C) Res		**1.0E+0**	kg		
Materials input					
	0.00072		m^3	Water, unspecified natural origin, GLO	*Ecoinvent Centre*
	-0.165		kg	Iron scrap, unsorted {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.116		kg	Lime, hydrated, packed {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.23058		kg	Sulfuric acid {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	-0.04218		kg	Lithium carbonate {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.025		kg	Chemical, inorganic {GLO}| market for chemicals, inorganic | Conseq, U	*Ecoinvent Centre*
Energy and Processes					
	0.14		kWh	Electricity, medium voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical factory, organics {GLO}| market for | Conseq, U	*Ecoinvent Centre*
Emissions to air					
Sulfur dioxide	4.5E-6		kg	Sulfur dioxide	*Ecoinvent Centre*

Water	0.000108		m^3	Water/m3	*Ecoinvent Centre*
NMVOC	2.5E-6		kg	NMVOC, non-methane volatile organic compounds, unspecified origin	*Ecoinvent Centre*
Emissions to water					
	0.000612		m^3	Water, GLO	*Ecoinvent Centre*
	1.0E-8		kg	Hydrocarbons, unspecified	*Ecoinvent Centre*
	6.0E-5		kg	BOD5, Biological Oxygen Demand	*Ecoinvent Centre*
	1.7E-8		kg	Cobalt	*Ecoinvent Centre*
	3.0E-5		kg	COD, Chemical Oxygen Demand	*Ecoinvent Centre*
	1.65E-8		kg	Nickel	*Ecoinvent Centre*
	3.0E-8		kg	Fluoride	*Ecoinvent Centre*
	1.65E-8		kg	Copper	*Ecoinvent Centre*
	1.11111111111111E-5		kg	TOC, Total Organic Carbon	*Ecoinvent Centre*
	1.2E-5		kg	Suspended solids, unspecified	*Ecoinvent Centre*
	1.11111111111111E-5		kg	DOC, Dissolved Organic Carbon	*Ecoinvent Centre*
Waste and emissions to treatment					
	0.15		kg	Non-Fe-Co-metals, from Li-ion battery, hydrometallurgical processing {GLO}| market for | Conseq, U (LFP-C)	*Ecoinvent Centre, adapted for this study*

	0.0787800680723281		kg	Waste gypsum {Europe without Switzerland}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*
	0.003724008540136 03		kg	Waste gypsum {CH}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*
	0.256495923387536		kg	Waste gypsum {RoW}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*
	0.005350472101350 52		kg	Waste plastic, mixture {Europe without Switzerland}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.000348453639088 094		kg	Waste plastic, mixture {CH}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.0593010742595614		kg	Waste plastic, mixture {RoW}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.0122419779008239		kg	Waste graphical paper {Europe without Switzerland}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.000323282174386 735		kg	Waste graphical paper {CH}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.0524347399247894		kg	Waste graphical paper {RoW}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.502		kg	Inert waste, for final disposal {CH}| market for inert waste, for final disposal | Conseq, U	*Ecoinvent Centre*

12.2.1.2 LMO-C

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Used Li-ion battery {GLO}| treatment of used Li-ion battery, hydrometallurgical treatment | Conseq, U (LMO-C) Res		**1.0E+0**	kg		
Materials input					
	0.00072		m^3	Water, unspecified natural origin, GLO	*Ecoinvent Centre*
	-0.165		kg	Iron scrap, unsorted {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.116		kg	Lime, hydrated, packed {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.23058		kg	Sulfuric acid {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	-0.01776		kg	Lithium carbonate {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.025		kg	Chemical, inorganic {GLO}| market for chemicals, inorganic | Conseq, U	*Ecoinvent Centre*
Energy and Processes					
	0.14		kWh	Electricity, medium voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical factory, organics {GLO}| market for | Conseq, U	*Ecoinvent Centre*
Emissions to air					
Sulfur dioxide	4.5E-6		kg	Sulfur dioxide	*Ecoinvent Centre*
Water	0.000108		m^3	Water/m3	*Ecoinvent Centre*

