Consolidated Framework for Establishing a Lithium-Ion Battery Facility in a European Context

ELiMINATE Deliverable 6.4 of Task 6.4

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

Summary

This report is deliverable 6.4 in the ERA-MIN Horizon 2020 (funded by Vinnova on the Swedish counterpart) project End-of-life Li-ion battery management integration and technology evaluation (ELiMINATE) project, which aims to evaluate different battery recycling processes and deliver an implementation framework to advise on the best way forward in terms of establishing local end-of-life lithium-ion battery treatment facilities. The project was done in close collaboration between the South African (SA) coordinator Stellenbosch University and IVL as work packages (WPs) 1-3 were tailored to the SA and European Union (EU) regions by each partner, respectively. As the SA context tasks had a larger share of the budget, the EU context tasks used and adjusted the SA context tasks for the EU region, both for the work packages for which both partners had responsibilities, but also for this report deliverable.

The report first goes through the various screening assessments done in ELiMINATE, such as Industry practice, Reagent Availability, Availability of buyers for product types, Metals recovery & purity, Environmental analysis using Life Cycle Assessment (LCA), Economic Indicator (Net Present Value comparison), and a Need Approach Benefit Competition assessment. Material Recovery technologies are selected from the screening and consequently they are used in the value chain integration to create the business model canvas.

This report is aimed at actors who plan to open a material recovery plant and plan to do so using the assessment methods included here. As the EU region is complex, it faces different challenges in the end-of-life lithium-ion battery market compared to the South African context. Thus, this report will be a useful complement to the South African counterpart for those who seek guidance on assessing regions with similarities to the EU, or in the EU itself.

Abbreviations

BMC	Business Model Canvas
CAPEX	Capital Expenditure
EBA	European Battery Alliance
ELiMINATE	End-of-life Li-ion battery management integration and technology evaluation
EOL	End-of-Life
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LFP	Lithium-Iron-Phosphate
LIB	Lithium-ion Battery
LMO	Lithium-Manganese-Oxide
NABC	Needs Approach Benefit Competition
NCA	Nickel-Cobalt-Aluminum
NMC	Nickel-Manganese-Cobalt
NPV	Net Present Value
OPEX	Operational Expenditure
PHEV	Plug-in Hybrid Electric Vehicle
RLN	Reverse Logistics Network
SA	South Africa
TEA	Techno-Economic Assessment

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1 Purpose

This chapter provides the reasoning behind this report and the project. This report is Deliverable 6.4 in the ERA-MIN Horizon 2020 (funded by Vinnova on the Swedish counterpart) project End-of-life Li-ion battery management integration and technology evaluation (ELiMINATE) project, which aims to evaluate different battery recycling processes and deliver an implementation framework to advise on the best way forward in terms of establishing local end-of-life lithium-ion battery (LIB) treatment facilities. The task description for D6.4 reads: "Adjust market analysis and business model work based on data revealed during work in WP3 and WP5. Combine the findings of work packages 1 – 5 to provide a framework for the establishment of a lithium-ion recycling industry and processing facility in the European context."

In the ELiMINATE project, work packages (WPs) 1 to 3 were done twice, once for the South Africa (SA) context by the project coordinator Stellenbosch University, and once for the European Union (EU) context by IVL. This was done with collaboration between the project partners by bringing insights and expertise to their respective contexts, but also to between the contexts. As the project coordinator had a more substantial budget and several master's students working on the work packages, much of the work was done initially for the SA context and then adopted for the EU context. Through this approach, the strengths from both partners were fully used and the tasks could be completed more effectively than if they had been done separately.

For a complete understanding of the consolidated network for the EU context it is thus useful to also consider reading the report on the SA context (D6.3). In the chapters and sections where it is recommended to read SA context report, it will be specified in the text.

Also see the South African report for the following:

- "The ELiMINATE Project"
- "Target Audience and Desired Outcomes"

1.1 Why Recycle Lithium-ion Batteries in the EU?

Battery recycling in the EU is a critical component of the region's energy transition to a more sustainable and circular economy. LIBs will be used to displace fossil-based mobility solutions, store energy from the grid, and utilize more sustainable electricity produced from renewable sources. The rationale for promoting battery recycling is part the EU strategy to become a global leader in sustainable battery industry and expand the battery production, use, and recycling through the European Battery Alliance (EBA) (European Commission, 2017) and a set of legislatures led by the Green Deal (European Commission, 2023) and the accompanying Battery Regulation (EU) 2023/1542 and other laws.

As Europe is one of the leaders of the transition to electrification and in contrast to the South African case, the waste flows of LIBs in the EU are both quickly changing and are expected to be made up of a growing portion of End-of-Life (EOL) Electric Vehicle (EV) applications. This transition has coaxed the market to open cell production facilities in the region and battery recyclers to process the burgeoning volumes of battery waste.

The recycling technology is not stagnant in the energy transition. In previous years, recyclers in Europe have been able to follow the Battery Directive and recover minimal amounts of important battery metals. The Battery Regulation now places minimum recycling limits on these metals, necessitating new material recovery technologies and equipment that can reach the higher limits. Additionally, the recycling capacities needed to handle the incoming wave of EOL LIBs due to the increased LIB production and use will require increases in processed volumes and entirely new actors to enter the market. The raw material produced in the material recovery can be used for battery production, creating a more circular economy that recovers more of its materials. Therefore, the role of recyclers is very important in this shift to electrification with circular economy in the EU.

2 Background

This chapter gives some background to LIBs in the context of the European market. Also, see the South African report for the following:

- "LIB Structure and Operating Principle"
- "Process Options for Recycling Facility"

2.1 Waste LIB Generation Rate and Market

Table 1 shows some common LIB cathode and anode materials and their applications. In general, the cathode materials hold most of the value in EOL LIBs, hence the focus on these materials when recycling. The battery chemistry is usually only referred to by its cathode chemistry (e.g. NCA) with the assumption of a graphite unless specified.

Table 1 Chemistries for different applications of lithium-ion batteries (Wu & Lindman, 2022)

Chemistry	Cathode	Anode	Applications
LCO	$LiCoO_2$	Graphite	Mobile phones, laptops, tablets, cameras
LFP	$LiFePO_4$	Graphite	Electric cars (with lower demand of range) energy storage systems (ESS), power tools, utility vehicles, HEV buses, replacement of lead-acid batteries
LMO	$LiMn_2O_4$	Graphite	Older (and recently: new and relatively cheap) models of electric cars, power tools, medical devices, e-bikes, e-scooters
NCA	$LiNiCoAlO_2$	Graphite	Electric cars (Tesla), laptops, medical devices, e-scooters
NMC	$LiNiMnCoO_2$	Graphite	BEVs. power tools, energy storage systems (ESS), medical devices, e-bikes, industrial
LTO	LiNiMnCoO or $LiMn_2O_4$	$Li_4Ti_5O_{12}$	Electric buses (good for opportunity charging), e-bikes

The automotive industry has substantially grown the market for LIBs with the increased demand for plug-in hybrid vehicles (PHEVs) and fully electrical vehicles. Early fully electrical vehicles used lithium-iron-phosphate (LFP), and this is still the case in China and for electric cars with lower demand of range, but leading actors on the European and US markets have progressed to use a combination of nickel-manganese-cobalt (NMC) and lithium-manganese-oxide (LMO) type batteries or NCA. (2022 Wu A., Lindman R.) LFP is a cheaper alternative than both NCA and

NMC, and LFP is suitably used in electric buses (which are charged often), as well as in e-bikes and electric cars with lower demand of range. (Wu & Lindman, 2022).

Figure 1 and Figure 2 show the increases in volumes of LIBs by application and battery chemistry, respectively, that have been (or will be) collected and are (or will be) readily available for recycling using data from Circular Energy Storage[1].

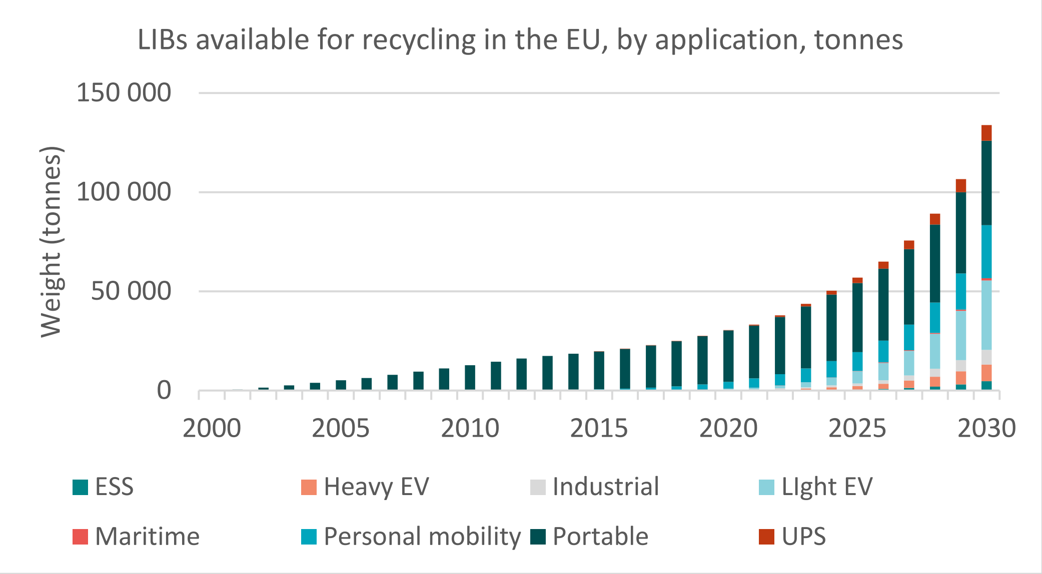

Figure 1: LIBs available for recycling in EU, by application, tonnes. (Wu & Lindman, 2022)

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[1] circularenergystorage.com/ces-online

