Carbon Neutral European Battery Cell Production with Sustainable, Innovative Processes and 3D Electrode Design to Manufacture

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HORIZON-CL5-2021-D2-01 - Environmentally sustainable processing techniques applied to large scale electrode and cell component manufacturing for Li ion batteries

D2.1 – Final report on screening LCA including recycling and safety

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Executive Summary

This report contains a screening life cycle assessment of NMC622 battery cells. It is based on literature review focused on environmental impact and safety of battery manufacturing, production of battery material and recycling of batteries. The draft report was a basis for an idea generation workshop in Stockholm 2023-09-28. In the workshop the BatWoMan consortium was brainstorming ideas for environmental improvement of NMC622 battery cells.

The screening LCA points towards recycling and choice of cathode materials as especially important areas for eco-design of battery cell production. Nickel and cobalt have significant contributions, but their impact could be minimized by sourcing from the right locations and ensuring high recycling rates. Considering the use phase is very important for total life cycle impacts, i.e., to produce a light, safe and efficient cell with long service life is crucial. The workshop resulted in 36 ideas on how to improve the environmental performance of NMC622 batteries, which are documented in the report, which will guide the future design work in the BatWoMan project.

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List of Abbreviations

Acronym / Short Name	Meaning
ADP	Abiotic depletion potential
BOM	Bill of material
C	Carbon
CAS	Chemical Abstracts Service
C65	Nano carbon black conductive additive
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalents
CF	Carbon footprint
CML	Institute of Environmental Sciences (CML), which is an institute of the Faculty of Science of Leiden University in the Netherlands
kWh	Kilowatt hour
ILCD	International life cycle data system
LCA	Life cycle assessment
LCO	Lithium carbonate, Li_3CO_3
NMC	Nickel, Manganese, Cobalt
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
NMP	N-Methylpyrrolidone
O_2	Oxygen
PFAS	Per- and polyfluoroalkyl substances
PVDF	Polyvinylidene fluoride
RISE	Research Institutes of Sweden
Sb-eq	Antimony equivalents

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1 Introduction

The study was carried out within the framework of the BatWoMan project, Carbon Neutral European Battery Cell Production with Sustainable, Innovative Processes and 3D Electrode Design to Manufacture. The report and conclusions in their current form aim to provide a basis for eco-design of the manufacturing of an NMC622 battery cell.

The BatWoMan project develops new sustainable and cost-efficient Li-ion battery cell production concepts, paving the way towards carbon neutral cell production. This is realized via primarily:

1) energy-efficient, no volatile organic compounds (VOCs) processed electrodes, with slurries of high dry mass content;
2) innovative dry room reducing concept with improved electrolyte filling, and;
3) low-cost and energy-efficient cell conditioning (wetting, formation, and ageing).

The technological improvements will be supported digitally via creating an AI-driven, innovative platform for smart re-tooling in response to changes in the desired cell properties. A battery passport and dataspace will contain all essential information about the manufacturing process, including the carbon footprint and efficiency of the individual production steps.

2 Method

This life cycle assessment, LCA, is performed in accordance with ISO 14044 (ISO 2006) and the ILCD Handbook (Wolf and Pant 2012), though in a screening or simplified form. At the end of the project a full and complete life cycle assessment will be made, including the real project data where possible. At the kick-off meeting, held on 29-30 September 2022, in Vienna, Austria, with representatives from all project partner institutions, the LCA work was outlined as follows:

- Elaboration of a draft screening LCA report during the first project year
- An idea generation workshop at the end of the first year, preliminary planned to 28-29 September 2023 in Stockholm
- Finalizing screening LCA report in autumn 2023. This report will serve as an inspiration and guideline for eco-design of the battery cell production
- Carrying out a full LCA at the end of the three-year project

Simplified LCA has been used in the screening LCA, both in the sense that data for upstream production of energy, metals, etc. are generic, i.e., taken from generally available data[1] and generally represent global or European averages, and in the sense that only a general and preliminary bill-of material for an NMC622 cell could be established before autumn 2023. LCA software SimaPro[2] 9.5.0.0 was used for the calculations.

2.1 Functional unit or declared unit

The main functional unit used in this screening LCA is 1 kWh manufactured cell capacity. The kWh based functional unit will be based on a preliminary NMC622 bill-of-materials, BOM. For some materials a mass based unit will be used, presenting climate impact per kilogram of material. The idea is to give designers access to the environmental impacts of different materials, both compared to each other and in the context of an NMC622 cell, enabling **informed design choices.**

For the future full LCA, other, but related, functional units, like delivered kWh or even vehicle km, could be relevant. These two functional units both imply that the use phase of the cell is included. Vehicle km implies knowledge of the vehicle in which the battery is used, whereas delivered kWh not necessarily need knowledge of the application.

For the battery passport, the Battery Regulation specifies reporting of the carbon footprint of the battery, calculated as “kg of carbon dioxide equivalent per one kWh of the total energy provided by the battery over its expected service life” and “differentiated according to life cycle stage” (as shares

[1] RISE own database and the commercial database Ecoinvent

[2] Internal note: project Battery Systems II

of the overall carbon footprint). This functional unit is the same as 1 delivered kWh mentioned above. Information on how to determine the expected service life, needed to be able to calculate the carbon footprint (CF) per delivered kWh, is proposed in a draft from the EU Joint Research Centre (JRC 2023). For light-duty EVs, the proposal is to connect it to the specific vehicle application and its WLTP test cycle data, while for heavy-duty EVs and all other batteries, the number of full cycle equivalents somehow determined would be used as a basis for the calculations.

The CF should be given together with administrative information about manufacturer and manufacturing location as well as a web link to a public study supporting the CF declaration. The Battery Regulation requires four lifecycle stages to be within the CF system boundary:

Stage 1: Raw material acquisition and pre-processing

Stage 2: Main product production

Stage 3: Distribution

Stage 4: End of life and recycling (collection, dismantling and recycling)

Note that the use phase is to be excluded from the Battery passport. This brings us to a discussion of system boundaries.

2.2 System boundaries

Principle system boundaries for this LCA study are shown in Figure 1.

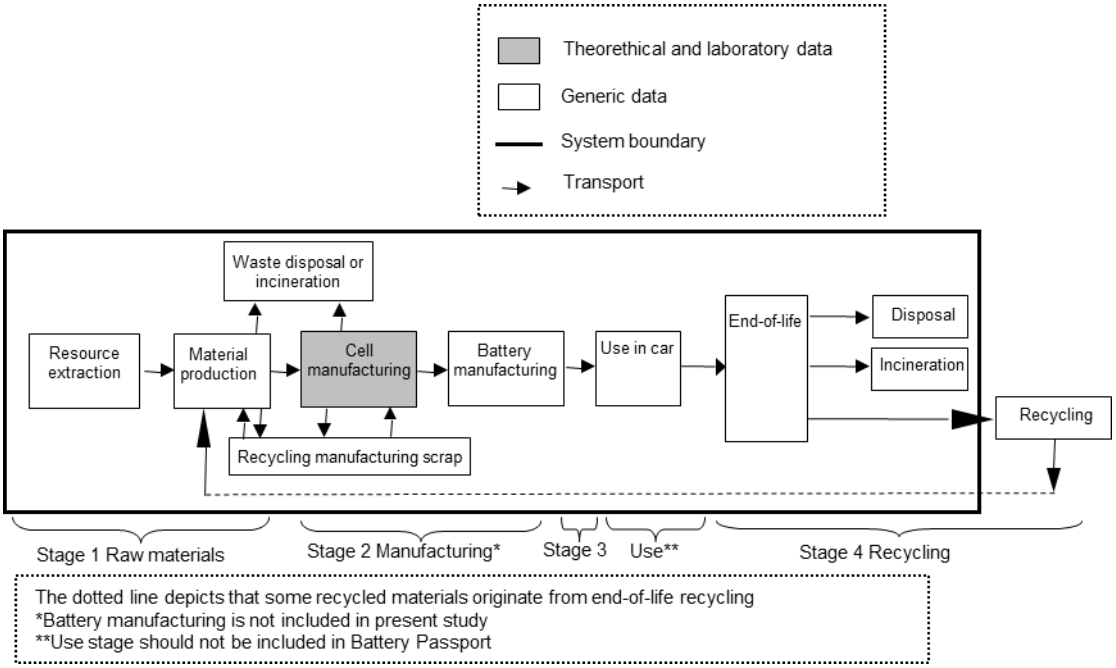


Figure 1 Study system boundaries

It should be noted that internal recycling of manufacturing scrap is treated very differently compared to end-of-life scrap. As specified by the JRC (2023) and the GBA Greenhouse Gas Rulebook (GBA & Sphera 2023), “Process scrap within the same plant shall not be considered in calculating the recycled content rather only scrap or waste originating from outside the plant.”

The end-of-life recycling is outside the system boundary, which is consistent with the cut-off approach to recycling recommended by the GBA Greenhouse Gas Rulebook (GBA & Sphera 2023) and the Battery Pass Consortium (SYSTEMIQ 2022). Background data with cut-off modelling will probably be used for the full LCA and therefore also used in this screening LCA. Nevertheless, recycling of internal manufacturing scrap will be studied and modelled in the LCA. It should be noted that, contrary to the recommendations of industry (GBA&Sphera 2023), the JRC (2023) proposes using the Circular Footprint Formula, CFF, which includes parts of the end-of-life recycling using parameters that is often not available, since end-of-life recycling happens in the future.

Regarding temporal system boundaries, both historical and current and future emissions are included without temporal limitations in the generic data from the database Ecoinvent 3.9.1 (Wernet et al 2019) that are normally used. The Ecoinvent database normally also includes emissions and resources for necessary infrastructure, such as production equipment, roads, facilities, etc..
Focus for the BatWoMan project innovation and also for the LCA is the cell manufacturing. Cell manufacturing details are described in Figure 2. It is important to emphasize that within the project BatWoMan the aim is to reduce dry room needs. Figure 2 shows the conventional process, the project aims to reduce the dry room needs to an absolute minimum. In the project, stack drying and electrolyte filling will not be carried out under dry room conditions.

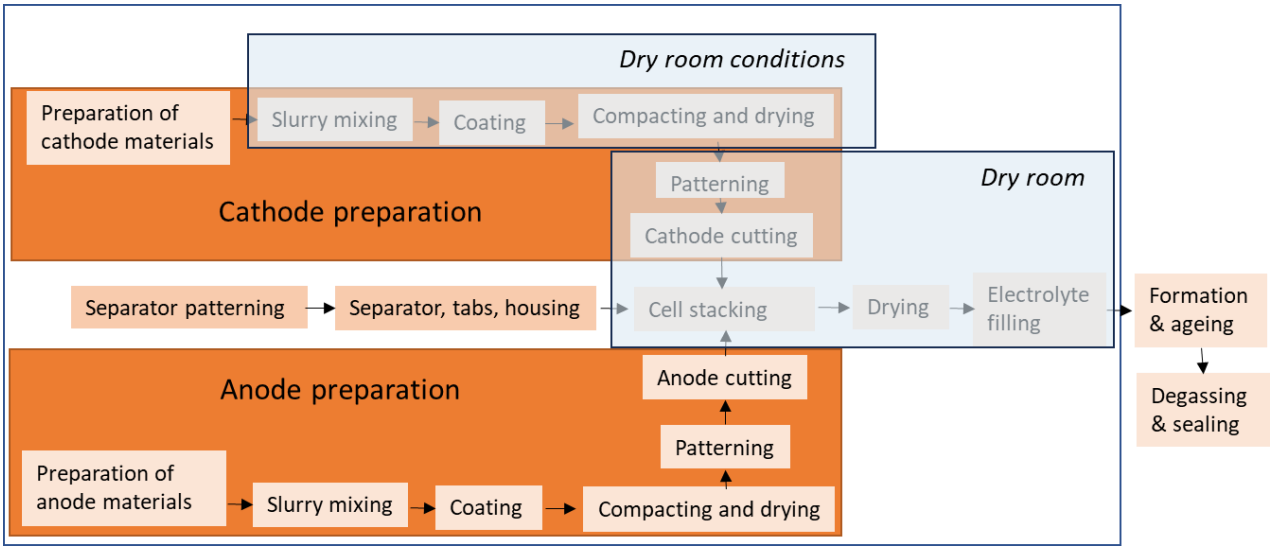


Figure 2 Conventional cell manufacturing details. In BatWoMan, stack drying, electrolyte filling and slurry mixing will not be carried out under dry room conditions.

2.3 Environmental impact assessment

In the context of vehicle electrification, it is relevant to be able to assess trade-offs between tailpipe emissions and material resource use. Two relevant environmental impact categories for LCA of vehicles and traction batteries, but also for electrification in general, are climate impact and resource depletion (Zackrisson 2021). The methods used to account for these impact categories in this study are described below.
Climate impacts are calculated with the Environmental Footprint 3.1 (adapted) method as it was implemented in SimaPro 9.5.0.0. The unit for climate impact is kilogram of carbon dioxide equivalents, CO_2-eq.
The indicator recommended by the PEFCR for batteries (Recharge 2020) for resource depletion is also calculated with the method Environmental Footprint 3.1 (adapted). Only depletion of mineral reserves is reported since the climate impact indicator, above, is considered to cover depletion of fossil fuels. The unit for abiotic depletion potential, ADP, is milligrams of antimony equivalents, Sb-eq. In addition, abiotic resource depletion is calculated with the non-baseline CML-IA method as recommended by Zackrisson (2021).[3] The reason for this recommendation is that the recommended method is based on ultimate reserves, which is roughly proportional to the average concentration (of the resource) in the crust of the earth. This creates a robust long-term measure (Oers 2020), but it does not capture the criticality of common battery materials as lithium, cobalt and nickel (Zackrisson 2021).

[3] Reserve in material sourcing terminology means proven economically mineable part of a Mineral Resource. The non-baseline (CML) abiotic depletion measure in LCA (named “elements, economic reserve”) is probably based on this definition of Reserve. Note the confusing naming (*ultimate reserves*) of the recommended LCA abiotic depletion measure.

3 Modelling

During the kick-off meeting, the following was decided concerning cell materials, format, and production:

- Large coin cell in trials and later pouch cell will be used
- Graphite on the anode
- Different binders and amount of binder
- High power diode lasers with temperature control for drying
- Water-based processing
- 70-80wt% solid content for anodes and cathodes
- Novel one-step calendaring-drying process. Decrease drying time by more than 75wt%
- Electrode structuring with laser
- Material scrap can be used for recycling tests, by AIT or Cidetec
- 8 micrometer thick copper foil (for anode)
- Ceramic coated separators
- Exact BOM will be negotiated bilaterally between AIT and Cidetec and decided at a later stage

3.1 Materials

The data below reflect what was known or estimated summer 2023 and is based on interviews with project participants and literature. During the remaining part of the project, project specific data for the LCA will be collected and shared in an excel sheet named Production data input template, see Figure 3 below. The template is available for all partners on the BatWoMan share point

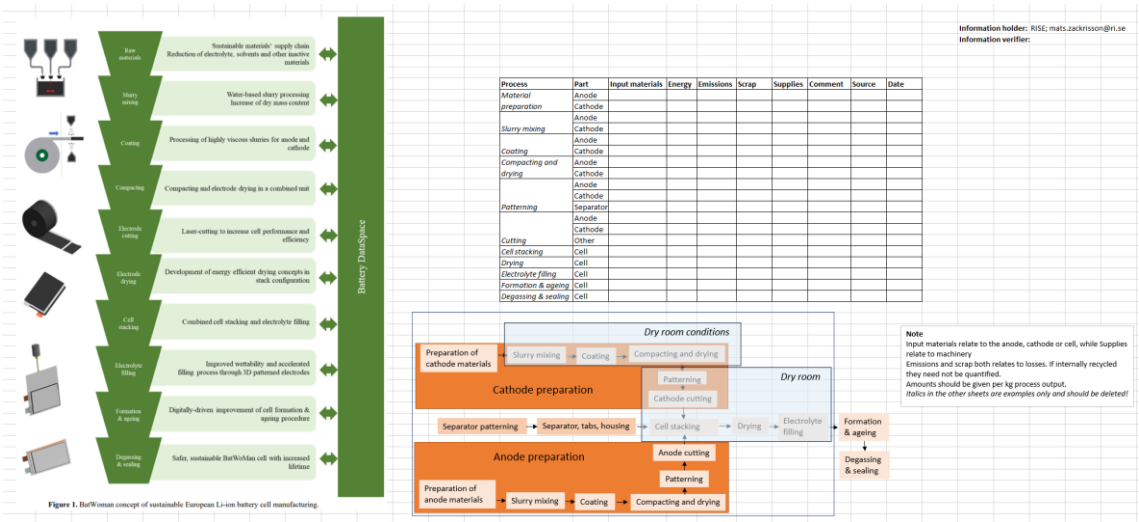


Figure 3 Production data input template

3.1.1. NMC622 BOM

Several bill-of-materials, BOMs, for NMC622 are available in literature. Sun et al. (2020) includes a BOM and, in the Supporting material, an LCA model of active materials of the 72.5 kWh battery pack. Von Drachenfels et al (2022) gives a BOM for a NMC622 cell with a total weight of 651 grams in pouch cell format. This BOM (Drachenfels et al 2022) combined with background information from the same source will be used as a model for an NMC622 battery in this screening LCA, see Table 1.

To make calculations per energy capacity or delivered energy at battery level, assumptions about the relation between the cell and the rest of the battery pack and the application of the battery in a vehicle are needed. In this screening LCA, it will be assumed that the cells weigh as much as the rest of the battery pack. See Figure 4 for resulting LCA-model cell and rest-of-pack. Note the correspondence with the life cycle stages required by the Battery regulation, see 2.1 Functional unit or declared unit.