NMVOC	2.5E-6		kg	NMVOC, non-methane volatile organic compounds, unspecified origin	*Ecoinvent Centre*
Emissions to water					
	0.000612		m^3	Water, GLO	*Ecoinvent Centre*
	1.0E-8		kg	Hydrocarbons, unspecified	*Ecoinvent Centre*
	6.0E-5		kg	BOD5, Biological Oxygen Demand	*Ecoinvent Centre*
	1.7E-8		kg	Cobalt	*Ecoinvent Centre*
	3.0E-5		kg	COD, Chemical Oxygen Demand	*Ecoinvent Centre*
	1.65E-8		kg	Nickel	*Ecoinvent Centre*
	3.0E-8		kg	Fluoride	*Ecoinvent Centre*
	1.65E-8		kg	Copper	*Ecoinvent Centre*
	1.11111111111111E-5		kg	TOC, Total Organic Carbon	*Ecoinvent Centre*
	1.2E-5		kg	Suspended solids, unspecified	*Ecoinvent Centre*
	1.11111111111111E-5		kg	DOC, Dissolved Organic Carbon	*Ecoinvent Centre*
Waste and emissions to treatment					
	0.15		kg	Non-Fe-Co-metals, from Li-ion battery, hydrometallurgical processing {GLO}| market for | Conseq, U (LFP-C)	*Ecoinvent Centre, adapted for this study*
	0.07878006807232 81		kg	Waste gypsum {Europe without Switzerland}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*

	0.003724008540136 03		kg	Waste gypsum {CH}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*
	0.256495923387536		kg	Waste gypsum {RoW}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*
	0.005350472101350 52		kg	Waste plastic, mixture {Europe without Switzerland}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.000348453639088 094		kg	Waste plastic, mixture {CH}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.059301074259561 4		kg	Waste plastic, mixture {RoW}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.012241977900823 9		kg	Waste graphical paper {Europe without Switzerland}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.000323282174386 735		kg	Waste graphical paper {CH}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.052434739924789 4		kg	Waste graphical paper {RoW}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.502		kg	Inert waste, for final disposal {CH}| market for inert waste, for final disposal | Conseq, U	*Ecoinvent Centre*

12.2.1.3 NMC-C

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					

Used Li-ion battery {GLO}| treatment of used Li-ion battery, hydrometallurgical treatment | Conseq, U (NMC-C) Res		**1.0E+0**	kg		
Materials input					
	0.00072		m^3	Water, unspecified natural origin, GLO	*Ecoinvent Centre*
	-0.165		kg	Iron scrap, unsorted {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.116		kg	Lime, hydrated, packed {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.23058		kg	Sulfuric acid {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	-0.01786		kg	Cobalt {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	-0.060		kg	Lithium carbonate {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.025		kg	Chemical, inorganic {GLO}| market for chemicals, inorganic | Conseq, U	*Ecoinvent Centre*
Energy and Processes					
	0.14		kWh	Electricity, medium voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical factory, organics {GLO}| market for | Conseq, U	*Ecoinvent Centre*
Emissions to air					
Sulfur dioxide	4.5E-6		kg	Sulfur dioxide	*Ecoinvent Centre*
Water	0.000108		m^3	Water/m3	*Ecoinvent Centre*
NMVOC	2.5E-6		kg	NMVOC, non-methane volatile organic compounds, unspecified origin	*Ecoinvent Centre*

Emissions to water					
	0.000612		m^3	Water, GLO	*Ecoinvent Centre*
	1.0E-8		kg	Hydrocarbons, unspecified	*Ecoinvent Centre*
	6.0E-5		kg	BOD5, Biological Oxygen Demand	*Ecoinvent Centre*
	1.7E-8		kg	Cobalt	*Ecoinvent Centre*
	3.0E-5		kg	COD, Chemical Oxygen Demand	*Ecoinvent Centre*
	1.65E-8		kg	Nickel	*Ecoinvent Centre*
	3.0E-8		kg	Fluoride	*Ecoinvent Centre*
	1.65E-8		kg	Copper	*Ecoinvent Centre*
	1.11111111111111E-5		kg	TOC, Total Organic Carbon	*Ecoinvent Centre*
	1.2E-5		kg	Suspended solids, unspecified	*Ecoinvent Centre*
	1.11111111111111E-5		kg	DOC, Dissolved Organic Carbon	*Ecoinvent Centre*
Waste and emissions to treatment					
	0.15		kg	Non-Fe-Co-metals, from Li-ion battery, hydrometallurgical processing {GLO}| market for | Conseq, U (LFP-C)	*Ecoinvent Centre, adapted for this study*
	0.07878006807232811		kg	Waste gypsum {Europe without Switzerland}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*
	0.003724008540136003		kg	Waste gypsum {CH}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*

	0.256495923387536		kg	Waste gypsum {RoW}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*
	0.005350472101350 52		kg	Waste plastic, mixture {Europe without Switzerland}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.000348453639088 094		kg	Waste plastic, mixture {CH}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.059301074259561 4		kg	Waste plastic, mixture {RoW}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.012241977900823 9		kg	Waste graphical paper {Europe without Switzerland}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.000323282174386 735		kg	Waste graphical paper {CH}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.052434739924789 4		kg	Waste graphical paper {RoW}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.502		kg	Inert waste, for final disposal {CH}| market for inert waste, for final disposal | Conseq, U	*Ecoinvent Centre*