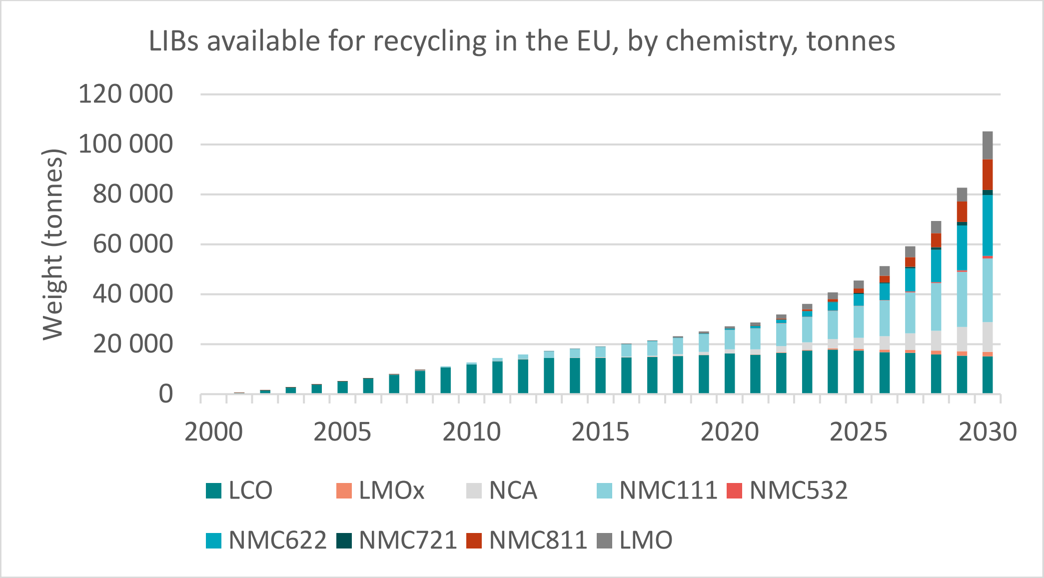

Figure 2: LIBs available for recycling in EU, by chemistry, tonnes (Wu & Lindman, 2022)

(Emilsson & Ozturk, 2023) converted the weights of EOL batteries, battery packs, and black mass into a gravimetric volume equivalent which they called cell-weight equivalents. The market volumes for LIBs were then visualized:

- For LIB material recovery in Figure 3 to Figure 5
- For LIB pre-processing in Figure 6 to Figure 8

Figure 3: Material recovery nodes and processing volumes for 2022 in tonnes of cell equivalents

Figure 4: Material recovery nodes and processing volumes for 2026 in tonnes of cell equivalents

Figure 5: Material recovery nodes and processing volumes for 2030 in tonnes of cell equivalents

Figure 6: Pre-processor nodes and processing volumes for 2022 in tonnes of cell equivalents

Figure 7: Pre-processor nodes and processing volumes for 2026 in tonnes of cell equivalents

Figure 8: Pre-processor nodes and processing volumes for 2030 in tonnes of cell equivalents

Battery production scrap is also a source of EOL LIBs, whose volumes are expected to increase as the production capacity in Europe increases. The market volumes for LIBs were also visualized:

- For LIB cell producers in Figure 9 to Figure 11

Figure 9: Producer nodes and production volumes for 2022 in tonnes of cell equivalents

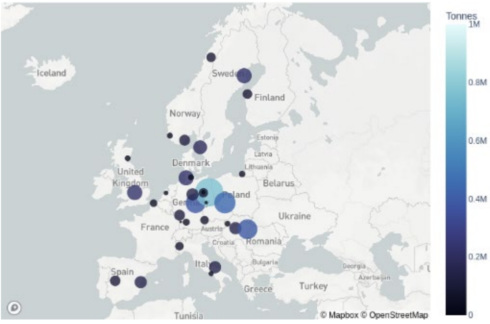

Figure 10: Producer nodes and production capacity volumes for 2026 in tonnes of cell equivalents

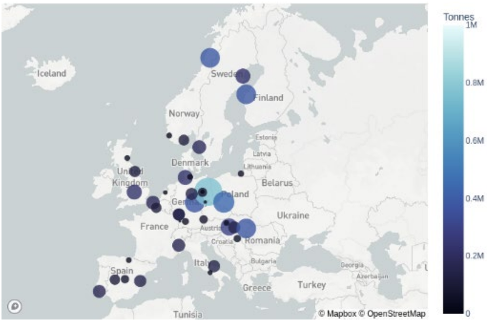

Figure 11: Producer nodes and production volumes for 2030 in tonnes of cell equivalents

The Appendix contains the underlying data for the figures above from (Emilsson & Ozturk, 2023).

3 Screening potential recycling process routes

See the South African report for this chapter.

4 Screening potential recycling process routes

The following sub-chapters are copied almost in their entirety from (Ozturk, Kuhn, & Wu, 2024), except for subchapter *4.5 Screening by Life Cycle Assessment*, which came mostly from the screening Life Cycle Assessment (LCA) for EU Deliverable 2A (Elginöz Kanat, Ozturk, Maritz, Van Schalkwyk, & Dorfling, 2023) and the Full LCA for the EU Deliverable 2B (Elginoz, Ozturk, Maritz, Van Schalkwyk, & Dorfling, 2023).

Also, see the South African report for the following chapters:
- ‘Pre-treatment’,
- ‘Hydrometallurgy vs Pyrometallurgy’,
- ‘Hydrometallurgy Processes Considered’, and
- ‘Metals Recovery and Purity’.

4.1 Categories as the Base for Screening

Text from SA Consolidative Framework:

The project participants’ knowledge and expertise in the ELiMINATE project were used to compare the advantages and disadvantages of the nine process options in seven categories. The information came from two industry experts and research conducted by Doctoral candidates participating in the ELiMINATE project, together with information from the literature. The following screening categories were considered, explained more thoroughly in the following sections:

- *Industry practice,*
- *Reagent Availability,*
- *Availability of buyers for product types,*
- *Metals recovery & purity,*
- *Environmental analysis using LCA,*
- *Economic Indicator (Net Present Value (NPV) comparison),*
- *Need Approach Benefit Competition.*

4.2 Screening by Industry Practice

This section aims to prioritize options with better practicality for the LIB technologies. (Kuhn, 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 H2SO4 – 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, H2SO4 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 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 Screening by Reagent Availability

In this study, the proposed LIB recycling technologies involve various chemicals detailed in Wu, Ozturk, & Kuhn (2024) and (Maritz, 2022). 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.

4.4 Screening by the Availability of Buyers

In 2022, Khun conducted a buyer availability analysis utilizing ELIMINATE project data for current technologies. The findings indicate that HCL – NMC and H2SO4 – 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, 2023).

The products of novel technologies differ from than current ones. While novel technologies differ in processing steps and leaching reagents used, they yield identical final products: manganese dioxide (MnO2), nickel hydroxide (Ni(OH)2), cobalt tetroxide (Co3O4), and lithium carbonate (Li2CO3). 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.

4.5 Screening by Life Cycle Assessment

Life cycle assessment methodology was first developed to identify the environmental hot spots of production systems, quantify their environmental sustainability performance, and define the possibilities for improvement. However, it is also widely used to evaluate new technologies in their process design stage before their application in the industrial scale and to compare different technologies with the same function. This prospective approach provides environmental performance information before the technology is applied when the design freedom of the technology is higher (Arvidsson, o.a., 2017) and therefore the evaluation can help designing the technology in a more sustainable manner. In the light of this knowledge, in ELIMINATE project, different process technologies for recycling batteries were compared regarding their environmental performance.

The first step was to compare available recycling technologies. Although in the proposal stage it was suggested that a screening LCA would be applied for this comparison, a detailed study was conducted to be able to evaluate different technologies. The end point results of this study showed that, for all available technologies that are evaluated, the environmental gain provided by recovering metals from waste batteries is higher than the environmental burdens caused by using energy and material sources during the recycling process when all impact categories are considered (Figure 12). Therefore, the total environmental impact results are all negative which shows that the more we recycle batteries the more environmental gain we will provide.

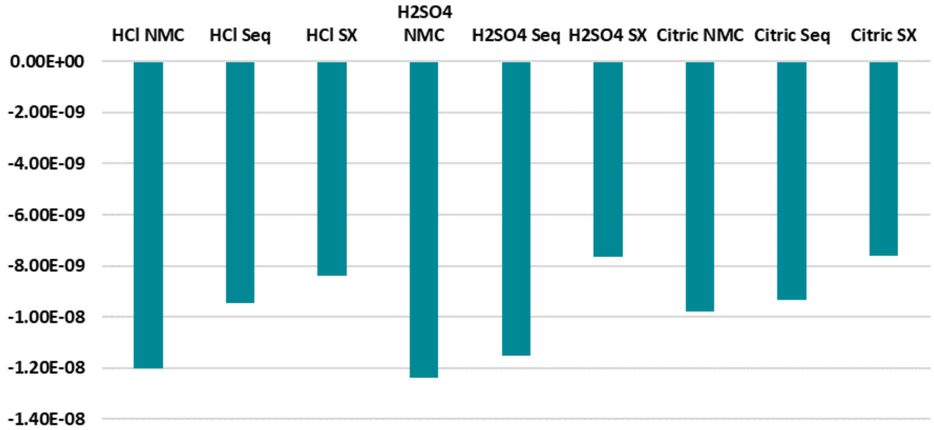

Figure 12: Normalized and weighted CML 2016 results for all hydrometallurgical recycling cases. Normalization reference: CML 2016 (Centrum voor Milieukunde Leiden, 2016), EU 25 + 3, year 2000, excl. biogenic carbon. Weighting method: Sphera thinkstep life cycle impact assessment (LCIA) Survey 2012, Europe, CML 2016, excl. biogenic carbon. (Elginöz Kanat, Ozturk, Maritz, Van Schalkwyk, & Dorfling, 2023)

> *"…the total environmental impact results are all negative which shows that the more we recycle batteries the more environmental gain we will provide"*

The results also show that H2SO4 NMC performs best when the normalized and weighted results (end point) are compared. On the other hand, if the impact categories are evaluated separately, we see that global warming potential result is only negative for H2SO4 NMC but positive for all other technologies. Therefore, it is suggested that both ways of evaluation (mid-point and end point) give valuable information.

