Technology Selection for Hydrometallurgical Lithium-ion Battery Recycling

ELiMINATE Project Deliverable – Work Package 1
“Business case screening and business model scenario analysis”

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Lithium-ion battery, Hydrometallurgical recycling, Business case screening, business model scenario analysis, business model development, Europe

Summary

This report serves as a deliverable for the ongoing Era-MIN project named ELiMINATE funded by Vinnova on the Swedish side, aiming perform a business case screening for the proposed end-of-life (EoL) lithium-ion batteries (LIBs) recycling technologies within the project and provide value chain integration scenarios for them. The name of the deliverable is “Business case screening and business model scenario analysis”. This deliverable is the results of six different tasks presented in the work-package one. The integration of these tasks in one deliverable was convenient given the overlaps of the business/market context between South Africa (SA) and European Union (EU) due to the global nature of the LIB recycling market.

There are two parts in this deliverable: business case screening and business model development. In the first part, -business case screening-, a selection was done for 9 current and 2 novel LIB recycling technology categories by using the Needs, Approaches, Benefits and Competition (NABC) methodology. As part of the NABC method, a technoeconomic assessment and a lifecycle assessment (from Work Package 2) were included. After completing the first part of the study, two top-performing technologies have been selected within each category. In the second part, -business model development-, the purpose was to develop a business model for these two top-performing LIB recycling technologies. Different value chain scenarios were first developed and discussed for EU and SA respectively. The best performing value chain scenarios have been selected based on their profitability results by applying a comparative techno-economic assessment. After this, business model canvas methodology has been used for two selected technologies to evaluate best performing scenarios to give more insights to reader.

According to the business case screening study results the best performing LIB recycling technology within the current technologies category is H2SO4 – NMC in both EU and SA context. In addition, the best technology within the novel technologies category is H2SO4 – Novel in both EU and SA context. During business model development chapter, three value chain scenarios were developed for EU and four scenarios were developed for SA. Best performing scenarios – Establishment of an in-house recycling plant by Battery Producers (for EU) and Zero EoL LIBs cost & outbound logistics costs passed on (for SA) – were used for the next step. After conducting a thorough business model canvas study for the selected technologies within selected value chain integration scenarios, a clear

overview of how these technologies can be used in the real life is explained at the end of the report.

In summary, the existing LIB recycling market is highly competitive and globally dynamic. An essential factor for investment in LIB technology while competing with the global market is achieving high production capacity at low costs. Moreover, environmental considerations play a very important role, particularly in a competitive landscape with evolving regulations. As a result, this study offers multifaceted perspectives for prospective LIB recycling investors and stakeholders, shedding light on the feasibility of establishing a company or adopting newly innovated LIB recycling technologies within the EU and SA regions.

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Abbreviations

Abbreviation	Phrase and/or Definition
BMC	Business Model Canvas
EoL	End of life
EU	European Union
EV	Electric Vehicle
LCA	LCA – Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCO	Lithium – Cobalt – Oxide cathode chemistry
LIB	Lithium-ion Battery
NABC	Needs-Approaches-Benefits-Competition
NCA	Nicke – Cobalt – Aluminium cathode chemistry
NMC	Nickel – Manganese – Cobalt cathode chemistry
MSA	Methanosulfonic acid
SA	South Africa
SADC	South African Development Community
SRI	Stanford Research Institute
SX	Solvent Extraction
TEA	Techno-economic assessment
TIPS	Trade and Industrial Policy Strategies

1 Introduction

This study is 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". The ELiMINATE project focuses on the technical, logistical, business, and environmental aspects of LIB recycling, taking into account both the European Union (EU) and South African (SA) contexts. The project is undertaken by a consortium comprising five partners: Stellenbosch University, the Swedish Environmental Research Institute (IVL), Karadeniz Technical University, Chalmers University of Technology, and Exitcom Recycling.

To achieve the project's overarching goal, the project has set specific objectives, and one of them involves conducting a thorough business case screening and business model development for the LIB recycling technologies that have been proposed under this project (nine current and two novel technologies).

In order to offer a comprehensive grasp of the study, the tasks undertaken within this deliverable are outlined in the following list:

Business case screening:

- Task 1A.3 Business case screening of current process technologies in SA context
- Task 1B.3 Business case screening of current process technologies in EU context
- Task 1A.4 Business case screening of a novel process technology in SA context
- Task 1B.4 Business case screening of a novel process technology in EU context

Business model development:

- Task 1A.5 Business model scenario analysis for selected process technology in SA context
- Task 1B.5 Business model scenario analysis for selected process technology in EU context

It was considered relevant to combine the SA and EU contexts in a single report since there are so many overlaps from marketing point of view. The necessary information regarding the differences in SA and EU context will be highlighted in each chapter.

In this study, nine current and two novel technologies will be compared within their categories in the business case screening part, and final two selected technologies from each category will be further investigated in the second part – business model development. The details of each recycling technologies can be found in the Appendix A: Background Information.

1.1 Business Case Screening

The business case screening process involved a comparison between nine current technologies and two novel technologies in the context of EoL LIBs treatment and recycling proposed throughout the project. To conduct the business case screening evaluation, the Needs-Approach-Benefits-Competition (NABC) (Stanford Research Institute, 2006) methodology was employed.

Approaches made in each step was summarized as follows:

1. Needs: A market analysis was conducted to identify needs.
2. Approaches: Unique approaches to meet the identified needs were explained.
3. Benefits: Techno-economic assessment (TEA) and environmental impact assessment through life cycle assessment (LCA) were utilized to identify main benefits and additional comparison aspects.
4. Competition: Competitive forces in the EU and SA were discussed.

These aspects collectively provided a comprehensive basis for comparing LIB recycling technologies. At the end of the business model screening chapter, two LIB recycling technologies (H_2SO_4 – NMC and H_2SO_4 – Novel) were selected and further investigated in the subsequent chapter. The Figure 1 below illustrates the current and novel technologies compared in this study. The green-coloured boxes represent the technologies that have been selected for the business model development study.

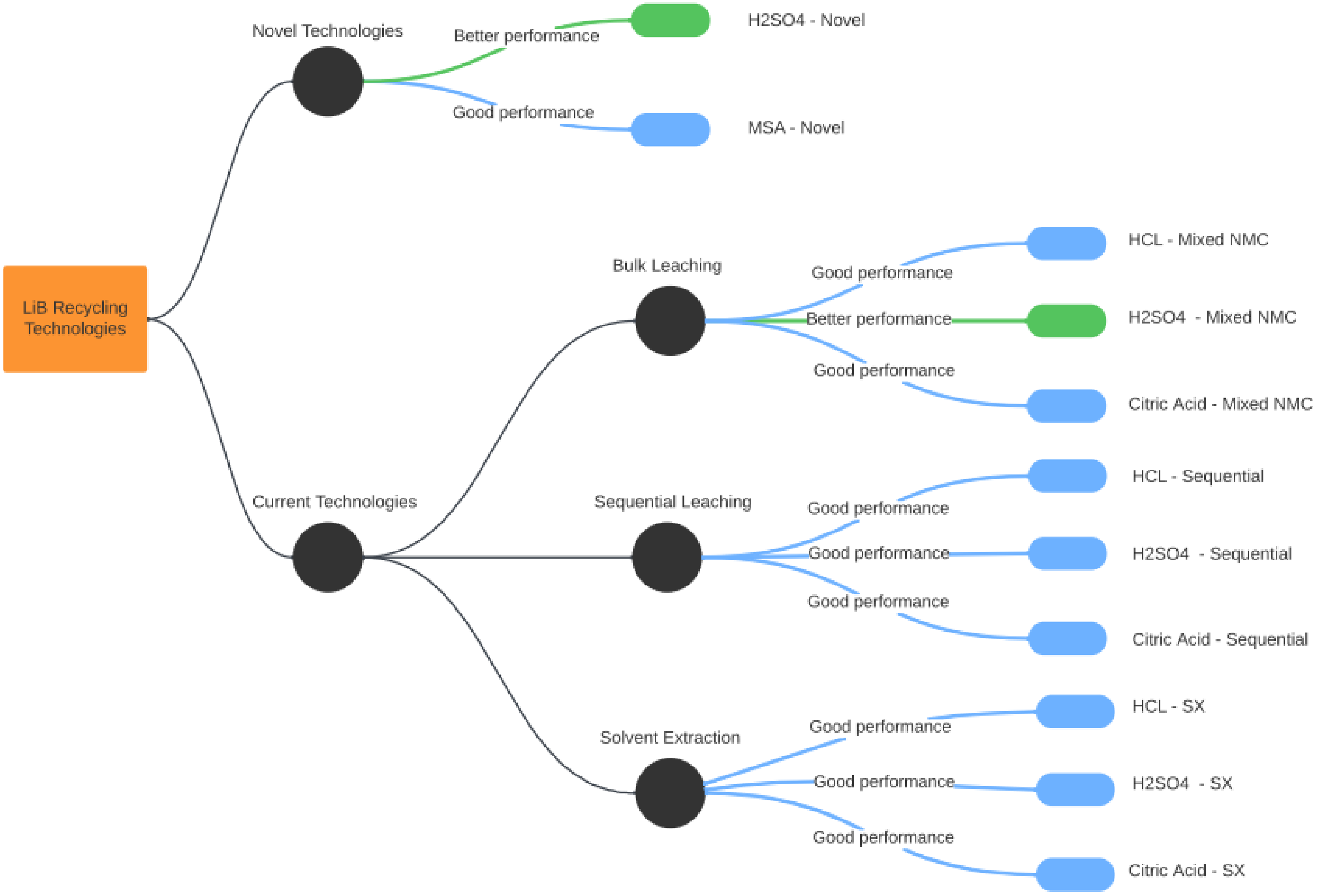
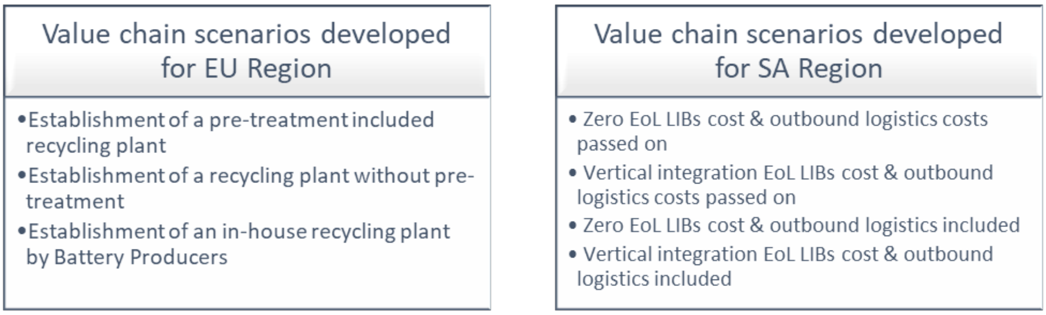


Figure 1 Diagram of LIB Recycling Technologies evaluated in ELiMINATE

1.2 Business Model Development

The ELIMINATE project aims to create a framework for establishing local end-of-life lithium-ion battery (LIB) treatment facilities. One critical aspect of this project is developing a business model, and the goal is to figure out the best strategies for integrating the selected technologies into the value chain. To achieve this objective, first different value chain integration scenarios developed within the EU and SA contexts separately, these scenarios are presented in the following Figure 2.

Figure 2. Value chain integration scenarios that have been developed separately for the EU and SA regions.



Value chain scenarios developed for EU Region

- Establishment of a pre-treatment included recycling plant
- Establishment of a recycling plant without pre-treatment
- Establishment of an in-house recycling plant by Battery Producers

Value chain scenarios developed for SA Region

- Zero EoL LIBs cost & outbound logistics costs passed on
- Vertical integration EoL LIBs cost & outbound logistics costs passed on
- Zero EoL LIBs cost & outbound logistics included
- Vertical integration EoL LIBs cost & outbound logistics included

Figure 2 Value chain integration scenarios that have been developed separately for the EU and SA regions.

The value chain scenarios are developed in Ozturk (2024) and Kuhn (2023) theses for EU and SA respectively. In addition, the profitability calculations have been done and presented in these theses to identify the most profitable scenarios. At the end, one scenario has been selected from each region that has the highest potential to create a successful local EoL LIB recycling business.

The business model canvas (BMC) methodology was employed by defining the key elements for selected (H2SO4 – NMC and H2SO4 – Novel) technologies within the selected value chain integration scenarios (In-house recycler plant and Zero EoL LIBs cost & outbound logistics costs passed on scenarios). At the end of the chapter, a BMC summary is presented. This business strategy, built on the BMC framework, provides a comprehensive roadmap for successfully commercializing the two selected LIB recycling technologies.

There are different BMC approaches in the literature, however, the Osterwalder & Pigneur's (2010) nine building blocks will be used for this study which is the most commonly used business model development tool (Osterwalder & Pigneur, 2010). The nine building blocks are listed as follows with a short description from the tool are shown:

1. Customer segments – An organization serves one or more customer segments.

2. Value propositions – It seeks to solve customer problems and satisfy customer needs with value propositions.

3. Channels – Value propositions are delivered to customers through communication, distribution, and sales channels.

4. Customer relationships – Customer relationships are established and maintained with each customer segment.

5. Revenue streams – Revenue streams result from value propositions successfully offered to customers.

6. Key resources – Key resources are the assets required to offer and deliver the previously described elements…

7. Key activities – …by offering a number of key activities.

8. Key partnerships – Some activities are outsourced and some resources are acquired outside the enterprise.

9. Cost structure – The business model elements result in the cost structure.

In the context of this study, two of these building blocks, specifically (distribution) channels and customer relationships, were not subjected to in-depth investigation. Further research is recommended to explore these aspects more comprehensively.

1.3 Structure of the Report

Chapter 1 – Introduction: Short description of the report purpose and structure of the report.

Chapter 2 – Background Information:

Chapter 3 – Methodology: This chapter will be describing the business case screening and business model development methodologies which are NABC and business model canvas respectively.

Chapter 4 – Results – Business Case Screening: All the results regarding the NABC methodology will be presented in this chapter.

Chapter 5 – Results – Business Model Development: The results for business model canvas will be presented in this part.

Chapter 6 – Conclusions

Chapter 7 – Recommendations

Chapter 8 – References

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

2 Methodology

Nowadays, the increasing presence of fully or hybrid electric cars, electric buses, E-scooters, and E-bikes on the streets signifies substantial growth in the battery-powered electric vehicle industry (Melin E. , 2018). The growth is driven by the recommendation of electric vehicles (EVs) as a primary technological solution to reduce greenhouse gas emissions and combat air pollution, particularly in urban areas (Zimm, 2021). At the core of the electric vehicle is its battery, playing a crucial role in the transition to sustainable energy and decarbonization by storing energy and powering these vehicles. Although the majority of batteries entering the global market are expected for use in both light and heavy Evs, their importance also extends to consumer products. In this context, the market is propelled forward by the demand for portable and cordless alternatives.

Currently, the preference for the most promising lithium-ion batteries (LIBs) among energy storage users is driven by their advantageous performance-cost ratio, extended service life, compact size, high battery voltage, and lightweight build (Etacheri, Marom, Elazari, Salitra, & Aurbach, 2011). According to the World Economic Forum reports, a significant rise in global production of LIBs is expected, projected to increase from around 700 GWh annually in 2022 to an14stimateed 4.7 TWh by 2030 (Fleischmann, et al., 2023). Furthermore, Europe is anticipated to close the gap with China and emerge as a leading producer and consumer of LIBs in the forthcoming years. The expansion in the battery market is credited to recent regulatory changes and a broader inclination towards localizing supply chains. Hence, the surge in production requires the construction of a minimum of 120 to 150 new battery plants worldwide between now and 2030 (Fleischmann, o.a., 2023).

However, this expansion also raises concerns, foreseeing a substantial surge in the volume of battery waste generated throughout battery production, usage, and end-of-life disposal. While rechargeable batteries boast reusability, they are not eternal; they have a finite lifespan and eventually reach a stage where they must be appropriately handled and disposed of once their usefulness ends (Melin E. , 2018). With the increase in EOL LIB volumes it is therefore necessary to anticipate heightened environmental standards for treatment facilities and a surge in the need for enhanced metal recovery rates in the future. Hydrometallurgy recycling technologies (extracting metals from other materials using an aqueous solution) have been evaluated as having the highest potential to meet these forthcoming market demands. See the ELiMINATE market analysis report (Wu & Lindman, 2022) for more in-depth information as to why hydrometallurgy has a high potential compared to other technologies. Moreover, the increase in LIBs production has heightened worries about resource scarcities and the risks associated with geographically concentrated resources, especially concerning lithium and cobalt—which are essential elements utilized in these batteries (Grosjean, Miranda, Perrin, & Poggi, 2012). The escalating demand for electric vehicles poses a risk of future depletion for lithium and cobalt resources (Ma, Azhari, & Wang, 2021). Therefore, the crucial recovery of battery materials like cobalt, nickel, manganese, and lithium via hydrometallurgical recycling will be pivotal in securing material supply for the battery market. Projected estimations suggest that by 2040, recycled sources could alleviate approximately 12% of the overall primary supply of essential LIB materials (IEA, 2021).

To reduce the environmental impact of discarded batteries and preserve valuable resources, there's a growing focus on developing circular and environmentally friendly recycling approaches for LIBs. The aim of these processes is to recover and reuse materials such as lithium, cobalt, nickel, and manganese from LIBs, fostering a closed-loop circular system. This initiative aims to decrease reliance on mining and the production of new materials. LIBs consist of various components, including cathodes and anodes. Recovering only cathode materials can result in a reduction of over 20% in the total production costs of a LIB (Mayyas, Steward, & Mann, 2019) (Ahmed, Nelson, Gallahger, & Susarla, 2017). Embracing sustainable recycling practices for LIBs can facilitate the shift towards a resource-efficient circular economy with reduced carbon footprint.

This shift to recovering more of the LIBs materials is projected to revolutionize the LIB manufacturing sector, emphasizing nickel-based cathode chemistries such as nickel-manganese-cobalt (NMC) and nickel-cadmium-aluminum (NCA). Additionally, there will be a greater focus on local production and sourcing of raw materials, consequently amplifying the demand for materials in nickel-based chemistries (Wu & Lindman, 2022). Batteries based on different chemistries undergo various LIB recycling process routes, including mechanical, pyrometallurgy, and hydrometallurgy. It's a common approach to combine two or more of these methods to optimize the extraction of valuable metals. Hydrometallurgy processes are projected to have a growing significance in EoL LIB recycling due to their advantages over pyrometallurgical methods (Wu & Lindman, 2022).

2.1 LIB Recycling Technologies

LIBs and Components

Rechargeable LIBs have transformed the global energy storage sector, finding extensive applications across various fields, spanning from mobile devices to electric vehicles (DeMeuse, 2021). LIBs are sophisticated battery products comprising multiple components that function collectively. These essential components are segmented into four key elements within LIBs: the cathode, anode, electrolyte, and separator, working in unison (Johnson, 2022). As the battery discharges, the lithium-ions move migrate from the anode to the cathode. When the battery is fully discharged, the lithium atoms are exclusively contained within the cathode (Yoshino, 2014).

Existing Recycling Technologies

Recycling presents a promising solution to reduce environmental impacts from spent LIBs and tackles sustainability concerns. It is crucial for conserving critical and scarce raw materials like cobalt and lithium. The cathode, housing rare elements, is the most valuable part of a battery (Kachate, Sharma, & Baidya, 2023). Lowering cathode production costs is a big advantage for battery producers. The ELiMINATE project focuses on recycling cathode materials. Existing recycling methods can safely and sustainably recover valuable materials from the cathode component of batteries.

Recycling of LIBs generally involves a few crucial stages. Initially, it aims to minimize the volume of battery scrap generated. Subsequently, it concentrates on segregating various battery components for appropriate treatment. Lastly, the goal is to extract valuable metals from the batteries for subsequent reuse. To accomplish these goals, two main recycling process categories are utilized: physical processes and chemical processes (Xu, o.a., 2008).

Physical processes in LIB recycling encompass mechanical and thermal pre-treatments. Mechanical pre-treatment includes manual sorting, disassembly, shredding (crushing), and separation (screening and/or magnetic separation). This method primarily targets removing plastics, carbon, aluminum, iron, and copper from the battery, enhancing material surface area for further processing. The outcome is a powder called “black mass,” a common term in the market, containing cathode and/or anode active materials (Kaya, 2022). Chemical recycling methods then extract metals from this black mass. Thermal pre-treatment can potentially be done before chemical recycling to eliminate binder materials, like graphite and organic compounds, binding the battery components.

Chemical recycling methods for LIBs include pyrometallurgy, hydrometallurgy, and bioleaching. Pyrometallurgy involves using high temperatures to extract valuable metals from battery materials. It's an old and straightforward method (also called smelting) in LIB recycling. Hydrometallurgical recycling, another effective method, uses chemical processes in water solutions to separate and recover valuable metals. While pyrometallurgy is less costly, it requires a lot of energy and yields lower material recovery rates (Wu & Lindman, 2022). It produces alloys and slag materials that need further hydrometallurgical processing for critical material recovery. In contrast, hydrometallurgy uses less energy and achieves higher material recovery rates, but at a higher cost. Bioleaching, using microorganisms to extract metals from various materials in water, is an eco-friendly and established method (Roy, Cao, & Madhavi, 2021).

Direct recycling, a technology currently under research and development, preserves the original chemical structure of battery components, allowing their direct recovery and reuse in different applications. (ReCell, 2024)

Battery Value Chain

The linear value chain of LIBs involves diverse industries and stakeholders. The mining sector supplies essential raw materials like lithium, cobalt, nickel, and graphite. These materials then undergo processing in the inorganic chemical industry, crafting cathodes and electrolytes. Separators and binders, crucial for battery construction, emerge from the polymer industry. Concurrently, the metal and electronics industries contribute cans, foils, and intricate battery management systems. Illustrated in Figure 3 below, diverse battery recycling pathways contribute to closing the loop within the LIB life cycle, transitioning the system from a linear model to a circular one. The "pyro process recycling" involves smelting and refining waste batteries, while the "hydro process recycling" focuses on producing battery precursor materials for new cathode production. These recycling methods were previously detailed as pyrometallurgy, hydrometallurgy, and direct recycling.

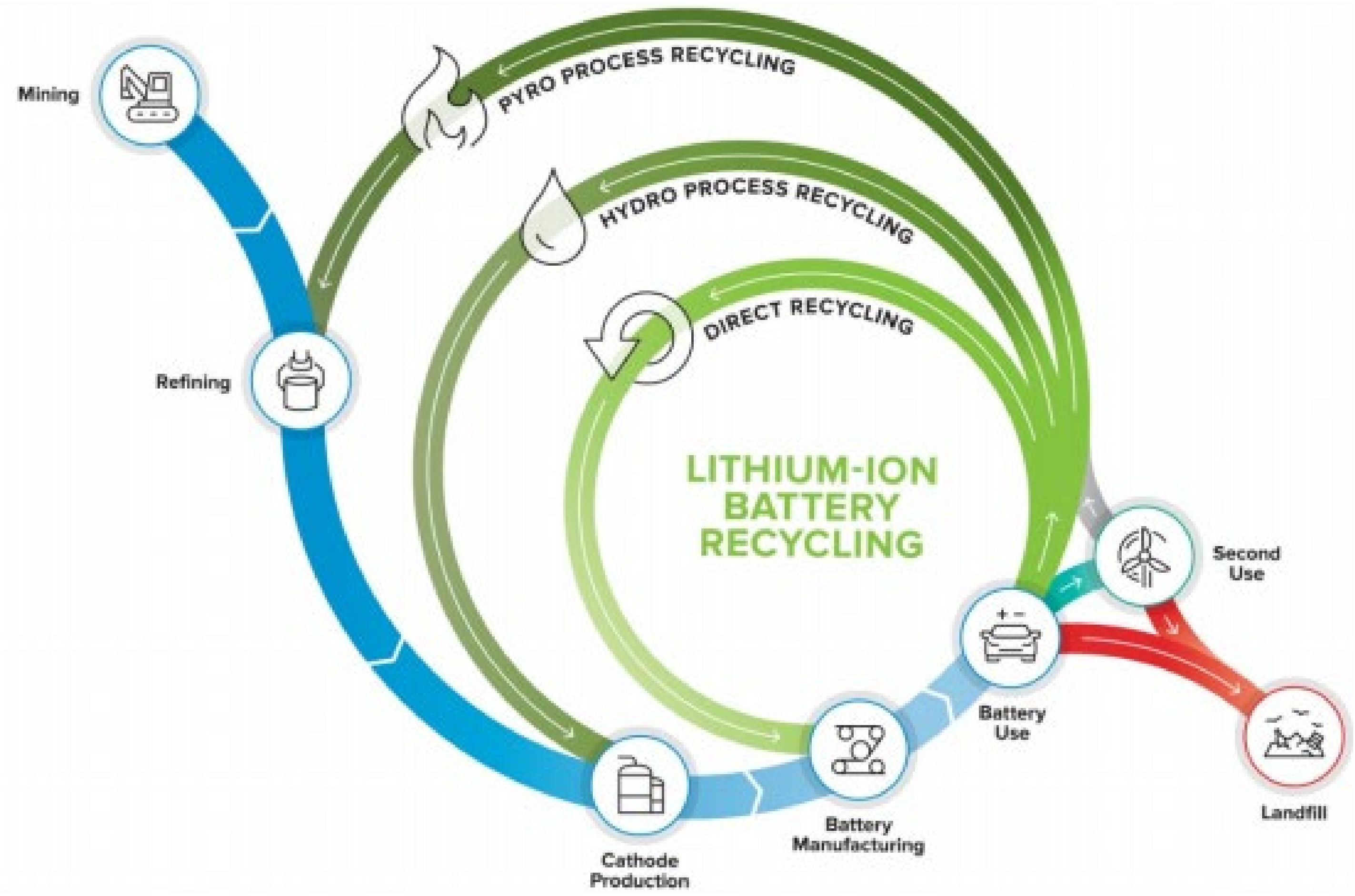


Figure 3. Circular economy pathways for end-of-life of LIBs (ReCell, 2024)

Hydrometallurgical processes stand out as potentially being more efficient and environmentally friendly compared to the current battery recycling methods (such as pyrometallurgy). Recent research studies and battery manufacturers prioritize the use of environmentally friendly methods to reduce recycling costs, driven by both intense industry competition and the urgent need for effective recycling solutions.

In the EU, increasing competition highlights the need for an enhanced focus on hydrometallurgical LIB recycling technologies. Conversely, in SA, the necessity for establishing the first battery recycling facility is driven by economic advancement and environmental considerations. In both regions, prioritizing the development and implementation of hydrometallurgical LIB recycling technologies are essential for addressing these distinct challenges and advancing sustainable practices in the battery industry.

