Project Report
26702

Life cycle assessment of lithium ion battery recycling - The ReLion process

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Research Institutes of Sweden

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Project Report 26702

Preface

This report contains a life cycle assessment, LCA, of recycling of battery cells. It was performed in the context of the Swedish ReLion project, financed by Energimyndigheten. The life cycle assessment, LCA, has been carried out by Mats Zackrisson at RISE IVF. Members of the ReLion project have delivered detailed data about recycling related to lithium battery cells. A list of acronyms and abbreviations used is provided below.

CFCs	Chlorofluorocarbons
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalents
CH_4	Methane
C_2H_4	Ethene
CTU	Comparative Toxic Unit
EPD	Environmental Product Declaration
EEA	European Environment Agency
HFCs	Hydrofluorocarbons
ISO	International Organization for Standardization
Kg	Kilogram
KW	Kilowatt
KWh	Kilowatt-hour, 1 kWh = 3.6 MJ
LCA	Life Cycle Assessment
LFP	Lithium iron phosphate, $LiFePO_4$, battery cell
Li	Lithium
LMO	Lithium manganese oxide, $LiMn_2O_4$, battery cell
MJ	Megajoule
MWh	Megawatt-hour
NCA	Lithium nickel cobalt aluminium oxide battery cell
NMC	Lithium nickel manganese cobalt oxide battery cell
NMP	N-Methyl-2-pyrrolidone
NO_x	Nitrogen oxides
PEFCR	Product Environmental Footprint Category Rules
PHEV	Plug-in hybrid electric vehicle
PO_4	Phosphorus
PS	Polystyrene
PVDF	Polyvinylidenfluoride
PP	Polypropylene
RER S	RER = Region Europe, S=system process
Sb	Antimony
SO_2	Sulphur dioxide
SF_6	Sulphur hexafluoride

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Summary

This report contains a life cycle assessment, LCA, of recycling of lithium ion battery cells. It was performed in the context of the Swedish ReLion project. The study aims to highlight environmental hotspots with LIB recycling and show the potential of LIB recycling. In short, the results indicate that the ReLion process:

- replicated in full scale, can potentially recover at least 10% of the climate impacts of producing an NMC traction battery, the currently most common traction battery chemistry
- decoking with air and water instead of liquid oxygen gives a bit more climate avoidance, 0.2 kg CO_2/kg cell and a bit more abiotic depletion avoidance. If it can be done easily and without much extra cost this option should be utilized.
- The ReLion process is not dependant on carbon-lean electricity to potentially avoid at least 10% of the climate impacts of producing an NMC traction battery

Introduction

This report contains a life cycle assessment, LCA, of recycling of lithium ion batteries. It was performed in the context of the Swedish ReLion project, financed by Energimyndigheten.

The purpose of the LCA is to highlight environmental hotspots with battery cell recycling in order to improve it as well as to verify environmental benefits with battery cell recycling. LCA is generally considered very useful in the product development stage in order to identify environmental hot-spots and aid in directing development efforts in relevant areas (Rebitzer et al. 2004) (Mats Zackrisson et al. 2008). Battery design needs to consider the recyclability of the batteries at end-of-life as well as the possibility to use recycled materials in the original design, i.e. aim for a circular material usage.

Method in general

The LCA was performed in the context of the Swedish ReLion project. The LCA has been carried out by Mats Zackrisson in close cooperation with Guozhu Ye at Swerim and Pekka Väänänen at uRecycle Oy and reviewed by Patrik William-Olsson at RISE IVF. Material and energy needs were determined by experience, theoretical calculations and pilot scale smelting tests. Associated resources and emissions were found in existing databases for LCA and represent in general European or global averages. Data has mainly been drawn from the database Ecoinvent 3.5 (Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B. 2016). PEFCR- Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications, was also used as a data source as well as general guidance for the study (The Advanced Rechargeable & Lithium Batteries Association 2018).

SimaPro 9.0.0.48 was used for the calculations. The software includes several databases and is thus a source of generic data. It was also used to store the collected site-specific data, see project ReLion and EBaR. The study is protected in the software. Only the author of this study has access to the project specific data.

Functional unit

The PEFCR-guide (The Advanced Rechargeable & Lithium Batteries Association 2018) defines the functional unit as 1 kWh of the total energy provided over the service life of the battery system, and the associated reference flow, Rf, as kg of battery per kWh of the total energy provided. It prescribes calculation of the reference flow with consideration to both the application need and the battery capacity according to the formula:

1. Rf= Reference flow=Nb*mass/AS, where,
    a) Nb is number of batteries per application, known or calculated as Nb=AS/QuA
    b) mass= mass of battery

c) AS=Total kWh needed by application

d) QuA= Total kWh delivered by battery, thus

e) Rf=Reference flow=mass/QuA=mass/Total kWh delivered by battery, if the application is unknown or of less interest

For a 24 kWh Nissan Leaf battery (Mats Zackrisson 2018) weighing 294 kg and using 0,186 kWh/km, assuming 80% depth of discharge[1] and 200000 km design service life: equation 1 would yield 1*294 kg / (200000 km * 0,186 kWh/km) = 0,0079 kg battery/kWh and equation d) would yield 294 kg / (2000 cycles * 0,8 depth of discharge * 24 kWh) = 0,0077 kg battery/kWh, so around 8 g battery is needed per delivered kWh. However, maximum service life according to (Burzio and Parena 2012) is 226716 km. Equation 1 then yields 294 kg / (226716 km * 0,186 kWh/km) = 0,0070 kg battery/kWh.

The PEFCR-guide deviates from earlier guidelines to put traction batteries in an application context (Del Duce et al 2013), which recommend presenting LCA results as environmental impact per vehicle kilometre. The vehicle context is realized via data about vehicle weight and electricity consumption from tests or assumptions. Calculating impacts per km facilitates comparisons with vehicle emission targets, e.g. the European passenger car standards 95 g CO_2-eq/km fleet average to be reached by 2021 by all manufacturers (EC 2000).

Some studies of traction batteries report environmental impacts per kg of battery or per kWh of battery nominal capacity. Thus, there is an obvious risk of misunderstanding data when comparing between studies, since so many different reference flows are used: mass/Total kWh delivered; vehicle kilometre; mass of battery; and nominal capacity of battery.

Since this study concerns mostly the end-of-life part of traction battery cells, the application is not obvious. Input data was given per ton or kilogram of battery black mass (BM). **Environmental impact results are mainly given as environmental impact per kg of battery cell and per kg battery (assuming 0.5 kg cellin 1 kg battery pack).**

System boundary

The system boundary for the lithium-ion study is shown below. Note that only the End-of-life stage is inside the system boundary, i.e. included in the study. However, the environmental impact of the end-of-life stage is compared to the production related environmental impacts from other studies in the discussion.

[1] 80% depth of discharge means that maximum 80% of the nominal battery capacity is used each charge cycle, so a 24 kWh battery would actually only deliver 19.2 kWh before it is recharged.

