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Research Institute

Full LCA report of selected process technologies for the South African and European contexts

ELiMINATE project deliverables of work package 2:
- 2B.1 – Scope and inventory analysis
- 2B.2 – Impact assessment and interpretation of findings
- 2B.3 – Adaptation of LCA for South African Context

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Summary

This report is the final deliverable for the ongoing Era-MIN project ELIMINATE work package 2 (WP2B): Full LCA. Initially, nine current and two novel hydrometallurgical LIB recycling technologies were proposed and subjected to a screening LCA study in the previous part of WP2 (WP2A, Screening LCA). The results of the screening LCA was reported in the first deliverable (Techno-environmental Screening of Hydrometallurgical Techniques for Li-ion Battery Recycling). The outcomes of the screening showed that H_2SO_4- Mixed NMC and H_2SO_4 – Novel technologies are demonstrating the best environmental performance within their respective current and novel technology categories.

In this report, the main purpose was to conduct full LCA studies for above mentioned technologies. Accordingly, a comparative analysis was done to compare the environmental impacts of two selected technologies in European Union and South African contexts. The life cycle inventory (LCI) for the current and novel technologies generated based on laboratory and pilot plant tests at different times, utilizing different battery waste material compositions. That is why, before starting to make full LCAs, LCI data for current technology have been updated to align with novel technology experiment`s waste material composition. Secondly, different LCA studies have been completed for the EU and SA regions by using regional electricity mixesand further details can be found in the report.

Full LCA studies (four in total) conducted, and five impact categories selected to evaluate the environmental impacts. According to the findings of the full LCA studies conducted for current and novel technologies, it has been found that the current technology presents slightly better environmental performance than the novel technology in each EU and SA context from the following impact categories which are Abiotic depletion (ADP elements), Acidification potential (AP), Eutrophication Potential (EP), Global warming potential excluding biogenic carbon (GWP), Ozone layer depletion Potential (ODP) covered by CML 2001 methodology. Geographically, the EU showcased better environmental performance owing to electricity being the primary source of adverse impact in SA.

In summary, the environmental impact difference between current and novel technologies is insignificant, with current technology slightly outperforming novel one. Additionally, the geographical analysis underscores the EU as presenting a more favorable environmental performance for hydrometallurgical LIB battery recycling technologies.

Abbreviation	Phrase and/or Definition
ADP	Abiotic Depletion Potential
AP	Acidification Potential
EP	Eutrophication Potential
EoL	End of Life
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LIB	Lithium-ion Battery
MSA	Methane Sulfonic Acid
ODP	Ozone Layer Depletion Potential
SDC	Solvent Dependent Crystallization
WP	Work Package

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1 Introduction

1.1 About this report

This report is named as “LCA report of selected process technologies for the South African and European contexts” and prepared for the ongoing ERA-MIN ELiMINATE project, WP2. The LCA studies are conducted by IVL Swedish Environmental Research Institute on behalf of ELiMINATE research project. The studied products are two different hydrometallurgical LIBs recycling technology named as current (H_2SO_4 NMC – Mixed) and novel (H_2SO_4 – Novel) technologies, will be explained in the following parts. The “current” technology refers to an available technology implied in this project (already in the literature), while the “novel” phrasing highlights a novel method developed by project partners Karadeniz Technical University (KTU) and Exitcom Recycling during this project.

The previous deliverable of the ELIMINATE project WP2 was focused on the "Techno-environmental Screening of Hydrometallurgical Techniques for Li-ion Battery Recycling". This assessment successfully identified the most environmentally favorable methods by employing screening LCA methodology for two categories: current and novel technologies. Among the current technologies, the H_2SO_4-NMC Mixed recycling process emerged as the preferred option due to its positive environmental performance. Similarly, within the novel technologies category, the H_2SO_4-Novel recycling process was chosen as the most promising option. However, the previous study did not directly compare the current and novel technologies with each other, leaving an important aspect of the evaluation unaddressed. Consequently, the current phase of the project aims to compare the full LCAs of the selected current (H_2SO_4 – NMC Mixed) and novel technologies (H_2SO_4 – Novel) with each other. In addition, as part of the project, EU and SA contexts will be investigated to understand the geographical impacts on the LIB recycling technologies.

The LCI for the current technologies generated based on literature and process modelling done by Stellenbosch University. The generation of LCI is explained in the detail in the screening deliverable mentioned above and for the results of the full LCA the thesis can be consulted. The LCI for the novel technologies generated based on experiments conducted at Karadeniz Technical University (KTU) for developing the technologies and process modelling completed by Stellenbosch University. However, the feed composition of the waste batteries for the current and novel technologies were different so it was impossible to compare the results of the full LCAs. To ensure a fair and accurate comparison between the current and novel technologies, Stellenbosch University partners made feed composition adjustments in their process model of environmentally best performing current technology. These adjustments were made to align the feed compositions for both technologies, effectively standardizing the input data. As a result, the LCI data for the current technologies was updated to match the conditions of the novel technologies. Subsequently, in this study, the LCA study for the current technology was updated using the new LCI data. At the end, regarding the novel technology (H_2SO_4 – Novel), a new full LCA was developed from scratch and is presented in this study.

In addition, EU and SA contexts are also compared by changing values and doing a new LCA study for the technologies. To adopt the SA region, only electricity mix data have been updated from EU to SA, the reason for this update have been explained in the Chapter 1.6 detailly.

After conducting the separate LCA studies for the current and the novel technologies, the results were compared based on their respective environmental impacts.

1.2 Goal

The goal of conducting these full LCA studies for selected End-of-Life (EOL) LIB recycling technologies is to identify the most environmentally favorable hydrometallurgical process for LIB recycling. This evaluation is achieved by comparing the environmental performance of one current (H_2SO_4 – Mixed NMC) recycling technology with one novel (H_2SO_4 – Novel) technology which they were selected as the best within their categories in the previous “Screening LCA of Current and Novel Technologies” deliverable.

By doing so, the aim is to determine which option offers superior environmental benefits. While searching for the superior option, EU and SA contexts will be examined..

The outcome of this study intended to use in the ongoing ELiMINATE project while fulfilling the project purposes in the relevant work packages.

1.3 Scope and studied product systems

The studied products in this report are the hydrometallurgical LIB recycling technologies proposed under the ELIMINATE project. The production process of two battery recycling technologies is explained for both recycling methods. The proposed flowsheets are presented in the Appendix A.

Current Technology: 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 Na2CO3 is also used to precipitate lithium from the leach solution.

Novel Technology: A mixture of LCO, LFP, LMO and NMC111 batteries was subjected to leaching using a 1 M solution of sulfuric acid and 30% vol H_2O_2 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.

1.4 Type of study

The LCA performed is a comparative LCA, with a focus on two different LIB recycling processes. This comparative study is an attributional LCA where it estimates the environmental impact that belongs to the studied system.

1.5 Functional unit

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 in both EU and SA context.

1.6 System boundaries

In this section the applied system boundaries of the LCAs are specified. Aspects such as boundaries towards nature and geographical boundaries, as well as methodological aspects concerning system expansion and allocation are defined and explained.

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 where the waste lithium-ion batteries (LIBs) are assumed to enter the system without additional burdens, as any burdens incurred during their production are attributed solely 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 European Union and South Africa. Where possible, datasets prepared for Europe and South Africa were used.

The system boundaries for both current and novel technologies are illustrated in Figure 1 and Figure 2, respectively.

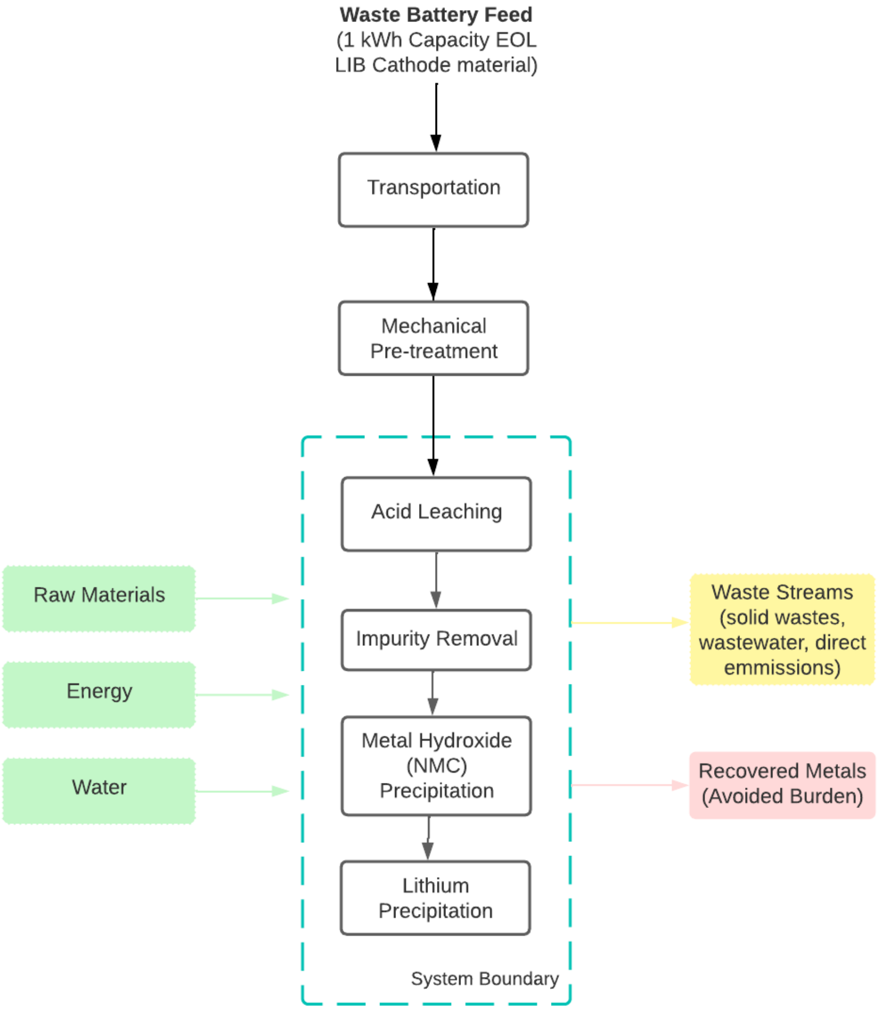

Figure 1. System boundary for current technology LCA study (EU and SA contexts)