The ongoing studies in the hydrometallurgical recycling processes for LIBs emphasize a crucial need for continuous improvement in recycling efficiency, aiming for a balance between low cost and high capacity. Scientists are actively engaged in exploring new technologies and improving existing methods to increase material recovery effectiveness. This includes optimizing separation techniques, exploring alternative recycling pathways, and delving into advanced treatment processes. However, in previous years, over 70% of lithium-ion battery recycling studies centered around hydrometallurgy were conducted in South Korea (Melin H. , 2019). Hence, it is imperative for the EU and SA to intensify their emphasis on research studies related to hydrometallurgical LIB recycling. Furthermore, the global significance of advancing innovative hydrometallurgical LIB recycling technologies, with a specific focus on cathode materials, cannot be overstated. The hydrometallurgical LIB recycling methods hold the promise of transforming the LIB cathode recycling industries in both the EU and SA, paving the way for future processes that are both cost-effective and high-capacity.

2.2 LIB Recycling Market

LIB Recycling Market in Europe

The undeniable reality remains: the battery recycling market is rapidly expanding, witnessing continuous intensification in competition among stakeholders. Within the EU, the push to recycle a greater volume of LIBs to meet the rising demand for electric vehicles and tools presents an invaluable opportunity for potential new entrants or investors. The drive toward a more circular and self-reliant LIB recycling market propels the emergence of these new players. However, amidst this landscape, competition emerges as the most substantial threat.

In Europe, LIB recycling capacity in 2020 was about 45,900 tons per year. Germany leads with 7 plants totaling 20,700 tons, followed by France with 3 plants at 12,000 tons, and Belgium's Umicore plant at 7,000 tons. Most active recycling plants are in the Nordics, Central, and Eastern Europe. (Wu & Lindman, 2022). The majority of the plants employ mechanical or pyrometallurgical methods. The largest plants using hydrometallurgical recycling are Umicore in Belgium and Veolia in France, having capacities of 7,000 tons and 6,000 tons respectively (Wu & Lindman, 2022). In 2017 the European Commission launched the European Battery Alliance (EBA). The EBA250 analysis indicates over 35 LIB recycling initiatives in progress or planned in Europe. These projects, supported by the EU, are anticipated to have substantial impacts, with some commencing operations before 2025. (EIT

InnoEnergy , 2023) EoL LIB recycling processing is growing, with more involvement anticipated from battery manufacturers and recyclers from China and South Korea. Manufacturers are likely to invest in recycling facilities for both internal battery scrap and end-of-life batteries, fostering a circular economy that minimizes waste and optimizes resource use. (Grünig, Kampman, van Esses, & Duleep, 2011).

Europe is gearing up to enhance LIB pre-processing capacity while improving recycling potential and securing critical raw materials. Policies emphasizing LIB recycling and the circular economy align with the goal of achieving zero carbon emissions by 2050 (Hoarau & Lorang, 2022) Competition in the EU calls for cost-effective LIB recycling methods to sustain a competitive battery industry. Initiatives like the European Battery Alliance, launched in 2017, and the Raw Materials Initiative aim to enhance resource efficiency in battery recycling (EIT InnoEnergy , 2023) (European Union Commission, 2008).

LIB Recycling Market in South Africa

South Africa confronts a pressing issue concerning electronic waste, as it represents the fastest-growing waste stream in the country (Cape E-Waste, n.d.). Based on an analysis of LIB waste generation rates, it is estimated that laptops will be the greatest source of LIB waste in South Africa, followed by mobile phones (between 2017 to 2031). Furthermore, from 2021 to 2031, the tonnes/year of LIB waste generated will be more than double. The LCO (lithium-cobalt-oxide) battery chemistry will form the majority of the LIBs generated in South Africa up to 2031 (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023). Moreover, it is important to note that the country does not have any LIB recycling industry (TIPS, 2021). This absence results in end-of-life LIBs either being disposed of in landfills or exported for recycling. It is evident that a circular economy model for LIBs hasn't been established within the South African context. Embracing a circular economy not only fosters sustainability throughout the LIB value chain but also holds potential economic advantages through material reuse. By recycling LIBs, the materials employed in their production can be reintegrated back into the manufacturing process (Smit, 2019). LIB waste collection needs to take this aspect into consideration and focus on forming secure collection strategies for these two sources.

In a study by the Trade and Industrial Policy Strategies (TIPS) (2021), the opportunities in SA's LIB value chain were explored. In the study, LIB recycling emerged as a potential avenue for development among four identified possibilities.

However, the study highlighted the current uncertainty regarding the economic feasibility of such a plant. It emphasized the necessity for comprehensive research into market conditions, collection methods, storage, and processing strategies. This detailed research could serve as a catalyst for establishing a recycling facility. Similarly, Foli (2020) conducted a study titled “SADC e-Mobility Outlook: Accelerating the Battery Manufacturing Value Chain,” revealing that while South Africa boasts a well-established lead-acid battery recycling industry, the same infrastructure is not in place for lithium-ion batteries. It is proposed that the South African Development Community (SADC) establishes a regulatory framework for LIB recycling, aiming to foster a circular economy and ensure safe disposal practices (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023).

2.3 Competitive Forces for LIB Recyclers

The LIB recycling market operates within the commodity market, characterized by limited control over product and supplier prices, and competition with producers of virgin materials. As individual entities, LIB recyclers are considered "price takers," resulting in limited bargaining power over the selling price of their commodity products. Understanding the competitive dynamics within the LIB recycling sector becomes crucial due to these market conditions.

Porter’s Five Forces is a framework for understanding the competitive forces in an industry. The underlying drivers for profitability are the same across different industries and the framework can be used to assess competition, strategic positions, and to identify industry trends (Harvard Business School, n.d.). The framework identifies the following five forces: 1) *Bargaining power of buyers, 2) Bargaining power of suppliers,* 3) *Threat of new entrants,* 4) *Threat of substitute products or services,* 5) *Rivalry among current competitors.*

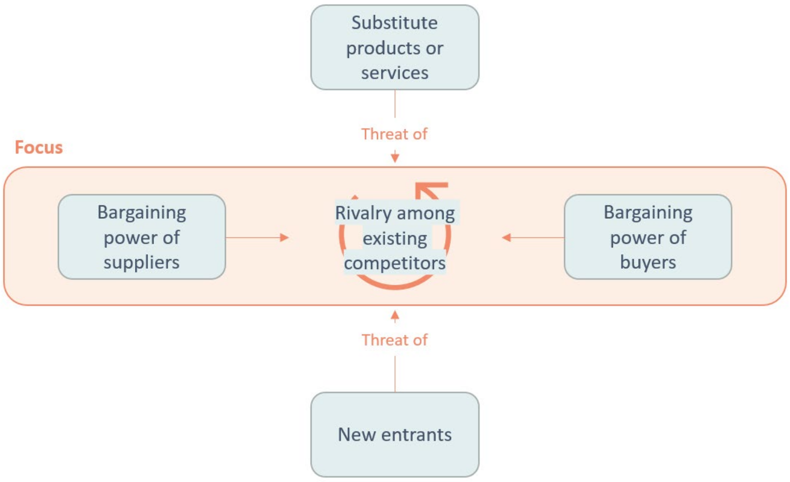


Figure 4. The performed analysis focused on the highlighted three parts of the Porter's Five Forces framework: bargaining power of suppliers, bargaining power of buyers, and rivalry among current competitors (Authors' own elaboration).

New Entrants – Barriers to Entry

Every industry presents its own set of barriers that can pose significant challenges for startups aiming to break in. These hurdles not only make it tough for new entrants to establish themselves but also serve as deterrents for potential competitors. New entrants need to know which obstacles they will be facing and what is needed to overcome them, while current competitors need to be able to protect their position in the industry by building up barriers to entry for any other new entrants (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023). The following barriers to entry are particularly relevant for new LIB recyclers seeking to enter the market:

Capital investment: Venturing into a new industry demands a substantial capital investment that can vary significantly across different sectors. This investment is allocated towards acquiring machinery, infrastructure, research and development, marketing, and covering potential early-stage losses. New entrants inevitably need robust financial support to navigate these initial phases (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023).

Economies of scale: Economies of scale come into play as the unit costs of products typically decrease with higher production volumes or extended periods. This phenomenon results from the spreading out of fixed costs over a larger number of units, not only on the production side but also on the purchasing side, where discounts are often applied to larger orders. Achieving the same economies of scale as existing industry players may pose a time-consuming challenge for new entrants (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023).

Product differentiation: Product differentiation proves challenging within commodity-based industries, as products inherently lack distinct characteristics that set them apart from direct competitors. While variations in product purities may exist, these differences typically cater to specific market segments rather than serving as a means of differentiation within the broader market. Producing higher purities often entails additional costs and is usually driven by the need to meet specific market expectations. Therefore, product purity aligns with meeting targeted market expectations. While the product itself lacks differentiation opportunities, companies can distinguish themselves through other means within the market landscape.

Differentiation in terms of price would also not occur, as commodity market theory states that all products would be able to be sold at the market price, and any prices under the market price will not increase sales volumes. Consequently, offering prices below the market price does not yield any advantageous outcomes.

Distinguishing the company through exceptional customer service is another viable option to differentiate and to stand out from other companies. Areas within customer service in which the company can strive to be the best at would include on-time delivery, post-sale customer service, and quality guarantees.

Bargaining Power of Suppliers

Regarding the influence of EoL LIB suppliers on recycling companies, it is anticipated that the raw materials furnished to the LIB recycling plant would align with established market prices. The recycling company itself would lack control over the pricing of its inputs. Similarly, individual suppliers wouldn't possess the authority to raise their supply prices beyond market rates.

Bargaining Power of Buyers

Concerning the influence of buyers of recycled products on recycling companies, it is anticipated that the prices of these products will stick to established market rates. An individual LIB recycler or their product buyers would generally lack substantial influence to push prices either above or below the market price.

Substitute Products of Services

Mixed Hydroxide Precipitate (MHP) serves as an intermediary chemical product, sourced from nickel laterite ores, boasting approximately 30-40% Nickel content and up to 10% Cobalt. It has garnered favor among cathode manufacturers due to its cost efficiency and heightened availability compared to conventional nickel salts. Consequently, MHP producers now directly supply cathode manufacturers, reducing the necessity for further refinement. This shift presents a competitive challenge to the Nickel and Cobalt sulphate market within the LIB industry, particularly affecting LIB Recycling plants using a sequential/SX (SX = solvent extraction) approach to generate nickel and cobalt salt products. In response, a Mixed NMC production process could present a more resilient alternative in the face of this evolving landscape (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023).

Rivalry Among Current Competitors

In the European LIB recycling market, a mix of established and emerging recyclers exists, with an anticipated transition from largely mechanical and pyrometallurgical technologies to favoring hydrometallurgical methods. The growth of the LIB market and associated demand as well as EU policy priorities to secure the supply of critical battery materials (as reflected in the new EU Battery Regulation) will incentivize new recycling actors on the market, while at the same time increasing the number of competitors between current and new players and increasing the competition on the market.

On the other hand, in South Africa, the potential LIB recycling plant explored in this report is considered to be the first LIB recycling plant in South Africa. Consequently, the current scenario assumes an absence of rivalry among existing competitors until new entrants join the South African landscape. While products exported from the plant will contend on a global scale against international competitors, those sold domestically in South Africa will also face competition from imported goods.

2.4 Competitive Advantage Strategy for a LIB Recycler

European Union Context

In the European Union's LIB recycling industry, several key differentiation factors have emerged. Among these factors, a notable one is the shift towards producing precursors using recycled materials instead of relying solely on virgin content, providing a competitive edge over traditional virgin material refineries. Furthermore, there's a growing emphasis on social responsibility, particularly noticeable among cathode manufacturers who prioritize ethical and sustainable procurement practices. These factors reflect the industry's commitment to sustainability and environmentally responsible practices, positioning EU LIB recyclers at the forefront of the global effort to create a more circular and eco-friendly battery ecosystem.

The landscape shaping the entry of a new LIB recycler into the market is versatile. Successful market entry demands adept competition skills, achieved through recycling batteries with heightened capacity at reduced costs. Moreover, recent EU regulations governing LIBs recycling impose efficiency targets, emphasizing the need for innovative and environmentally sustainable processes. In addition, to establish a competitive edge, forging robust collaborations, partnerships, or alliances with diverse stakeholders within the EU proves pivotal. With over 16 prominent recyclers already operating in the region, the market is witnessing the arrival of new contenders from North America and Asia, as documented by Navarro et al., 2022 (Navarro, Seidel, Kolk, Krug, & Lenz, 2022). For instance, Stena Recycling is currently constructing a cutting-edge LIBs recycling plant. In their official statements, Stena Recycling underscores the surging demand for LIBs recycling, intensifying competition among major players, the significance of collaborative ventures, the imperative for scalable high-capacity production, and the adoption of highly efficient processes. Their facility is strategically designed to address these requirements, positioning them as a robust player in the emergent LIBs recycling market. (Stena Recycling, 2023)

In terms of business development strategies, the methods and operational complexities involved in supplying recycled LIB products to specific buyers, such as primary battery manufacturers, will differ among various recyclers. Companies aspiring to extract value from spent LIBs within the future EU battery recycling industry should embrace a strategic vision centred on several key elements. These include prioritizing cost leadership, expanding recycling capacities, tailoring production to meet customer needs, fostering customer collaboration, managing a green and secure supply chain, and ensuring swift delivery. To effectively execute these strategic objectives, companies must adopt innovative and efficient technologies, continually pursue developments, establish sustainable sourcing channels, minimize battery collection expenses, and decrease purchasing costs. By placing emphasis on these aspects, companies can elevate their operational efficiencies and contribute significantly to sustainable practices across the EU's battery recycling sector.

South Africa Context

The absence of a LIB recycling facility in South Africa, as highlighted by TIPS in 2021, creates a notable opportunity for a potential LIB recycler to establish a robust competitive advantage in the region (TIPS, 2021). Currently, used LIBs in South Africa are either disposed of in landfills or exported for recycling, leading to the loss of valuable economic and social benefits for the country. Introducing efficient local LIB recycling processes can significantly reduce the reliance on costly international shipments, create employment opportunities, stimulate economic progress, and contribute to the principles of the circular economy. This strategic position as a local LIB recycler aligns with environmental sustainability goals and economic growth objectives, presenting an attractive opportunity in a market that seeks innovative solutions.

To optimize its competitive advantage, a LIB recycling company can strategically employ the "cost leadership" competitive strategy by combining a lower-cost advantage with a broad target competitive scope. This strategy entails the potential LIB recycling company striving to provide products at reduced production costs while aligning with market prices, recognizing that sales do not increase significantly below the market price. For a LIB recycler in SA, reducing costs stands as a primary approach to enhance its profit margin, considering they are bound by the prevailing market price as "price takers." Adopting a strategy of cost leadership involves implementing numerous cost-minimization techniques. For instance, ensuring a recycling plant operates at high efficiency rates with minimal downtime is crucial. Alternative strategies might encompass establishing distinctive relationships with suppliers and distributors. Successful cost-leading companies frequently exhibit vertical integration within the broader value system. Achieving high production volumes proves advantageous for cost leaders as it enables economies of scale in both production and procurement processes.

2.5 The Description of Current and Novel Technologies

In this study, nine current and two novel technologies will be compared within their categories in the business case screening part, and final two selected technologies from each category will be further investigated in the second part – business model development. The details of each recycling technologies can be found in the Appendix A: Background Information.

3 Methodology

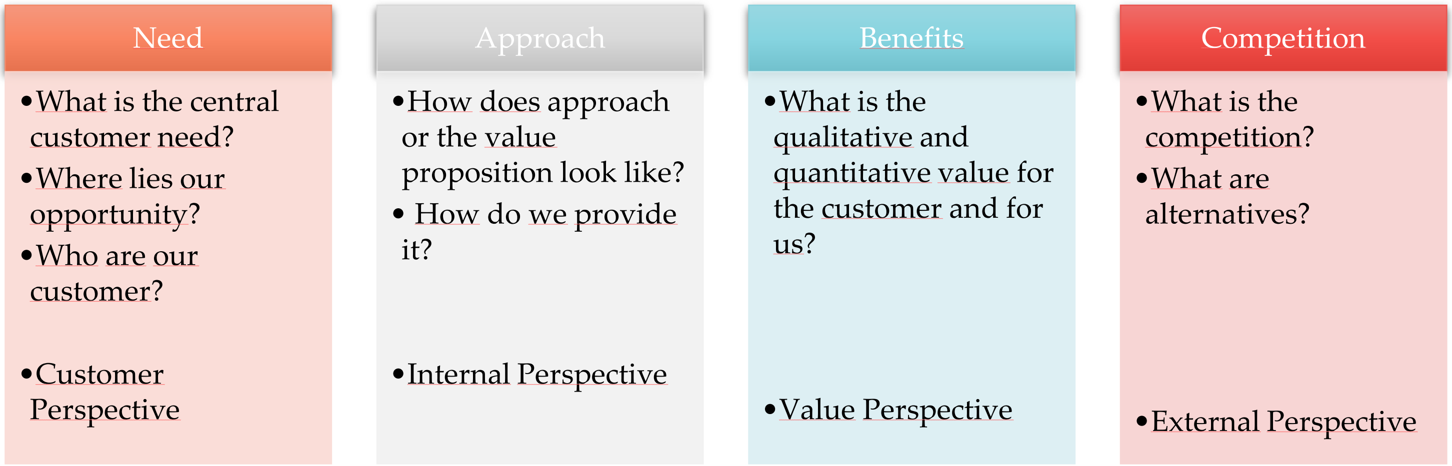
This chapter covers the methodology of the business case screening and business model development.

3.1 Business Case Screening

Within this assessment, there were eleven different technologies which were categorized into two groups: current and novel technologies. This study aims to assess the viability and the potential for further investment or advancement of these technologies, ultimately culminating in the selection of the most suitable method from the pool of eleven. This business case screening will be executed through the systematic application of the Need-Approach-Benefit-Competition (NABC) analysis methodology. By adopting this structured framework, the analysis aims to pinpoint crucial aspects such as market demands, practical feasibility, potential advantages, the competitive landscape, and financial implications.

The NABC approach was formulated by the Stanford Research Institute (SRI) as a strategic methodology tailored to fulfill a market or client requirement through an innovative strategy, accompanied by compelling advantages over rival offerings. NABC, which abbreviates Need, Approach, Benefit, and Competition, was developed to facilitate the structured evaluation of business propositions and projects. A straightforward illustration provided by the SRI exemplifies the NABC concept in everyday contexts: recognizing a state of hunger as the underlying need, proposing a visit to the SRI Cafe as the chosen approach, emphasizing its proximity, culinary quality, and conducive ambiance for uninterrupted work as the associated benefits, and contrasting this with the clamor typically experienced at McDonald's during lunch hours as the competitive alternative. (Stanford Research Institute, 2006).

What makes the NABC unique is that the market or customer need is at the center point of the whole model. The SRI believes that this is the first step towards developing a more detailed business plan or proposal. Additionally, the NABC methodology embraces an iterative approach, permitting the revisitation of steps—a crucial aspect for continual improvement within this framework (Stanford Research Institute, 2006). The NABC framework offers a systematic avenue to evaluate the viability of both current and novel LIB recycling technologies. This assessment follows key criteria outlined in the Need-Approach-Benefit-Competition (NABC) framework, as shown in Figure 5.



Need	Approach	Benefits	Competition
• What is the central customer need? • Where lies our opportunity? • Who are our customer?	• How does approach or the value proposition look like? • How do we provide it?	• What is the qualitative and quantitative value for the customer and for us?	• What is the competition? • What are alternatives?
• Customer Perspective	• Internal Perspective	• Value Perspective	• External Perspective

Figure 5. Summary of NABC methodology, Source: (Steinhöfel, 2016)

More information about the needs, approach, benefits, and competition will be discussed in the forthcoming chapters.

3.1.1 Needs

In the NABC (Needs, Approach, Benefits, Competition) methodology, the first phase is dedicated to uncovering and defining the fundamental market or customer needs that a proposed project or technology aims to address. This initial step lays the foundation for the entire analysis process, ensuring that the project effectively addresses a genuine problem or fulfills a demand in the market. This step is crucial because a business idea that fails to meet a real need is likely to struggle or fail in the long run. The need should relate to a market opportunity, where the end customers and the size of the market are defined (Stanford Research Institute, 2006). In this analysis, the focus of the needs assessment is on relation to LIB battery recycling considering the rapid and significant growth of the LIBs industry on a global scale.

3.1.2 Approach

The Approach phase provides an internal perspective, focusing on crafting solutions to fulfill the identified needs. It encompasses defining the approach and value proposition, as well as outlining the means to deliver these solutions. In this report the term “approach” here includes the recycling processes to produce the products and not only the product or service offering. Consequently, the related question becomes:

- What are the current and novel processes in the market to meet these needs?

3.1.3 Benefits

In the Benefits part, the focus is on understanding the value generated by the chosen approach for both customers and the business, particularly when compared to other methods. This involves recognizing the benefits, both in terms of quality and quantity, that the solution brings to the target audience or market. Evaluating these advantages assists in measuring the project's value proposition and potential return on investment. The implementation potential of a new process serves as a benefit, aligning with the strategy for scalability.

Different benefits, such as cost-effectiveness, high performance, and speedy response, can arise from different methods. This study assesses benefits by comparing profits and environmental impacts using Life Cycle Assessment (LCA) and Techno-economic Assessment (TEA). In addition, industry practice (practical considerations), reagent availability, availability of product buyers, material recovery and purity rates, and CAPEX/OPEX (CAPEX = Capital Expenditures, OPEX = Operating Expenditures) comparison added to this part to strengthen the reason behind the selection of the two technologies. The main question addressed is: What are the pros and cons of these proposed hydrometallurgical LIB recycling processes?

3.1.3.1 LCA Comparison

The ELIMINATE project aimed to identify the most environmentally sustainable methods among current and novel technologies. Two key deliverables were produced:

1. Techno-environmental screening of nine current and two novel technologies within their specific categories,
2. Full LCA comparison of one current and one novel technology.

The LCA analysis were conducted using LCA for Experts version 9.2.1 and the CML 2001 methodology (Guinee, 2002) to calculate life cycle impact assessment (LCIA) results. These results were then used to compare between the technologies. Additional details on these LCA studies can be found in the relevant deliverables, with links provided in the Appendix.

3.1.3.2 Techno-Economic Assessment – Net Present Value (NPV) Comparison

Comparing the profitability of current and novel technologies is crucial to determine the economically superior options. This economic comparison study involved a conventional techno-economic assessment aimed at evaluating the potential profitability of future LIBs recycling plants. The assessment, conducted at the conceptual design level, entailed estimated values for Fixed Capital (FC) and profits.

The profitability of the current and novel technologies has been predicted by using Net Present Value (NPV) key financial indicator. NPV serves as an effective method to demonstrate profitability by capturing the cumulative cash flow over the project's lifetime. For each recycling process option, NPV was computed based on the calculated CAPEX, OPEX, and revenues. A positive NPV signifies a profitable investment in the recycling plant, while a negative NPV indicates an unprofitable one. NPV proves valuable for ranking different processes, where the option with the highest NPV is deemed the most favourable.

As previously outlined, the comparative analysis encompassed nine existing technologies and two innovative technologies within the EU and SA regions separately. To ensure a comprehensive and fair comparison, the profitability calculations were executed in three steps:

1. Profitability comparison of current technologies in SA context,
2. Profitability comparison of novel technologies in EU context,
3. Profitability comparison of selected current and novel technologies in EU Context.

In each study, NPV was determined, these three steps will be further explained in the subsequent chapters.

Profitability Comparison of Current Technologies in SA Context

In this part, the profitability of nine current hydrometallurgical recycling technologies have been compared with each other based on their NPV results. This technology screening study aimed to forecast the profitability of hypothetical process plants, throughout a 13-year operational period starting from day one. Maritz (2022) conducted a NPV analysis of nine current LIB recycling process options for SA region. The process specifications were as follows:

- Compared Technologies: Nine current technologies.

- Geographical Scope: South Africa
- Plant Capacity: 868 t/year

Maritz's study is a relative NPV comparison of current technologies, and the plant capacity were equal to 868 t/year. To determine the plant capacity that is feasible in SA region, it was necessary to gather data pertaining to SA human population, e-waste generation rate, recycling rate, LIBs rate in total e-waste generation rate, and plant availability. This data played an important role in computing the overall market share in SA allocated to LIB recycling, amounting to 868 t/year. Given the absence of other LIB recycling plants in SA, this maximum market share was selected as the plant capacity.

Following this investigation, two out of the nine LIB recycling technologies emerged as the most profitable options within the SA region. For a detailed analysis, please refer to the study provided in Appendix B.

Profitability Comparison of Novel Technologies in EU Context

The economical comparison of two novel technologies within their respective category was conducted as part of the Ozturk (2024) thesis within the ELIMINATE project, specifically focusing on the EU region. The process specifications were as follows:

- Compared Technologies: Two novel technologies,
- Geographical Scope: European Union,
- Plant Capacity: 6,000 t/year.

The Ozturk (2024) thesis conducted a comparative analysis of current technologies based on their Net Present Value (NPV), considering a plant capacity of 6000 t/year. Below is a description of how the figure was determined for the novel technologies in the EU context.

In the Ozturk (2024) thesis, the plant capacity calculation for the EU involved the selection of representative countries—Germany, Italy, and Sweden—to represent the EOL LIB volumes through all three countries. Followingly, same as Maritz's methodology, data collection encompassed human population figures, e-waste generation rates, recycling rates, LIBs proportion in total e-waste, and plant availability within these chosen countries. This information was instrumental in computing the proportional market share dedicated to LIB recycling in the EU, totalling 18,132 t/year.

The proportional market share in the three countries was then set to equal the average annual maximum plant capacity, i.e. 18,132 t/year. However, recognizing the competitive landscape and the presence of established recycling facilities within the EU market, setting a plant capacity aiming to capture the entire market would be imprudent. Hence, the plant capacity was pragmatically set at 33% of the maximum capacity, amounting to 6,000 t/year.

At the end of the Ozturk (2024) thesis, two novel technologies’ NPV’s are calculated, and their profitability have been compared for EU region. While the thesis has been approved, the report remains inaccessible due to confidentiality constraints.

Profitability Comparison of Selected Current and Novel Technologies in EU Context

The final part of profitability calculations involves a comparison of selected current and novel technologies in the entire region instead of just Germany, Italy, and Sweden. The EU was used to make this comparison since the data availability is better than SA when it comes to battery recycling. Therefore, the NPV analysis was updated for current technologies from SA to the EU and the plant capacity. The updates and details of this study are outlined in Appendix B. The process specifications were as follows:

- Compared Technologies: Two current and two novel technologies,
- Geographical Scope: European Union,
- Plant Capacity: 98,667 t/year.

At the end of this part, two out of four technologies were selected as the most profitable LIB recycling technologies.