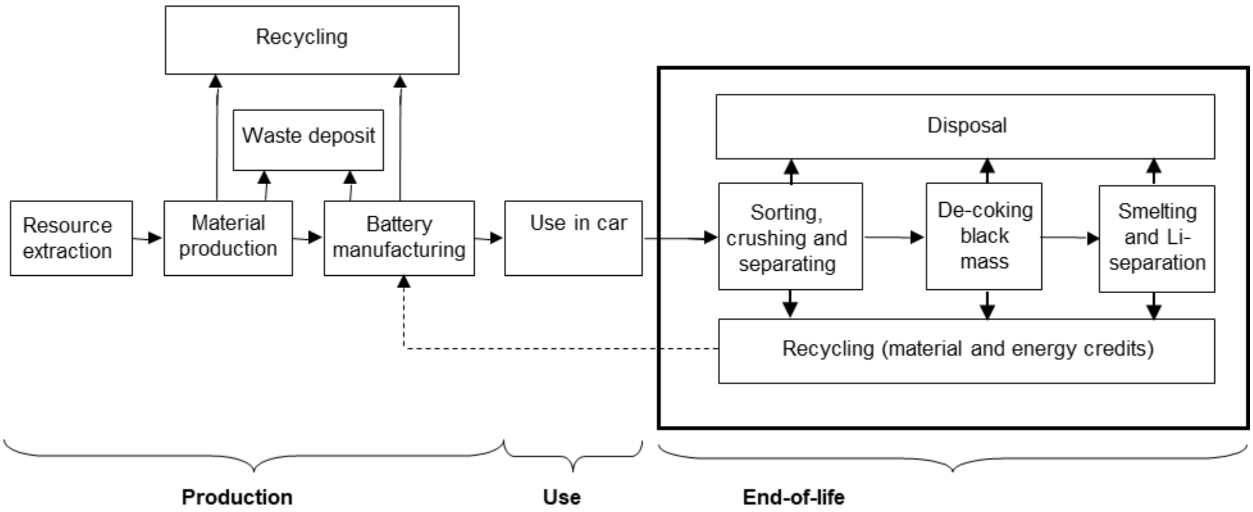

Figure 1 System boundary for lithium-ion study

Environmental impact assessment

LCA of traction batteries inevitably leads to comparisons of electric vehicles, EV, with internal combustion engine vehicles, ICEV. Such LCAs should therefore be able to assess trade-offs between tailpipe emissions, material resource use and toxicological impacts. Thus, relevant environmental impact categories for LCA of vehicles and traction batteries in particular are climate impact, resource depletion and toxicity.

Climate impacts in accordance with the Intergovernmental Panel on Climate Change (IPPC 2013). The unit is climate impact in grams or kilograms of carbon dioxide equivalents, CO2-eq. Europe’s emissions in 2005 corresponded to 11200 kg CO2 equivalents per person (EEA 2005). To avoid unwanted climate impact requires global yearly emissions to be reduced by between 50 to 85% by 2050 on current levels, according to (Barker 2007). This would translate to a sustainable emission level at approximately 1000 kg CO2-eq per capita world average.

Resource depletion, or abiotic resource depletion is calculated with the method CML-IA baseline[2], version 3.02 as recommended by the ILCD handbook (Wolf and Pant 2012). Only depletion of mineral reserves is reported since the climate impact indicator, above, is considered to cover environmental impacts and depletion of fossil fuels. Abiotic depletion is measured in kilogram Antimony equivalents, abbreviated kg Sb-eq. It should be mentioned that there is no universal consensus within the LCA community on methodology and on the relative ranking of resource depletion impacts (Klinglmair, Sala, and Brandão 2014). (Peters and Weil 2016) cautions against far-reaching conclusions regarding abiotic depletion while confirming that the recommended CML method is the best available today.

Earlier studies have shown that current methods for toxicity evaluation have considerable inadequacies related to metals and lithium in particular; among other

[2] This CML baseline method contained in SimaPro is also used to calculate the climate impacts.

there is a lack of data concerning lithium emissions during the life cycle and a lack of characterization factors to translate such emissions into toxic impacts (M. Zackrisson et al. 2016). Toxicity has therefore not been assessed in this study.

Modelling

Sorting, crushing and separating

The modelling of sorting, crushing and separating is based on ecoinvent process "Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Alloc Rec, U. (Kwade and Diekmann 2018) presents a value of 58,3 kWh for disassembly, crushing, drying, air-separation and sieving for a 346 kg battery pack in connection to the LithoRec recycling process. The processes used are similar to those envisioned in the ReLion project to produce a black mass. See figure below.

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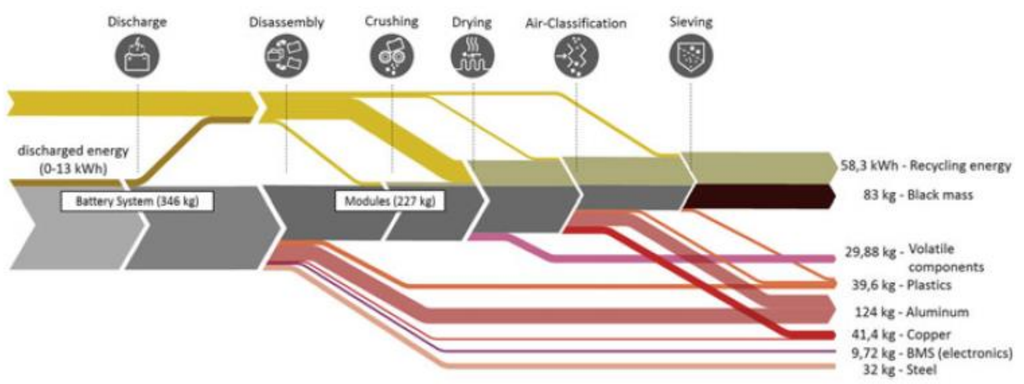


Fig. 16.7 Modeled energy and material flows from the LithoRec process

Figure 2 The Lithorec process from (Kwade and Diekman 2018).

Considering that the discharged energy (0-13 kWh) can be credited, only 50 kWh would be needed per 346 kg battery system which is equal to 0,14 kWh/kg battery or 0,28 kWh/kg cell if we assume that the battery contains 50% cells (Ellingsen et al. 2013). See figure below. This figure is assumed in the calculations.

For the diesel, the same value, 0.1 MJ/kg, as in the original process Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Alloc Rec, U was assumed. Other additions to the original process include:

- avoided products (0,232 kg copper per kg cell and 0,418 kg aluminium per kg cell) based on Leaf NMC battery BOM-list (according to Ellingsen et al 2013) minus what is left in black mass as measured by Swerim in pilot scale tests. Note that most of the aluminium stem not from the cell but from the rest of the pack (which is 50% of the battery). Note that recovered steel, electronics and plastics have not been considered to avoid any virgin materials in the calculations.

- Transports from bilskrot to sorting facility assumed 300 km according to (Cullbrand, Fråne, and Jensen 2015), see details below.

Since the Lithorec process includes separation of the electrolyte, no hydrocarbon emissions were assumed.

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Category	Comment
Sorting, crushing and separating waste LIB traction batteries	1	kg	Mass	100 %	Electronics waste	

Outputs to technosphere. Avoided products	Amount	Unit	Comment

Inputs

Inputs from nature	Subcompartmer	Amount	Unit	Distribution	Comment

Inputs from technosphere: materials/fuels	Amo	Unit	M	Comment
Diesel, burned in building machine {GLO}| market for | Cut-off, S	0,1	MJ		Based on ecoinvent process "Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Alloc Rec, U but assumed 10 times more diesel than that process.

Inputs from technosphere: electricity/heat	Amount	Unit	Comment
Electricity, medium voltage {SE}| market for | Cut-off, S	prodel*0,14 = 0,14	kWh	The electricity was adjusted from 0,01 kWh/kg to 0,14 kWh/kg cell based on data for the Lithorec process presented by Kwade and Diekman 2018.
Electricity, medium voltage {ENTSO-E}| market group for | Cut-off, S	(1-prodel)*0,14 = 0	kWh	
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight,	300	kgkm	Transports from bilskrot to sorting facility assumed 300 km according to Cullbrand et al 2015.
EOL Copper recycling	1*(0,121-0,005) = 0,116	kg	Avoided products based on Leaf NMC BOM-list (according to Ellingsen et al 2013) minus what is left in BM as measured by Ye 2019.
EOL Aluminium recycling	1*(0,214-0,0048) = 0,209	kg	24,5 g in the cell and 189,5 g i restofpack

