
Techno-environmental screening of hydrometallurgical techniques for Li-ion battery recycling

ELiMINATE project deliverables of work package 2:
Screening LCAs of current process technologies (2A.1) and
Screening LCAs of novel process technologies (2A.2)



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Summary

This report serves as a deliverable for the ongoing Era-MIN project ELiMINATE, aiming to elucidate the comparison and selection process of the most environmentally sustainable Lithium-ion battery (LIB) recycling technologies, in two different categories, namely current and novel methods. The name of the deliverable is *“Deliverable 2A.1 Screening Life Cycle Assessment (LCA) report of current and novel process technologies”*. This deliverable is the results of Work-package 2, *Task 2A.1* and *Task 2A.2*. The results of these tasks are presented together in this report, namely *“Task 2A.1 Screening LCA of current process technologies”* and *“Task 2A.2 Screening LCA of novel process technologies”*. Within the scope of ELiMINATE project, there are two different hydrometallurgical LIBs recycling technique categories: current and novel technologies. Of these, nine methods have been designated as "Current Technologies" due to their higher Technology Readiness Level (TRL) which is 2 out of 9 and are published in the literature but have not yet been utilized on an industrial scale. Another two methods are referred to as "Novel Technologies" since their Technological Readiness Level is 1 out of 9, and they have never been published in the literature and developed by the ELiMINATE project partner Karadeniz Technical University. In summary, nine current technologies and two novel hydrometallurgical LIB recycling technologies were under investigation within their categories in this study.

In this work package, to be able to compare their environmental impacts within each category and select the best ones within each group, first, a literature study about LCAs of lithium-ion battery recycling was done. Accordingly, a comparative analysis was done for current LIB recycling technologies by conducting screening LCA for each technique. In the case of two novel technologies, a techno-environmental comparison was conducted and the Life Cycle Inventory (LCI) data which has been collected and presented within the ELiMINATE project was considered sufficient to facilitate the screening and subsequently determine the best-performing novel technology. In addition, the screening LCA results for nine different current technologies further reinforce the selection of novel technologies and have helped in arriving at the conclusions with its results.

According to the findings of the screening LCA study conducted for current technologies, the HCL and H₂SO₄ Mixed NMC methods are recognized as the best options from the following impact categories which are Abiotic depletion (ADP elements), Acidification potential (AP), Eutrophication Potential (EP), Global

warming potential excluding biogenic carbon (GWP), Human Toxicity Potential (HTP), Ozone layer depletion Potential (ODP) covered by CML 2001 methodology. In the case of two novel technologies, based on the techno-environmental comparison that uses LCI data, H₂SO₄ – Novel technology was selected as the best option for novel technologies according to its reduced waste generation, lower chemical consumption, and other associated benefits. To summarize, two current LIB recycling technologies (HCL and H₂SO₄ Mixed NMC) and one novel LIB technology (H₂SO₄ – Novel) have been selected based on their lower environmental impacts. The findings from this deliverable will serve as a foundation for the subsequent evaluation of these technologies as part of the ELiMINATE project's next phases.

Abbreviation	Phrase and/or Definition
ADP	Abiotic Depletion Potential
AP	Acidification Potential
EP	Eutrophication Potential
EoL	End of Life
FAETP	Freshwater aquatic Ecotoxicity potential
GWP	Global Warming Potential
HTP	Human Toxicity Potential
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LIB	Lithium-ion Battery
MAETP	Marine Aquatic Ecotoxicity Potential
MSA	Methane Sulfonic Acid
ODP	Ozone Layer Depletion Potential
POCP	Photochemical Ozone Creation Potential
SDC	Solvent Dependent Crystallization
TETP	Terrestrial Ecotoxicity Potential

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1 Introduction

These screening LCA and techno-environmental comparison studies are part of the Era-MIN project ELiMINATE which has the overall aim *“to develop an implementation framework to advise on the best way forward in terms of establishing a local end-of-life (EOL) lithium-ion batteries (LIBs) treatment facility and recycling industry in both the South African and the EU context”*. To reach this aim, specific objectives were defined for the project, and one of them is to compare the environmental impacts of different current and novel LIB hydrometallurgical recycling technologies within each category throughout the project. It is crucial to highlight that this deliverable is not intended to make a direct comparison between current and novel technologies.

In this study, the environmental impacts of nine current technologies are compared within their category by screening LCA and two novel technologies are compared with each other with a techno-environmental comparison study. Screening LCA for current technologies have been done based on a literature survey for the current technologies. The comparison of novel technologies done based on an LCI data achieved in this project for the novel technologies. Among the nine current technologies, two have been identified as the most environmentally friendly options, and similarly, one novel technology has been selected as the most environmentally friendly among the two novel options.

1.1 Structure of report

Chapter 1 – Introduction: This chapter provides general information related to the purpose of this deliverable and clarifies the structure of the report.

Chapter 2 – Survey of Literature: This chapter provides a brief overview of the literature survey. The report then explains the data collection process for life cycle inventories of both current and novel technologies.

Chapter 3 – Screening LCA of Current Technologies: This chapter delves into the screening LCA of nine different current technologies. It begins with an overview of these technologies and later presents the methodology and results of the screening LCA.

Chapter 4 – Techno-environmental Comparison of Novel Technologies: The methodology and results of the techno-environmental comparison of the two novel technologies are presented in this chapter.

Chapter 5 – Conclusions: The results and comments are presented in this chapter for both the selection of current and novel technologies.

Chapter 6 – References

Appendices: At the end of the report, a separate section containing appendices is included.

2 Survey of literature

LIBs are at the forefront of energy storage technologies, possessing the highest energy density of all the state-of-the-art energy storage systems (Abu, et al., 2023). Despite being considered an environmentally friendly and sustainable energy storage solution, the soaring demand for LIBs has raised concerns about their environmental impact. Issues such as raw material extraction, greenhouse gas (GHG) emissions during production, energy consumption, and disposal-related problems like land degradation and water pollution have become pressing concerns (Costaa, et al., 2021) (Gu, et al., 2017). As demand for Lithium-ion batteries (LIBs) rises, there's a heightened interest in assessing their environmental footprint across production, application, and use stages. Extensive research, primarily through Life Cycle Assessment (LCA), has studied the environmental impacts of LIB production and usage. However, despite the in-depth exploration of LCA in these areas, the realm of recycling LIBs has only recently emerged in LCA studies.

In the beginning of this LCA screening and techno-environmental comparison study, a literature review on LIB recycling LCAs has been conducted. The review highlighted a scarcity of studies concentrating on the environmental impacts of LIB recycling through LCA. Yet, it indicated a burgeoning interest in this field, signalling an increasing recognition of the importance of scrutinizing the environmental consequences linked to LIB recycling using LCA. One example of an LCA study in this context is the work conducted by Zackrisson in 2019 by means of ReLion process which covers (1) sorting, crushing, and separating, (2) de-coking black mass (3) smelting and Li-separation (Zackrisson, 2019). The results of the study showed that the total avoided burden due to copper, aluminium, steel, manganese, cobalt, nickel, and lithium recovery is higher than the environmental burdens caused by resource consumption during recycling processes for climate change and abiotic depletion impact categories. The climate change avoidance is 4.5 kg CO₂/kg per cell, and it can be increased to 4.67 kg CO₂/kg per cell by using air and water instead of liquid oxygen in the de-coking process, it also decreases by 10% if the European mix is applied in the modelling instead of the Swedish electricity mix. Other publications (Buchert, et al., 2011) (Cusenza, et al., 2019) also report climate impact avoidance due to LIB recycling. Consequently, the primary question explored in this screening study is "Which recycling pathway results in greater burden avoidance?"

2.1 Data collection procedure for LCIs

The data to create life cycle inventories is collected in two different ways for current and novel technologies. Life cycle inventories of current hydrometallurgical technologies were generated per FU for recycling processes using HSC software where H, S and C stand for enthalpy, entropy, and heat capacity. HSC is a software running thermodynamic calculations and is used here for process simulations by Stellenbosch University. The current hydrometallurgical recycling processes are simulated based on data from the literature (Table 1) in the HSC software.

In the case of novel technology data collection, a different path is used than the current technologies. In order to establish preliminary flowsheets for novel technologies, first data collected from the literature (Table 1) and small-batch scale pilot plant tests were conducted at Exitcom Recycling's facilities by Karadeniz Technical University, which is another partner of the ELiMINATE project. These pilot tests provided sufficient data that is used to complete Excel mass balance calculations. Additionally, HSC has been utilized for only energy balance calculations in these novel technologies. Once the data is collected, life cycle inventories are prepared by integrating the results of Excel and HSC analyses.

The literature studies that have been used for data collection for both current and novel technologies is given together in Table 1. The combination of literature-based data and experimental results from pilot plant tests allows for a thorough evaluation of the current and novel technologies.

Table 1 Literature used for simulation of the recycling processes.

	Research Studies
1	(Guimarães, et al., 2022)
2	(Yao, et al., 2015)
3	(Porvali, et al., 2019)
4	(Li J, 2009)
5	(Wang & Friedrich, 2011)
6	(Musariri, et al., 2019)
7	(Zhang, et al., 1998)
8	(Chen, et al., 2016)
9	(Petranikova, et al., 2022)
10	(Zackrisson, 2019)
11	(Boyden, et al., 2016)
12	(Buchert, et al., 2011)
13	(Cusenza, et al., 2019)
14	(Fisher, et al., 2006)
15	(Li, et al., 2013)
16	(Melin, 2019)
17	(Nordelöf, et al., 2019)
18	(Raugei & Winfield, 2019)
19	(Romare & Dahllöf, 2017)
20	(Temporelli, et al., 2020)
21	(Wang & Yu, 2021)
22	(Zhao & You, 2019)

3 Screening LCAs of current technologies

This chapter aims to conduct a comparative analysis of nine current LIB recycling technologies using screening LCA to identify the most environmentally favourable option(s). The initial section provides brief descriptions of the nine current recycling technologies under investigation. Subsequently, the LCA methodology employed in this study is elaborated upon, outlining the approach taken to assess the environmental impacts of these technologies. Lastly, the analysis results are presented, identifying the two most promising methods. These methods will undergo further investigation through LCA to gain deeper insights into their environmental performance, although this detailed analysis is not included in this deliverable.

3.1 Current technologies

The focus of the nine current LIB recycling technologies is on various hydrometallurgical pathways. Hydrometallurgical processes involve crushing the feed material (spent LIBs) and then submerging it in a strong acid to dissolve valuable metals (which are Li, Co, Ni, and Mn in the case of this study). The acid leaching step can be done by bulk leaching, where all the metals are dissolved and precipitated together. Within this study, three current methods extract metals by using bulk leaching in the form of a Nickel-Manganese-Cobalt (NMC) mixture. However, selective leaching is also viable and can be achieved by techniques such as selective precipitation and solvent extraction. Consequently, the next three methods utilize a sequential precipitation technique by adding extra process steps to recover metals one by one. Lastly, the remaining three current technologies out of nine, employ solvent extraction techniques to recover metals selectively from the leach solution. Within this screening study, nine current hydrometallurgical recycling methods employing these three techniques are compared in terms of their environmental impacts.