To enhance the "benefits" analysis within the NABC methodology, several comparative categories complement the findings from the LCAs and TEAs. These additional comparison categories are presented in the following list:

- OPEX and CAPEX comparison,
- Industry practice,
- Reagent availability,
- Availability of product buyers,
- Recovery and product impurities.

The assessment of these elements relies on insights derived from Wu & Lindman (2022), Maritz's thesis (2022), and an extensive literature review. Although Wu & Lindman (2022) and Maritz (2022) predominantly concentrated on current technologies, the literature review was instrumental in capturing data relevant to novel technologies. The subsequent section elaborates on the reasons for providing more detailed information on these items.

3.1.3.3 CAPEX and OPEX Comparison

Comparing OPEX and CAPEX is crucial when evaluating the advantages of a LIB recycling technology for potential investors or entrepreneurs. This comparison offers insights into the potential initial investment intensity and subsequent ongoing operational costs. The OPEX and CAPEX comparisons were conducted for two novel and two current technologies based on the findings of the "Profitability Comparison of Selected Current and Novel Technologies in the EU Context" study.

3.1.3.4 Industry Practice

Assessing industry practices helps ensure that the selected recycling technologies align with existing processes and standards within the LIB recycling industry. Technologies that closely adhere to industry norms are often more feasible and viable for implementation. The general information regarding the existing technologies and industry practices is given in the Chapter 2.

3.1.3.5 Reagent Availability

The availability of reagents, such as chemicals used in the hydrometallurgical recycling process, is critical while understanding the benefits of different recycling technologies. Technologies requiring rare or scarce reagents (e.g., organic and inorganic acids) may face challenges in scaling up or maintaining consistent production. Evaluating reagent availability ensures that a chosen technology can operate sustainably without resource constraints within the EU or SA region.

3.1.3.6 Availability of Product Buyers

Knowing the availability of product buyers is very important for technology selection in this study. A recycling method may generate valuable materials, but if there are no buyers or demand for these materials, the technology may not be economically viable. Assessing the markets in EU and SA regions for recycled products is essential to determine whether there is a feasible route to sell recovered materials.

3.1.3.7 Recovery and Purity Rates

Recovery and purity rates directly impact the efficiency and effectiveness of a recycling technology. High recovery rates indicate that a technology can successfully reclaim a significant portion of valuable materials from spent batteries. Similarly, high purity rates ensure that the recovered materials meet industry standards and can be used in new battery production without significant purification efforts. Therefore, in this study, the recovery and purity rates of the proposed current and novel technologies have been compared.

3.1.4 Competition

Finally, the competition phase takes an external perspective to assess the competitive landscape and compares the benefits of the approach chosen to those offered by competitors. This phase seeks to uncover advantages and disadvantages associated with the processes and explore how these processes distinguish themselves in the competitive arena.

The conclusion of the NABC evaluation involves selecting the two methods for the subsequent business model development chapter.

3.2 Business Model Development

Strategic business model development is a crucial aspect for potential investors and entrepreneurs, providing them with insights to recognize potential advantages, opportunities, and challenges. Consequently, this chapter delves into the exploration of diverse value chain integration strategies, distinctly for the EU and SA. The schematic representation of the research approach is summarized in Figure 6, and this methodology will be applied separately to both the EU and SA contexts.

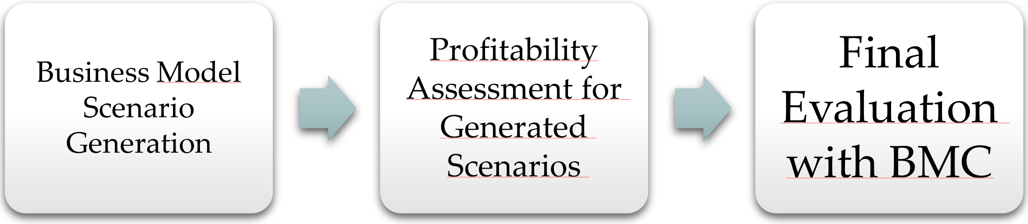


Figure 6. Scheme of the methodological approach on Business Model Development

The importance of business model scenario generation lies in its ability to shed light on how various business models affect the profitability of selected EoL LIBs recycling technologies. The results from the profitability assessments in Kuhn (2023) and Ozturk (2024) theses were used as basis for identifying the most promising scenarios. Subsequently, the BMC methodology will be applied to these chosen technologies, offering a comprehensive view of the strategic elements and value propositions associated with the selected EoL LIBs recycling technologies.

BMC provides structured approaches to visualize, analyze, and iterate on the different components of a business model. It enables organizations to identify areas for improvement, explore new opportunities, and make necessary adjustments. Hence, Pigneur (2010)'s method of viewing a business model through the 9 building blocks of the BMC is selected to be used because it is the most commonly used business model development tool (Osterwalder & Pigneur, 2010). In addition, it is very well known, easy to understand and apply, uncomplicated in comparison to other business models and provides a thorough high-level overview. BMC provides structural approaches to visualize, analyze, and iterate on the different components of a business model. It enables organizations to identify areas for improvement, explore new opportunities, and make necessary adjustments.

The business model snapshot of the current combination of resources and activities can thus be described by Osterwalder & Pigneur (2010)'s 9 building blocks:

- Customer Segments: the specific group of customers that are targeted.
- Value Proposition: solves customer problems and offers unique benefits compared to competitors.
- Revenue Streams: identifies sources and sizes of revenue from provided value.
- Key Resources: the resources required to create the value proposition.
- Key Activities: the critical tasks done by the business to survive and create the value proposition.
- Key Partnerships: collaborative relationships for supply, resources, or strategic alliances.
- Cost Structure: defines incurred costs, highlights high-cost activities/resources, and determines cost or value focus.
- Distribution Channels: describes how the customers are reached and connected with.
- Customer Relationships: explains interaction and relationship maintenance with customers.

In the next section, the distinct business model scenarios will be developed separately for EU and SA regions, allowing for a comprehensive analysis of recycling strategies within each context.

4 Results – Business Case Screening

In this part of the study, the NABC methodology results are outlined, focusing on understanding the most promising recycling options. The conclusion highlights the superior choices among current and novel technologies.

4.1 Need

General trends within the LIB recycling industry globally presented in the Chapter 2: Background Information, the regional additional information presented here.

EU vs. SA

As the demand for recycling LIBs surges to power more electric vehicles and tools within the EU, it creates a promising prospect for new entrants and investors. In SA, the market landscape differs from that of the EU, yet the imperative for battery recycling remains unchanged. Creating a LIB recycling sector in SA holds considerable significance due to various reasons. Primarily, SA currently lacks a dedicated LIB recycling facility (TIPS, 2021), resulting in the disposal of spent batteries in landfills or their exportation for recycling purposes. This situation leads to a considerable economic and social loss associated with recycling (Smit, 2020). Additionally, the recovery of valuable metals from these batteries could be contributing to the establishment of a circular economy (Smit, 2019).

Moreover, in SA, the absence of a proper mechanism for handling spent LIBs poses risks to both human health and the environment, contrasting with the safer alternatives offered by recycling processes (Smit, 2020). Establishing a LIB recycling industry in SA is not only about addressing current gaps but also about seizing economic opportunities, promoting environmental sustainability, and safeguarding human health by adopting responsible waste management practices.

Need for Current and Novel Technologies

In both regions, among the current proposed technologies (nine in total), the anticipated future demand for the Nickel-Manganese-Cobalt (NMC) cathode chemistry stands out among all other cathode chemistries. Within the NMC cathode market, there exists a demand for both metal sulphates and NMC hydroxide. However, purchasers of metal sulphates tend to be adaptable when sourcing NMC hydroxide, whereas those procuring NMC hydroxide are typically less flexible in acquiring metal sulphates. Hence, NMC choices become more attractive, particularly when utilizing the widely adopted and practical sulfuric acid (H_2SO_4) for leaching.

In both regions, the primary contrast in the two novel technologies (H_2SO_4 - Novel and MSA - Novel) lies in the choice of acid for leaching - organic Methanosulfonic acid (MSA;CH_3SO_3H) versus the commonly used inorganic sulfuric acid (H_2SO_4). Although the organic option holds promise for future environmental benefits, at present, sulfuric acid proves more economically feasible and practical. Research on the organic acid's use in LIB plants remains limited. Opting for Methanosulfonic acid (MSA;CH_3SO_3H) leaching may not be the optimal choice for the EU to establish a competitive new plant. Additionally, in SA, the lack of expertise emerging from the absence of a recycling facility diminishes the attractiveness of Methanosulfonic acid (MSA;CH_3SO_3H) leaching as a less familiar option.

4.2 Approach

There are nine current and two novel technologies that has been proposed in this study. Brief descriptions of these recycling methods are presented in this section, with more comprehensive details available in Appendix A. This screening study provides a comparative analysis of these nine existing hydrometallurgical recycling methods, which employ these three distinct approaches.

Current Technologies

The focus of the nine existing LIB recycling technologies, see Figure 7, 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 existing 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 existing technologies out of nine, employ solvent extraction techniques to recover metals selectively from the leach solution.

Novel technologies

One technology uses an organic leaching agent called Methanosulfonic acid (MSA; CH_3SO_3H) during the leaching process, while the other technology uses sulphuric acid (H_2SO_4), inorganic acid, as a leaching agent. The two novel technologies are 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;CH_3SO_3H) 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. The short name of the processes is H_2SO_4 – Novel and MSA – Novel.

The short summary of the proposed technologies has been presented in the following Figure 7.

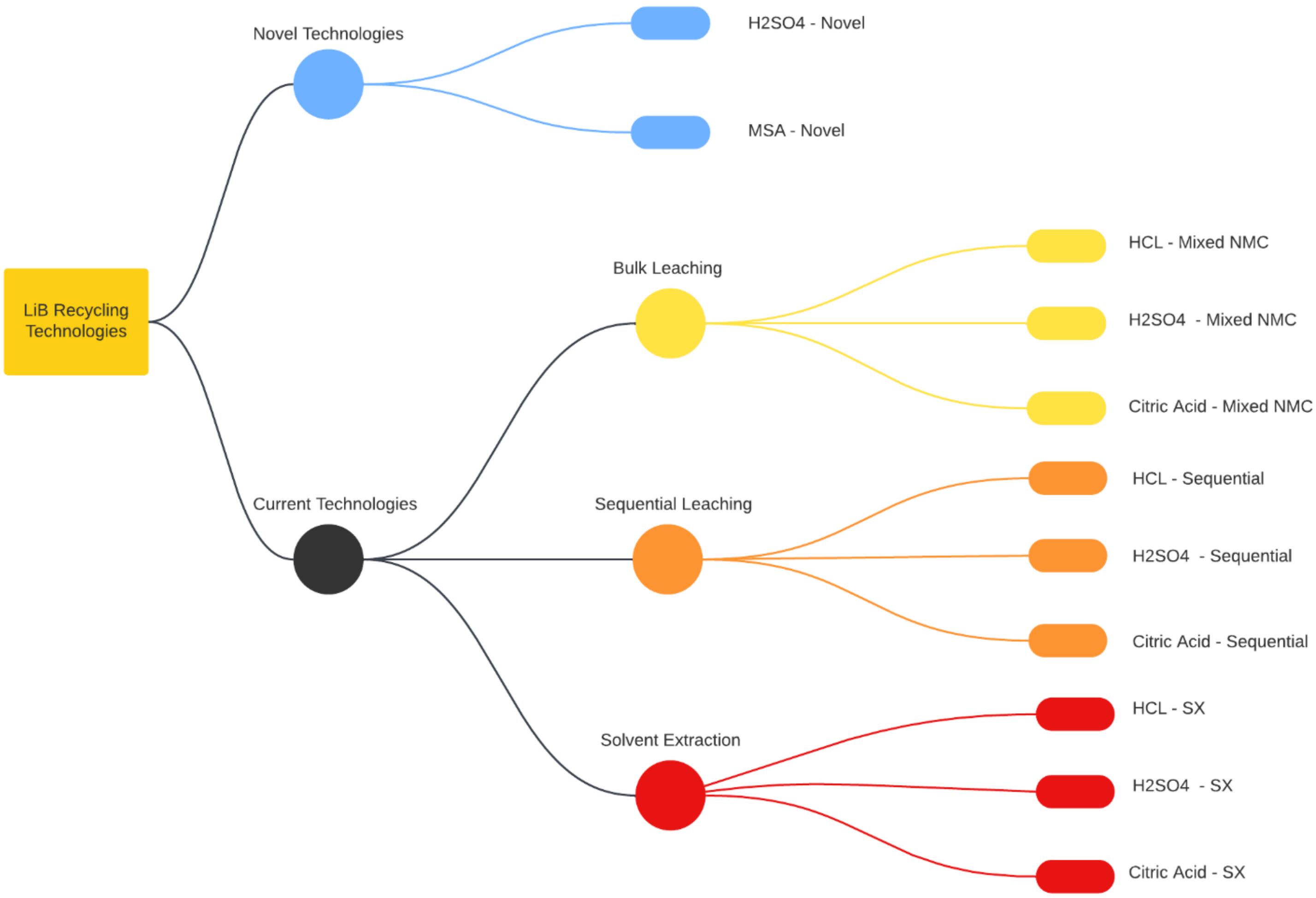


Figure 7. Summary of proposed LIB recycling technologies

4.3 Benefit

4.3.1 LCA Comparison

The first deliverable of this report, “Techno-environmental screening of nine current and two novel technologies within their specific categories”, revealed that considering the strong current focus on climate change, H_2SO_4 – NMC might be preferred over other processes. Of the nine processes, two processes are considered for the full LCA, namely the H_2SO_4 - NMC and HCL - NMC. The H_2SO_4 – Novel technology, resulting in a lower amount of environmental impacts and the similar level of efficiency.

The second LCA deliverable in this report, "Full LCA comparison of one current and one novel technology", showed that the current technology (H_2SO_4 – NMC) presented a slightly higher environmental benefit when it is compared with the novel technology (H_2SO_4 – Novel).

4.3.2 Techno-Economic Assessment – NPV Comparison

4.3.2.1 Profitability Comparison of Current Technologies in SA Context

Maritz (2022) conducted a comparative study for nine different processes for recycling LIBs in SA, using a NPV assessment. The comparison was based on the HCl Sequential precipitation process being the baseline at 100%. The NPV comparison of nine current technologies, outlined in Figure 8, identified three NMC precipitate processes as notably outstanding in NPV performance.

Particularly, the HCl - NMC and H_2SO_4 - NMC processes emerged as the best-performing technology within in terms of profitability. For a more comprehensive understanding, one can refer to Maritz's thesis for detailed insights into this techno-economic assessment (Maritz, 2022).

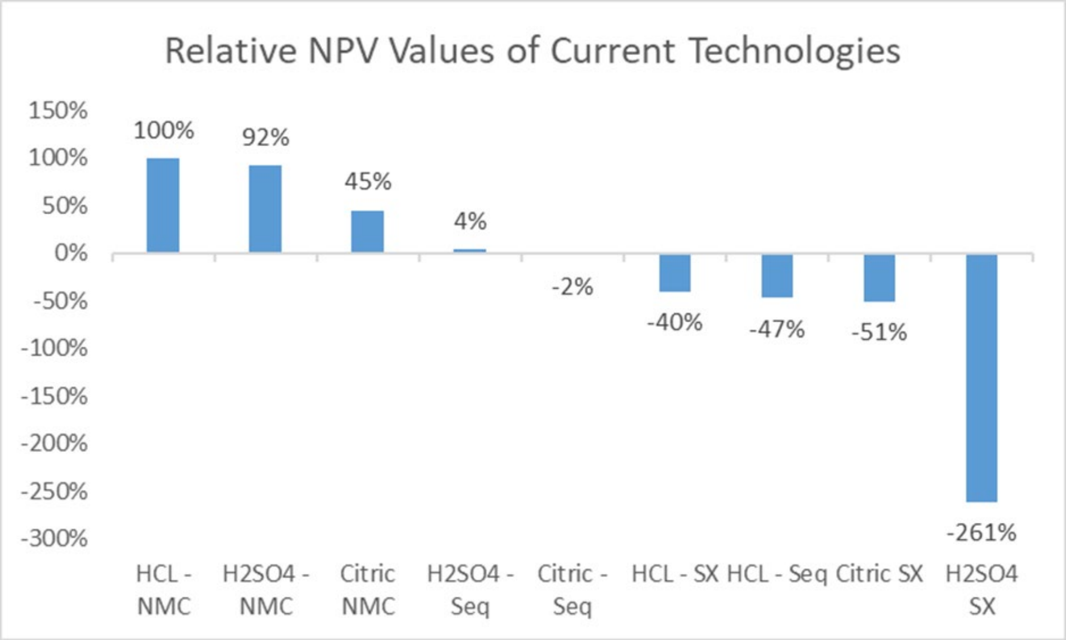


Figure 8. Comparative NPV performance of current technologies for SA (Maritz, 2022)

4.3.2.2 Profitability Comparison of Novel Technologies in EU Context

Ozturk (2024) performed a comprehensive profitability analysis on two novel technologies for recycling LIBs within the EU, employing a TEA. These findings offer a valuable means of comparison between the two novel recycling technologies. Presented in Figure 9, the profitability assessment data has been normalized using the H_2SO_4 – Novel process as the reference point. Notably, the H_2SO_4 – Novel recycling process displays a favourable NPV over MSA – Novel, showcasing its potential viability. Conversely, the MSA – Novel process demonstrates an NPV close to zero, indicating limited economic feasibility. This underscores the superior promise of the H_2SO_4 – Novel process compared to its counterpart. The primary factor driving this difference lies in the OPEX, including raw material expenses, wherein the MSA option proves significantly pricier compared to the H_2SO_4 – Novel alternative.

Detailed profitability calculations for both technologies are available in the Appendix.

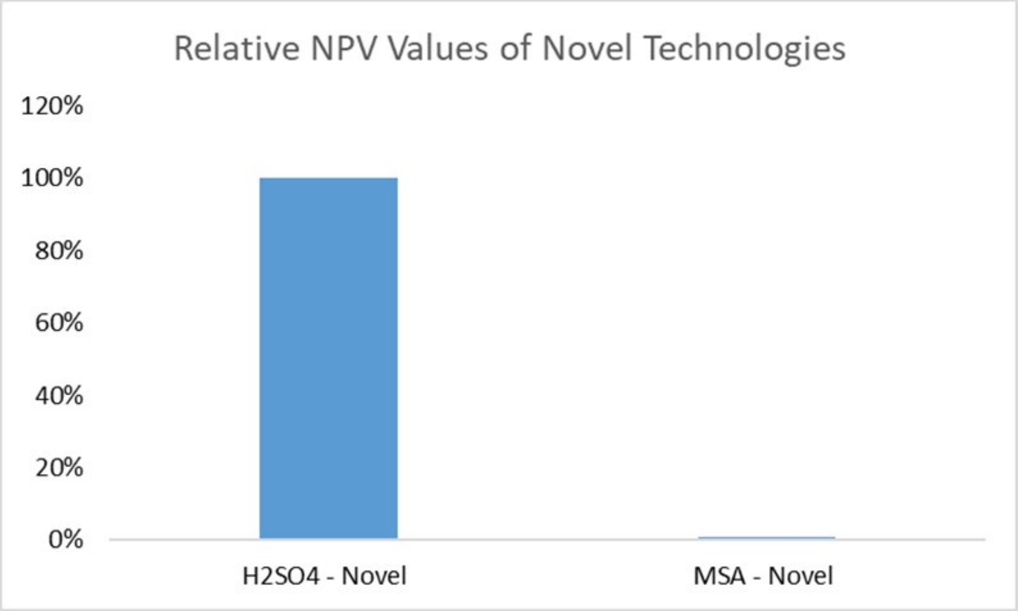


Figure 9. Comparative NPV performance of novel technologies for EU

In conclusion, the *H_2SO_4* – Novel process emerges as the economically best-performing technology within EU in terms of profitability.

4.3.2.3 Profitability Comparison of Selected Current and Novel Technologies in EU Context

The ELIMINATE project aimed to identify the most sustainable methods among the current and novel technologies that were evaluated. In the previous two TEA studies, the best current and novel technologies have been selected within SA and EU regions respectively. However, to be able to compare the current and novel technologies, a separate TEA was generated for EU by updating the SA TEA for current and novel technologies.

Based on this update, where the update methodology and details are presented in the Appendix, the NPV results of two current technologies and two novel technologies have been compared by normalizing the results based on the H_2SO_4 – Novel option in the following Figure 10.

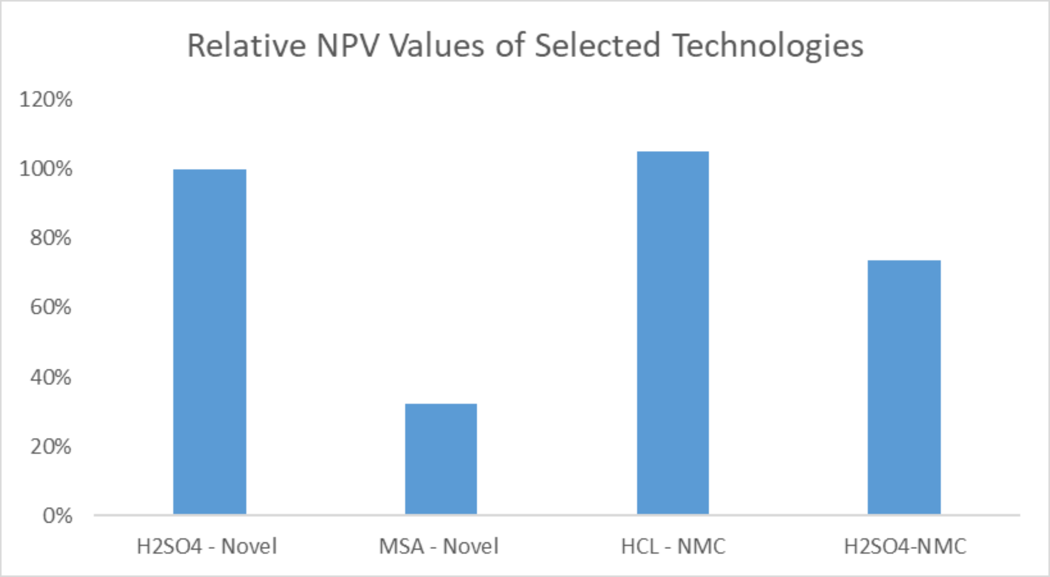


Figure 10. Comparative NPV performance of two current and two novel technologies for EU (updated)

To offer detailed insights and depict the NPV changes over the years, Figure 11 illustrates the results for the four technologies. Notably, the HCL – NMC and H_2SO_4 – Novel technologies emerge as the most promising in terms of their potential economic success.

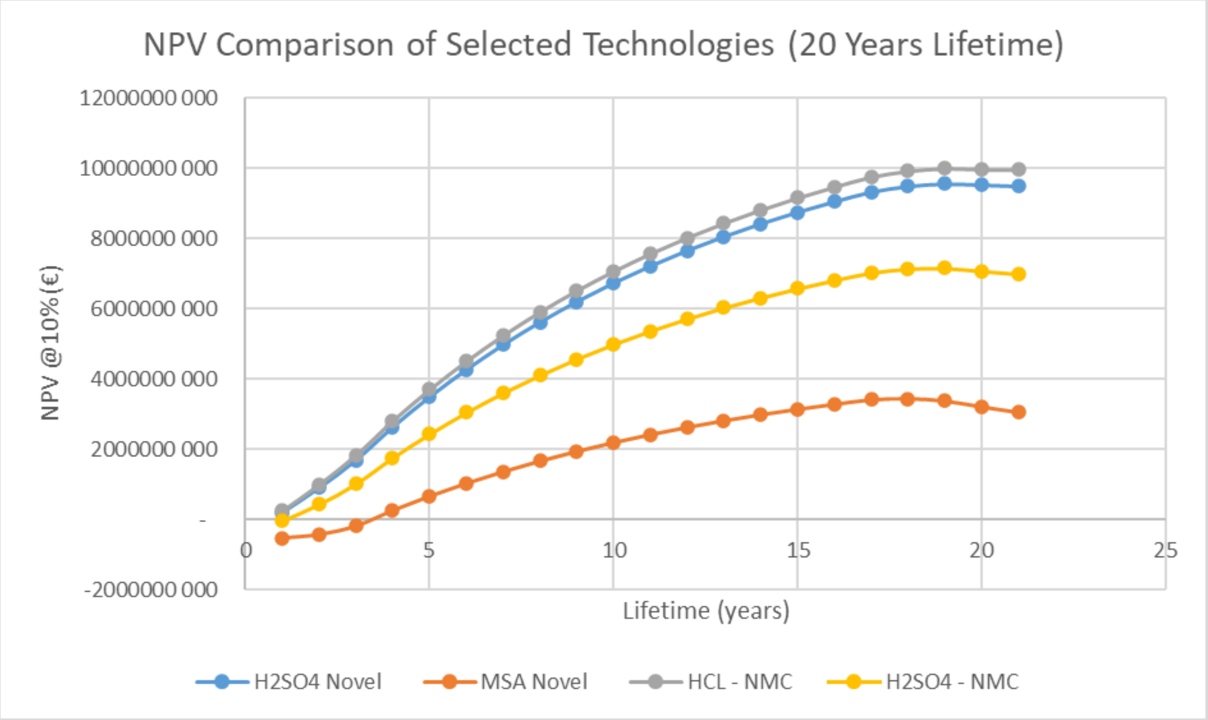


Figure 11. NPV Comparison of current and novel technologies during the 20 years period in the EU context.

4.3.3 CAPEX and OPEX Comparison

CAPEX and OPEX comparison have been done based on the third TEA results (Profitability comparison of selected current and novel technologies in EU Context) for two current (H_2SO_4 - NMC and HCL - NMC) and two novel technologies (H_2SO_4 - Novel and MSA - Novel). To present the more representative CAPEX and OPEX results, the TEA results from the 11th year of the 20 years projected plant lifetime were used. Detailed CAPEX and OPEX results for the entire 20-year duration are available in Appendix C for a more thorough understanding.

CAPEX results, presented in the Figure 12 reveals that the current technologies have a better position when it is compared with the novel technologies. Both current and novel technologies in their respective categories share the same CAPEX values, preventing further comparisons within each category. This similarity arises from both current and novel technologies utilizing very similar production routes, resulting in minimal distinction in equipment selection between them.

