Swedish Environmental Research Institute

Optimizing Resource Recovery of Lithium-Ion Battery Recycling

Early-Stage Scenario Analysis of Material Flow Mapping and Reverse Logistics Optimization for Sustainable Battery Recycling in a European Context Up to 2030

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Summary

This report covers the material flow analysis (MFA) mapping Task 3B.1 and optimization Task 3B.2 in WP3 EU in the ERA-MIN project ELiMINATE funded by Vinnova on the Swedish side. End-of-life (EOL) lithium-ion batteries (LIBs) are expected to become an important source for new battery materials to fuel the energy transition. The volumes are expected to expand quickly in coming years, continuing to grow through and beyond 2030. In the project ELiMINATE, several material recovery technologies have been assessed and selected. This study will assess these technologies by their total cost and carbon emissions in Europe. Key players in the EU region are mapped by their LIB (Part 1), and consequently the possibilities of adding material recovery facilities with their new reverse logistics networks are evaluated with optimizations on their total (gross) monetary costs and CO_2-emissions. (Part 2).

In Part 1, battery scrap, new cells, and black mass were converted to cell-weight equivalents using battery bill-of-materials so they could be compared in the mapping and optimization. They were then displayed in Sankey charts and geographical maps that showed the increase of both the total number of actors and the aggregated volumes to increase significantly from 2022, to 2026, and to 2030.

In Part 2, the optimization was done to determine the best network setup (to minimize cost) for a single- or multi-facility network using pretreatment and one of the hydrometallurgical recovery technologies developed and evaluated in ELiMINATE's other work packages together. The facility or facilities were to process 98,667 tons/year of EOL LIBs and black mass in cell-weight equivalents, which was close to the obtained remainder of batteries that were collected in 2026, but not processed by other recyclers. The optimization was performed for the accumulated fixed costs and transportation costs in 2030 from a facility that was constructed in 2023. Similar as for monetary costs, another optimization was done to find the minimum for CO_2-emissions from the facility and transportation.

Optimizing was shown to have benefits with the system modelled. The potential savings from optimizing the number of facilities ranged from at least 1-41% up to over 100% of the minimum value for the optimal number of facilities. It is made clear in the results of this study that there could be potential monetary and environmental savings if data is made available and leveraged properly.

Table of contents

Abbreviations

Abbreviation	**Definitions**
API	Application Programming Interface. Different APIs were used to do analyses on the routes and for the visualizations. For example, to determine the distances between nodes, the API Matrix Service in openrouteservice was called with Python.
BEV	Battery Electric Vehicle, which in this report includes all types of light-, medium-, and heavy-duty private, industrial, and commercial type vehicles.
CES	Circular Energy Storage: Volume, price and market data for the global lithium-ion battery end-of-life market.
CES AfR	Circular Energy Storage Available for Recycling: A category of volumes of EOL LIBs in CES representing "batteries that have reached EOL and which are estimated to not be attractive enough to be considered for reuse, or are deemed to recycling for other reasons." Does not include production scrap but does include cell-weigh equivalents of black mass from pre-processing.
CES POM	Circular Energy Storage Placed on the Market: A category of volumes of End-of-Life flows in Circular Energy Storage representing LIBs "that have been sold and delivered [to the European] market". Also includes LIBs "that are been imported in while in use in their original host product (such as in used electric vehicles)" and EOL LIBs "that are reused".
EOL	The final stage of the product's life cycle. This stage is from which the product (in our case EOL LIBs) are collected for material recovery but also from which other processes can occur, such as second-life, collection, and pre-processing.
LIB	Lithium-ion battery
LP	Linear Programming, an optimization method used in this project.
MFA	Material Flow Analysis
WP	Work Package

1 Introduction

This report is the sole deliverable D3B.1 from the work package (WP) 3B Material Flow Analysis (MFA) EU context in the Vinnova-funded ERA-MIN project ELiMINATE. It covers both tasks T3B.1 Material Flow Mapping, and T3B.2 Material Flow Optimization. A similar and parallel analysis was done in WP 3A for the South African context, but in another report.

Europe is undergoing a rapid transformation from fossil-fuel dependence to an electrified society. It is foreseen that this transformation will create a dependency on various materials that are limited in available supply today and in the foreseeable future. For electricity storage, lithium-ion batteries (LIBs) are currently the most promising state-of-the-art energy storage technology for various applications such as transportation, electronics, and more. As such, the reverse logistics chain is integral for the European battery market to be sustainable and the electrified society to function over time.

This work package is essentially two interrelated parts in one: the MFA mapping (henceforth named Part 1) and the reverse logistics chain optimization (henceforth named Part 2). The former maps the flows of end-of-life (EOL) LIBs in Europe for the years 2022, 2026, and 2030. The latter evaluates possible network structures for the reverse logistics supply chain with the placement of one or more new material recovery facility in Europe. The lowest cost alternatives, both in terms of monetary costs and carbon dioxide emissions “costs”, are found using linear programming optimization techniques. Different material recovery facility technologies that were selected for the ELiMINATE project (as a whole) were evaluated.

In the context of the ELiMINATE project timeline, Part 1 was started relatively early in the project and did not depend heavily on results from other work packages. However, the data and modeling from Part 1 was also used for Part 2, and this interdependence between the parts required for the modelling choices to be synced. To that effect, discussions and harmonization with the project group were necessary from the start. Part 2 of this report (MFA optimization) was done after the respective MFA (WP 3A) on the South African market. Part 2 also relied on data from other work packages and perhaps most importantly the quantitative results from the technoeconomic analysis of WP 1 and the carbon emissions from WP2.

There are significant differences in the South African and EU markets, which are reflected in both the modelling choices and the assumptions on the parameters used in the modelling. As such, a workshop was also held with the project group to discuss perceived impacts and probabilities of factors that could affect the flows in the European context.

The discussions and feedback from the entire ELiMINATE consortium has helped ground this work in both with the assumptions for the recycling technologies and the also the European context of the EOL LIB supply chain. A heartfelt *thank you* goes out to Dominic Vooght (WP 3A, MFA South African Context), Ayse Nur Ozturk (technoeconomic analysis for the EU), and Faizan Muneer (literature Review for hydrometallurgical processing of Lithium-ion batteries) for taking the time and interest to go into deeper discussions and support that helped raised the quality of the work in this report.

Part 1 aims at visualizing the European EOL LIB volumes in 2022, 2026, and 2030, by quantifying the flows of materials from a combined bottom-up/top-down approach.

Part 2 aims to propose possible new material recovery construction locations in the EU that minimize costs and environmental burden (only carbon emissions) for the four selected technologies by the ELiMINATE consortium.

2 Methodology

A high-level methodology for the mapping and optimization is presented in this chapter, and a more thorough methodology description can be found in the Appendix.

Part 1 Methodology

The European battery value chain is modelled for 2022, 2026, and 2030 with the general principle for an MFA that all flows of materials are accounted for, i.e.:

$$\sum In - \sum Out = Accumulated \quad \textbf{(1)}$$

The conceptual system and system boundary is visualized in Figure 1. It is a simplification of the battery value chain which does not account for several important aspects, such as losses due to e.g., dissipation or black-market activities, accumulated flows (e.g., second-life batteries), differences in recycling technologies, and several other aspects. It also assumes that there is no downcycling of the battery materials. The actual system modelled is an adjustment on Figure 1 mainly through the data availability on the volumes of EOL LIBs and how the volumes are expressed.