Figure 3 LCA model of sorting, crushing and separating waste lithium cells

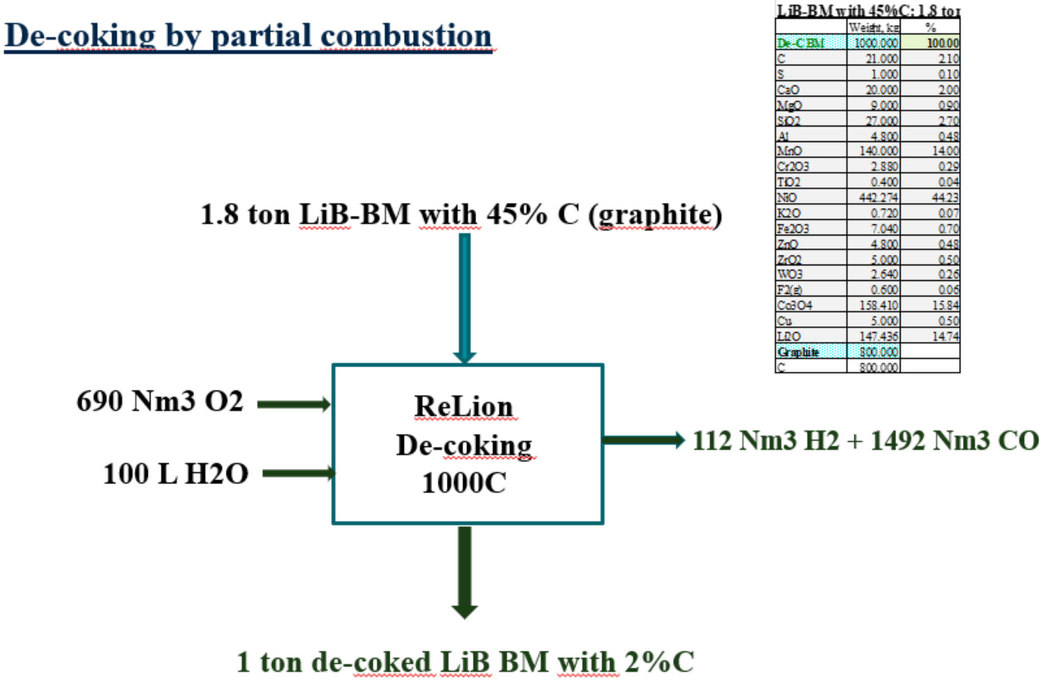
About the LithoRec process

The LithoRec Process (Kwade and Diekman 2018) combines mechanical, mild thermal and hydrometallurgical treatment to regain nearly all materials of a battery system. One of the main results of the first Lithorec project was a concept for the mechanical separation of the components of a battery system in different fractions including the coating materials. Therefore, manual and automated processes for the disassembly of battery systems as well as different classifying and sorting processes for the material separation were investigated in laboratory scale. The recovered coating materials were treated hydrometallurgically afterwards. The project partner Chemetall GmbH realized a pilot plant for this part of the process in Langelsheim; combining leaching, filtration and different precipitation steps. This kind of hydrometallurgical treatment regains the valuable materials nickel, cobalt, manganese, and lithium hydroxide or lithium carbonate. It was found that small impurities of aluminum have no negative impact on the electrochemical performance of battery test cells with lithium nickel cobalt manganese oxide (NCM) as a cathode material. Furthermore, the project partners investigated new ways for the recovery of electrolyte solvents and the conducting salt. Processes like vacuum condensation and extraction via supercritical carbon dioxide showed positive results. Ecologic and economic assessments were carried out for the investigated concept. While the ecological impact was high, the process is only economically feasible at high throughputs and as such, very sensitive to the market for electric driving systems. The follow-on project

LithoRec II started July 2012 and focused on the detailing of the scientific and technical results, and the realization of the optimized process steps in a pilot plant.

De-coking black mass

De-coking black mass is based on data from the ReLion project run by Swerim. Input output data for de-coking based on pilot scale tests by Swerim described in ReLion flowsheets, see figure below. Transports based on data from Urecycle on recycling of ZnC/Alkaline big block batteries (distance between Karlskoga and Skellefteå 880 km).



LiB-BM with 45%C: 1.8 ton

	Weight, kg	%
De-C BM	1000.000	100.00
C	21.000	2.10
S	1.000	0.10
CaO	20.000	2.00
MgO	9.000	0.90
SiO2	27.000	2.70
Al	4.800	0.48
MnO	140.000	14.00
Cr2O3	2.880	0.29
TiO2	0.400	0.04
NiO	442.274	44.23
K2O	0.720	0.07
Fe2O3	7.040	0.70
ZnO	4.800	0.48
ZrO2	5.000	0.50
WO3	2.640	0.26
F2(g)	0.600	0.06
Co3O4	158.410	15.84
Cu	5.000	0.50
Li2O	147.436	14.74
Graphite	800.000	
C	800.000	

Figure 4 Step 1: decoke, separation of C from cathode material

The outputs and inputs related to 1 ton of de-coked LIB black mass (BM) are shown in Figure 4 and modeled in Simapro as shown below. The output hydrogen and CO gas is estimated to replace 590 m^3 natural gas based on heating value. 880 km transport equal to the distance between Karlskoga and Skellefteå assumed.

Outputs to technosphere: Products and co-produ	Am	Unit	Quantity	Allocatic	Category	Comm
De-coked LIB BM	1	ton	Mass	100 %	Electronics waste	

Outputs to technosphere. Avoided products	Amount	Uni	Comment
Natural gas, high pressure {DE}| natural gas productio	590	m3	Replacing 112 nM3 hydrogen and 1492 nm3 co according to Ye

Inputs

Inputs from nature	Subcompartm	Amount	Unit	Distributio	Comment

Inputs from technosphere: materials/fuels	Amount	Unit	Comment
Oxygen, liquid {RER}| market for | Cut-off, S	985	kg	690 Nm3 gas motsvarar 985 kg flytande enligt Ye
Tap water in Sweden, at user/RER System	100	kg	
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market	1,8*880 = 1,58E3	tkm	1,8 ton input/ton. 880 km transport from karlskoga to Skellefteå assumed

Figure 5 Model of 1 ton of de-coked lithium ion black mass

An alternative decoking process is also possible using air and water instead of liquid oxygen. This would give the same output gases, plus 2597 Nm^3 of nitrogen which is modelled as an emission. See Figure 6 below.

Outputs to technosphere: Products and co-produ	Am	Unit	Quantity	Allocatic	Category	Comm
De-coked LIB BM, alternative	1	ton	Mass	100 %	Electronics waste	
Add line						

Outputs to technosphere. Avoided products	Amount	Uni	Comment
Natural gas, high pressure {DE}| natural gas productio	590	m3	Replacing 112 nM3 hydrogen and 1492 nm3 co according to Ye
Add line			

Inputs

Inputs from nature	Subcompartm	Amount	Unit	Distributio	Comment
Air	in ground	3290*1,225 = 4,03E3	kg		1,225 kg/m3 acc to https://en.wikipedia.org/wiki/Density_of_air
Add line					

Inputs from technosphere: materials/fuels	Amount	Unit	Comment
Tap water in Sweden, at user/RER System	90	kg	
Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transpc	1,8*880 = 1,58E3	tkm	1,8 ton input/ton. 880 km transport from karlskoga to Skellefteå assumed
Add line			

Inputs from technosphere: electricity/heat	Amount	Unit	Comment
Add line			

Outputs

Emissions to air	Amount	Unit	Comment
Nitrogen, atmospheric	2597*1,16 = 3,01E3	kg	2597 Nm3 N2 according to Ye. 1,16 kg/NM3 according to http://www.airproducts.com/Products/Gases/gas-facts/conversion-formulas/weight-and-volume-equivalents/nitrogen.aspx

Figure 6 Alternative model of 1 ton of de-coked lithium ion black mass

Figure 7 shows the relationships between the amount of traction batteries, NMC cells, wet black mass and de-coked black mass. Since the batteries only contain 50% cells, 2 kg traction battery is needed for 1 kg of cells. 1,8 kg wet BM give 1 kg de-coked BM, see Figure 4. From Figure 2 it can be deduced that wet BM is 31,8% of battery content (BM plus Volatile components). 2 kg battery containing 31,8% wet BM, then gives 2*0,314/1,8=0,349 decoked BM. The parameter ALT1 gives possibility to switch between decoking with air instead of oxygen, see above.