Table 1 Bill-of-material of 39.6 Ah NMC622 cell weighing 651 grams according to Drachenfels et al (2022). BOM from Sun et al (2020) for comparison

		Sun et al (2020)		Drachenfels et al (2022)	
Part of cell	**Material**	**Mass (kg)**	**wt%**	**Mass (g)**	**wt%**
Anode	Graphite	96.2	15.30	158.9	24.4
Anode	PVDF			4.1	0.6
Anode	Carbon black			1.6	0.2
Anode	Water			Evap. (82.3)	0.0
Anode	Copper foil	54.1	8.60	56.8	8.7
Cathode	NMC622	168.3	26.70	246.3	37.9
Cathode	PVDF	12	1.9	6.5	1.0
Cathode	C65			6.5	1.0
Cathode	NMP			Evap. (103.7)	0.0
Cathode	Al foil	114	18.1	23.8	3.7
Separator	Polymer	9.6	1.5	12	1.8
Tabs	Al foil			0.9	0.1
Housing	Pouch foil			30.3	4.7
Electrolyte	LiPF6	126,3	19	102.7	15.8
Restofpack		**68.7**	11		
Total in cell		**580**		**651**	100

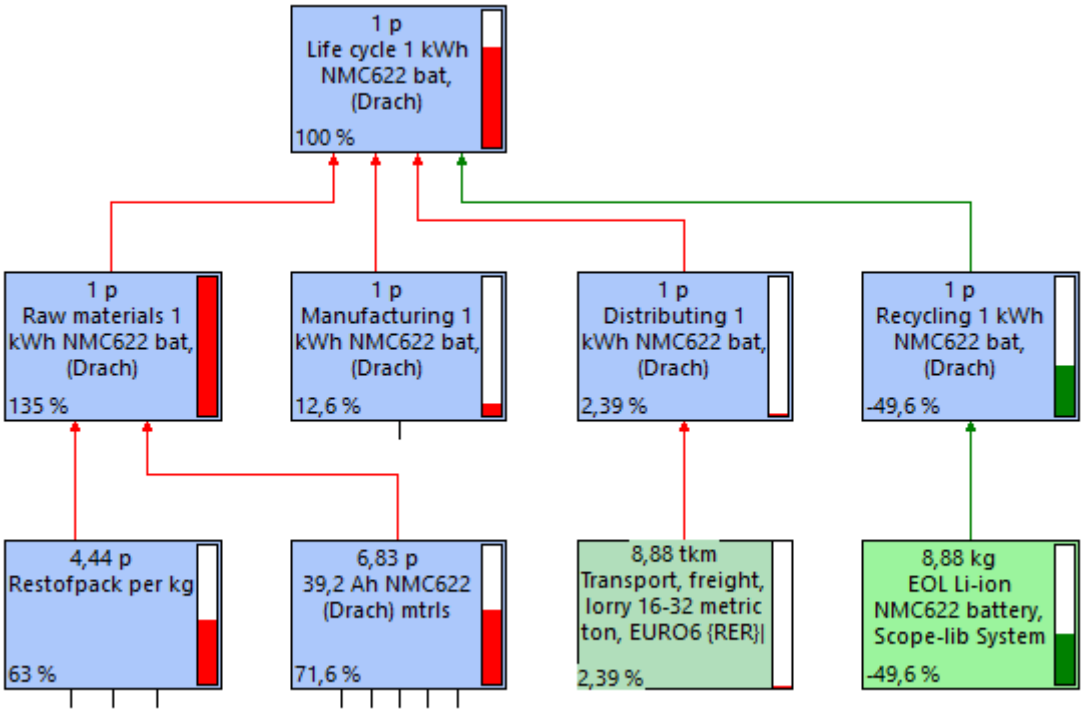


Figure 4 LCA-model of cell and rest-of-pack of 1 kWh NMC622 battery system, assuming 1:1 relationship between cell and rest-of-pack

3.1.2. Anode materials

The anode materials consist of copper, graphite, PVDF and carbon black. In Table 2 available LCA background data and sourcing information is described. Possible alternatives to data used in the model are shaded. Name in Ecoinvent database is in italics.

Table 2 Anode material background data

Anode materials	kg CO_2-eq/kg	Dataset/reference	Comment
Copper	6.86	*Copper, cathode {GLO}| market for copper, cathode | Cut-off, S*	
Manufacturing process related to above	0.54	*Sheet rolling, copper {GLO}| market for sheet rolling, copper*	Rolling copper into copper foil
Graphite	1.67	*Graphite, battery grade {GLO}| market for graphite, battery grade | Cut-off, S*	Made from coke
PVDF	34.4	*PVDF, Hu 2022 System*	From Hu 2022 and Yadav 2021. Non-fluorinated alternatives would be preferable.
Carbon black	2.37	*Carbon black {GLO}| market for carbon black | Cut-off, S*	Made from petroleum with furnace black process
Alternatives			
Copper	5 (+-3)	Kallitsis et al. (2022)[4]	Median value 5 (minimum and maximum value)
Graphite	8 (-2+12)	Kallitsis et al. (2022)	Median value 8 (minimum and maximum value)
Graphite	6.06	*Anode, graphite, for Li-ion battery {CN}| market for anode, graphite, for Li-ion battery | Cut-off, S*	Chinese origin
Graphite	4.69	*Anode, graphite, for Li-ion battery {RoW}| market for anode, graphite, for Li-ion battery | Cut-off, S*	RoW, Rest of the World
Graphite	6.24	*Anode, silicon coated graphite, for Li-ion battery {CN}| market for anode, silicon coated graphite, for Li-ion battery | Cut-off, S*	Silicon coated. Consist of 92wt% *Synthetic graphite, battery grade {RoW}| market for synthetic graphite*
Graphite	4.88	*Anode, silicon coated graphite, for Li-ion battery {RoW}| market for anode, silicon coated graphite, for Li-ion battery | Cut-off, S*	
Synthetic graphite	5.39	*Synthetic graphite, battery grade {CN}| market for synthetic graphite, battery grade | Cut-off, S*	Is it natural when it is not synthetic? No it is synthetic.
Synthetic graphite	4.01	*Synthetic graphite, battery grade {RoW}| market for synthetic graphite, battery grade | Cut-off, S*	
Natural graphite	1.7	(Pell et al., 2021)	Production by Woxna in Sweden
Natural graphite	1.48	(Talga, 2021)	By Talga depicting Talnode-C
Natural graphite	9.6 +- 0.3	Engels et al. (2022)	

Graphite, with its large share of the total cell weight and large differences between datasets, is a prime candidate for finding a closer fit between the model and reality sourcing choice.

3.1.3. Cathode materials

The cathode materials are most significant from a climate point of view. In Table 3 available LCA background data and sourcing information is described. Possible alternatives to the data used in the model are shaded. Name in Ecoinvent database is in italics.

[4] Kallitsis et al 2022 is a preprint which is hopefully published when this deliverable is due.

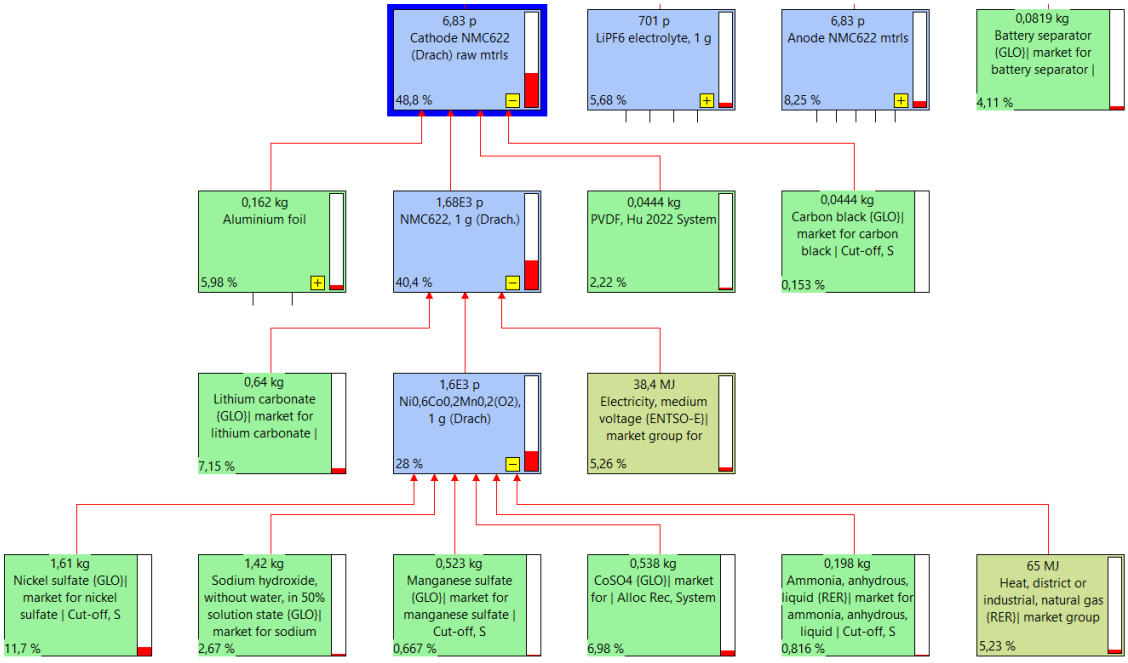


Figure 5 LCA model of 1 kWh NMC622 battery system, focus on cathode

As can be seen in Figure 5, cathode materials include aluminium, PVDF, Carbon black, lithium carbonate, nickel sulfate, sodium hydroxide, manganese sulfate and cobalt sulfate. Here is only described the model, the significance of impacts will be discussed later.

Table 3 Cathode material background data[5]

Cathode materials	**kg CO_2-eq/kg**	**Dataset/reference**	**Comment**
Aluminium foil			
Aluminium	21.8	*Aluminium, primary, ingot {RoW}| aluminium production, primary, ingot	Cut-off, S*	
Rolling	0.48	*Sheet rolling, aluminium {RER}| sheet rolling, aluminium	Cut-off, S*	
PVDF	34.4	*PVDF, Hu 2022 System*.	Based on Hu 2022 and Yadav 2021. Own model with Ecoinvent processes for Europe.
Carbon black	2.37	*Carbon black {GLO}| market for carbon black	Cut-off, S*	Made from petroleum with furnace black process
Lithium carbonate, Li_2CO_3	7.67	*Lithium carbonate {GLO}| market for lithium carbonate	Cut-off, S*	Also LiOH used in some cases, see examples below
Nickel sulfate, $NiSO_4$	4.98	*Nickel sulfate {GLO}| market for nickel sulfate	Cut-off, S*	
Sodium hydroxide, NaOH	1.29	*Sodium hydroxide, without water, in 50% solution state {GLO}| market for sodium hydroxide	Cut-off, S*	
Manganese sulfate, $MnSO_4$	0.88	*Manganese sulfate {GLO}| market for manganese sulfate	Cut-off, S*	

[5] Possible alternatives to data used in the model are shaded. Name in Ecoinvent database is in italics.

Cathode materials	kg CO_2-eq/kg	Dataset/reference	Comment
Cobalt sulfate,, $COSO_4$	8.93	*CoSO4 {GLO}| market for | Alloc Rec, System*	
Alternatives			
Aluminium	16 (5-24)	Kallitsis et al. (2022)	Median value 16 (minimum and maximum value), without rolling
PVDF			Kolla med Emanuel
PVDF binder, 1g	173	*PVDF binder, 1g*	PVDF=PE/2+TFE/2
Carbon black	2.31	*Carbon black {GLO}| carbon black production | Cut-off, S*	So transportation only adds 0,06 kg CO_2/kg
Carbon black	2.67	*Carbon black SVEFF*	Production of carbon black for the rubber industry at Nordisk Carbon Black AB, Malmö, 1996.
Lithium carbonate, Li_2CO_3	7.5 (3-33)	Kallitsis et al. (2022)	Median value 7,5 (minimum to maximum value)
Lithium hydroxide, LiOH	10 (6-19)	Kallitsis et al. (2022)	Median value 10 (minimum to maximum value)
Nickel sulfate	5.5 (2-23)	Kallitsis et al. (2022)	Median value 5,5 (minimum to maximum value)
Nickel sulfate	4.0	(Mistry et al 2016)	Nickel sulphate hexahydrate, from Nickel Institute
Nickel	13	(Mistry et al 2016)	Class 1, from Nickel Institute
Nickel	17.2	*Nickel, class 1 {GLO}| market for nickel, class 1 | Cut-off, S*	Ecoinvent 3.9.1.
Sodium hydroxide, NaOH	1.5 (1,5-2)	Kallitsis et al. (2022)	Median value 1,5 (minimum to maximum value)
Manganese sulfate, $MnSO_4$	2 (1-5)	Kallitsis et al. (2022)	Median value 2 (minimum to maximum value)
Cobalt sulfate, $CoSO_4$	7 (4-36)	Kallitsis et al. (2022)	Median value 7 (minimum to maximum value)

3.1.4. Electrolyte

The electrolyte has a considerable mass share, 16wt% in our example case, see Table 1. In Table 4 available LCA background data and sourcing information is described. Possible alternatives to the data used in the model are shaded. Name in Ecoinvent database is in italics.

As can be seen in Figure 6, electrolyte materials include lithium hexafluorophosphate, ethylene, DEC (diethyl carbonate) and vinyl carbonate. Here is only described the model, the significance of impacts will be discussed later.

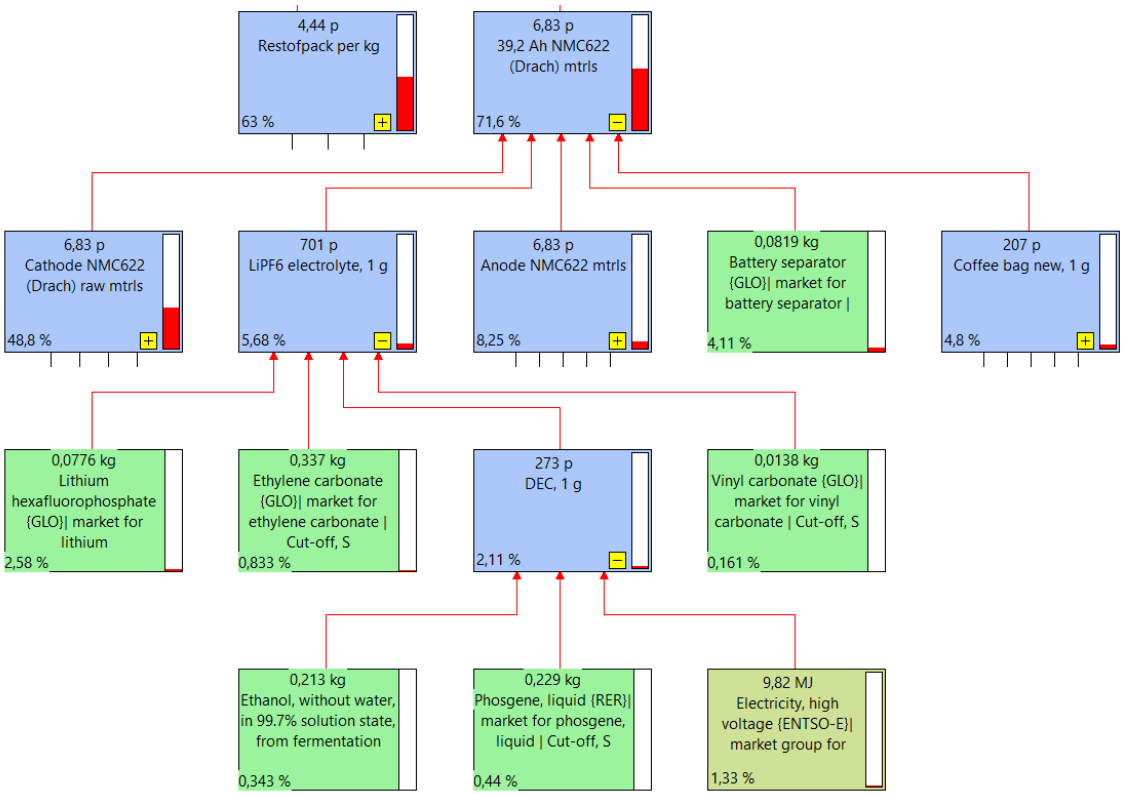


Figure 6 LCA model of 1 kWh NMC622 battery system, focus on electrolyte

Table 4 Electrolyte material background data[5]

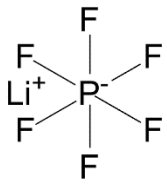
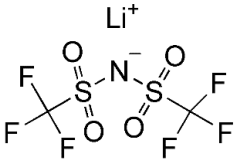
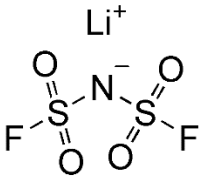
Electrolyte materials	**kg CO_2-eq/kg**	**Dataset/reference**	**Comment**
Lithium hexafluorophosphate, $LiPF_6$	22.8	*Lithium hexafluoro-phosphate {GLO}| market for lithium hexafluoro-phosphate | Cut-off, S*	
Ethylene carbonate, EC	1.7	*Ethylene carbonate {GLO}| market for ethylene carbonate | Cut-off, S*	
Diethyl carbonate, DEC	5.3	*DEC, 1 g*	From ethanol and phosgene and electricity (63% of CF)
Vinylene carbonate, VC	8.04	*Vinyl carbonate {GLO}| market for vinyl carbonate | Cut-off, S*	
EC/DMC (dimethyl carbonate)	2 (0.5-3)	Kallitsis et al. (2022)	Median value 2 (minimum to maximum value)

As can be seen in Figure 6 electrolyte materials include lithium hexafluorophosphate, ethylene carbonate, diethyl carbonate. $LiPF_6$ is the baseline standard electrolyte to use in the cell. Two alternative salts in the pipeline to substitute the standard LiPF6 are:

- LiTFSI – Lithium bis(trifluoromethanesulfonyl)imide. CAS no: 90076-65-6
- LiFSI – Lithium bis(fluorosulfonyl)amide. CAS no: 171611-11-3

A summary of the hazardous properties of these three electrolytes are given in Table 5.