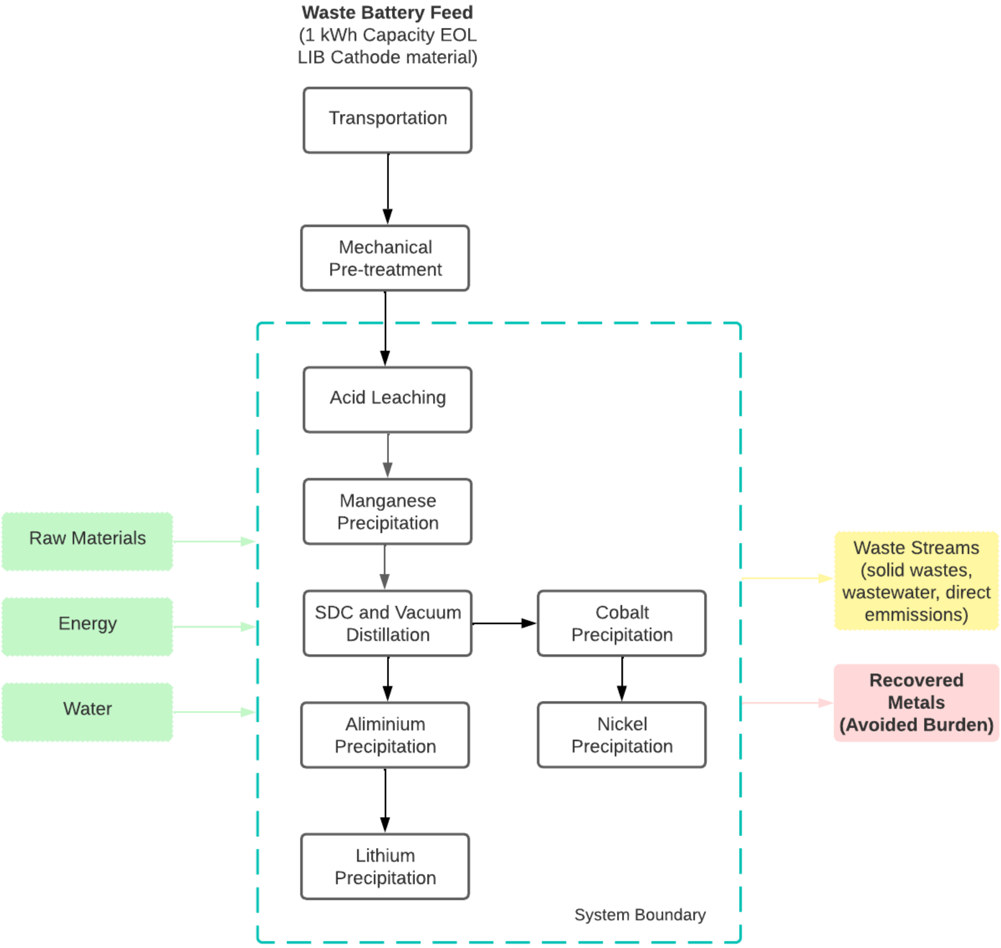

Figure 2. System boundary for novel technology LCA study (EU and SA contexts)

The LCA study highlights certain processes that were included and excluded, detailed in Table 1, showing the scope of the analysis for both current and novel technologies.

Table 1. Summary of processes included in or excluded from the LCA studies.

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

In this study, allocation is not applied since avoided burden approach is more suitable for this case which results with a net environmental gain in all impact categories. 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.

Geographical scope: EU and SA

The ELIMINATE project aims to understand the potential of establishing an EoL LIB recycling plant in the EU and South Africa. This investigation centers on understanding the regional variations in potential environmental impacts, offering insights into the pros and cons of investing in such a battery recycling facility.

Initially, LCAs were conducted solely for the EU region, utilizing data exclusively sourced from the Europe in the LCA software. However, extending this analysis to South Africa required a preliminary study to identify reliable data sources, as some datasets lacked credibility due to insufficient information in South Africa. Consequently, Stellenbosch University partners conducted a preliminary study to evaluate the implications of transitioning data sources from the EU to SA.

This research study delved into assessing differences in energy generation and chemical production, particularly focusing on chemicals like sulphuric acid, and sodium hydroxide. Findings indicated that South African processes were less environmentally friendly than European ones, with differences reaching around 40% in current (H_2SO_4 – Mixed NMC) precipitation process. Primarily, these differences caused from contrasting electricity generation sources. Countries in Europe heavily relies on nuclear energy, sustainable energy sources like wind and hydro power, with occasional fossil fuel use, predominantly natural gas. In contrast, nearly 90% of South Africa's energy grid relies on hard coal consumption (Sphera, 2022a)

In summary, while investigating the South African context, it became evident that any potential process differences were largely outweighed by disparities in energy sources between South Africa and Europe. Thus, variations in raw materials and water did not significantly alter the results. Consequently, during the LCA study of South Africa for current and novel technology, only electricity data were modified.

1.7 Methodology choices

The LCA has to a large extent been aligned with the general and common rules according to the requirements of ISO 14044:2006. CML 2001 methodology (Guinee, 2002) version August 2016 is chosen to calculate life cycle impact assessment (LCIA) results.

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

1.8 Selected impact categories

Characterization results for five midpoint impact categories covered by CML 2001 methodology are calculated which are Abiotic depletion (ADP elements), Acidification potential (AP), Eutrophication Potential (EP), Global warming potential excluding biogenic carbon (GWP) and Ozone layer depletion Potential (ODP) and the units are presented in Table 2. The hydrometallurgical recycling methods used in metal recycling have a significant influence across all impact categories in LCA study. These impacts arise from the primary drawbacks associated with this technique, including chemical consumption and generation of waste that necessitates reprocessing. In this study, to highlight differences between current and novel technologies, five categories primarily associated with chemical and electricity consumption and waste generation have been chosen.

Normalization and weighting are two optional steps in an LCA according to the 14040-14044 standards and were not applied in this study since only two options were compared and it is possible to compare the options without normalization and weighting.

Table 2. The selected environmental impact categories.

Impact Categories	Unit
Abiotic Depletion, ADP elements, ADPE	kg Sb Equivalent
Acidification Potential AP	kg SO2 Equivalent
Eutrophication Potential EP	kg Phosphate Equivalent
Global Warming Pot. (Excluding biogenic carbon)	kg CO2 Equivalent
Ozone Depletion Pot. ODP steady state	kg R11 Equivalent

1.9 Review procedure

This study and report have been internally reviewed and approved in accordance with IVL's audited and approved management system. No third-party review has been performed.

1.10 Life Cycle Inventories

The previous deliverable utilized an LCI for the current H_2SO_4 – Mixed NMC technology, yet differences that might affect the comparison arose as the process feed amount and composition values did not align with the LCI data for the novel technology. To create a fair comparison, Stellenbosch University updated the current technology's LCI data by redoing the process simulations and mass balances for current technology on HSC software.

Table 3 presents both the initial dataset and the updated values for the current (H_2SO_4 – Mixed NMC) technology, alongside the LCI data for the novel technology. Notably, the total feed rate of cathode material in both technologies are equal. This alignment ensures a more accurate comparison between the environmental impacts of these technologies.