EOL Li-ion NMC cells, 1 kg, ReLion	Finished	Comparable with EOL li-ion NMC battery cell, 1 kg based on PEFCR

Materials/Assemblies	Amount	Unit	SD	Mi	M	Comment
Add line						

Processes	Amount	Unit	S	Min	Ma	Comment
Sorting, crushing and separating waste Lithium traction batteries	2	kg				Since the batteries only contain 50% cells, 2 kg are nedded for 1 kg of cells
De-coked LIB BM	(1-ALT1)*2*0,314/1,8 = 0,349	kg				1,8 kg uncoked BM give 1 kg decoked BM. 2 kg battery containing 31,8% wet BM, then gives 2*0,314/1,8=0,349 decoked BM
De-coked LIB BM, alternative	ALT1*2*0,314/1,8 = 0	kg				
Smelting incl Li-separation of de-coked BM	2*0,314/1,8 = 0,349	kg				

Figure 7 Relationships between amounts of traction battery, NMC cells, wet black mass and de-coked black mass

Smelting and lithium separation

Smelting and lithium separation is based on data from the ReLion project run by Swerim. Input output data based on pilot scale tests by Swerim as shown in the figures below.

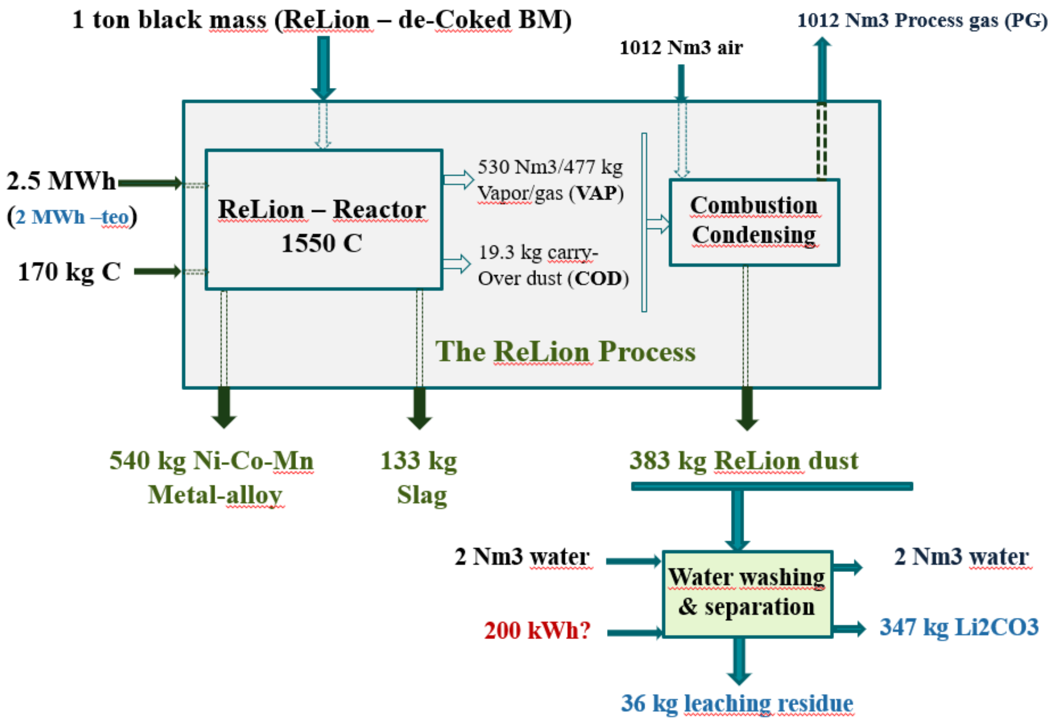


Figure 8 Step 2: Smelting reduction for Ni-Co-Mn recovery and Li-separation

The outputs and inputs related to smelting and lithium separation of 1 ton of de-coked LIB BM are shown in Figure 8 and modelled in Simapro as shown below. The process gas contains 21% CO_2, 12% H_2O, 67% N_2 and 0,2% SO_2 and is modelled as emissions of those gases. The model allows for calculation with different electricity mixes (Swedish or European).

Outputs to technosphere: Products and co-produ	Am	Unit	Quantity	Allocatic	Category	Comm
Smelting incl Li-separation of de-coked BM	1	ton	Mass	100 %	Electronics waste	
Add line						

Outputs to technosphere. Avoided products	Amount	Uni	Comment
Avoided products, LIB recycling	-1	tor	
Add line			

Inputs

Inputs from nature	Subcompartm	Amount	Unit	Distribu	Comment
Air	in ground	1012*1,225 = 1,24E3	kg		1012 Nm3 air input according to Flowsheet ReLion with de-coked BM
Add line					

Inputs from technosphere: materials/fuels	Amount	Unit	Comment
Hard coal {RoW}| market for | Cut-off, S	170	kg	according to Flowsheet ReLion with de-coked BM
Tap water in Sweden, at user/RER System	2000	kg	according to Flowsheet ReLion with de-coked BM
Add line			

Inputs from technosphere: electricity/heat	Amount	Unit	Comment
Electricity, high voltage {SE}| market for | Cut-off, S	Prodel*2500 = 0	kWh	according to Flowsheet ReLion with de-coked BM
Electricity, high voltage {SE}| market for | Cut-off, S	Prodel*(200+100) = 0	kWh	200 kWh according to Flowsheet ReLion with de-coked BM. For 99,9% lithium carbonate purity we assume an extra 100 kWh electricity
Electricity, high voltage {ENTSO-E}| market group for | Cut-off, S	(1-Prodel)*2500 = 2,5E3	kWh	
Electricity, high voltage {ENTSO-E}| market group for | Cut-off, S	(1-Prodel)*(200+100) = 300	kWh	
Add line			

Outputs

Emissions to air	Amount	Unit	:	Comment
Carbon dioxide, fossil	1361*0,208 = 283	kg		
Nitrogen, atmospheric	1361*0,67 = 912	kg		20,8% CO2, 12% H2O, 67% N2 and 0,2% SO2 in 1009 m3 or 1361 kg process gas according to Ye
Water	1361*0,12 = 163	kg		
Sulfur dioxide	1361*0,002 = 2,72	kg		

Figure 9 Model of reduction for Ni-Co-Mn recovery and Li-separation

Avoided products are modelled as in Figure 10. Since the slag contains 41% manganese, that amount is assumed to replace manganese and the rest is slag for deposit. 95% lithium carbonate purity was obtained in pilot tests. With additionally 100 kWh electricity, 99,9% lithium carbonate purity is assumed to be obtained, see Figure 10 below.

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Category	Comment
Avoided products, LIB wet BM recycling	1	ton	Mass	100 %	Electronics waste	

Outputs to technosphere. Avoided products	Amount	Unit	Comment
Nickel, 99.5% {GLO}| production | Cut-off, System	539*0,63 = 340	kg	63% Nickel of 539 kg Ni-Co-Mn metal alloy according to ReLion Flowsheet with detailed process data
Cobalt {GLO}| production | Cut-off, S	539*0,21 = 113	kg	21% Cobalt of 539 kg Ni-Co-Mn metal alloy according to ReLion Flowsheet with detailed process data
Manganese {RER}| production | Cut-off, S	539*0,0986 = 53,1	kg	9,86% Mn of 539 kg Ni-Co-Mn metal alloy according to ReLion Flowsheet with detailed process data
Blast furnace slag {GLO}| blast furnace slag, Recycled Content cut-off | Cut-off, S	(1-0,41*54,9/70,9)*133 = 90,8	kg	133 kg slag according to Flowsheet ReLion with de-coked BM, containing 41% mangan, therefore assumed to replace managan and the rest is slag for deposit
Lithium carbonate {GLO}| production, from concentrated brine | Cut-off, S	347*0,999 = 347	kg	347 KG Li2CO3 according to Flowsheet ReLion with de-coked BM, 95% purity, but we assume 99,9% purity with an extra 100 kWh electricity
Manganese {RER}| production | Cut-off, S	133*0,41*54,9/70,9 = 42,2	kg	133 kg slag according to Flowsheet ReLion with de-coked BM, containing 41% manganeseoxide, therefore assumed to replace manaan 54,9/70,9 and the rest is slag for deposit

Figure 10 Avoided product from LIB recycling

Model parameters

In order to calculate the results using, e.g., different electricity mixes, the model parameters in SimaPro are manipulated according to the figure below. Base case conditions assume Swedish average electricity for all recycling operations, de-coking according to lab test and transporting between Karlskoga and Skellefteå between, shredding and metallurgical treatment. Parameters EL and GAS has no meaning for LIB recycling.