Table 5 Hazardous properties of candidate electrolytes

Materials/CAS	Chemical formula	Hazard	Comment
Lithiumhexafluorophosphate **CAS** 21324-40-3		**H302** Acute toxicity, oral; **H314** Causes severe skin burns and eye damage; **372** Causes damage to organs through prolonged or repeated exposure	No PFAS
LiTFSI - Lithium bis(trifluoromethanesulfonyl)imide **CAS** 90076-65-6		**H301** Toxic if swallowed; **H311** Toxic in contact with skin; **H314** Causes severe skin burns and eye damage; **H373** May cause damage to organs through prolonged or repeated exposure; **H412** Harmful to aquatic life with long lasting effects	PFAS after new definition
LiFSI – Lithium bis(fluorosulfonyl)amide **CAS**: 171611-11-3		**H301** Toxic if swallowed; **H314** Causes severe skin burns and eye; **H315** Causes skin irritation; **H341** Suspected of causing genetic defects (Germ cell mutagenicity); **H361** Suspected of damaging fertility or the unborn child (Reproductive toxicity); **H360** May damage the unborn child	No PFAS

3.1.5. Separator

The separator has not a large mass share, see Figure 6. The Ecoinvent dataset used, *Battery separator {GLO}| market for battery separator | Cut-off, S,* models a porous polyethylene membrane of approximately 15-25 µm thickness, see Yin et al. (2019) for more details.

3.1.6. Coffee bag

A popular cell packaging is the coffee bag. As with the separator it has not a large mass share. See Figure 7 for details of the model. As can be seen, the coffee bag contains aluminium, polypropylene and nickel. Here is only described the model, the significance of impacts will be discussed later.

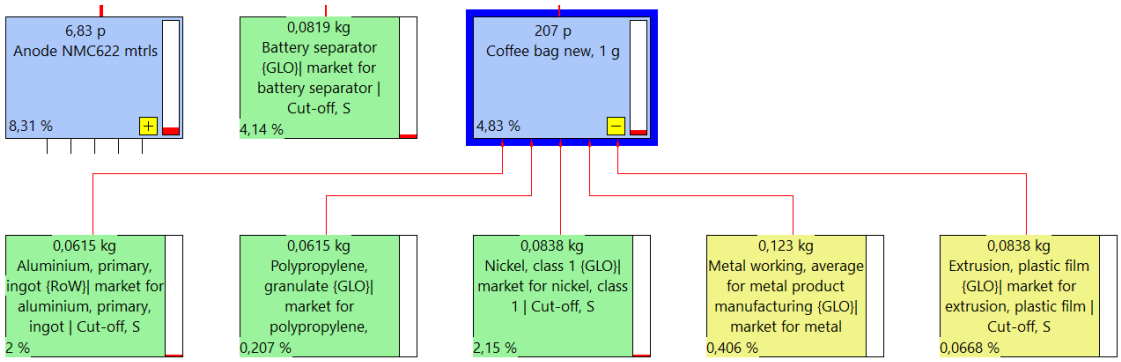


Figure 7 LCA model of 1 kWh NMC622 battery system, focus on coffee bag

3.1.7. Transports

All raw materials and upstream manufacturing have been modelled with "market" processes, if possible, which include upstream transports. Distribution involving 1000 km transport of the fabricated battery by lorry from the battery manufacturing plant to the car manufacturing plant, is included in the model, see Figure 4. Here is only described the model, the significance of impacts will be discussed later.

3.2 Assembly energy

The model by Drachenfels et al (2022) contains detailed energy data about the whole cell manufacturing, see Figure 2. These energy data (Drachenfels et al 2022) are used in the current model, see Figure 8 below. It is possible to switch between Swedish average electricity and European average electricity, see Table 6. Natural gas is assumed for some heating purposes.

Table 6 Electricity from different sources

Resource/material	kg CO_2-eq/kWh	Dataset/reference	Comment
Electricity, Swedish average	0.036	Electricity, medium voltage {SE}| market for | Cut-off, S	
Electricity, European average	0.338	Electricity, medium voltage {ENTSO-E}| market group for | Cut-off, S	

Manufacturing energy is inserted in processes:

- *Cathode NMC622 processing*: Cathode dry and wet mixing; coating and drying (both electricity and gas); calendaring; slitting; intensive drying (both electricity and gas); and cutting
- *Anode NMC622 processing*: Anode dry and wet mixing; coating and drying (both electricity and gas); calendaring; slitting; intensive drying (both electricity and gas); and cutting
- *NMC622 stacking to filling:* Stacking, contacting, assembly, housing and electrolyte filling
- *NMC622 cell sealing, formation, testing, dry room*: sealing (only electricity); formation (both electricity and gas); testing (only electricity); dry room (only electricity); and aging (only gas)

Here is only described the model, the significance of impacts will be discussed later.

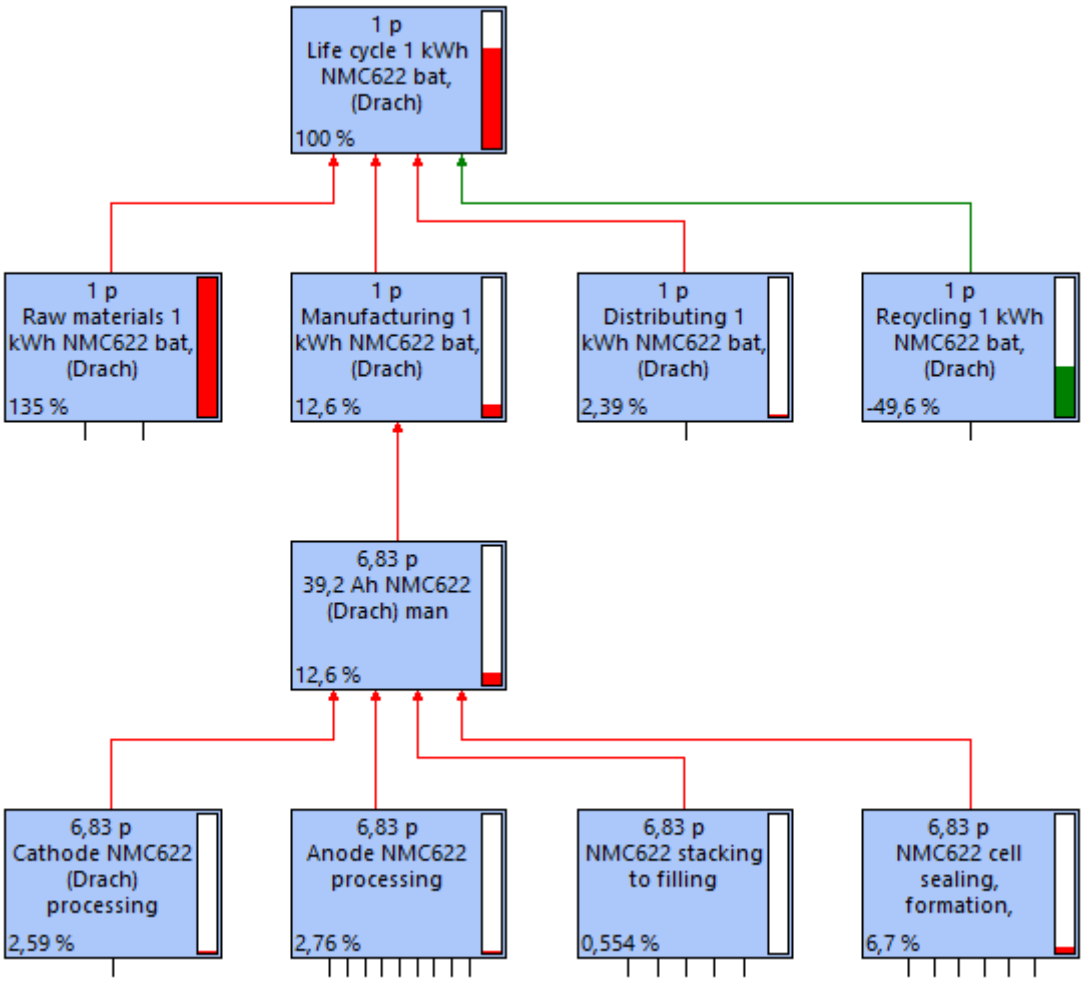


Figure 8 LCA model of 1 kWh NMC622 battery system, focus on energy, here calculated with European average electricity

4 Material sourcing

Material sourcing is described in a separate report, deliverable *D2.2 – Report on sustainable raw materials supply chain*. Since material sourcing is intimately connected to the upstream LCA material data used in the LCA model, the intention is to connect these two sections in the final LCA report.

5 Battery Passport

The scope of the Battery Passport is not, or will not be, the same as life cycle assessment data and results (system boundary of the LCA), but there will be a lot of overlap, especially regarding the calculation of the Carbon Footprint of Electric Vehicle Batteries (CFB-EV). In the full LCA, D2.3 of the BatWoMan project, it will be examined how "our" LCA deviates and aligns with the Battery Passport Rules (Bassi et al 2023).

6 Health and safety risks in a life cycle perspective

Health and safety issues with lithium-ion batteries have mostly been connected to recycling and accidental releases. Health and safety issues have not been incorporated in this screening LCA since there is presently no uniform and agreed way of incorporating health and safety risks in LCA. Section 6 is therefore a strictly qualitative description based on Lukasz et al (2023), which seems to be the only review study available to date that tries to encompass the whole battery life cycle: from winning of

primary raw materials in underdeveloped regions, cell manufacturing and use in vehicle, to attempting to win those materials back by recycling used battery cells.

Concerning the severity of negative effects on environmental, social and governance dimensions from **raw material sourcing** for lithium-ion batteries, Lèbre et al 2020 places mining of cobalt and manganese on second and third place. Copper scores eighth, nickel 10th, aluminium 12th while iron and lithium are 17th and 18th among 20 analysed commodities. Platinum is, by far, the metal associated with most negative effects on environmental, social and governance dimensions, according to Lèbre et al 2020.

Cobalt is a prime example of an energy transition metal, which supply chain is considered not sustainable and harmful for environment and communities. There have been reports on problems with child labour and conflicts in Congo, but this is linked with illegal or poorly regulated artisanal mining, not with the large-scale mining industry involved in the sourcing for lithium-ion batteries. Exposure to cobalt dust is linked with aging, cancer, memory function as well as acute toxicity. Metallic nickel, despite its widespread use in cooking utensils, coins, and stainless steel, is classified as possibly cancerogenic (group 2B), while nickel salts and oxides are classified as class 1 cancerogenic (Straif et al 2009) and also have other toxic effects. While lithium production entails ecological risks, its toxicity its well understood and even used, for example, in bipolar disorder therapy (Lukasz et al 2023).

Depending on the level of production process automatization, operators can be exposed to solvents, electrolytes or metal powders used in the **battery production**. The BatWoMan project will not use the very toxic N-Methylpyrrolidone (NMP), but water, to dissolve the binder during cathode coating. Contact with the cathode metal powders must be controlled during raw material refining, forming of active cathode material, as well as during the battery production process (eg slurry mixing). The table below from Lukasz et al (2023), Figure 9, contain occupational exposure limits for lithium, cobalt, manganese and nickel. In addition, lithium (especially in the powder form), being an alkali metal, is very reactive in contact with moisture, while nickel and aluminium are a reactive metal pair, which must be kept separated (Lukasz et al 2023). The reactivity is one reason to use dry rooms for some battery manufacturing processes, as well as keeping electrodes free of contamination. Dry room conditions also imply a safe working environment for the operators in the dry room, but as dry rooms use a lot of energy, their usage is minimized within the BatWoMan project. Cathode material mixing is for example normally not carried out in dry room conditions when processed with NMP. Dry room conditions are not necessary for aqueous cathode slurry mixing in the BatWoMan project, see Figure 2.

Table 2. Occupational exposure limits for active metal cathode components (based on [87])

Organization	Exposure limit type	Active metal cathode component			
		lithium hydride	cobalt metal, dust and fume	manganese, compounds and fume	nickel, metal and insoluble compounds
OSHA	PEL-TWA (8-hour)	0.025 mg/m^3	0.1 mg/m^3		1 mg/m^3
	PEL-STEL				
	PEL-C			5 mg/m^3	
NIOSH	REL-TWA (up to 10-hour)	0.025 mg/m^3	0.05 mg/m^3	1 mg/m^3	0.015 mg/m^3
	REL-STEL			3 mg/m^3	
	REL-C				
ACGIH	TLV-TWA (8-hour)		0.02 mg/m^3 (inhalable particulate matter)	0.02 mg/m^3 (respirable particulate matter) 0.1 mg/m^3 (inhalable particulate matter)	elemental: 1.5 mg/m^3 (inhalable particulate matter) insoluble inorganic compounds (NOS): 0.2 mg/m^3 (inhalable particulate matter)
	TLV- STEL				
	TLV-C	0.05 mg/m^3 (inhalable particulate matter)			
CaI/OSHA (DOSH)	PEL-TWA (8-hour)		0.020 mg/m^3	0.2 mg/m^3	0.5 mg/m^3 (metal) 0.1 mg/m^3 (insoluble compounds)
	PEL-STEL			3 mg/m^3	
	PEL-C				

ACGIH – American Conference of Governmental Industrial Hygienists; CaI/OSHA – California Occupational Safety and Health Administration; DOSH – Division of Occupational Safety and Health; NIOSH – National Institute for Occupational Safety and Health.
C– ceiling (the concentration that should not be exceeded during any part of the working exposure); PEL – permissible exposure limit; REL – recommended exposure limits; STEL – short-term exposure (15-minute time-weighted average exposure that should not be exceeded at any time during a workday); TLV – threshold limit value; TWA – time-weighted average (over given period of time).

Figure 9 Occupational exposure limits for lithium, cobalt, manganese and nickel (Lukasz et al (2023)

European exposure limits (TWA 8 hour) for nickel range from 0.1 to 0.005 mg/m^3, and for manganese from 1 to 0.05 mg/m^3 (TWA 8 hour). For lithium hydride, European exposure limits are consistently 0,025 mg/m^3 (TWA 8 hour) (Visser et al 2014).

Hazardous chemicals like Lithium hexafluorophosphate, Ethylene carbonate, Diethyl carbonate, Vinylene carbonate, Ethyl methyl carbonate, Dimethyl carbonate and Propylene carbonate could be part of the electrolyte. Electrolyte emissions may occur during electrolyte mixing and filling and in connection with the formation. During formation, gases are formed (mainly from electrolyte reduction/oxidation): H_2, CO, CO_2, methane, ethane, ethylene, propane, propylene, etc. It is the most safety-critical step during cell manufacturing. Gases formed during the formation are highly flammable (Zackrisson & Schellenberger 2020).

Risks during use are mostly related to accidents including thermal runaway, leading to release of a mixture of flammable, toxic, and corrosive volatiles, including carbon di- and monoxide, hydrogen, oxygen, short chain hydrocarbons (e.g., ethane, methane), gaseous hydrogen fluoride (HF), phosphorus pentafluoride (PF_5) and phosphoryl fluoride (POF_3) and compounds containing fluorine (Hynynen et al 2023). Use phase accident-related emission risks are carried over to the recycling stage, which often involve penetration, i.e. abuse that may start fires, and thermal treatment.

7 Recycling

7.1 Recycling in screening LCA model

Table 7 shows the NMC622 bill-of-materials and recycling assumptions in this screening LCA. It is based on the findings in in the Scope-lib project in which an efficiency of 96wt% of NMC622 recovery was estimated (Hu, Mousa et al 2021) (Zackrisson 2023). Table 7 gives the details of the combined pyro and hydro recycling model used in this screening LCA (Zackrisson 2023).

Table 7 NMC622 bill-of-materials and recycling assumptions

		Von Drachenfels et al 2022		**Assumption about recycling at end-of-life**	**Reco-vered mass**
Part of cell	**Material**	**Mass (g)**	**wt%**		
Anode	Graphite	158.9	24.4	Burnt (Zackrisson 2023)	
Anode	PVDF	4.1	0.6	Burnt (Zackrisson 2023)	
Anode	Carbon black	1.6	0.2	Burnt (Zackrisson 2023)	
Anode	Water	Evap. (82,3)	0.0		
Anode	Copper foil	56.8	8.7	100wt% recovery (Zackrisson 2019)	56.8
Cathode	NMC622	246.3	37<.9	96wt% recovery (Zackrisson 2023)	236
Cathode	PVDF	6.5	1.0	Burnt (Zackrisson 2023)	
Cathode	C65	6.5	1.0	Burnt (Zackrisson 2023)	
Cathode	NMP	Evap. (103,7)	0.0		
Cathode	Al foil	23.8	3.7	100wt% recovery (Zackrisson 2023)	23.8
Separator	Polypropyl ene	12	1.8	Burnt (Zackrisson 2023)	
Tabs	Al foil	0.9	0.1	100wt% recovery	0.9
Housing	Pouch foil	30.3	4.7	70wt% rec. (Al 30wt%, Nickel 40wt%, 30wt% polyprop burnt, Zackrisson 2017)	21.2
Electrolyte	LiPF6	102.7	15.8	90wt% recovered as solvent (Zackrisson 2023)	92.4
Total		**650**	100		432 (66wt%)

7.2 Recycling options

The significant increase in battery production is creating two challenges: a) the generation of a large waste streams of spent batteries, and b) the increasing demand for raw materials required for production. Those challenges are prompting enormous interest and development in battery recycling technologies.

According to recent market research conducted between 2010 and 2030, NMC811 chemistry will dominate the market after 2025, while NMC622 will continue to lead market returns until 2030 (Abdelbaky, Peeters et al.). To make battery recycling economically feasible, most efforts focus on the recovery of valuable metals such as cobalt, lithium, nickel, and manganese from the cathode, given their high cost and criticality (European commission, 2020b). The recovery of graphite, electrolyte solvent, and current collectors could also increase interest in recycling. These valuable materials can be reused for reproducing new batteries, thereby decreasing the need for new raw materials and reducing environmental pollution (Baars, Domenech et al. 2021). The recovery rates for cobalt, manganese, and nickel are estimated to reach 90wt% by the end of 2027 and 95wt% by the end of 2031. For lithium, the recovery rate from waste batteries is expected to reach 50wt% by 2027 and increase to 80wt% by 2031 (European Commission, 2022b).

Many studies and reviews showed that for NMC battery types, pyrometallurgical, hydrometallurgical routes, a combination of both methods, and direct recycling, have been used (Brückner, Frank et al. 2020, Makuza, Tian et al. 2021, Neumann, Petranikova et al. 2022).
In this section, the different recycling strategies for NMC622 chemistry are explored, along with their advantages, disadvantages, and challenges. Lithium-ion batteries (LIBs) recycling e.g., NMC-type, is highly researched in the literature, and only a few studies focus mainly on NMC622 chemistry recycling. General recycling processes are described in Figure 10.