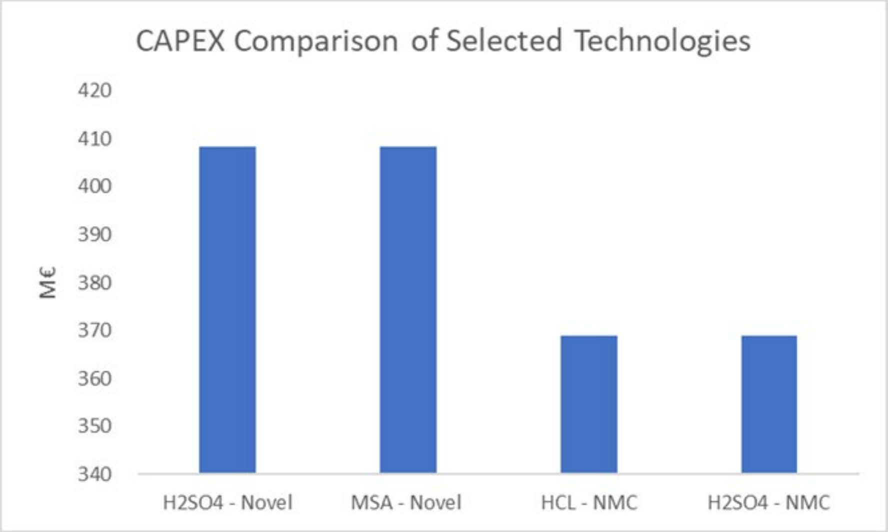


Figure 12. CAPEX comparison of two current and two novel technologies

In terms of OPEX, results presented in the Figure 13, the MSA - Novel and H_2SO_4 – NMC options emerge as less favourable, primarily due to differences in the chemicals utilized during production, influencing OPEX costs significantly. The difference in OPEX constitutes the most substantial difference between these technologies, notably driven by expenses related to raw materials and utility costs.

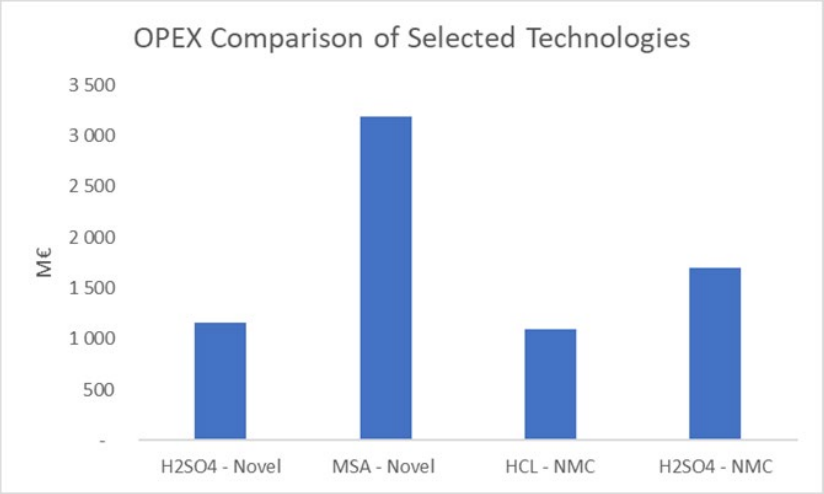


Figure 13. OPEX comparison of two current and two novel technologies

Analysing both CAPEX and OPEX outcomes, it becomes evident that the H_2SO_4 – Novel and HCL - NMC options exhibit the better economic viability.

4.3.4 Industry Practice

This section aims to prioritize options with better practicality for the LIB technologies. Khun (2023) highlights that among the current technologies, NMC production processes stand out for their relative ease, lower demands, and superior recoveries. As per the study's findings, the more favourable technologies among the nine current options are HCL – Sequential and NMC, as well as H_2SO_4 – Sequential and NMC.

In terms of novel technologies, comparing them solely based on practicality isn't straightforward since their flowcharts share similarities. Their distinctions lie in the chemicals used during the acid leaching. Instead of a direct comparison of the technologies themselves, it's more illuminating to focus on the acid employed in these processes. In the industry, H_2SO_4 stands out as the most cost-effective acid option. However, a comprehensive economic analysis should consider various factors, including equipment size and other operational expenses. Organic acids like citric acid or MSA, on the other hand, face challenges in industrial practice. These acids haven't proven themselves on an industrial scale, primarily due to their higher costs and potential side reactions with other chemicals. Additionally, recycling organic reagents poses a significant challenge, further diminishing the practicality of MSA as a novel technology when compared to alternative options.

From a technical standpoint, the novel technologies boast the capability to process various battery chemistries, eliminating the limitation to a specific type of battery chemistry like current technologies. However, when contrasting these novel technologies with existing ones like NMC options, they entail additional steps in the production of end products, potentially reducing practicality in comparison to current technologies.

4.3.5 Reagent Availability

In this study, the proposed LIB recycling technologies involve various chemicals detailed in the Appendix (chemicals listed for current technologies presented in the Maritz (2022) thesis). Of particular significance among these chemicals are the leaching agents, categorized as either organic (e.g., citric acid) or inorganic (e.g., sulfuric acid) acids.

In the EU, reagent availability benefits from a well-established chemical industry and robust supply chains. Regulatory frameworks prioritize safety, quality, and environmental concerns, ensuring a consistent supply of both organic and inorganic acids.

In South Africa (SA), reagent availability may fluctuate due to factors such as market demand, local production capabilities, and economic conditions. While SA possesses a chemical industry, certain reagents' availability might be influenced by import dependencies, infrastructure, and distribution networks, leading to potential variations in supply and pricing.

Despite the global availability of reagents across both the EU and SA, inorganic acids seemingly exhibit higher availability compared to organic acids within these contexts in the market.

4.3.6 Availability of Product Buyers

In 2022, Khun conducted a buyer availability analysis utilizing ELIMINATE project data for current technologies. The findings indicate that HCL – NMC and H_2SO_4 – NMC (producing NMC Hydroxide) exhibit greater potential for future buyers in both SA and EU contexts. For additional information, refer to Khun's work in 2023 for detailed insights (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023).

The products of novel technologies different than current ones. While novel technologies differ in processing steps and leaching reagents used, they yield identical final products: manganese dioxide (MnO_2), nickel hydroxide ($Ni(OH)_2$), cobalt tetroxide (Co_3O_4), and lithium carbonate (Li_2CO_3). Lithium carbonate holds substantial industrial importance, primarily serving as a precursor in Li-ion batteries. Consequently, the products derived from novel technologies are equally accessible, positioning them as potentially superior alternatives to current technologies on a global scale.

4.3.7 Recovery Rates and Purity

In Khun's (2023) thesis, a comparison of recovery rates and purity was conducted for current technologies. In typical chemical processes, there is often a trade-off between purity and recovery. In this analysis, it was assumed that all product purities meet the required grades, shifting the focus to recovery as the important factor in ranking the processes.

The evaluation revealed that mixed NMC processes yield low-purity products but with high recoveries, while sequential precipitation (and SX) processes result in relatively lower recoveries of manganese (Mn), nickel (Ni), and lithium (Li), but yield high-purity products. However, given the assumption that battery-grade purity can be achieved across all approaches for selection purposes, the prominence shifts to recovery as a more crucial factor than purity. Hence, considering their higher recovery rates, mixed NMC processes can be deemed superior to other methods.

In the context of novel technologies, mirroring the approach of current methods, the assumption - proven by laboratory tests - is that battery-grade purity can be attained in both technologies. As previously mentioned, the novel technologies have been developed within this project by Karadeniz Technical University, underwent small-scale laboratory tests at Exitcom Recycling. The initial phase of these laboratory scale tests involved completing the H_2SO_4 – Novel tests, wherein waste batteries were dissolved and resulting products precipitated sequentially. Recovery rates proved sufficient at the end of the analysis.

For the second technology, first MSA leaching was conducted in laboratory tests. However, the rest of the tests are not completed. The rationale behind this choice stemmed from the fact that, after the initial leaching step, the leachate underwent identical procedural steps as the previous H_2SO_4 - Novel method. Consequently, the expectation is for recovery rates and purities to be highly similar for both novel technologies, despite variations in chemical quantities, types, and the number of process steps involved.

When comparing current (mixed NMC processes, considered the superior option) and novel technologies, a notable distinction lies in the products they yield. In the initial study of current technologies, the precipitate comprises a mix of various metals, whereas in the novel technologies, the products are individually precipitated. Consequently, this comparison might not offer comprehensive insights, especially considering that all technologies have demonstrated achieving battery-grade recovery rates.

4.4 Competition

In the EU region, there's a need for the development of economically viable, high-capacity, and cost-effective LIBs recycling methods to sustain a competitive battery industry. In the SA region, the market lacks existing recycling facilities, requiring newcomers to compete on a global scale. For detailed insights on the competitive landscape in both the EU and SA regions, refer to Chapter 2: Background Information in the report.

To thrive in the LIB recycling markets of the EU and SA, mastery of competitive skills and deployment of cost-effective, high-capacity recycling methods are paramount. New EU regulations emphasizing LIB recycling efficiency further highlight the need for innovative, environmentally friendly processes. Additionally, forming robust partnerships with diverse stakeholders in both regions offers a potent counterstrategy against entrenched competitors. Ultimately, a competitive strategy centered on low-cost, high-capacity production is imperative in both the EU and SA markets.

4.5 Technology Selection for Business Model Development

NABC study showed that some of the technologies are better than the others. Based on the results, H2SO4 - NMC for current technologies and H2SO4 – Novel for novel technologies selected as the best methods for the next step: business model development.

5 Results – Business Model Development

5.1 Value Chain Integration Scenarios for EU

Based on the context provided, three distinct value chain integration scenarios have been formulated specifically for the EU region. These scenarios, outlined as follows:

- Scenario 1: Establishment of a pre-treatment included recycling plant
- Scenario 2: Establishment of a recycling plant without pre-treatment
- Scenario 3: Establishment of an in-house recycling plant by Battery Producers

These scenarios have been designed and discussed for the ELiMINATE project based on research outlined in the Ozturk (2024) thesis. While the thesis remains unpublished due to confidentiality constraints, the essential details pertaining to these scenarios were presented comprehensively within this report.

Scenario 1: Establishment of a pre-treatment included recycling plant

In the initial scenario, a LIB recycler strategically invests in the construction of a cutting-edge mechanical pre-treatment plant and an innovative hydrometallurgical recycling facility situated in a single location. This integrated setup of pre-treatment and recycling is aims to optimizing operational efficiency. Relying on the strategic decisions of investors, the battery recycling facility has the flexibility for establishment in any EU local, where gathering and accessing battery waste is convenient, with the aim to reduce transportation costs. For a deeper comprehension of material flow analysis topic, please refer to the ELiMINATE report by Emilsson & Ozturk (2023).

To commence, the battery recycler acquires spent LIBs from designated collectors, by paying the associated expenses. The collected spent LIBs are subsequently transported to the recycling facility for further processing. Via pre-treatment and recycling phases, the recycler efficiently recovers valuable raw materials from the LIBs and produce products that can be used by the LIB producers. Any type of battery (e-vehicles, electronics etc.) can be transported to this facility based on the company’s priorities and strategic decisions. The core value proposition revolves around battery recycling.

Upon concluding the recycling stages, the recycler's responsibility expands to identifying potential battery producers (customers) interested in utilizing the recycled LIB products. Leveraging the expertise of its sales and marketing division, the recycler seeks partnerships with battery producers capable of effectively utilizing these products. These collaborations facilitate the delivery of quality products to battery producers while compensating the recycler for its efforts. Key alliances with collectors and battery manufacturers remain essential. Financially, the primary revenue stream for the recycler comes from the target customers (battery producers in this scenario) who purchase the recycled LIB products, constituting the most significant income source. To comprehensively outline this initial scenario, a diagram (Figure 14) has been crafted to visually represent the flow of funds, materials, and information within the proposed business model. This visual aid aims to provide stakeholders with an in-depth understanding of the intricate dynamics involved, emphasizing the value proposition inherent in the recycler's operations.

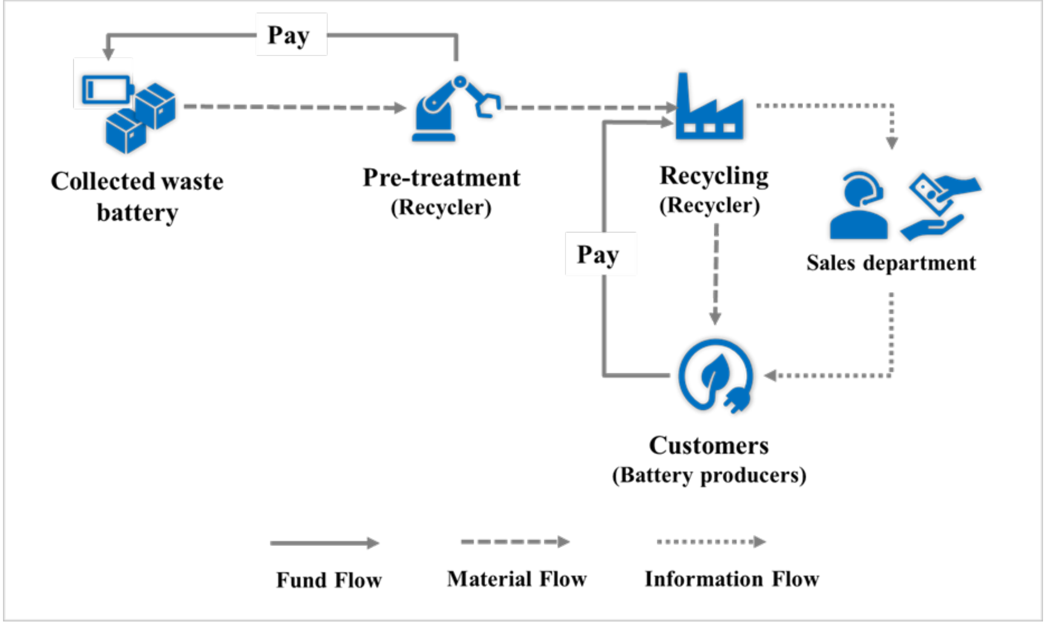


Figure 14. Flowsheet of Business Model Scenario 1

There are some assumptions in this scenario:

- The collector(s) operates independently from the recycler and is responsible for classifying LIBs based on their chemistries and determining their future

lifecycle scenarios (remanufacturing or recycling). Only batteries requiring recycling will be forwarded to the recycler, with the collector fulfilling the sorting and delivery requirements as requested by the recycler.
- The assumption here is that the transportation costs associated with the logistics of spent LIBs fall under the responsibility of the collector(s). This report does not delve into discussions about the proximity or optimal placement of collection centres, as minimizing transportation distances isn't the primary focus of this research. Hence, detailed insights regarding collection centre placement won't be provided.

Scenario 2: Establishment of a recycling plant without pre-treatment

The literature review revealed a strong presence of established pre-treatment plants exclusively for LIBs. These plants serve a distinct market focused on a material called "black mass,". As previously indicated, "black mass" denotes the final product derived from the processing of spent LIBs in pre-treatment plants.

In this second scenario, the LIBs recycler makes a strategic move by investing in a hydrometallurgical recycling plant. This unique plant skips the mechanical pre-treatment stage, unlike Scenario 1. Here, the recycling company acquires black mass as its main input for the hydrometallurgical recycling process. How the black mass producer treats the material (using thermal or mechanical methods) varies based on their operational choices. To ensure a consistent supply of black mass, the recycling company strikes a mutually beneficial deal with the producer, compensating for the acquired material. Key partners include these black mass producers.

After the hydrometallurgical recycling, the recycling company takes on the responsibility of marketing and selling the recycled products. Their main customers in this scenario are battery producers. To give a visual representation of this business model (Scenario 2), Figure 15 outlines the process stages, material flows, and the value proposition of the hydrometallurgical recycling method.

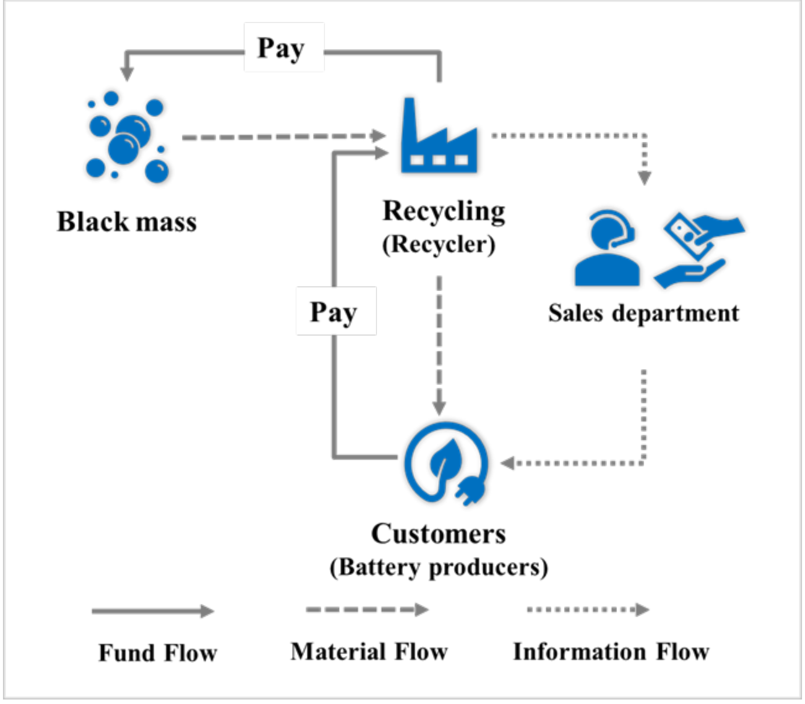


Figure 15. Flowsheet of Business Model Scenario 2

In this scenario, it's assumed that the black mass producer(s) are responsible for covering the transportation costs associated with the logistics of black mass.

Scenario 3: Establishment of an in-house recycling plant by Battery Producers

In this third scenario, the business model adopts the concept of "reverse logistics/supply chain." It involves LIBs producers or suppliers offering a buy-back option to customers (Kachate, Sharma, & Baidya, 2023). In this setup, the battery producer invests in an in-house pre-treatment plant and a hydrometallurgical recycling facility. The focus here is on establishing effective collaboration with customers and clear communication channels to facilitate the collection of spent LIBs. The main goal is to create a circular approach to LIBs recycling, boosting recycling rates by actively involving customers in the recycling process.

In Figure 16, the circular business model scenario 3 begins with customers purchasing LIBs for their electric vehicles or tools. During this purchase, customers are informed about recycling options and possible incentives for returning spent LIBs in the future. Their details are logged into the LIBs producer's communication center database as "future suppliers of spent LIBs". As the LIBs approach the end of their life cycle, either the customer or battery producer can start the return process by contacting the communication center. If customers don't initiate the return, the battery producer can proactively contact them using the estimated end-of-life timeframe for the LIBs.

Collectors or outsourced logistics providers assist in gathering spent LIBs from customers and transporting them to the LIBs producer for recycling. These spent LIBs then head to the battery producer's recycling facility for mechanical pre-treatment and hydrometallurgical recycling. The recycled materials are used to make new LIBs. Additionally, the in-house recycling facility handles intermediate materials or defective LIBs from production, adding more value for the LIBs producer. Customers can choose to buy the new product from the same LIBs producer.

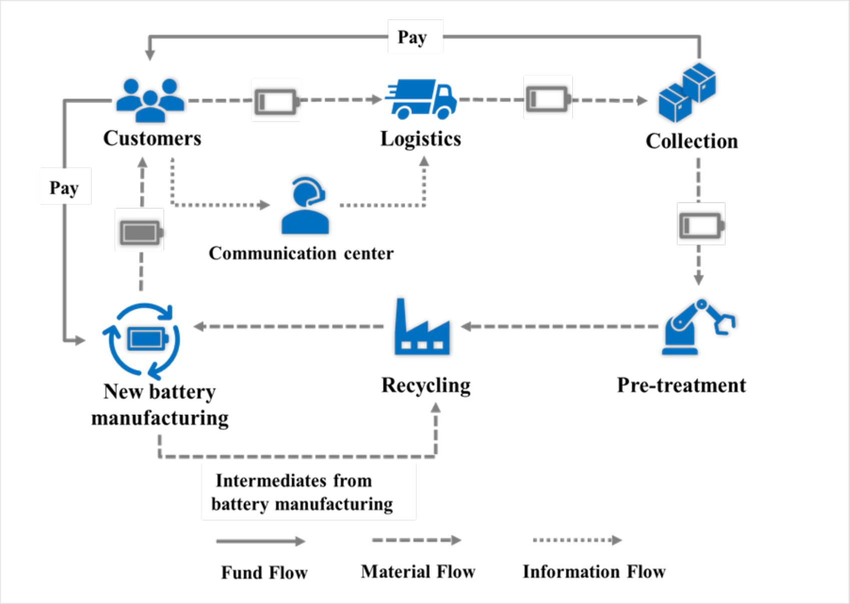


Figure 16. Flowsheet of Business Model Scenario 3

This business model scenario creates varied value for both customers and battery producers, showcasing different cost and revenue streams compared to earlier scenarios. Importantly, the focus shifts from battery manufacturers to battery users. Setting up recollection and repurposing centers involves choosing construction sites, but analyzing their specific locations isn't covered in this study.

Additionally, this scenario mainly prioritizes spent electric vehicle LIBs. As battery production rates are expected to increase, electric vehicle batteries are larger and may be more straightforward to recycle compared to smaller batteries used in personal tools.

5.1.1 Profitability Results of Business Model Scenarios

The scenarios are presented and discussed in the previous part. To be able to understand which scenarios are giving the higher predicted profitability, a techno-economic assessment conducted within the thesis of Ozturk (2024), the details of this TEA have been presented in the Appendix.

The NPV values of these scenarios, considering selected novel technology (H2SO4 -Novel), have been compared and illustrated in Figure 17.

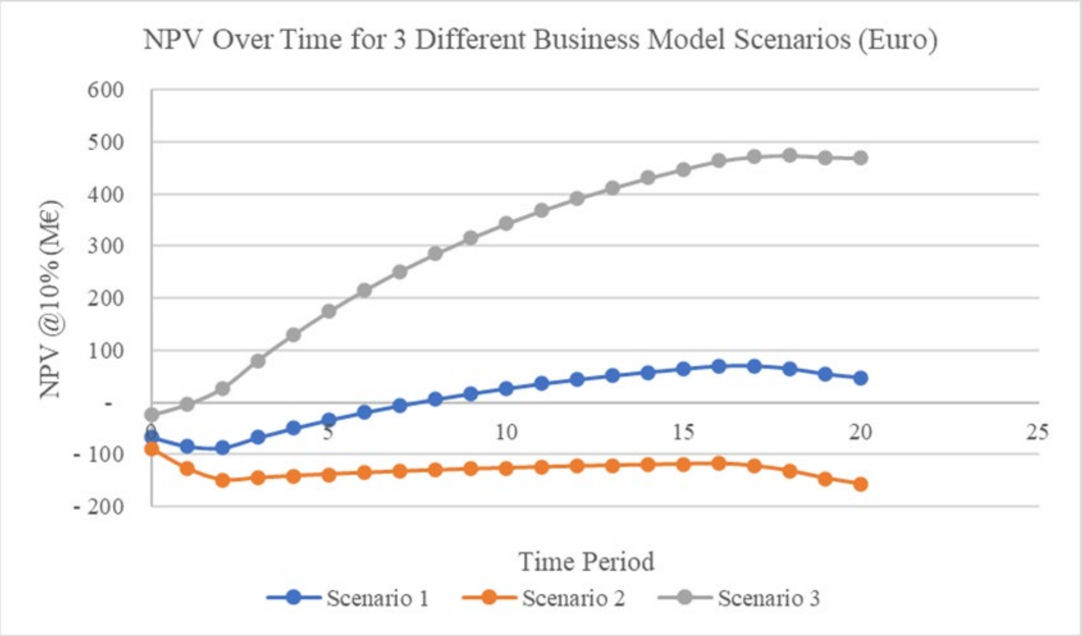


Figure 17. NPV values for EU value chain integration scenarios

In this analysis, the NPV initially shows a decline in scenarios 1 and 2, attributed to increased capital usage during plant expansion. Subsequently, growth decelerates during decommissioning as plant capacity diminishes. Notably, scenario 3 emerges as a superior performer compared to the others.

5.2 Value Chain Integration Scenarios for SA

As it has been mentioned in the introduction, the value chain scenarios for SA region have been developed in Khun (2023) and Vooght (2022) thesis, the summary of the scenarios and the rationale of a prediction of the most likely scenario a LIB recycler in SA will face have been explained here. In case there is need for further explanations, the theses of Khun (2023) and Vooght (2022) has been included in the Appendix for further reference.

Four distinct value chain business model scenarios significantly impact the overall financial outcomes of an LIB recycling plant within the SA region. These scenarios underwent a financial comparison considering two EoL LIB supply options and two outbound logistics cost scenarios. These business model scenarios include:

- Scenario 1: Zero EoL LIBs cost & outbound logistics costs passed on,
- Scenario 2: Vertical integration EoL LIBs cost & outbound logistics costs passed on,
- Scenario 3: Zero EoL LIBs cost & outbound logistics included,
- Scenario 4: Vertical integration EoL LIBs cost & outbound logistics included.

Outbound logistics, the management of goods leaving a company to reach customers or distribution channels, is pivotal in the value chain. To understand the impact of outbound logistics, the first two scenarios exclude its costs, while the latter two scenarios incorporate these costs. Also, in two scenarios, feed costs are assumed to be zero, while the other two include costs from vertical integration. Vooght (2022) introduced a vertically integrated collection system, integrating the LIB recycling plant into a setup where it's part of the same company overseeing dismantling centers. These centers both generate revenue and incur costs, covering the entirety of the network's expenses.

To make a comparison, the economic profitability of four different scenarios calculated for the current technology H2SO4-NMC process. While this sufficed for prioritizing scenarios within the SA region, calculations for the novel technology were not completed, as it was analysed within the EU value chain scenarios.