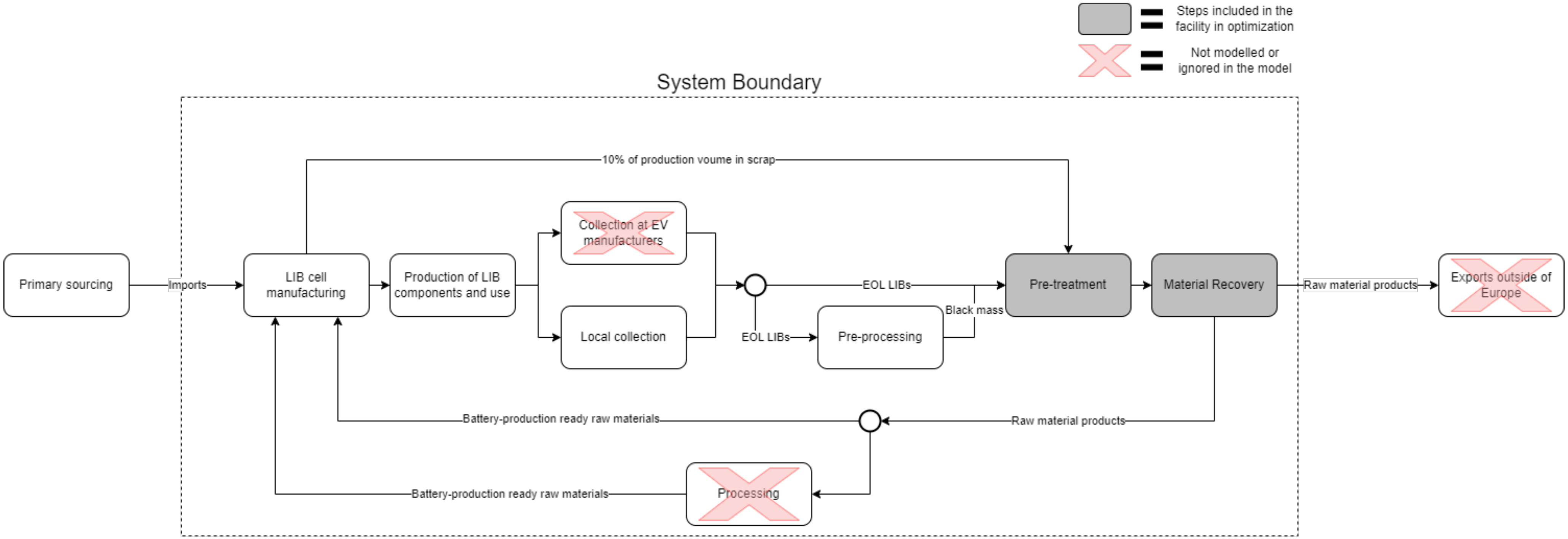

Figure 1 System boundary for the modelling of the MFA in ELiMINATE. The red crosses show flows and processes that are not included in the model for Part 1 (and by extension the input data in Part 2).

The choice was made in our model to remove the outward flows of EOL LIBs as exports outside the system boundary. This means that we assumed there to be no exports of EOL products. This is a big simplification is based on the EU's strategy to keep more of the battery materials within the region. The new Battery Regulation (European Commission, 2023) is perhaps the most compelling piece of evidence to support this statement. There is also no import of EOL LIB waste in our model.

Cell-Weight Equivalents and Supply/Demand Nodes

In both the mapping and the optimization, nodes are the points on the map that represent different actors. Each node has its own pair of coordinates and a flow of EOL LIBs or EOL LIB-related materials. These flows are normalized to "cell-weight equivalents", which essentially creates an equivalence for the mass for the battery materials (cobalt, nickel, lithium, manganese) as they are found in different types of batteries or battery-material-containing flows. For example, in EV battery packs, black mass, or as battery products for resale to battery producers. For these calculations two things are used:

- the battery chemistry and aggregated flows for each year in Europe is taken from Circular Energy Storage (CES, 2022), and

- a LIB bill-of-materials (essentially a LIB ingredients list for a battery pack or cell) is taken from GREET (Dai, Kelly, Dunn, & Beavides, 2018) and used to recalculate all battery flows of all battery chemistry types or applications to cell-weight equivalents.

The conversion to cell-weight equivalents enables the comparison of the flows in Part 1 and the optimization of flows in Part 2. For Part 2, it was additionally required to categorize different actors as either demand or supply nodes that represented the possible (respective) in- or out-flows of volumes to or from the candidate hydrometallurgical facilities. These supply and demand nodes are also visualized in Part 1 and are calculated from different data sources which are described in Figure 2 and more in the Appendix. The same green and pink colors in Figure 2 are used throughout the report to symbolize the same respective Supply and Demand flows/nodes.

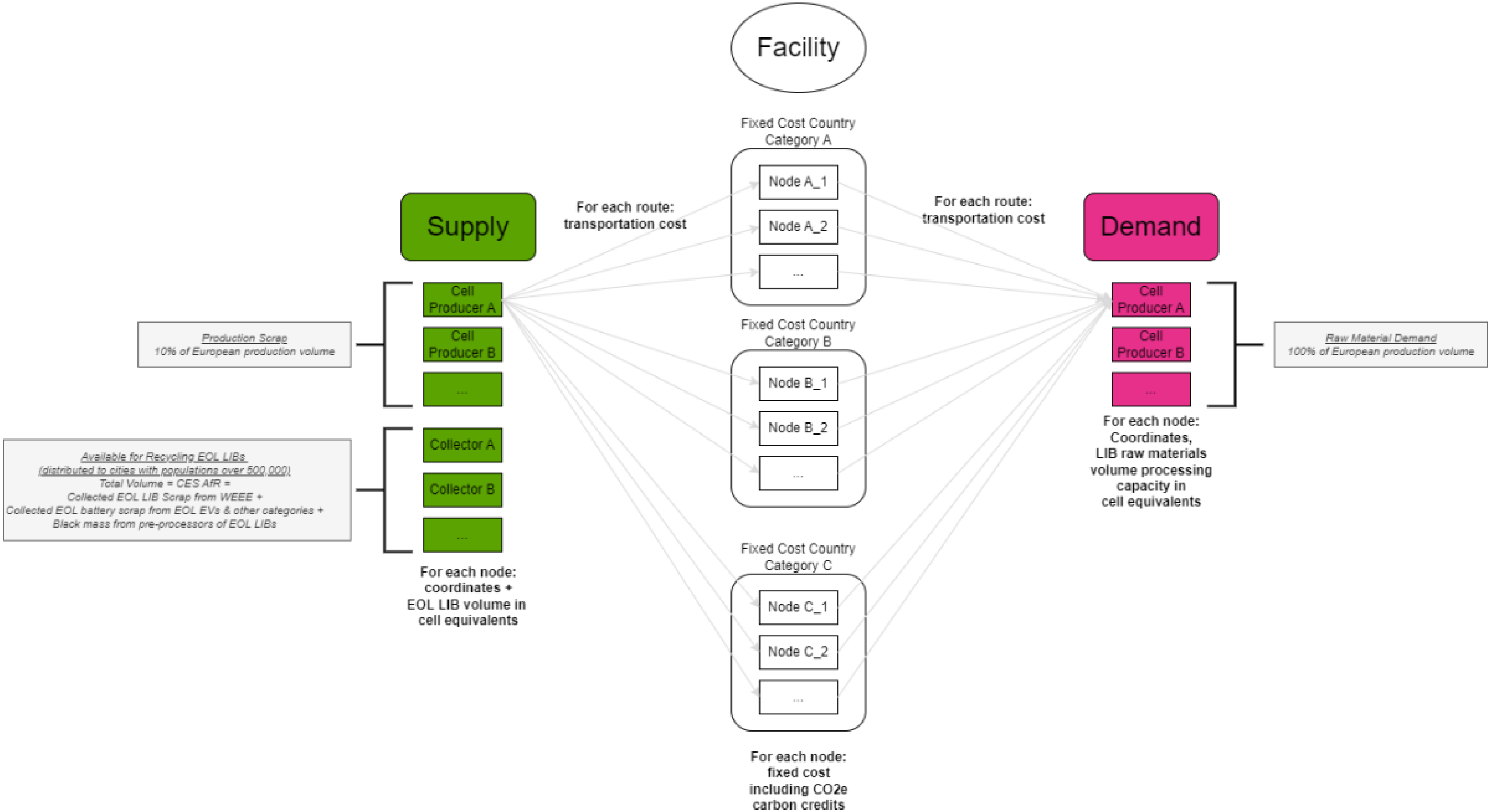

Figure 2 Diagram showing the main actor categories (Supply in green, Facility, Demand in pink) in the optimization. Suppliers are a combination of cell producer production scrap nodes and EOL LIB collector nodes. The production scrap from each producer is approximate to be 10 percent of each producer's 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. See the Appendix for more information on the CES datasets. EV = Electrical Vehicles. WEEE = Waste from Electrical and Electronic Equipment.