1A. HCL – Mixed NMC

A mixture of LCO, LFP and NMC₁₁₁ batteries is leached using a 4 M solution of hydrochloric acid at a solids/liquid ratio (S/L ratio) of 20 g/L to form a pregnant leach solution (PLS). The pH and metal ratio of Ni, Mn, and Co in the PLS is then adjusted and NaOH is used to precipitate a mixed Ni-Mn-Co hydroxide (NMC)

product. The remaining leach solution is then subjected to evaporation and finally, Na_2CO_3 is also used to precipitate lithium from the leach solution. The mixed NMC product can be used during the production of NMC batteries.

1B. HCL – Sequential

A mixture of LCO, LFP and NMC₁₁₁ batteries is leached using a 4 M solution of hydrochloric acid at an S/L ratio of 20 g/L to form a PLS. The pH is then adjusted, and a variety of precipitants are used to selectively precipitate first Mn, followed by Ni and then Co. The remaining leach solution is then subjected to concentration by evaporation and finally Na_2CO_3 is used to precipitate lithium from the leach solution.

1C. HCL – SX

A mixture of LCO, LFP and NMC₁₁₁ batteries is leached using a 4 M solution of hydrochloric acid at an S/L ratio of 20 g/L to form a PLS. The pH is then adjusted, and a variety of precipitants are used alongside solvent extraction to selectively precipitate first Mn, followed by Ni and then Co. The remaining leach solution then undergoes concentration by evaporation and finally Na_2CO_3 is used to precipitate lithium from the leach solution.

2A. H₂SO₄ – Mixed NMC

A mixture of LCO, LFP and NMC₁₁₁ batteries is leached using a 2 M solution of sulphuric acid with 10 %vol H₂O₂ at an S/L ratio of 20 g/L to form a PLS. The pH and metal ratio of Ni, Mn and Co in the PLS is then adjusted and NaOH is used to precipitate a mixed Ni-Mn-Co hydroxide product. The remaining leach solution then undergoes concentration by evaporation and finally Na_2CO_3 is also used to precipitate lithium from the leach solution.

2B. H₂SO₄ – Sequential

A mixture of LCO, LFP and NMC₁₁₁ batteries is leached using a 2 M solution of H₂SO₄ acid with 10 %vol H₂O₂ at an S/L ratio of 20 g/L to form a PLS. The pH is then adjusted, and a variety of precipitants are used to selectively precipitate first Mn, followed by Ni and then Co. The remaining leach solution then undergoes concentration by evaporation and finally Na_2CO_3 is used to precipitate lithium from the leach solution.

2C. H₂SO₄ – SX

A mixture of LCO, LFP and NMC₁₁₁ batteries is leached using a 2 M solution of H₂SO₄ acid with 10 %vol H₂O₂ at an S/L ratio of 20 g/L to form a PLS. The pH is then adjusted, and a variety of precipitants are used alongside solvent extraction to selectively precipitate first Mn, followed by Ni and then Co. The remaining leach solution then undergoes concentration by evaporation and finally Na₂CO₃ is used to precipitate lithium from the leach solution.

3A. Citric – Mixed NMC

A mixture of LCO, LFP and NMC₁₁₁ batteries is leached using a 2 M solution of citric acid with 2 %vol H₂O₂ at an S/L ratio of 20 g/L to form a PLS. The pH and metal ratio of Ni, Mn and Co in the PLS is then adjusted and NaH₂PO₄ is used to precipitate a mixed Ni-Mn-Co phosphate product. The remaining leach solution then undergoes concentration by evaporation and finally NaH₂PO₄ is also used to precipitate lithium from the leach solution.

3B. Citric – Sequential

A mixture of LCO, LFP and NMC₁₁₁ batteries is leached using a 2 M solution of citric acid with 2 %vol H₂O₂ at an S/L ratio of 20 g/L to form a PLS. The pH is then adjusted, and a variety of precipitants are used to selectively precipitate first Mn, followed by Ni and then Co. The remaining leach solution then undergoes concentration by evaporation and finally H₃PO₄ is used to precipitate lithium from the leach solution.

3C. Citric – SX

A mixture of LCO, LFP and NMC₁₁₁ batteries is leached using a 2 M solution of citric acid with 2 %vol H₂O₂ at an S/L ratio of 20 g/L to form a PLS. The pH is then adjusted, and a mixture of precipitation and solvent exchange is used to selectively remove first Mn, followed by Ni and then Co from solution. The remaining leach solution then undergoes concentration by evaporation and finally H₃PO₄ is used to precipitate lithium from the leach solution.

The generated life cycle inventories for all nine current LIB recycling technologies are given in the Appendix A: Current Technologies in an aggregated form in the Table 5, Table 6 and Table 7 respectively.

3.2 Goal

The goal of these screening LCA and LCI studies is to determine the best current hydrometallurgical processes for LIB hydrometallurgical recycling in terms of environmental performance.

In this part, nine current recycling technologies are compared within their category. This comparison was completed based on three different acids: hydrochloric, sulfuric and citric. All three acid-based processes were applied with three process types: Mixed NMC precipitation, Sequential precipitation, and Solvent Extraction (SX). Hence there are nine cases to be compared.

3.3 What is LCI and LCA?

LCI is a systematic method of gathering and quantifying data on the inputs and outputs of a process at each stage, and it is commonly presented as a detailed inventory that forms the basis for conducting LCA studies. LCA investigate the environmental impacts related to a product or a process system during its entire life cycle. This includes evaluating energy and resource consumption as well as emissions, from all life cycle stages including material production, manufacturing, use and maintenance, and end-of-life. A schematic overview of a life cycle is shown in Figure 1.

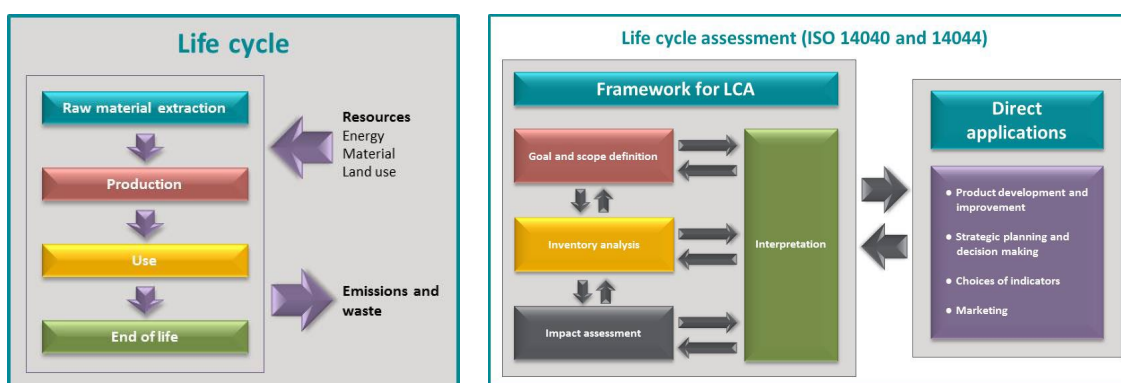


Figure 1. Illustration of the LCA system and the framework for life cycle assessment.

Life Cycle Assessment (LCA) stands as a broadly embraced and utilized methodology for assessing the environmental performance of diverse products and systems. Considering the time and resources needed for detailed LCAs, in this study screening LCA was chosen as a method to select the current process

technologies with the least environmental impact and LCI was chosen as the method to assess and select the best novel technology.

3.3.1 Functional unit and system boundaries

The functional unit is: the processing of a feed stream of LIB waste with a storage capacity of 1 kWh. The composition of the feed stream was a mixture of LCO, NMC and LFP batteries, in the ratio of the market share of the respective battery types. The functional unit is the same for current and novel technologies LCA studies.

The mechanical processes before hydrometallurgical processes are kept out of the system boundary considering that their impact will be the same for all cases. The use and end-of-life phases of recycled products are also outside the system boundaries. The study investigates the system from a waste management perspective and the waste LIBs are considered to enter the systems with no burdens since the burdens during battery production stem from and are here assigned to the battery manufacturing process.

This is a gate-to-gate study starting with waste LIBs and finishing with recycled products. The recycling processes are considered to take place in Europe. Where possible, datasets prepared for Europe were used.

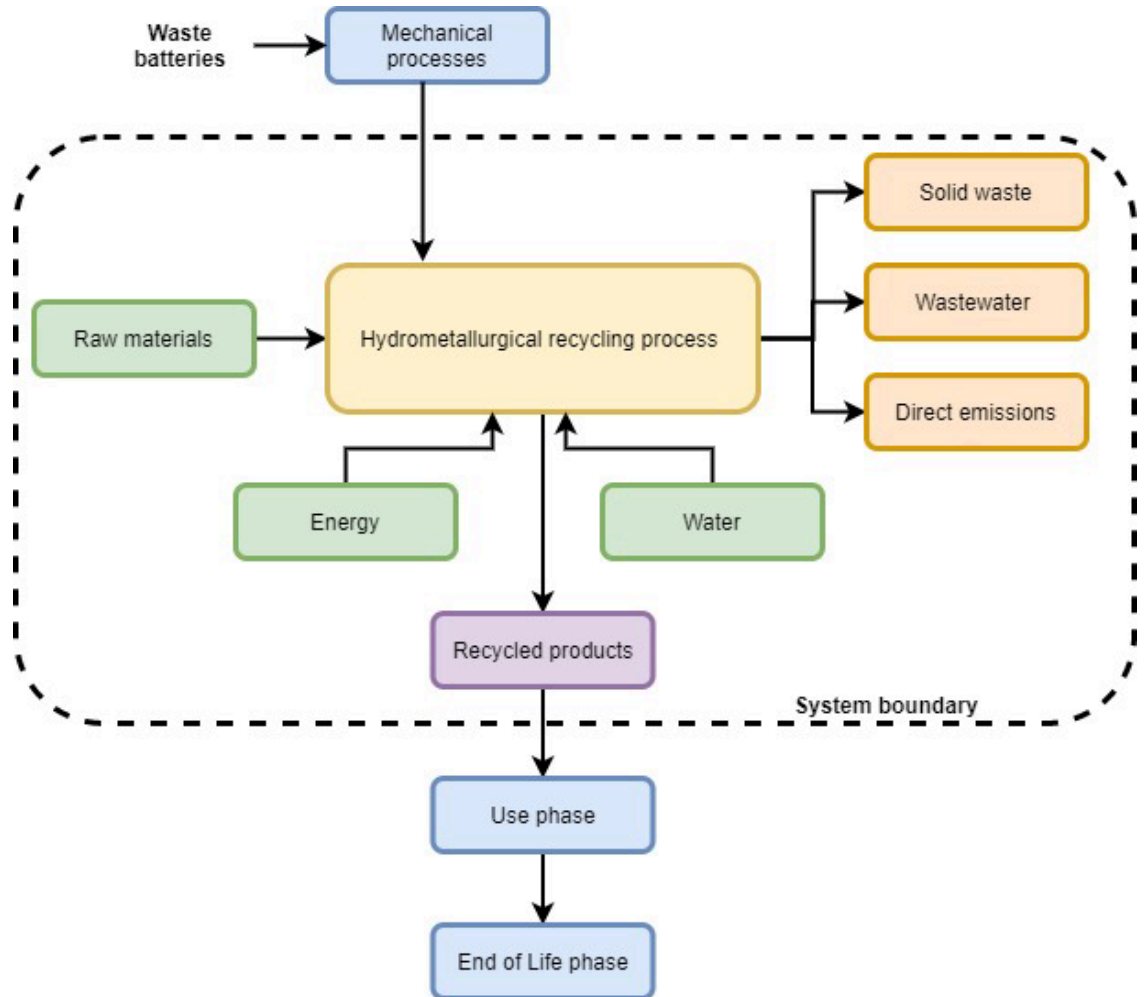


Figure 2. System boundary (generic for all pathways)

Table 2 Summary of recycling processes included in or excluded from the study.