Input parameters	Value	Distribut	SD2 or 2SI	Min	Ma	Hid	Comment
Prodel	1	Undefin				☐	0=europeisk el, 1=svensk el
EL	1	Undefin				☐	EL=0=gas; EL=1=el
GAS	0	Undefin				☐	GAS=1=gas for processes; GAS=0=el for processes
ALT1	0	Undefin				☐	ALT1=0=decoking according to labtest; ALT1=1=decoking with air instead of oxygene
Pol	0	Undefin				☐	1=Transport to Poland; 0=Transport to Skellefteå
Bol	1	Undefin				☐	1=Transport to Boliden in Skellefteå; 0=Transport to Poland

Figure 11 SimaPro model parameters

Electricity

It is possible to do the calculations with different electricity mixes. The alternatives used in the calculations are given in the table below.

Table 1 Electricity mixes

Name of data set	Gram CO_2-eq/kWh	Comment	Para-meter
Electricity, high voltage {SE}| market for | Alloc Rec, S	41.5	Simulates current smelting in Sweden and future European conditions.	Prodel=0

Name of data set	Gram CO_2-eq/kWh	Comment	Para-meter
Electricity, medium voltage {SE}| market for | Alloc Rec, S	44	Simulates current sorting/ crushing in Sweden and future European conditions.	Prodel=1
Electricity, medium voltage {ENTSO-E}| market group for | Cut-off, S	417	Simulates current sorting/ crushing in western Europe and average global condi-tions.	Prodel=0
Electricity, high voltage {ENTSO-E}| market group for | Cut-off, S	414	Simulates recycling in western Europe and average global conditions.	Prodel=0

Avoided products

Recycling avoids using other material resources. Thereby recycling is often calculated as having a net benefit to the environmental impact. However, it is not evident which material should be considered as being avoided or replaced, because the quality of the material output from the recycling is not obvious. The figure below shows some of the replacement choices used in this project.

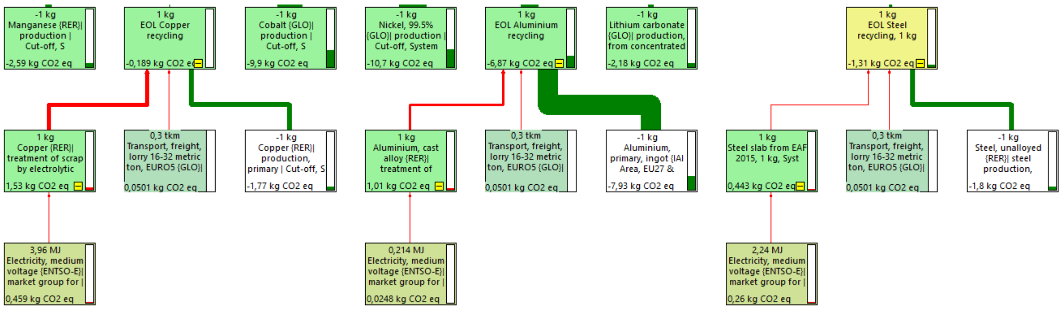


Figure 12   Avoided products

It was assumed that the recycling output of copper, aluminium and steel needed transport and remelting in order to replace virgin copper, aluminium and steel respectively. On the other hand, it was assumed that the recycling output of manganese, cobalt, nickel and lithium carbonate could replace virgin manganese, cobalt, nickel and lithium carbonate respectively without further treatment. In Figure 12 the calculation is done with European average electricity for remelting but that could be changed to Swedish average electricity production with parameter Prodel, see Table 1.

Results

In the figures below, the thickness of the arrows corresponds to the global warming impact measured in carbon dioxide equivalents from respective process. The amount of CO_2-eq in gram 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.

ReLion

Recycling lithium ion cells with the ReLion method avoids potentially around 4.5 kg CO_2 per kg cell in total. However, most of this avoided burden stem from the rest of the battery pack, not from the cells. Since roughly half of a traction battery pack consist of cells and the other half is packaging, cooling and battery management system, BMS, 2 kg of battery pack is needed for 1 kg of cells.

Sorting, crushing and separating a LIB pack avoids 2.9 kg CO_2 per kg LIB cell due to avoided burdens associated with copper and aluminium recycling from the pack (packaging, cooling, BMS)[3], see figure below. Base case conditions are assumed (Swedish average electricity for all recycling operations, de-coking according to lab test and transportation between Karlskoga and Skellefteå between shredding and metallurgical treatment.) Transportation of batteries from car scrap yards is included and give a climate impact at the same level as internal energy needs.

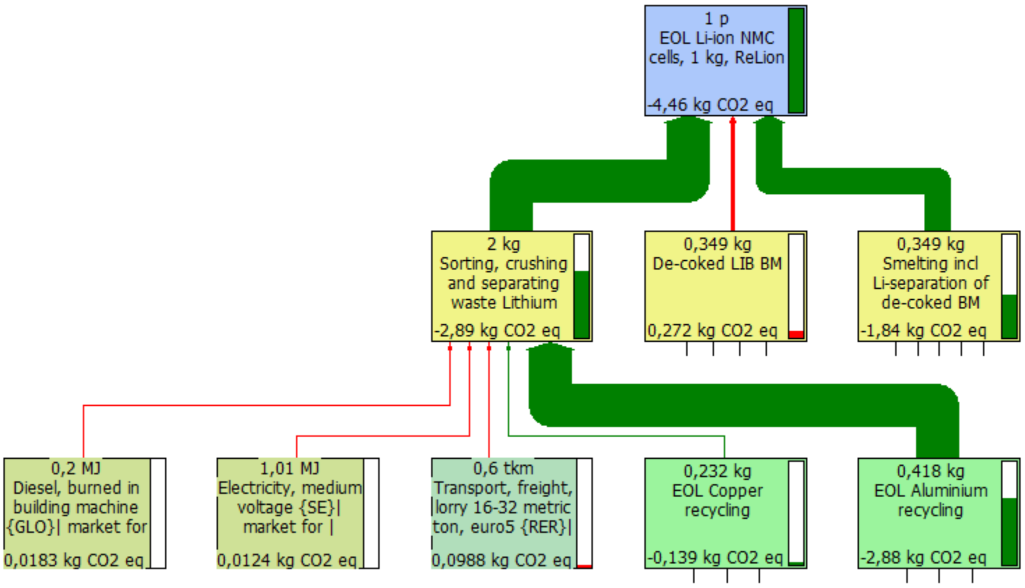


Figure 13 Climate impact of end-of-life recycling of lithium ion cells according to ReLion, sorting, crushing and separating, base case conditions

De-coking, smelting including lithium separation avoids the balance, i.e. 1.6 kg CO_2/kg cell, see Figure 14 and Figure 15.