12.2.1.4 NCA-C

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Used Li-ion battery {GLO}| treatment of used Li-ion battery, hydrometallurgical		**1.0E+0**	kg		

treatment | Conseq, U (NCA-C) Res					
Materials input					
	0.00072		m^3	Water, unspecified natural origin, GLO	*Ecoinvent Centre*
	-0.165		kg	Iron scrap, unsorted {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.116		kg	Lime, hydrated, packed {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.23058		kg	Sulfuric acid {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	-0.0111		kg	Cobalt {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	-0.0492		kg	Lithium carbonate {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.025		kg	Chemical, inorganic {GLO}| market for chemicals, inorganic | Conseq, U	*Ecoinvent Centre*
Energy and Processes					
	0.14		kWh	Electricity, medium voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical factory, organics {GLO}| market for | Conseq, U	*Ecoinvent Centre*
Emissions to air					
Sulfur dioxide	4.5E-6		kg	Sulfur dioxide	*Ecoinvent Centre*
Water	0.000108		m^3	Water/m3	*Ecoinvent Centre*
NMVOC	2.5E-6		kg	NMVOC, non-methane volatile organic compounds, unspecified origin	*Ecoinvent Centre*
Emissions to water					
	0.000612		m^3	Water, GLO	*Ecoinvent Centre*

	1.0E-8		kg	Hydrocarbons, unspecified	*Ecoinvent Centre*
	6.0E-5		kg	BOD5, Biological Oxygen Demand	*Ecoinvent Centre*
	1.7E-8		kg	Cobalt	*Ecoinvent Centre*
	3.0E-5		kg	COD, Chemical Oxygen Demand	*Ecoinvent Centre*
	1.65E-8		kg	Nickel	*Ecoinvent Centre*
	3.0E-8		kg	Fluoride	*Ecoinvent Centre*
	1.65E-8		kg	Copper	*Ecoinvent Centre*
	1.11111111111111E-5		kg	TOC, Total Organic Carbon	*Ecoinvent Centre*
	1.2E-5		kg	Suspended solids, unspecified	*Ecoinvent Centre*
	1.11111111111111E-5		kg	DOC, Dissolved Organic Carbon	*Ecoinvent Centre*
Waste and emissions to treatment					
	0.15		kg	Non-Fe-Co-metals, from Li-ion battery, hydrometallurgical processing {GLO}| market for | Conseq, U (LFP-C)	*Ecoinvent Centre, adapted for this study*
	0.07878006807232 81		kg	Waste gypsum {Europe without Switzerland}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*
	0.00372400854013603		kg	Waste gypsum {CH}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*
	0.256495923387536		kg	Waste gypsum {RoW}| market for waste gypsum | Conseq, U	*Ecoinvent Centre*

	0.005350472101350 52		kg	Waste plastic, mixture {Europe without Switzerland}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.000348453639088 094		kg	Waste plastic, mixture {CH}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.059301074259561 4		kg	Waste plastic, mixture {RoW}| market for waste plastic, mixture | Conseq, U	*Ecoinvent Centre*
	0.012241977900823 9		kg	Waste graphical paper {Europe without Switzerland}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.000323282174386 735		kg	Waste graphical paper {CH}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.052434739924789 4		kg	Waste graphical paper {RoW}| market for waste graphical paper | Conseq, U	*Ecoinvent Centre*
	0.502		kg	Inert waste, for final disposal {CH}| market for inert waste, for final disposal | Conseq, U	*Ecoinvent Centre*

12.2.2 Treatment of non-Fe-Co-metals, from used Li-ion residential battery, hydrometallurgical processing

12.2.2.1 LFP-C

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Non-Fe-Co-metals, from Li-ion battery, hydrometallurgical processing {GLO}|		**1.0E+0**	kg		

treatment of non-Fe-Co-metals, from used Li-ion battery, hydrometallurgical processing | Conseq, U (LFP-C)					
Materials input					
	0.17		m^3	Water, river, GLO	*Ecoinvent Centre*
	-1.7		kg	Sulfuric acid {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	-0.0706		kg	Copper, from solvent-extraction electro-winning {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.000174664510680074		kg	Ammonia, liquid {RER}| market for | Conseq, U	*Ecoinvent Centre*
	0.001525335489319 93		kg	Ammonia, liquid {RoW}| market for | Conseq, U	*Ecoinvent Centre*
Energy and Processes					
	2.28		kWh	Electricity, medium voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
	1.15		kWh	Electricity, high voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
	5.15		kWh	Electricity, high voltage {RoW}| electricity production, hydro, run-of-river | Conseq, U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical factory, organics {GLO}| market for | Conseq, U	*Ecoinvent Centre*
Emissions to air					