Included	Excluded
Chemicals and auxiliary materials	Battery production and use phases
Production of the consumed energy	Collection of waste batteries
Water consumption	Mechanical pre-treatment (sorting, crushing and separating) of waste batteries
Wastewater treatment	Use and end-of-life phases of recycled products
Waste disposal	Manufacturing of the machinery used in recycling processes
	Transportation of auxiliary materials and chemicals to the recycling plant
	Transportation of waste to treatment or disposal facilities.

In this study, allocation is not applied, instead of allocation, the avoided burden approach is used. In this approach, system boundaries are extended to cover the production of recycled products by means of conventional, virgin material based, processes and the burdens that arise from conventional production processes are subtracted from the burdens of the investigated system. The summary of recycling processes included or excluded from the study is listed in the Table 2.

3.3.2 Selection of LCIA methodology and impact categories

CML 2001 methodology (Guinee, 2002) is chosen to calculate life cycle impact assessment (LCIA) results. Characterization results for all midpoint impact categories covered by CML 2001 methodology are calculated which are Abiotic depletion (ADP elements and ADP fossil), Acidification potential (AP), Eutrophication Potential (EP), Freshwater aquatic Ecotoxicity potential (FAETP), Global warming potential excluding biogenic carbon (GWP), Human Toxicity Potential (HTP), Marine Aquatic Ecotoxicity Potential (MAETP), Ozone layer depletion Potential (ODP), Photochemical ozone creation potential (POCP) and Terrestrial Ecotoxicity Potential (TETP), the equivalents are presented in the Table 3. Since the main aim of the study is to compare the recycling cases characterization results are normalized and weighted using “sphere LCIA survey 2012, Europe, CML 2016, excluding biogenic carbon” to calculate endpoint results.

Table 3 The examined environmental impact categories

Impact Categories	Equivalent
Abiotic Depletion, ADP elements, ADPE	kg Sb Equivalent
Abiotic Depletion, ADP fossil, ADPF	MJ
Acidification Potential AP	kg SO ₂ Equivalent
Eutrophication Potential EP	kg Phosphate Equivalent
Freshwater A. Ecot. P. FAETP inf.	kg DCB Equivalent
Global Warming Pot. (Excluding biogenic carbon)	kg CO ₂ Equivalent
Human Toxicity Potential HTP inf.	kg DCB Equivalent
Marine A. Ecotox. Pot. MAETP inf.	kg DCB Equivalent
Ozone Depletion Pot. ODP steady state	kg R11 Equivalent
Photochem. Ozone Creat. Pot. POCP	kg Ethylene Equivalent
Terrestrial Ecotox. Pot. TETP inf.	kg DCB Equivalent

3.3.3 Software and database

The LCA has been modelled in GaBi version 9.2.1 with professional database provided by Sphera Solutions GmbH.

3.3.4 Critical review procedure

For these screening LCAs there was no critical review.

3.4 Results of screening LCA for current technologies

3.4.1 Midpoint results

To understand the environmental impacts of the current technologies, midpoint indicator results were generated as part of the LCA process. Out of the 11 indicators listed in Table 4, this report focuses on providing more detailed information on six specific ones: ADP elements, AP, GWP, HTP, EP, and ODP.

Table 4 Indicators that are selected for midpoint analysis

CML2001 – Aug. 2016	Midpoint Indicators
ADP elements	Abiotic Depletion
ADP fossil	Abiotic Depletion
AP	Acidification Potential
EP	Eutrophication Potential
FAETP	Freshwater Aquatic Ecotoxicity Potential
GWP	Global Warming Potential
HTP	Human Toxicity Potential
MAETP	Marine Aquatic Ecotoxicity Potential
ODP	Ozone Layer Depletion Potential
POCP	Photochemical Ozone Creation Potential
TETP	Terrestrial Ecotoxicity Potential

For each indicator a comparison graph generated to present the results, in those graphs the positive y-axis of the charts indicates a negative environmental impact and that the negative y-axis indicates a positive impact due to the use of the avoided burden method.

For ADP Elements, from Figure 5 it can be said that the performance is related with the leaching agent, HCL have the best performance, H₂SO₄ follows it, and the worst option is citric acid. From the precipitation method point of view, NMC seems to be the best followingly Sequential, and the worst is the SX technique. For the AP category HCl – NMC and H₂SO₄ – SX are the best and the worst options respectively, similar to ADP category. In this category values are closer to each other. The NMC precipitation process generally has the largest avoided burden followed by the sequential precipitation and then the solvent extraction process (except again in the case of hydrochloric acid). Regarding the performance of the different lixivants, all 3 acids are seemingly equal in performance when considering AP, except for the citric sequential precipitation process which outperforms the sulphuric and hydrochloric acid sequential precipitation processes.

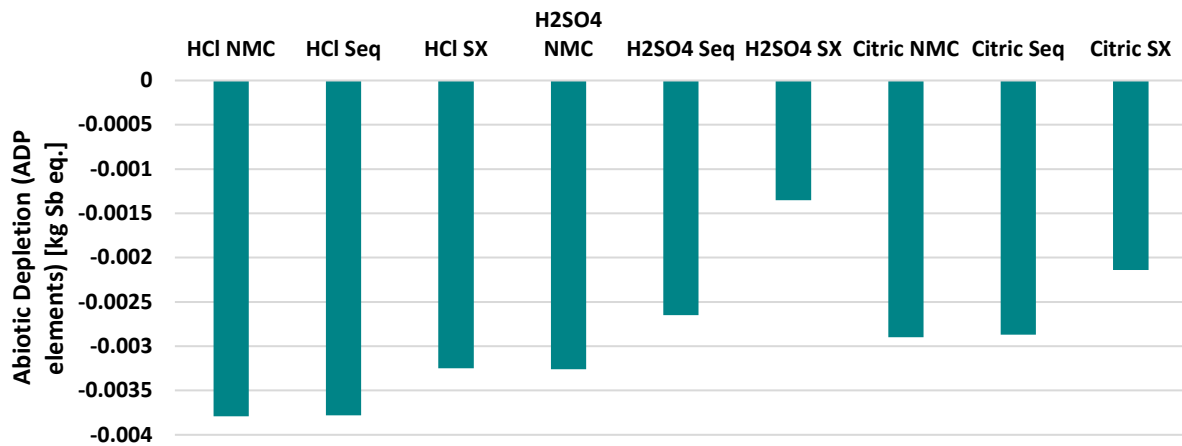


Figure 5. CML 2001, August 2016 version, ADP results for all cases.

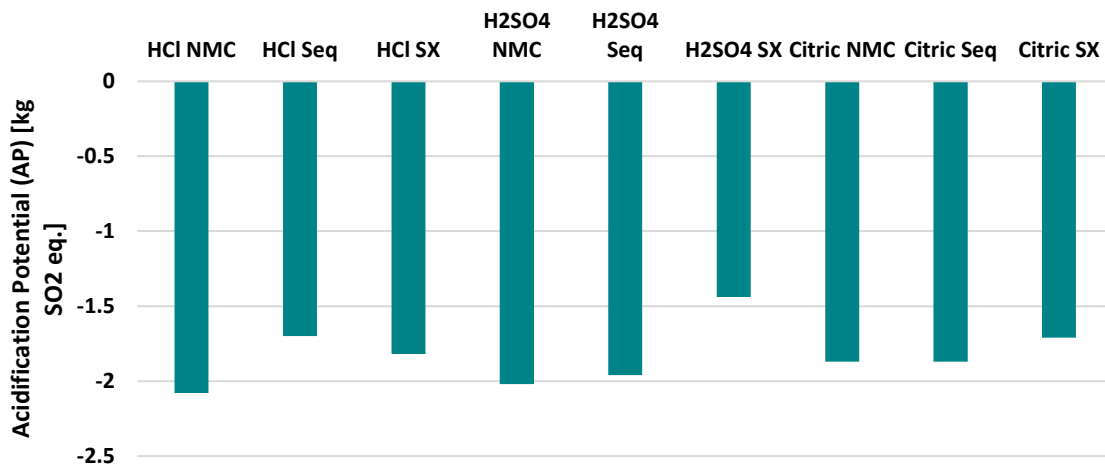


Figure 6. CML 2001, August 2016 version, AP results for all cases.

The GWP category results are different than the others. The environmental gains provided by recycling cannot overcome the environmental burdens and the net impact is a burden, except in the case of H₂SO₄ – NMC.

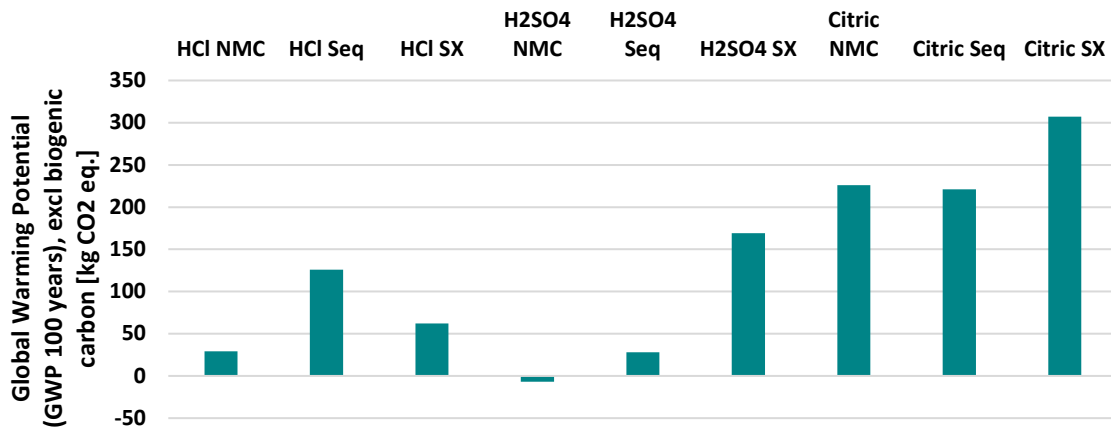


Figure 7. CML 2001, August 2016 version, GWP results for all cases.

For HTP and EP categories, HCl – NMC and H₂SO₄ – NMC are the best options.