After the novel technologies, H2SO4-novel and MSA-novel in short, have been developed by KTU in the project, a screening LCA study based on the experience from the first comparison study and flow sheets developed by SU, was conducted by IVL. This was the second step of the LCA studies. The results of this study showed that H2SO4-novel performs better than MSA-novel (Elginöz Kanat, Ozturk, Maritz, Van Schalkwyk, & Dorfling, 2023).

The third step was to compare the best (in terms of environmental performance) available technology with the best novel technology. Since the composition of the input battery waste in the evaluation of available technologies was different from the composition in the evaluation of novel technologies, a direct comparison was not possible. Therefore, the flow sheet of the chosen available technology was revised using the input waste battery composition in the experiments conducted for the development of novel technologies. Using the revised flow sheet for the available technology and the flow sheet developed based on the experiments for the chosen novel technology, a comparative full LCA was conducted. The results of this comparative LCA done in Elginoz, Ozturk, Maritz, Van Schalkwyk, & Dorfling (2023) are shown in Figure 13. The graph shows that although both technologies result in net environmental gain, the available technology performs better than the novel technology providing a higher gain in all impact categories.

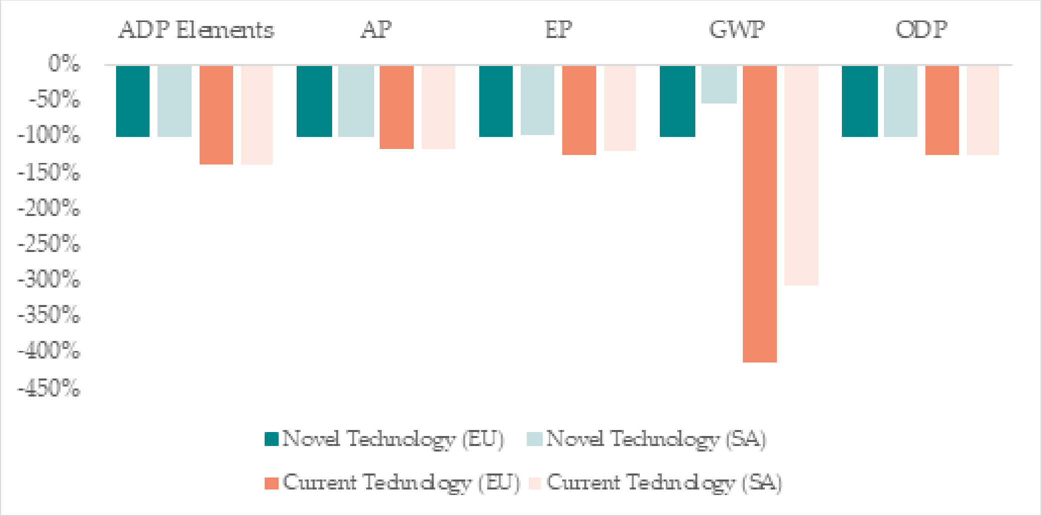

Figure 13: Visual presentation of impact category results normalized to novel technology in EU (Elginoz, Ozturk, Maritz, Van Schalkwyk, & Dorfling, 2023)

The LCA studies conducted in the ELIMINATE project show the importance of sustainability assessment during design stage of new recycling technologies and quantifies the gain that can be provided by recycling waste batteries.

4.6 Screening by Economic Indicator: Net Present Value

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 Techno-economic Assessment (TEA). These findings offer a valuable means of comparison between the two novel recycling technologies. Presented in Figure 14, the profitability assessment data has been standardized using the H2SO4 – Novel process as the reference point.

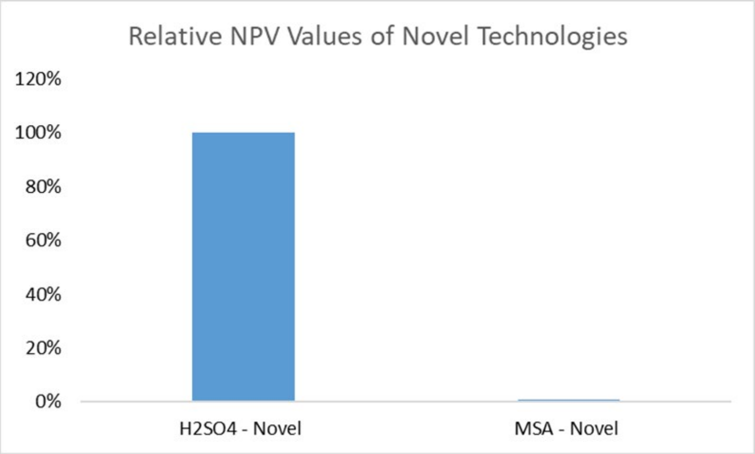

Figure 14: Comparative NPV performance of novel technologies for EU

Notably, the H2SO4 – Novel recycling process displays a favorable NPV, 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 H2SO4 – Novel process compared to its counterpart. The primary factor driving this difference lies in the OPEX and raw material expenses, wherein the MSA option proves significantly pricier compared to the sulfuric acid alternative.

Detailed profitability calculations for both technologies are available in *Appendices B – Methodology* in (Ozturk, Kuhn, & Wu, 2024).

Profitability comparison of selected current and novel technologies in EU Context

The ELIMINATE project aimed to identify the most sustainable methods among current and novel technologies. 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 new TEA generated for the EU region by updating the TEA from the SA region for the current and novel technologies.

Based on this update, where the update methodology and details are presented in the appendix in (Ozturk, Kuhn, & Wu, 2024), the NPV results of two current technologies and two novel technologies have been compared by normalizing the results based on the H2SO4 – Novel option in the following Figure 15.

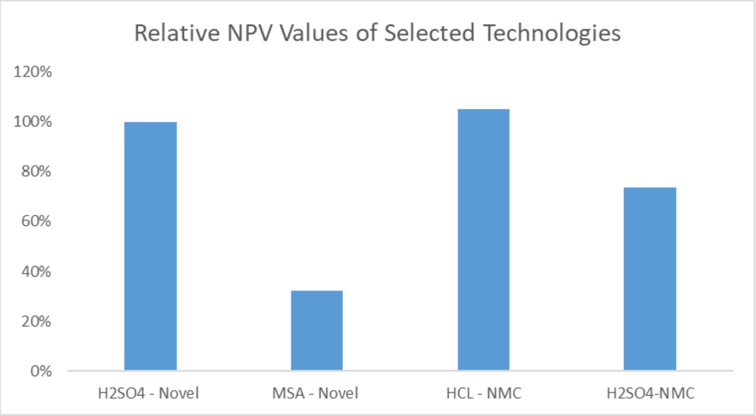

Figure 15: Comparative NPV performance of two current and two novel technologies for EU

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 H2SO4 – Novel technologies emerge as the most promising in terms of their potential economic success.

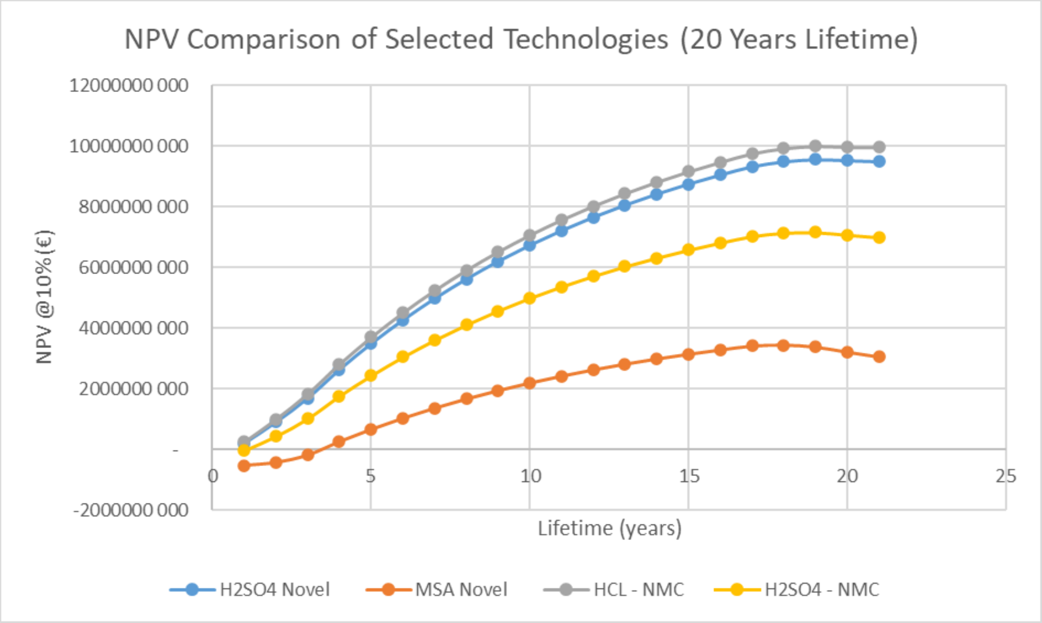

Figure 16: NPV Comparison of current and novel technologies during the 20 years period

4.7 Screening by Needs Approach Benefits Competition (NABC)

Needs

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 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 (H2SO4) for leaching.

In both regions, the primary contrast in novel technologies (H2SO4 - Novel and MSA - Novel) lies in the choice of acid for leaching - organic Methanosulfonic acid (MSA;CH3SO3H) versus the commonly used inorganic sulfuric acid (H2SO4). 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;CH3SO3H) 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;CH3SO3H) leaching as a less familiar option.

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* in Ozturk, & Kuhn, & Wu (2024).