	0.0255		m^3	Water/m3	*Ecoinvent Centre*
Emissions to water					
	0.1445		m^3	Water, GLO	*Ecoinvent Centre*
Waste and emissions to treatment					
	0.1008		kg	Aluminium scrap, post-consumer {GLO}| market for | Conseq, U	*Ecoinvent Centre*

12.2.2.2 LMO-C

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Non-Fe-Co-metals, from Li-ion battery, hydrometallurgical processing {GLO}| treatment of non-Fe-Co-metals, from used Li-ion battery, hydrometallurgical processing | Conseq, U (LMO-C)		**1.0E+0**	kg		
Materials input					
	0.17		m^3	Water, river, GLO	*Ecoinvent Centre*
	-1.7		kg	Sulfuric acid {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	-0.0868		kg	Manganese {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	-0.166		kg	Copper, from solvent-extraction electro-winning {GLO}| market for | Conseq, U	*Ecoinvent Centre*

	0.000174664510680074		kg	Ammonia, liquid {RER}| market for | Conseq, U	*Ecoinvent Centre*
	0.001525335489319 93		kg	Ammonia, liquid {RoW}| market for | Conseq, U	*Ecoinvent Centre*
Energy and Processes					
	2.28		kWh	Electricity, medium voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
	1.15		kWh	Electricity, high voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
	5.15		kWh	Electricity, high voltage {RoW}| electricity production, hydro, run-of-river | Conseq, U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical factory, organics {GLO}| market for | Conseq, U	*Ecoinvent Centre*
Emissions to air					
	0.0255		m^3	Water/m3	*Ecoinvent Centre*
Emissions to water					
	0.1445		m^3	Water, GLO	*Ecoinvent Centre*
Waste and emissions to treatment					
	0.1008		kg	Aluminium scrap, post-consumer {GLO}| market for | Conseq, U	*Ecoinvent Centre*

12.2.2.3 NMC-C

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference

Functional Unit					
Non-Fe-Co-metals, from Li-ion battery, hydrometallurgical processing {GLO}| treatment of non-Fe-Co-metals, from used Li-ion battery, hydrometallurgical processing | Conseq, U (NMC-C)		**1.0E+0**	kg		
Materials input					
	0.17		m^3	Water, river, GLO	*Ecoinvent Centre*
	-1.7		kg	Sulfuric acid {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	-0.0868		kg	Manganese {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	-0.147		kg	Copper, from solvent-extraction electro-winning {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.000174664510680074		kg	Ammonia, liquid {RER}| market for | Conseq, U	*Ecoinvent Centre*
	0.001525335489319 93		kg	Ammonia, liquid {RoW}| market for | Conseq, U	*Ecoinvent Centre*
Energy and Processes					
	2.28		kWh	Electricity, medium voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
	1.15		kWh	Electricity, high voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
	5.15		kWh	Electricity, high voltage {RoW}| electricity	*Ecoinvent Centre*

				production, hydro, run-of-river | Conseq, U	
Infrastructure					
Facility	4.0E-10		p	Chemical factory, organics {GLO}| market for | Conseq, U	*Ecoinvent Centre*
Emissions to air					
	0.0255		m^3	Water/m3	*Ecoinvent Centre*
Emissions to water					
	0.1445		m^3	Water, GLO	*Ecoinvent Centre*
Waste and emissions to treatment					
	0.1008		kg	Aluminium scrap, post-consumer {GLO}| market for | Conseq, U	*Ecoinvent Centre*

12.2.2.4 NCA-C

Description	**Input**	**Output**	Unit	Process name in SimaPro libraries	Reference
Functional Unit					
Non-Fe-Co-metals, from Li-ion battery, hydrometallurgical processing {GLO}| treatment of non-Fe-Co-metals, from used Li-ion battery, hydrometallurgical processing | Conseq, U (NCA-C)		**1.0E+0**	kg		
Materials input					
	0.17		m^3	Water, river, GLO	*Ecoinvent Centre*
	-1.7		kg	Sulfuric acid {GLO}| market for | Conseq, U	*Ecoinvent Centre*