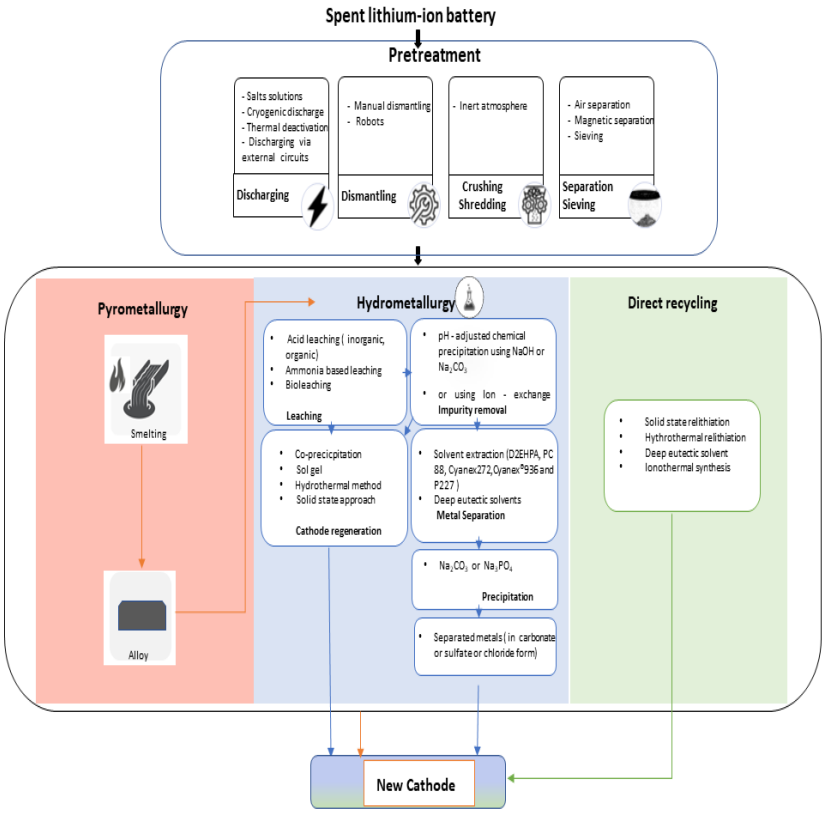


Figure 10 General recycling processes for lithium-ion batteries

7.2.1. Pre-treatment

LIBs recycling process starts with a pre-treatment process. The batteries are initially discharged to reduce the risk of short-circuiting and self-ignition, ensuring a safe recycling procedure. This could be realized by submerging the battery in salt-water solutions, cryogenic deactivation by freezing in liquid nitrogen (N_2), electrical discharge, and thermal deactivation (Ojanen, Lundström et al. 2018). For salt-water solutions, NaCl solutions are the most preferable. $Na_2S_2O_3$ was also tested for battery discharge, however, it has shown rapid corrosion. Pyrolysis in inert gas or vacuum is used to deactivate the battery. It has been applied in Accurec (Germany) and REDUX (Germany) battery recycling processes.
Once discharged, NMC batteries are manually or mechanically dismantled, and the casing, plastics, steel, cables, and other parts are collected. In some processes, the batteries are mechanically crushed, shredded, sieved, and separated based on density and magnetic properties, producing a black mass rich in valuable materials. The shredding or crushing could be performed in inert atmospheres; N_2 (used by Northvolt -Sweden and Duesenfeld start-up -Germany), argon, vacuum (Accurec), and carbon dioxide CO_2 (applied by Batrec) to avoid battery explosions in an O_2 environment.
Additionally, the dismantled or shredded batteries could be subjected to thermal or solvent treatment to remove electrolytes solvents, any additives and binder, and separate the active materials from the current collectors, aluminum (Al) and copper (Cu) foils. This step is very important, especially for hydrometallurgy and direct recycling. It has been shown that the separation of the cathode materials from the Al foil is more challenging than liberating the anode from the Cu foil. Mechanical separation

was used for this purpose, but it resulted in low separation efficiency and a high content of Al impurities. Cryogenic grinding was used to remove the Al current collector from the $LiCoO_2$ electrode in two steps: pre-freezing and low temperature grinding (Wang, Liu et al. 2019). Similarly, high-temperature methods such as incineration and pyrolysis have shown high separation efficiency (Yu, Huang et al. 2021). However, pyrolysis is a complicated process that requires high energy, and the incineration could lead to the emission of toxic gases and requires temperature control since the Al foils can melt (Yu, Huang et al. 2021). Furthermore, thermal treatment easily causes changes in the structure, composition, and morphology of cathode materials, whereas saving the morphology of recovered electrodes for direct recycling is very critical. N-methyl-2-pyrrolidone (NMP) and N, N-Dimethylformamide (DMF), as solvents for the organic binder polyvinylidene difluoride (PVDF), have shown good separation results, however, they are not suitable for large-scale operations (Yu, Huang et al. 2021). Their use has been restricted because of their high toxicity. Alternative greener methods for cathode liberation were developed. Yaocai B. Y. Bai and co-workers (Bai, Hawley et al. 2020) have efficiently separated NMC622 cathode from Al foil using a green and sustainable method based on the use of Cyrene.

The pretreatment is an important step for increasing the recovery rate and recycling efficiency (Windisch-Kern, Gerold et al. 2022). It differs from one recycling process to another. For example, pyrometallurgical methods in some cases do not require further pretreatment as they can burn LIBs with no pretreatment such as the process developed by Umicore (Belgium).

7.2.2. Pyrometallurgy

Pyrometallurgy is a robust process based on smelting or roasting batteries. The process applies to various spent LIBs with different chemistries. At high temperatures, the metal oxide components are reduced and commonly recovered as metallic alloys. The lithium usually ends up in the slag and the plastics and electrolytes are burnt. This slag can be utilized in the cement industry. It is important to note that both the price and the amount of cobalt in batteries have a significant impact on how economically efficient the pyrometallurgical process is. For low cobalt cathodes like NMC622, the extraction of lithium from the slag becomes necessary to make the process more economically viable. Recently, X. Hu et al. have developed a recovery process for Co, Ni, Mn, and Li from NMC622 batteries by smelting reduction at laboratory scale and in an electric arc furnace (EAF) at pilot scale (Hu, Mousa et al. 2021, Hu, Mousa et al. 2021). Co, Ni, and Mn are recovered as an alloy and Li is concentrated and recovered in the flue dust in the form of Li_2CO_3. A. Holzer and co-authors have developed a novel reactor using the so-called InduRed reactor concept to further recover Li and phosphorous from the gas phase in the pyrometallurgical processing of different battery types, including LFP, LCO and NMC622 (Holzer, Wiszniewski et al. 2022). Nevertheless, some Li is still lost in the slag.

Combined pyrometallurgical processes are commercially applied by Accurec and Umicore, where Li is recovered from the slag and flue dust using hydrometallurgy (see Figure 11) The accurec process stars with manual sorting of the batteries. Then are subjected to vacuum thermal recycling temperatures ≤ 250°C to remove the organic volatile components and the pre-treatment can reach up 600°C to avoid oxidization of Al. For Umicore, the electrolyte is removed at 300 ° C**.** The pyro metallurgy in the Umicore process needs to be 1200-1450° C.

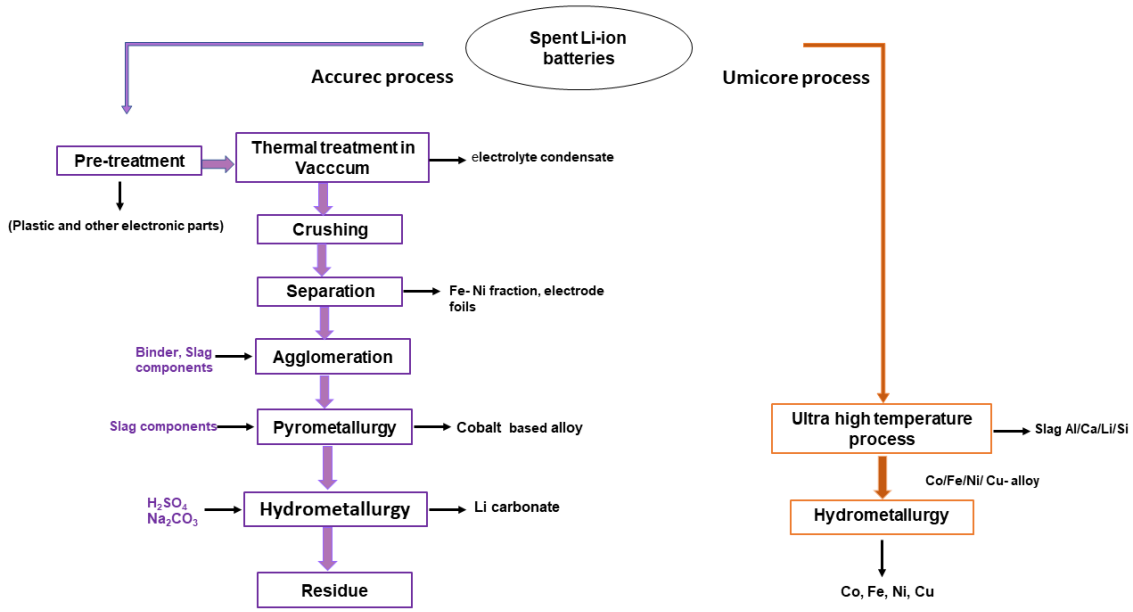


Figure 11 Flow sheet of Accurec and Umicore recycling processes.

The advantage of pyrometallurgy is seen in its simplicity and flexibility to different battery types. However, it showed a very low selectivity by alloy forming and Li slagging. Higher selectivity for metals and the possibility of Li recovery can be seen for hydrometallurgy.

7.2.3. Hydrometallurgy

Hydrometallurgy is currently applied by many companies in Europe such as Northvolt, Fortum, Retriev, Recupyl, Eramet, etc. and mostly dominated by Chinese industries. It is foreseen as one of the most preferable technologies in the future given the high recovery efficiency and high purity of recovered materials (Neumann, Petranikova et al. 2022). J. Dunn et al. have estimated a material recovery rate of 95wt% for all cathode materials (Dunn, Slattery et al. 2021).

Hydrometallurgy is generally used for metals recovery from LIBs with different chemistries. It is based on leaching, separation, and recovery steps applied to the black mass output of the pre-treatment process. The black mass contains Li, Co, Ni, Mn, Cu, Al, and Fe. A possible flow sheet for hydrometallurgical processing is presented in Figure 12. The leaching can be performed in acidic, biological, or ammonia-based solutions to obtain a metal-rich ion solution. The optimal conditions for a highly efficient recovery, such as concentration of leaching media, solid-to-liquid ratio, time, and temperature of solution were investigated.

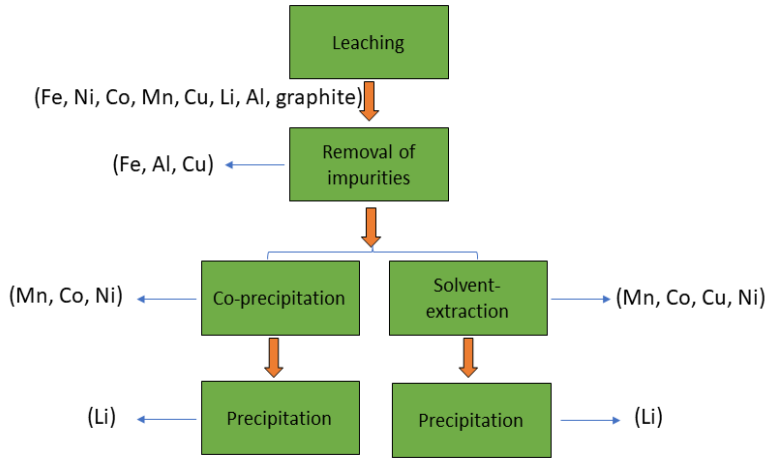


Figure 12 Example of hydrometallurgical processing

Several mineral acids, such as sulfuric acid H_2SO_4, hydrochloric acid HCl, nitric acid HNO_3, and many organic acids such as citric acid, DL—malic acid, tartaric acid, and oxalic acid have been used for leaching the NMC black mass where the metals are converted into an ionic solution in the leachate. Organic acids are more environmentally friendly, but their industrial use is hampered by their low leaching rates and very high cost (Joulié, Laucournet et al. 2014, Golmohammadzadeh, Rashchi et al. 2017, Liu, Chen et al. 2021).

H_2SO_4 has been identified as the acid of choice for leaching in industrial applications due to its low price and high availability. The amount of leaching acid varies depending on the NMC type. Additionally, a combination with a reducing agent such as hydrogen peroxide (H_2O_2) or ferrous iron during leaching enhances the leaching efficiency, especially for Co. A full study on the optimal conditions for leaching NMC622 in H_2SO_4 was done by the Industrial Materials recycling group (Promphan 2020, Vieceli, Benjamasutin et al. 2023). The presence of H_2O_2 during leaching significantly enhanced the leaching efficiency for Co, Ni, and Mn. However, the leaching efficiency for Li was not significantly improved. Lithium was observed to leach easily compared to other elements and reach an efficiency of 100wt% without addition of the reducing agent H_2O_2.. Complete leaching was achieved for all metals within 15 min at 50 °C by adding H_2O_2 to the H_2SO_4 media and an initial addition of H_2O_2 is recommended. Moreover, the leaching efficiency of Co, Ni, and Mn has been improved by the presence of Al and Cu impurities coming from NMC622 current collectors.

The NMC622 leaching equations using H_2SO_4 and citric acids are:

$$10LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2(s) + 15H_2SO_4(aq) + H_2O_2 \longrightarrow 6\,NiSO_4(aq) + 2CoSO_4(aq) + 2MnSO_4(aq) + 3Li_2SO_4(aq) + 16H_2O(l) + 3O_2(g)$$

$$15\,LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2\,(s) + 90C_6H_8O_7(aq) + 12H_2O_2 \longrightarrow 3Ni_3(C_6H_5O_7)2(aq) + Co_3(C_6H_5O_7)_2(aq) + Mn_3(C_6H_5O_7)_2(aq) + 5Li_3C_6H_5O_7(aq) + 323H_2O\,(l) + 114O_2\,(g)$$

Generally, for LIBs, HCl leaching shows better leaching efficiency compared to other leaching media; however, its use generates Cl_2 gas which poses environmental concerns. W. Xuan et al. (2021) have investigated the leaching kinetics in HCl of NMC622 cathodic material, showing that NMC811 and NMC622 dissolve faster at 54 °C compared to NMC532 and NMC111. This result was consistent with the expectations that Ni would enhance the dissolution and Mn would stabilize the NMC structure.

In another study (Liu, Chen et al. 2021), the effect of leaching agents (HCl, HNO_3, H_2SO_4, and H_3PO_4) on the leaching efficiency of NMC622 was studied in the absence of reducing agents. H_2SO_4 and HNO_3 showed similar leaching capacities and had the highest efficiency in extracting Li, at nearly 90wt%. The efficiency for Ni, Co, and Mn leaching reached approximately 40wt% (Liu, Chen et al. 2021). In HCl solution, the highest leaching efficiency (>99wt%) was achieved for all elements at 20 g/L pulp density, 70 °C for 50 min, while H_3PO_4 leaching showed the lowest leaching efficiency.

A leaching method in an ammonia-based solution of discarded NMC622 powder was developed and the leaching efficiency of Li, Ni, and Co was 93.45wt%, 96.08wt%, and 94.42wt%, respectively, under the optimal conditions of 6 M [NH3] T, 0.2 M sulfite, pH 10.0, and 140°C for 90 min (Zhu, Guo et al. 2022).

Bioleaching is an ecofriendly alternative to acid and ammonia-based leaching. It involves the use of bacteria such as fungi, Acidithiobacillus ferrooxidans and Acidithioacillus thiooxidans to dissolve metals in a low-cost and eco-friendly way. The bacteria utilize sulfur powder (S°) or $FeSO_4$ as their main energy sources, resulting in the production of H_2SO_4 in the culture solution. This results in the dissolution of metals like Co, Li, Ni, Mn, and Cu from spent LIBs. Several studies have focused on the bioleaching of NMC cathodes (Jegan Roy, Srinivasan et al. 2021). This process is green; however, it is long, has slow kinetics, and not widely used in large volumes for battery recycling. In the case of NMC622, the same procedure used for other NMC chemistries could be applied with optimization of some parameters.

In traditional hydrometallurgical processing, the graphite can be removed after leaching using filtration. The impurities like Al, Fe, and Cu present in the pregnant solution with high critical metals can be removed using pH-adjusted chemical precipitation using NaOH or Na_2CO_3 or using ion-exchange.

Once the impurities are removed, two methodologies can be followed: (I) Co, Ni, Mn, Li metals are separated using different organic extractants. Generally, for LIBs, D2EHPA, PC-88, Cyanex 272, and

recently Cyanex®936 have been used. P227 extractant P227 was used to coextract Co, Mn, Ni directly from the NMC622 leachate and separate them from Li (Liu, Chen et al. 2021).
Solvent extraction is implemented in the industry (Northvolt and Nickelhütte) and has been widely used. However, it is very complicated since it is difficult to separate the metals in only one step from the complex leach mixture. The final active cathode materials can be recovered as metals salts. They can be used as precursors for the regeneration of new cathode owing to their high purity. Recently, deep eutectic solvents have been used to extract critical metals from mixed NMC materials with high selectivity and efficiency. (II) Closed-loop recycling where the liquor obtained from leachate, contains a mixture of leached metals, is used to regenerate new NMC cathode powder. NMC111 was generated from the output of HCl-based hydrometallurgy of NMC622 (Chu, Zhang et al. 2020). In another study, NMC622 was regenerated from spent batteries using a bioleaching process mediated by acid thiobacillus ferroxidase (Do, Jegan Roy et al. 2022).
Hydrometallurgy has shown higher efficiency when combined with mechanical treatment and pyrometallurgy (Neumann, Petranikova et al. 2022).