Current Technologies

The focus of the nine existing LIB recycling technologies is on various hydrometallurgical pathways. Hydrometallurgical processes involve crushing the feed material (spent LIBs) and then submerging it in a strong acid to dissolve valuable metals (which are Li, Co, Ni, and Mn in the case of this study). The acid leaching step can be done by bulk leaching, where all the metals are dissolved and precipitated together. Within this study, three 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. This screening study provides a comparative analysis of these nine existing hydrometallurgical recycling methods, which employ these three distinct approaches.

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, inorganic acid, as a leaching agent. The two novel technologies will be compared based on their differences.

Both technologies are using hydrometallurgical processes to recycle the LIBs. The first method uses H_2SO_4 as a main leaching agent and utilizes a solvent displacement crystallization (SDC) system, which involves the use of acetone for the efficient precipitation of cobalt (Co), lithium (Li) and nickel (Ni). The end products of this method include cobalt in the form of Co_3O_4 as well as lithium in the form of sulphate and carbonate. In the second approach, Methanosulfonic acid (MSA;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 17.

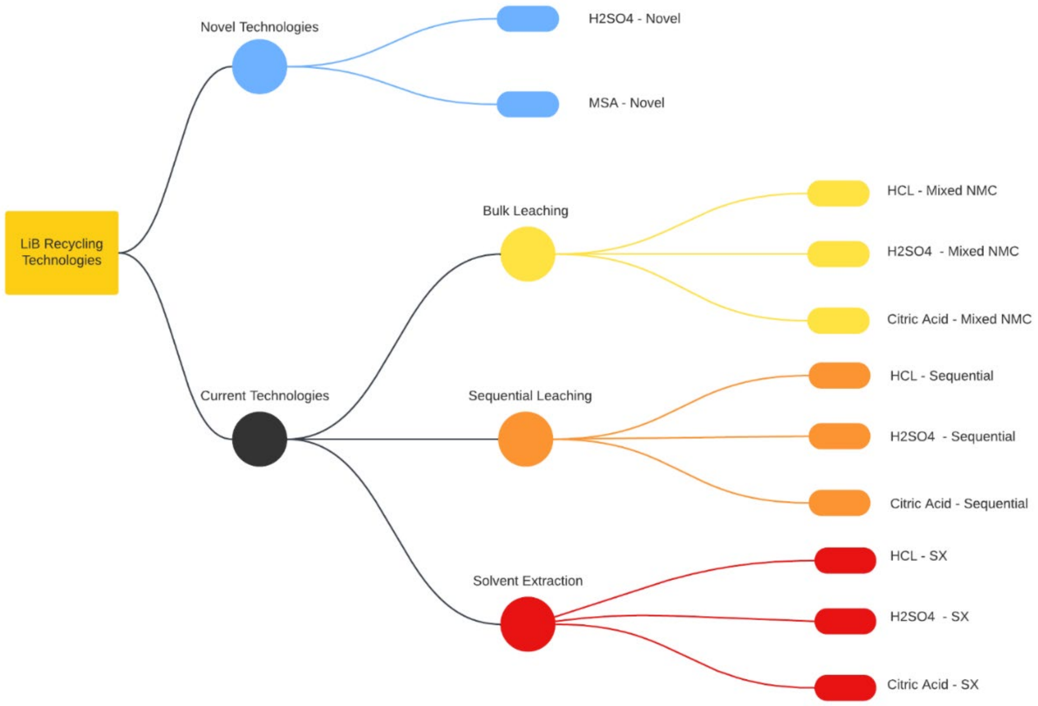

Figure 17: Summary of proposed LIB recycling technologies

Benefits

Sub-chapters 4.2 *Screening by Industry Practice* to 4.6 *Screening by Economic Indicator: Net Present Value* cover the benefits for the EU.

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 by Ozturk, Kuhn, & Wu (2024).

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.

4.8 Screening Conclusion

NABC study showed that some of the technologies are better than the others. Based on the results, H_2SO_4 - NMC for current technologies and H_2SO_4 – Novel for novel technologies selected as the best methods for the next step: business model development.

5 Value Chain Integration Framework

Subchapter 5.1 in this chapter comes almost entirely from the business model development chapter in Ozturk & Kuhn, & Wu (2024) and ties the scenarios to the business models in that report. Subchapter 5.2 models the Reverse Logistics Network (RLN) as per the report by Emilsson & Ozturk (2023).

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 aims to optimize operational efficiency. Relying on the strategic decisions of investors, the battery recycling facility has the flexibility for establishment in any EU locale, where gathering and accessing battery waste is convenient, with the aim to reduce transportation costs.

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 18) 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.

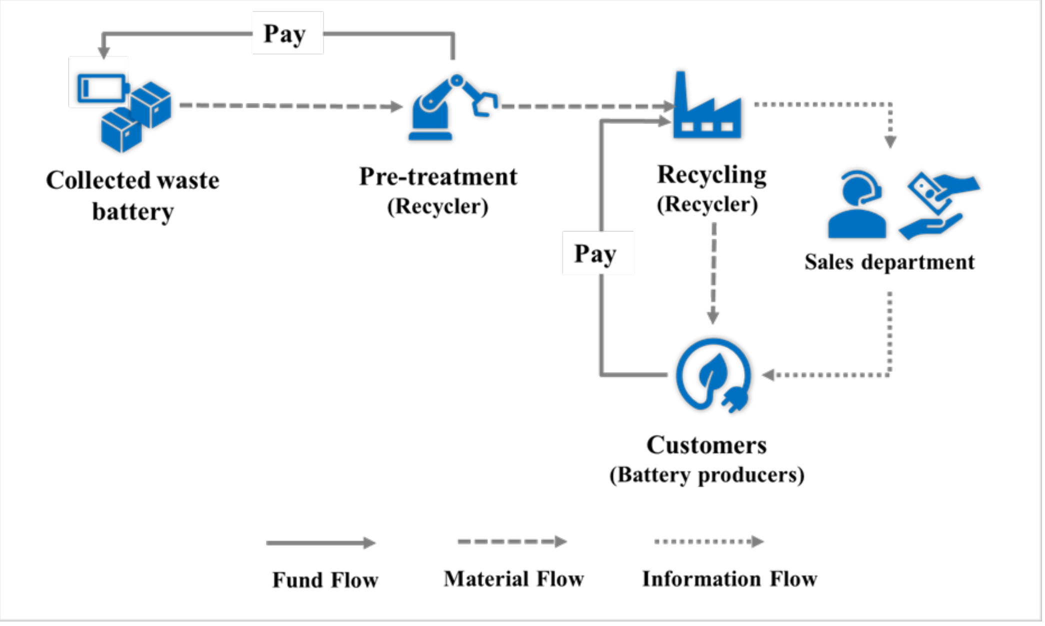

Figure 18: Flowsheet of Business Model Scenario 1

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,". "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 19 outlines the process stages, material flows, and the value proposition of the hydrometallurgical recycling method.

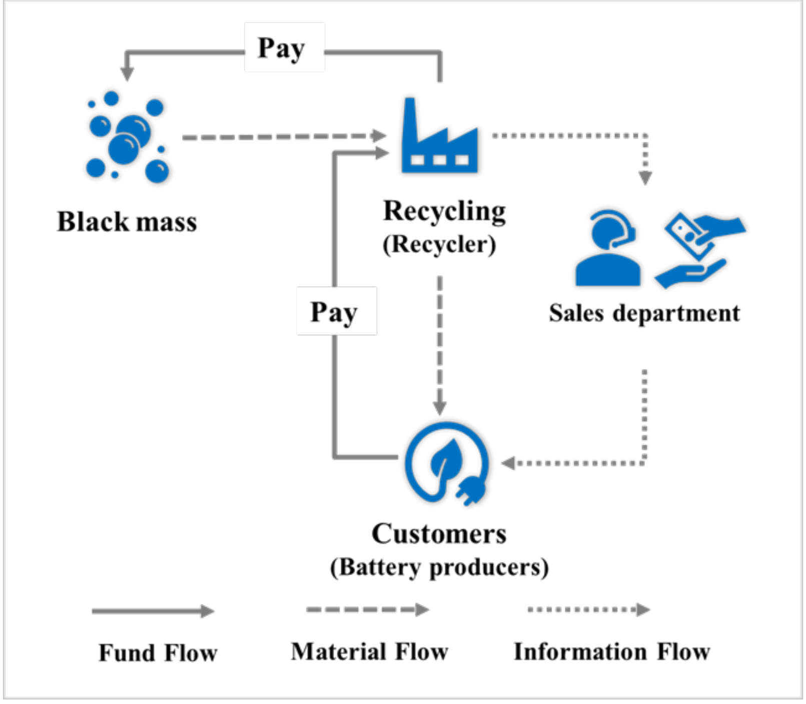

Figure 19: Flowsheet of Business Model Scenario 2

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, & Kaidya, 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.

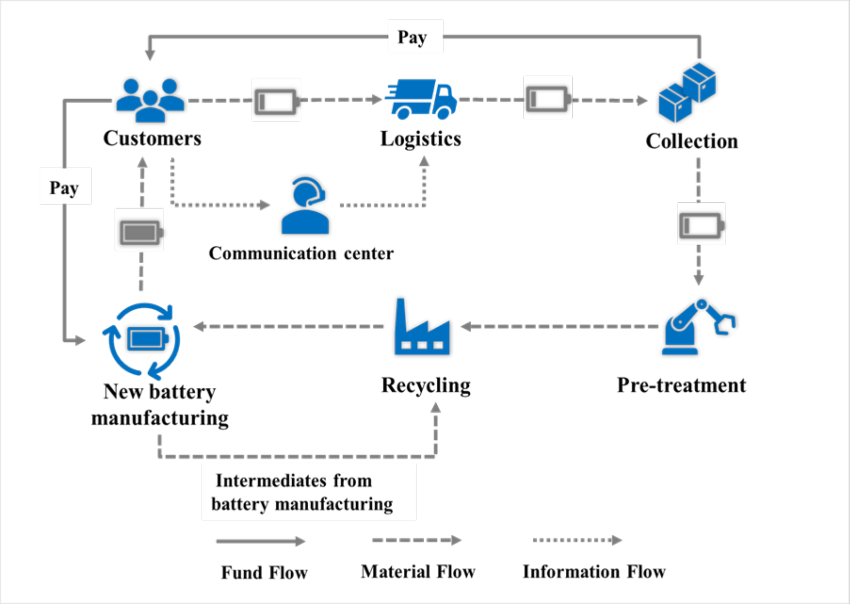

Figure 20: Flowsheet of Business Model Scenario 3

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 B* in (Ozturk, Kuhn, & Wu, 2024).