	-0.122		kg	Copper, from solvent-extraction electro-winning {GLO}| market for | Conseq, U	*Ecoinvent Centre*
	0.000174664510680074		kg	Ammonia, liquid {RER}| market for | Conseq, U	*Ecoinvent Centre*
	0.001525335489319 93		kg	Ammonia, liquid {RoW}| market for | Conseq, U	*Ecoinvent Centre*
Energy and Processes					
	2.28		kWh	Electricity, medium voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
	1.15		kWh	Electricity, high voltage {GLO}| market group for | Conseq, U	*Ecoinvent Centre*
	5.15		kWh	Electricity, high voltage {RoW}| electricity production, hydro, run-of-river | Conseq, U	*Ecoinvent Centre*
Infrastructure					
Facility	4.0E-10		p	Chemical factory, organics {GLO}| market for | Conseq, U	*Ecoinvent Centre*
Emissions to air					
	0.0255		m^3	Water/m3	*Ecoinvent Centre*
Emissions to water					
	0.1445		m^3	Water, GLO	*Ecoinvent Centre*
Waste and emissions to treatment					
	0.1008		kg	Aluminium scrap, post-consumer {GLO}| market for | Conseq, U	*Ecoinvent Centre*

12.3 Market's residential li-ion battery composition mass percentage and performance

12.3.1.1 Raw residential LFP-C

Brand name	Sonnenbatterie	Alpa-ESS	Powervault	SolaX BOX	Ampetus
Model name	Eco 8.2/16 Single phase	Storion ECO S5	G200Li 6kWh + G200S4kWh	All in one Solax BOX	energy pod
Nominal capacity (kWh)	10	14.4	11	15	14.4
Usable storage capacity (kWh)	10.00	12.9	10	12	11.52
Cycle life expectancy (cycles)	10000	6000	4000	4000	4400
Cycle depth of discharge (%)	1.00	90%	90%	80%	80%
Round trip efficiency (%)	86%	95%	95%	94%	97%
weight of battery modules (kg)	145.00	189	250	144	190.8
Weight of hybrid inverter (kg)	27.7	30	27.7	27.7	27.7
Weight of other components (kg)	14.30	100	85	28.3	116.3
total weight of batteries (kg)	187.00	319	362.7	200	334.8
Steady power output (W)	2500.00	5000	1600	4600	5000
energy stored during battery's lifetime (kWh)	77400	66485	33858	40608	44251
kWh of lifetime energy storage/kg of battery module	534	352	135	282	232

Brand name	BYD	Delta	Simpliphi	Fronius	Deep cycle systems
Model name	Mini energy storage	Hybrid E5	PHI 3.4 Smart-Tech battery	Energy package Battery 12.0	PV 10W
Nominal capacity (kWh)	3.75	6	3.4	12	10.42
Usable storage capacity (kWh)	3	4.8	2.75	9.6	10

Cycle life expectancy (cycles)	6000	6000	10000	8000	5000
Cycle depth of discharge (%)	80%	80%	80%	80%	100%
Round trip efficiency (%)	98%	90%	98%	90%	98%
weight of battery modules (kg)	57.31	62.11	34.8	136	81.4
Weight of hybrid inverter (kg)	27.7	30	27.7	19.9	27.7
Weight of other components (kg)	10.99	11.89	3.6	40	15.6
total weight of batteries (kg)	96	104	66.1	195.9	124.7
Steady power output (W)	3000	3000	3100	4000	5000
energy stored during battery's lifetime (kWh)	15876	23328	23990	62208	45952
kWh of lifetime energy storage/kg of battery module	277	376	689	457	565

12.3.1.2 Raw residential LMO-C

Brand name	Nissan	Samsung
Model name	Xstorage 6kWh	ESS AIO 10.8
Nominal capacity (kWh)	6	10.8
Usable storage capacity (kWh)	5.4	9.72
Cycle life expectancy (cycles)	3650	6000
Cycle depth of discharge (%)	90%	90%
Round trip efficiency (%)	95%	95%
weight of battery modules (kg)	83	135
Weight of hybrid inverter (kg)	37	27.7
Weight of other components (kg)	15	76.3
total weight of batteries (kg)	135	239
Steady power output (W)	4600	4980
energy stored during battery's lifetime (kWh)	16852.05	49863.6
kWh of lifetime energy storage/kg of battery module	203	369

12.3.1.3 Raw residential NMC-C

Brand name	Tesla	LG	Mercedes-Benz	Leclanche	GCL

Model name	Powerwall 2AC	Resu 6.5 EX with expansion pack 2.9 + 5.9	Energy storage home 10, standing	Apollion cube x2 in parallel	E-KwBe 5.6
Nominal capacity (kWh)	13.20	9.8	10	6.7	6.2
Usable storage capacity (kWh)	13.20	8.8	9.2	5.4	5.6
Cycle life expectancy (cycles)	7300.00	6000	8000	5000	2555
Cycle depth of discharge (%)	1.00	90%	80%	80%	90%
Round trip efficiency (%)	89%	95%	97%	97%	97%
weight of battery modules (kg)	70.80	66	128	78	40
Weight of hybrid inverter (kg)	27.70	27.70	27.7	27.7	27.7
Weight of other components (kg)	23.50	9	5	17	7.5
total weight of batteries (kg)	122.00	102.70	160.7	122.7	75.2
Steady power output (W)	5000.00	5000	4600	3300	3000
energy stored during battery's lifetime (kWh)	77184.36	45246.6	55872	23396.4	12446.2737
kWh of lifetime energy storage/kg of battery module	1090	686	437	300	311