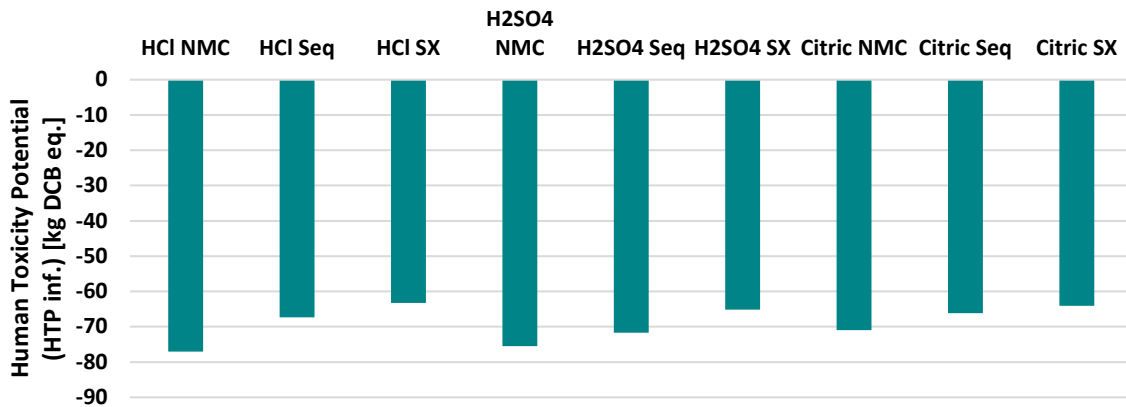


Figure 8. CML 2001, August 2016 version, HTP results for all cases.

For EP, there exists a clear pattern where the NMC precipitation process has the largest avoided burden for all 3 lixiviant systems, followed by sequential precipitation and then solvent extraction.

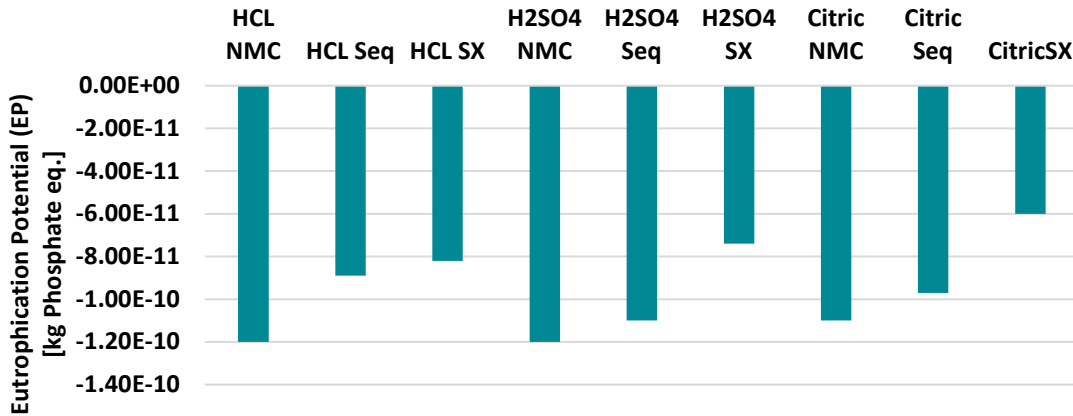


Figure 9. CML 2001, August 2016 version, EP results for all cases.

For ODP, HCL – NMC and Citric – NMC seems to be the best options. When comparing the different lixiviant system to each other it is found that citric acid has the largest avoided burden followed by hydrochloric and then sulphuric acid, which contrasts all results seen up until now. However, when comparing the different flowsheet configurations, the same familiar pattern is formed where mixed NMC precipitation outperforms sequential precipitation and SX.

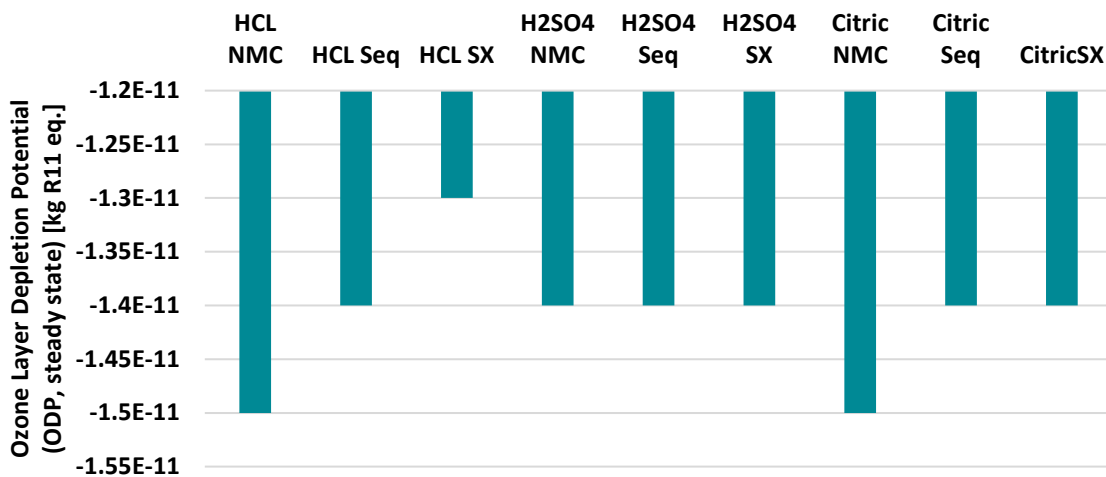


Figure 10. CML 2001, August 2016 version, ODP results for all cases.

3.4.2 Endpoint results

Since the main aim of this part of the study is to determine the environmentally best hydrometallurgical process from current LIB recycling processes, the normalized and weighted LCA results are compared first, in Figure 3. As explained

in the method section only the recycling of the battery part is investigated in this study and the impacts from production and use of the batteries are excluded. This results in the appearance of the results on the negative side of the graph which means all hydrometallurgical cases provide net environmental gain when endpoint scores are considered.

In this comparison, it is seen that the H_2SO_4 -NMC case provides more environmental gain than all the others and the HCL-NMC case follows it with very little difference. Citric – NMC, HCl – Sequential, and Citric – Sequential results are very close to each other. H_2SO_4 – SX and Citric – SX cases provide the least gain. This graph also shows that, despite the consumption of chemicals and energy, all the investigated hydrometallurgical recycling of LIBs provides net environmental gain. When considering the three process types for each respective acid, the mixed NMC processes outperform the sequential processes, which outperform the SX processes in return.

Some of the key factors contributing to the differences between the results will be discussed here. **Requirement of different chemicals and high rate of chemical consumption:** Amongst others, the poor performance of the SX processes can be attributed to a large amount of organic solvent required, with the associated impact of solvent production. In addition, the SX process entails a large amount of working fluid that requires energy for heating and pumping. The precipitant in the mixed NMC process consists only of caustic soda, which is less specialized than the precipitants used in the sequential process, with a lower environmental impact associated with its manufacture.

Production steps: The NMC processes fared well in general. This can be ascribed to the fact that NMC is precipitated in a single step, requiring only a single precipitant, whereas sequential precipitation requires the addition of several precipitants in sequence.

Leaching agent consumption rates: When comparing the leaching acids with each other, the H_2SO_4 generally outperforms HCl, which outperforms the citric acid. Due to inherent requirements for the citric acid leach reaction, a larger mass of citric acid is consumed. The concentrations of chemicals in the citric processes are also lower than the concentrations applied in HCl and H_2SO_4 processes, which results in larger working volumes that require heating.

Manufacturing of leaching agents: Finally, it was also found that the production of citric acid has a very large burden due to its consumption of fossil fuels and large amounts of greenhouse gas emissions giving it a very high global warming potential when compared to sulphuric and hydrochloric acid.

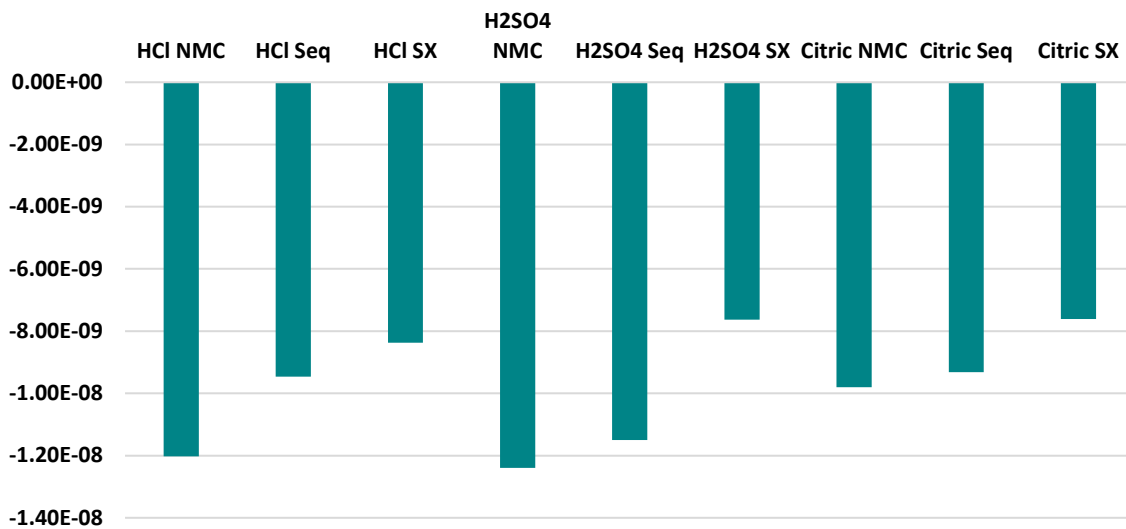


Figure 3. Normalized and weighted CML 2016 results for all hydrometallurgical recycling cases. Normalization reference: CML 2016 (Centrum voor Milieukunde Leiden, 2016), EU 25 + 3, year 2000, excl. biogenic carbon. Weighting method: Sphera thinkstep life cycle impact assessment (LCIA) Survey 2012, Europe, CML 2016, excl. biogenic carbon).

The contribution analysis for the endpoint results for all cases is given in Figure 4 and Figure 5. The analysis in Figure 5 shows that the main gain is provided by recovering the cobalt from the waste LIBs. In addition to cobalt, nickel, lithium, and other metals provide the rest of the gain.

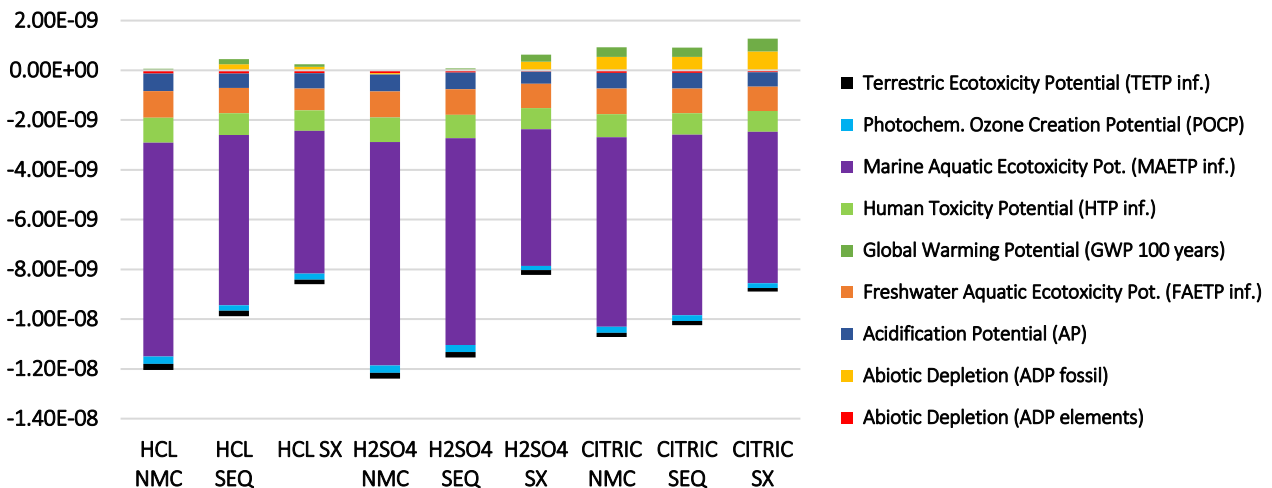


Figure 4. Contribution graph of normalized and weighted CML 2016 results for all hydrometallurgical recycling cases with impact categories. Normalization reference: CML 2016 (Centrum voor Milieukunde Leiden, 2016), EU 25 + 3, excl. biogenic carbon. Weighting method: Sphera life cycle impact assessment (LCIA) Survey 2012, Europe, CML 2016, excl. biogenic carbon).