The NPV values of these scenarios, considering selected novel technology (H2SO4 - Novel), have been compared and illustrated in Figure 21.

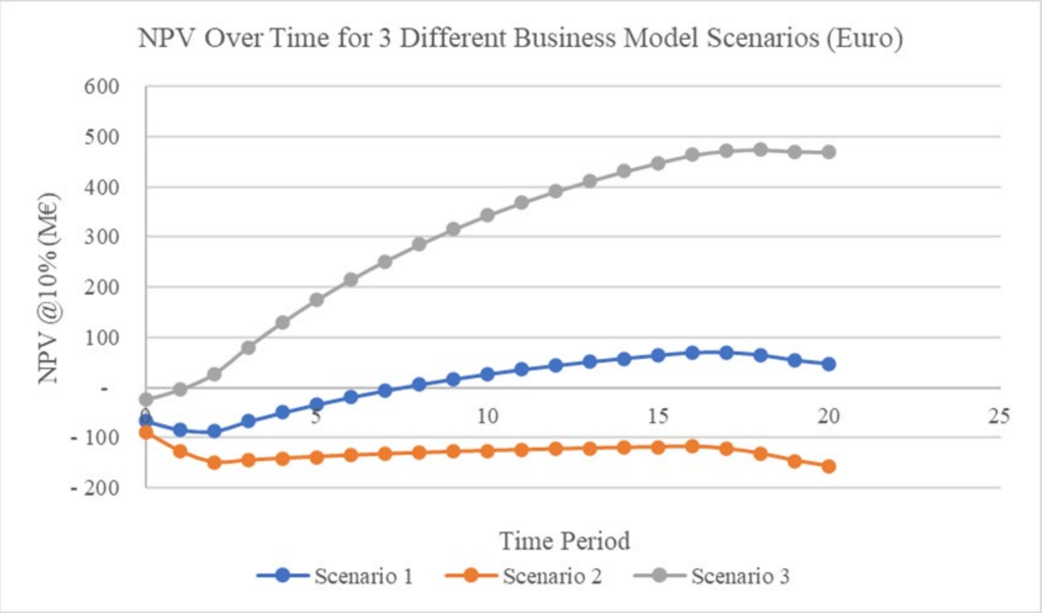

Figure 21: NPV values for EU value chain integration scenarios

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 Vertically Integrated Network and Process Screening

As a preface to this sub-chapter, it is a good idea to look at the SA version of the consolidated framework and Vooght (2022) for an alternative method of network optimization done with Anylogistix software instead of the open-source option for the EU context. If you're short on time or not experienced with using Python or other programming languages, opting for specialized software can make things more user-friendly.

An RLN optimization is done to find the best location(s) for one or more material recovery facility/facilities in the European Union with respect to total costs of the facility and the transportation costs. This is done for all the selected technologies to find out their performance with respect to the network between the supplier of EOL LIBs, the material recovery facility, and the buyer of the raw material products from the material recovery facility. An general diagram for how this was done in the EU is shown in the Appendix.

The RLN optimization was done with Linear Programming in the Python PuLP package. The preceding steps as well as the method in which the results were presented are shown in this sub-chapter.

In the context of the scenarios shown in the previous sub-chapter, the RLN optimization was a combination of scenario 1 and 3 as the pre-treatment was included and the option existed that the material recovery facility would be located on top of existing collection points. Additionally, the optimization was done for one or multiple processing facilities, without scaling up over the plant lifetime as many recyclers are doing in the region.

5.2.1 Assumptions for the EU

Several simplifications to the work done in the value chain scenarios were necessary for the EU context, as it is a complex region in many ways (e.g. variations in geographical income distribution, being sea-locked, and more). Compared to the SA case, Europe has a more dynamic market with regards to LIBs. Thus, a more simplistic model was necessary in the practical application of optimization. The results were also less conclusive (and will be quicker to become outdated) as many of the assumptions will change.

Although the EU is made up of several countries/members, they operate as a single market which reduces complexity in trade between Union members. They also share many policies which give additional advantages to other Union members. With regards to logistics, when EU members trade with one another, there usually are no trade tariffs required to be paid. However, as EOL LIBs contain hazardous substances, it is sometimes classified as such and thus there is an additional layer of complexity in road and sea transports that must be considered as there are associated costs that actors in the EOL LIB supply chain must pay.

To model this complex system, several assumptions had to be made, which are developed in more detail in (Emilsson & Ozturk, 2023). The next sections will walk through some of the main assumptions and methods used for the RLN optimization of the EU EOL LIB supply chain for a new material recovery facility.

Volume data and Total Plant Capacity

Past and predicted future total volumes of EOL LIBs were done in a material flow mapping in (Emilsson & Ozturk, 2023) and one of the results for 2026 is shown in Figure 22. The total plant capacity was done estimated with the 'Accumulated, exported, or lost EOL LIBs/BM' for the year 2026, and an adjustment to the calculations in (Ozturk, Kuhn, & Wu, 2024) for all of Europe was used as a control to check if the volume was reasonable. The total plant capacity was then used as one of the parameters in the facility location optimization.

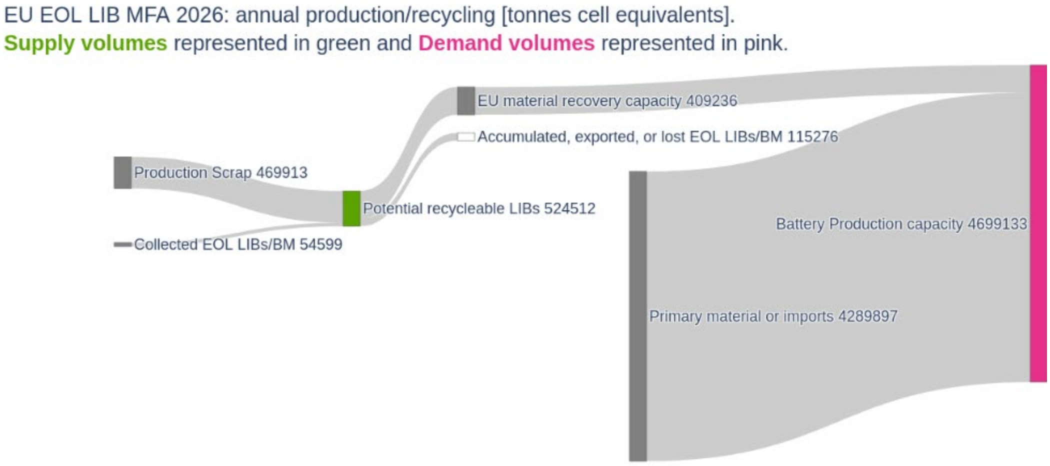

Figure 22: Sankey chart of total recycling flows, compared to battery production capacity, through Europe forecasted for 2026. BM = black mass.

Multiple Facilities and the Square Root Law of Logistics

To approximate the additional costs of adding more facilities to process the given volumes of EOL LIBs, the principle of the Square Root Law of Logistics was used. Essentially adding more facilities to process the same volume of EOL LIBs will increase the total facility costs, but at a diminishing rate for each additional facility (due to the square root). This is a simplification, and thus there are limitations to this approach which should be handled according to the type of logistics problem that is being solved and the requirements on its robustness.

Collectors

The number of collectors in the EU is much greater than anticipated in the early stages of the project, and as such, some simplifications were done to make the problem manageable (otherwise the data collection on its own would be unreasonably large). The countries' populations served as proxy proportions for the volumes of EOL LIBs collected in each. Capital cities and cities over a minimum population served as nodes on which the volumes were "distributed".

Regionalizing and Calculating the Material Recovery Facility's Costs

The total plant capacities calculations in (Ozturk, Kuhn, & Wu, 2024) were adjusted to the larger volumes in the material flow mapping and optimization in (Emilsson & Ozturk, 2023).

In facility location optimization problems, the facility costs are often aggregated into a total cost representing all associated costs with the facility, excluding transportation. The CAPEX and OPEX were thus aggregated. Each facility location can have a different cost, and to test this the CAPEX and OPEX were calculated for different regions in (Ozturk, Kuhn, & Wu, 2024). Since only three countries (Sweden, Germany, and Italy) were selected, the total facility cost of a facility located in the rest of the EU countries were mapped to the cost of the three calculated ones by using a combination of per-capita GDP and electricity mix carbon intensity as points. The resulting distribution of these total costs is seen in Figure 23.

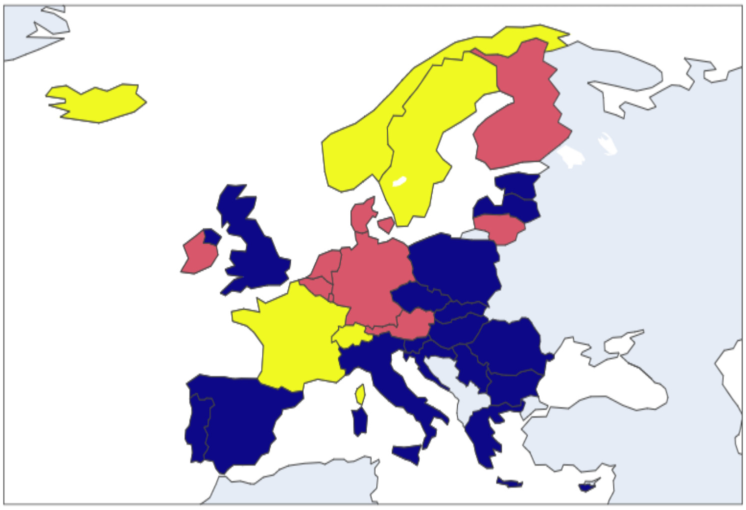

Figure 23: Country categories based on GDP per capita and carbon intensity. Countries received scores for GDP per capita (low score = low GDP per capita), and electricity mix carbon intensity (low score = high carbon intensity). Blue countries (Italy-based) = lowest scores, red countries (Germany-based) = medium, yellow countries (Sweden-based) = high.