7.2.4. Direct recycling and other methods

Direct recycling creates a closed-loop system where active materials, cathode and anode, are recovered for reconditioning and reuse in remanufactured LIBs.
This method offers several benefits, including the preservation of the cathode structure, avoiding the different steps of breaking down the cathode into small fragments and eliminating the multiple steps required for processes like hydrometallurgy and pyrometallurgy. It is mainly based on healing the defect caused during LIBs life cycle. Relithiation with lithium sources such as Li_2CO_3 and LiOH and thermal treatment are used to directly return the materials to a new cathode production process.
This method is widely studied at lab scale. Sustainable recycling of NMC622 cathode scraps via Cyrene-based separation has been investigated (Bai, Hawley et al. 2020). The Cyrene was used to separate the cathode from the Al foil. The recovered cathode was calcined in air at 600 °C, mixed with NMP to produce the slurry and reused in a cell. The recovered NMC622 cathode materials showed similar crystal structure, morphology, and electrochemical performance compared with the pristine cathode materials.
New research on Li leaching from spent ternary lithium-ion batteries ($Li_{0.8}Ni_{0.6}Co_{0.2}Mn_{0.2}O_2$) was investigated where 95.02wt% of Li in spent NMC622 was leached under 2.5 V in 3 h by using a direct electro-oxidation method (Yang, Gao et al. 2023).

7.2.5. Graphite and electrolyte solvent recovery

The focus in recycling was dedicated to metals recovery but recently there has been a growing interest in the development of new recovery processes for anode and electrolyte materials. This is because the extraction of graphite and electrolytes from NMC cathodes can significantly reduce the cost of producing new batteries, increase recycling profit margins, and reduce the environmental impact and safety risks of battery recycling and production. Additionally, electrolytes are flammable and toxic, can complicate the recycling process, and may damage the recycling plant.
Instead of burning and evaporating the electrolytes, several methods have been used for electrolyte solvents recovery from LIBs such as supercritical fluid extraction, vacuum pyrolysis, and solvent extraction. N. Zachmann et al. (Zachmann, Petranikova et al. 2023) have suggested a low temperature thermal treatment process for the recovery of the electrolyte of spent EV LIBs where the linear and cyclic carbonates DMC, EMC, and EC were successfully recovered in liquid phase with a high recovery rate in 80 min at 130 °C processing temperature. Duesenfeld has also developed a method for electrolyte recovery.
Similar to electrolyte, graphite recovery approaches have been reported in literature, including pre-treatment, pyrolysis, hydrometallurgy, supercritical, and water treatment. In hydrometallurgical processing, the graphite is removed using filtration after leaching. H. Qiu et al. investigated the graphite and cathode active materials NMC622 using pre-treatment and flotation (Qiu, Peschel et al. 2022).

7.2.6. Production scraps recycling

Battery manufacturing leads to a large amount of electrode scrap that could range from ~5–30wt% depending on the maturity of the process. Manufacturing scraps come from electrode cutting and failures during production. The scrap rate depends on the weight of the components (current collector, electrode loading, pouch foil, etc.) The composition of the scraps can be different and can include various materials (Gaines, Zhang et al. 2023). They can be produced during the production process: Coat- Fold or roll- Assemble and fill-Test (see Figure 13). Between Coat and Fold or roll comes cutting, which will always produce anode and cathode scrap of the same quality.

As seen from Figure 14, until 2030, production scrap is projected to be the main source of battery materials for recycling, but after that, end of life batteries will be the dominant source. However, only a few reported studies have explored recycling options for these scraps (Song, Wang et al. 2013, Song, Wang et al. 2014, Zhang, Xue et al. 2016, Gaines, Zhang et al. 2023).

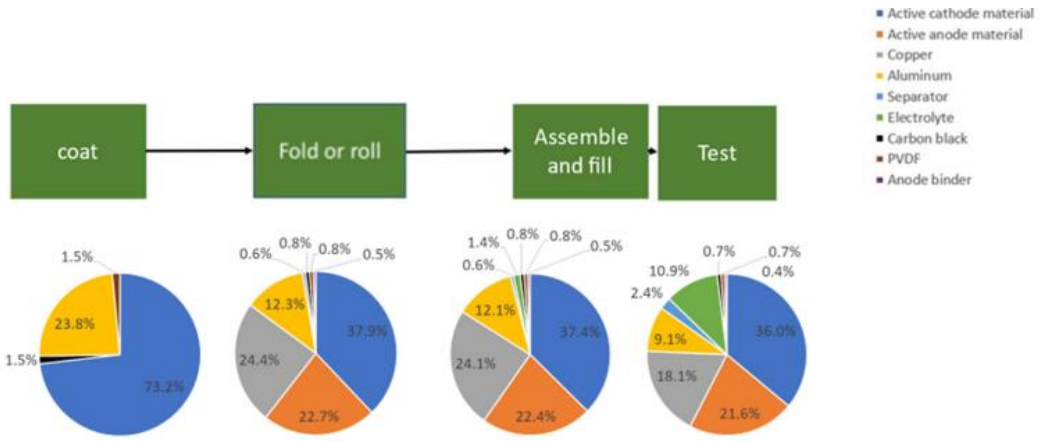


Figure 13 Composition and origin of production scrap (Gaines, Zhang et al. 2023; Knehr et al.2022)

Compared to end-of-life batteries, production scraps present many advantages in terms of recycling. The electrodes are only bound to the current collectors Al and Cu and are not put together into cells. They have not yet been in contact with the electrolyte and binder, no further electrochemical tests (such as charging-discharging) were performed, and they are not yet degraded. Thus, the composition, structure, and properties of the electrodes are not modified, which makes their regeneration and material recovery much easier compared to their regeneration from spent batteries. Fewer recovery steps and less solvents can be applied to the scraps, making the process less expensive and more environmentally friendly compared to used batteries.

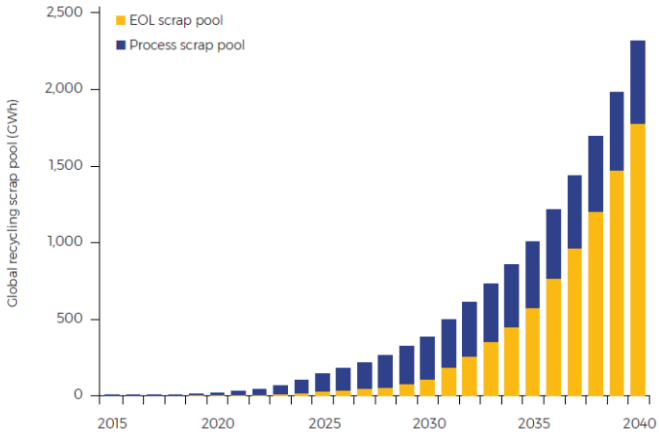


Figure 14 Global recycling scrap evolution (resource Benchmark Q2 2022 recycling Report, 10 September 2022 in Batteries, Manufacturing, Market Background, Materials, Recycling)

For conventional production scraps, the liberation of cathode from the foils by removing the PVDF binder is a very crucial step in the recycling process. The bonding between the cathode and Al foil is strong which makes the separation complicated. It could be realized using mechanical treatment, thermal treatment, and organic solvents dissolution. Many research works focused on this separation of cathode from the current collectors (Zhang, He et al. 2013, Wang, Tan et al. 2019, Yu, Huang et al. 2021).

X. Zhang et al. have used direct calcination, NMP solvents dissolution and basic solution dissolution using NaOH combined with thermal treatment to separate cathode foil and regenerate $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathode from production scraps (Zhang, Xue et al. 2016). The regenerated cathodes showed sufficient electrochemical performances comparable with commercial $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathodes, depending on the separation method and calcination temperatures of the regeneration process. DMF and ethanol were used to remove PVDF and recover scrap materials from $LiCoO_2$ (Song, Wang et al. 2014). DMF and heat treatment were also used to recover $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ materials from cathode scraps (Song, Wang et al. 2013). The best electrochemical performances were observed for the unheat-treated ones with solvent method.

Xiaoxiao Zhang et al. have used direct calcination, NMP solvents dissolution and basic solution dissolution using NaOH combined with thermal treatment to separate cathode foil and regenerate $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathode from production scraps (Zhang, Xue et al. 2016). The regenerated cathodes showed sufficient electrochemical performances comparable with commercial Li $(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathodes, depending on the separation method and calcination temperatures of the regeneration process. N,N-Dimethylformamide (DMF) and ethanol were also used to remove PVDF and recover scrap materials from $LiCoO_2$ (Song, Wang et al. 2014). Sintering method and N,N-Dimethylformamide (DMF) were also used to recover cathode materials from $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ scraps (Song, Wang et al. 2013).

Those methods can be tested for other LIBs chemistries, such as NMC622. NMP and DMF are toxic, so the development of safe and green methods is very important. Cyrene was used to liberate NMC622 powder coming from the trimmings of NMC622 cathode that was fabricated using a pilot-scale slot-die coater (Bai, Hawley et al. 2020). Triethyl phosphate was also used for NMC622 cathode separation (Bai, Essehli et al. 2021).

A combination of pyrometallurgy and hydrometallurgy could also be efficient (Nguyen, Lee et al. 2014). Production electrode scraps can be shredded, sieved, and thermally treated to remove the PVDF binder. The cathodic powder is then leached (as described above for hydrometallurgy). Al impurities could be removed, and the rest of metals solution can be further processed to elementary extract metals or used for cathode regeneration. But this method would consume more solvents, energy, and time.

Concerning the anode, its peel-off from the current collector is not very complicated owing to the weak bonding between the Cu foil and graphite and this could be applied to all types of LIBs. The methods used for cathode /Al separation are also efficient for anode delamination (Natarajan, Akshay et al. 2022). Y. Bai et al. have easily separated the anode from Cu foil without any damage by simply immersing the anode coatings in water (Bai, Li et al. 2023).

The choice of recycling methods for scrap production depends strongly on the composition of the scrap. Switching from NMP to water-based processing of NMC cathode can facilitate the removal of the binder and recovery of valuable materials. J. Li et al (Li, Lu et al. 2020) have developed a green and more sustainable manufacturing method for LIBs where no hazardous organic solvent is used during electrode manufacturing and recycling. The regenerated cathode compound showed comparable electrochemical performance to the pristine.

According to BatWoMan, in NMC622 production, the scraps are obtained after cathode and anode cutting. The removal of the binder with one of the methods mentioned above, especially the green

and sustainable one such as the use of water and Cyrene for binder removal, could be an efficient and inexpensive way of recycling manufacturing scraps.

The choice of recycling methods for scrap production depends strongly on the composition of the scrap. According to BatWoMan, in NMC622 production, the scraps are obtained after cathode and anode cutting. The removal of the binder with one of the methods mentioned above, especially the green and sustainable one, could be an efficient and inexpensive way of recycling manufacturing scraps.

7.2.7. Environmental aspect, and cost of recycling technologies

When selecting a suitable recycling technology, the environmental impact and sustainability of the process should be highly considered in addition to the recovery efficiency. In pyrometallurgy, Li is lost in the slag, and a large amount of energy is required in this process compared to hydrometallurgy and direct recycling (Fan, Li et al. 2020) and it is more suitable for LMO and LFP batteries. On the other hand, for NMC batteries, hydrometallurgy combined with pre-treatment steps is more effective in recovering all the metals, including Li, with minimal loss despite the high amount of chemicals used in this process and the generated wastewater. Many studies have focused on investigating the environmental and economic aspects of battery recycling processes in China, the US, and Germany. Rebecca Riez et al. (2019) have compared the greenhouse gas (GHG) emissions, energy inputs, and costs associated with producing and recycling NMC-622 lithium-ion batteries (pouch and cylindrical cells). The study highlighted the high potential for reducing life cycle greenhouse gas emissions observed for direct recycling. Many studies presented a comparison of the battery recycling processes and the overall process and environmental impacts of pyro- and hydrometallurgical processes (Harper, Sommerville et al. 2019, Hantanasirisakul and Sawangphruk 2023). It is found that the overall environmental impact of primary energy consumption and greenhouse gas emissions can be reduced by 40% and 20% using hydrometallurgy and pyrometallurgy, respectively compared to LIBs produced from newly mined materials, (Hantanasirisakul and Sawangphruk 2023). In the Scope-lib project, using a combination of pyro- and hydrometallurgy, it was estimated that the gain from recycling could be 48% of production phase climate impacts (Hu, Mousa et al 2021) (Zackrisson 2023). J.L. Popien et al. (2022) studied how battery sizes and chemistry affect the recycling network. They found that hydrometallurgical processing of larger NMC622 batteries requires fewer materials and energy, leading to lower corresponding CO_2-equivalents compared to average or small NMC622.

The cost of battery recycling is currently expensive, primarily due to the high cost of the process, including collection, transportation, and separation, making it economically challenging to recycle batteries. Everbatt model was designed to determine closed-loop battery recycling cost and environmental impacts, including all possible variations of the recycling process of NMC622 and other chemistries. For electrode cutting scraps, hydrometallurgy methods are probably the most suitable. See the section on Hydrometallurgy.

8 Results

The life cycle climate impact of the batteries applied in the vehicles is summarized in Figure 15 to Figure 23 below. As mentioned earlier, the use phase is excluded. In the figures below, the thickness of the arrows corresponds to the climate impact measured in carbon dioxide equivalents from respective process. The amount of CO_2-eq in kg is shown in the lower left corner of each box. Green arrows or minus in the box means avoided emissions in the Sankey diagram. Some Sankey diagrams show abiotic depletion.

8.1 Per kWh battery

Results are shown below for 1 kWh battery capacity assuming 50wt% battery cells in the battery pack. Assumptions regarding recycling see Table 7. According to Figure 15, the raw materials of the cell entails 49 kg CO_2-eq/kWh while the raw materials of the rest-of-the-pack entails 43 kg CO_2-eq/kWh. A 1000 km transport of the fabricated battery by lorry from the battery manufacturing plant to the car manufacturing plant would entail 1.6 kg CO_2-eq/kWh. By recycling battery materials at the end-of-life, 34 kg CO_2-eq/kWh could be recuperated, and if so, contribute to a total life cycle climate impact of

68.7 kg CO_2-eq/kWh, not including the use phase. In a European perspective, with European average electricity, the use phase, here omitted, could amount to around four times of the raw materials and manufacturing climate impact (Zackrisson 2021). Thus, **any action to decrease the raw materials and manufacturing phase impacts that could increase use phase impacts, must be carefully examined** in a complete life cycle perspective including the use phase.

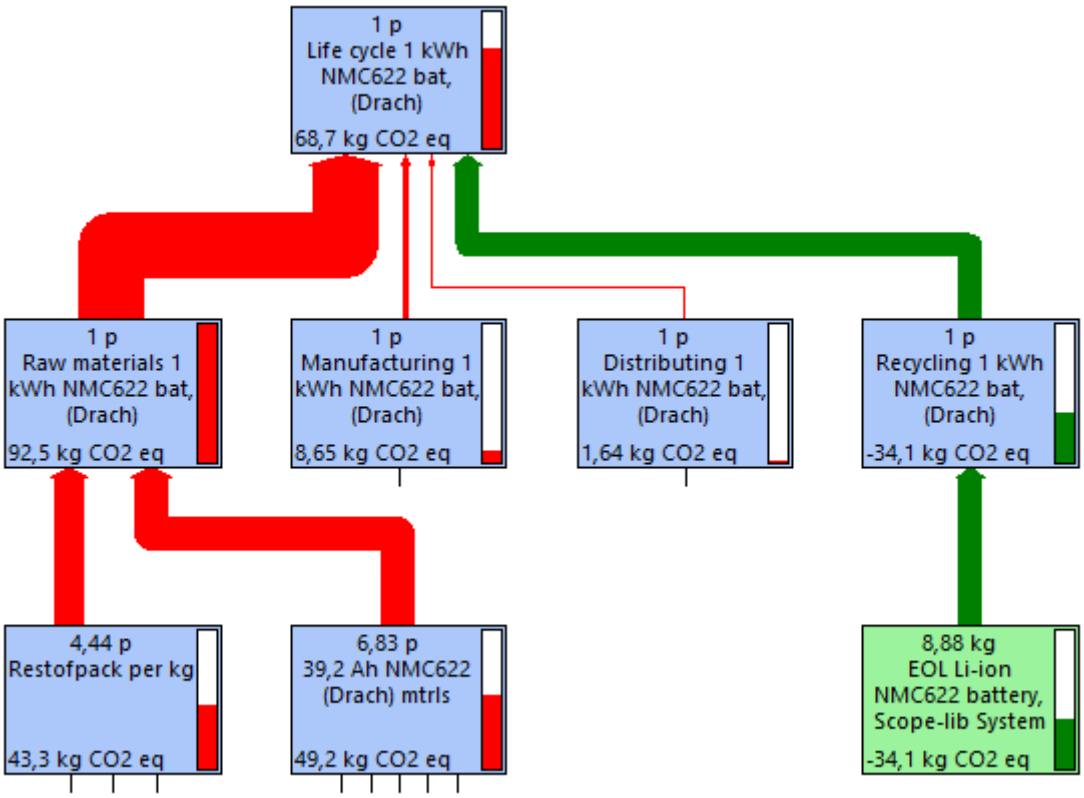


Figure 15 Life cycle climate impacts (excluding use phase) per kWh battery capacity

Recycling has the potential to retrieve a large part of the production climate impacts, see Figure 15. Most gains would come from the metals in the cells and in the rest of the pack.