Table 3. LCI data for current and novel technologies

H_2SO_4 - Mixed NMC LCI Data				**H_2SO_4 - Novel LCI Data**		
Flows	**Initial Values**	**Updated Values**	**Unit**	**Flows**	**Values**	**Unit**
Cathode Material (Chemistry)	8.26	82	kg	**Cathode Material (Chemistry)**	81.79	kg
LiCoO2 (LCO)	1.51	27,68	kg	LiCoO2 (LCO)	27,68	kg
LiFePO4 (LFP)	2.64	0,65	kg	LiFePO4 (LFP)	0,65	kg
LiNi0.33Mn0.33Co0.33O2 (NMC111)	3.14	8,65	kg	LiNi0.33Mn0.33Co0.33O2 (NMC111)	8,65	kg
LMO	0	7,41	kg	LMO	7,41	kg
Impurities	0.27	37,40	kg	Impurities	37,40	kg
Raw materials				**Raw Materials**		
Sulphuric Acid	37	80	kg	Sulphuric Acid	107	kg
Hydrogen peroxide	22	46	kg	Hydrogen peroxide	46	kg
Caustic soda	30	96	kg	Caustic soda	265	kg
Manganese Sulfate	2	23	kg	Potassium Permanganate	13	kg
Nickel Sulfate	2	36	kg	Persulphate	142	kg
Sodium Carbonate	3	10	kg	Sodium Carbonate	19	kg
Energy				Ion exchange resin (Dowex M4195)	10	kg
Electricity Consumption	131	392	kWh	**Energy**		
Cooling	61	190	kW	Electricity Consumption	352	kWh
Heating	192	583	kW	**Water**		
Water				Process Water	1 294	kg
Process Water	271	872	kg	Demineralised Water	2 612	kg
Demineralised Water	146	230	kg	**Waste**		
Waste				Solid waste (to landfill)	43	kg

Solid waste (to landfill)	0	47	kg	Metal Hydroxide Waste (to landfill)	7	kg
Metal Hydroxide Waste (to landfill)	1	1	kg	Ion exchange resin (Dowex M4195)	10	kg
Wastewater (municipal WWT)	31	154	kg	Wastewater (municipal WWT)	3 001	kg
Direct emission				**Direct emmission**		
Oxygen	10	9	kg	Water vapor	6	
Water vapor	422	1 128	kg	**Avoided products**		
Avoided products				Manganese Dioxide	11	kg
Lithium Carbonate precipitate	2	7	kg	Nickel Hydroxide	2	kg
Iron phosphate precipitate	2	0	kg	Cobalt Tetraoxide	19	kg
Sodium sulphate	49	110	kg	Lithium Carbonate precipitate	13	kg
NMC hydroxide mixture	7	71	kg			

2 Results and discussions

In this chapter, the results of the full LCA studies are presented that comparing the current and novel technologies within the context of Europe and SA.

Firstly, in section 2.1, the total environmental impact results of proposed technologies (current and novel) are presented for five selected environmental impact categories. Subsequently, in section 2.2, the contribution analysis results are presented for both technologies by separating the geographical boundaries.

2.1 LCIA results

Following Table 4 contains the total environmental impact results derived from the LCA studies for the current and innovative technologies within the EU and SA contexts. In the results of these LCA studies, negative values present an environmental benefit, whereas positive values indicate a negative impact on the environment..

Table 4. Total LCIA results for current and novel technologies based on the impact categories.

Impact Categories	Unit	Novel Technology (EU)	Novel Technology (SA)	Current Technology (EU)	Current Technology (SA)
Abiotic Depletion Potential (ADP) of Elements	kg Sb eq/kg	-2.90E-03	-2.90E-03	-4.06E-03	-4.05E-03
Acidification Potential (AP)	kg SO2 eq.	-1.36E+00	-1.35E+00	-1.61E+00	-1.60E+00
Eutrophication Potential (EP)	kg Phosphate eq.	-1.10E-01	-1.07E-01	-1.38E-01	-1.31E-01
Climate Change (GWP)	kg CO_2 eq.	-1.11E+01	-5.74E+00	-4.59E+01	-3.41E+01
Ozone Layer Depletion (ODP)	kg R11 eq.	-9.78E-06	-9.78E-06	-1.23E-05	-1.23E-05

For enhanced visual comprehension and comparability, all results have been normalized and standardized relative to the value of Novel Technology (EU) and are demonstrated in Table 5. The table also employs conditional formatting, utilizing percentages above or below 100% relative to the Novel Technology (EU) values. Some of the results are highlighted in green, signifying better environmental performance, while less favorable results are in red, denoting a lower environmental benefit relative to the Novel Technology (EU).

Table 5. Normalized total LCIA results for current and novel technologies based on the impact categories.

Impact Categories	Novel Technology (EU)	Novel Technology (SA)	Current Technology (EU)	Current Technology (SA)
Abiotic Depletion Potential (ADP) of Elements	-100%	-100%	-140%	-139%
Acidification Potential (AP)	-100%	-99%	-119%	-118%
Eutrophication Potential (EP)	-100%	-97%	-126%	-120%
Climate Change (GWP)	-100%	-52%	-415%	-308%
Ozone Layer Depletion (ODP)	-100%	-100%	-126%	-126%

Based on these results, it is clearly visible that current technology is presenting a better environmental gain when it compares with the novel one. In addition, EU presents a better environmental gain when it compares with SA.

To enhance the representation of these findings and emphasize the most significant differences between the technologies across impact categories, the following Figure 3 has been prepared based on the data from Table 5.

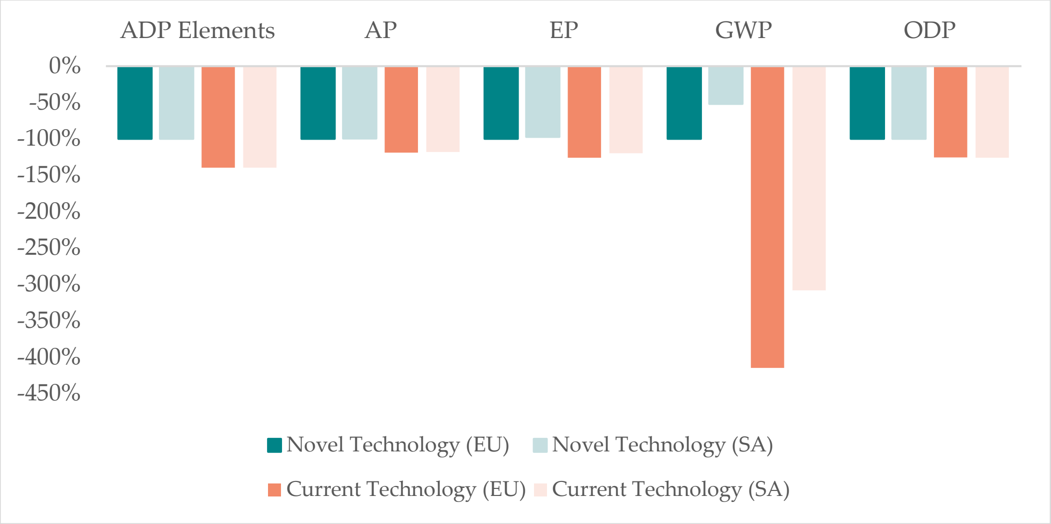

Figure 3. Visual presentation of impact category results normalized to novel technology in EU

All results on the bar chart fall along the negative y-axis, indicating that the contribution to the impact categories from the current and novel processes (electricity, chemicals etc.) is lower than the avoided burden attributed to metal recovery. The current technology consistently demonstrates a superior environmental impact across all impact categories, with particularly notable differences in GWP results. Likewise, the EU consistently exhibits superior outcomes compared to SA across all categories, with the most significant disparity evident in GWP results.

2.2 Contribution analysis

The primary objective of contribution analysis is to determine the impacts of various processes across various environmental categories, identifying the crucial components contributing to environmental outcomes. A fundamental understanding of processes with superior or inferior impacts is valuable for further investigation. In this study, contribution analysis compared the environmental impacts of current and novel technologies within five impact categories separately for EU and SA contexts.

The analysis aimed to identify the most environmentally impactful processes in the flowsheets for recycling EoL LIBs using proposed technologies. In order to achieve a fair comparison, the processes for novel and current technologies are classified similarly and presented in Table 6.

Table 6. Process categorization for novel and current technologies

Novel Technology – Processes	Current Technology – Processes
Electricity Consumption	Electricity Consumption
Waste streams	Waste streams
Chemical Consumption	Chemical Consumption
Water Consumption	Water Consumption
Lithium (Li_2CO_3) Recovery	Lithium (Li_2CO_3) Recovery
Manganese ($Mn(OH)_2$) Recovery	Manganese ($Mn(OH)_2$) Recovery
Nickel ($Ni(OH)_2$) Recovery	Nickel ($Ni(OH)_2$) Recovery
Cobalt ($Co(OH)_2$) Recovery	Cobalt ($Co(OH)_2$) Recovery
	Sodium Sulphate (Na_2SO_4) Recovery
	$FePO_4$ Recovery

The comparison highlights that while novel technology presents a decreased number of processes, the current technology demonstrates a shorter flowsheet, evident in Appendix A. The rationale behind this inconsistency lies in the fact that the current technology consolidates the recovery of manganese, nickel, and cobalt into a single product named as metal hydroxide (NMC Mixed) in a single process. However, for the purpose of a similar contribution analysis and comparison, the environmental impacts of each metal are individually assessed in the current technology case. This method enables a more precise comparison with the novel technology, facilitating a clearer comprehension of the environmental implications associated with each metal within the current technology's framework.