It is also seen that in all forms of citric acid cases chemical consumption causes more burdens than energy consumption. This is also true for the HCl – SX case. On the other hand, in the H₂SO₄ – SX case energy consumption causes more burdens compared to chemical consumption.

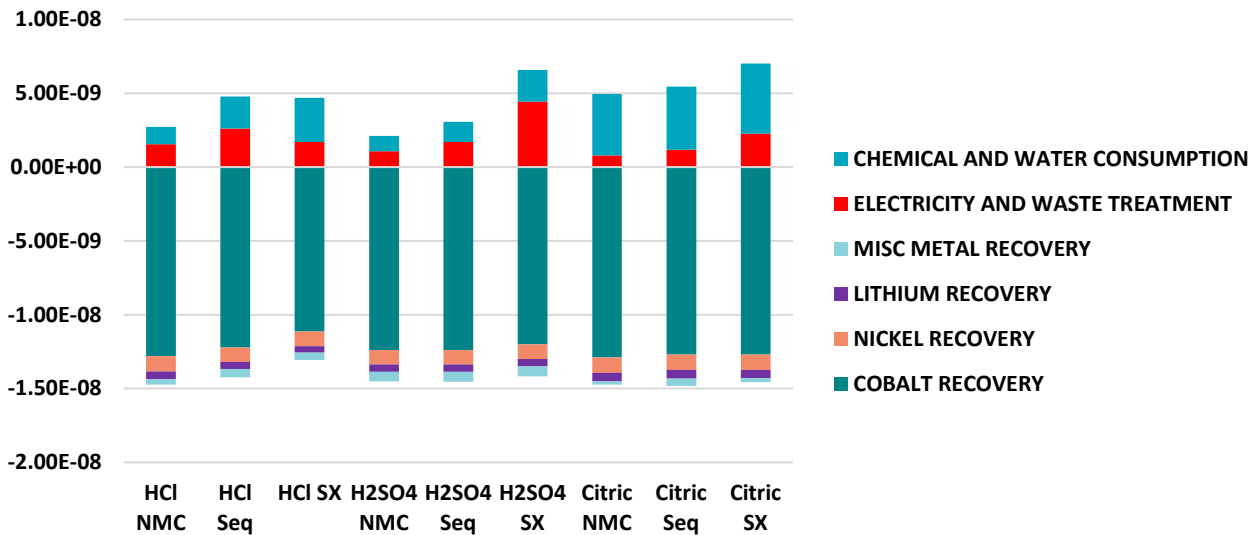


Figure 5. Contribution graph of normalized and weighted CML 2016 results for all hydrometallurgical recycling cases. Normalization reference: CML 2016 (Centrum voor Milieukunde Leiden, 2016), EU 25 + 3, excl. biogenic carbon. Weighting method: Sphera life cycle impact assessment (LCIA) Survey 2012, Europe, CML 2016, excl. biogenic carbon).

4 Techno-environmental comparison of novel technologies

The second part of the report compares two novel technologies used for battery recycling. The technologies have different ways of processing steps and chemical consumption. One technology uses a new leaching agent called Methanosulfonic acid (MSA; $\text{CH}_3\text{SO}_3\text{H}$) during the leaching process, while the other technology uses sulphuric acid as a leaching agent. The two novel technologies will be compared based on their differences.

Both technologies are using hydrometallurgical processes to recycle the LIBs. The first method uses H_2SO_4 as a main leaching agent and utilizes a solvent displacement crystallization (SDC) system, which involves the use of acetone for the efficient precipitation of cobalt (Co), lithium (Li) and nickel (Ni). The end products of this method include cobalt in the form of Co_3O_4 , as well as lithium in the form of sulphate and carbonate. In the second approach, Methanosulfonic acid (MSA; $\text{CH}_3\text{SO}_3\text{H}$) is utilized for the leaching step of LIBs, which results in the recovery of various metals, such as nickel (Ni), copper (Cu), and lead (Pb), as well as lithium in the form of carbonate. For the novel technologies, there will be a screening study using LCI data instead of an LCA study. Unlike the screening process for current technologies that involved comparing nine options, the screening of novel technologies considers only two processes. Once the best option is determined for the novel technologies, a subsequent step involving a full LCA study will be conducted, which is out of the scope of this specific report.

In this part of the study, the aim is to evaluate and compare H_2SO_4 – Novel and MSA – Novel hydrometallurgical LIB recycling technologies in terms of their environmental impact and choose the best one. Within this chapter, the rationale for selecting the more environmentally sustainable technology will be outlined and discussed. As previously mentioned, extensive pilot plant experiments and process modeling studies have been conducted to provide data for the creation of a comprehensive LCI for both novel LIB recycling technologies. These inventories have been presented in the Appendix B: Table 8 and serve as a foundation for a detailed comparison of the environmental impacts associated with each technology.

4.1 Novel technologies

1. H₂SO₄ – Novel

A mixture of LCO, LFP, LMO and NMC₁₁₁ batteries was subjected to leaching using a 1 M solution of sulfuric acid and 30% vol H₂O₂ at an S/L ratio of 100 g/L to form a PLS. Then Mn precipitated as Manganese Dioxide and the rest of the solution sent to SDC for separation of Al-Li and Co-Ni solutions. Acetone used in the SDC step with vacuum distillation. Subsequently, with sequential precipitation, Al-Li precipitated in one flow as lithium carbonate, while Co and Ni were precipitated in another flow, leading to the formation of cobalt tetroxide and nickel hydroxide end products.

2. MSA – Novel

A mixture of LCO, LFP, LMO and NMC₁₁₁ batteries was subjected to leaching using Methanesulfonic acid (MSA; CH₃SO₃H), which was supplemented with sulfuric acid and hydrogen peroxide. The leaching process resulted in the formation of a PLS, which was then processed further through sequential precipitation. This process yielded four end products which are manganese dioxide, nickel hydroxide, cobalt tetroxide, and lithium carbonate.

The generated inventories for two novel LIB recycling technologies are given in the Appendix B: Novel Technologies in an aggregated form.

4.2 Goal

The goal of this techno-environmental comparison is to determine the best novel hydrometallurgical processes for LIB hydrometallurgical recycling in terms of environmental performance within two options.

4.3 Results of techno-environmental comparison

The two novel technologies use the exact same feed materials (waste LIB chemistry) by means of its composition and feed rate. Notably, the end-product values of these technologies are also same, the rate of production is also same. Since the feed and product rates are exactly same, the inputs and outputs will be

changing for the processes. This allows for a clear assessment and comparison of the environmental impacts, specifically regarding raw material consumption, water and electricity consumption, waste generation, and direct emissions. The interpretation of the screening study was based on related literature review and several factors including:

- Different leaching agents: H₂SO₄-SDC technology utilized H₂SO₄ as the leaching agent, while the second method used Methane sulfonic acid (MSA; CH₃SO₃H).
- Raw materials consumption rates: H₂SO₄-SDC had lower raw material consumption rates, resulting in reduced environmental impacts.
- Water consumption and wastewater generation rates: H₂SO₄-SDC had lower water consumption and wastewater generation rates, indicating its potential for improved water management.
- Energy consumption rates: H₂SO₄-SDC had lower energy consumption rates compared to the second method.

As it can be seen, some of the categories are also touched upon in the results of current technologies in Chapter 3. Further detailed explanations and comments on these factors are provided in the subsequent chapter.

Compare H₂SO₄ and Methane sulfonic acid (MSA; CH₃SO₃H):

The novel technologies are also using hydrometallurgical methods like the current technologies. In the beginning of processes, there is a leaching step that uses the higher amount of chemical consumption rates. This acid leaching step can be describing as the most important step since the metals are going into the aqueous phase (Guimaraes, et al., 2022). In the first hydrometallurgical novel technology, sulfuric acid and hydrogen peroxide is added as leaching agents. In the second method, the main leaching agent is an organic acid methane sulfonic acid (MSA; CH₃SO₃H). Secondary agents are sulfuric acid and hydrogen peroxide. Total chemical consumption rates for the novel methods are presented in the following Figure 11.

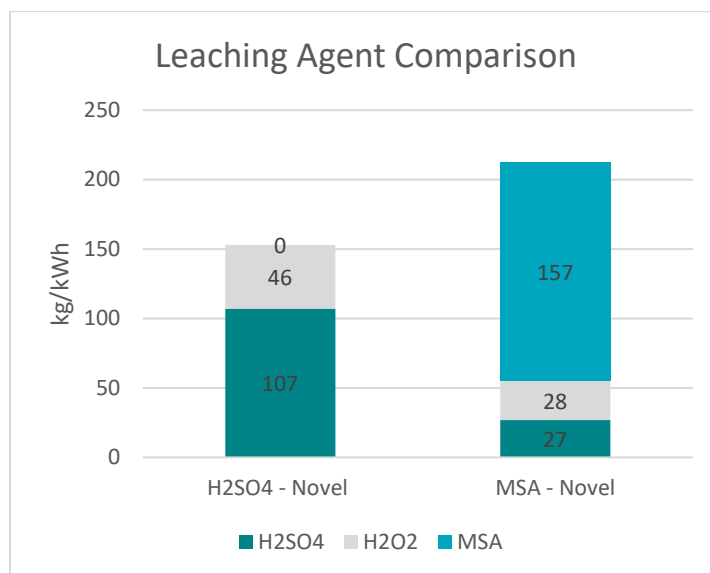


Figure 11. Leaching (Lixiviant) agent consumption comparison

Sulfuric acid is a strong acid and a widely used leaching agent in the metal recovery industry with some drawbacks such as toxic gas generation and safety risks (Guimaraes, et al., 2022). On the other hand, methane sulfonic acid (MSA; $\text{CH}_3\text{SO}_3\text{H}$) is a solvent that have been shown useful recently for metal recovery from secondary metal resources , such as WEEE (Wang, et al., 2019) (Jadhao, et al., 2023).

H_2SO_4 is a widely used and produced acid for metal recovery. This makes the sulfuric acid a relatively cheap and more current acid when you compare with the methane sulfonic acid (MSA; $\text{CH}_3\text{SO}_3\text{H}$), methane sulfonic acid (MSA; $\text{CH}_3\text{SO}_3\text{H}$) is a relatively new acid. Efficiency and safety regulations/issues of sulfuric acid is also makes it a more popular choice. However, the most important comparison should be made on environmental impacts of these chemicals in the two methods. In the second method, three different chemicals are used which is increasing the safety risks and all the environmental impacts during the usage of chemicals. The first technology presents lesser chemical consumption and lesser number of chemicals, which makes this method more environmentally reliable.