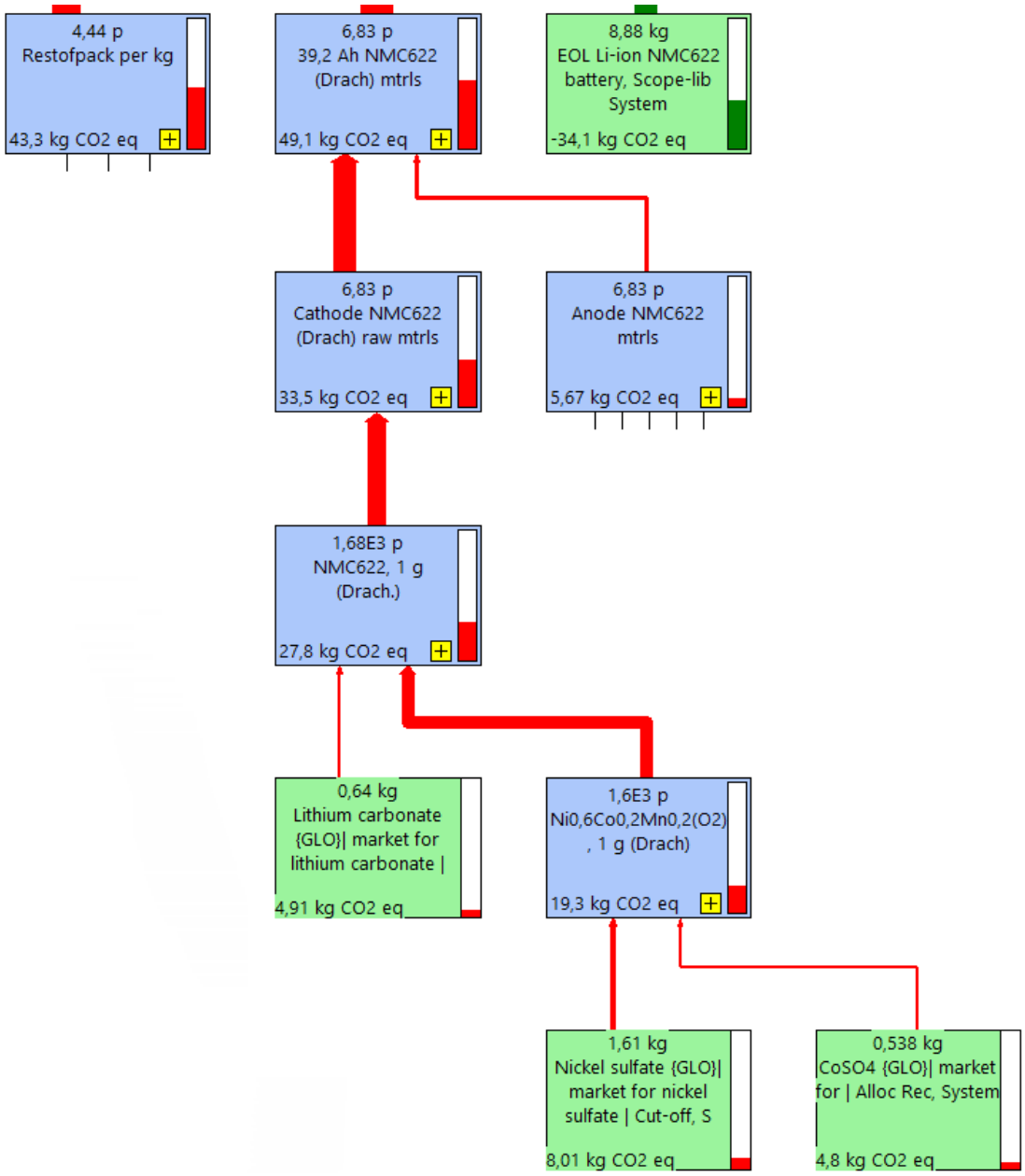


Figure 16 Life cycle climate impacts per kWh battery capacity with focus on cathode, cut-off[6] 4.5%

Most climate impact stem from the cathode, and in particular from the nickel and cobalt in the NMC622, see Figure 16.

[6] With cut-off 4,5.% in Figure 16 (and other figures), means that only processes that contribute more than 4.5% to the total are *shown* in the image. However, all processes are included in the calculations.

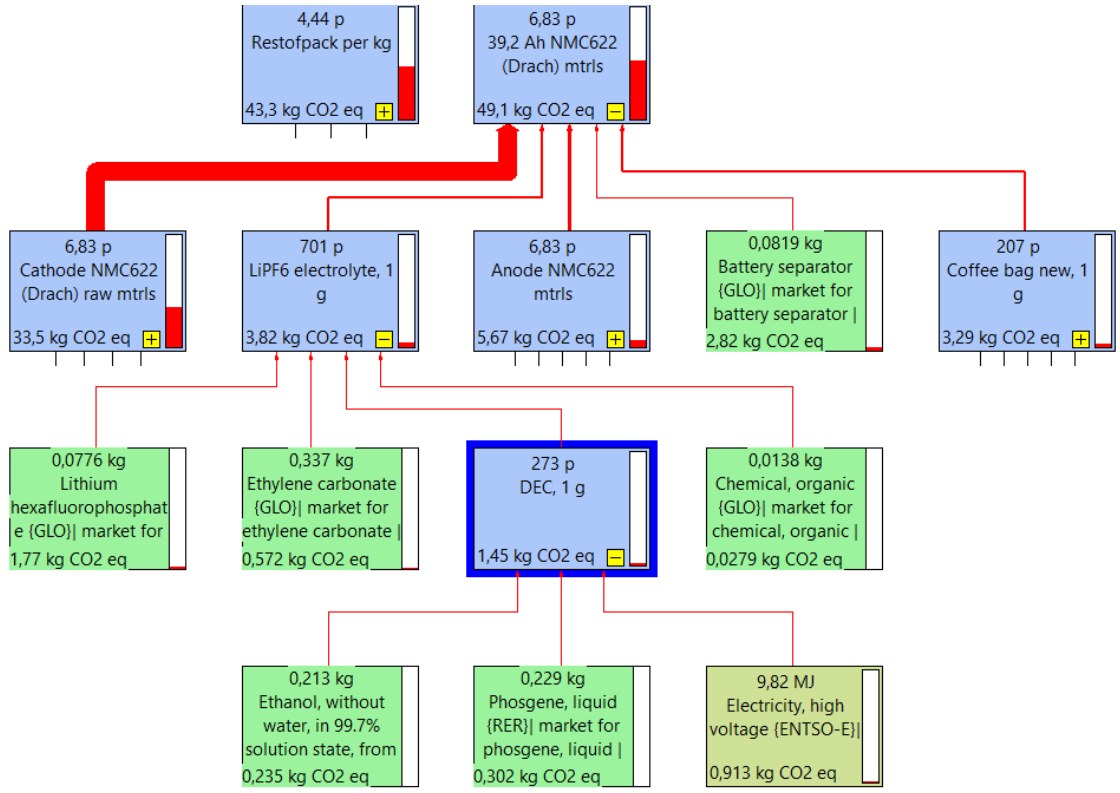


Figure 17 Life cycle climate impacts per kWh battery capacity with focus on electrolyte

The electrolyte has a considerable mass share, 16wt% in our example case, see Table 1. But it consists mainly of solvents and the climate impact is therefore much smaller than from the cathode and dominated by $LiPF_6$, see Figure 17.

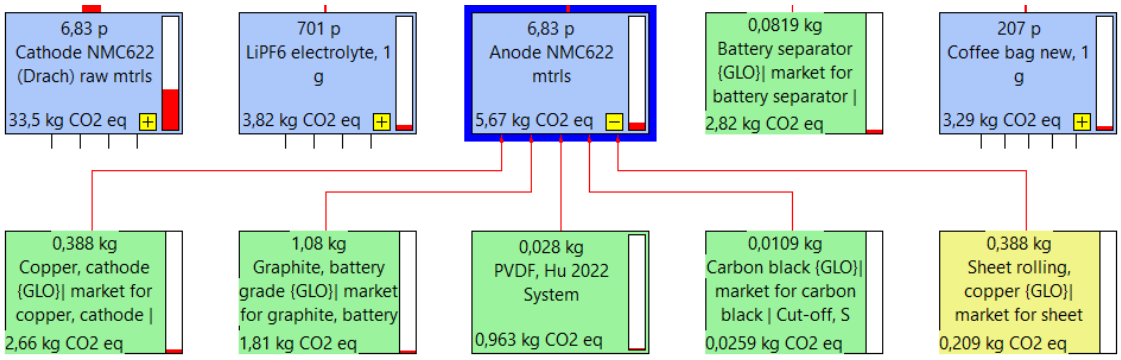


Figure 18 Life cycle climate impacts per kWh battery capacity with focus on anode

Anode climate impacts stem mainly from copper, graphite and PVDF, Figure 18. Another binder, CMC/SBR, carboxymethyl cellulose and styrene-butadiene rubber, for the anode is envisaged for the BatWoMan cell.

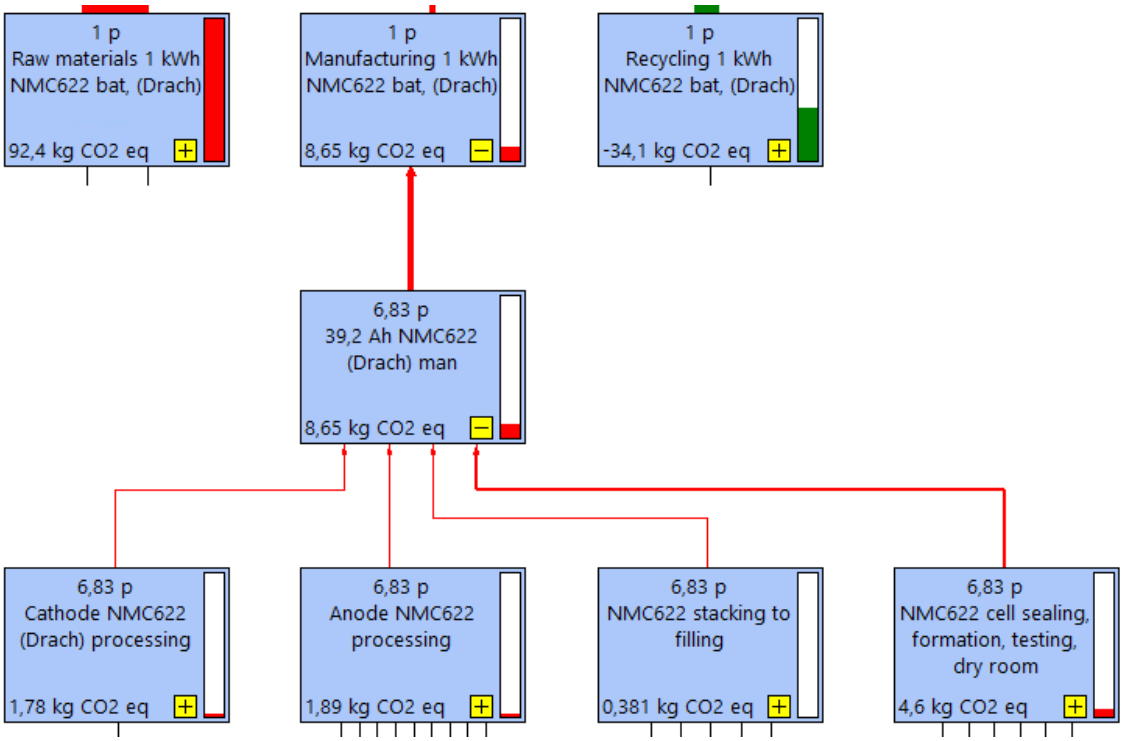


Figure 19 Life cycle climate impacts per kWh battery capacity with focus on manufacturing energy

Energy use for the manufacturing is here modelled with European average electricity and gas, see Figure 19. See Figure 20 below, for model with Swedish average electricity. Electricity for the formation is dominating the climate impact. See section 8.4 for further details on energy use in manufacturing.

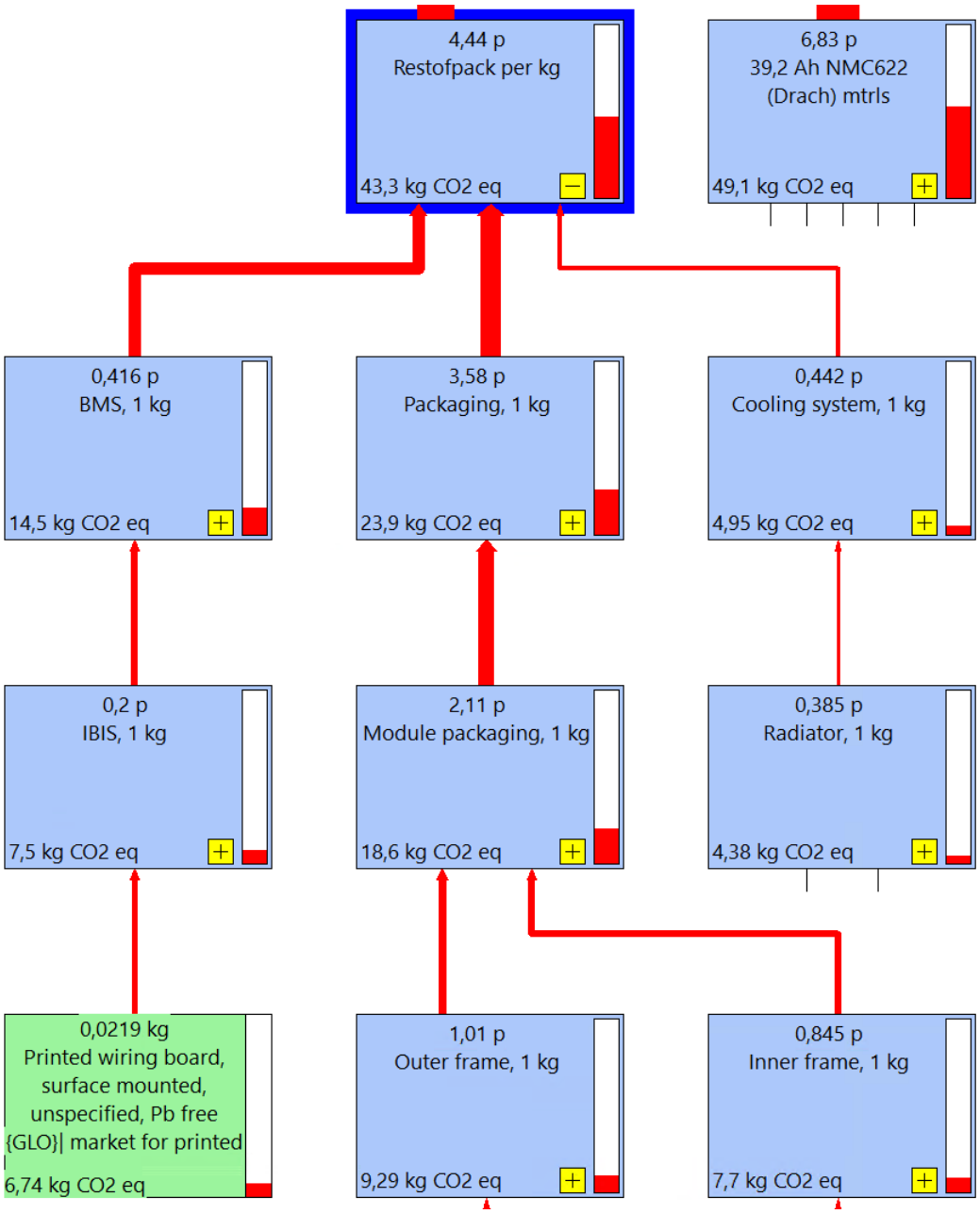


Figure 20 Life cycle climate impacts per kWh battery capacity with focus on rest-of-pack, cut-off 4.5%

The packaging (aluminium) is dominating climate impacts from the rest-of-pack. Significant contributions are also seen from electronic components in the BMS.

Resource depletion is shown in Figure 21 below. The overall picture is the same as for the climate impact, which is that most impact stems from the cell (especially cathode) but also a lot of impact stems from the rest-of-pack, and a large part can be recuperated by recycling.

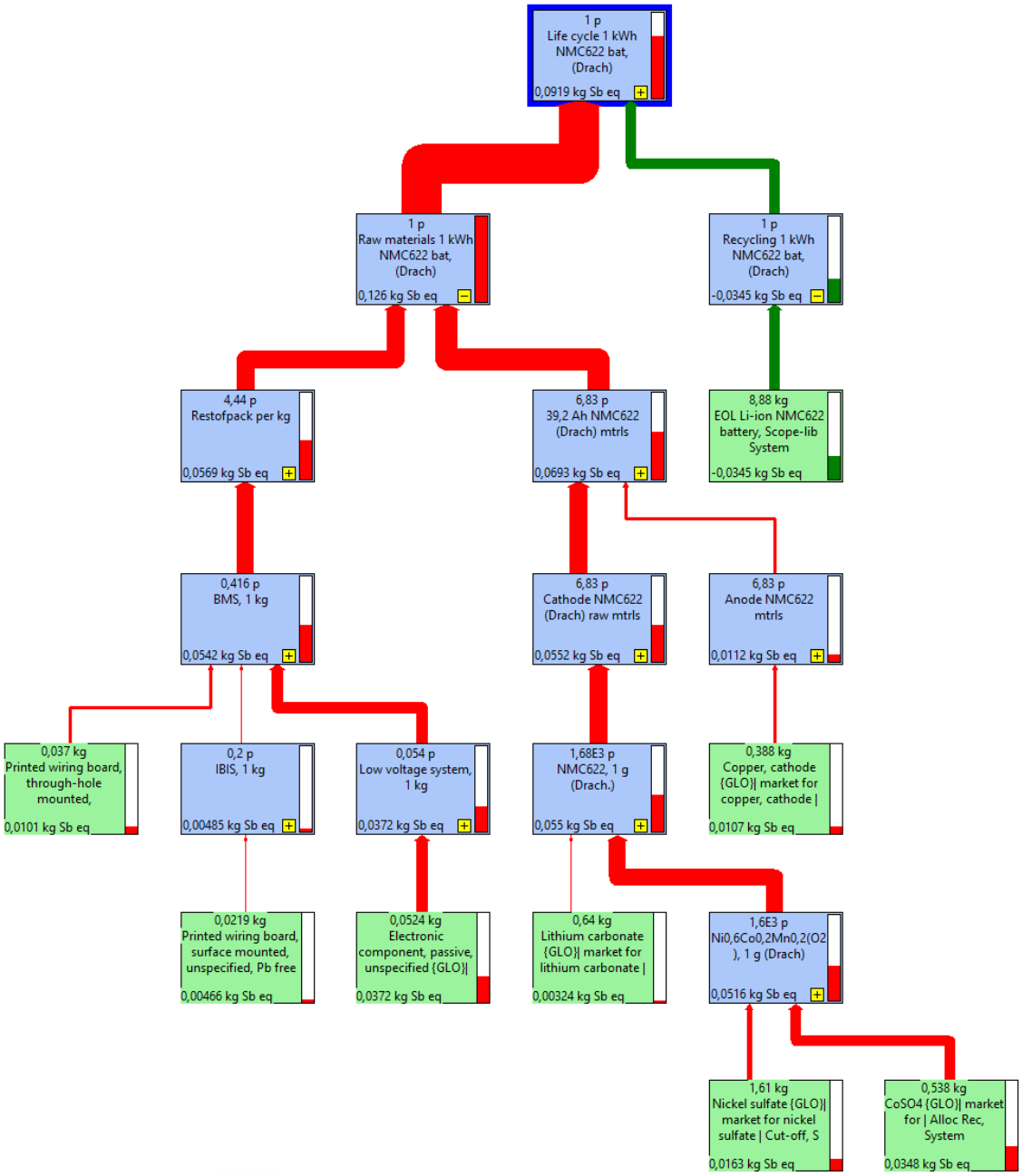


Figure 21 Life cycle abiotic depletion (elements, economic reserve) per kWh battery capacity, cut-off 2.4%

8.1.1. Parameter variations

The source of electricity for the production can be switched between European average and Swedish average. The rest-of-pack percentage could be set to any number, see Table 8. In the SimaPro model the rest-of-pack parameter is called Weightofcellsinpack. Base case conditions are defined as European average electricity and rest-of-pack equals 0,5. Parameters are varied one at a time meaning that when the electricity is changed, base case conditions apply for rest-of-pack, and vice versa.