[3] So it would in a way be more correct to say that sorting, crushing and separation 2 kg och lithium ion traction battery pack avoids 2.9 kg CO_2

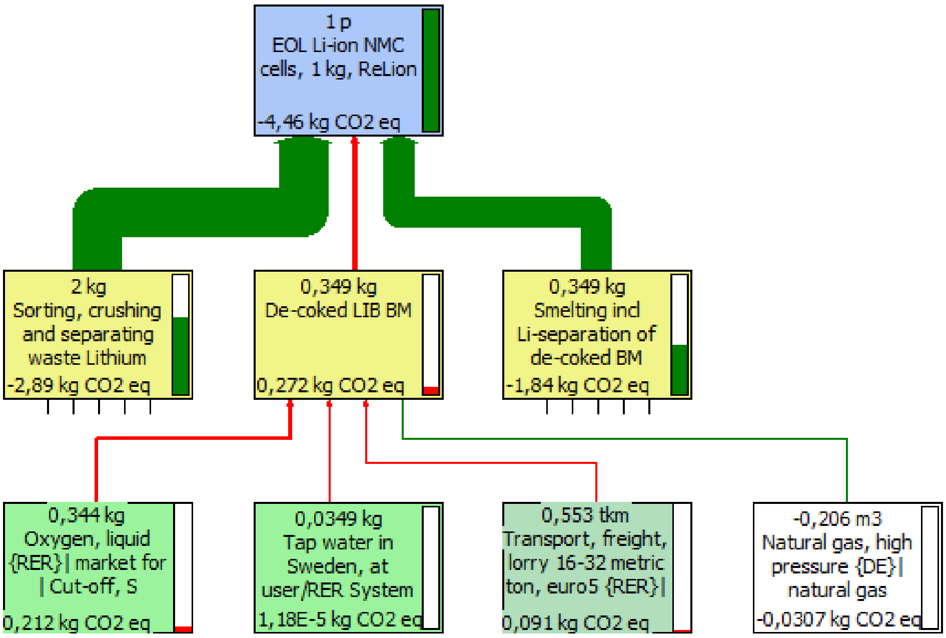


Figure 14   Climate impact of end-of-life recycling of lithium ion cells according to ReLion, decoking, base case conditions

Nickel, cobalt and lithium carbonate recovery and recycling save substantive climate impact, as can be seen in the figure below.

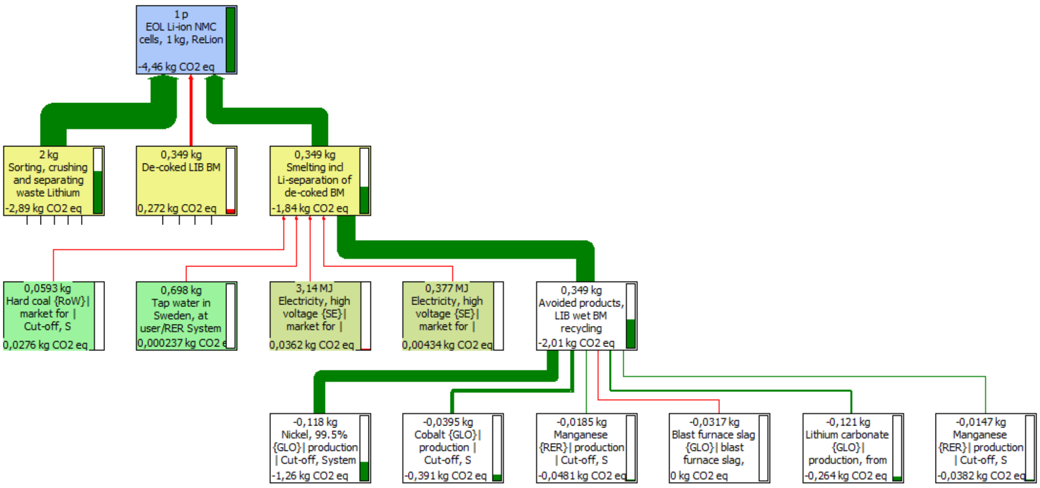


Figure 15   Climate impact of end-of-life recycling of lithium ion cells according to ReLion, smelting and Li-separation, base case conditions

The figure below shows abiotic depletion. The main trend that copper, aluminium and nickel give substantive contributions is the same as for climate impact. However, copper has changed place with aluminium as the most important contributor to the impact category. Processes contributing with less than 5.3% of the total are not shown (5.3% cut-off).

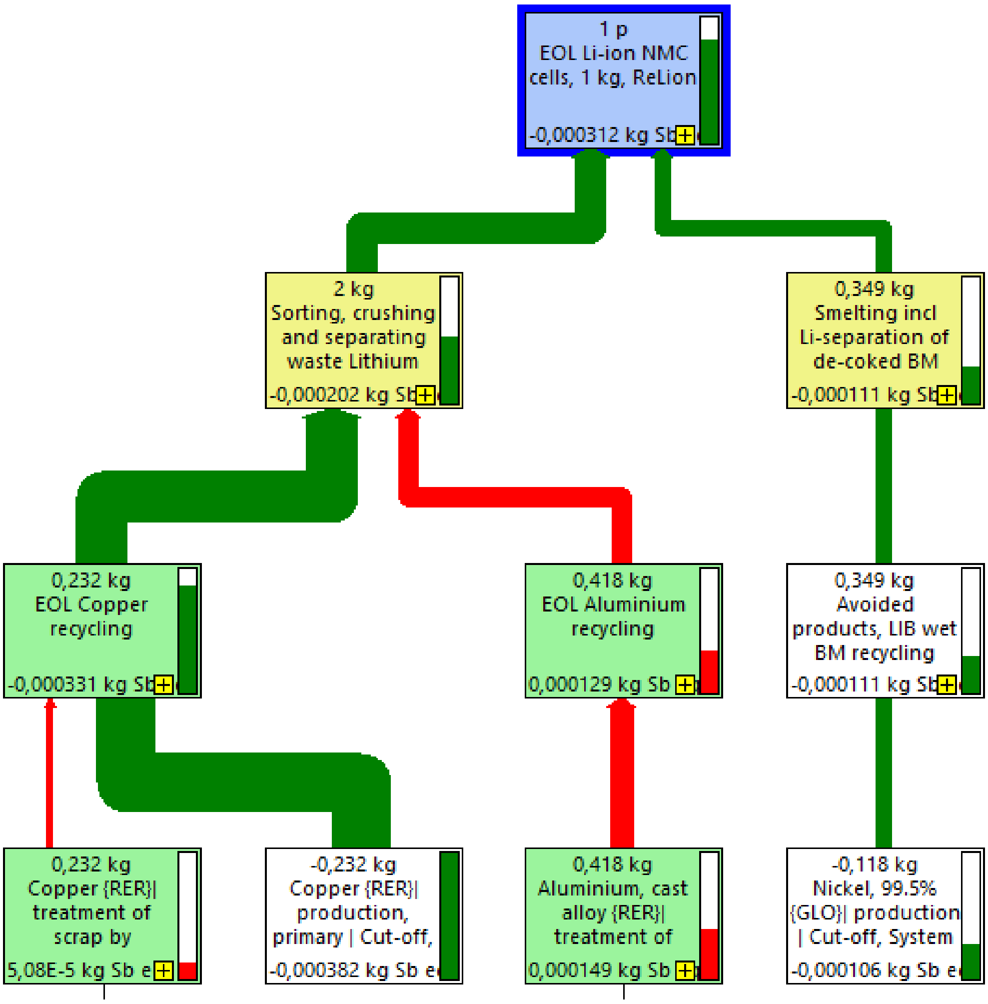


Figure 16 Abiotic depletion of end-of-life recycling of lithium ion cells according to ReLion, base case conditions, 5.3% cut-off

Alternative de-coking

An alternative decoking process is possible using air and water instead of liquid oxygen. The total climate impact of using this alternative is avoidance of 4.67 kg CO_2/kg cell, see figure below.