The EU and SA specific LCA results will be presented under each impact category session, offering insights into different processes and their impacts in the processes. Given the similarity between the EU and SA contexts except for the electricity factor, some comments might be more concise in the SA context. Negative values in the contribution analysis graphs present an environmental gain, whereas positive values indicate a negative impact on the environment.

2.2.1 Abiotic Depletion Potential (ADP) elements

European Union Context

Abiotic Depletion Potential (ADP) elements results of current and novel technologies has been compared in Figure 4, revealing that, for the current technology, the most substantial environmental gains result from the recovery of sodium sulfate, cobalt, and nickel. Conversely, the most pronounced negative impacts are associated with chemical consumption. For the novel technology, the environmental gains are largely attributed to the cobalt and nickel recovery processes. Similar to the current technology, the negative environmental impacts predominantly arise from chemical consumption rates.

Notably, when comparing with the novel technology in the EU context, the current technology demonstrates significantly higher environmental impacts. Both current and novel technologies employ the same leaching agent, H_2SO_4. However, the divergence in environmental impacts between them is primarily due to additional factors beyond the shared leaching agent. This distinction highlights that while the core leaching process remains consistent, other elements or processes unique to each technology significantly influence their respective environmental footprints.

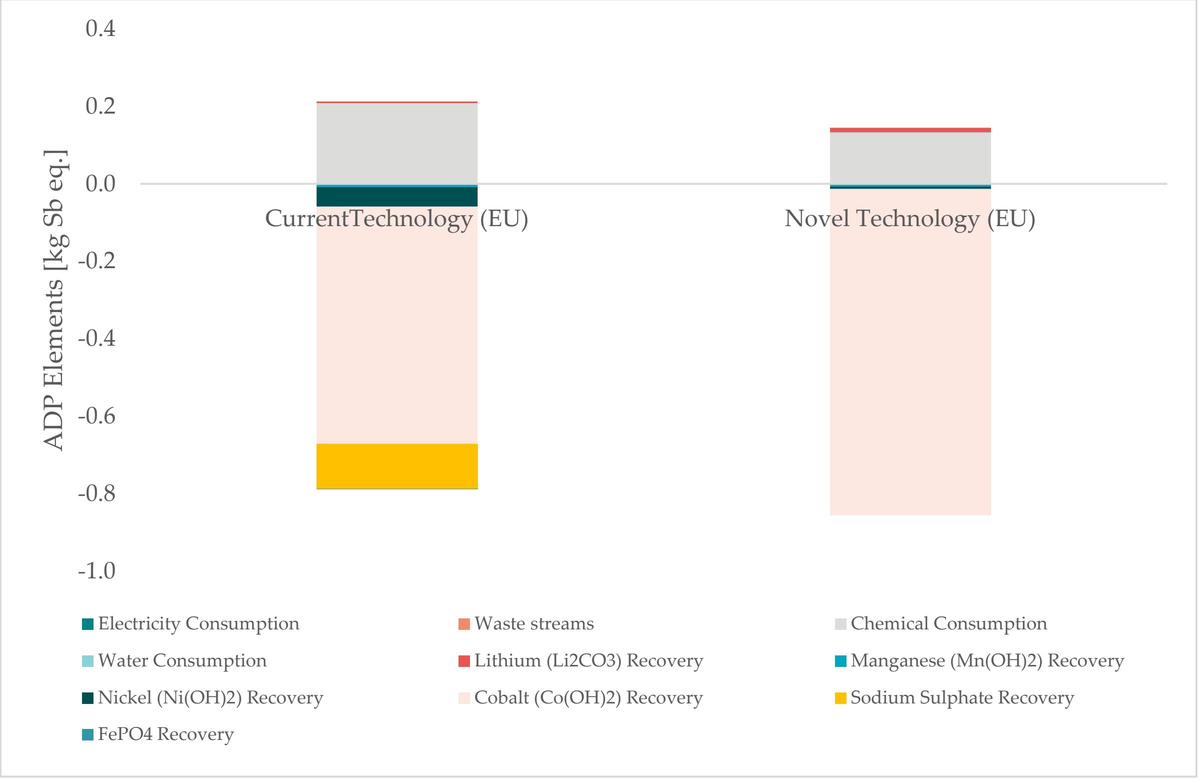

Figure 4. Comparison of ADP results of current and novel technologies in EU context

Despite the lower total chemical consumption rates in the current technology, the negative impact is notably higher compared to the novel technology. This disparity can be attributed to the consumption of manganese and nickel sulfates in the current technology. Sulfates, which contain sulfur as a critical component, contribute to the negative impact, particularly within the Abiotic Depletion Potential (ADP) category due to the associated depletion potential linked to sulfur extraction and utilization. This significance is further supported by sulfur's inclusion among the top 20 elements contributing to the global abiotic depletion of elements in 2015, underscoring the importance of sulfur consumption in influencing the global ADP of elements (van Oers, et al., 2020).

South Africa Context

Abiotic Depletion Potential (ADP) elements of current and novel technologies for SA region have been compared in Figure 5. Comparing the environmental impacts of current and novel technologies in the SA context reveals a similarity to the EU context. This similarity is noticeable because, while analyzing the ADP value in SA context, the only update made was to the electricity value. The rationale behind the consistent findings across both regions (EU and SA) could be the nature of the changes made to electricity. If the adjustments in electricity involve shifting between energy sources with comparable abiotic depletion potentials (ADPs), it's plausible that the overall impact on ADP remains relatively unchanged across different regional contexts.

That is why, the previous explanations provided for the EU region are applicable and sufficient to understand this section.

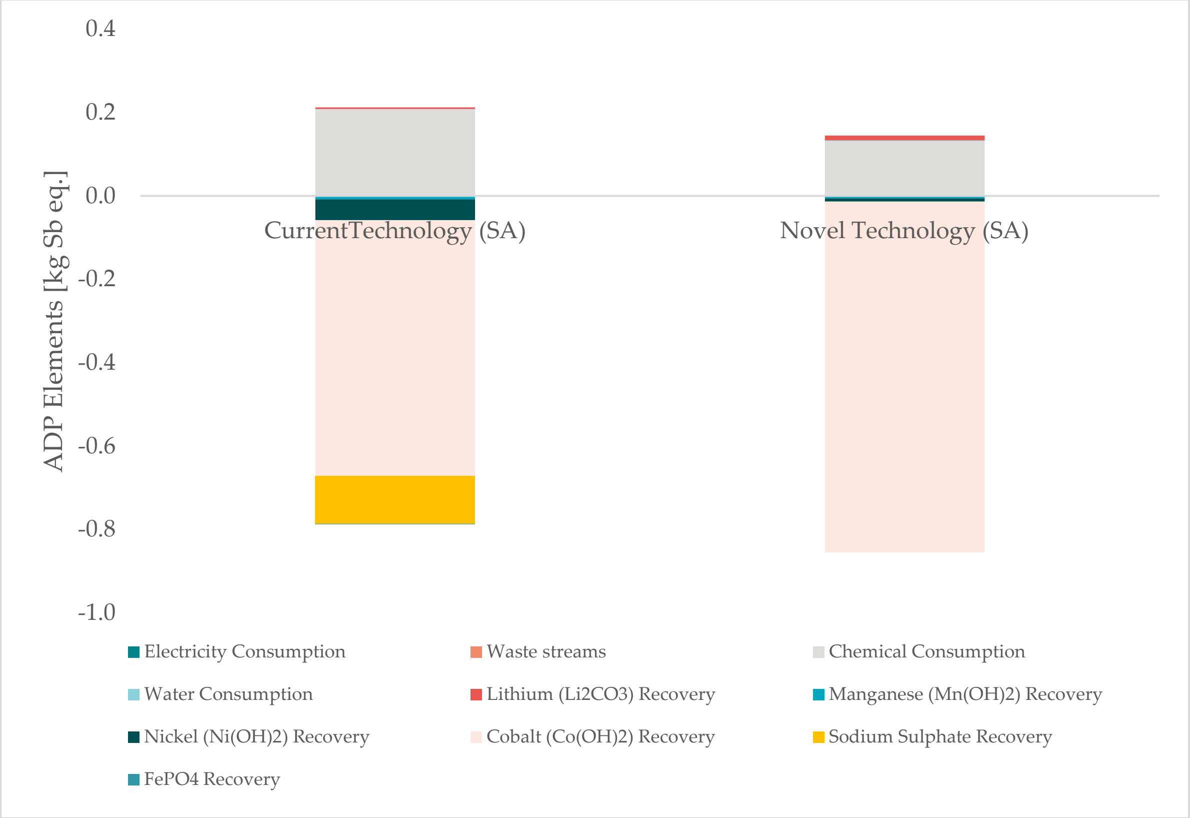

Figure 5. Comparison of ADP results (SA context)

2.2.2 Acidification Potential (AP)

European Union

Acidification potential (AP) results of the categorized processes for both current and novel technologies are presented in the following Figure 6. These results reveal that current technologies exhibit environmental gains from metal recovery, with nickel and cobalt having the most significant impacts. Conversely, the most adverse environmental impacts stem from chemical consumption. In the case of the novel technology, cobalt recovery, lithium recovery, electricity consumption, and manganese recovery contribute most to environmental gains, while negative impacts persist due to chemical consumption.