Table 8 Significant parameters/processes and the resulting variance in kg CO_2-eq/kWh battery capacity

Parameter name in SimaPro model	**Parameter**	**Life cycle climate impact**
Rest-of-pack (Weightofcellsinpack) Base case: 0.5	0.3 (0.7)	53.1
	0.7 (0.3)	105
Prodel, 1=Swedish electricity; 0= European average electricity, for the cell production and assembly Base case: European average electricity	0	68.7
	1	59.7

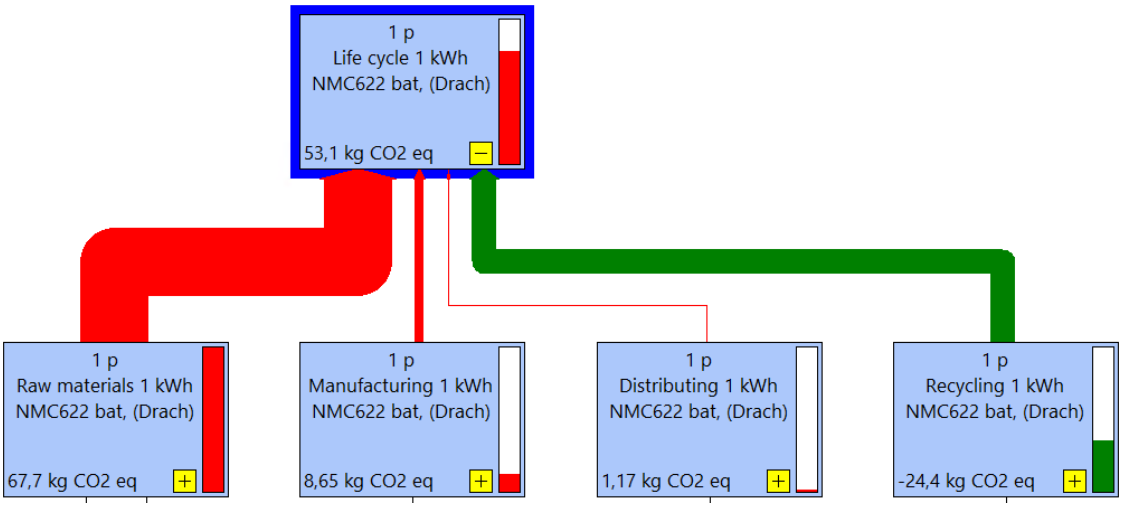


Figure 22 Life cycle climate impacts per kWh battery with rest-of-pack 0,3

Reducing the rest-of-pack from 0.5 to 0.3 is a drastic change that would lead to a considerable improvement (decrease) in climate impact, see Figure 22. Note that recycling gains also decrease since there is less material (from the rest-of-pack) to recycle. Increasing the rest-of-pack from 0.5 to 0.7 is an even more drastic change (and very unusual). It would lead to a considerable increase in climate impact, see Figure 23. Note that recycling gains also increase since there is much more material (from the rest-of-pack) to recycle. 1000/6.34=158 Wh/kg and 1000/14.8=68 Wh/kg, is the respective energy density at battery level.

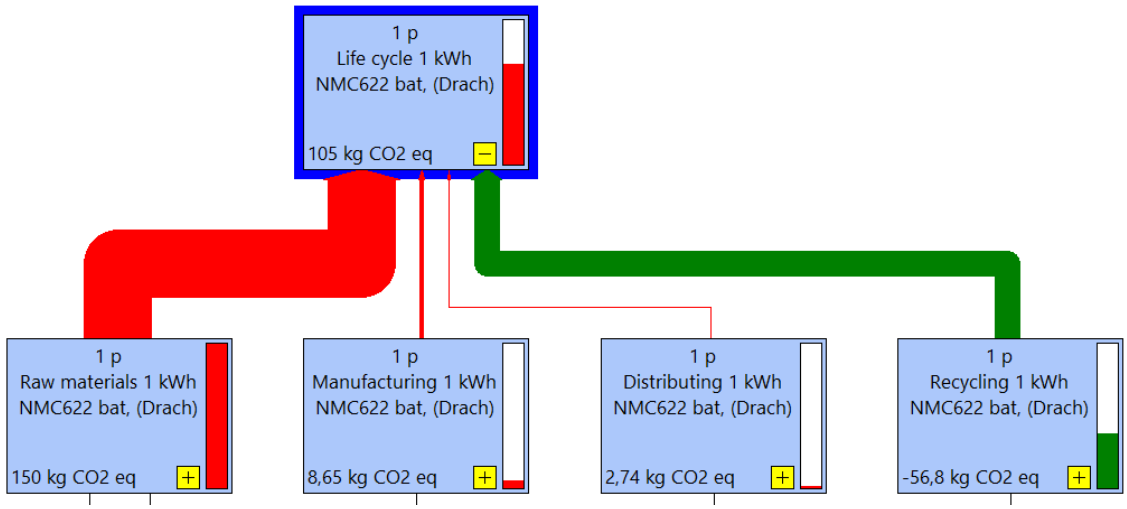


Figure 23 Life cycle climate impacts per kWh battery with rest-of-pack 0,7

8.2 Results per km

Results per km should include the use phase and thus an application still unknown. So no results per km in this screening LCA report.

8.3 Results per delivered kWh

The battery passport requires reporting of the carbon footprint as declared in kg of carbon dioxide equivalent per one kWh of the total energy provided by the battery over its expected service life and differentiated per life cycle stage. Guidelines (JRC 2023) provide numerous ways of calculating delivered kWh, some connected to the application, others not. For the purpose of this screening LCA report, we will just conclude that the life cycle stages, excluding the use stage, leaves the raw materials stage, the manufacturing stage, the distribution stage and the end-of-life stage, and the relation between these stages would be the same for delivered kWh as for nominal battery capacity, see below.

However, delivered kWh, factors in the longevity, the lifetime, of the cell. The longer life, the more delivered kWh to distribute the climate impact on (from raw materials, production, distribution, and recycling).
As mentioned before, the use phase could be (with European average electricity) four times the manufacturing phase. See Figure 24.

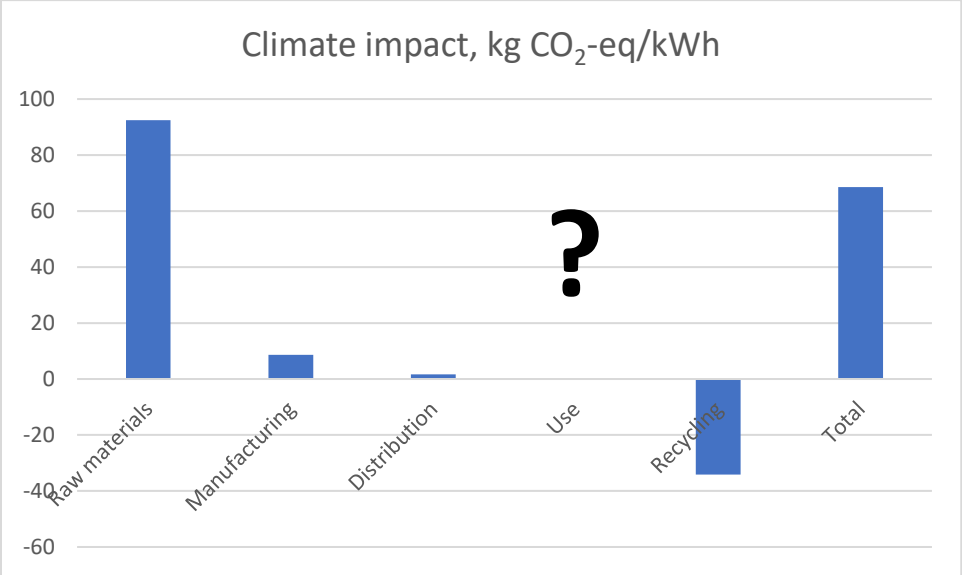


Figure 24 Life cycle climate impacts per kWh battery capacity. The relation between life cycle stages would be the same for delivered kWh as for battery capacity

8.4 Energy use

Since BatWoMan has specific targets related to energy use in manufacturing, these are scrutinized below. The model by Drachenfels et al (2022) contains detailed energy data about the whole cell manufacturing, see Figure 2. Table 9 gives the energy use in specific cell manufacturing processes in MJ gas or electricity used per kWh cell capacity and the resulting carbon footprint (CF), see Figure 19.

Table 9 Energy use in cell manufacturing. kWh energy and CF per kWh capacity[7]

Process	**MJ gas/kWh**	**MJ electricity/kWh**	**CF kg CO_2-eq/kWh**
Cathode NMC622 processing			
Cathode dry and wet mixing		0.29	0.027
Coating and drying		1.88	0.177
Calendaring		0.75	0.071
Slitting		0.21	0.020
Intensive drying		0.14	0.013
Cutting		0.02	0.0019
Coating and drying	20.7		1.14
Intensive drying	5.8		0.32
Anode NMC622 processing			
Anode dry and wet mixing		0.31	0.029
Coating and drying		2.01	0.189
Calendaring		0.803	0.0755
Slitting		0.226	0.0212
Intensive drying		0.147	0.0139
Cutting		0.0197	0.00185
Coating and drying	22.1		1.22

[7] with European average electricity mix

Process	MJ gas/kWh	MJ electricity/kWh	CF kg CO_2-eq/kWh
Intensive drying	6.19		0.34
NMC622 stacking to filling			
Stacking		0.909	0.0855
Contacting		0.138	0.0129
Assembly		0.138	0.0129
Housing		0.138	0.0129
Electrolyte filling		2.73	0.256
NMC622 cell sealing, formation, testing, dry room			
Sealing		0.103	0.0097
Formation		35.7	3.36
Testing		3.57	0.336
Dry room		8.22	0.773
Aging	0.89		0.0493
Formation	1.43		0.0789
Total of all processes	**57**	**58**	**9**
Total kWh energy per kWh battery	(57+58)/3.6=**32 kWh/kWh**		

It should be noted that 32 kWh energy per kWh cell is a low value. Zackrisson (2021) estimated 60 +- 10 kWh energy per kWh cell.

9 Discussion and conclusions

9.1 Discussion

9.1.1. The importance of the use phase

It should be noted that the use phase, though excluded, is the dominant phase with European average electricity, maybe four times the production phase, and with Chinese electricity maybe eight times the production phase. So, production phase improvements, that will lead to more use phase impacts, are rarely real improvements. For example, cells that need more cooling than other cells, would not only raise the rest-of-pack ratio, but, due to the extra weight, also increase the electricity consumption per kilometre. Cells needing more cooling, also have lower efficiency, which would also lead to use phase losses. Producing a light, safe and efficient cell with long service life is very important and desirable.

9.1.2. Recycling is important

The example shows that recycling well can “recuperate” a considerable amount of production phase impacts. In this context it should be pointed out that there is no production scrap in the present model, which could amount to 5-30wt%. This will be added for the full LCA as well as the methods for recycling production scrap that will be tested in the project.

9.1.3. Cathode materials

Cathode materials, especially nickel and cobalt, have very significant climate and resource depletion impact. The sourcing of nickel and cobalt is therefore very important and will be especially investigated. As shown by Kallitsis et al (2022), there is a large span between minimum and maximum values. What stands out as significant in the screening LCA are approximately median values, which are closer to the minimum values (than to the maximum values). Thus, it makes a difference to source materials at the lower end, and it is probably worth the transportation effort, even though this needs to be checked and validated. It is of course also very important to recycle cathode production scrap.

9.1.4. Manufacturing energy

The data for energy use in manufacturing, from Drachenfels et al. 2022, will be replaced by project specific data in the full LCA. The sum of the manufacturing energy in this screening LCA indicates that the value does not consider scrap rates (which could be 5-30wt%) and is very low compared to values measured in existing industry.

9.2 Conclusions

This screening LCA points towards recycling and choice of cathode materials as especially important areas for eco-design of battery cell production. Nevertheless, to produce a light, safe and efficient cell with long service life is very important for total life cycle (i.e. including the use phase) impacts.

10 References

Andreasi Bassi, S., Peters, J.F., Candelaresi, D.,Valente, A., Ferrara, N., Mathieux, F., Ardente, F. (2023). Rules for the calculation of the Carbon Footprint of Electric Vehicle Batteries (CFBEV. JCR Science for Policy Report. Final draft 2023.

Dlamini, N., Mukaya, H. E., & Nkazi, D. (2022). Carbon-based nanomaterials production from environmental pollutant byproducts: A Review. Journal of CO2 Utilization, 60, 101953. https://doi.org/10.1016/J.JCOU.2022.101953

Drachenfels, N. von. Husmann, J. Khalid, U. Cerdas, F. Herrmann, C. 2022. Life Cycle Assessment of the Battery Cell Production: Using a Modular Material and Energy Flow Model to Assess Product and Process Innovations. Energy Technology.

GBA & Sphera. (2023). Global Battery Alliance Battery Passport Greenhouse Gas Rulebook Generic Rules-Version 1.5.

Hynynen, J., Willstrand, O., Blomqvist, P., & Andersson, P. (2023). Analysis of combustion gases from large-scale electric vehicle fire tests. Fire Safety Journal, 139. https://doi.org/10.1016/j.firesaf.2023.103829

Kallitsis, Evangelos. 2023. Preprint. Think global act local: the dependency of global lithium-ion battery emissions on production location and material sources. Research Square.

Lèbre É, Stringer M, Svobodova K, Owen J R, Kemp D, Côte C, et al. The social and environmental complexities of extracting energy transition metals. Nature Communications. 2020;11(1). https://doi.org/10.1038/s41467-020-18661-9.

Łukasz, B., Rybakowska, I., Krakowiak, A., Gregorczyk, M., & Waldman, W. (2023). Lithium batteries safety, wider perspective. International Journal of Occupational Medicine and Environmental Health. https://doi.org/10.13075/ijomeh.1896.01995

Mistry, M., Gediga, J., Boonzaie, S. 2016. Life cycle assessment of nickel products. The International Journal of Life Cycle Assessment.

Oers, Lauran Van. 2020. Abiotic Resource Depletion Potentials (ADPs) for Elements Revisited - Updating Ultimate Reserve Estimates and Introducing Time Series for Production Data. International Journal of Life Cycle Assessment.

Pell, R., Whattoff, P., & Lindsay, J. J. (2021). Life Cycle Assessment of Spheronized Coated and Micronized Graphite Products from the Preliminary Economic Assessment Stage Woxna Graphite Anode Project. https://leadingedgematerials.com/wp-content/uploads/2022/03/2021-Woxna-Graphite-LCA-report-by-Minviro.pdf

RECHARGE (2020). PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications. The Advanced Rechargeable & Lithium Batteries Association.

Straif K, Benbrahim-Tallaa L, Baan R, Grosse Y, Secretan B, El Ghissassi F. et al. A review of human carcinogens – part C: metals, arsenic, dusts, and fibres. Lancet Oncol. 2009;10(5):453-454. https://doi.org/10.1016/s1470- 2045 (09)70134-2.

Sun, X., Luo, X., Zhang, Z., Meng, F., & Yang, J. (2020). Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. Journal of Cleaner Production, 273, 123006. https://doi.org/10.1016/J.JCLEPRO.2020.123006

SYSTEMIQ. (2022a). Battery Pass. WP2a: GHG Footprint. Analysing the Cut-off approach, the Substitution approach, and the Circular Footprint Formula as basis for Battery Pass End of life and recycling rules. www.thebatterypass.eu

SYSTEMIQ. (2023). Battery Passport Content Guidance. Achieving compliance with the EU Battery Regulation and increasing sustainability and circularity. Version 1.0 / April 2023. www.thebatterypass.eu.

Talga. (2021). Life Cycle Assessment Highlights Talga's World-Leading Green Battery Anode. https://talgagroup.eu-central-1.linodeobjects.com/app/uploads/2021/09/16045230/ IndustryLeadingGreenBatteryAnodeLCAResults.pdf

Zackrisson, M., Fransson, K., Hildenbrand, J., Lampic, G., & O'Dwyer, C. (2016). Life cycle assessment of lithium-air battery cells. Journal of Cleaner Production, 135. https://doi.org/10.1016/j.jclepro.2016.06.104

Zackrisson, M. (2017). Life cycle assessment of long life lithium electrode for electric vehicle batteries-cells for LEAF, Tesla and Volvo bus. www.swereaivf.se

Zackrisson, M., & Schellenberger, S. (2020). Toxicity of lithium ion battery chemicals-overview with focus on recycling.