Brand name	Magellan	BMZ	Senec	Nissan
Model name	HESS	ESS 9.0	Home Li 10.0	Xstorage 7.5kWh
Nominal capacity (kWh)	19.2	8.5	10	7.5
Usable storage capacity (kWh)	17.28	6.8	10	6.75
Cycle life expectancy (cycles)	4000	5000	12000	3650
Cycle depth of discharge (%)	90%	80%	100%	90%
Round trip efficiency (%)	97%	97%	94%	95%

weight of battery modules (kg)	202.5	81.4	100	83
Weight of hybrid inverter (kg)	27.7	40	23.5	37
Weight of other components (kg)	119.8	15.6	28.5	15
total weight of batteries (kg)	350	137	152	135
Steady power output (W)	5000	8000	2500	6000
energy stored during battery's lifetime (kWh)	60341.76	29682	101520	21065.0625
kWh of lifetime energy storage/kg of battery module	298	365	1015	254

12.3.1.4 Raw residential NCA-C

Brand name	Tesla
Model name	Powerpack
Nominal capacity (kWh)	210
Usable storage capacity (kWh)	210
Cycle life expectancy (cycles)	3000
Cycle depth of discharge (%)	100%
Round trip efficiency (%)	89%
weight of battery modules (kg)	1443
Weight of hybrid inverter (kg)	1200
Weight of other components (kg)	277
total weight of batteries (kg)	2920
Steady power output (W)	50000
energy stored during battery's lifetime (kWh)	76535.55
kWh of lifetime energy storage/kg of battery module	53

12.4 Standardization of components using a 10 kWh battery module reference

12.4.1.1 LFP-C

Brand name	Sonnenbatterie	Alpa-ESS	Powervault	SolaX BOX	Ampetus

Model name	Eco 8.2/16 Single phase	Storion ECO S5	G200Li 6kWh + G200S4kWh	All in one Solax BOX	energy pod
Nominal capacity (kWh)	10	11.2	11	12.5	12.5
Usable storage capacity (kWh)	10.00	10.0	10	10	10.0
Cycle life expectancy (cycles)	10000.00	6000.0	4000	4000	4400.0
Cycle depth of discharge (%)	1.00	0.9	90%	80%	0.8
Round trip efficiency (%)	0.86	1.0	95%	94.00%	1.0
weight of battery modules (kg)	145.0	146.5	250.0	120.0	165.6
Weight of hybrid inverter (kg)	27.7	30	27.7	27.7	27.7
Weight of other components (kg)	14.3	77.5	85.0	23.6	101.0
total weight of batteries (kg)	187.00	254	362.7	171.3	294.3
Steady power output (W)	2500.00	5000	1600	4600	5000
energy stored during battery's lifetime (kWh)	77400	51539	33858	33840	38412
kWh of lifetime energy storage/kg of battery module	534	352	135	282	232

Brand name	BYD	Delta	Simpliphi	Fronius	Deep cycle systems
Model name	Mini energy storage	Hybrid E5	PHI 3.4 Smart-Tech battery	Energy package Battery 12.0	PV 10W
Nominal capacity (kWh)	12.5	12.5	12.376	12.5	10.42
Usable storage capacity (kWh)	10.0	10.0	10.01	10.0	10
Cycle life expectancy (cycles)	6000.0	6000.0	10000	8000.0	5000
Cycle depth of discharge (%)	0.80	0.80	80%	0.8	100%

Round trip efficiency (%)	0.98	0.90	98%	0.9	98%
weight of battery modules (kg)	191.0	129.4	126.7	141.7	81.4
Weight of hybrid inverter (kg)	27.7	30.0	27.7	19.9	27.7
Weight of other components (kg)	36.6	24.8	13.1	41.7	15.6
total weight of batteries (kg)	255.4	184.1	167.5	203.3	124.7
Steady power output (W)	3000	3000.0	3100	4000	5000
energy stored during battery's lifetime (kWh)	52919	48592	87325	64821	45952
kWh of lifetime energy storage/kg of battery module	277	376	689	457	565