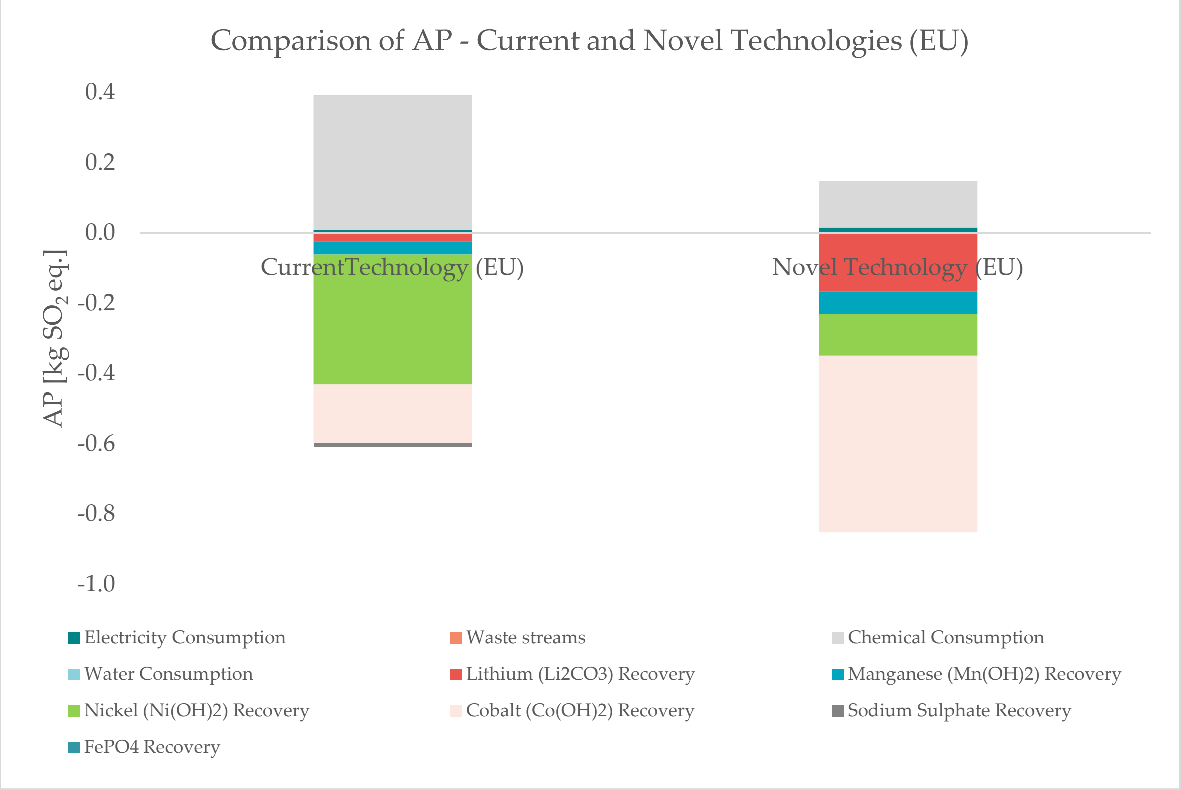

Figure 6. Comparison of AP results (EU context)

In the context of metal recovery, all the results are negative, all results exhibit negativity, signifying that metal recovery processes contribute positively to the deacidification of the environment. This is attributed to the benefits of avoiding the burden associated with primary metal production, which outweighs the environmental impacts of recycling these metals. The novel technology significantly outperforms the current technology in the total environmental gain derived from metal recovery. This superior performance can be attributed to the more impactful recoveries of cobalt, lithium, and manganese within the novel technology. Conversely, while the current technology excels in nickel recovery, presenting a larger environmental gain compared to the novel one, it falls behind in the overall metal recovery.

Moreover, parallel to the ADP results, the current technology shows more negative impacts in chemical consumption rates.

South Africa

The following Figure 7 provides the results of the categorized processes for both current and novel technologies for SA region. When assessing the environmental impacts of current and novel technologies in the SA context, similarities to the EU context emerge. This similarity is evident as the analysis in the SA context focused solely on updating the AP value related to electricity, mirroring the approach taken in the EU context. There is a minor negative environmental impact increase in the SA, emerging from the electricity change. This change reflects the contrast between Europe's diverse use of sustainable energy—comprising nuclear, hydroelectric, and wind sources, supplemented by a mix of 20% natural gas, 10% hard coal, and 10% lignite—and South Africa's reliance on nearly 90% hard coal for electricity generation, with minimal reliance on sustainable energy sources (Sphera, 2022a).

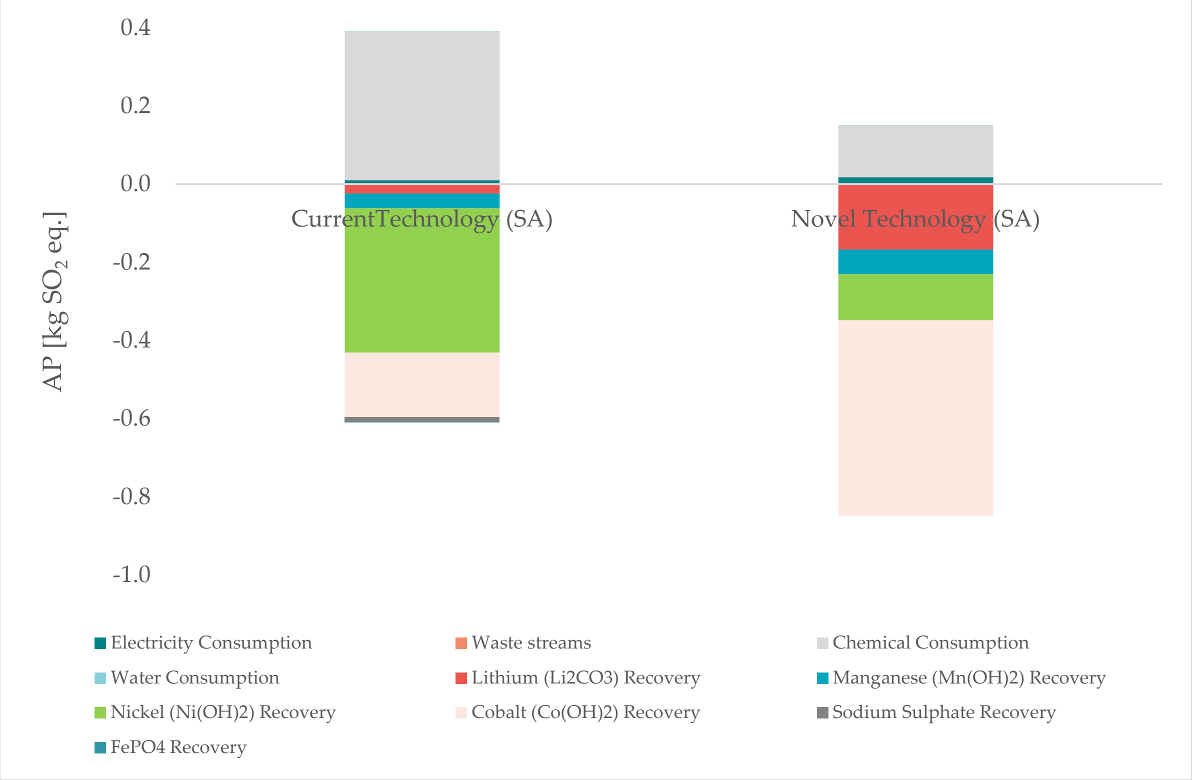

Figure 7. Comparison of AP results (SA context)

2.2.3 Eutrophication Potential (EP)

European Union

Eutrophication potential (EP) results for categorized processes in both current and novel technologies are illustrated in Figure 8. The results reveal a similarity in environmental gains and losses between the two technologies. In current technologies, the environmental gains predominantly yielded from metal recoveries, with cobalt being the most significant contributor. Conversely, the negative impacts primarily arise from chemical consumption and electricity consumption. For the novel technology, environmental gain arises from metal recovery, with cobalt and lithium recovery playing major roles. However, distinct from current technologies, the negative impacts in the novel technology are mainly attributed to chemical consumption and waste streams. Cobalt and lithium are the primary metals contributing significantly to the avoided burden in both current and novel recycling technologies. According to LCA for Experts database, EP for cobalt production mostly coming from aerial NOx emissions, while for lithium carbonate production, it's mainly due to the discharge of organic material into freshwater.