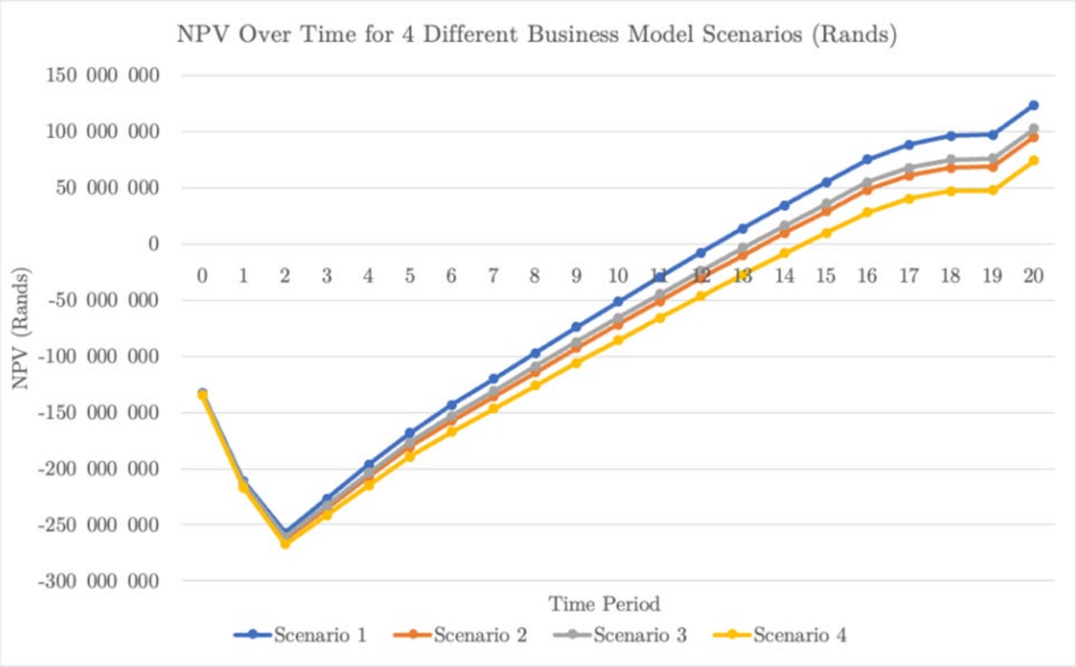


Figure 18 . Visual depiction of the NPV for the four scenarios

NPV initially dips due to additional capital used for plant expansion and decelerated NPV growth occurs during decommissioning as plant capacity diminishes. Year 20 witnesses a significant NPV surge from the salvage value of invested capital.

Finally, based on this assessment, value chain business model Scenario 1 emerged as the most likely scenario for adoption.

5.3 Business Model Canvas

At the conclusion of the value chain integration scenario development part, the potentially best scenarios for both the EU and SA have been identified. Although the scenarios are rooted in differing regional contexts, there are significant commonalities among them. These key consistencies are illustrated in Figure 19, highlighting the no outbound logistic costs and no feed costs (EoL LIB batteries are acquired for free).

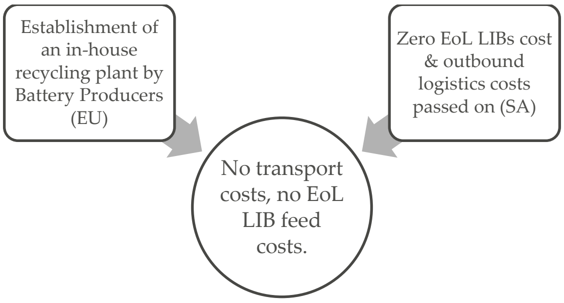


Figure 19. Commonalities of selected value chain scenarios for EU and SA regions

Based on the selected value chain integration scenarios, final part of this study is to streamline the approach, Business Model Canvases (BMCs) was crafted, distinguishing between the current and novel technologies (if there are any). As it has been mentioned previously, the most advantageous value chain integration scenarios for this study involves assuming zero EoL LIB costs while eliminating outbound logistics. As a result, only one BMC was created, segregating the regions and scenario specific details accordingly.

The BMC were applied to recognize new aspects in the developed value chain scenarios for current and novel technologies within the EU and SA regions. To enhance clarity, different colours were employed within the BMC, explained in Table 1, aiding readers in identifying additional benefits and requirements.

Table 1. Color codes for BMC elements

Colour Code		**Representation in BMC**
Black	⬛	Commonalities between EU- SA regions and value chain integration scenarios
Orange	🟧	EU-specific
Green	🟩	SA-specific
Red	🟥	Elements applicable in establishing an in-house recycling plant

Within Table 1, black-coloured sections indicate commonalities between the EU and SA regions, as well as across value chain scenarios. Focusing solely on the EU requires attention to the orange-coloured elements combining with the black parts, while emphasis on the SA involves consideration of the green-coloured items alongside the black parts.

To illustrate differences between value chain integration scenarios, blue highlights items relevant only to zero EoL LIBs cost and outbound logistics, while red signifies additional elements applicable when establishing an in-house battery recycling plant.

The BMC findings are summarized in Table 2, followed by detailed explanations in subsequent sections.

Table 2. BMC for selected technologies (EU and SA region)

<table>
<tr>
<td rowspan="2">**Key Partners**
EoL LIB collectors
EoL LIB distributers
Raw material providers
Technology providers (etc. universities)
LIB recycling experts
Research institutes
Government
Financial partners (Banks, investors)
Customers (battery users)
Battery producers (X)
Current LIB recyclers
Current non-LIB recyclers</td>
<td>**Key Activities**
EoL LIB recycling
Metal production by recycling
Networking between different stakeholders (battery users, battery producers, EoL battery collectors, government etc.)
R&D
Circular logistics (buy-back option for customers)</td>
<td rowspan="2">**Value Propositions**
Waste LIB recycling
Environmentally friendly supply chain - low CO_2
Cheap and sustainable waste handling
Available and secure raw materials supply for LIB production
Recycling mid-production wastes and defective batteries
Cost reduction
Buy-back at the EoL: reverse logistics.</td>
<td>**Customer Relationships**
Business to Business (B2B)
Business to Customer (B2C)
Personal assistance
Long-term relations</td>
<td rowspan="2">**Customer Segments**
LIB producers (local and international)
Government bodies</td>
</tr>
<tr>
<td>**Key Resources**
Patented LIB recycling technology
Collaboration and cooperation with different stakeholders
Battery producer experts
Providing distribution channels
Workers (for battery production, service, and customer dialogue)</td>
<td>**Channels**
Website – email
Marketing
Social media
Customer communication center
Mobile application
Eco-labels, certificates
Direct contact with the potential stakeholders
Events, conferences, and congresses.</td>
</tr>
<tr>
<td colspan="2">**Cost Structure**
CAPEX – OPEX
Production costs (utilities, raw materials etc.)
Workers (e.g., salary expenses) and administrative costs
Waste management
Reverse logistics: cost of buy-back and return of waste LIBs.
Marketing expenses</td>
<td colspan="3">**Product sales**
Government incentives
Continuous/fixed direct sales to customers (pay-back option)
Reusing the mid-production wastes, defective or unsellable LIBs (cost reduction and value from waste).</td>
</tr>
</table>

5.3.1 Value Proposition

Leveraging innovative EoL LIB recycling technologies is crucial for creating value in the recycling process. These technologies not only facilitate the production of new products from waste LIBs but also contribute to reducing the demand for primary metal production. By establishing an environmentally friendly supply chain for battery production, these innovations result in improved CO2 emission outcomes. Additionally, such technologies present more sustainable solutions and potentially lower prices for products used in LIB production by battery manufacturers. Another crucial value proposition is ensuring an accessible and secure local raw materials supply for LIB production.

If a battery recycling facility operates within a battery production plant, there are added value propositions. These include recycling mid-wastes and defective batteries in the recycling process easily, leading to cost reductions. Additionally, offering a buy-back option for EoL LIBs entails establishing a reverse logistics system for returning batteries.

5.3.2 Customer Segment, Relationship, and Channels

The LIB recycling facility's main customers are LIB or non-LIB producers, both local and potentially international depending on the facility's location. This will mainly involve Business-to-Business interactions. Additionally, government bodies responsible for landfilling and waste management may also engage as customers, particularly in cases requiring landfill cleaning and waste remediation.

The customer relationships will primarily revolve around Business-to-Business interactions, emphasizing the need for continuing partnerships to ensure a sustainable supply chain for these customers. In scenario involving an in-house battery recycling facility, the dynamics may shift towards a business-to-customer model as batteries are sold and collected from customers. Personalized assistance will be important in these instances to foster healthy and supportive customer relationships.

Various communication channels can be utilized to engage with customers and society, including social media, websites, direct interactions with stakeholders, participation in events, conferences, and congresses. Additionally, eco-labels and certificates can serve as channels to communicate environmental contributions.

In scenarios where the LIB recycling facility is integrated into the battery production facility, establishing a dedicated communication channel between the battery plant and customers for collecting waste batteries becomes crucial. This can be facilitated through a specialized customer communication centre and a mobile application.

5.3.3 Key Resources, Activities, and Partners

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5.3.4 Cost Structure and Revenue Streams

The key components of the cost structure for a LIB recycling plant include CAPEX, OPEX, production costs, raw materials, and labour. Another important element is the cost associated with waste management. Since the proposed current and novel technologies involve hydrometallurgical LIB recycling, an effective waste management system becomes necessary for the overall operational efficiency of the plant.

An in-house recycling plant with a buy-back option requires a reverse logistics system for collecting batteries from customers, adding to operational costs. Moreover, the competitive LIB recycling market in the EU may necessitate increased marketing expenses to address the challenges posed by this competitive landscape.

The main revenue streams include sales of recycled products and government incentives. Government incentives are currently fundamental to overcoming the costs associated with recycling and contribute significantly to the profitability of the LIB recycling company. Given the environmental benefits of LIB recycling, these incentives are crucial and actively supported by governments.

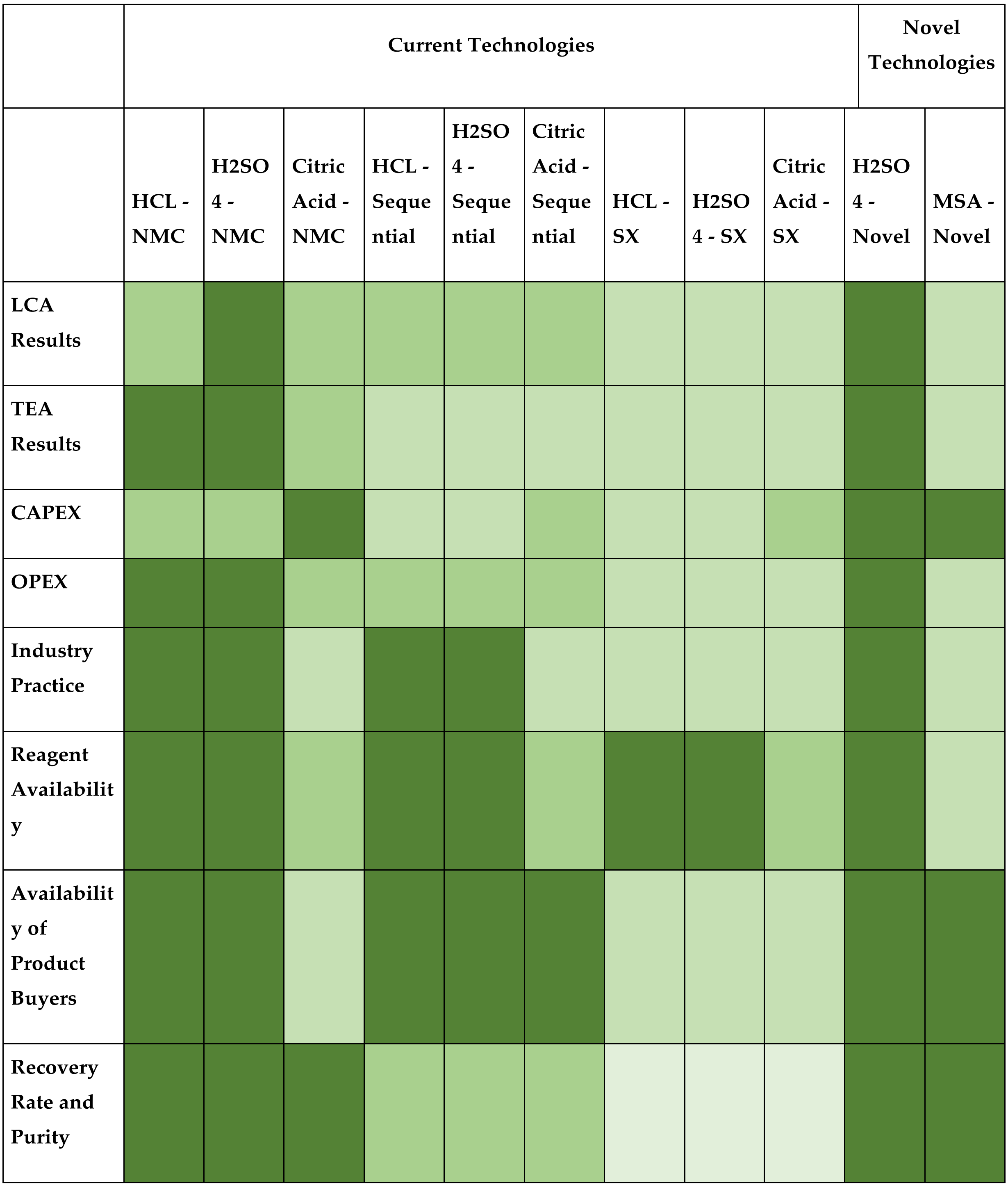
In the case of in-house LIB recycling plant, the revenues are described as cost reduction in the battery production system. Additionally, a continuous direct sale to customers based on a buy-back option allows customers to purchase new batteries while leaving the old ones, enabling planned sales based on battery life estimates.

6 Conclusions

6.1 Business Case Screening

During the business case screening, the NABC methodology helped identify top-performing EoL LIB recycling technologies, encompassing both current and novel options. The findings underscore a critical need in both the EU and SA for innovative solutions that can surpass existing market challenges. Valuable insights, particularly from the "benefits" section, guided the comparison process. Table 3 shows each technology's potential benefits, with varying shades of green indicating their comparative advantages—darker shades denote higher benefits compared to others.

Table 3. Results of business case screening



	Current Technologies									**Novel Technologies**	
	HCL - NMC	**H2SO4 - NMC**	**Citric Acid - NMC**	**HCL - Sequential**	**H2SO4 - Sequential**	**Citric Acid - Sequential**	**HCL - SX**	**H2SO4 - SX**	**Citric Acid - SX**	**H2SO4 - Novel**	**MSA - Novel**
LCA Results	▓	■	▓	▓	▓	▓	▒	▒	▒	■	▒
TEA Results	■	■	▓	▒	▒	▒	▒	▒	▒	■	▒
CAPEX	▓	▓	■	▒	▒	▓	▒	▒	▓	■	■
OPEX	■	■	▓	▓	▓	▓	▒	▒	▒	■	▒
Industry Practice	■	■	▒	■	■	▒	▒	▒	▒	■	▒
Reagent Availability	■	■	▓	■	■	▓	■	■	▓	■	▒
Availability of Product Buyers	■	■	▒	■	■	■	▒	▒	▒	■	■
Recovery Rate and Purity	■	■	■	▓	▓	▓	░	░	░	■	■

In the competition part of the business case screening, a critical revelation emerged: low-cost, high capacity production stand out as fundamental competitive strategy for new entrants in both the EU and SA markets. Additionally, the environmental advantages offered by the selected technologies were key considerations in this strategic assessment.

The business case screening study identified H_2SO_4 – NMC from current technologies and H_2SO_4 – Novel from novel technologies as the optimal choices for both the SA and EU markets. Interestingly, the differences between these regions didn't significantly impact these selections, given the globalization of the battery industry.

6.2 Business Model Development

The aim of developing the business models in this deliverable was to identify optimal approaches for implementing a battery recycling facility utilizing proposed LIB recycling technologies. Through evaluation, three value chain integration scenarios were presented for selected technologies within the EU and four for the SA region. One value chain integration scenario was chosen for each region. Despite differing market landscapes in SA and EU, the selected scenarios share commonalities, particularly the no feed cost approach in EoL LIBs. Consequently, a combined BMC was created encompassing the chosen technologies and their respective scenarios.

The BMC results highlight the significance of partnerships with various stakeholders to extract value from these technologies and address prevailing market challenges. Moreover, the implementation of innovative recycling solutions like in-house battery treatment plants holds potential for local application. Such reverse logistics options could secure sustainable profitability for future companies, potentially offering a less competitive landscape.

In summary, this deliverable outlined potential business opportunities by employing the proposed current and novel technologies within the EU and/or SA. The presented value chain integration scenarios offered diverse perspectives for various stakeholders, allowing readers to assess and determine the most favorable scenarios. The document served as a comprehensive resource for individuals interested in exploring investment strategies and opportunities in these specific regions.

7 Recommendations

- Future studies could explore how LIB recyclers and producers can collaborate to establish businesses together, optimizing symbiotic relationships.
- The background information in this report emphasizes the rapid evolution within the battery industry, a trend expected to continue. Such shifts significantly impact techno-economic assessments, these kinds of studies should be up-to date as much as possible. Also, the economic analysis in this study largely relied on estimations, potentially leading to margins of error. A more detailed assessment with first degree data from companies could improve accuracy in the further studies.
- Business models' dynamic nature poses challenges for assessing long-term adaptability and performance using current evaluation methods. Future investors consulting this study might benefit from updating the BMC to reflect industry changes.
- Furthermore, future studies may explore novel BMCs that prioritize circularity and sustainability aspects of innovative EoL LIB technologies, such analyses could be conducted to enhance our understanding of their circularity potential.

8 References

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Appendices

Appendix A – Background Information

Description of LIB Recycling Technologies

Current Technologies

Three different hydrometallurgical processes were considered for three different acids. Pre-treatment only included mechanical pre-treatment. Maritz’s study included the process options considered by Smit but added HCL and sulphuric acids as leaching agent options to the solvent extraction process, as well as sulphuric acid as leaching agent option to both the sequential precipitation and mixed NMC precipitation processes. This resulted in the following 9 process options included in his research. The following options were considered for each of the three acids (HCl, Citric and sulphuric), resulting in a total of nine processes:

1) HCL Acid
   a. HCL as leaching agent with Sequential Precipitation

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 Na2CO3 is used to precipitate lithium from the leach solution.

   b. HCL as leaching agent with Solvent Extraction (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 Na2CO3 is used to precipitate lithium from the leach solution.

   c. HCL as leaching agent with Mixed NMC_{111} Precipitation

A mixture of LCO, LFP and NMC_{111} 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.

2) Citric Acid

d. Citric acid as leaching agent with Sequential Precipitation

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.

e. Citric acid as leaching agent with Solvent Extraction (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.

f. Citric acid as leaching agent with NMC_{111} Precipitation

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.

3) Sulphuric Acid

g. Sulphuric acid (H_2SO_4) as leaching agent with Sequential Precipitation

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 Na2CO3 is used to precipitate lithium from the leach solution.

h. Sulphuric acid (H_2SO_4) as leaching agent with Solvent Extraction (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.

i. Sulphuric acid (H_2SO_4) as leaching agent with NMC_{111} Precipitation

A mixture of LCO, LFP and NMC_{111} batteries is leached using a 2 M solution of sulphuric acid with 10 %vol H_2O_2 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.

Novel Technologies

The two novel technologies that are subject to this study are developed by the project partners of the ELIMINATE project.

H_2SO_4 – Novel Technology

A mixture of LCO, LFP, LMO and NMC_{111} 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.

MSA – Novel Technology

A mixture of LCO, LFP, LMO and NMC_{111} batteries was subjected to leaching using Methanosulfonic acid (MSA; CH_3SO_3H), 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.

Appendix B – Background Information

Profitability Comparison of Novel Technologies in EU Context

The profitability calculations for novel technologies in this study relied on Ozturk's (2024) thesis. Although the full thesis couldn't be published due to confidentiality concerns, the TEA methodology and results from Ozturk's work are taken from her thesis and presented here.

Techno-Economic Assessment for Novel Technologies

TEA is a methodology used to evaluate the financial viability of a process, and in this study, serves as a tool for making preliminary comparison between novel technologies. According to an international classification system AACE cost estimate classification matrix for process industries, this study is considered as Class 5, which means the expected accuracy rate is changing between -20% to +30% (Christensen, LR, & J, 2020). TEA was conducted for these novel recycling methods by considering three different business model scenarios, for each business model scenario, one TEA was performed.

The TEA was conducted using quantitative data collected from various sources, including pilot plant tests conducted by ELIMINATE project partner EXITCOM A.S., former thesis studies related to ELIMINATE project (Maritz, 2022) (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023), literature review and secondary resources. This data was used to estimate CAPEX, OPEX, revenues, equipment depreciation and taxes for each case. Key financial indicators such as net present value (NPV), and internal rate of return (IRR) were evaluated. A breakeven analysis was performed to show what price is needed to cover CAPEX and OPEX costs within the 20 years lifespan. This 20 years lifespan is a common choice since it is helping long term reasonable projection and reasonable lifespan to demonstrate financial feasibility. The details of CAPEX, OPEX and revenues will be explained in the following section.

The following steps were explained in this chapter:

1. Key Financial Indicators
2. Determination of the geographical scope of TEA,
3. Determination of feasible recycling plant capacity within the geographical scope,
4. Calculation of CAPEX,
5. Calculation of OPEX,
6. Calculation of revenues,
7. Outline of the TEA approach.

Key Financial Indicators

Net Present Value (NPV)

The best method to show profitability in this case is to use the cumulative cash flow over a project lifetime, and a cumulative cash flow of a project at a given moment in time is defined as NPV metric. For each novel recycling process option, the NPV over a 20-year period was determined based on the calculated CAPEX, OPEX, and revenues. A positive NPV indicates that the investment in the recycling process plant is profitable, while a negative NPV signifies an unprofitable investment. NPV is a useful tool for ranking different processes, with the option yielding the highest NPV considered the most favourable. The NPV values of novel recycling technologies are calculated by the following equation 1:

$$Net\ Present\ Value\ (NPV) = \sum_{t}^{N} \frac{R_t}{(1+i)^t} \qquad (1)$$

Where N is the year, i is the discount rate, R_t is the cash flow in year t presented in €.

Internal Rate of Return (IRR)

IRR is the rate of return that makes the NPV of an investment 0. It is calculated by the following equation 2:

$$IRR = NPV = \sum_{t}^{N} \frac{R_t}{(1+i)^t} = 0 \qquad (2)$$

Process Descriptions

Table 4. Feed Battery Chemistries for both the Novel Technologies

Feed (Waste) Battery Chemistries	Unit	Amount
LiCoO2 (LCO)	kg/kWh	3.6
LiFePO4 (LFP)	kg/kWh	1.1
LiNi0.33Mn0.33Co0.33O2 (NMC111)	kg/kWh	0.1
LMO	kg/kWh	1.0
Impurities (carbon)	kg/kWh	4.9

Table 5. Products and production rates for the Novel Technologies

Products	Details	Unit	Production Rate
Manganese dioxide	MnO_2	kg/kWh	1.4
Nickel hydroxide	$Ni(OH)_2$	kg/kWh	0.3
Cobalt tetroxide	Co_3O_4	kg/kWh	2.5
Lithium carbonate	Li_2CO_3	kg/kWh	1.7

Table 6. Aggregated Process Inventory of H2SO4 – Novel and MSA – Novel Processes

H_2SO_4 - Novel		
Flow	**Unit**	**Flowrate**
Cathode Material/Black Mass	kg	82
Raw materials		
Sulfuric Acid	kg	107
Hydrogen peroxide		46
Caustic soda	kg	265
Potassium Permanganate	kg	13
Potassium Persulphate	kg	142
Sodium Carbonate	kg	19
Ion exchange resin (Dowex M4195)	kg	-
Acetone	kg	0.04
Energy		
Electricity Consumption	kWh	319
Water		
Process Water	kg	17 717
Demineralized water	kg	2 612
Waste		
Unleached solid waste (to landfill)	kg	43
Metal Hydroxide Waste (to landfill)	kg	7
Ion exchange resin (Dowex M4195)		-
Wastewater (municipal WWT)	kg	4 280
Cooling water	kg	-
Direct emission		
Water vapor	kg	6
Products		
Manganese dioxide	kg	11
Nickel Hydroxide	kg	2
Cobalt tetroxide	kg	19
Lithium Carbonate	kg	13

MSA - Novel		
Flow	**Unit**	**Fl**
Cathode Material/Black Mass	kg	
Raw materials		
Methane sulfonic acid	kg	
Sulfuric Acid	kg	
Hydrogen peroxide	kg	
Caustic soda	kg	
Potassium Permanganate	kg	
Potassium Persulphate	kg	
Sodium Carbonate	kg	
Ion exchange resin (Dowex M4195)	kg	
Sodium sulphate	kg	
Acetone	kg	
Energy		
Electricity Consumption	kWh	
Heat loss	kWh	
Water		
Process Water	kg	
Demineralized water	kg	
Waste		
Unleached solid waste (to landfill)	kg	
Metal Hydroxide Waste (to landfill)	kg	
Ion exchange resin (Dowex M4195)		
Wastewater (municipal WWT)	kg	
Direct emission		
Water vapor	kg	
Products		
Manganese dioxide	kg	
Nickel Hydroxide	kg	
Cobalt tetroxide	kg	
Lithium Carbonate	kg	

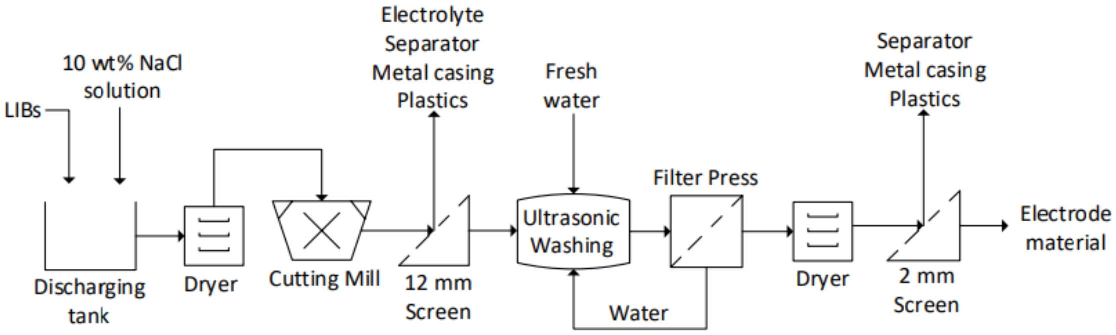


Figure 20. Flowsheet of proposed mechanical pre-treatment process *(Smit, 2020)*

Determination of the Geographical Scope for EU

To ensure reliable assumptions for EU, three countries within the EU, namely Germany, Italy, and Sweden, have been chosen for analysis, as depicted in Figure 20. Whenever average price data for the EU is accessible, it has been utilized; however, in cases where such data is unavailable, price data from the aforementioned countries has been collected and used to determine the average value.