12.4.1.2 LMO-C

Brand name	Nissan	Samsung
Model name	Xstorage 6kWh	ESS AIO 10.8
Nominal capacity (kWh)	11.1	11.1
Usable storage capacity (kWh)	10.0	10.0
Cycle life expectancy (cycles)	3650	6000
Cycle depth of discharge (%)	90%	90%
Round trip efficiency (%)	95%	95%
weight of battery modules (kg)	153.55	138.92
Weight of hybrid inverter (kg)	37	27.7
Weight of other components (kg)	27.75	78.5127
total weight of batteries (kg)	218.3	245.1
Steady power output (W)	4600	4980
energy stored during battery's lifetime (kWh)	31176	51310
kWh of lifetime energy storage/kg of battery module	203	369

12.4.1.3 NMC-C

Brand name	Tesla	LG	Mercedes-Benz	Leclanche	GCL

Model name	Powerwall 2AC	Resu 6.5 EX with expansion pack 2.9 + 5.9	Energy storage home 10, standing	Apollion cube x2 in parallel	E-KwBe 5.6
Nominal capacity (kWh)	10.0	11.1	10.9	12.4	11.1
Usable storage capacity (kWh)	10.0	10.0	10.0	10.0	10.0
Cycle life expectancy (cycles)	7300.00	6000	8000	5000	2555
Cycle depth of discharge (%)	1.00	90%	80%	80%	90%
Round trip efficiency (%)	0.89	95%	97%	97%	97%
weight of battery modules (kg)	53.6	75.0	139.1	144.3	71.4
Weight of hybrid inverter (kg)	27.70	27.70	27.7	27.7	27.7
Weight of other components (kg)	17.8	10.2	5.4	31.5	13.4
total weight of batteries (kg)	99.1	112.9	172.3	203.5	112.5
Steady power output (W)	5000.00	5000	4600	3300	3000
energy stored during battery's lifetime (kWh)	58473	51400	60733	43283	22229
kWh of lifetime energy storage/kg of battery module	1090	686	437	300	311

Brand name	Magellan	BMZ	Senec	Nissan
Model name	HESS	ESS 9.0	Home Li 10.0	Xstorage 7.5kWh
Nominal capacity (kWh)	11.1	12.5	10.0	11.1
Usable storage capacity (kWh)	10.0	10.0	10.0	10.0
Cycle life expectancy (cycles)	4000	5000	12000	3650
Cycle depth of discharge (%)	90%	80%	100%	90%

Round trip efficiency (%)	97%	97%	94%	95%
weight of battery modules (kg)	117.2	119.7	100.0	122.9
Weight of hybrid inverter (kg)	27.7	40	23.5	37
Weight of other components (kg)	69.3	22.9	28.5	22.2
total weight of batteries (kg)	214.2	182.7	152	152
Steady power output (W)	5000	8000	2500	6000
energy stored during battery's lifetime (kWh)	34920	43662	101520	31197
kWh of lifetime energy storage/kg of battery module	298	365	1015	254

12.4.1.4 NCA-C

Brand name	Tesla
Model name	Powerpack
Nominal capacity (kWh)	10
Usable storage capacity (kWh)	10
Cycle life expectancy (cycles)	3000
Cycle depth of discharge (%)	100%
Round trip efficiency (%)	89%
weight of battery modules (kg)	68.7
Weight of hybrid inverter (kg)	37
Weight of other components (kg)	13.2
total weight of batteries (kg)	152
Steady power output (W)	N/A
energy stored during battery's lifetime (kWh)	3645
kWh of lifetime energy storage/kg of battery module	53

12.5 Comparing batteries per impact category

Environmental pollution category	Score for 1 kg of LFP	Score for 1 kg of LMO	Score for 1 kg of NMC	Score for 1 kg of NCA
Global warming depletion (GWP)	7.96E+00	7.97E+00	7.63E+00	8.15E+00
Climate change (human)	1.09E-05	1.10E-05	1.05E-05	1.12E-05
Climate change (ecosystems)	6.18E-08	6.22E-08	5.93E-08	6.34E-08
Cumulative energy demand (CED)	2.08E+02	2.10E+02	2.04E+02	2.14E+02
Metal depletion potential (MDP)	7.34E-01	1.26E+00	1.12E+00	8.21E-01
Fossil fuel depletion potential (FDP)	4.01E-01	4.00E-01	3.80E-01	4.11E-01
Abiotic depletion (ADP)	6.44E-04	7.21E-04	7.06E-04	6.86E-04
Acidification & Eutrophication potential (AP & EP)	1.93E-01	2.20E-01	2.26E-01	2.36E-01
Human toxicity potential (HTP)	2.56E-06	2.19E-06	2.09E-06	2.31E-06
Ecotoxicity (terrestrial, freshwater, marine)	2.05E+01	3.35E+01	3.21E+01	2.89E+01
Ozone depletion potential (ODP)	1.80E-09	1.71E-09	1.64E-09	1.79E-09
Particulate matter formation (PMF)	6.96E-06	8.61E-06	8.04E-06	8.02E-06
Ecosystem damage potential (land occupation & transformation) (EDP)	3.83E+02	4.46E+02	3.65E+02	3.93E+02
Single score (human health, Ecosystems, Resources)	1.56E+00	2.03E+00	1.86E+00	1.67E+00
Single score (human health, Ecosystems, Resources)	1.05E+00	9.90E-01	9.55E-01	1.04E+00
Normalisation (human health, Ecosystems, Resources)	1.50E-03	1.60E-03	1.51E-03	1.58E-03