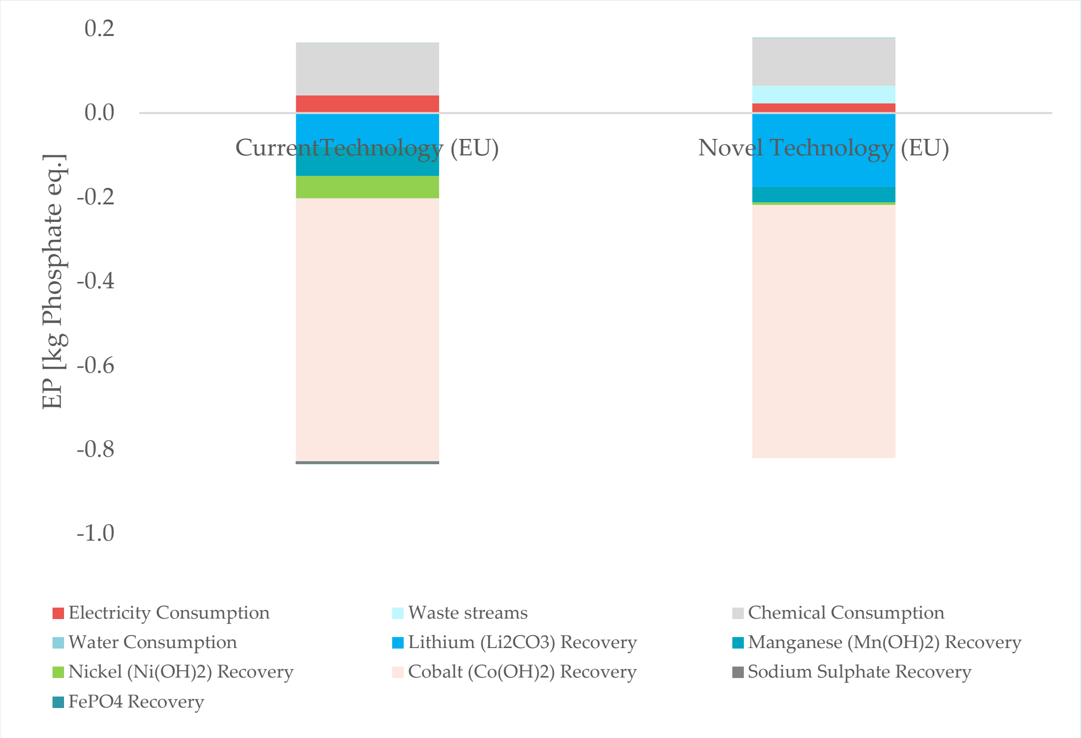

Figure 8. Comparison of EP results (EU context)

The negative impacts of waste streams in the novel technology might be attributed to the notably higher generation of solid waste and wastewater compared to the current technology. For instance, the novel technology generates 3001 kg of solid waste and 154 kg of wastewater, potentially contributing to environmental impacts. Wastewater, in particular, is closely related to eutrophication due to its nutrient content, including nitrogen and phosphorus (Wang, et al., 2020). Despite the current technology initially presenting a worse overall impact caused by chemical consumption than the novel one, the significant impact of waste streams, especially wastewater production, makes the environmental impacts of these two technologies almost comparable. This highlights the crucial role of managing and mitigating wastewater generation to limit potential eutrophication hazards in environmental assessments.

Comparing the current and novel technologies, the elimination of primary raw material extraction in both methods leads to a notably decreased risk of eutrophication, resulting in closely aligned results between the two approaches.

South Africa

The following Figure 9 provides the EP results of the categorized processes for both current and novel technologies for SA region. When assessing the environmental impacts of current and novel technologies in the SA context, similarities to the EU context emerge. This similarity is evident as the analysis in the SA context focused solely on updating the EP value related to electricity, mirroring the approach taken in the EU context. There's a noticeable surge in the negative environmental impact in the SA context due to the change in electricity source. This change reflects the contrast between Europe's diverse use of sustainable energy—comprising nuclear, hydroelectric, and wind sources, supplemented by a mix of 20% natural gas, 10% hard coal, and 10% lignite—and South Africa's reliance on nearly 90% hard coal for electricity generation, with minimal reliance on sustainable energy sources (Sphera, 2022a).

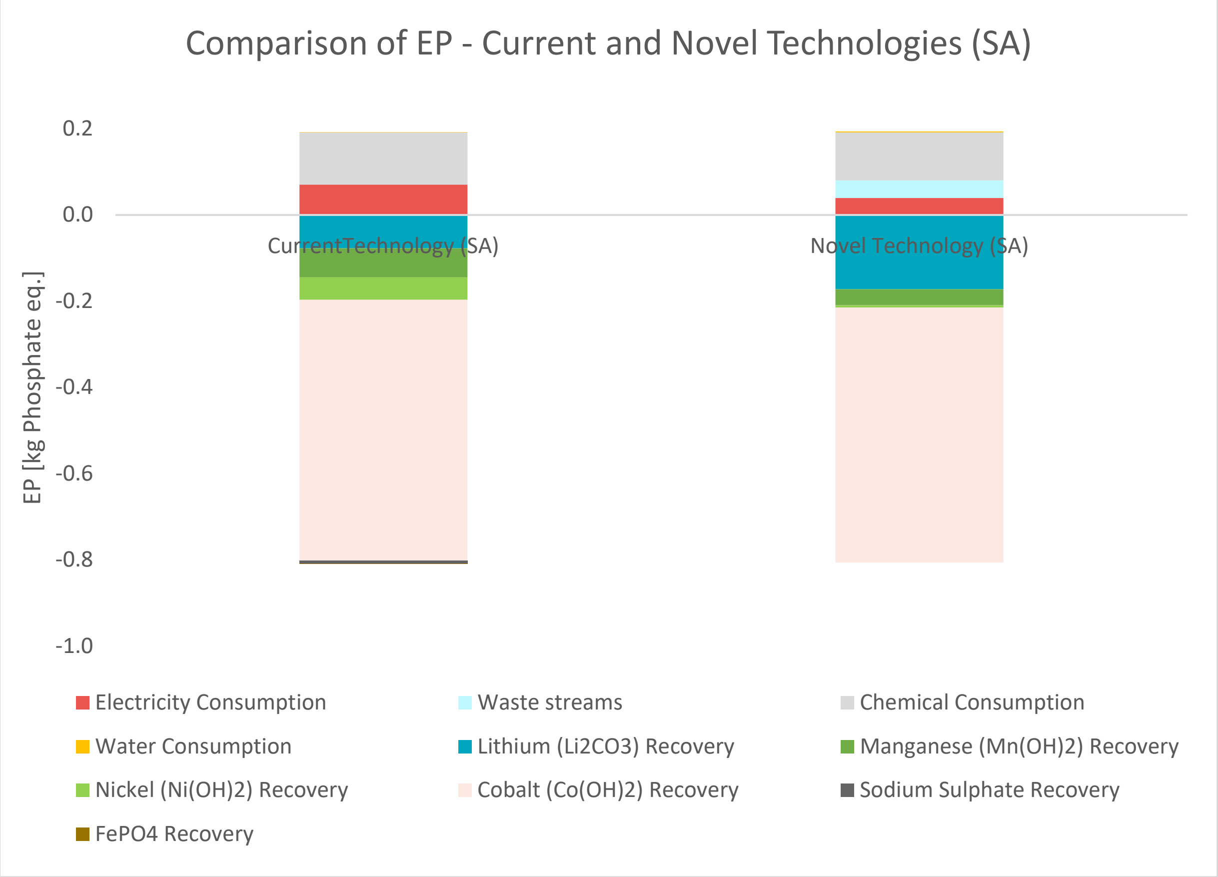

Figure 9. Comparison of EP results (SA context)

2.2.4 Global Warming Potential (GWP)

European Union

Global Warming Potential (GWP) results are presented in the following Figure 10 for both current and novel technologies. At first glance, it appears that the current technology holds a slightly more favorable environmental impact than the novel one. In the stacked contribution analysis (Figure 10), both current and novel technologies reveal that chemical and electricity consumptions significantly contribute to the GWP. In the current technology, the most significant gain is observed in metals recovery, contributing to an avoided burden. Similarly, in the novel technology, positive gains derive from metal recovery, although slightly less favorable compared to the current technology. Cobalt, lithium and nickel the primary metals recovered in these processes, significantly reduce the GWP. This reduction is attributed to avoiding considerable amount of carbon dioxide and methane emissions during their primary production routes through recycling. Finally, in the novel technology, negative impacts arise from chemical and electricity consumption, along with waste generation.