Technologies Assessed

In addition to varying the total costs by region, the hydrometallurgical technologies were also used as a variable. Essentially H2SO4 (Novel 1), MSA (Novel 2), HCl-NMC (Current 1), and H2SO4-NMC (Current 2) had different costs.

Transportation Costs

The question of transport costs for EOL LIB logistics in the EU is one of uncertainty as the Battery Regulation changes the dynamics and rules of the region. Therefore, a minimum and a maximum transport cost were implemented based on logistics costs of commodities on the low end vs. a high estimate for EOL LIBs in literature.

Existence of Other Networks

It is no secret that the EU market is developing quickly and that other networks for recycling exist and are planned for the next decade (or longer). The existence of these networks in modelling presents a tricky problem. Given that the project group did not know how the other networks were built up, some major simplifications had to be done which significantly lowered the robustness of the final results compared to the SA case where the market is comparably more static and known.

There are various ways in which to face this problem. The project description required all of the EU to be considered, meaning that it wasn't possible to minimize the geographical scope. Otherwise, that would be one way of minimizing the impact of other networks on the final results.

Simplification of the Supply Chain

As Europe is undergoing the energy transition there are changes in various fronts. Creating a boundary for where the analysis starts and ends is a vital step to ensure that it is balanced in terms of complexity and practicality. shows a diagram of the system that is being considered for the RLN optimization, including some flows and steps which weren't included for reasons such as data availability.

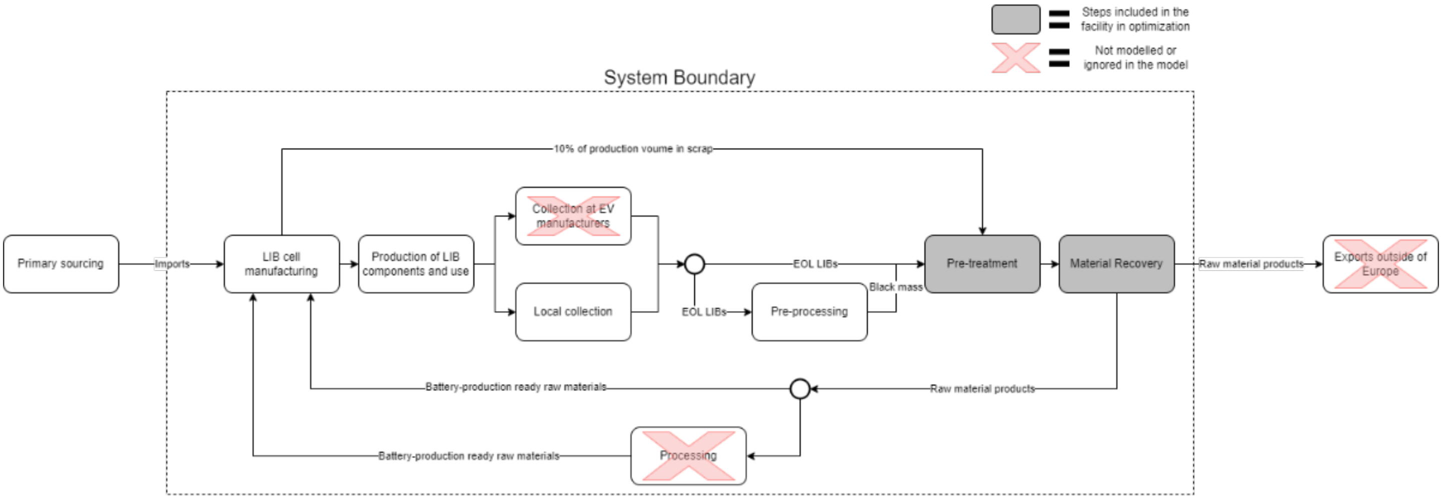

Figure 24: Simple diagram of the flows and processes that were considered and ignored for the RLN optimization.

5.2.2 Optimization and Results

Here a quick presentation of the results from (Emilsson & Ozturk, 2023) is presented in . Optimizations were run for set number of facilities, the low/high transportation costs, and for each material recovery technology assessed. The lowest values represent the overall optimum based on the model and assumptions.

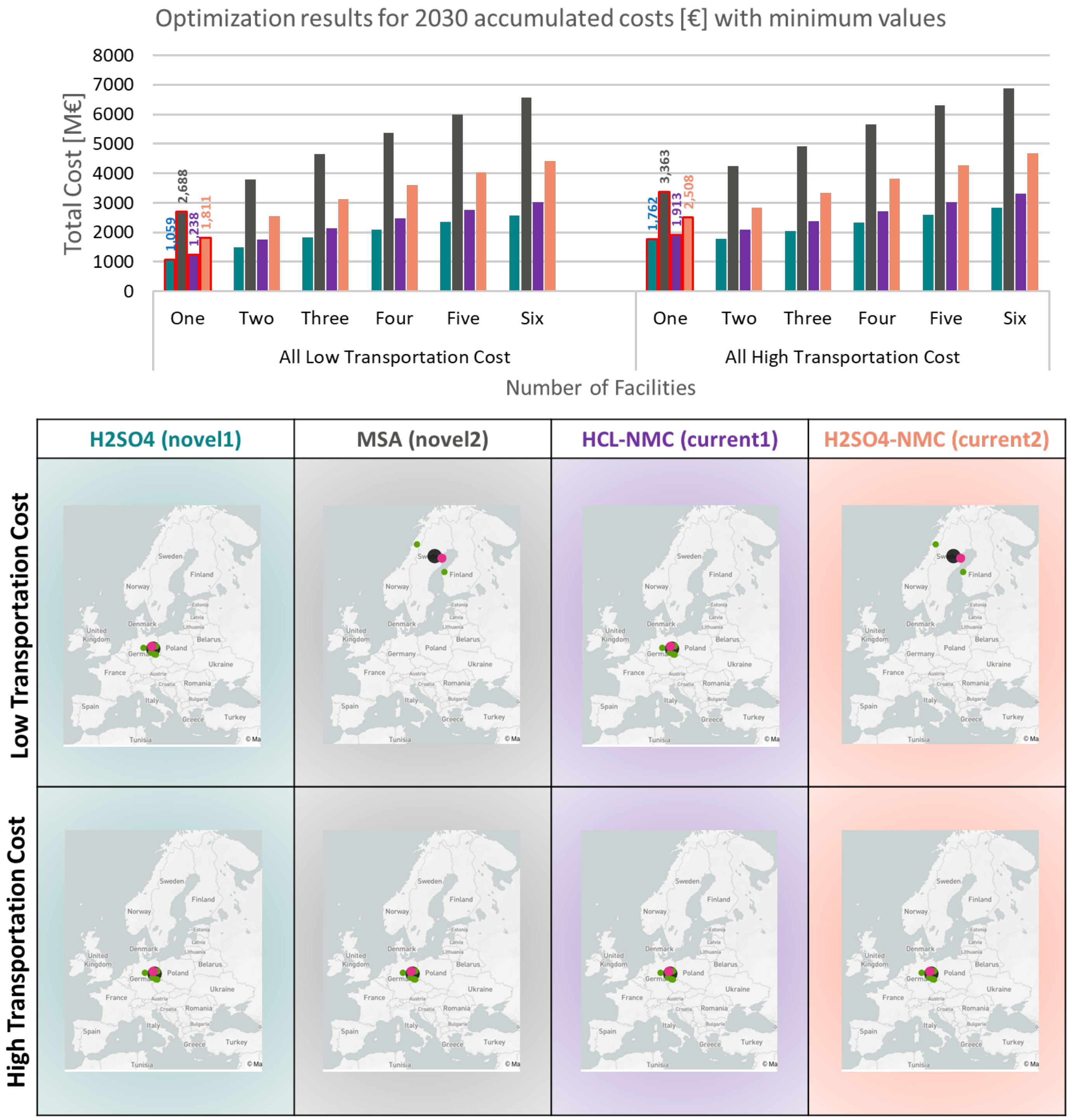

Figure 25: Monetary optimization result of the four technologies for both low- and high transportation cost estimates. In the graphs, the bars with red outlines and values over them are also the minimum values of facilities for their respective technologies. Each colored bar represents a hydrometallurgical technology. In the maps which shows the optimal supply-chain configuration, green represents selected supply nodes, black represents the selected facility node, and pink represents selected demand nodes. Please note that the sizes of the circles are not proportional to the volumes in this figure.

A similar RLN optimization was done for carbon intensity as well, showing the flexibility of optimizations in improving not just cost, but environmental impacts for supply chains.

6 Market Model and Competitive Strategy of a LIB Recycler

See the South African report for this chapter.

7 The Business Model Canvas for Mixed-NMC Production

This chapter is copied from (Ozturk, Kuhn, & Wu, 2024). See the appendix for the business model canvas and see the South African report for the following:

- ‘The Building Blocks of the Business Model Canvas’’

7.1 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.

7.2 Customer Segments

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.

7.3 Revenue Streams

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.

7.4 Distribution Channels and Customer Relationships

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.

7.5 Cost Structure

The key components of the cost structure for a LIB recycling plant include Capital Expenditure (CAPEX), and Operational Expenditure (OPEX), production costs, raw materials, and labor. 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.

7.6 Value Chain Key Resources

The most important resource of an innovative LIB recycling company can be a patented LIB recycling technology and holding this patent at hand. In addition, key resources such as collaboration and cooperation with different stakeholders, using the experience of experts in this field and using the well-trained workers to enable to reach efficient production rates are crucial. In the context of an in-house battery recycling scenario, establishing effective distribution and collection channels for customers emerges as another critical resource contributing to the company's success.