Part 2 Methodology

For the reverse logistics problem, a capacitated facility location optimization problem was modelled and solved with linear programming. Each network is made up of a supply-facility-demand chain is calculated for an integer value of one, or more, number of hydrometallurgical facilities. Additionally, the "facility" is the combination of a pre-treatment and hydrometallurgical material recovery plant. The Appendix has a thorough description of the problem being solved expressed mathematically, including the constraints. The problem is solved for total monetary costs and CO_2-impacts of the four technologies selected in the other ELiMINATE work packages:

- Novel 1: H_2SO_4
- Novel 2: MSA
- Current 1: HCL-NMC
- Current 2: H_2SO_4 NMC

Each technology has different fixed costs for a facility which starts construction in 2022 and with accumulated costs up to and including the year 2030. However, those fixed costs are also varied based on their geographical location in Europe. Based on a country-selection described in the Appendix, each facility in each country has one of three values for electricity cost or carbon impact, etc.

To find the transport costs or CO_2-emissions of a transport route, the real or mapped road-transport distances (in km) between all nodes were multiplied with the volumes transported (tons cell-equivalents) and by either Euro/ton-km or tons-CO_2/ton-km.

Another variation is added in the transport costs, specifically monetary costs. A "low" estimate for transport costs represents what could be representative of commodities that don't require any extra investment in transports. A "high" estimate represents what might be currently realistic transportation costs for EOL LIB flows based on a literature review (with a lot of variation and uncertainty). Both are included in the results for all technologies. See the Appendix for more information on this estimate.

Part 2 On CO_2-emissions assumptions

There are some notable differences between the WP2 LCA-results and the CO_2-emissons used in this report:

1) Only the factory energy use is considered as a source of CO_2-emissions in the facility processes. This contrasts with the WP2 LCAs where, for example, emissions of CO_2 from the processing chemicals are included in the calculations.
2) No CO_2-emission crediting is done in the optimization.
3) The H_2SO_4 (novel 1) and MSA (novel 2) were based on the energy usage of the screening LCA, whereas the technologies HCl-NMC (current 1) and H_2SO_4-NMC (current 2) were based on the energy usage of the full LCAs. This difference is due to the project schedule for the full novel technologies LCA results came after the writing of this report.
4) The waste battery composition in LCAs of existing technologies was different than the waste battery composition that were later used in the laboratory experiments conducted to analyse the novel technologies. Therefore, the LCA results all technologies are not directly comparable, and by extension, the MFA optimization results are not directly comparable either.

It is important to keep in mind these differences when comparing the CO_2-impacts of the technologies, and especially between the current and the novel technologies.

The Square Root Law

To estimate the additional cost of having more facilities that process the same total volume of cell material, the Square Root Law of logistics was used. This law states that splitting the processed volumes between two facilities instead of processing everything in a single facility will increase the fixed cost by about 1.41 (i.e., the square root of 2). The same pattern is used for adding additional facilities and it is done similarly for the CO_2-emissions.

3 Results

This section presents the results for the mapping (T3B.1) and optimization (T3B.2) results. The mapping shows the flows for 2022, 2026, and 2030 while the optimization only considers the year 2030 for the four hydrometallurgical technologies (including the pre-treatment).

3.1 Material Flow Mapping Results

The approximated (2022) and forecast (2026 & 2030) capacities and demands in the LIB reverse supply chain are shown in maps and Sankey charts in Figure 3 to Figure 8. The figures are color coordinated with the green nodes representing the suppliers and the pink nodes representing the customers. These nodes and values were used in the optimization (only 2030). For a more thorough overview of each separate type of actor, refer to the Appendix.

The ‘accumulated, exported, or lost EOL LIBs/BM represents the annual net volumes of EOL LIBs or black mass in the European value chain. These volumes are collected batteries that represent flows that other actors can, in theory, use for their recycling processes and sell as products. In 2022, these flows are 46 kton, in 2026 115 kton, and in 2030 233 kton. These results are in the same range as the 98.667 kton per year result obtained in the technoeconomic analysis for Europe. Therefore, the optimization problem will also use 98.667 kton per year as an input value to the model.

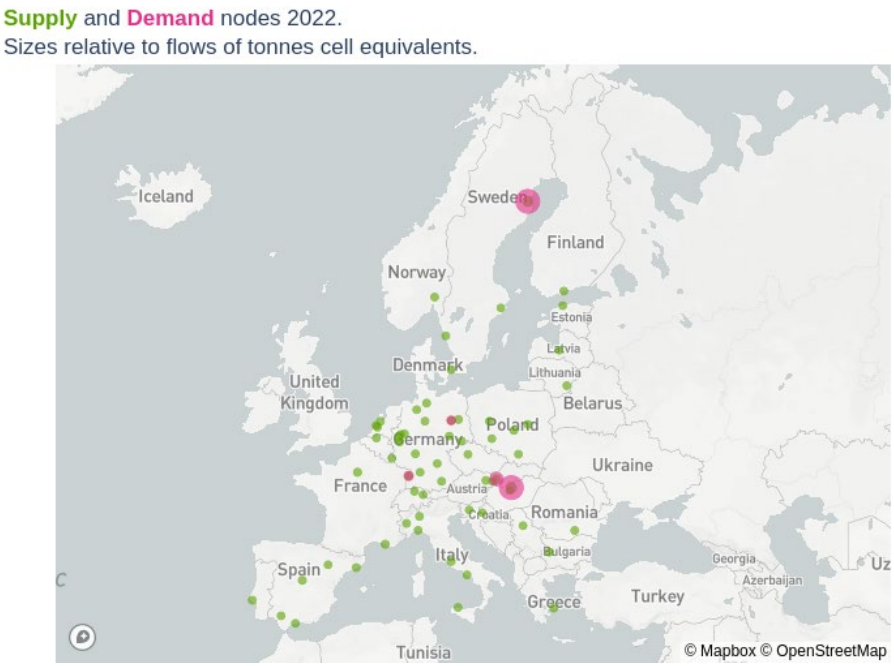

Figure 3 Locations and relative volumes from supply nodes (in green) and demand nodes (in pink) for 2022. Note that some points are superimposed and are hard to see.

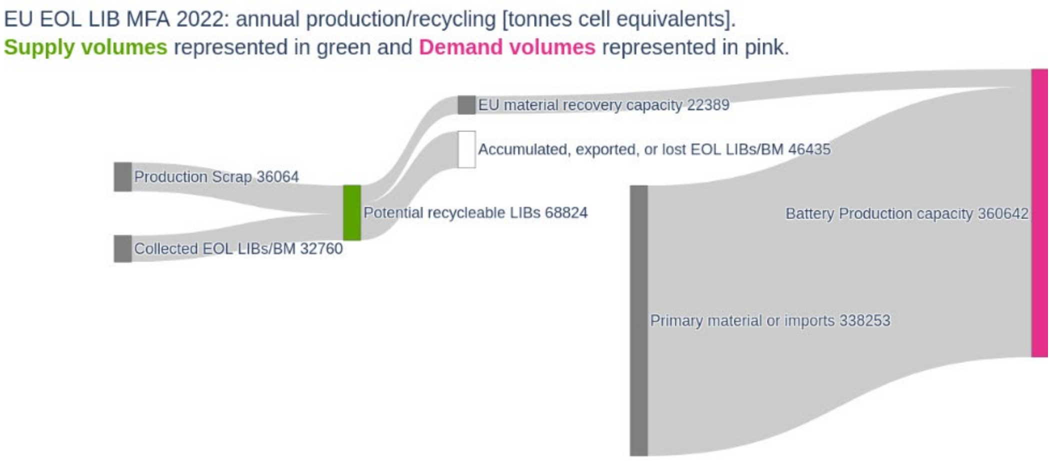

Figure 4 Sankey chart of total recycling flows, compared to battery production capacity, through Europe approximated for 2022.