Raw Materials Consumption:

Based on the results of LCI study, the number of reagents and their total amounts that have been used in the two novel technologies are different, and it is presented in the Figure 12. The total amount of raw materials is 602 kg/kWh and 778 kg/kWh respectively.

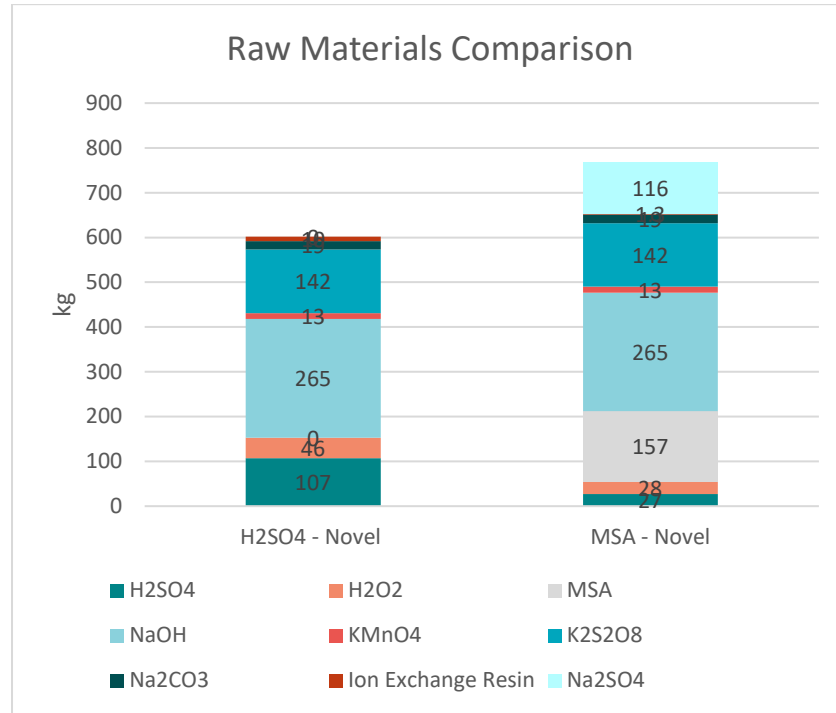


Figure 12. Raw materials consumption comparison

Different chemicals might create further problems in the wastewater treatment or increasing the toxicity of landfill waste. Based on raw material consumption rates, the first novel technology, which employs H₂SO₄ as a leaching agent, appears to have superior environmental performance compared to the second novel recycling method.

Water Consumption and Wastewater Generation:

There are two different types of water used in the novel technologies, these are process water and demineralized water. Water consumption for the novel technologies and their wastewater generation rates presented in the following Figure13. Notably, the second technology exhibits a higher water consumption rate. Wastewater generation is a critical issue for battery recycling since it requires treatment processes before discharging to the environment. From the cost point of view, it's also important to take wastewater treatment rates into account to make a comparison.

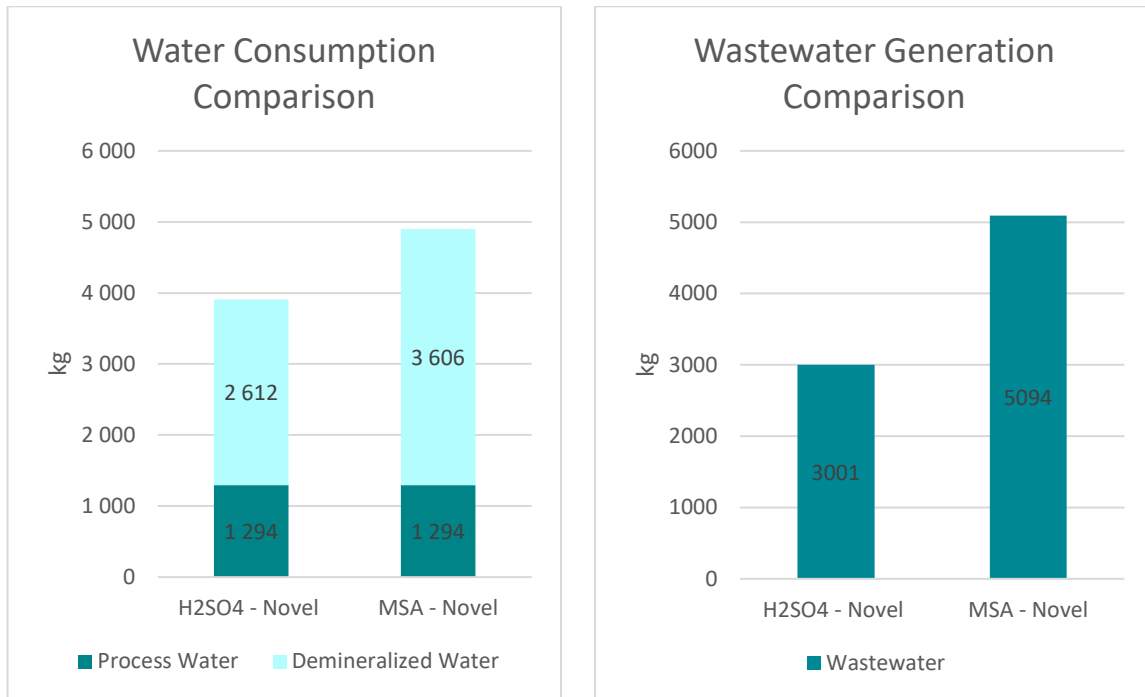


Figure 13. Water consumption and wastewater generation rate comparisons

Energy Consumption:

Monitoring energy consumption is one of the most crucial steps in comparing the environmental impacts of two different novel technologies since energy consumption can be directly associated with greenhouse gas emissions (Lic, et al., 2023). By evaluating the electricity consumption of novel technologies, it is possible to identify the most energy-efficient method. Electricity consumption rates for H₂SO₄ – Novel and MSA – Novel are presented in the following Figure 14. In the figure, it can be seen that the second technology has an additional energy lost caused by heat loss equal to 240 kWh. According to energy consumption rates, it can be said that the first novel technology uses less energy to produce the same products.

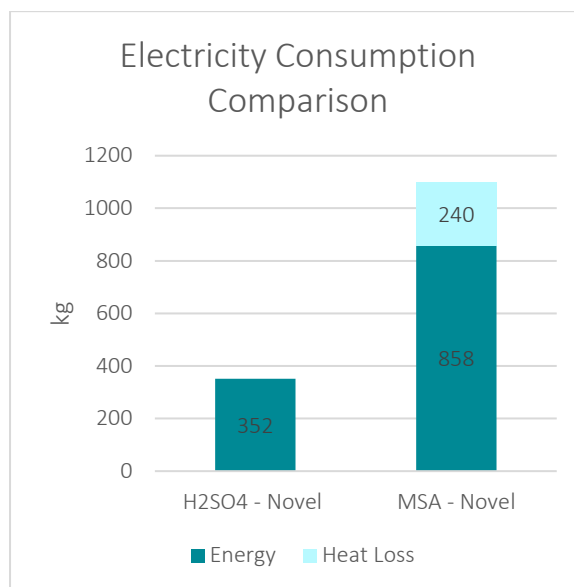


Figure 14. Electricity consumption comparisons

Waste Generation – Landfilling:

The hydrometallurgical processes in novel lithium-ion battery recycling technologies have an impact for toxicity because of the landfill waste generation. The total unleached solid waste generation rates for the first and second novel technologies are 50 kg/kWh and 42 kg/kWh, respectively.

Process Plant Capacity:

In the MSA – Novel technology, the amount of raw materials and water consumption higher which may lead to elevated environmental burdens, particularly due to the requirement of additional working fluids for solution transfer.

Optimization opportunities:

Both of the novel technologies utilize the same flowsheet for lithium-ion battery recycling but differ in their choice of leaching agents in the main leaching process. The first novel technology employs an inorganic leaching agent, while the second option utilizes an organic leaching agent. Organic leaching agents offer an environmentally friendly alternative that minimizes harmful chemical emissions, fostering greener recycling practices. On the other hand, inorganic leaching agents

demonstrate exceptional metal recovery rates, playing a vital role in maximizing resource extraction.

However, it is noteworthy that in the case of these novel technologies, the second option employing organic acid results in higher waste generation, electricity consumption, and raw material consumption compared to the inorganic alternative, all while achieving the same recovery rate. Nevertheless, there is potential for future improvements in organic acid methods to reduce their environmental impact and ultimately reach comparable recovery rates with the inorganic counterparts.

5 Conclusions

5.1 Screening LCA: current technologies

The screening LCAs have shown that all the potential recycling processes will result in a net environmental gain, should they be implemented. This can be attributed to the recovery of primarily cobalt, but also nickel and lithium. The avoided burdens of producing these metals from other sources outweighs the environmental burdens of the recycling processes. It was found that the mixed NMC precipitation processes were the most environmentally friendly and that solvent extraction processes fared the worst. Among solvent extraction methods, H₂SO₄ processes performed the best, followed by HCl, and citric acid performed the worst. The poor performance of citric acid is notable since organic acids are perceived to be more environmentally friendly than mineral acids. If the environmental performance of the recycling processes is to be improved, focus should be on the consumption of chemicals and energy in the processes. The mid-point analyses of the processes were discussed for the categories ADP, AP, GWP, EP ODP and HTP. In all cases except GWP, the environmental impact of recycling resulted in an avoided burden. When considering the GWP only H₂SO₄ – NMC precipitation led to a reduction in CO₂ eq. emissions.

Considering the strong current focus on climate change, H₂SO₄ – NMC might be preferred over other processes. Of the nine processes, two processes will be considered for the full LCA, namely the mixed NMC H₂SO₄ and HCL.

5.2 Techno-environmental comparison: novel technologies

In conclusion, the study aimed to evaluate and compare two novel hydrometallurgical LIB recycling technologies in terms of their environmental impact, with the goal of selecting the more environmentally sustainable technology. The study found that the first novel technology, H₂SO₄ – Novel, presented a more sustainable option compared to the second method due to its lower environmental impacts in areas such as raw material consumption, water and energy consumption, and waste generation. The study's findings were based on a comprehensive LCI that provided data for a detailed comparison of the environmental impacts associated with each technology. It was known that both

technologies used the same feed materials amount/chemistry and achieved similar end-product values, which allowed for a clear assessment and comparison of their environmental impacts.

The H₂SO₄ – Novel technology, resulting in a lower amount of environmental impacts and the similar level of efficiency. The findings will be used in the next stages of the project to evaluate this technology further.