7.7 Value Chain Key Activities

The key activities of an EoL LIB recycling company involve metal production through recycling, development networks among various stakeholders for continuous improvement (battery users, producers, EoL battery collectors, government, etc.), and ongoing research and development (R&D) studies, with innovation as a key focus. In the scenario of an in-house battery recycling facility, implementing circular logistics for customers to simplify their experience becomes another key activity.

7.8 Key Partnerships

Establishing a successful LIB recycling facility requires strategic partnerships with various entities, including EoL LIB collectors/distributors, raw material suppliers, technology providers (e.g., universities), LIB recycling experts, research institutes, government bodies, and financial partners (e.g., banks or investors).

In an in-house battery recycling scenario, forming key partnerships with battery producers and users is essential to ensure a consistent supply of waste LIBs. In the EU context, existing LIB and non-LIB recyclers could also be potential partners.

8 Conclusion

The EU is a complex region that is rapidly changing in its industry efforts to move towards electrification. Over the three-year period in which the ELiMINATE project has spanned, the developments in the EOL LIB industry have been continually changing, as they will continue to do. The assessments for the EU context are also varied with respect their regional dependency and capacity to withstand changes in e.g the market conditions and/or stocks and flows of EOL LIBs. For instance, the RLN optimization is highly dependent on changes to the market and the available EOL LIB data while the business model is based on core aspects of the business which are more rigid, like for example the customers profiles. With that being said, no assessment is completely independent of changes to legislature, the market, the data available, battery and battery recycling technology, and other factors. Thus, it is important to consider all when reconstructing and executing an assessment of this type.

With regards to data, it will be interesting to see how the effects of the new Battery Regulation can have on these assessments with respect to the EU, and possibly other countries and regions too. More data being available might mean better LCA results, business models, and RLN optimizations as necessary data that was previously unavailable becomes open for some to use, which may in turn open the possibility for more precise results and/or nuanced analyses.

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Appendices

Appendix A: RLN Model example used in ELiMINATE for EU context

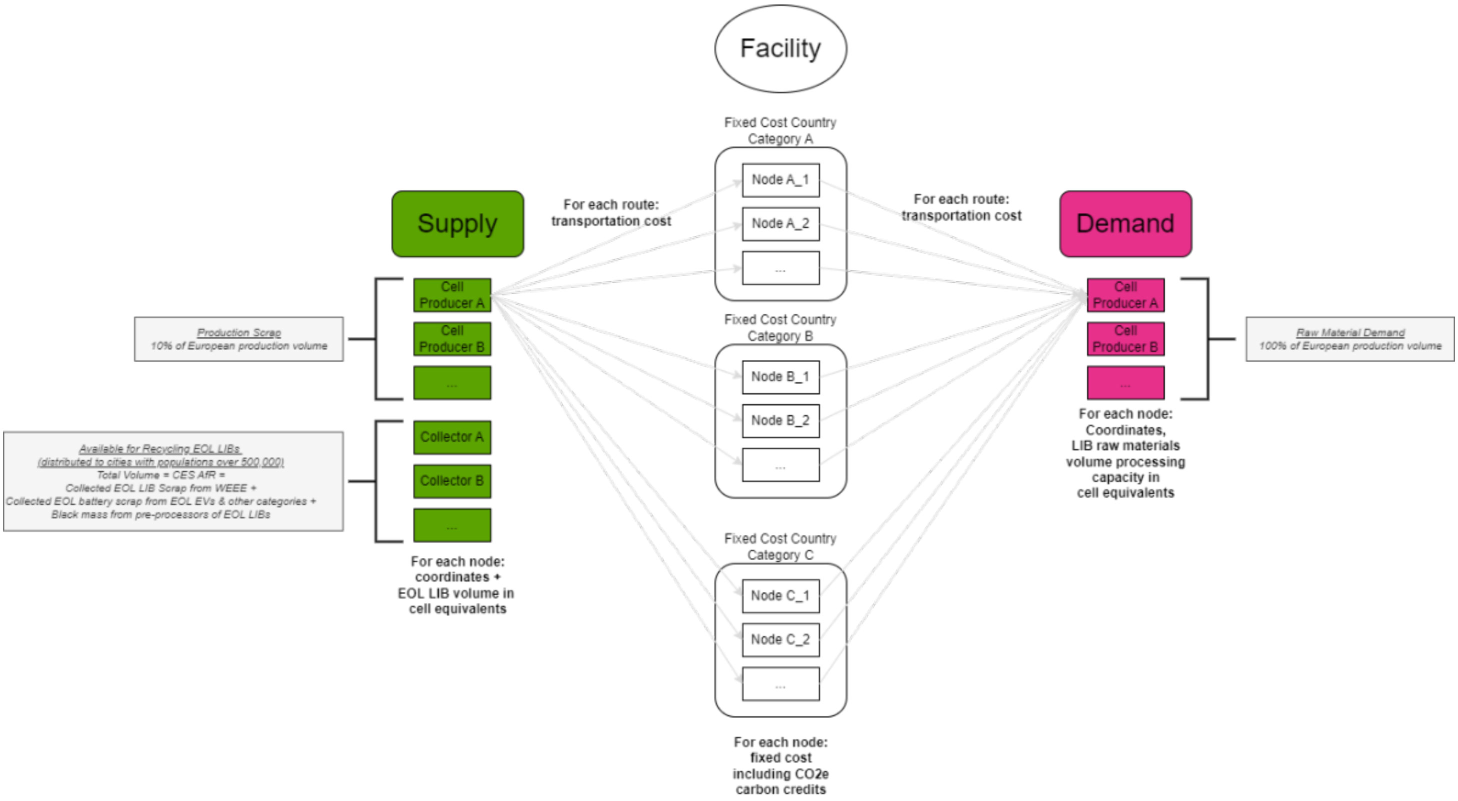

Figure 26: Diagram showing the main actor categories (Supply in green, Facility, Demand in pink) in the RLN optimization. Suppliers are a combination of cell producer production scrap nodes and EOL LIB collector nodes. The production scrap from each producer is approximate to be 10 percent of each producer's maximum production capacity. Customers (demand) are cell producers. CES AfR = Circular Energy Storage (CES) Available for Recycling dataset. CES POM = Circular Energy Storage Placed on the Market (POM) dataset. WEEE = Waste from Electrical and Electronic Equipment.

Appendix B: Planned Recycling and Production Capacities for 2022, 2026, and 2030

Table 2: European battery recyclers, their coordinates, and tons of processed EOL LIBs in cell-weight equivalents. (2023 Emilsson E. & Ozturk A. N.)

Name	Type	Latitude	Longitude	Tonnes in 2022	Tonnes in 2026	Tonnes in 2030
Accurec	Material Recovery	51.3317	6.5594	0	0	0
BASF	Material Recovery	51.4831	13.8667	0	50000	50000
Duesenfeld	Material Recovery	52.2642	10.5264	0	0	0
Ecopro CNG	Material Recovery	51.1167	17.0333	0	20000	50000
Elemental Holding	Material Recovery	52.1025	20.6225	0	30000	30000
Eramet	Material Recovery	48.8569	2.3508	0	20000	20000
Erlos	Material Recovery	50.7167	12.5000	3000	5000	5000
Euro Dieuze (Veolia)	Material Recovery	48.8110	6.7201	2000	20000	20000
Finnish Minerals Group/CNGR/SE	Material Recovery	60.1698	24.9381	0	20000	20000
Fortum	Material Recovery	61.3167	22.1336	3000	25000	25000
Glencore Nikkelverk	Material Recovery	58.1447	7.9983	3700	3700	3700
Johnson Matthey	Material Recovery	51.5002	-0.1262	0	20000	20000
Kyburz Group	Material Recovery	47.5333	8.5833	100	500	500
Nickelhütte	Material Recovery	50.5896	12.6970	1000	1000	1000
Orano Group	Material Recovery	46.1091	1.3681	0	0	0
Primobius	Material Recovery	50.9983	8.1094	1000	20000	20000
Redwood Materials	Material Recovery			0	20000	50000
Northvolt Revolt	Material Recovery	64.7511	20.9537	0	25000	125000
SNAM	Material Recovery	45.6314	5.1119	0	20000	20000
Sungeel	Material Recovery	47.9906	19.8309	0	50000	50000
TES-AMM	Material Recovery	45.1943	5.7317	0	10000	10000
Umicore	Material Recovery	51.1746	4.3508	2333.333333	8333.333333	8333.333333
Umicore	Material Recovery	51.1441	4.8600	2333.333333	8333.333333	8333.333333
Umicore	Material Recovery	50.1333	8.9167	2333.333333	8333.333333	8333.333333
Accurec	Pre-processing	51.3317	6.5594	5000	5000	5000
Akkuser	Pre-processing	63.9299	24.9606	1000	1000	1000
BASF	Pre-processing	51.4831	13.8667	5000	15000	15000
CIAK	Pre-processing	46.0333	15.9167	0	1500	1500
Daimler	Pre-processing	48.8275	8.2544	0	10000	10000
Duesenfeld	Pre-processing	52.2642	10.5264	3000	20000	20000
Ecobat	Pre-processing	50.3333	8.7500	3200	3200	3200
Ecopro CNG	Pre-processing	51.1167	17.0333	0	20000	20000
Elemental Holding	Pre-processing	52.1025	20.6225	12000	30000	30000