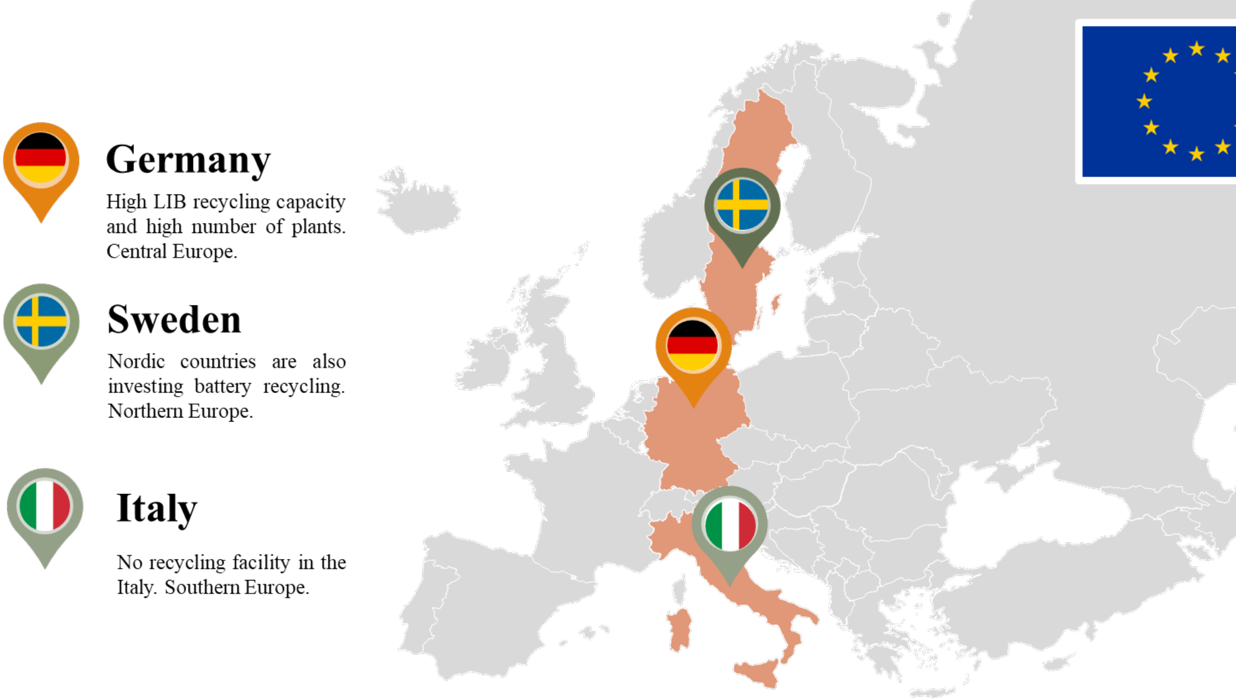


Figure 21. Selected countries for TEA

There are valid justifications for selecting these specific countries as representatives of EU, which are elaborated in detail in the subsequent section.

I. Geographical and Geopolitical Location: Germany serves as a representative of Central Europe due to its strategic location and strong economic influence within the region. Sweden, on the other hand, represents Northern Europe, known for its advanced technological advancements and environmental consciousness. Lastly, Italy stands as a representative of Southern Europe, renowned for its rich cultural heritage and diversified industrial landscape. By selecting these countries, which cover different geographical regions within Europe, the analysis encompasses a broader perspective and takes into account the unique characteristics and dynamics of each region.

II. Investments in LIBs Production: The provided Figure 21 presents the announced LIB production capacities in European countries as of 2021. Germany, Sweden, and Italy have been specifically chosen to represent the EU according to their future LIB production projections.

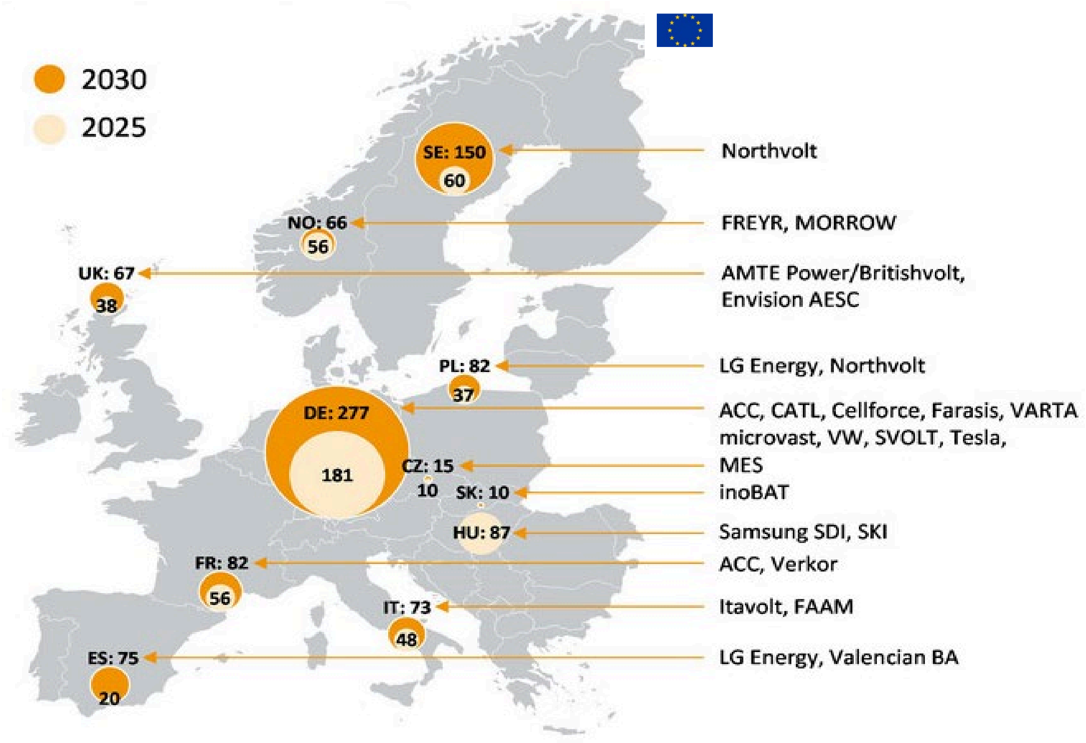


Figure 22. Announced LIB production capacities in the EU, as of 2021 (in GWh) *(Degen, 2023)*

III. Investments in LIBs Battery Recycling: According to IVL report, the total LIBs recycling capacity in Europe was 45,900 tonnes per year in 2021. Among the selected countries, Germany has the highest recycling capacity at 20,700 tonnes per year, while Sweden represents a smaller portion with 300 tonnes per year. These countries also have "planned" recycling facilities for future implementation. However, Italy currently lacks any operational recycling plant, and there are no "planned" recycling capacities reported at this time (Wu & Lindman, 2022). That is why, Italy's inclusion in the analysis is crucial to provide a comprehensive and reliable assumption for the EU region.

IV. Future Recycling Network: Countries such as Germany and Sweden trying to create a network between the battery producers, machine manufacturers, recyclers, and university partners to establish a co-operative network for the LIBs recycling in long term. For example, ongoing ELIMINATE project and

LIBRI research project are established for this (Hoyer, Kieckhäfer, & Spengler, 2014).

Total Plant Capacity

In order to enable comparison between the two technologies in this study, the plant capacities for both novel technologies are identical. The plant capacity assumptions TEA of a LIBs recycling facility depends on some aspects and these aspects presented in the following Equation 3, and this equation was used to calculate maximum plant capacity by applying a weighted average for the countries.

$$Max\ Plant\ Capacity = Population \times Ewaste\ Generation\ Rate \times Recycling\ Rate \times LIBs\ rate \quad (3)$$

The mechanical pre-treatment plant and recycling plants’ equipment and process considerations were designed based on the result of this calculation.

Plant Capacity Calculation for mechanical pre-treatment and recycling facilities:

$$Germany = \left(83 Million \times \frac{19.4\ kg\ Ewaste}{person} \times 52\%\ recycling\right) \times 3\%\ LIBs = 25{,}119 \frac{tonne}{year} \quad (4)$$

$$Sweden = \left(11\ Million \times \frac{20.1\ kg\ Ewaste}{person} \times 68\%\ recycling\right) \times 3\%\ LIBs = 4{,}510 \frac{tonne}{year} \quad (5)$$

$$Italy = \left(59\ Million \times \frac{17.5\ kg\ Ewaste}{person} \times 35\%\ recycling\right) \times 3\%\ LIBs = 10{,}841 \frac{tonne}{year} \quad (6)$$

$$Weighted\ Average\ of\ Annual\ Max\ Plant\ Capacity = 18{,}132 \frac{tonne}{year} \quad (7)$$

$$Maximum\ Plant\ Capacity\ per\ day = \frac{Annual\ Plant\ Capacity}{Days\ in\ a\ year \times (1 - Down\ time)} = \frac{18{,}132\ tonne/year}{365 \times 92\%} = 54 \frac{tonne}{day} \quad (8)$$

Capital Expenditures (CAPEX)

The determination of total capital investment for future recycling companies' production plant involves the consideration of both fixed capital investment (FCI) and working capital investment (WCI), simply, the total capital investment is composed of fixed and working capital. Fixed capital costs equal to sum of direct and indirect costs. All these direct, indirect costs are estimated with the factorial method or the "major equipment cost ratio" method will be employed in this study. This method involves calculating the contribution of each cost stream as a percentage of the purchased equipment cost. Table 4**Error! Reference source not found.** presents the various factors that contribute to the overall capital investment. The total capital costs for mechanical pre-treatment and recycling are equal for both of the novel technologies.

In this table, the ratios for the cost streams are adopted from literature and previous ELIMINATE project these studies, all the relevant references added to this. Purchased equipment costs of mechanical pre-treatment and recycling methods were calculated to estimate CAPEX.

Table 7. CAPEX for both novel technologies

Cost Stream	**% of Purchased Equipment Cost**	**Mechanical Pre-treatment + Recycling**	**Recycling**
	Direct Costs		
Purchased Equipment Delivered	100%	16 053 244	14 810 650
Equipment Installation	39%	6 260 765	5 776 153
Piping (installed)	31%	4 976 506	4 591 301
Instrumentation and controls	26%	4 173 844	3 850 769
Electrical Systems (installed)	11%	1 765 857	1 629 171

Cost Stream	% of Purchased Equipment Cost	Mechanical Pre-treatment + Recycling	Recycling
Utilities	45%	7 223 960	6 664 792
Off-sites	20%	3 210 649	2 962 130
Building (incl Services)	29%	4 655 441	4 295 088
Site Preparation	16%	2 568 519	2 369 704
Indirect Costs			
Engineering Design	20%	3 210 649	2 962 130
Supervision	25%	4 013 311	3 702 662
Maintenance	3%	481 597	444 319
Construction and Expenses	34%	5 458 103	5 035 621
Legal Expenses (Taxes, insurance etc.)	4%	642 130	592 426
Contractors Fee	21%	3 371 181	3 110 236
Contingency	35%	5 618 636	5 183 727
Total Fixed Capital Investment (FCI)	**Direct + Indirect Costs**	73 684 392	67 980 882
Working Capital	15%	2 407 987	2 221 597
Total Capital Cost	**FCI + Working Capital**	**76 092 379**	**70 202 479**

Purchased Equipment Costs of Recycling Plant

In this study, purchasing equipment costs for each equipment have been calculated by the ELIMINATE project partners at Stellenbosch University this year. These cost estimations specifically pertain to the context of South Africa, where the plant's capacity was initially estimated at 868 t/yr. To accommodate this increased capacity, the Cost Capacity Scaling Rule was employed as it was mentioned in the previous part.

To calculate the equipment purchasing costs for the recycling plant:

$$Recycling\ \ Plant\ CAPEX\ = 4{,}642{,}963\ € \times \left(\frac{6{,}000\ t/year}{868\ t/year}\right)^{0.6} = 14{,}810{,}650\ € \tag{9}$$

Purchased Equipment Costs of Mechanical Pre-treatment Plant

To calculate the equipment purchasing costs for the mechanical pre-treatment step, three steps will be followed. These steps are updating price data from Smit, 2020 to current date by using CEPCI adjustment, increasing the total plant capacity 8% since the losses in the process and increasing plant capacity from 868 t/year to 6,522 t/year by applying "Cost Capacity Scaling Rule".

The following calculations are demonstrating the adjusted mechanical pre-treatment plant capacity after the 8% increase:

$$Mechanical\ Pretreatment\ Plant\ Capacity = \frac{6{,}000t}{year} \times \frac{1}{8\%} = 6{,}522\ t/year \tag{10}$$

$$Discharge\ Tank\ Adjustment\ = 426{,}995\ € \times \left(\frac{6{,}522\frac{t}{year}}{868\frac{t}{year}}\right)^{0.6} = 1{,}242{,}595\ € \tag{11}$$

1. The price data for the mechanical pre-treatment data adopted from Smit, 2020. That study conducted in 2020 and the price data should be updated to

2023. Each of the equipment costs presented in the previous flowsheet needs to be adjusted the current time by using following equation 13.

$$Equipment\ Price\ Adjustment = Current\ Price \times \frac{CEPCI\ 2023}{CEPCI\ 2020} \quad (12)$$

2. It was assumed that 8% of the valuable metals are lost during the pre-treatment plant section (Smit, 2020). Therefore, the mechanical pre-treatment plant capacity needs to be increased by 8% in order to feed the required total of black mass to the subsequent recycling step.
3. The plant capacity in Smit, 2020 study was limited to 868 t/year, but in this study the mechanical pre-treatment plant capacity should be 6,522 t/year. To adjust the costs from 868 t/year to 6,522 t/year, "Cost Capacity Scaling Rule" was used, which is presented in the following equation 14. By applying this rule, the plant capacity was aligned with the desired scale for further comparison.

$$C_2 = C_1 \left(\frac{Q_2}{Q_1}\right)^m \qquad (13)$$

4. Finally, the total purchased equipment cost placed in the previous total capital cost table. To calculate total capital costs for the mechanical pre-treatment plant.

The rule of six-tenths or cost capacity scaling rule, which has been developed and refined over the years, proves to be highly effective in providing reasonably accurate cost estimates with a margin of error of approximately plus or minus 20%. This rule enables the estimation of a new facility with the desired capacity by considering the cost of an existing facility of a different size. The cost capacity scaling rule equation incorporates several variables: Q1 represents the established plant capacity, Q2 denotes the desired size of the new plant, m signifies the coefficient, C1 corresponds to the known plant cost, and C2 signifies the estimated plant cost after the capacity increase. The coefficient m varies based on the industry under investigation. For this study, the coefficient m has been determined as 0.6 (Towler & Sinnott, 2008). By utilizing this equation, the equipment purchasing prices of mechanical pre-treatment and recycling has been appropriately adjusted, considering the desired capacity expansion, industry-specific factors, and the known plant costs.

Table 8. Equipment purchasing costs for recycling and mechanical pre-treatment plants

Recycling Equipment Costs	**Price (€) 2023 for 868t/y**	**Price (€) After Cost Scaling**	**Mechanical Pre-treatment Equipment Costs**	**Price (€) (Smit, 2020)**	**Date Adjusted Price (€) 2023**	**Price (€) After Cost Scaling**
Product dryer	3 082	9 831	Discharge tank	8 024	10 251	34 377
Storage tanks and hoppers	641 784	2 047 235	Dryer after discharge	1 815	2 319	7 778
Intermediate tanks	41 177	131 350	Crushing	34 888	44 571	149 471
Solid waste tanks	87 194	278 141	12 mm screen	1 223	1 562	5 239
Liquid waste tanks	1 442 614	4 601 814	Ultrasonic washing	1 223	1 562	5 239
Wet solid product tanks	26 812	85 528	Ultrasonic wash agitator	14 942	19 089	64 017
Dry solid product tanks	58 045	185 159	Filter press 1	225 145	287 631	964 587
Agitated reaction vessels	114 874	366 437	Continuous dryer (LIBs feed)	1 551	1 982	6 646
Mixer vessels	47 562	151 719	2mm screen	1 223	1 562	5 239

pH adjustment vessels	26 567	84 747
Agitators	59 298	189 155
Mixer agitators	23 035	73 480
pH adjustment agitators	24 626	78 556
Filter presses	1 867 554	5 957 337
Distillation	14 788	47 172
Heat exchangers	60 749	193 783
Reboiler (kettle boiler)	79 296	252 946
Oven	23 907	76 260
Total	**4 642 963**	**14 810 650**

Total	**290 034**	**370 530**	**1 242 595**

Operating Expenditures (OPEX)

To perform a techno-economic assessment, it is crucial to calculate four significant operational cost streams: raw materials costs (C_{RM}), utility costs (C_{UT}), labour costs (C_{OL}), and waste management/treatment costs (C_{WT}), in addition to them, C_{TOC} means the total operating costs. To calculate the total operational costs, it is essential to determine direct operational costs, fixed operational costs, and general expenses associated with the operations. FCI have been calculated for both mechanical pre-treatment and recycling plants in the previous chapter. To calculate the rest of the operational costs, following 9 was used in the TEA (Smit, 2020) (Maritz, 2022).

Table 9. Total OPEX components and ratios for H_2SO_4 and MSA-Novel processes

Operating Cost Component	Expense Factor
Direct Costs	
Raw materials	$1C_{RM}$
Waste treatment	$1C_{WT}$
Utilities	$1C_{UT}$
Operating labor	$1C_{OL}$
Direct supervisory and clerical labor	$0.18C_{OL}$
Maintenance and repairs	0.06FCI
Operating supplies	0.009FCI
Laboratory charges	$0.15C_{OL}$
Patents and royalties	$0.03C_{TOC}$
Total Direct Costs	$C_{RM} + C_{WT} + C_{UT} + 1.33C_{OL} + 0.03C_{TOC} + 0.069FCI$
Fixed Costs	
Depreciation	0.1FCI
Local taxes and insurance	0.032FCI
Plant overhead costs	$0.708C_{OL}$ + 0.036FCI
Total Fixed Costs	$0.708C_{OL} + 0.168FCI$
General Costs	
Administration costs	$0.177C_{OL}$ + 0.009FCI
Distribution and selling costs	$0.11C_{TOC}$
Research and development	$0.05C_{TOC}$
Total General Costs	$1.77C_{OL} + 0.016C_{OM} + 0.009FCI$
Total Operating Expenses	$C_{RM} + C_{WT} + C_{UT} + 2.215C_{OL} + 0.190C_{TOC} + 0.246FCI$

Raw Materials Costs

The total raw materials to operate the plant for one year needs to be calculated with calculating the costs of total chemicals (including process water), scrap cathode materials and cathode black mass. The cost associated with each chemical (including process water) was calculated using the annual mass flowrate (kg/hr) and the price of the raw material (€/ton). All the chemicals that have been used in the novel technologies and their prices with references have been presented at the end of this chapter. In addition to these chemicals, feed material of the processing plants is also considered as a raw material in this study. The prices for raw materials, LIB battery scrap, and black mass during mechanical pre-treatment and recycling stages are also provided in this chapter with their annual flowrates.

Table 10. Raw materials for H_2SO_4 process

Raw Materials	Details
Process water	H_2O, Liquid
Demineralized water	H_2O, Liquid
Sulphuric acid	H_2SO_4
Hydrogen peroxide	NaCl, Solid (Crystals)
Potassium permanganate	$MnSO_4$, Solid (Crystals)
Potassium persulphate	$NiSO_4$, Solid (Crystals)
Sodium carbonate	Na_2CO_3, Solid (Crystals)
Ion Exchange resin	Dowex M4195
Acetone	Liquid

Table 11. Raw materials for MSA – Novel process

Raw Materials	Details
Process water	H_2O, Liquid

Raw Materials	Details
Demineralised water	H_2O, Liquid
Methane sulfonic acid (MSA)	CH_3SO_3H, Liquid
Sulphuric acid	H_2SO_4, Liquid
Hydrogen peroxide	H_2O_2, Liquid
Caustic soda	HCl, 33%
Potassium permanganate	$KMnO_4$, Solid (Crystals)
Potassium persulphate	$K_2S_2O_8$, Solid (Crystals)
Sodium carbonate	Na_2CO_3, Solid (Crystals)
Ion Exchange resin	Dowex M4195
Sodium sulphate	Na_2SO_4, Solid (Crystals)

Table 12. Raw material consumptions for H2SO4-Novel and MSA-Novel processes

Raw Materials	**Flowrates for H_2SO_4 - Novel (kg/hr)**	**Flowrates for MSA-Novel (kg/hr)**	**Average Price (€/kg)**	**References (2023)**
LIB Battery Scrap	808	808	4.4	Metal.com
Black Mass	744	744	4.9	Metal.com

Raw Materials	Flowrates for H_2SO_4 - Novel (kg/hr)	Flowrates for MSA-Novel (kg/hr)	Average Price (€/kg)	References (2023)
Process Water	11780	11780	0.003	Waternewseurope.com
Demineralized Water	23773	32819	0.004	Hydrogeneurope.eu
MSA	-	1429	2.7	IndiaMart.com
Sulfuric Acid	974	246	0.1	Chemanalyst.com
Hydrogen Peroxide	419	255	0.5	Chemanalyst.com
Caustic Soda	-	2412	0.1	Sansirs.com
Potassium Permanganate	118	118	2.3	IndiaMart.com
Potassium Persulphate	142	1292	1.7	IndiaMart.com
Sodium Carbonate	173	173	0.3	IndiaMart.com
Sodium Sulphate	-	1058	0.0	IndiaMart.com
Ion Exchange Resin	-	91	0.8	ALIBaba.com
Acetone	0.3	0.4	1.3	Chemanalyst.com

Utilities

The most important utility in the novel technologies is electricity consumption. Total electricity consumptions for each novel technology have been presented in this chapter and the electricity prices used for Germany, Sweden Italy are reported as 0.02 kWh/year, 0.07 kWh/year and 0.14 kWh/year respectively (Statista , 2023). By multiplying the energy requirements by the corresponding electricity prices, the total electricity consumption for each technology can be calculated.

Table 13. Utility Costs

	H_2SO_4-Novel	MSA-Novel
Germany		
Electricity Price (€/kWh)	0.02	0.02
Total Electricity Consumption (kWh/year)	23 383 863	62 965 526
Total Electricity Costs (€/year)	360 111	969 669
Sweden		
Electricity Price (€/kWh)	0.07	0.07
Total Electricity Consumption (kWh/year)	23 383 863	62 965 526
Total Electricity Costs (€/year)	1 613 487	4 344 621
Italy		
Electricity Price (€/kWh)	0.14	0.14
Total Electricity Consumption (kWh/year)	23 383 863	62 965 526
Total Electricity Costs (€/year)	3 184 882	8 575 905
Average Electricity Cost (€/year)	1 719 493	4 630 065

Labour Costs

The labour requirements for the mechanical pre-treatment plant and recycling plant were calculated separately, considering the number of equipment and their respective labour requirements associated with operating each piece of equipment. All the major process equipment, such as vessels, crushers, screens, dryers, furnaces, heat exchangers, pumps, compressors, fans, filters, agitators, dryers, etc., have been included to labor cost calculations for mechanical pre-treatment and recycling. To ensure sufficient coverage for shifts, it is recommended to hire 4.8 operators per shift position (Turton, Bailie, Whiting, Shaeiwitz, & Bhattacharyya, 2012). This factor takes into consideration during labour costs calculations, allowing for the inclusion of holidays, vacations, and weekends. The total operating labour costs were calculated by multiplying the labour requirement with the average salary of a chemical plant worker.

Table 14. Labor requirements for Mechanical Pre-treatment and Recycling plants

Process Unit	# of workers per process unit per shift	# of process units	# of workers required per shift
Discharge Tank	0.5	1	0.5
Dryers	0.5	2	1
Cutting Mill	0.5	1	0.5
Screens	1	2	2
Ultrasonic washing	1	1	1
		Total	**6 workers**
Recycling Plant			
Tanks and hoppers	0.2	19	3.8
Agitated reaction vessels and agitators	0.2	8	1.6

Dryers	0.5	4	2
Distillation	1	1	1
Ion Exchange	0.5	1	0.5
Heat Exchangers	0.5	2	1
Reboiler	0.5	1	0.5
Oven	1	1	1
Auxiliary pumps	0.4	8	3.2
		Total	**21 workers**

Based on the findings from the literature review and process flowsheets, the labour requirements for the mechanical pre-treatment plant requires a total of 6 workers, while the recycling plant requires 21 workers. The annual average costs of chemical plants workers in Germany, Sweden, and Italy are 48.5k€, 38.2k€, and 33.5k€ respectively (ERI, 2023) (Salary Explorer, 2023) (ERI, 2023). Considering an average cost of 43.2 k€ for a chemical plant operator, derived from the values obtained from the three countries, the total labour costs can be calculated as follows:

$$Pretreatment\ Labour\ Costs\ = \frac{6\ workers}{annual} \times 4.8\ \times 43{,}200\ €\ = 1.24\ M€ \qquad (14)$$

$$Recycling\ Labour\ Costs\ = \frac{21\ workers}{annual} \times 4.8\ \times 43{,}200\ €\ = 4.27\ M€ \qquad (15)$$

Waste Treatment

To calculate the waste treatment costs, two key pieces of information must be known: the flowrates of the waste streams generated by the novel recycling facilities, and the associated treatment costs. Estimated waste treatment costs of the different waste streams are calculated by utilizing data obtained from relevant literature sources. To be able to calculate the costs, the waste streams are categorized as either solid or liquid, and the following Equation 4 is employed.

$$C_{S,U} = \alpha(CEPCI) + b\left(C_{S,f}\right) \qquad (16)$$

In the provided equation, $C_{S,U}$ represents the cost of waste treatment, α and b are the coefficients and $C_{S,f}$ is the fuel price in €/GJ. The "Chemical Engineering Plant Cost Index" (CEPCI) is a metric used for estimating prices in various calculations related to chemical engineering plant costs.

In the context of this study, CEPCI values from Table 18 have been used (Smit, 2020).

Table 15. CEPCI values

Year	CEPCI
2019	607.5
2023	761.7

For the solid waste streams such as pre-treatment plant wastes, leach residue etc. the coefficient factors α and b have been selected as 2×10^{-3} and 0 respectively according to literature data (Smit, 2020). When the coefficient factors, CEPCI, and heating oil prices (after the unit conversation from €/L to €/GJ) are used in equation 13 and the average waste treatment cost for solid waste streams is calculated as 1472 €/tonne waste. For the liquid waste streams, the calculation of waste treatment costs is determined by using different α and b coefficients in the following equation 17. The coefficient α is calculated with the following equation 17 where q is the wastewater flow rate in m^3/s and for this case, the coefficient b has been selected as 0.1 (Smit, 2020). By using these equations, the average wastewater treatment cost is determined as 4 €/L.

$$\alpha = 0.0005 + 1 \times 10^{-4} q^{-0.6} \qquad (17)$$

According to Global Petrol Prices, the latest fuel prices for heating oil in Germany, Sweden, and Italy are reported as 1.1 €/L, 1.2 €/L, and 1.4 €/L respectively (Global Petrol Prices, 2023). In the subsequent analysis, the waste treatment costs for each country were calculated using their respective heating oil prices. These individual cost calculations are then averaged to obtain the overall total waste treatment costs, which will be utilized for subsequent stages of the techno-economic assessment.