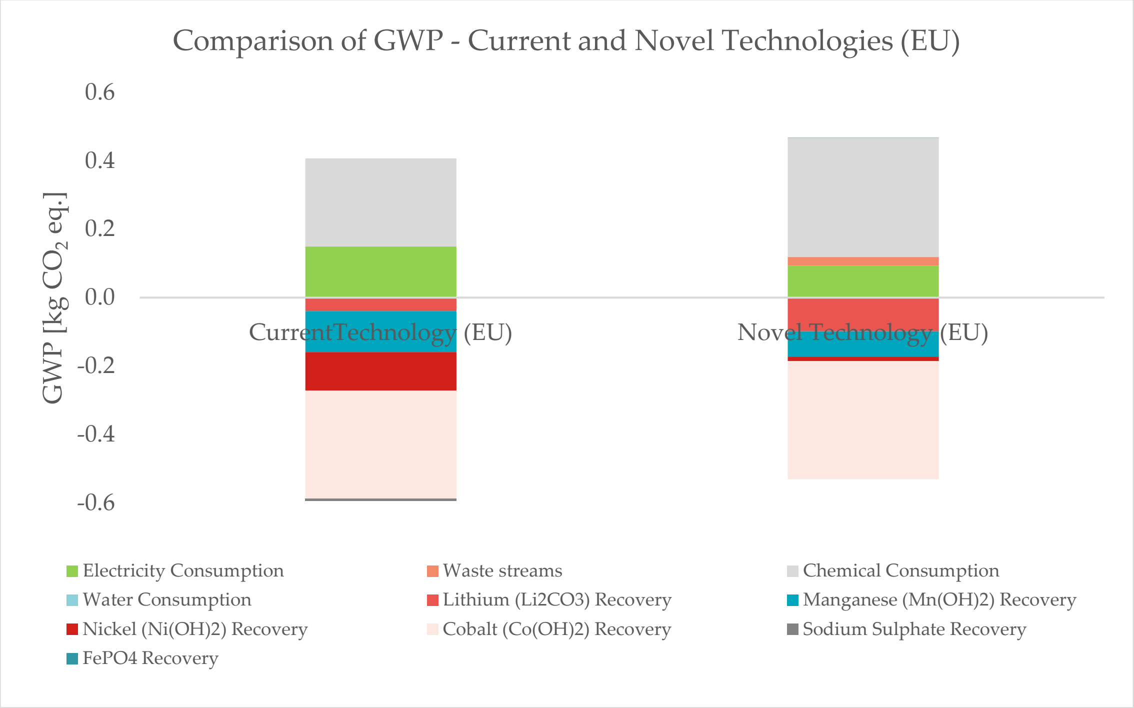

Figure 10. Comparison of GWP results (EU context)

South Africa

Figure 11 illustrates the GWP results of categorized processes for both current and novel technologies in SA context. There's a noticeable increase in the negative environmental impact in the SA context due to the change in electricity source. The noticeable rise in negative environmental impact in SA comes from changing the electricity sources from EU to SA context. Europe uses diverse sustainable energy like nuclear, hydroelectric, and wind power, while South Africa mostly relies on hard coal (almost 90%) for electricity, using very little sustainable energy (Sphera, 2022a).

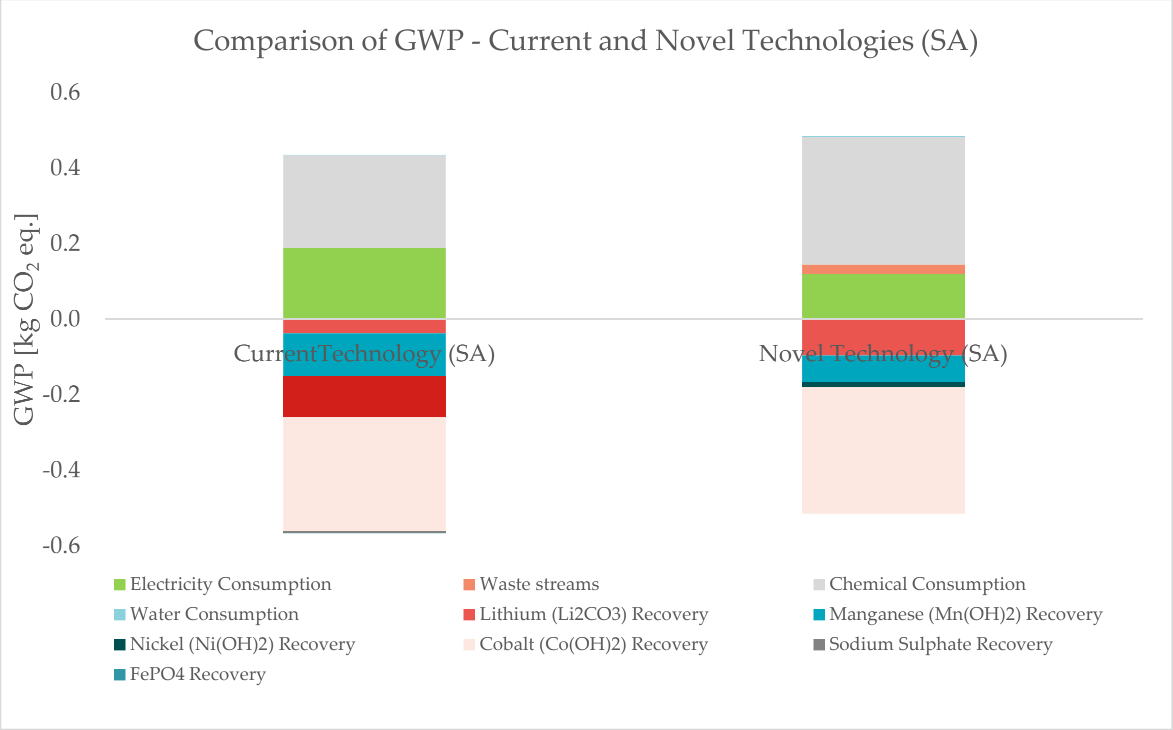

Figure 11. Comparison of GWP results (SA context)

2.2.5 Ozon Depletion Potential (ODP)

European Union

Ozon depletion (ODP) results of current and novel technologies have been presented in the following Figure 12. In the graph, the biggest contribution to the environmental gain for both technologies are the cobalt recovery process. It can be said that there is no negative environmental impact when it comes to ODP for both of the technologies. The following graph illustrates how the positive environmental gains from avoided burden in cobalt recovery can impact ODP results. This influence is tied to potential emissions associated with cobalt's extraction, processing, and utilization.

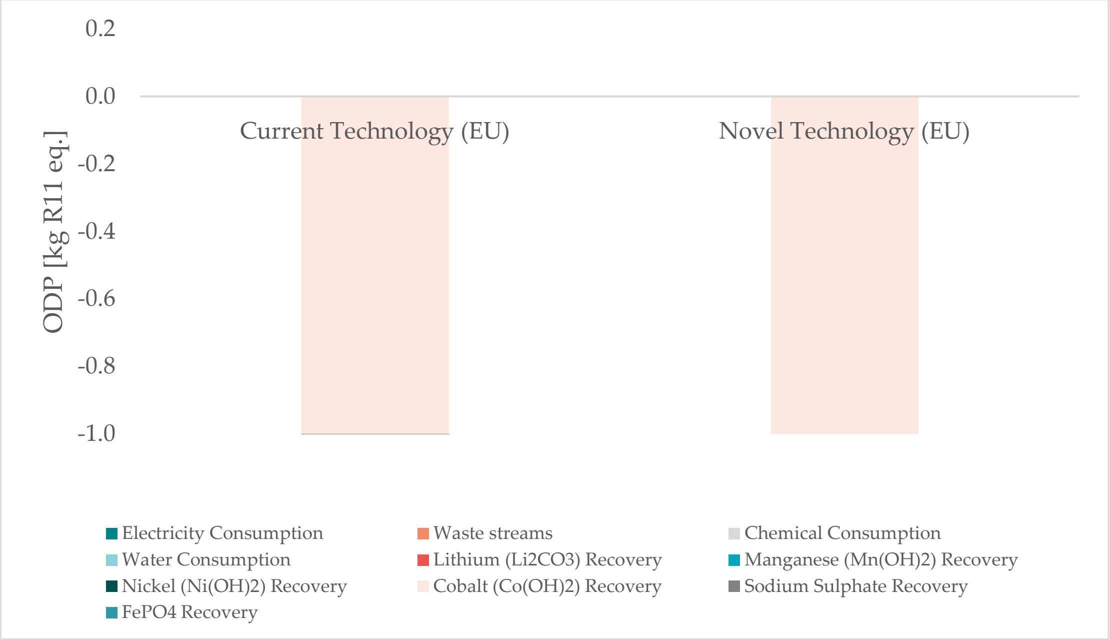

Figure 12. Comparison of ODP results (EU context)

South Africa

Figure 13 displays the Ozone Depletion Potential (ODP) results for the SA region, mirroring the earlier findings from the EU analysis. In both cases, cobalt recovery emerges as the most important process yielding the most significant environmental gain.