6 References

- Abu, S. M., Hannan, M., Lipu, M. H., Mannan, M., Ker, P. J., Hossain, M., & Mahlia, T. I. (2023). State of the art of lithium-ion battery material potentials: An analytical evaluations, issues and future research directions. *Journal of Cleaner Production*, 394, 136246.
- Boyden, A., Soo, V. K., & Doolan, M. (2016). The Environmental Impacts of Recycling Portable Lithium-Ion Batteries. *Procedia CIRP*, 188-193.
- Buchert, M., Jenseit, W., Merz, C., & Schüler, D. (2011). *Ökobilanz zum „Recycling von Lithium-Ionen-Batterien“ (LithoRec)*. Freiburg: Öko-Institut e.V.
- Buchert, M., Manhart, A., Bleher, D., & Pingel, D. (2011). Recycling critical raw materials from waste electronic equipment . *Öko Institute*.
- Chen, X., Fan, B., Xu, L., Zhou, T., & Kong, J. (2016). An atom-economic process for the recovery of high value-added metals from spent lithium-ion batteries. *Journal of Cleaner Production*, 112, 3562-3570.
- Costaa, C., Barbosaa, J., Gonçalves, R., Castro, H., Campo, F. D., & Lanceros-Méndez, S. (2021). Recycling and environmental issues of lithium-ion batteries: Advances, challenges and opportunities. *Energy Storage Materials*, 37, 433-465.
- Cusenza, M. A., Bobba, S., Ardente, F., Cellura, M., & Persio, F. D. (2019). Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. *Journal of Cleaner Production*, 215, 634-649.
- Cusenza, M., Guarino, F., & Longo, S. (2019). Energy and environmental benefits of circular economy strategies: The case study of reusing used batteries from electric vehicles. *The Journal of Energy Storage*.
- Fisher, K., Wallén, E., Laenen, P. P., & Collins, M. (2006). *Battery Waste Management Life Cycle Assessment* . ERM.
- Gu, F., Guo, J., Yao, X., Summers, P. A., Widijatmoko, S. D., & Hall, P. (2017). An investigation of the current status of recycling spent lithium-ion batteries from consumer electronics in China. *Journal of Cleaner Production*, 161, 765-780.

- Guimaraes, L., Botelho Junior, A., & Espinosa, D. (2022). Sulfuric acid leaching of metals from waste Li-ion batteries without using reducing agent . *Minerals Engineering* .
- Guimarães, L., Junior, A. B., & Espinosa, D. (2022). Sulfuric acid leaching of metals from waste Li-ion batteries without using reducing agent. *Minerals Engineering*, 183.
- Guinee, J. (2002). Handbook on Life Cycle Assessment. An Operational Guide to the ISO Standards. *The International Journal of Life Cycle Assessment* .
- Jadhao, P. R., Mishra, S., Singh, A., & K.K. Pant, K. N. (2023). A sustainable route for the recovery of metals from waste printed circuit boards using methanesulfonic acid. *Journal of Environmental Management*.
- Li J, S. P. (2009). A combined recovery process of metals in spent lithium-ion batteries. *Chemosphere* , 77, 1132-1136.
- Li, L., Dunn, J. B., Zhang, X. X., Gaines, L., Chen, R. J., Wu, F., & Amine, K. (2013). Recovery of metals from spent lithium-ion batteries with organic acids as leaching reagents and environmental assessment. *Journal of Power Sources*, 233, 180-189.
- Lic, J., Li, L., Yang, R., & Jiao, J. (2023). Assessment of the lifecycle carbon emission and energy consumption of lithium-ion power batteries recycling: A systematic review and meta-analysis. *Journal of Energy Storage* .
- Melin, H. E. (2019). *State-of-the-art in reuse and recycling of lithium-ion batteries – A research review*. London: Circular Energy Storage.
- Musariri, B., Akdogan, G., Dorfling, C., & Bradshaw, S. M. (2019). Evaluating organic acids as alternative leaching reagents for metal recovery from lithium ion batteries. *Minerals Engineering*, 137, 108-117.
- Nordelöf, A., Poulikidou, S., Chordia, M., & Oliveira, F. B. (2019). Methodological Approaches to End-Of-Life Modelling in Life Cycle Assessments of Lithium-Ion Batteries. *Batteries*.
- Petranikova, M., Naharro, P. L., Vieceli, N., Lombardo, G., & Ebin, B. (2022). Recovery of critical metals from EV batteries via thermal treatment and

leaching with sulphuric acid at ambient temperature. *Waste Management*, 140, 164-172.

Porvali, A., Agarwal, V., & Lundström, M. (2019). Circulation of Sodium Sulfate Solution Produced During NiMH Battery Waste Processing. *Mining, Metallurgy & Exploration*, 36, 979-991.

Raugei, M., & Winfield, P. (2019). Prospective LCA of the production and EoL recycling of a novel type of Li-ion battery for electric vehicles. *Journal of Cleaner Production*, 213, 926-932.

Romare, M., & Dahllöf, L. (2017). *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries A Study with Focus on Current Technology and Batteries for light-duty vehicles*. IVL.

Temporelli, A., Carvalho, M. L., & Girardi, P. (2020). Life Cycle Assessment of Electric Vehicle Batteries: An Overview of Recent Literature. *Electric Systems for Transportation*.

Wang, B., Lin, X.-Y., & Wang, Q. &.-Y. (2019). Recycling LiCoO₂ with methanesulfonic acid for regeneration of lithium-ion battery electrode materials. *Journal of Power Sources*.

Wang, H., & Friedrich, B. (2011). Hydrometallurgical processing of Li-Ion battery scrap from electric vehicles. Dusseldorf: 6th European Metallurgical Conference (EMC).

Wang, S., & Yu, J. (2021). A comparative life cycle assessment on lithium-ion battery: Case study on electric vehicle battery in China considering battery evolution. *Waste Management & Research*, 39(1), 156-164.

Yao, L., Fenga, Y., & Xi, G. (2015). A new method for the synthesis of LiNi_{1/3}Co_{1/3}Mn_{1/3}O₂ from waste lithium ion batteries. *RSC Advances*(55).

Zackrisson, M. (2019). *Life cycle assessment of lithium ion battery recycling - The ReLion process*. Stockholm: RISE IVF.

Zhang, P., Yokoyama, T., Itabashi, O., Suzuki, T. M., & Inoue, K. (1998). Hydrometallurgical process for recovery of metal values from spent lithium-ion secondary batteries. *Hydrometallurgy*, 47(2-3), 259-271.

Zhao, S., & You, F. (2019). Comparative Life-Cycle Assessment of Li-Ion Batteries through Process-Based and Integrated Hybrid Approaches . *ACS Sustainable Chem. Engineering*, 5082-5094.

Appendices

Appendix A: current technologies

Table 5 Aggregated inventories for HCL-Mixed NMC, HCL- Sequential and HCL- SX technologies

HCL - Mixed NMC			HCL - Sequential			HCL - SX		
Flows	Unit	Amount	Flows	Unit	Amount	Flows	Unit	Amount
Waste battery chemistries			Waste battery chemistries			Waste battery chemistries		
LiCoO2 (LCO)	kg/kWh	1.51	LiCoO2 (LCO)	kg/kWh	1.51	LiCoO2 (LCO)	kg/kWh	1.51
LiFePO4 (LFP)	kg/kWh	2.64	LiFePO4 (LFP)	kg/kWh	2.64	LiFePO4 (LFP)	kg/kWh	2.64
LiNi0.33Mn0.33Co0.33O2 (NMC111)	kg/kWh	3.14	LiNi0.33Mn0.33Co0.33O2 (NMC111)	kg/kWh	3.14	LiNi0.33Mn0.33Co0.33O2 (NMC111)	kg/kWh	3.14
Impurities	kg/kWh	0.27	Impurities	kg/kWh	0.27	Impurities	kg/kWh	0.27
Raw materials			Raw materials			Raw materials		
Hydrochloric Acid	kg/kWh	55.35	Hydrochloric Acid	kg/kWh	81.97	Hydrochloric Acid	kg/kWh	55.66
Caustic soda	kg/kWh	60.51	Caustic soda	kg/kWh	87.18	Sulphuric Acid	kg/kWh	2.81
Manganese Sulfate	kg/kWh	2.06	Potassium Permanganate	kg/kWh	3.41	Caustic soda	kg/kWh	56
Nickel Sulfate	kg/kWh	2.27	Dimethylglyoxime	kg/kWh	0.22	Potassium Permanganate	kg/kWh	3.41
Sodium Carbonate	kg/kWh	3.11	Ammonia	kg/kWh	3.5	PC-88A	kg/kWh	1.18
Energy			Energy			Energy		
Electricity Consumption	kWh/kWh	190.16	Electricity Consumption	kWh/kWh	318.98	Cobalt Chloride	kg/kWh	1.29
Cooling	kWh/kWh	77.28	Cooling	kWh/kWh	91.09	Ammonium Oxalate	kg/kWh	3.95
Heating	kWh/kWh	267.44	Heating	kWh/kWh	410.07	Sodium Carbonate	kg/kWh	2.57
Water			Water			Energy		
Process Water	kg/kWh	184.7	Process Water	kg/kWh	335.08	Electricity Consumption	kWh/kWh	207.89
Demineralised Water	kg/kWh	294.99	Demineralised Water	kg/kWh	450.14	Cooling	kWh/kWh	37.08
Waste			Waste			Water		
Solid waste (to landfill)	kg/kWh	0.9	Unleached solid waste (to landfill)	kg/kWh	1.21	Process Water	kg/kWh	342.31
Metal Hydroxide Waste (to landfill)	kg/kWh	0.74	Metal Hydroxide waste (to landfill)	kg/kWh	1.85	Demineralised Water	kg/kWh	286.46
Wastewater (municipal WWT)	kg/kWh	4.68	Wastewater (municipal WWT)	kg/kWh	12.86	Waste		
Direct emission			Direct emission			Waste		
Oxygen	kg/kWh	0.12	Oxygen	kg/kWh	0.12	Unleached solid waste (to landfill)	kg/kWh	1.25
Hydrogen Gas	kg/kWh	0.03				Metal Hydroxide waste (to landfill)	kg/kWh	1.77

Water vapor	kg/kWh	475.55	Hydrogen Gas	kg/kWh	0.03	Wastewater (municipal WWT)	kg/kWh	57.72
Avoided products			Water vapor	kg/kWh	779.06	Direct emission		
Lithium Carbonate precipitate	kg/kWh	2.17	Avoided products			Oxygen	kg/kWh	0.36
Sodium Chloride	kg/kWh	80.6	Manganese Hydroxide	kg/kWh	0.14	Hydrogen Gas	kg/kWh	0.27
Iron Phosphate	kg/kWh	2.17	Manganese Dioxide	kg/kWh	1.53	Water vapor	kg/kWh	503.2
NMC hydroxide mixture	kg/kWh	6.91	Nickel Hydroxide	kg/kWh	0.89	Avoided products		
			Cobalt Hydroxide	kg/kWh	2.28	Manganese Hydroxide	kg/kWh	0.14
			Iron Phosphate	kg/kWh	1.36	Manganese Dioxide	kg/kWh	1.53
			Sodium Chloride	kg/kWh	115.26	Nickel Hydroxide	kg/kWh	0.91
			Lithium Carbonate precipitate	kg/kWh	2.04	Cobalt Oxalate	kg/kWh	4.68
						Iron Phosphate	kg/kWh	1.36
						Salt	kg/kWh	76.38
						Lithium Carbonate precipitate	kg/kWh	1.79

Table 6 Aggregated inventories for H₂SO₄- Mixed NMC, H₂SO₄- Sequential and H₂SO₄- SX technologies