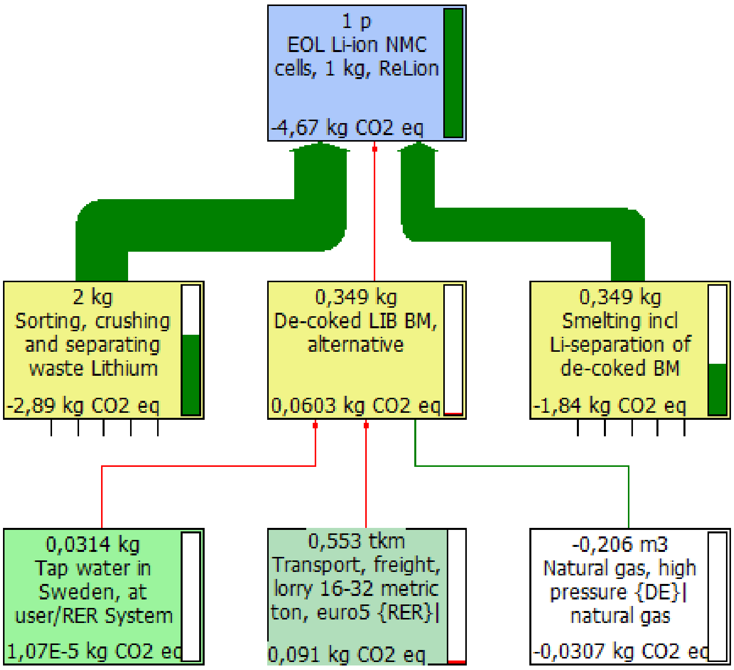


Figure 17 Climate impact of end-of-life recycling of lithium ion cells according to ReLion, decoking with air and water

In the figure below the calculations are done with European average electricity mix. Otherwise base conditions apply. The climate impact avoidance decreases to 3.9 kg CO_2/kg cell.

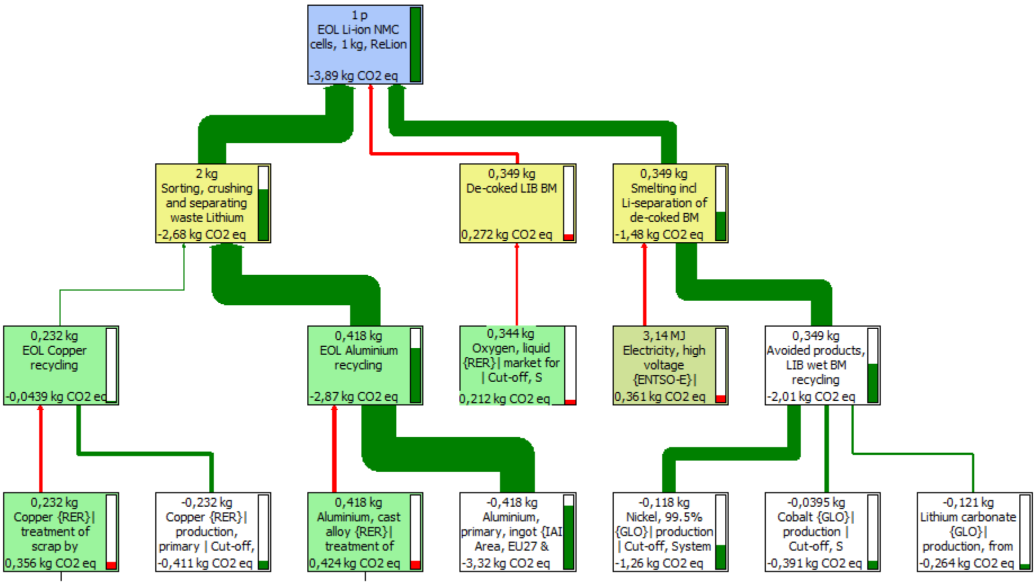


Figure 18 Climate impact of end-of-life recycling of lithium ion cells according to ReLion, European electricity mix

Comparing with PEFCR

For comparison, recycling with the data given in PEFCR is calculated below. The model is based on the information given in Annex 4 of the PEFCR-guide (RECHARGE 2018). It should be emphasized that the PEFCR only consider LIB cells while ReLion consider LIB packs. Thus, the avoided 2.9 kg CO_2 burdens associated with copper and aluminium recycling from the pack is not included in the PEFCR model. So it is more fair to compare the PEFCR avoided 0.1 kg CO_2/kg cell burden with the 3,9-2,7=1.2 kg CO_2/kg cell balance in Figure 18.

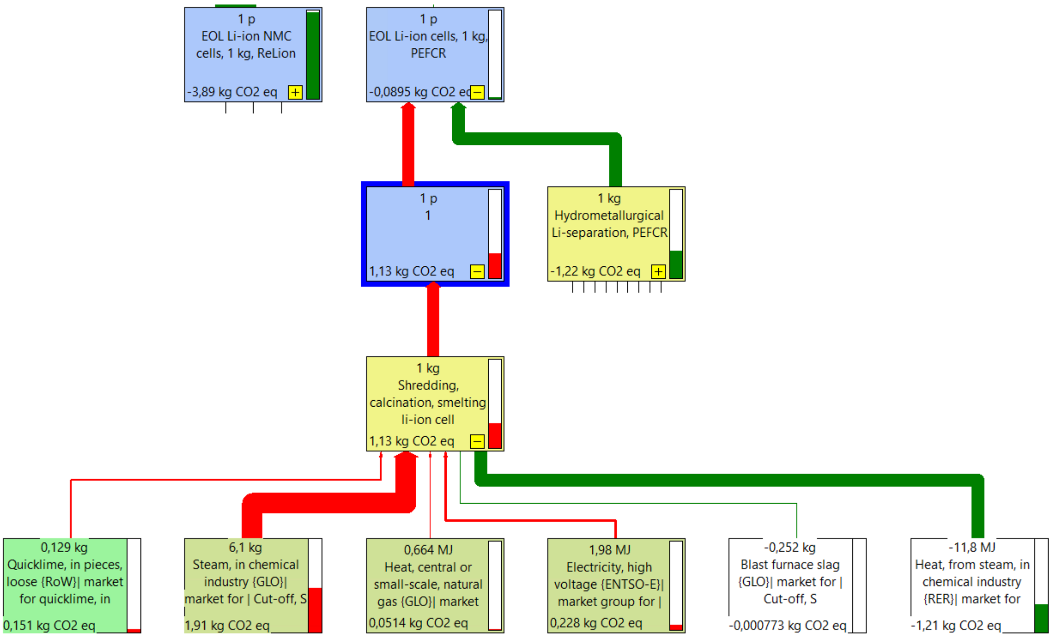


Figure 19   Climate impact of end-of-life recycling of lithium ion cells. ReLion process compared with PEFCR data, European electricity mix

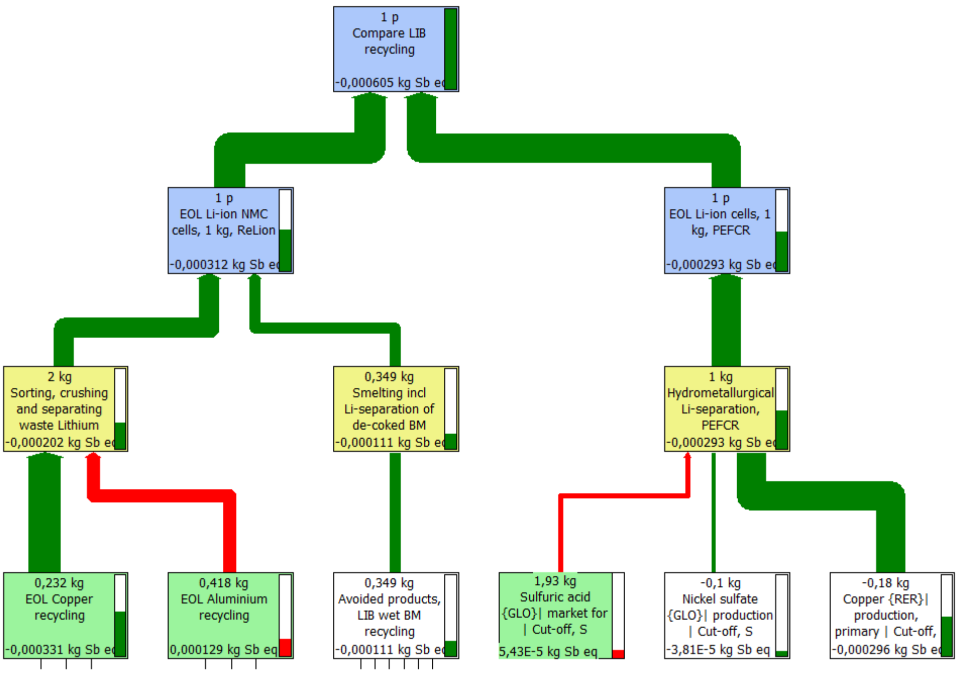


Figure 20   Abiotic depletion of end-of-life recycling of lithium ion cells. ReLion process compared with PEFCR data, European electricity mix. 3.5% cut-off

From a resource perspective, the ReLion process is much more similar to the PEFCR, as can be seen in the figure above. Savings are around 0.003 kg Sb/kg cell for both processes.