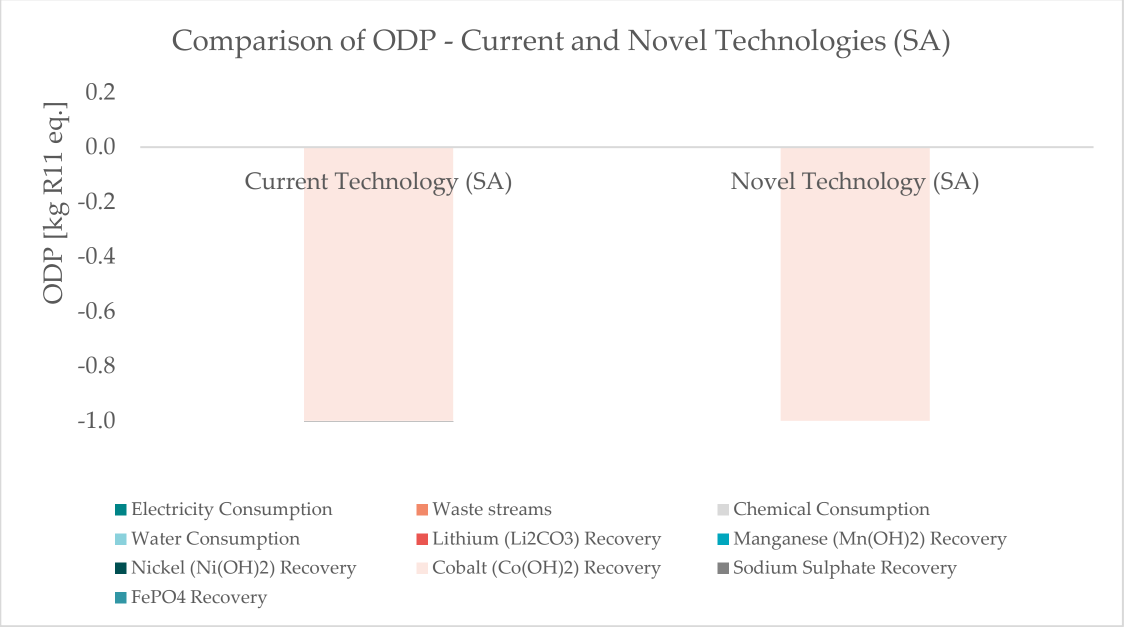

Figure 13. Comparison of ODP results (SA context)

3 Conclusions and recommendations

This study was conducted as a comparison study for two EOL LIB recycling technologies that have been proposed under the ELIMINATE project. The data for this LCA study came from laboratory and pilot scale LIB recycling plant and process modelling. The impact categories chosen for this study included: ADP, AP, EP, GWP and ODP.

Recycling LIB metals instead of extracting virgin raw materials showed environmental benefits, notably observed in the ADP, EP and ODP impact categories among the five selected. Both current and novel recycling technologies demonstrated significant environmental gains through the recovery of cobalt, lithium, manganese, and nickel.

These results are crucial for advancing novel recycling technologies, providing valuable insights and opportunities for further environmental improvements in these recently developed methods. The results of this study can be used to improve the environmental performance of the novel technology that is being developed in the context of ELIMINATE project. Since LCA of the novel technology is based on laboratory scale data and process modelling it is recommended that the study is reconducted in higher technology readiness levels of the developed technology.

At last, the current technology presented a slightly higher environmental gain when it is compared with the novel technology.

4 References

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Appendix A: Flowsheets of current and novel technologies

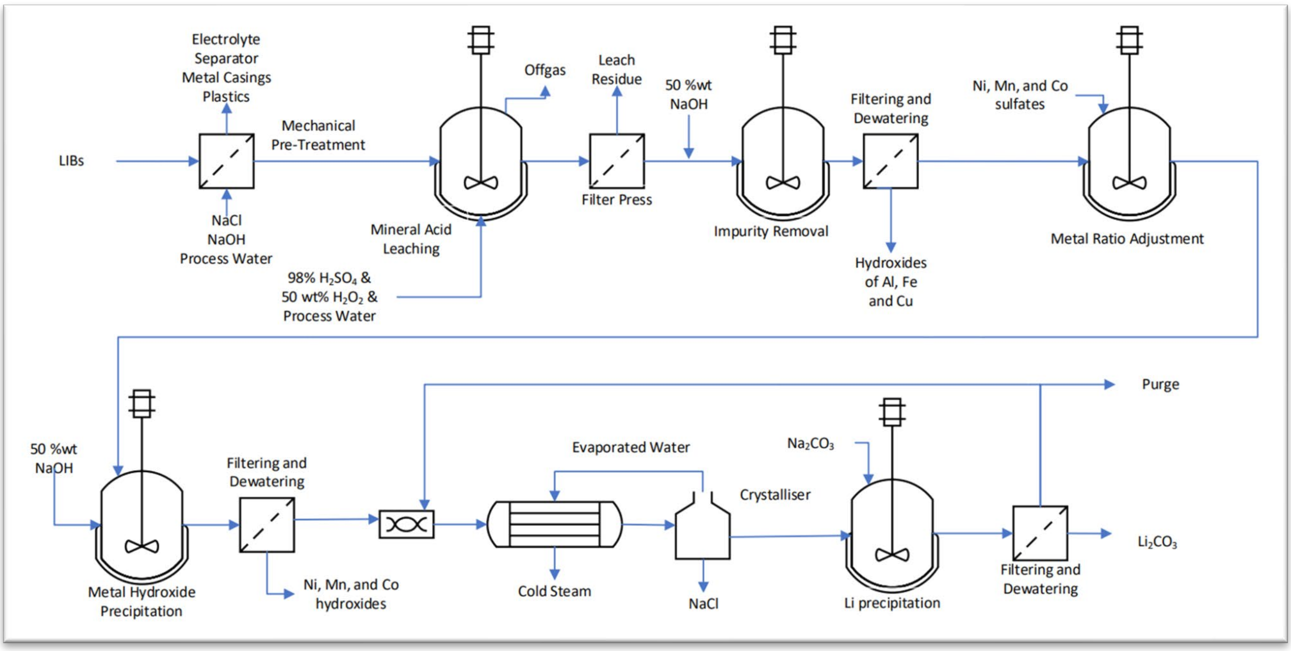

Figure 14. Simplified process flow diagram for current technology.

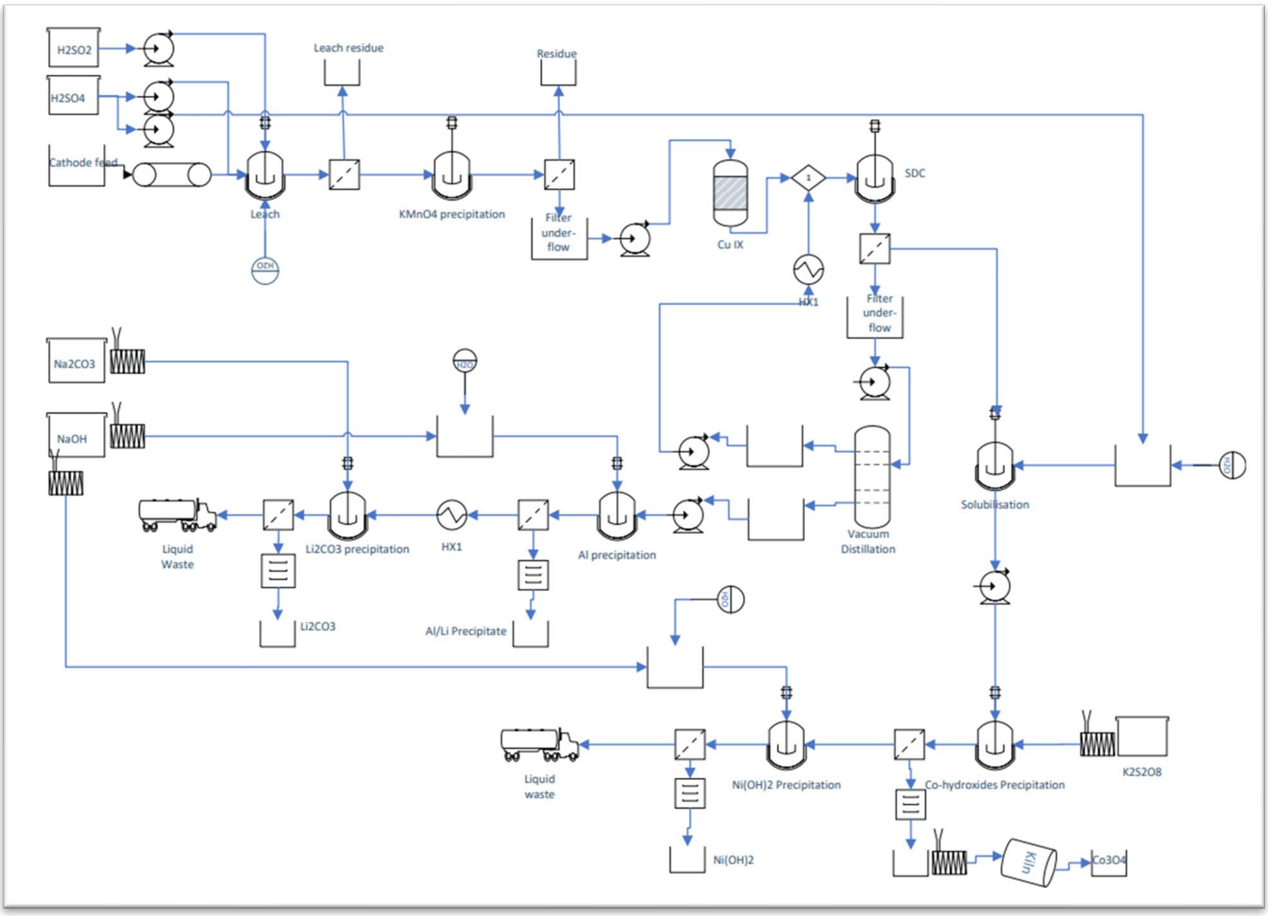

Figure 15. Simplified process flow diagram for novel technology.

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