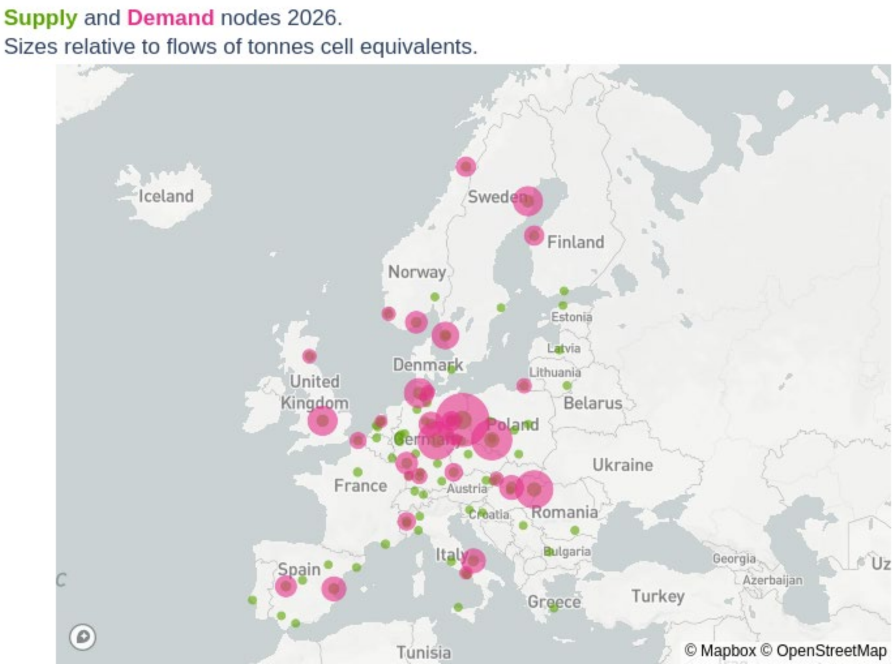

Figure 5 Locations and relative volumes from supply nodes (in green) and demand nodes (in pink) for 2026. Note that some points are superimposed and are hard to see.

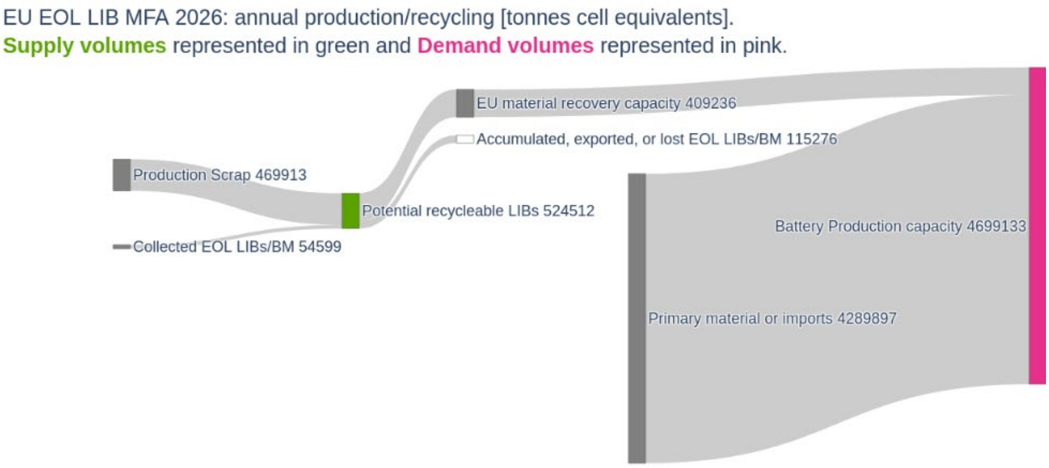

Figure 6 Sankey chart of total recycling flows, compared to battery production capacity, through Europe forecasted for 2026.

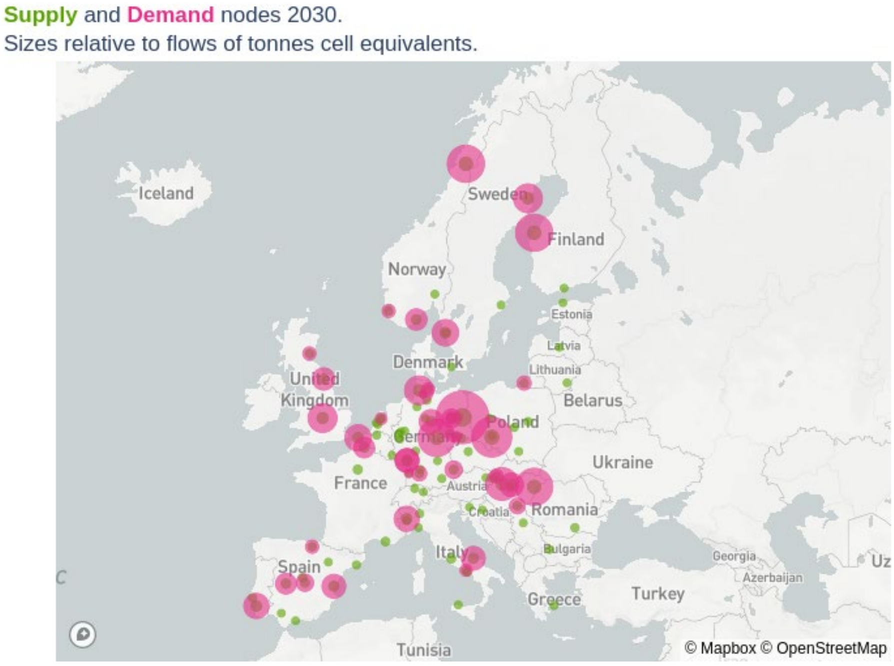

Figure 7 Locations and relative volumes from supply nodes (in green) and demand nodes (in pink) for 2030. Note that some points are superimposed and are hard to see.

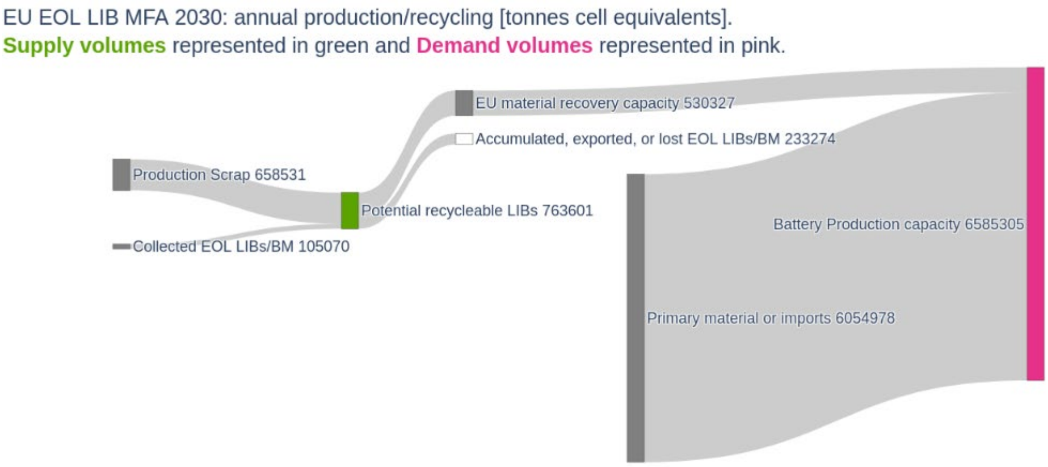

Figure 8 Sankey chart of total recycling flows, compared to battery production capacity, through Europe forecasted for 2030.