Table 16 Waste Stream Costs

	Waste Stream	Flowrate (kg/hr)	Treatment cost ($)	Waste Treatment Expense ($/year)	Waste Treatment Expense (€/year)
BM 1	LIB Battery waste(Pre-processing)	64	1 472	792 156	760 470
	Unleached solid waste	391	1 472	4 844 011	4 650 250
	Metal Hydroxide Waste (to landfill)	64	1 472	788 560	757 017
	Wastewater (municipal WWT)	38 954	3	1 087 725	1 044 216
	Ion exchange resin (Dowex M4195)	0	0	0	0
BM 2	LIB Battery waste (Pre-processing)	0	1 472	0	0
	Unleached solid waste	391	1 472	4 844 011	4 650 250
	Metal Hydroxide Waste (to landfill)	64	1 472	788 560	757 017
	Wastewater (municipal WWT)	38 954	3	1 087 725	1 044 216

	Ion exchange resin (Dowex M4195)	0	0	0	0
BM 3	LIB Battery waste(Pre-processing)	64	1 472	792 156	760 470
	Unleached solid waste	391	1 472	4 844 011	4 650 250
	Metal Hydroxide Waste (to landfill)	64	1 472	788 560	757 017
	Wastewater (municipal WWT)	38 954	3	1 087 725	1 044 216
	Ion exchange resin (Dowex M4195)	0	0	0	0

Revenues

Both of the novel recycling technologies yield the same 4 products (since their designs, Appendix A), these are namely manganese dioxide, nickel hydroxide, cobalt tetroxide and lithium carbonate. For both novel technologies, products and their flowrates are equal. The annual revenue for each product is determined by multiplying the annual product yield with the corresponding selling price. The specific calculations for the determination of yearly product revenue are provided at the end of this chapter.

In addition to primary revenues, scrap material from the mechanical pre-treatment is also added to the calculations. The scrap pricing estimation have been done by Khun, 2023 (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023) and the value updated to the current plant capacity.

Table 17. Revenues for Both Novel Technologies

Products	Details	Purity	Flowrate (kg/hr)	Plant Availability	Yearly Working Hour	Price (€/kg)	Price (M€/year)	Reference
Manganese Dioxide	MnO_2	>99.5 %	98	92%	8059.2	1.51	1.2	ALIBaba.com (2023)
Nickel Hydroxide	$Ni(OH)_2$	>97.5 % - 99.5 %	18	92%	8059.2	14.1	2.1	ALIBaba.com (2023)
Cobalt Tetroxide	Co_3O_4	>85 % - >98 %	173	92%	8059.2	40.9	57.0	ALIBaba.com (2023)
Lithium Carbonate	Li_2CO_3	>93 % - 99%	118	92%	8059.2	36.2	34.5	Metal.com (2023)

Outline of the Techno-Economic Assessment Approach

To calculate the profitability of recycling processes TEA outline have been prepared. The assumptions that have been used are listed in the following Table 18. *Outline of the TEA approach*

Table 18. Outline of the TEA approach

Item	Assumption
Operation Life	20 years
Annual Inflation Rate	4.5%
Discount Factor on future cash flows	10%
Production Capacity	The production capacity will progressively increase by 50%, the first three years, with full operation commencing in the the final four years, the production capacity will decline to and 10% respectively.
CAPEX Payment Distribution	CAPEX will be paid out annually, with 50% in the first year, and 15% in the subsequent two years. The equipment will b of the operation life for 20% of the original costs.
Working Capital	15% of fixed capital investment and will be paid just befor start in the 3rd year. The working capital will be fully production stops.
Maintenance and Repair	1% of fixed capital investments (FCI)
Tax Rate	20% (average for Germany, Sweden, Italy)
Salvage Value	10% of the fixed capital investments (FCI).
Distribution and Selling the Products	1% of total revenue. The products are either sold after produ directly used for battery recycling.
Depreciation	Straight line method with a 20 years of plant lifetime.
Annual Government Subsidies	22.5% of annual revenue
Land Costs	Neglected
Transportation Costs	Neglected

Adjustment of Current Technologies from SA to EU Contexta and Increasing the capacity for Novel Technologies for EU

To facilitate a comparison between current and novel technologies, it was necessary to increase plant capacities to handle 98,667 tons/year of End-of-Life (EoL) LIBs and update the data from South Africa (SA). To achieve this comparison, the following steps were undertaken:

1. **Adjusting the plant capacity for CAPEX:**

The prior studies determined the recycling technologies' capacities as 868 tons/year within the SA context and 6,000 tons/year for the EU respectively. However, to ensure comparability with novel technologies in the EU context and align the research study with other work packages, it became essential to standardize the capacities. To achieve this alignment and facilitate a comparative analysis between the current and novel technologies, the study set an annual processing target of

98,667 tons of End-of-Life (EOL) LIBs. This volume aimed to represent a feasible and sustainable capacity that could be maintained beyond 2026.

The "Cost Capacity Scaling Rule" was employed to increase the SA and EU plant capacities to match the new one and calculate the CAPEX of the increased plant capacity. The rule of six-tenths or cost capacity scaling rule, which has been developed and refined over the years, proves to be highly effective in providing reasonably accurate cost estimates with a margin of error of approximately plus or minus 20%. This rule enables the estimation of a new facility with the desired capacity by considering the cost of an current facility of a different size. The cost capacity scaling rule equation incorporates several variables: Q1 represents the established plant capacity, Q2 denotes the desired size of the new plant, m signifies the coefficient, C1 corresponds to the known plant cost, and C2 signifies the estimated plant cost after the capacity increase. The coefficient m varies based on the industry under investigation. For this study, the coefficient m has been determined as 0.6 (Towler & Sinnott, 2008). By utilizing this equation, the equipment purchasing prices of mechanical pre-treatment and recycling has been appropriately adjusted, considering the desired capacity expansion, industry-specific factors, and the known plant costs.

$$\boldsymbol{C_2 = C_1 \left(\frac{Q_2}{Q_1}\right)^m} \qquad (18)$$

2. **Adjusting the OPEX:**

Initially, price data was updated to incorporate changes in factors like labor, raw materials, utilities, and waste management costs. These updates aimed to adapt to the specific conditions of the EU context while considering the increased plant capacity. Subsequently, the "Cost Capacity Scaling Rule" was applied to align the calculations.

3. **Updating product prices:**

All product prices associated with the current recycling technologies were updated to reflect the current market conditions (from 2022 data to 2023 data). Given the price volatility observed in the LIBs recycling industry, the most recent and relevant data available were used.

4. **Conducting the techno-economic assessment:**

"Outline of the TEA approach" for the novel technology study listed in the previous Table 18 were used throughout the adjustment TEA. Same calculations have been done after updating all the price data, exactly same methodology used to perform the TEA for each business model scenario.

Appendix C – Background Information

Table 19 – 22. OPEX and CAPEX Results from Adjusted TEA Work Conducted by ELIMINATE

for 98667 t/y		**Novel Technology 1 (H_2SO_4 - Novel)**									
	Year	Fixed Capital Investment [€] (CAPEX)	OPEX Costs [€]								**Total Costs [€]**
			Labour	Raw Materials	Utilities	Waste Tretment		Depreciation	Fixed Operational Costs	Total OPEX	
Germany	2023	204 137 866	40 128 574	106 364 432	6 657 026	110 060 756	-	18 372 408	60 664 813	444 621 658	**648 759 523**
	2026	408 275 731	47 854 071	126 841 563	7 938 627	131 249 499	-	36 744 816	98 388 248	578 246 334	**986 522 065**
	2030	408 275 731	57 066 870	151 260 923	9 466 961	156 517 469	-	36 744 816	104 910 910	666 668 572	**1 074 944 304**
	2034	408 275 731	68 053 304	180 381 465	11 289 527	186 649 993	-	36 744 816	112 689 305	772 113 736	**1 180 389 468**
Sweden	2023	204 137 866	24 945 580	99 918 824	29 826 935	110 060 756	-	18 372 408	49 915 254	423 750 015	**627 887 880**
	2026	408 275 731	29 748 069	119 155 056	35 569 175	131 249 499	-	36 744 816	85 569 198	553 356 511	**961 632 243**
	2030	408 275 731	35 475 125	142 094 620	42 416 903	156 517 469	-	36 744 816	89 623 954	636 986 996	**1 045 262 727**
	2034	408 275 731	42 304 746	169 450 478	50 582 946	186 649 993	-	36 744 816	94 459 326	736 717 904	**1 144 993 636**
Italy	2023	204 137 866	22 755 929	85 885 088	58 875 777	110 060 756	-	18 372 408	48 364 980	436 299 432	**640 437 297**
	2026	408 275 731	27 136 868	102 419 565	70 210 459	131 249 499	-	36 744 816	83 720 468	568 321 925	**976 597 656**
	2030	408 275 731	32 361 220	122 137 236	83 727 278	156 517 469	-	36 744 816	87 419 310	654 833 530	**1 063 109 261**
	2034	408 275 731	38 591 357	145 650 926	99 846 336	186 649 993	-	36 744 816	91 830 246	758 000 228	**1 166 275 959**

for 98667 t/y		**Novel Technology 2 (MSA - Novel)**									
	Year	Fixed Capital Investment [€] (CAPEX)	OPEX Costs [€]								**Total Costs [€]**
			Labour	Raw Materials	Utilities	Waste Tretment		Depreciation	Fixed Operational Costs	Total OPEX	
Germany	2023	204 137 866	40 128 574	930 830 930	22 452 910	173 661 929	-	18 372 408	60 664 813	1 560 502 589	**1 764 640 455**
	2026	408 275 731	47 854 071	1 110 033 198	26 775 512	207 095 080	-	36 744 816	98 388 248	1 686 496 718	**2 094 772 450**
	2030	408 275 731	57 066 870	1 323 735 236	31 930 297	246 964 736	-	36 744 816	104 910 910	2 253 563 528	**2 661 839 260**
	2034	408 275 731	68 053 304	1 578 578 891	38 077 473	294 510 041	-	36 744 816	112 689 305	2 664 515 489	**3 072 791 220**
Sweden	2023	204 137 866	24 945 580	929 841 908	100 600 699	173 661 929	-	18 372 408	49 915 254	1 614 241 399	**1 818 379 265**
	2026	408 275 731	29 748 069	1 108 853 771	119 968 205	207 095 080	-	36 744 816	85 569 198	1 973 039 631	**2 381 315 363**
	2030	408 275 731	29 748 069	1 322 328 748	143 064 316	246 964 736	-	36 744 816	85 569 198	2 314 324 499	**2 722 600 230**
	2034	408 275 731	42 304 746	1 576 901 628	170 606 858	294 510 041	-	36 744 816	94 459 326	2 755 650 139	**3 163 925 871**
Italy	2023	204 137 866	22 755 929	914 767 272	198 577 033	173 661 929	-	18 372 408	48 364 980	1 710 601 423	**1 914 739 288**
	2026	408 275 731	27 136 868	1 090 876 987	236 806 805	207 095 080	-	36 744 816	83 720 468	2 087 950 752	**2 496 226 483**
	2030	408 275 731	32 361 220	1 300 891 098	282 396 520	246 964 736	-	36 744 816	87 419 310	2 467 019 172	**2 875 294 903**
	2034	408 275 731	38 591 357	1 551 336 832	336 763 102	294 510 041	-	36 744 816	91 830 246	2 919 065 314	**3 327 341 045**

for 98667 t/y		**Current Technology 1 (HCL-NMC)**									
	Year	Fixed Capital Investment [€](CAPEX)	OPEX Costs [€]								**Total Costs [€]**
			Labour	Raw Materials	Utilities	Waste Tretment		Depreciation	Fixed Operational Costs	Total OPEX	
Germany	2023	184 493 147	41 167 433	229 213 249	7 492 283	140 594 856	-	16 604 383	58 296 459	632 286 030	**816 779 176**
	2026	368 986 293	49 092 929	273 341 063	8 934 687	167 661 981	-	33 208 766	93 057 628	797 417 850	**1 166 404 143**
	2030	368 986 293	58 544 231	325 964 302	10 654 781	199 940 031	-	33 208 766	99 749 150	861 892 167	**1 230 878 461**
	2034	368 986 293	69 815 085	388 718 494	12 706 024	238 432 206	-	33 208 766	107 728 914	1 088 367 780	**1 457 354 073**
Sweden	2023	184 493 147	25 591 378	229 338 298	33 569 321.72	140 594 856	-	16 604 383	47 268 612	621 886 124	**806 379 270**
	2026	368 986 293	30 518 194	273 490 187	40 032 040.56	167 661 981	-	33 208 766	79 906 716	785 015 769	**1 154 002 062**
	2030	368 986 293	36 393 514	326 142 135	47 738 952.99	199 940 031	-	33 208 766	84 066 442	915 448 786	**1 284 435 079**
	2034	368 986 293	43 399 942	388 930 562	56 929 589.42	238 432 206	-	33 208 766	89 026 993	1 070 992 586	**1 439 978 879**
Italy	2023	184 493 147	23 345 040	227 066 988	66 262 922.00	140 594 856	-	16 604 383	45 678 205	653 301 743	**837 794 889**
	2026	368 986 293	27 839 394	270 781 606	79 019 767.02	167 661 981	-	33 208 766	78 010 125	822 479 479	**1 191 465 772**
	2030	368 986 293	33 198 995	322 912 102	94 232 541.99	199 940 031	-	33 208 766	81 804 723	960 124 958	**1 329 111 251**
	2034	368 986 293	39 590 420	385 078 688	112 374 059.11	238 432 206	-	33 208 766	86 329 851	1 124 269 751	**1 493 256 044**

for 98667 t/y		**Current Technology 2 (H2SO4 - NMC)**									
	Year	Fixed Capital Investment [€] (CAPEX)	OPEX Costs [€]								**Total Fixed Costs [€]**
			Labour	Raw Materials	Utilities	Waste Tretment		Depreciation	Fixed Operational Costs	Total OPEX	
Germany	2023	184 493 147	41 167 433	533 771 088	5 189 263	138 574 403	-	16 604 383	58 296 459	1 002 791 358	**1 187 284 505**
	2026	368 986 293	49 092 929	636 531 951	6 188 293	165 252 553	-	33 208 766	93 057 628	1 239 252 346	**1 608 238 639**
	2030	368 986 293	58 544 231	759 076 192	7 379 654	197 066 744	-	33 208 766	99 749 150	1 457 134 354	**1 826 120 647**
	2034	368 986 293	69 815 085	905 212 478	8 800 375	235 005 757	-	33 208 766	107 728 914	1 716 962 701	**2 085 948 994**
Sweden	2023	184 493 147	25 591 378	534 095 516	23 250 593	138 574 403	-	16 604 383	47 268 612	982 896 045	**1 167 389 192**
	2026	368 986 293	30 518 194	636 918 837	27 726 765	165 252 553	-	33 208 766	79 906 716	1 215 526 815	**1 584 513 108**
	2030	368 986 293	36 393 514	759 537 561	33 064 683	197 066 744	-	33 208 766	84 066 442	1 428 841 217	**1 797 827 510**
	2034	368 986 293	43 399 942	905 762 669	39 430 250	235 005 757	-	33 208 766	89 026 993	1 683 222 609	**2 052 208 902**
Italy	2023	184 493 147	23 345 040	528 598 264	45 894 650	138 574 403	-	16 604 383	45 678 205	997 922 177	**1 182 415 323**
	2026	368 986 293	27 839 394	630 363 263	54 730 223	165 252 553	-	33 208 766	78 010 125	1 233 445 757	**1 602 432 050**
	2030	368 986 293	33 198 995	751 719 916	65 266 810	197 066 744	-	33 208 766	81 804 723	1 450 209 888	**1 819 196 181**
	2034	368 986 293	39 590 420	896 439 982	77 831 884	235 005 757	-	33 208 766	86 329 851	1 708 705 146	**2 077 691 439**

Appendix D – Financial Models of Value Chain Scenarios

EU Region Scenarios – by using Novel Technology

Table 23. Financial Model of H2SO4 – Novel process – EU region Value Chain Scenario 1

Year		Capital Expenditures (CAPEX)				Depreciation	Fixed Capital Investment	SALES (tpa)								Costs				Taxes (20%)					10%	
		Plant	Maintenance&Repair	Working Capital	Total	Plant	FCI	Production Delivered	1	2	3	4	Scrap	100% Production	Sales (M€)	Direct Costs	Fixed Costs	General Expenses	Total COM	Cash Flow	Profit	Tax	After Tax Cashflow	Cum Cashflow	Disc Cashflow 10%	Cum DCF
2023	0	-38 046 189	-	-	-38 046 189	-3 424 157	38 046 189	253 506	786	147	1 394	954	100	507 013	66 247 284	58 196 570	9 915 757	11 375 365	79 487 691	-47 862 440	-13 240 408	-	-47 862 440	-47 862 440	-47 862 440	-47 862 440
2024	1	-26 632 333	-646 785	-	-27 279 118	-6 087 390	64 678 522	405 610	786	147	1 394	954	100	507 013	105 995 654	60 240 224	14 389 988	11 724 936	86 355 148	-1 551 222	19 640 505	-3 928 101	-5 479 323	-53 341 763	-4 981 203	-52 843 643
2025	2	-11 413 857	-760 924	-11 413 857	-23 588 637	-6 962 453	76 092 379	456 311	786	147	1 394	954	100	507 013	119 245 110	61 107 701	16 041 193	11 870 285	89 019 179	13 599 747	30 225 931	-6 045 186	7 554 560	-45 787 203	6 243 438	-46 600 205
2026	3	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	-4 823 789	30 776 420	-15 823 785
2027	4	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	36 139 626	27 978 563	12 154 778
2028	5	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	77 103 040	25 435 057	37 589 835
2029	6	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	118 066 454	23 122 780	60 712 615
2030	7	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	159 029 869	21 020 709	81 733 323
2031	8	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	199 993 283	19 109 735	100 843 059
2032	9	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	240 956 698	17 372 486	118 215 545
2033	10	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	281 920 112	15 793 170	134 008 715
2034	11	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	322 883 526	14 357 427	148 366 141
2035	12	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	363 846 941	13 052 206	161 418 348
2036	13	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	404 810 355	11 865 642	173 283 990
2037	14	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	445 773 770	10 786 947	184 070 937
2038	15	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	486 737 184	9 806 316	193 877 253
2039	16	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	61 104 112	15 927 054	11 868 370	88 899 537	49 682 420	43 595 030	-8 719 006	40 963 414	527 700 598	8 914 832	202 792 085
2040	17	-	-760 924	-	-760 924	-6 848 314	76 092 379	380 259	786	147	1 394	954	100	507 013	99 370 925	61 104 112	15 927 054	11 868 370	88 899 537	16 558 779	10 471 388	-2 094 278	14 464 501	542 165 099	2 861 724	205 653 810
2041	18	-	-760 924	-	-760 924	-6 848 314	76 092 379	253 506	786	147	1 394	954	100	507 013	66 247 284	61 104 112	15 927 054	11 868 370	88 899 537	-16 564 863	-22 652 253	-	-16 564 863	525 600 236	-2 979 336	202 674 473
2042	19	-	-760 924	-	-760 924	-6 848 314	76 092 379	101 403	786	147	1 394	954	100	507 013	26 498 913	61 104 112	15 927 054	11 868 370	88 899 537	-56 313 233	-62 400 624	-	-56 313 233	469 287 003	-9 207 664	193 466 810
2043	20	15 218 476	-608 739	11 413 857	26 023 594	-6 848 314	60 873 903	50 701	786	147	1 394	954	100	507 013	13 249 457	59 984 166	14 892 198	11 694 140	86 570 504	-40 449 140	-73 321 047	-	-40 449 140	428 837 863	-6 012 507	187 454 303

Table 24. Financial Model of H2SO4 – Novel process – EU region Value Chain Scenario 2

Year		Capital Expenditures (CAPEX)				Depreciation	Fixed Capital Investment	SALES (tpa)							Costs				Taxes (20%)					10%	
		Plant	Maintenance&Repair	Working Capital	Total	Plant	FCI	Production Delivered	1	2	3	4	100% Production	Sales (M€)	Direct Costs	Fixed Costs	General Expenses	Total COM	Cash Flow	Profit	Tax	After Tax Cashflow	Cum Cashflow	Disc Cashflow 10%	Cum DCF
2023	0	-35 101 240	-	-	-35 101 240	-3 159 112	35 101 240	203 506	786	147	1 394	954	407 013	66 127 617	55 988 546	8 569 750	9 053 077	73 611 373	-39 425 884	-7 483 756	-	-39 425 884	-39 425 884	-39 425 884	-39 425 884
2024	1	-24 570 868	-596 721	-	-25 167 589	-5 616 198	59 672 107	325 610	786	147	1 394	954	407 013	105 804 187	57 874 012	12 697 655	9 375 589	79 947 257	6 305 539	25 856 930	-	6 305 539	-33 120 345	6 305 539	-33 120 345
2025	2	-10 530 372	-702 025	-10 530 372	-21 762 769	-6 423 527	70 202 479	366 311	786	147	1 394	954	407 013	119 029 710	58 674 343	14 221 049	9 509 688	82 405 080	21 285 389	36 624 630	-	21 285 389	-11 834 956	21 285 389	-11 834 956
2026	3	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	43 741 777	55 576 733	43 741 777
2027	4	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	99 318 510	55 576 733	99 318 510
2028	5	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	154 895 244	55 576 733	154 895 244
2029	6	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	210 471 977	55 576 733	210 471 977
2030	7	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	266 048 710	55 576 733	266 048 710
2031	8	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	321 625 444	55 576 733	321 625 444
2032	9	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	377 202 177	55 576 733	377 202 177
2033	10	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	432 778 911	55 576 733	432 778 911
2034	11	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	488 355 644	55 576 733	488 355 644
2035	12	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	543 932 377	55 576 733	543 932 377
2036	13	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	599 509 111	55 576 733	599 509 111
2037	14	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	655 085 844	55 576 733	655 085 844
2038	15	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	710 662 577	55 576 733	710 662 577
2039	16	-	-702 025	-	-702 025	-6 318 223	70 202 479	407 013	786	147	1 394	954	407 013	132 255 233	58 671 031	14 115 745	9 507 922	82 294 698	55 576 733	49 960 535	-	55 576 733	766 239 311	55 576 733	766 239 311
2040	17	-	-702 025	-	-702 025	-6 318 223	70 202 479	305 259	786	147	1 394	954	407 013	99 191 425	58 671 031	14 115 745	9 507 922	82 294 698	22 512 925	16 896 727	-	22 512 925	788 752 236	22 512 925	788 752 236
2041	18	-	-702 025	-	-702 025	-6 318 223	70 202 479	203 506	786	147	1 394	954	407 013	66 127 617	58 671 031	14 115 745	9 507 922	82 294 698	-10 550 883	-16 167 082	-	-10 550 883	778 201 352	-10 550 883	778 201 352
2042	19	-	-702 025	-	-702 025	-6 318 223	70 202 479	81 403	786	147	1 394	954	407 013	26 451 047	58 671 031	14 115 745	9 507 922	82 294 698	-50 227 453	-55 843 652	-	-50 227 453	727 973 899	-50 227 453	727 973 899
2043	20	14 040 496	-561 620	10 530 372	24 009 248	-6 318 223	56 161 983	40 701	786	147	1 394	954	407 013	13 225 523	57 637 774	13 160 992	9 347 177	80 145 943	-36 592 949	-66 920 420	-	-36 592 949	691 380 950	-36 592 949	691 380 950

Table 25. Financial Model of H2SO4 – Novel process – EU region Value Chain Scenario 3

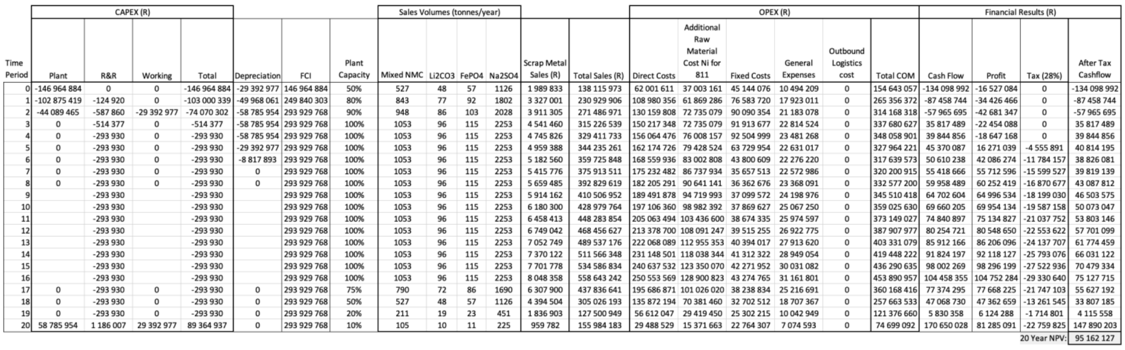
Year		Capital Expenditures (CAPEX)				Depreciation	Fixed Capital Investment	SALES (tpa)								Costs				Taxes (20%)					10%	
		Plant	Maintenance&Repair	Working Capital	Total	Plant	FCI	Production Delivered	1	2	3	4	Scrap	100% Production	Sales (M€)	Direct Costs	Fixed Costs	General Expenses	Total COM	Cash Flow	Profit	Tax	After Tax Cashflow	Cum Cashflow	Disc Cashflow 10%	Cum DCF
2023	0	-38 046 189	-	-	-38 046 189	-3 424 157	38 046 189	253 506	786	147	1 394	954	100	507 013	66 247 284	28 529 338	9 915 757	10 544 988	48 990 082	-17 364 831	17 257 201	-3 451 440	-20 816 271	-20 816 271	-20 816 271	-20 816 271
2024	1	-26 632 333	-646 785	-	-27 279 118	-6 087 390	64 678 522	405 610	786	147	1 394	954	100	507 013	105 995 654	30 565 455	14 389 988	10 650 847	55 606 291	29 197 635	50 389 363	-10 077 873	19 119 763	-1 696 509	17 381 603	-3 434 669
2025	2	-11 413 857	-760 924	-11 413 857	-23 588 637	-6 962 453	76 092 379	456 311	786	147	1 394	954	100	507 013	119 245 110	31 429 702	16 041 193	10 691 749	58 162 644	44 456 282	61 082 467	-12 216 493	32 239 789	30 543 280	26 644 453	23 209 785
2026	3	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	96 191 923	49 322 797	72 532 581
2027	4	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	161 840 565	44 838 906	117 371 488
2028	5	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	227 489 208	40 762 642	158 134 130
2029	6	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	293 137 851	37 056 947	195 191 077
2030	7	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	358 786 494	33 688 134	228 879 211
2031	8	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	424 435 136	30 625 576	259 504 787
2032	9	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	490 083 779	27 841 433	287 346 220
2033	10	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	555 732 422	25 310 394	312 656 614
2034	11	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	621 381 064	23 009 449	335 666 063
2035	12	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	687 029 707	20 917 681	356 583 744
2036	13	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	752 678 350	19 016 073	375 599 817
2037	14	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	818 326 992	17 287 339	392 887 156
2038	15	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	883 975 635	15 715 763	408 602 920
2039	16	-	-760 924	-	-760 924	-6 848 314	76 092 379	507 013	786	147	1 394	954	100	507 013	132 494 567	31 426 113	15 927 054	10 689 834	58 043 002	80 538 956	74 451 565	-14 890 313	65 648 643	949 624 278	14 287 057	422 889 977
2040	17	-	-760 924	-	-760 924	-6 848 314	76 092 379	380 259	786	147	1 394	954	100	507 013	99 370 925	31 426 113	15 927 054	10 689 834	58 043 002	47 415 314	41 327 924	-8 265 585	39 149 729	988 774 007	7 745 565	430 635 542
2041	18	-	-760 924	-	-760 924	-6 848 314	76 092 379	253 506	786	147	1 394	954	100	507 013	66 247 284	31 426 113	15 927 054	10 689 834	58 043 002	14 291 672	8 204 282	-1 640 856	12 650 816	1 001 424 823	2 275 360	432 910 903
2042	19	-	-760 924	-	-760 924	-6 848 314	76 092 379	101 403	786	147	1 394	954	100	507 013	26 498 913	31 426 113	15 927 054	10 689 834	58 043 002	-25 456 698	-31 544 088	-	-25 456 698	975 968 125	-4 162 374	428 748 529
2043	20	15 218 476	-608 739	11 413 857	26 023 594	-6 848 314	60 873 903	50 701	786	147	1 394	954	100	507 013	13 249 457	30 310 474	14 892 198	10 654 867	55 857 539	-9 736 175	-42 608 082	-	-9 736 175	966 231 950	-1 447 220	427 301 309