H2SO4 - Mixed NMC			H2SO4 - Sequential			H2SO4 - SX		
Flows	Unit	Amount	Flows	Unit	Amount	Flows	Unit	Amount
Waste battery chemistries			Waste battery chemistries			Waste battery chemistries		
LiCoO2 (LCO)	kg/kWh	1.51	LiCoO2 (LCO)	kg/kWh	1.51	LiCoO2 (LCO)	kg/kWh	1.51
LiFePO4 (LFP)	kg/kWh	2.64	LiFePO4 (LFP)	kg/kWh	2.64	LiFePO4 (LFP)	kg/kWh	2.64
LiNi0.33Mn0.33Co0.33O2 (NMC111)	kg/kWh	3.14	LiNi0.33Mn0.33Co0.33O2 (NMC111)	kg/kWh	3.14	LiNi0.33Mn0.33Co0.33O2 (NMC111)	kg/kWh	3.14
Impurities	kg/kWh	0.27	Impurities	kg/kWh	0.27	Impurities	kg/kWh	0.27
Raw materials			Raw materials			Raw materials		
Sulphuric Acid	kg/kWh	37.32	Sulphuric Acid	kg/kWh	37.32	Sulphuric Acid	kg/kWh	61.66
Hydrogen peroxide	kg/kWh	21.89	Hydrogen peroxide	kg/kWh	21.89	Hydrogen peroxide	kg/kWh	21.89
Caustic soda	kg/kWh	30.39	Caustic soda	kg/kWh	26.06	Caustic soda	kg/kWh	25.2
Manganese Sulfate	kg/kWh	2.2	Potassium Permanganate	kg/kWh	1.99	Potassium Permanganate	kg/kWh	1.99
Nickel Sulfate	kg/kWh	2.29	Dimethylglyoxime	kg/kWh	0.23	Cyanex 272	kg/kWh	0.8
Sodium Carbonate	kg/kWh	2.98	Hydrochloric acid	kg/kWh	0.72	Kerosene/Dodecane	kg/kWh	2.59
Energy			Ammonium Oxalate	kg/kWh	3.36	Ammonium Oxalate	kg/kWh	0
Electricity Consumption	kWh /kWh	131.03	Sodium Carbonate	kg/kWh	2.98	Sodium Carbonate	kg/kWh	2.98
Cooling	kWh /kWh	60.87	Energy			Energy		
Heating	kWh /kWh	191.89	Electricity Consumption	kWh /kWh	205.76	Electricity Consumption	kWh /kWh	539.52
Water			Cooling			Cooling	kWh /kWh	63.41
Process Water	kg/kWh	270.88	Heating	kWh /kWh	276.53	Heating	kWh /kWh	468.05
Demineralised Water	kg/kWh	146.27	Water			Water		
Waste			Process Water	kg/kWh	469.84	Process Water	kg/kWh	615.45
Solid waste (to landfill)	kg/kWh	0.43	Demineralised water	kg/kWh	134.01	Demineralised Water	kg/kWh	132.47
Metal Hydroxide Waste (to landfill)	kg/kWh	1.03	Waste			Waste		
Wastewater (municipal WWT)	kg/kWh	31.48	Unleached solid waste (to landfill)	kg/kWh	1.02	Unleached solid waste (to landfill)	kg/kWh	1
Direct emission			Metal Hydroxide Waste (to landfill)	kg/kWh	1	Metal Hydroxide Waste (to landfill)	kg/kWh	1
Oxygen	kg/kWh	10.3	Wastewater (municipal WWT)	kg/kWh	47.83	Wastewater (municipal WWT)	kg/kWh	80.62
Water vapor	kg/kWh	421.67	Direct emission			Direct emission		
Avoided products			Oxygen	kg/kWh	10.41	Oxygen	kg/kWh	10.45
Lithium Carbonate precipitate	kg/kWh	2.08	Water vapor	kg/kWh	596.73	Water vapor	kg/kWh	726.57
Iron phosphate precipitate	kg/kWh	2.49	Carbon dioxide	kg/kWh	0.21	Avoided products		
Sodium sulphate	kg/kWh	48.94	Avoided products			Manganese hydroxide	kg/kWh	0.09
NMC hydroxide mixture	kg/kWh	6.80	Manganese hydroxide	kg/kWh	0.09	Manganese Dioxide	kg/kWh	1.34

Manganese dioxide	kg/kWh	1.34	Nickel Hydroxide	kg/kWh	0.91
Nickel Hydroxide	kg/kWh	0.89	Cobalt Sulfate	kg/kWh	3.73
Cobalt Oxalate	kg/kWh	3.61	Iron phosphate precipitate	kg/kWh	2.49
Iron phosphate precipitate	kg/kWh	2.49	Sodium sulfate	kg/kWh	39.21
Sodium sulphate	kg/kWh	38.13	Lithium carbonate	kg/kWh	2.08
Lithium Carbonate	kg/kWh	2.08			

Table 7 Aggregated inventories for Citric – Mixed NMC, Citric – Sequential and Citric – SX technologies

Citric - Mixed NMC			Citric - Sequential			Citric - SX		
Flows	Unit	Amount	Flows	Unit	Amount	Flows	Unit	Amount
Waste battery chemistries			Waste battery chemistries			Waste battery chemistries		
LiCoO2 (LCO)	kg/kWh	1.51	LiCoO2 (LCO)	kg/kWh	1.51	LiCoO2 (LCO)	kg/kWh	1.51
LiFePO4 (LFP)	kg/kWh	2.64	LiFePO4 (LFP)	kg/kWh	2.64	LiFePO4 (LFP)	kg/kWh	2.64
LiNi0.33Mn0.33Co0.33O2 (NMC111)	kg/kWh	3.14	LiNi0.33Mn0.33Co0.33O2 (NMC111)	kg/kWh	3.14	LiNi0.33Mn0.33Co0.33O2 (NMC111)	kg/kWh	3.14
Impurities	kg/kWh	0.27	Impurities	kg/kWh	0.27	Impurities	kg/kWh	0.27
Raw materials			Raw materials			Raw materials		
Citric acid	kg/kWh	36.53	Citric acid	kg/kWh	37.11	Citric acid	kg/kWh	36.53
Hydrogen peroxide	kg/kWh	32.88	Hydrogen peroxide	kg/kWh	32.88	Hydrogen peroxide	kg/kWh	32.88
Caustic soda	kg/kWh	19.29	Caustic soda	kg/kWh	18.91	Caustic soda	kg/kWh	21.37
Magnesium Sulfate salt	kg/kWh	2.3	Potassium Permanganate	kg/kWh	3.36	Dimethylglyoxime	kg/kWh	0.24
Nickel sulfate salt	kg/kWh	2.34	Dimethylglyoxime	kg/kWh	0.24	Hydrochloric acid	kg/kWh	0.77
Monosodium phosphate	kg/kWh	8.54	Hydrochloric acid	kg/kWh	0.76	Sulphuric acid	kg/kWh	3.99
Energy			Oxalic acid	kg/kWh	2.7	Oxalic acid	kg/kWh	0
Electricity Consumption	kWh /kWh	97.36	Phosphoric acid	kg/kWh	2.03	Ammonium oxalate	kg/kWh	3.85
Water			Energy			Phosphoric acid	kg/kWh	1.99
Process Water	kg/kWh	209.66	Electricity Consumption	kWh /kWh	144.12	Sodium carbonate	kg/kWh	8.2
Demineralised water	kg/kWh	104.66	Cooling	kWh /kWh	104.19	Sodium Di-(2ethyl)phosphoric acid	kg/kWh	1.58
Waste			Heating	kWh /kWh	248.31	Kerosene/Dodecane	kg/kWh	4.62
Solid waste (to landfill)	kg/kWh	0.66	Water			Tributyl Phosphate	kg/kWh	0.4
Wastewater (municipal WWT)	kg/kWh	76.52	Process Water	kg/kWh	335.31	Energy		
Direct emission			Demineralised Water	kg/kWh	103.9	Electricity Consumption	kWh /kWh	265.07
Oxygen	kg/kWh	15.71	Waste			Water		
Water vapor	kg/kWh	316.77	Solid waste (to landfill)	kg/kWh	1.1	Process Water	kg/kWh	539.55
Carbon Dioxide	kg/kWh	0.01	Wastewater (municipal WWT)	kg/kWh	79.02	Demineralised Water	kg/kWh	108.81
Avoided products			Direct emission			Waste		

Lithium Phosphate precipitate	kg/kWh	2.35	Oxygen	kg/kWh	15.71	Solid waste (to landfill)	kg/kWh	0.79
NMC phosphate mixture	kg/kWh	9.19	Water vapor	kg/kWh	436.01	Wastewater (municipal WWT)	kg/kWh	173.64
Iron phosphate precipitate	kg/kWh	2.43	Carbon dioxide	kg/kWh	1.13	Direct emission		
Avoided products						Oxygen	kg/kWh	15.71
Manganese Dioxide				kg/kWh	2.15	Water vapor	kg/kWh	555.94
Nickel Hydroxide				kg/kWh	0.95	Nitrogen gas	kg/kWh	0.07
Cobalt oxalate				kg/kWh	3.68	Carbon dioxide	kg/kWh	1.73
Lithium Phosphate precipitate						Avoided products		
Iron phosphate precipitate				kg/kWh	2.43	Manganese Hydroxide	kg/kWh	0.91
						Nickel Hydroxide	kg/kWh	0.95
						Cobalt oxalate	kg/kWh	3.69
						Lithium Phosphate precipitate	kg/kWh	2.35

Appendix B: novel technologies

Table 8 Aggregated inventories for H2SO4 – Novel and MSA – Novel Technologies Citric – Sequential and Citric – SX technologies

H2SO4 - Novel			MSA - Novel		
Flows	Unit	Amount	Flows	Unit	Amount
Black mass (total)	kg	82	Black mass (total)	kg	82
Raw materials			Raw materials		
Sulphuric Acid	kg	107	Methanesulfonic acid	kg	157
Hydrogen peroxide	kg	46	Sulphuric Acid	kg	27
Caustic soda	kg	265	Hydrogen peroxide	kg	28
Potassium Permanganate	kg	13	Caustic soda	kg	265
Persulphate	kg	142	Potassium Permanganate	kg	13
Sodium Carbonate	kg	19	Persulphate	kg	142
Ion exchange resin (Dowex M4195)	kg	10	Sodium Carbonate	kg	19
Energy			Ion exchange resin (Dowex M4195)	kg	10
Electricity Consumption	kWh	352	Sodium sulphate	kg	116
Water			Energy		
Process Water	kg	1 294	Electricity Consumption	kWh	858
Demineralised Water	kg	2 612	Heat Loss	kWh	240
Waste			Water		
Solid waste (to landfill)	kg	43	Process Water	kg	1 294
Metal Hydroxide Waste (to landfill)	kg	7	Demineralised Water	kg	3 606
Ion exchange resin (Dowex M4195)	kg	10	Waste		
Wastewater (municipal WWT)	kg	3001	Solid waste (to landfill)	kg	35
Direct emission			Metal Hydroxide Waste (to landfill)	kg	7
Water vapor	kg	6	Wastewater (municipal WWT)	kg/kWh	5 094
Avoided products			Ion exchange resin (Dowex M4195)	kg/kWh	19
Manganese Dioxide	kg	11	Direct emission		
Nickel Hydroxide	kg	2	Water vapor	kg/kWh	6
Cobalt Tetraoxide	kg	19	Avoided products		
Lithium Carbonate precipitate	kg	13	Manganese Dioxide	kg/kWh	11

Nickel Hydroxide	kg/kWh	2
Cobalt Tetraoxide	kg/kWh	19
Lithium Carbonate precipitate	kg/kWh	13



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This report has been reviewed and approved in accordance with IVL's audit and approval management system.