3.2 Material Flow Optimization Results

The results presented were done for monetary costs and CO_2-impacts of the four technologies for a facility which starts construction in 2022 and with accumulated costs up to and including the year 2030.

3.2.1 Cost Results

Figure 9 shows the results for the cost optimization. The optimal number of facilities for monetary costs for all technologies was one facility, regardless of the hydrometallurgical technology employed. However, the minimum costs varied between technologies and transportation cost estimates. For the low-transport estimate: H_2SO_4 (novel 1) at 1,059 M€ beat the competition, followed by (in order) HCL-NMC (current 1), H_2SO_4-NMC (current 2), and MSA (novel 2). For the high-transport estimate, H_2SO_4 (novel 1) also beat the competition with 1,76M € again followed by the other technologies in the same order.

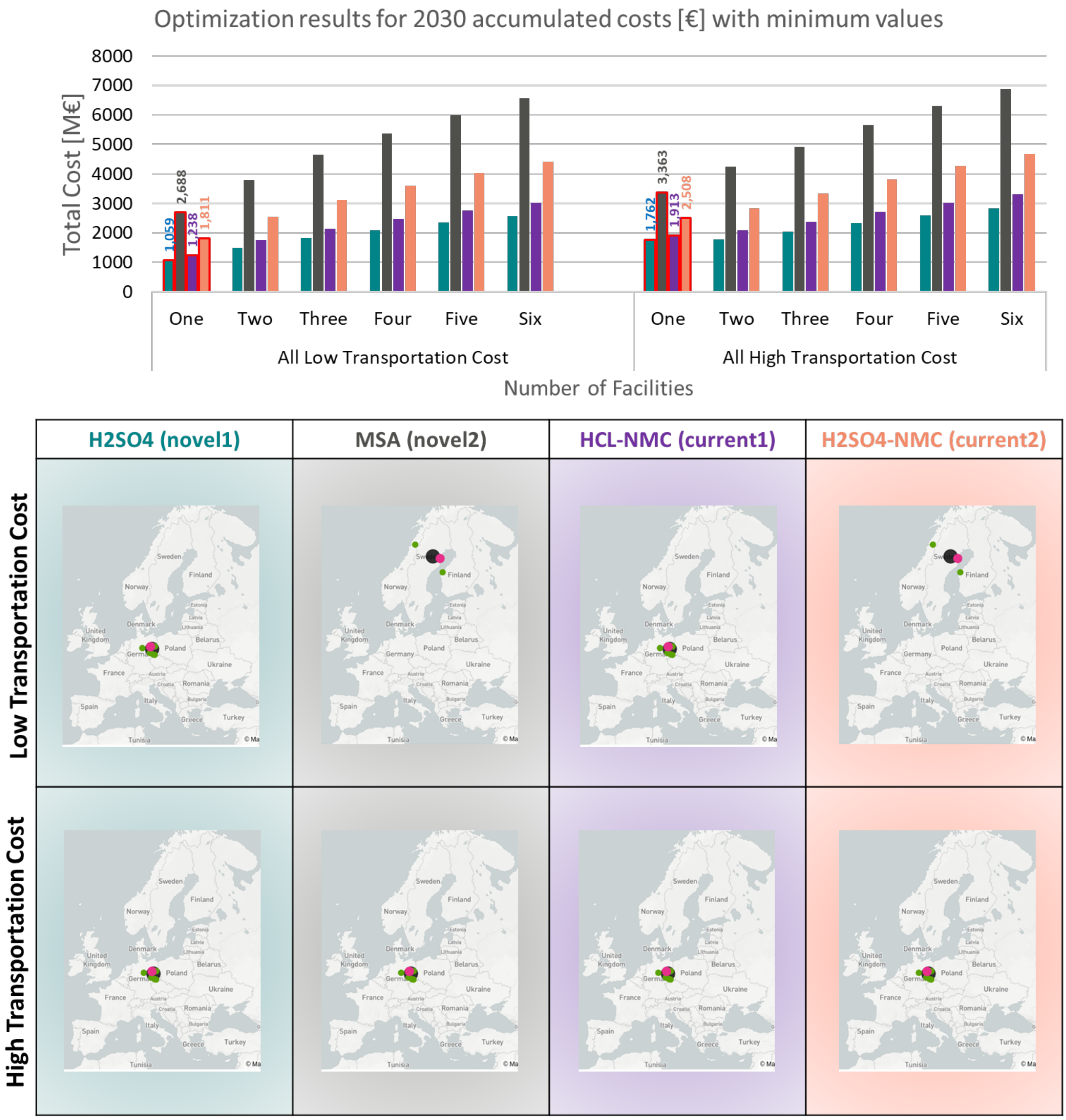

Figure 9: Monetary optimization result of the four technologies for both low- and high transportation cost estimates. In the graphs, the bars with red outlines and values over them are also the minimum values of facilities for their respective technologies. Each colored bar represents a hydrometallurgical 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.

For the low transportation cost estimate, the locations of the technologies with lower total costs H_2SO_4 (novel 1) and HCl-NMC (current 1) had optimal facility locations and supply/customers in the Nordics whereas the more expensive technologies had their optimal facility locations and supply/customers in Central Europe.

For the high transportation cost estimate, all technologies had optimal facility locations and supply/customers in Central Europe.

3.2.2 CO_2 Results

Keeping in mind that there are limitations when comparing the technologies by CO_2-emissions, Figure 10 shows the numeric results for each of the four technologies based on the optimization of CO_2-emissions.

For the low-transport estimate: H2SO4-NMC (current 2) at 7.012 kt CO_2-emissions beat the competition, followed by (in order) HCL-NMC (current 1), H_2SO_4 (novel 1), and MSA (novel 2).

For three of the technologies H_2SO_4 (novel 1), HCl-NMC (current 1), and H_2SO_4-NMC (current 2), four facilities were shown to be the optimal number for Europe. These facilities are spread mainly over the Nordics, but also in Germany. For the MSA (novel 2) technology, the optimal number of facilities is one, placed in Northern Europe.