SA Region Scenarios – by using Current Technology

Table 26. Financial Model of H2SO4 – NMC811 process – SA region Value Chain Scenario 1 (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023)

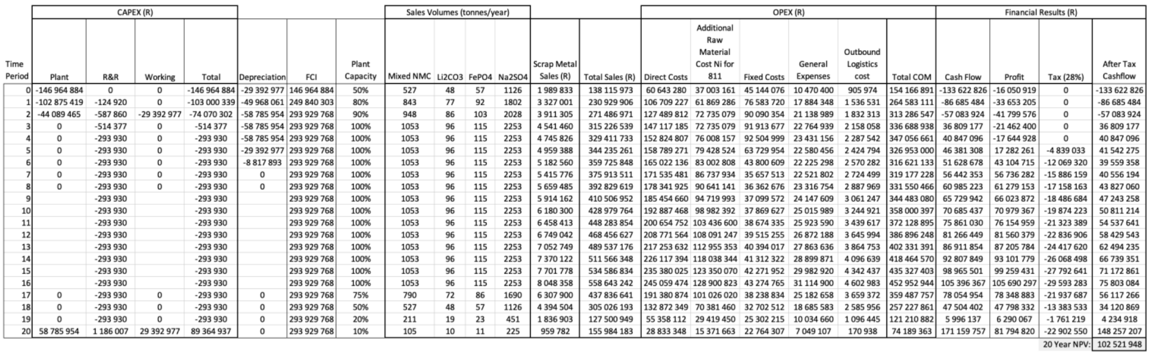
	CAPEX (R)							Sales Volumes (tonnes/year)						OPEX (R)						Financial Results (R)			
Time Period	Plant	R&R	Working	Total	Depreciation	FCI	Plant Capacity	Mixed NMC	Li2CO3	FePO4	Na2SO4	Scrap Metal Sales (R)	Total Sales (R)	Direct Costs	Additional Raw Material Cost Ni for 811	Fixed Costs	General Expenses	Outbound Logistics cost	Total COM	Cash Flow	Profit	Tax (28%)	After Tax Cashflow
0	-146 964 884	0	0	-146 964 884	-29 392 977	146 964 884	50%	527	48	57	1126	1 989 833	138 115 973	60 643 280	37 003 161	45 144 076	10 422 717	0	153 213 235	-132 669 170	-15 097 262	0	-132 669 170
1	-102 875 419	-124 920	0	-103 000 339	-49 968 061	249 840 303	80%	843	77	92	1802	3 327 001	230 929 906	106 709 227	61 869 286	76 583 720	17 803 478	0	262 965 710	-85 068 082	-32 035 804	0	-85 068 082
2	-44 089 465	-587 860	-29 392 977	-74 070 302	-58 785 954	293 929 768	90%	948	86	103	2028	3 911 305	271 486 971	127 489 812	72 735 079	90 090 354	21 042 552	0	311 357 796	-55 155 173	-39 870 825	0	-55 155 173
3	0	-514 377	0	-514 377	-58 785 954	293 929 768	100%	1053	96	115	2253	4 541 460	315 226 539	147 117 185	72 735 079	91 913 677	22 651 357	0	334 417 298	39 080 817	-19 190 759	0	39 080 817
4	0	-293 930	0	-293 930	-58 785 954	293 929 768	100%	1053	96	115	2253	4 745 826	329 411 733	152 824 807	76 008 157	92 504 999	23 310 759	0	344 648 722	43 255 034	-15 236 989	0	43 255 034
5	0	-293 930	0	-293 930	-29 392 977	293 929 768	100%	1053	96	115	2253	4 959 388	344 235 261	158 789 271	79 428 524	63 729 954	22 452 835	0	324 400 585	48 933 723	19 834 676	-5 553 709	43 380 014
6	0	-293 930	0	-293 930	-8 817 893	293 929 768	100%	1053	96	115	2253	5 182 560	359 725 848	165 022 136	83 002 808	43 800 609	22 090 020	0	313 915 573	54 334 238	45 810 275	-12 826 877	41 507 361
7	0	-293 930	0	-293 930	0	293 929 768	100%	1053	96	115	2253	5 415 776	375 913 511	171 535 481	86 737 934	35 657 513	22 378 407	0	316 309 335	59 310 246	59 604 176	-16 689 169	42 621 077
8	0	-293 930	0	-293 930	0	293 929 768	100%	1053	96	115	2253	5 659 485	392 829 619	178 341 925	90 641 141	36 362 676	23 164 756	0	328 510 499	64 025 190	64 319 120	-18 009 354	46 015 837
9		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	5 914 162	410 506 952	185 454 660	94 719 993	37 099 572	23 986 490	0	341 260 715	68 952 307	69 246 237	-19 388 946	49 563 361
10		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 180 300	428 979 764	192 887 468	98 982 392	37 869 627	24 845 203	0	354 584 691	74 101 144	74 395 074	-20 830 621	53 270 523
11		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 458 413	448 283 854	200 654 752	103 436 600	38 674 335	25 742 558	0	368 508 245	79 481 679	79 775 608	-22 337 170	57 144 508
12		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 749 042	468 456 627	208 771 564	108 091 247	39 515 255	26 680 294	0	383 058 360	85 104 337	85 398 267	-23 911 515	61 192 823
13		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 052 749	489 537 176	217 253 632	112 955 353	40 394 017	27 660 228	0	398 263 230	90 980 016	91 273 946	-25 556 705	65 423 311
14		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 370 122	511 566 348	226 117 394	118 038 344	41 312 322	28 684 258	0	414 152 319	97 120 100	97 414 030	-27 275 928	69 844 172
15		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 701 778	534 586 834	235 380 025	123 350 070	42 271 952	29 754 371	0	430 756 417	103 536 488	103 830 417	-29 072 517	74 463 971
16		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	8 048 358	558 643 242	245 059 474	128 900 823	43 274 765	30 872 638	0	448 107 699	110 241 613	110 535 543	-30 949 952	79 291 661
17	0	-293 930	0	-293 930	0	293 929 768	75%	790	72	86	1690	6 307 900	437 836 641	191 380 874	101 026 020	38 238 834	24 990 060	0	355 635 787	81 906 924	82 200 853	-23 016 239	58 890 685
18	0	-293 930	0	-293 930	0	293 929 768	50%	527	48	57	1126	4 394 504	305 026 193	132 872 349	70 381 460	32 702 512	18 549 480	0	254 505 802	50 226 461	50 520 391	-14 145 709	36 080 752
19	0	-293 930	0	-293 930	0	293 929 768	20%	211	19	23	451	1 836 903	127 500 949	55 358 112	29 419 450	25 302 215	9 976 952	0	120 056 729	7 150 290	7 444 220	-2 084 382	5 065 909
20	58 785 954	1 186 007	29 392 977	89 364 937	0	293 929 768	10%	105	10	11	225	959 782	155 984 183	28 833 348	15 371 663	22 764 307	7 040 110	0	74 009 428	171 339 692	81 974 755	-22 952 931	148 386 761
																						20 Year NPV:	123 634 345

Table 27. Financial Model of H2SO4 – NMC811 process – SA region Value Chain Scenario 2 (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023)



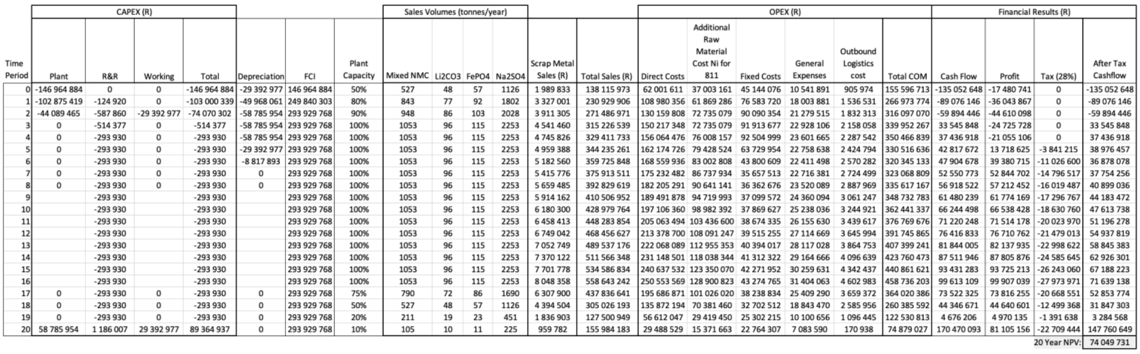
	CAPEX (R)							Sales Volumes (tonnes/year)						OPEX (R)						Financial Results (R)			
Time Period	Plant	R&R	Working	Total	Depreciation	FCI	Plant Capacity	Mixed NMC	Li2CO3	FePO4	Na2SO4	Scrap Metal Sales (R)	Total Sales (R)	Direct Costs	Additional Raw Material Cost Ni for 811	Fixed Costs	General Expenses	Outbound Logistics cost	Total COM	Cash Flow	Profit	Tax (28%)	After Tax Cashflow
0	-146 964 884	0	0	-146 964 884	-29 392 977	146 964 884	50%	527	48	57	1126	1 989 833	138 115 973	62 001 611	37 003 161	45 144 076	10 494 209	0	154 643 057	-134 098 992	-16 527 084	0	-134 098 992
1	-102 875 419	-124 920	0	-103 000 339	-49 968 061	249 840 303	80%	843	77	92	1802	3 327 001	230 929 906	108 980 356	61 869 286	76 583 720	17 923 011	0	265 356 372	-87 458 744	-34 426 466	0	-87 458 744
2	-44 089 465	-587 860	-29 392 977	-74 070 302	-58 785 954	293 929 768	90%	948	86	103	2028	3 911 305	271 486 971	130 159 808	72 735 079	90 090 354	21 183 078	0	314 168 318	-57 965 695	-42 681 347	0	-57 965 695
3	0	-514 377	0	-514 377	-58 785 954	293 929 768	100%	1053	96	115	2253	4 541 460	315 226 539	150 217 348	72 735 079	91 913 677	22 814 524	0	337 680 627	35 817 489	-22 454 088	0	35 817 489
4	0	-293 930	0	-293 930	-58 785 954	293 929 768	100%	1053	96	115	2253	4 745 826	329 411 733	156 064 476	76 008 157	92 504 999	23 481 268	0	348 058 901	39 844 856	-18 647 168	0	39 844 856
5	0	-293 930	0	-293 930	-29 392 977	293 929 768	100%	1053	96	115	2253	4 959 388	344 235 261	162 174 726	79 428 524	63 729 954	22 631 017	0	327 964 221	45 370 087	16 271 039	-4 555 891	40 814 195
6	0	-293 930	0	-293 930	-8 817 893	293 929 768	100%	1053	96	115	2253	5 182 560	359 725 848	168 559 936	83 002 808	43 800 609	22 276 220	0	317 639 573	50 610 238	42 086 274	-11 784 157	38 826 081
7	0	-293 930	0	-293 930	0	293 929 768	100%	1053	96	115	2253	5 415 776	375 913 511	175 232 482	86 737 934	35 657 513	22 572 986	0	320 200 915	55 418 666	55 712 596	-15 599 527	39 819 139
8	0	-293 930	0	-293 930	0	293 929 768	100%	1053	96	115	2253	5 659 485	392 829 619	182 205 291	90 641 141	36 362 676	23 368 091	0	332 577 200	59 958 489	60 252 419	-16 870 677	43 087 812
9		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	5 914 162	410 506 952	189 491 878	94 719 993	37 099 572	24 198 976	0	345 510 418	64 702 604	64 996 534	-18 199 030	46 503 575
10		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 180 300	428 979 764	197 106 360	98 982 392	37 869 627	25 067 250	0	359 025 630	69 660 205	69 954 134	-19 587 158	50 073 047
11		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 458 413	448 283 854	205 063 494	103 436 600	38 674 335	25 974 597	0	373 149 027	74 840 897	75 134 827	-21 037 752	53 803 146
12		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 749 042	468 456 627	213 378 700	108 091 247	39 515 255	26 922 775	0	387 907 977	80 254 721	80 548 650	-22 553 622	57 701 099
13		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 052 749	489 537 176	222 068 089	112 955 353	40 394 017	27 913 620	0	403 331 079	85 912 166	86 206 096	-24 137 707	61 774 459
14		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 370 122	511 566 348	231 148 501	118 038 344	41 312 322	28 949 054	0	419 448 222	91 824 197	92 118 127	-25 793 076	66 031 122
15		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 701 778	534 586 834	240 637 532	123 350 070	42 271 952	30 031 082	0	436 290 635	98 002 269	98 296 199	-27 522 936	70 479 334
16		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	8 048 358	558 643 242	250 553 569	128 900 823	43 274 765	31 161 801	0	453 890 957	104 458 355	104 752 284	-29 330 640	75 127 715
17	0	-293 930	0	-293 930	0	293 929 768	75%	790	72	86	1690	6 307 900	437 836 641	195 686 871	101 026 020	38 238 834	25 216 691	0	360 168 416	77 374 295	77 668 225	-21 747 103	55 627 192
18	0	-293 930	0	-293 930	0	293 929 768	50%	527	48	57	1126	4 394 504	305 026 193	135 872 194	70 381 460	32 702 512	18 707 367	0	257 663 533	47 068 730	47 362 659	-13 261 545	33 807 185
19	0	-293 930	0	-293 930	0	293 929 768	20%	211	19	23	451	1 836 903	127 500 949	56 612 047	29 419 450	25 302 215	10 042 949	0	121 376 660	5 830 358	6 124 288	-1 714 801	4 115 558
20	58 785 954	1 186 007	29 392 977	89 364 937	0	293 929 768	10%	105	10	11	225	959 782	155 984 183	29 488 529	15 371 663	22 764 307	7 074 593	0	74 699 092	170 650 028	81 285 091	-22 759 825	147 890 203
																						20 Year NPV:	95 162 127

Table 28. Financial Model of H2SO4 – NMC811 process – SA region Value Chain Scenario 3 (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023)



	CAPEX (R)							Sales Volumes (tonnes/year)						OPEX (R)						Financial Results (R)			
Time Period	Plant	R&R	Working	Total	Depreciation	FCI	Plant Capacity	Mixed NMC	Li2CO3	FePO4	Na2SO4	Scrap Metal Sales (R)	Total Sales (R)	Direct Costs	Additional Raw Material Cost Ni for 811	Fixed Costs	General Expenses	Outbound Logistics cost	Total COM	Cash Flow	Profit	Tax (28%)	After Tax Cashflow
0	-146 964 884	0	0	-146 964 884	-29 392 977	146 964 884	50%	527	48	57	1126	1 989 833	138 115 973	60 643 280	37 003 161	45 144 076	10 470 400	905 974	154 166 891	-133 622 826	-16 050 919	0	-133 622 826
1	-102 875 419	-124 920	0	-103 000 339	-49 968 061	249 840 303	80%	843	77	92	1802	3 327 001	230 929 906	106 709 227	61 869 286	76 583 720	17 884 348	1 536 531	264 583 111	-86 685 484	-33 653 205	0	-86 685 484
2	-44 089 465	-587 860	-29 392 977	-74 070 302	-58 785 954	293 929 768	90%	948	86	103	2028	3 911 305	271 486 971	127 489 812	72 735 079	90 090 354	21 138 989	1 832 313	313 286 547	-57 083 924	-41 799 576	0	-57 083 924
3	0	-514 377	0	-514 377	-58 785 954	293 929 768	100%	1053	96	115	2253	4 541 460	315 226 539	147 117 185	72 735 079	91 913 677	22 764 939	2 158 058	336 688 938	36 809 177	-21 462 400	0	36 809 177
4	0	-293 930	0	-293 930	-58 785 954	293 929 768	100%	1053	96	115	2253	4 745 826	329 411 733	152 824 807	76 008 157	92 504 999	23 431 156	2 287 542	347 056 661	40 847 096	-17 644 928	0	40 847 096
5	0	-293 930	0	-293 930	-29 392 977	293 929 768	100%	1053	96	115	2253	4 959 388	344 235 261	158 789 271	79 428 524	63 729 954	22 580 456	2 424 794	326 953 000	46 381 308	17 282 261	-4 839 033	41 542 275
6	0	-293 930	0	-293 930	-8 817 893	293 929 768	100%	1053	96	115	2253	5 182 560	359 725 848	165 022 136	83 002 808	43 800 609	22 225 298	2 570 282	316 621 133	51 628 678	43 104 715	-12 069 320	39 559 358
7	0	-293 930	0	-293 930	0	293 929 768	100%	1053	96	115	2253	5 415 776	375 913 511	171 535 481	86 737 934	35 657 513	22 521 802	2 724 499	319 177 228	56 442 353	56 736 282	-15 886 159	40 556 194
8	0	-293 930	0	-293 930	0	293 929 768	100%	1053	96	115	2253	5 659 485	392 829 619	178 341 925	90 641 141	36 362 676	23 316 754	2 887 969	331 550 466	60 985 223	61 279 153	-17 158 163	43 827 060
9		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	5 914 162	410 506 952	185 454 660	94 719 993	37 099 572	24 147 609	3 061 247	344 483 080	65 729 942	66 023 872	-18 486 684	47 243 258
10		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 180 300	428 979 764	192 887 468	98 982 392	37 869 627	25 015 989	3 244 921	358 000 397	70 685 437	70 979 367	-19 874 223	50 811 214
11		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 458 413	448 283 854	200 654 752	103 436 600	38 674 335	25 923 590	3 439 617	372 128 895	75 861 030	76 154 959	-21 323 389	54 537 641
12		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 749 042	468 456 627	208 771 564	108 091 247	39 515 255	26 872 188	3 645 994	386 896 248	81 266 449	81 560 379	-22 836 906	58 429 543
13		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 052 749	489 537 176	217 253 632	112 955 353	40 394 017	27 863 636	3 864 753	402 331 391	86 911 854	87 205 784	-24 417 620	62 494 235
14		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 370 122	511 566 348	226 117 394	118 038 344	41 312 322	28 899 871	4 096 639	418 464 570	92 807 849	93 101 779	-26 068 498	66 739 351
15		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 701 778	534 586 834	235 380 025	123 350 070	42 271 952	29 982 920	4 342 437	435 327 403	98 965 501	99 259 431	-27 792 641	71 172 861
16		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	8 048 358	558 643 242	245 059 474	128 900 823	43 274 765	31 114 900	4 602 983	452 952 944	105 396 367	105 690 297	-29 593 283	75 803 084
17	0	-293 930	0	-293 930	0	293 929 768	75%	790	72	86	1690	6 307 900	437 836 641	191 380 874	101 026 020	38 238 834	25 182 658	3 659 372	359 487 757	78 054 954	78 348 883	-21 937 687	56 117 266
18	0	-293 930	0	-293 930	0	293 929 768	50%	527	48	57	1126	4 394 504	305 026 193	132 872 349	70 381 460	32 702 512	18 685 583	2 585 956	257 227 861	47 504 402	47 798 332	-13 383 533	34 120 869
19	0	-293 930	0	-293 930	0	293 929 768	20%	211	19	23	451	1 836 903	127 500 949	55 358 112	29 419 450	25 302 215	10 034 660	1 096 445	121 210 882	5 996 137	6 290 067	-1 761 219	4 234 918
20	58 785 954	1 186 007	29 392 977	89 364 937	0	293 929 768	10%	105	10	11	225	959 782	155 984 183	28 833 348	15 371 663	22 764 307	7 049 107	170 938	74 189 363	171 159 757	81 794 820	-22 902 550	148 257 207
																						20 Year NPV:	102 521 948

Table 29. Financial Model of H2SO4 – NMC811 process – SA region Value Chain Scenario 4 (Kuhn, Towards a Business Model For Lithium-Ion Battery Recycling In South Africa, 2023)



	CAPEX (R)							Sales Volumes (tonnes/year)						OPEX (R)						Financial Results (R)			
Time Period	Plant	R&R	Working	Total	Depreciation	FCI	Plant Capacity	Mixed NMC	Li2CO3	FePO4	Na2SO4	Scrap Metal Sales (R)	Total Sales (R)	Direct Costs	Additional Raw Material Cost Ni for 811	Fixed Costs	General Expenses	Outbound Logistics cost	Total COM	Cash Flow	Profit	Tax (28%)	After Tax Cashflow
0	-146 964 884	0	0	-146 964 884	-29 392 977	146 964 884	50%	527	48	57	1126	1 989 833	138 115 973	62 001 611	37 003 161	45 144 076	10 541 891	905 974	155 596 713	-135 052 648	-17 480 741	0	-135 052 648
1	-102 875 419	-124 920	0	-103 000 339	-49 968 061	249 840 303	80%	843	77	92	1802	3 327 001	230 929 906	108 980 356	61 869 286	76 583 720	18 003 881	1 536 531	266 973 774	-89 076 146	-36 043 867	0	-89 076 146
2	-44 089 465	-587 860	-29 392 977	-74 070 302	-58 785 954	293 929 768	90%	948	86	103	2028	3 911 305	271 486 971	130 159 808	72 735 079	90 090 354	21 279 515	1 832 313	316 097 070	-59 894 446	-44 610 098	0	-59 894 446
3	0	-514 377	0	-514 377	-58 785 954	293 929 768	100%	1053	96	115	2253	4 541 460	315 226 539	150 217 348	72 735 079	91 913 677	22 928 106	2 158 058	339 952 267	33 545 848	-24 725 728	0	33 545 848
4	0	-293 930	0	-293 930	-58 785 954	293 929 768	100%	1053	96	115	2253	4 745 826	329 411 733	156 064 476	76 008 157	92 504 999	23 601 665	2 287 542	350 466 839	37 436 918	-21 055 106	0	37 436 918
5	0	-293 930	0	-293 930	-29 392 977	293 929 768	100%	1053	96	115	2253	4 959 388	344 235 261	162 174 726	79 428 524	63 729 954	22 758 638	2 424 794	330 516 636	42 817 672	13 718 625	-3 841 215	38 976 457
6	0	-293 930	0	-293 930	-8 817 893	293 929 768	100%	1053	96	115	2253	5 182 560	359 725 848	168 559 936	83 002 808	43 800 609	22 411 498	2 570 282	320 345 133	47 904 678	39 380 715	-11 026 600	36 878 078
7	0	-293 930	0	-293 930	0	293 929 768	100%	1053	96	115	2253	5 415 776	375 913 511	175 232 482	86 737 934	35 657 513	22 716 381	2 724 499	323 068 809	52 550 773	52 844 702	-14 796 517	37 754 256
8	0	-293 930	0	-293 930	0	293 929 768	100%	1053	96	115	2253	5 659 485	392 829 619	182 205 291	90 641 141	36 362 676	23 520 089	2 887 969	335 617 167	56 918 522	57 212 452	-16 019 487	40 899 036
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10		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 180 300	428 979 764	197 106 360	98 982 392	37 869 627	25 238 036	3 244 921	362 441 337	66 244 498	66 538 428	-18 630 760	47 613 738
11		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 458 413	448 283 854	205 063 494	103 436 600	38 674 335	26 155 630	3 439 617	376 769 676	71 220 248	71 514 178	-20 023 970	51 196 278
12		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	6 749 042	468 456 627	213 378 700	108 091 247	39 515 255	27 114 669	3 645 994	391 745 865	76 416 833	76 710 762	-21 479 013	54 937 819
13		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 052 749	489 537 176	222 068 089	112 955 353	40 394 017	28 117 028	3 864 753	407 399 241	81 844 005	82 137 935	-22 998 622	58 845 383
14		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 370 122	511 566 348	231 148 501	118 038 344	41 312 322	29 164 666	4 096 639	423 760 473	87 511 946	87 805 876	-24 585 645	62 926 301
15		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	7 701 778	534 586 834	240 637 532	123 350 070	42 271 952	30 259 631	4 342 437	440 861 621	93 431 283	93 725 213	-26 243 060	67 188 223
16		-293 930		-293 930		293 929 768	100%	1053	96	115	2253	8 048 358	558 643 242	250 553 569	128 900 823	43 274 765	31 404 063	4 602 983	458 736 203	99 613 109	99 907 039	-27 973 971	71 639 138
17	0	-293 930	0	-293 930	0	293 929 768	75%	790	72	86	1690	6 307 900	437 836 641	195 686 871	101 026 020	38 238 834	25 409 290	3 659 372	364 020 386	73 522 325	73 816 255	-20 668 551	52 853 774
18	0	-293 930	0	-293 930	0	293 929 768	50%	527	48	57	1126	4 394 504	305 026 193	135 872 194	70 381 460	32 702 512	18 843 470	2 585 956	260 385 592	44 346 671	44 640 601	-12 499 368	31 847 303
19	0	-293 930	0	-293 930	0	293 929 768	20%	211	19	23	451	1 836 903	127 500 949	56 612 047	29 419 450	25 302 215	10 100 656	1 096 445	122 530 813	4 676 206	4 970 135	-1 391 638	3 284 568
20	58 785 954	1 186 007	29 392 977	89 364 937	0	293 929 768	10%	105	10	11	225	959 782	155 984 183	29 488 529	15 371 663	22 764 307	7 083 590	170 938	74 879 027	170 470 093	81 105 156	-22 709 444	147 760 649
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This report has been reviewed and approved in accordance with IVL's audit and approval management system.