Recalculation with Swedish electricity does not give drastically improved results for the PEFCR data (0.3 kg CO_2/kg cell avoidance compared to 0.1), see figure below.

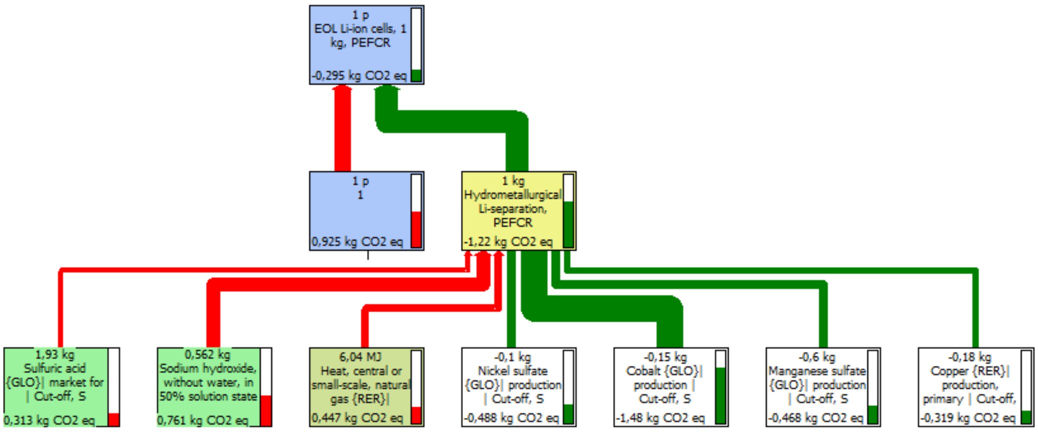


Figure 21 Climate impact of end-of-life recycling of lithium ion cells, PEFCR data, Swedish electricity mix

Discussion and conclusions

Comparison with other battery LCAs

As mentioned above, comparisons with PEFCR is halting due to that the PEFCR only consider LIB cells while ReLion consider LIB packs. Thus, the avoided 2.9 kg CO_2 burdens associated with copper and aluminium recycling from the pack is not included in the PEFCR model and it is therefore more relevant to compare the PEFCR avoided 0.1 kg CO_2/kg cell burden with the 3.9-2.7=1.2 kg CO_2/kg cell balance see Figure 17. But what does around 0.1-1.2 kg of CO_2/kg cell mean in the life cycle of a traction battery? In the figure below, life cycle climate impact for a 24 kWh NMC traction battery used in Nissan LEAF is shown (Mats Zackrisson 2018) compared to the ReLion process.

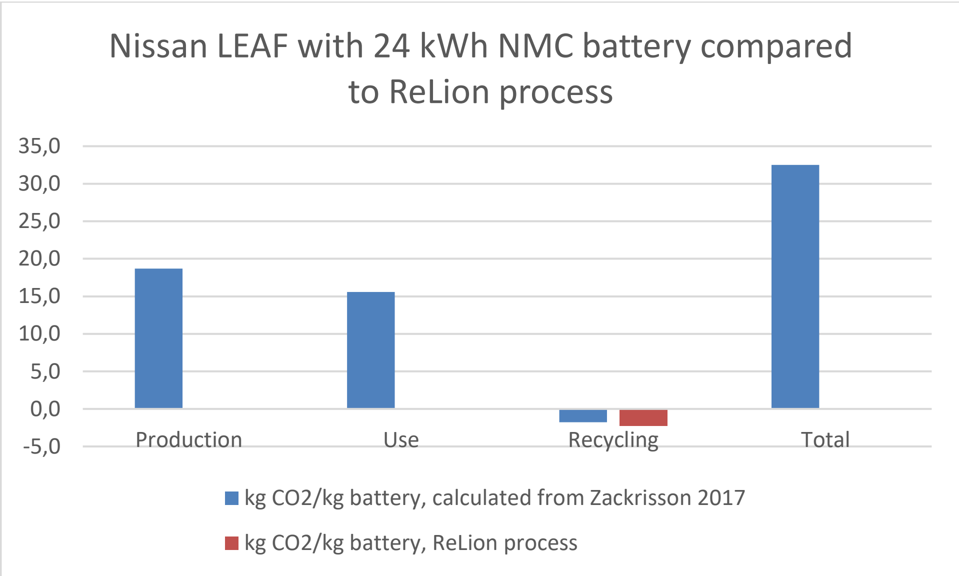


Figure 22 Nissan LEAF with 24 kWh NMC battery, life cycle climate impacts compared to ReLion process

In Zackrisson 2018, the recycling phase was estimated based on the assumption that 80% of metal content could be recycled at an environmental cost equal to half the avoided burden of the recycled materials. Recycling climate avoidance thus estimated amount to 9,5% of production phase impacts. The ReLion recycling process avoids 12% of the production phase impacts as modelled in Zackrisson 2018

(Cusenza et al. 2019) reports 8% climate impact recycling credits of total life cycle climate impact (for a LMO-NMC battery) but since the end-of-life burdens (approx. 4%) are included in the total, the total end-of-life climate avoidance should amount to around 5% of production impacts in that study. (Tagliaferri et al. 2016) reports around 20% climate impact recycling credits of production impacts, but here the whole vehicle (a Nissan LEAF with an NMC battery) is included.

In conclusion, the figures achieved by the ReLion process is somewhere in between figures received by other studies incorporating end-of-life of traction batteries. It seems therefore reasonable to assume that if the ReLion process can be replicated in full scale, it should be possible to recover at least 10% of the climate impacts of producing an NMC traction battery.

It should be mentioned that the climate impact of producing an NMC traction battery calculated by Zackrisson 2018 is at the higher end of those reported. Transformed to climate impact per delivered kWh it corresponds to 229 kg CO_2/kWh nominal battery capacity. (Emilsson and Dahllöf 2019) claim production of NMC traction batteries have a climate impact in the range 61-106 kg/kWh nominal battery capacity, where the range mainly is claimed to depend on electricity mix. If Emilsson and Dahllöf are correct, then recycling with the ReLion process could potentially avoid around 20% of production climate impacts.

Decoking

Decoking with air and water instead of liquid oxygen gives a bit more climate avoidance, 0.2 kg CO_2/kg cell. If it can be done easily and without much extra cost this option should be utilized.

Electricity mix

Using average European electricity mix instead of Swedish electricity mix only decrease the climate impact avoidance from 4.5 to 3.9 kg CO_2/kg cell. This shows that the ReLion process is not dependant on carbon-lean electricity.

Abiotic depletion

The abiotic depletion gains of the ReLion process follows the same trend as the climate impact gains.

Conclusions

The results indicate that the ReLion process:

- replicated in full scale, can potentially recover at least 10% of the climate impacts of producing an NMC traction battery, the currently most common traction battery chemistry
- decoking with air and water instead of liquid oxygen gives a bit more climate avoidance, 0.2 kg CO_2/kg cell and a bit more abiotic depletion avoidance. If it can be done easily and without much extra cost this option should be utilized.
- The ReLion process is not dependant on carbon-lean electricity to potentially avoid at least 10% of the climate impacts of producing an NMC traction battery

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