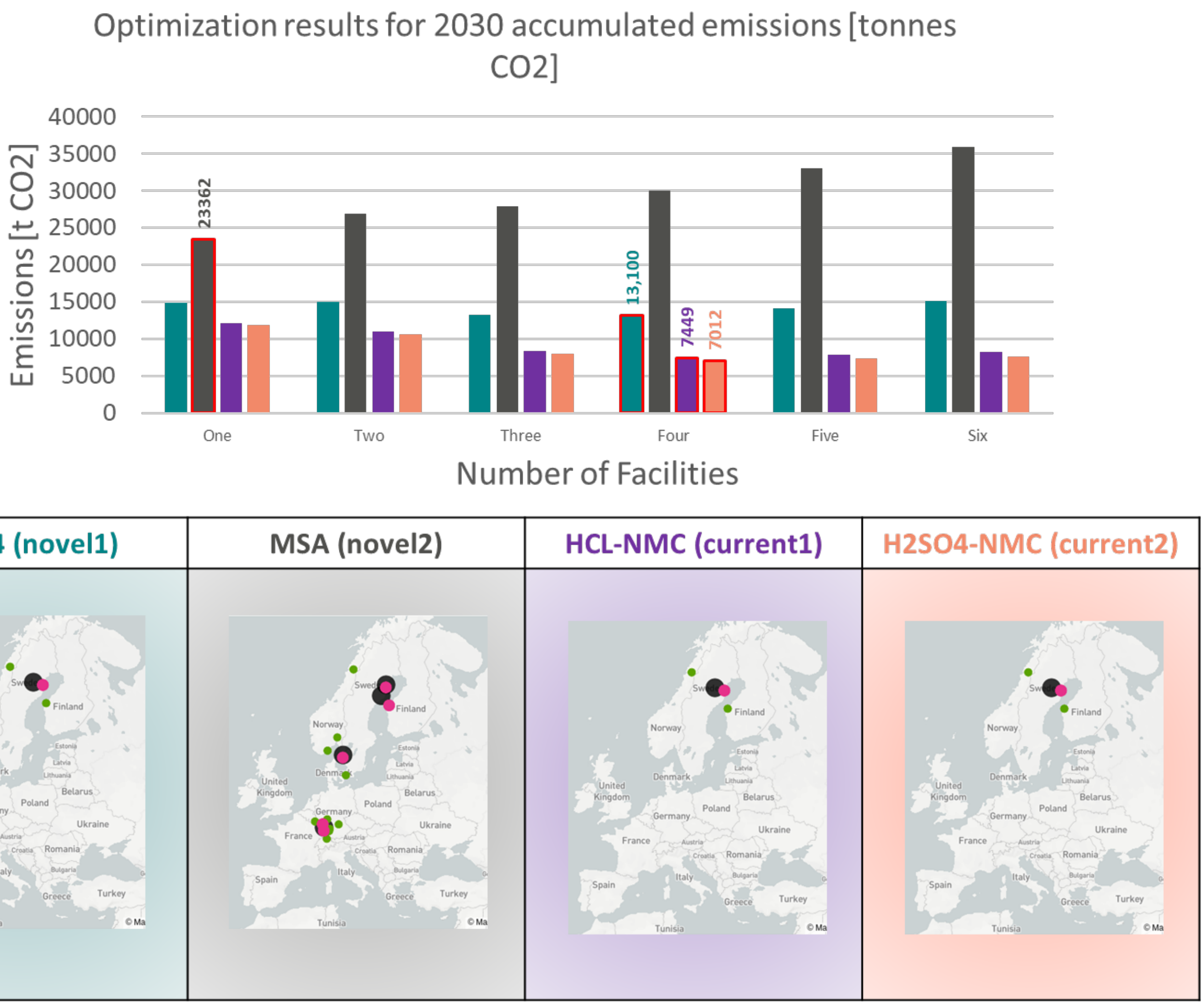

Figure 10: Optimization of CO_2 emission result of the four technologies. In the graphs, the bars with red outlines and values over them are also the minimum values of facilities for their respective technologies. Each colored bar represents a hydrometallurgical technology. In the maps which shows the 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.

3.3 Comparing Cost and CO_2 Optimizations

Figure 11 puts together the results for emissions and costs by how they vary for different number of facilities. The optimal number of facilities for each technology is normalized to 100 percent, so that each added (or subtracted) facility is compared to it.

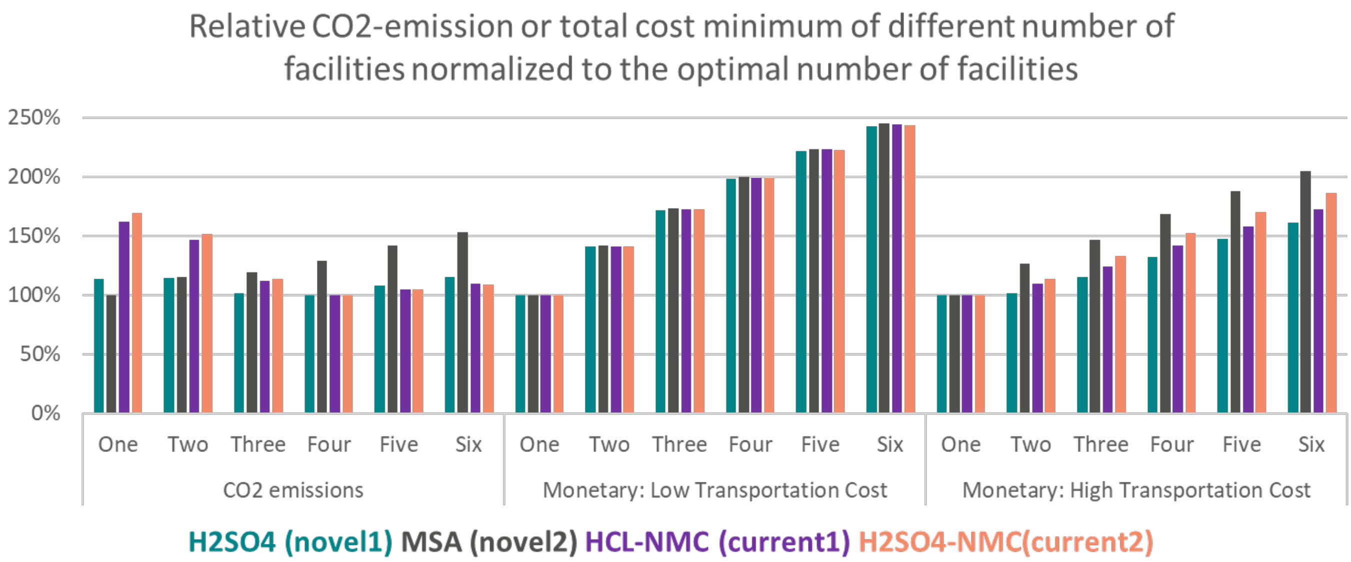

Figure 11: This graph is meant to show both the CO_2-emissions and monetary costs side-by-side by normalizing each scenario with the total minimum cost for the optimal number of facilities in each scenario, and then comparing the rest of the values to this normal. The relative carbon dioxide emissions or total costs are thus compared to the 100 percent respectively for optimal emissions or costs for the optimal number of facilities and network. The additional emissions or costs for adding or subtracting one facility to the optimum varies between technologies by 1-15% for CO_2-emissions, 41% for monetary costs with low transportation costs, and 1-26% for monetary costs with high transportation costs.

4 Discussion

This chapter evaluates several aspects of the results from the previous chapter.

Mapping in ELiMINATE WP3 EU

The mapping in this report combined data from various sources and visualized the total volumes that flow between actors in the European reverse logistics supply chain for EOL LIBs. The visualizations were mainly geographical representations of the actors in Europe and Sankey charts that showed the comparable volume sizes. This was done for the years 2022, 2026, and 2030.

Europe is a varied and dynamic region for battery recycling

Europe is a large and varied region in terms of geography as seen in some of the maps in this report. There are countries in islands, small/medium/large countries, countries that neighbor mostly water, others that don't have a coastline at all, and so on. Europe is also a region which has a plethora of country borders which may in some instances create more costs and waiting times for transporting EOL LIBs and/or black mass in some routes. The costs and carbon content of electricity and cost of labor differs between countries. Thus, there are many ways in which each country or region in Europe differs from the rest.

Europe is undergoing a rapid shift to renewables and electrification with several battery actors entering the market or expanding in the coming years. These differences in the region and changes to the market means that modelling the system requires several assumptions to make the analysis manageable. The differences also require the model to evaluate several of the uncertainties in the market over the coming years and the work was approached in a method as to be as transparent as possible on the existence of the factors that can affect the model and the model's limitations. The internal workshop and the assumptions laid out in the Appendix are an attempt to communicate the results of discussions on this topic.

Creating a model of a complex system that encompasses the entirety of Europe requires accepting that the reliability of the model may not be as high as it would be for a smaller system with access to more detailed data. To extract meaningful patterns and draw reliable conclusions from such a broad analysis, it's essential to carefully weigh the assumptions made against the results.

Comments on the CES and reported capacities as input data

The data choices were of high importance. WP3 for the EU focuses on the flows and the optimal monetary and CO_2-emission costs. The complexity and scale of the task required some outsourcing of the information collection to an EOL LIB market data firm to have sufficient budget to focus on the modelling. Circular Energy Storage was chosen due to its coverage of the flows of EOL LIBS in the European value chain. The details regarding the categories and battery chemistries in the flows were very helpful, as were the forecasts up to 2030. The market data was built in a bottom-up approach, however, the final figures that we received were aggregated flows. This meant that although it was theoretically possible to build the entire model in a bottom-up way, the aggregated data still had to go through a "top-down redistribution" of flows to the various actors for the optimizations. It is difficult to conclude what effects these redistributions had on the final results, but it is clear that the model would have benefited from use the bottom-up data directly. Note that project's version of the CES data was for January 2022 and updates can (possibly and hopefully) be more granular in future versions.