Zackrisson, Mats. 2021. "Life Cycle Assessment of Electric Vehicle Batteries and New Technologies." Doctoral thesis. KTH Royal University of Technology Södertälje.

Zackrisson, M., & Schellenberger, S. (2023). Life cycle assessment of lithium-ion battery recycling-The Scope-lib process. RISE Research Institutes of Sweden. http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-64287

Visser M.J., de Wit - Bos, L., Palmen, N.G.M., Bos, P.M.J.. 2014. Overview of Occupational Exposure Limits within Europe. RIVM Letter report 2014-0151. National Institute for Public Health and the Environment. Bilthoven. The Netherlands. www.rivm.nl/en.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2019). The ecoinvent database version 3 (part I): overview and methodology. The international journal of Life Cycle Assessment, 1218-1230.

Wolf, M-A., Pant, R. 2012. "The International Reference Life Cycle Data System." http://lct.jrc.ec.europa.eu/pdfdirectory/JRC Reference Report ILCD Handbook - Towards more sustainable production and consumption for a resource-efficient Europe.pdf

Yin, R., Hu, S., & Yang, Y. (2019). Life cycle inventories of the commonly used materials for lithium-ion batteries in China. Journal of Cleaner Production, 227, 960-971.

References for section Recycling

Abdelbaky, M., J. R. Peeters and W. Dewulf "On the influence of second use, future battery technologies, and battery lifetime on the maximum recycled content of future electric vehicle batteries in Europe." (1879-2456 (Electronic)).

Baars, J., T. Domenech, R. Bleischwitz, H. E. Melin and O. Heidrich (2021). "Circular economy strategies for electric vehicle batteries reduce reliance on raw materials." Nature Sustainability 4(1): 71-79.

Bai, Y., M. Li, C. J. Jafta, Q. Dai, R. Essehli, B. J. Polzin and I. Belharouak (2023). "Direct recycling and remanufacturing of anode scraps." Sustainable Materials and Technologies 35: e00542.

Bai, Y., R. Essehli, C. J. Jafta, K. M. Livingston and I. Belharouak (2021). "Recovery of Cathode Materials and Aluminum Foil Using a Green Solvent." ACS Sustainable Chemistry & Engineering 9(17): 6048-6055.

Bai, Y., W. B. Hawley, C. J. Jafta, N. Muralidharan, B. J. Polzin and I. Belharouak (2020). "Sustainable recycling of cathode scraps via Cyrene-based separation." Sustainable Materials and Technologies 25: e00202.

Brückner, L., J. Frank and T. Elwert (2020) "Industrial Recycling of Lithium-Ion Batteries—A Critical Review of Metallurgical Process Routes." Metals 10 DOI: 10.3390/met10081107.

Chu, W., Y. Zhang, X. Chen, Y. Huang, H. Cui, M. Wang and J. Wang (2020). "Synthesis of LiNi0.6Co0.2Mn0.2O2 from mixed cathode materials of spent lithium-ion batteries." Journal of Power Sources 449: 227567.

Ciez, R. E. and J. F. Whitacre (2019). "Examining different recycling processes for lithium-ion batteries." Nature Sustainability 2(2): 148-156.

Do, M. P., J. Jegan Roy, B. Cao and M. Srinivasan (2022). "Green Closed-Loop Cathode Regeneration from Spent NMC-Based Lithium-Ion Batteries through Bioleaching." ACS Sustainable Chemistry & Engineering 10(8): 2634-2644.

Dunn, J., M. Slattery, A. Kendall, H. Ambrose and S. Shen (2021). "Circularity of Lithium-Ion Battery Materials in Electric Vehicles." Environ Sci Technol 55(8): 5189-5198.

Fan, E., L. Li, Z. Wang, J. Lin, Y. Huang, Y. Yao, R. Chen and F. Wu (2020). "Sustainable Recycling Technology for Li-Ion Batteries and Beyond: Challenges and Future Prospects." Chemical Reviews 120(14): 7020-7063.

Gaines, L., J. Zhang, X. He, J. Bouchard and H. E. Melin (2023). "Tracking Flows of End-of-Life Battery Materials and Manufacturing Scrap." Batteries 9(7): 360.

Golmohammadzadeh, R., F. Rashchi and E. Vahidi (2017). "Recovery of lithium and cobalt from spent lithium-ion batteries using organic acids: Process optimization and kinetic aspects." Waste Management 64: 244-254.

Hantanasirisakul, K. and M. Sawangphruk (2023). "Sustainable Reuse and Recycling of Spent Li-Ion batteries from Electric Vehicles: Chemical, Environmental, and Economical Perspectives." Global Challenges 7(4): 2200212.

Harper, G., R. Sommerville, E. Kendrick, L. Driscoll, P. Slater, R. Stolkin, A. Walton, P. Christensen, O. Heidrich, S. Lambert, A. Abbott, K. Ryder, L. Gaines and P. Anderson (2019). "Recycling lithium-ion batteries from electric vehicles." Nature 575(7781): 75-86.

Holzer, A., L. Wiszniewski, S. Windisch-Kern and H. Raupenstrauch (2022) "Optimization of a Pyrometallurgical Process to Efficiently Recover Valuable Metals from Commercially Used Lithium-Ion Battery Cathode Materials LCO, NCA, NMC622, and LFP." Metals 12 DOI: 10.3390/met12101642.

Hu, X., E. Mousa, Y. Tian and G. Ye (2021). "Recovery of Co, Ni, Mn, and Li from Li-ion batteries by smelting reduction - Part I: A laboratory-scale study." Journal of Power Sources 483: 228936.

Hu, X., E. Mousa and G. Ye (2021). "Recovery of Co, Ni, Mn, and Li from Li-ion batteries by smelting reduction - Part II: A pilot-scale demonstration." Journal of Power Sources 483: 229089.

Jegan Roy, J., M. Srinivasan and B. Cao (2021). "Bioleaching as an Eco-Friendly Approach for Metal Recovery from Spent NMC-Based Lithium-Ion Batteries at a High Pulp Density." ACS Sustainable Chemistry & Engineering 9(8): 3060-3069.

Joulié, M., R. Laucournet and E. Billy (2014). "Hydrometallurgical process for the recovery of high value metals from spent lithium nickel cobalt aluminum oxide based lithium-ion batteries." Journal of Power Sources 247: 551-555.

Knehr, Kevin W., Kubal, Joseph J., Nelson, Paul A., & Ahmed, Shabbir (2022). Battery Performance and Cost Modeling for Electric-Drive Vehicles (A Manual for BatPaC v5.0). United States. https://doi.org/10.2172/1877590

Liu, T., J. Chen, X. Shen and H. Li (2021). "Regulating and regenerating the valuable metals from the cathode materials in lithium-ion batteries by nickel-cobalt-manganese co-extraction." Separation and Purification Technology 259: 118088.

Makuza, B., Q. Tian, X. Guo, K. Chattopadhyay and D. Yu (2021). "Pyrometallurgical options for recycling spent lithium-ion batteries: A comprehensive review." Journal of Power Sources 491: 229622.

Natarajan, S., M. Akshay and V. Aravindan (2022). "Recycling/Reuse of Current Collectors from Spent Lithium-Ion Batteries: Benefits and Issues." Advanced Sustainable Systems 6(3): 2100432

Nguyen, V. T., J.-c. Lee, J. Jeong, B.-S. Kim and B. D. Pandey (2014). "Selective recovery of cobalt, nickel and lithium from sulfate leachate of cathode scrap of Li-ion batteries using liquid-liquid extraction." Metals and Materials International 20(2): 357-365

Neumann, J., M. Petranikova, M. Meeus, J. D. Gamarra, R. Younesi, M. Winter and S. Nowak (2022). "Recycling of Lithium-Ion Batteries—Current State of the Art, Circular Economy, and Next Generation Recycling." Advanced Energy Materials 12(17): 2102917.

Ojanen, S., M. Lundström, A. Santasalo-Aarnio and R. Serna-Guerrero (2018). "Challenging the concept of electrochemical discharge using salt solutions for lithium-ion batteries recycling." Waste Management 76: 242-249.

Popien, J.-L., C. Thies and T. S. Spengler (2022). "Exploring recycling options in battery supply chains – a life cycle sustainability assessment." Procedia CIRP 105: 434-439.

Promphan, P. B. a. R. (2020). Determination of optimal parameters for the application of hydrogen peroxide as reducing agent in the leaching process, Department of Chemistry & Chemical Engineering Chalmers University Of Technology, Gothenburg, Master's thesis in Innovative and Sustainable Chemical Engineering.

Qiu, H., C. Peschel, M. Winter, S. Nowak, J. Köthe and D. Goldmann (2022) "Recovery of Graphite and Cathode Active Materials from Spent Lithium-Ion Batteries by Applying Two Pretreatment Methods and Flotation Combined with a Rapid Analysis Technique." Metals 12 DOI: 10.3390/met12040677.

Song, D., X. Wang, E. Zhou, P. Hou, F. Guo and L. Zhang (2013). "Recovery and heat treatment of the $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathode scrap material for lithium-ion battery." Journal of Power Sources 232: 348-352.

Song, D., X. Wang, H. Nie, H. Shi, D. Wang, F. Guo, X. Shi and L. Zhang (2014). "Heat treatment of $LiCoO_2$ recovered from cathode scraps with solvent method." Journal of Power Sources 249: 137-141.

Vieceli, N., P. Benjamasutin, R. Promphan, P. Hellström, M. Paulsson and M. Petranikova (2023). "Recycling of Lithium-Ion Batteries: Effect of Hydrogen Peroxide and a Dosing Method on the Leaching of LCO, NMC Oxides, and Industrial Black Mass." ACS Sustainable Chemistry & Engineering.

Wang, H., J. Liu, X. Bai, S. Wang, D. Yang, Y. Fu and Y. He (2019). "Separation of the cathode materials from the Al foil in spent lithium-ion batteries by cryogenic grinding." Waste Management 91: 89-98.

Wang, M., Q. Tan, L. Liu and J. Li (2019). "A Facile, Environmentally Friendly, and Low-Temperature Approach for Decomposition of Polyvinylidene Fluoride from the Cathode Electrode of Spent Lithium-ion Batteries." ACS Sustainable Chemistry & Engineering 7(15): 12799-12806.

Windisch-Kern, S., E. Gerold, T. Nigl, A. Jandric, M. Altendorfer, B. Rutrecht, S. Scherhaufer, H. Raupenstrauch, R. Pomberger, H. Antrekowitsch and F. Part (2022). "Recycling chains for lithium-ion

batteries: A critical examination of current challenges, opportunities and process dependencies." Waste Management 138: 125-139.

Xuan, W., A. de Souza Braga, C. Korbel and A. Chagnes (2021). "New insights in the leaching kinetics of cathodic materials in acidic chloride media for lithium-ion battery recycling." Hydrometallurgy 204: 105705.

Yang, L., Z. Gao, T. Liu, M. Huang, G. Liu, Y. Feng, P. Shao and X. Luo (2023). "Direct Electrochemical Leaching Method for High-Purity Lithium Recovery from Spent Lithium Batteries." Environmental Science & Technology 57(11): 4591-4597.

Yu, D., Z. Huang, B. Makuza, X. Guo and Q. Tian (2021). "Pretreatment options for the recycling of spent lithium-ion batteries: A comprehensive review." Minerals Engineering 173: 107218.

Zachmann, N., M. Petranikova and B. Ebin (2023). "Electrolyte recovery from spent Lithium-Ion batteries using a low temperature thermal treatment process." Journal of Industrial and Engineering Chemistry 118: 351-361.

Zackrisson, M., & Schellenberger, S. (2023). Life cycle assessment of lithium-ion battery recycling-The Scope-lib process. RISE Research Institutes of Sweden. http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-64287.

Zhang, T., Y. He, L. Ge, R. Fu, X. Zhang and Y. Huang (2013). "Characteristics of wet and dry crushing methods in the recycling process of spent lithium-ion batteries." Journal of Power Sources 240: 766-771.

Zhang, X., Q. Xue, L. Li, E. Fan, F. Wu and R. Chen (2016). "Sustainable Recycling and Regeneration of Cathode Scraps from Industrial Production of Lithium-Ion Batteries." ACS Sustainable Chemistry & Engineering 4(12): 7041-7049.

Zhu, J., G. Guo, J. Wu, X. Cheng and Y. Cheng (2022). "Recycling and reutilization of $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$ cathode materials from spent lithium-ion battery." Ionics 28(1): 241-250.

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12 Appendix 1 Idea generation workshop

This appendix documents the results of an idea workshop carried out 28 September 2023 in Stockholm, Sweden. The goal of the workshop was to generate ideas about environmental improvements of novel battery cells in the BatWoMan project. The starting point was a draft screening life cycle assessment of novel battery cells report.
The workshop resulted in 36 ideas. Of the 36 ideas generated, 12 were evaluated during the workshop.

12.1 Workshop execution

Participants in the workshop were Katja Fröhlich, Veronika Siska, Bernd Eschelmüller, Iratxe de Meatza, Giorgio Baraldi, Andrea Correnti, Viktoria Falkowski, Niclas Straßburger, Theresa Schredelseker, Susanna Beltrame, and Emanuel Bengtsson and Mats Zackrisson from RISE. The participation comprised idea generation as well as evaluation, see below. See also PowerPoint presentation Idea generation for improved environmental performance of novel battery cells.

12.2 Goal

The goal of the idea generation workshop was to generate ideas about possible environmental improvements of novel battery cells and to an extent agree about which are the best ideas; environmentally and from an implementation perspective. Environmental improvement was defined as in the screening LCA-study, i.e. decreased climate impact and abiotic depletion potential. The programme was the following:

13.30 Presentation/discussion of screening LCA
14.00 Brainstorming
15.15 Categorization of ideas
15.30 Evaluation of ideas
16.30 End

Criteria for the evaluation of the ideas were established to:

- Environmental improvement
- Chance to implement the idea successfully (time to technical feasibility and market)

The idea generation was based on the following results/conclusions of the screening LCA:

- The importance of the use phase was highlighted
- Recycling can recover considerable amount of production phase burdens
- Cathode materials have significant climate and resource depletion impacts
- Manufacturing energy may be more significant than shown in screening study

12.3 Idea generation

During the idea generation, ideas were born, written down on post-it stickers and read out loud to all participants during approximately 1 hour. No negative critique of the ideas was allowed during this part. In total 36 ideas were generated during this part, see appendix 1.

12.4 Evaluation

Before evaluation, the ideas were coarsely sorted under the following headings:

- Materials
- Manufacturing
- Use
- Recycling
- Regulation

As an introduction to the evaluation each one of the participants chose one idea to argue for. Choice of your own ideas as well as others was permitted. Criteria for the evaluation were:

- Environmental improvement potential where: 1= Little; 2= Medium; 3= Much
- Ease of implementation, i.e. chance to implement successfully considering time to technical feasibility and market potential etc. Where 1= >20 years; 2> 8 years; 3=within project time frame.

After discussing an idea, the group decided together on the scores for that idea.

12.5 Results

The result of the evaluation is given below. Of the 36 ideas, 12 were chosen for evaluation. Six were considered as possible to implement in the project time frame, of which one with large environmental improvement and four with medium environmental potential. The ideas are sorted after 1) chance to implement soon and 2) environmental improvement potential.

Twelve ideas were picked for evaluation, which implies some form of ranking. These ideas are presented first in Table 10 below; starting with the idea judged to be most easily implemented, and with largest environmental potential. The non-evaluated ideas are presented in Table 11.

Table 10 Evaluated ideas for environmental improvement

Description	**IMP[8]**	**ENV[9]**	**Comments**
Direct recycling – recovery of active materials from waterborne electrodes	Project	3	
Cellulose based separators (instead of polyolefin)	Project	2	
Improve quality controls during the manufacturing steps to avoid production of faulty cells to be scrapped	Project	2	
Improve cutting phase (electrodes) to reduce scraps. Laser? Better geometry?	Project	2	
Formation and ageing improvements	Project	2	
FAIR data for materials privacy – preserving data sharing	Project	1	
Improve raw material efficiency by working on their (micro)structure coating	8 years	2,5	
Regulations for raw material supply	8 years	2	
Collect heat generated from battery and convert to electric energy	8 years	2	
Sustainable raw materials supply chain	20 years	3	
Battery swapping system	20 years	2,5	
Papershell for battery box	20 years	1	Papershell is made from cellulose fibre and lignin and can be moulded much like reinforced plastics composites.

Table 11 Non-evaluated ideas for environmental improvement

Non-evaluated ideas related to Materials
Adding carbon nano tubes to increase cell efficiency
Binder that could be easily removed with water, no expensive/toxic dissolvents, no chemical wastes during recycling
Non-evaluated ideas related to Manufacturing
Improve wetting process
Reuse energy released during formation and ageing discharges
Dry electrode processing, reduced energy consumption

[8] IMP = chance to implement successfully during BatWoMan Project, which runs another 2 years, in 8 years, or in 20 years.

[9] ENV = environmental improvement potential: 1= Little; 2= Medium; 3= Much

Machines sealed with mini-environment to reduce dry room requirements
(Heat) flows re-use, e.g from air flow of EFM -> dry stack or recon zeolites
Produce in dry climate -> less energy to keep dry room conditions
Suitable pottings that can be easily separated from the cells (before shredding in recycling process). No potting between cells.
Factories with their own (green) power generators
Non-evaluated ideas related to Use phase
Increase longevity of cells/batteries
Consider use phase
Environment friendly transport
Exchange PFAS / fluorinated based binders
Manufacture in standardized modules that allow replacement/swapping
Non-evaluated ideas related to Recycling
Elaborate on using more recycled input material instead of primary
Intensify and standardize recycling
Battery packs that are easy to dismantle
Materials that can be processed at low temperature to save energy
Microbial recycling of cathode materials
Recycled plastics for module/pack housing
Non-evaluated ideas related to Regulations
Include information for reuse & recycling with battery (passport)
If / where decarbonization is not possible, enforce compensation (certified)
Deposit / Pand system for parts that have low return rate for recycling

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