	LFP-C	LMO-C	NMC-C	NCA-C
Lifetime energy storage (average of 90% of initial capacity kept)/ kg of total battery mass	258.99	190.1	350.95	232.3
Standard deviation	1.55E+02	8.61E+01	2.59E+02	39.3
Standard error of the mean	4.79E+01	5.69E+01	8.48E+01	8.38

Environmental pollution category	Environmental pollution score for 1 kg of LFP / number of kWh of energy that will be stored in 1 kg of LFP	Environmental pollution score for 1 kg of LMO / number of kWh of energy that will be stored in 1 kg of LMO	Environmental pollution score for 1 kg of NMC / number of kWh of energy that will be stored in 1 kg of NMC	Environmental pollution score for 1 kg of NCA / number of kWh of energy that will be stored in 1 kg of NCA
Global warming depletion (GWP)	3.07E-02	4.19E-02	2.17E-02	0.0351
Climate change (human)	4.21E-08	5.79E-08	2.99E-08	4.82E-08
Climate change (ecosystems)	2.39E-10	3.27E-10	1.69E-10	2.73E-10
Cumulative energy demand (CED)	8.03E-01	1.10E+00	5.81E-01	9.21E-01
Metal depletion potential (MDP)	2.83E-03	6.63E-03	3.19E-03	3.53E-03
Fossil fuel depletion potential (FDP)	1.55E-03	2.10E-03	1.08E-03	1.77E-03
Abiotic depletion (ADP)	2.49E-06	3.79E-06	2.01E-06	2.95E-06
Acidification & Eutrophication potential (AP & EP)	7.45E-04	1.16E-03	6.44E-04	1.02E-03
Human toxicity potential (HTP)	9.88E-09	1.15E-08	5.96E-09	9.94E-09
Ecotoxicity (terrestrial, freshwater, marine)	7.92E-02	1.76E-01	9.15E-02	1.24E-01
Ozone depletion potential (ODP)	6.95E-12	9.00E-12	4.67E-12	7.71E-12
Particulate matter formation (PMF)	2.69E-08	4.53E-08	2.29E-08	3.45E-08
Ecosystem damage potential (land occupation & transformation) (EDP)	1.48E+00	2.35E+00	1.04E+00	1.69E+00
Single score (human health, Ecosystems, Resources)	6.02E-03	1.07E-02	5.30E-03	7.19E-03
Single score (human health, Ecosystems, Resources)	4.05E-03	5.21E-03	2.72E-03	4.48E-03
Normalisation (human health, Ecosystems, Resources)	5.79E-06	8.42E-06	4.30E-06	6.80E-06

12.6 Contribution of the batteries' components to its total environmental pollution potential for the single score

	LFP-C	**LMO-C**	**NMC-C**	**NCA-C**
Assembly	7.47E-02	7.47E-02	7.47E-02	7.47E-02
Cell container/ cell casing	1.32E-01	1.32E-01	1.32E-01	1.32E-01
Battery pack casing/Housing/Battery packing	1.76E-01	1.76E-01	1.76E-01	1.76E-01
BMS, electronic parts, state of charge regulator	2.88E-01	2.88E-01	2.88E-01	2.88E-01
Cooling system	3.95E-02	3.95E-02	3.95E-02	3.95E-02
Hybrid current inverter	3.95E-01	3.95E-01	3.95E-01	3.95E-01
Positive electrode (Cathode)	1.82E-01	5.81E-01	5.27E-01	1.93E-01
Negative electrode (anode)	3.80E-01	7.99E-01	6.97E-01	6.09E-01
Electrolyte	6.47E-02	5.02E-02	5.25E-02	5.42E-02
Separator	1.22E-02	1.87E-02	1.28E-02	2.83E-02