Another important consideration for the data quality were the reported capacities of battery cells producer and recycler factories up to the year 2030. There are many types of battery cells and battery cell chemistries that make it a much more complex problem to get accurate prediction on which actors handle the types of batteries that ELiMINATE focuses on. Additionally, the reported numbers may be under- or overestimated as there is always some uncertainty tied to new projects. However, the authors of this report took the liberty of assuming all flows were the same with the asterisk that refinements of the model are possible if the model is ever updated, and data becomes available.

Mapping the EU EOL LIB reverse logistics supply chain into the future

The mapping in this report combined data from various sources and visualized the total volumes that flow between actors in the European reverse logistics supply chain for EOL LIBs. The visualizations were mainly geographical representations of the actors in Europe and Sankey charts that showed the comparable volume sizes. This was done for the years 2022, 2026, and 2030.

The mapping results show a general increase of the battery actors in Europe with especially the Nordics and Central Europe being the predominant regions with more actors and higher capacities. There are also some other regions such as the UK, Spain/Italy and Central/Eastern Europe that also will see some growth in actors and capacities. The general trend also shows that the battery cell capacities will "come first" and that recyclers are lagging a bit. Some producers also recycle materials, which might mean that the producers will not require any outside actors to recycle their cell scrap materials. Although the design choice was not made to remove these actors from the network that was analyzed, others doing a similar type of analysis might want to consider this as a possible way to make the model more realistic by more closely imitating the real situation.

The lack of imports in the flows in this model was chosen because of the EU strategy to try to keep the battery materials in the region. It is highly unlikely that all the EOL LIBs and their materials will stay in Europe. Thus, the locations of the flows may change over time from this work.

Using the Square Root Law creates specific patterns in the optimization results

In Figure 11, there is a 41% increase in adding an additional facility for the low transport cost estimate. This is value is very close to the square root (1.41), thus it is likely that the low transportation estimate's transportation monetary cost savings of adding another facility are so small that they barely matter in relation to the additional costs incurred from adding another facility. In the CO_2-emissions and the monetary costs for the high transportation estimates, the different technologies' graphs vary more and it is likely that the savings in transportation distance of adding another facility play a larger role in the minimum cost.

The square root law used in this analysis gave a maximum value to the doubling of the number of facilities. It is reasonable to question the validity of this assumption, not only because it is a clear simplification of a very complex system, but also due to the impact it has on the results.

The simplicity and linearity of the square root law might fail to capture certain aspects that come from scaling. Additionally, it might not consider the cost-saving or cost-increasing effects from other activities.

Differences in results based on transportation estimates

The Part 2 analysis indicated that centralizing pre-treatment and material recovery is generally more advantageous than having multiple smaller facilities. This is due to the square root law of logistics, where each additional facility introduces more cost. For most technologies and scenarios assessed, the extra cost was not offset by reduced transportation costs. Only in cases where fixed costs approached transportation costs (due to low fixed costs or high transportation costs) did the benefit of additional facilities become apparent.

The methodology for estimating the transportation of EOL LIBs was simplified and does not fully capture the complexity of this emerging field. By using two different cost estimates for transporting EoL LIBs, it was found that higher costs favored Central Europe due to fewer required travel routes. For lower transport costs, the Nordics emerged as a competitive location for more cost-effective technologies.

The assumption that EOL LIBs are more costly to transport than processed black mass suggests a potential benefit in processing EoL LIBs locally and centralizing the recycling of black mass. This is because the transportation cost differences create stronger financial incentives to locate facilities nearer to the supply and demand centers when transportation costs are high, rather than when they are low.

It's important to note that the costs of transporting raw material products from the recycling facility to customers are likely less than those associated with collecting and transporting EoL LIBs to the facility. The higher costs for EoL LIBs are partly due to the need for specialized infrastructure and services to manage safety and health risks, such as the potential for fires or explosions. This level of caution is not as critical for the transportation of recycled products. Future research models should focus more on these specific areas as the field evolves and more data becomes available.

CO2-emissions and facility location

For minimizing the CO2-emissions it appears that although the battery industry is concentrated in Central Europe, the Nordics is still a stronger contender. As the electricity mix is the main difference between candidate facility nodes, it is safe to say that the difference of electricity mix is one of the main drivers (in addition to supplier/customer node locations and supply/demand). The Nordics generally have a lower carbon content in the electricity mix. However, it is of importance to keep in mind the facility assumptions for CO2- between novel and current technologies are not as robust as those for costs. Additionally, a factor that wasn't considered was that the transportation emissions can in reality vary between regions and over time as well. In the current model they were assumed to be constant and reflect the 2022 values. As European transportation is moving to become more carbon-neutral the differences between regions could possibly be a considerable factor in the optimal network structure and resulting total CO_2-emissions.

Facility EOL LIB processing volume in Europe and network considerations

The study established an annual processing target of 98,667 tons of EOL LIBs to reflect a feasible volume that could be maintained beyond 2026. This target strikes a balance between the outcomes of a technoeconomic analysis and the mapping of the "accumulated, exported, or lost" value in Europe for the years 2026 and 2030. The decision to optimize the capacity to meet only the most efficient European network's needs meant ignoring other existing networks, which greatly oversimplifies the analysis. Consequently, the optimization findings should be interpreted as the ideal scenario rather than a practical strategy for the placement of facilities to minimize monetary costs and carbon emissions. Nonetheless, this model serves as a useful initial framework for creating more detailed models for specific European regions, provided that more localized data is available. The insights gained from this study help understand:

- The balance between proximity to other industry players and the cost implications of facility location.

- The interplay of factors like facility costs, processing volumes, technological choices, and

- the positioning of battery value chain participants in identifying optimal areas where more in-depth analysis would further improve upon the results.

The three regions and its implications in the results

Europe was represented by three regions in this analysis, which allowed for observing the interaction between transport costs and regional fixed costs. Despite its simplicity, this approach revealed that granularity could lead to more accurate results in large regions with diverse actors. The Nordic region, for example, demonstrated potential advantages in certain scenarios for 2030 due to lower fixed costs and carbon emissions from their energy mix compared to Central Europe.

The study acknowledges that the real-world scenario is far more intricate than what was represented by only three regions. Factors such as differences in labor costs, energy sources, and waste management expenses can significantly influence costs and carbon impacts within a country. Additionally, the proximity of supply chain entities, like a cell manufacturer near a recycler, could lead to cost savings that this analysis could not fully account for.

Unknown actors and volumes

Many potential actors and networks were not included in the study. Some were referenced in the Appendix due to their unpublished processing volumes, and others, like processors of virgin battery materials, were excluded to simplify the model.

As stated earlier, the data on the actors and their processed volumes is based on current data and may change in the coming years.

Only total costs / carbon emissions were assessed, not net costs /carbon emissions

The study assessed the overall expenses and carbon dioxide emissions but did not consider the financial gains or carbon credits. A more comprehensive analysis might be to consider the net costs and net CO_2 impact (with savings from material recovery). However, this approach would require additional scrutiny to balance the negative aspects against the positive ones within the LCA, particularly concerning the cut-off criteria.

Optimization can save monetary costs and CO_2 emissions by guiding networks

Figure 11 indirectly illustrates the advantages of optimization for both emissions and costs. It demonstrates the potential reductions, ranging from 1 to 41 percent, when transitioning from a network with a non-optimal number of facilities to one that is optimized, even if the difference is just one facility. These findings alone suggest that optimization is cost-effective and can lead to significant savings in CO2 emissions. It's noteworthy, though, that these results don't reflect the full extent of potential savings that could be achieved by optimizing the network beyond the current scope. Any further reductions would only reinforce the value of optimization.

Lastly, it's essential to recognize that the European EOL LIB market is still developing. As the industry evolves, we expect that the industry players and the resource flows will change. Hence, it will be necessary to regularly update the data and the capabilities of the facilities to keep pace with these changes.