EMR	Pre-processing	51.5002	-0.1262	5000	10000	10000
Endesa	Pre-processing	42.6167	-6.5667	0	8000	8000
Eramet	Pre-processing	48.8569	2.3508	0	20000	20000
Erlos	Pre-processing	50.7167	12.5000	3000	5000	5000
Euro Dieuze Veolia	Pre-processing	48.8110	6.7201	10000	20000	20000
Fenix Recycling	Pre-processing	52.5798	-2.0605	5000	10000	15000
Fortum	Pre-processing	61.3167	22.1336	6000	9000	9000
Gigamine	Pre-processing	51.5002	-0.1262	0	5000	5000
Hydrovolt	Pre-processing	59.19105829	10.97335479	8000	8000	8000
Kyburz Group	Pre-processing	47.5333	8.5833	100	500	500
Li-Cycle	Pre-processing	58.4595	8.7668	0	10000	10000
Li-Cycle	Pre-processing	50.1109	8.6795	0	10000	10000
Li-Cycle	Pre-processing	51.5002	-0.1262	0	10000	10000
Librec	Pre-processing	47.1833	7.5667	0	10000	10000
MAB Recycling	Pre-processing	51.0333	13.7333	1000	2500	2500
Nickelhütte	Pre-processing	50.5896	12.6970	1500	1500	1500
Orano Group	Pre-processing	46.1091	1.3681	1000	5000	10000
Primobius	Pre-processing	50.9983	8.1094	3000	20000	20000
ReCoNi	Pre-processing	51.1465	0.8676	10000	10000	10000
Recyclus	Pre-processing	52.5853	-2.1319	8300	8300	8300
Redux	Pre-processing	50.1049	8.7586	10000	10000	10000
Redwood Materials	Pre-processing			0	20000	30000
Northvolt Revolt	Pre-processing	64.7511	20.9537	25000	50000	50000
Roth International	Pre-processing	49.6750	12.1605	8000	8000	8000
Royal Bee	Pre-processing	51.2083	16.1603	4000	4000	4000
RS Bruce Metals	Pre-processing	53.3836	-1.4669	2500	2500	2500
SNAM	Pre-processing	45.6314	5.1119	7500	20000	20000
Spirit	Pre-processing	45.5469	11.2806	2500	2500	2500
Northvolt Stena Recycling	Pre-processing	56.6739	12.8500	0	10000	10000
Sungeel Hitech	Pre-processing	47.9906	19.8309	35000	55000	55000
Sungeel Hitech	Pre-processing	51.1167	17.0333	0	20000	20000
TES-AMM	Pre-processing	45.1943	5.7317	1000	10000	10000
Umicore	Pre-processing	51.1746	4.3508	7000	25000	50000
Volkswagen	Pre-processing	50.7167	12.5000	1000	12000	12000
Gelncore & Britishvolt	Pre-processing	51.4476	0.3248	0	10000	10000
Gelncore & Britishvolt	Material Recovery	51.4476	0.3248	0	10000	10000
Morrow Batteries, Li-Cycle and ECO STOR	Material Recovery	59.92822556	10.74410462	0	10000	10000
Italvolt Recycling	Material Recovery	45.3833	7.8333	0	0	0

Altilium Metals	Material Recovery	50.7256078	-3.517216708	0	10000	50000
Gigamine	Material Recovery			0	0	0
Veolia	Material Recovery	52.53344051	-1.765690443	0	5000	5000
Ecobat	Pre-processing	52.5690	-2.0348	500	20000	20000
ABEE	Pre-processing	54.93078049	-2.753961226	0	1000	1000
Aurubis	Pre-processing	51.1441	4.8600	0	0	0
TES SK Ecoplant	Pre-processing	45.1943	5.7317	2200	2200	2200
Groupe Renault Veolia	Material Recovery	49.2602	6.1424	0	4000	4000
EIT InnoEnergy	Pre-processing			0	0	0
Recypilas	Pre-processing	43.3043	-2.9755	0	0	0
EcoNiLi	Material Recovery	38.3453	-0.4831	0	45000	45000
Batrec	Pre-processing	46.6667	7.6333	500	500	500
Attero	Pre-processing			0	0	0
Nissan	Material Recovery			0	0	0
Bluewhale BMW	Material Recovery			0	0	0
Fortum	Pre-processing	61.7702	23.0643	3000	3000	3000
Aurubis	Material Recovery	53.54755813	10.01021896	0	0	1000
Fortum	Pre-processing	49.2038	8.9894	3000	3000	3000
Fortum	Material Recovery	49.2038	8.9894	3000	3000	3000
Northvolt	Material Recovery	54.1961	9.0933	0	0	0
Stena	Pre-processing	53.6500	7.9500	350	2500	2500
SungEel HiTech	Pre-processing	50.7169	11.3275	0	20000	20000
Walch Recycling	Pre-processing	49.6248	10.5374	1000	1000	1000
Fortum Battery Recycling	Material Recovery			0	0	0

Table 3 Cell producers capacities, their coordinates, and tons of produced EOL LIBs in cell-weight equivalents (2023 Emilsson E. & Ozturk A. N.)

Name	Country	Latitude	Longitude	Tonnes in 2022	Tonnes in 2026	Tonnes in 2030
Avesta Battery and Energy Engineering	Belgium	50.49875474	4.231160979	0	0	0
Magna Energy Storage MES	Czech Republic	49.77302772	18.44336293	0	0	0
Freyr Battery (Giga Vaasa)	Finland	63.10211148	21.64148423	0	25	100
Verkor	France	51.02951098	2.372810694	0	16	50
ACC (Stellantis/Saft)	France	49.45603248	7.748189332	0	0	40

BlueSolutions	France	47.98465828	-4.112220754	0	0	0
Envision AESC	France	50.35657793	3.047599944	0	0	30
Customcells	Germany	53.9333738	9.482168789	0	0.1	0.1
CATL	Germany	51.0244821	10.97583348	0	100	100
Tesla Gigafactory Berlin-Brandenburg	Germany	52.42230936	13.78568099	0	200	200
Nortvolt Drei	Germany	54.18965477	9.046323262	0	60	60
ACC (Stellantis/Saft)	Germany	49.44787547	7.704160679	0	32	40
SVOLT	Germany	52.35050156	12.59913339	0	24	24
SVOLT	Germany	51.4646716	13.77818075	0	0	0
Farasis	Germany	51.75167449	12.22749564	0	0	0
Microvast	Germany	52.40161274	12.59063206	1.5	6	6
VARTA	Germany	48.95464634	10.18652537	0	0	0
Leclanché	Germany	48.5349937	7.934903367	2.5	2.5	2.5
PowerCo SalzGiga (Volkswagen)	Germany	52.15029808	10.35919028	0	40	40
BMW	Germany	48.79164329	12.83515782	0	20	20
Cellforce	Germany	48.51288653	9.075136952	0	14	14
Blackstone Resources	Germany	51.11070352	13.17887359	0	4	4
EAS	Germany	51.48759677	10.74923126	0	0	0
UniverCell	Germany	54.25047193	10.02740727	0	10	10
SK Innovation	Hungary	47.74305073	18.11894637	0	0	77.3
Samsung Göd	Hungary	47.68212956	19.17416715	40	40	40
Samsung	Hungary			0	0	0
GS Yuasa Hungary	Hungary	48.11337553	20.8420227	0	0	0
EVE	Hungary			0	0	0
CATL Debrecen	Hungary	47.53728246	21.6382071	0	100	100
Italvolt	Italy	45.12970506	7.694889422	0	20	45
ACC	Italy	41.9948836	14.98120429	0	40	40
FAAM	Italy	41.01053586	14.1918837	0	8	8
Anodox	Latvia	56.93768998	24.12798089	0	0	0
Eurocell	Netherlands	52.3283333	4.913409613	0	7	7
Morrow	Norway	58.47364969	8.743842819	0	32	32
Panasonic, Equinor, Norsk Hydro	Norway			0	0	0
Beyonder	Norway	58.96160749	5.727296269	0	10	10
Freyr (Mo i Rana)	Norway	66.32013127	14.17097432	0	25	100
Elinor Batteries	Norway	63.43069362	10.48623371	0	0	0
LG Energy Solution	Poland	51.08609166	17.01168446	0	115	115
CALB	Portugal	37.99813176	-8.751229708	0	0	45

ElevenEs	Serbia	46.10657086	19.7944753	0	0	16
Inobat	Serbia	44.05111374	20.97014905	0	0	0
InoBat	Slovakia	48.30821158	17.55925319	10	10	10
Gigafactory Valencia: PowerCo (Volkswagen)	Spain	39.67643271	-0.271600547	0	40	40
Phi4tech	Spain	39.96766573	-3.436823644	0	0	20
Basquevolt	Spain	42.92635362	-2.64429758	0	0	10
Envision AESC	Spain	39.88996137	-5.512659564	0	30	30
Northvolt Ett	Sweden	64.7531286	20.96157515	40	60	60
Northvolt–Volvo Cars	Sweden	57.71182349	11.9316096	0	50	50
SCB	Switzerland			0	0	0
Volkswagen	**tba**			0	0	0
BYD	**tba**			0	0	0
Inobat	**tba**			0	0	0
PowerCo	**tba**			0	0	120
Prologium	**tba**			0	0	0
Tata Motors	**tba**			0	0	0
Rosatom	Russia	54.64619959	20.54508867	0	12	12
Britishvolt	United Kingdom	55.2040879	-2.093250451	0	0	0
Envision AESC	United Kingdom	54.90680498	-1.39088216	0	0	35
AMTE Power	United Kingdom	56.480303	-2.952725981	0	10	10
West Midlands	United Kingdom	52.37776907	-1.500483731	0	60	60
Nanotech Energy	United Kingdom			0	0	0

Appendix C: 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).

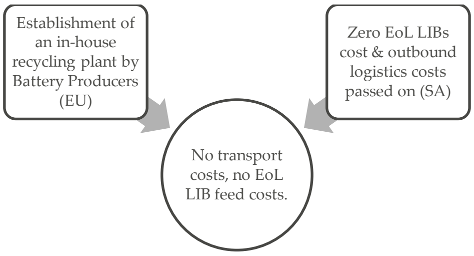

Figure 27: Commonalities of selected value chain scenarios for EU and SA regions

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 4, aiding readers in identifying additional benefits and requirements.

Table 4: 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 , 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 5.

Table 5: 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">Revenue Streams
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>

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