4.1 Recommendations for Model Improvements

This section will cover some of the possible improvements to the models for the mapping and optimization in this report. The suggestions are selected based on improving the model to fulfill the same goal, but also considering the development of the market and available data in coming years.

Actors, supply chain, and country recommendations

It is advised to shift the focus from cell producers to smelters and cathode material producers as the primary demand nodes. This recommendation aligns with insights from references such as Battery-News, which suggest that these actors are part of the supply chain for the reverse logistics supply chain for EOL LIBs.

A more detailed breakdown of producers based on cell chemistries would consider this effect on the available cell chemistries and battery metals that will enter the facility. By understanding the specific battery metals and compounds involved, we can optimize for both cost and environmental impact, tailoring recycling efforts to the nuances of each material. Battery-News (Battery-News, 2023) has some data for some producers currently, but it is not exhaustive.

To represent the available volumes of EOL LIBs available more accurately from the available collection points, two suggestions are presented. Firstly, if more data becomes available (e.g., from Circular Energy Storage) in a bottom-up fashion (i.e., volumes actor-by-actor), the volumes that are not being used in other networks can be modelled for an additional facility. Secondly is if more data becomes available in a smaller area, the geographical boundary for the analysis could be decreased to get more accurate results for that area.

The current model's simplification into three country categories does not capture the complexity of global operations. A cost breakdown by individual country is suggested. Further refining this approach could involve identifying areas with access to renewable energy and establishing unique values for these zones, allowing for more nuanced assessment of potential costs and carbon emissions.

The application of the square root law of operations management has been used to estimate the increased costs associated with adding new facilities. The efficacy of this law as a standalone measure is warranted because it has a significant effect on the fixed costs. A more robust analysis through a sensitivity analysis should be done to investigate its effect, and possible model weaknesses. This approach would give a sense of the possible effect of differences in price might have. Although the relationship between adding extra facilities and the costs may not be linear in real facilities, performing a sensitivity analysis should capture the broad strokes in terms of the fixed cost relative to the transportation costs.

Transport recommendations

The transportation aspect of the model is very simple in this model and could benefit from adding detail on many fronts.

The weight-difference of different flows could more accurately be represented between the incoming battery scrap or black mass from supply points and the finished products going to demand points. In the present report, a uniform weight has been assumed for all instances, which oversimplifies the model.

Using different truck models, or different fuel sources (e.g. diesel or electric) (Suzan, 2021), or different packing ratios could improve the model results further. As an early analysis it should be quite valuable to do a sensitivity analysis to note the effects on the results, and if necessary, do a more in-depth analysis if the effect is significant.

Country-specific differences for transports can be included in other models, considering factors such as carbon tax, energy mix, costs, and common truck driveline types. In light of the EU's transition towards reduced emissions in the transport sector (European Commission, 2023), there is a lot to be considered in the future with regards to the energy available and energy consumed. The effects of these future trends can be modelled in an optimization. In the current model, these factors were not considered for the year 2030.

It is also recommended to categorize EOL volumes from vehicles into distinct nodes that more accurately represent the intermediary actors they would pass through. These should be associated specifically with car manufacturing plants to provide clarity on different steps (i.e., pre-treatment) and potential second-life EOL LIBs in the automotive industry.

Implementing these recommendations would significantly bolster the model's robustness, providing a more realistic simulation of the battery production and recycling supply chain. This would ultimately lead to more informed decisions that could improve economic efficiency and environmental outcomes. As a parenthesis, most of these improvements will increase the complexity of the model and the processing speed of the optimization could suffer as a result.

Possible scope change to measure the effectiveness of Europe's existing networks

This report focused on adding one or more additional material recovery facilities to existing networks in Europe and the volumes of EOL LIBs that were estimated to be available for the facility was 98,667 tons. This was done to test the technologies assessed in the project.

However, one interesting additional analysis (that lies somewhat outside the scope of this report) could be to evaluate the existing network of recyclers. This could be done by first removing all the planned facilities to get a "clean slate", and then to run an optimization of their aggregated volume in Europe to return the optimal network with the lowest costs or carbon emissions.

To take this further, an optimal network configuration of the existing placement of recyclers can be done in parallel (with some adjustment to the objective function and constraints). The resulting costs and carbon emissions could be compared to the optimal network and thus the information would be enough to evaluate the efficiency of Europe's overall reverse logistics network system.

5 Conclusion

The analysis of the European market has revealed a comprehensive understanding of the market dynamics, key players, and material flows within the region. It's evident that the market is expanding, with battery production accelerating ahead of recycling efforts. New participants are emerging and scaling up, which in turn is opening up new channels for EOL LIBs and enhancing the opportunities for new networks.

In the strategic planning process, we designated an annual processing target of 98,667 tons for the recycling facility or facilities. This figure aligns with the anticipated excess materials that other recycling operations will not handle by 2026. This strategic plan yielded several outcomes based on numerous hypotheses, from which we can draw broad inferences. The prime locations for establishing recycling centers were identified as either the Nordic countries or Germany. The ideal number of facilities to construct varies between one and four, depending on the chosen technology and the associated transportation costs.

In terms of environmental impact, our optimization focused on reducing CO_2-emissions associated with the energy used. However, the scope of emissions considered was narrower than those assessed in the LCAs from WP2. While this project didn't extend to optimizing for other environmental impact categories, it's clear that applying a similar optimization approach could be beneficial.

The study demonstrates that optimization can lead to significant advantages within the modeled system. By optimizing the number of recycling facilities, we could achieve cost and environmental savings ranging from a modest 1-41% to potentially exceeding 100 percent of the baseline figures for the optimal facility count. The findings underscore the importance of data: with better access to relevant information, there's a substantial opportunity to realize further savings, both financially and environmentally.

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Appendices

Appendix A: Modelling Assumptions

Collection Points Assumptions

- **All batteries, including EOL EV LIBs, will be modelled to be collected in the same locations or geographical nodes.** EOL EVs would in practice likely go back to the vehicle manufacturers for pre-treatment and have their EOL LIBs removed there. (Bergh, 2020)

- **98,667 tons of EOL LIBs are available from any of the collector or producer (scrap) locations**. This essentially means that no other networks are present which can take up the available volumes of EOL LIBs, according to our simplification. This is done because the lack of data available on other networks and the uncertain nature of networks in general.

- **Only cities with populations above 500,000 inhabitants were chosen as collection points**, and the CES AfR volumes were used distributed amongst these cities based on the relative population sizes of the chosen collection points. This was done because the benefit to the optimization results gained did not outweigh the effort and computational expense needed to collect and model these point for all of Europe. A test was done for the Swedish market, which was found to have over 200 nodes, after which a modelling choice was done to use the city locations and population values as proxies for battery collection nodes and volumes.

- **Battery scrap is produced by all battery producers at an equivalent of 10% of their annual production capacity.** For example, if a battery producer has an annual LIB production capacity of 1000 tons, that same battery producer will then be (in our model) equivalent to a collection point with a flow of 100 tons EOL scrap per year. No distinction is made between the scrap from producers and from post-consumer waste, however, in practice the cathode scrap from producers is generally easier to access and more homogenous and therefore has better potential for material recovery. It is very likely that, in practice, this material will be recycled by the same company if the producer and the recycler are part of the same company.

EOL LIB Flow and Industry Assumptions

- **Flows of cells and black mass all contain the same battery chemistry or metal composition**. The CES volume data is mapped on a region level basis, e.g. Europe, meaning that the flows could not be distinguished further within the geographical region. Some actors that have plans to produce sodium-ion batteries or solid-state batteries are still in the model as LIB producers and scrap producers. Furthermore, **EOL LIB cells and black mass are also aggregated** in the flows as they are in the CES data, albeit in cell equivalents.

- **The volumes flowing through the producers and recyclers are assumed to be equal to their processing capacities**. The processing capacity of the facilities may not always be met.

- **No losses of materials in the facility.** Some losses of material are expected in the real-world scenario.

- **All flows are calculated to cell equivalents** for comparability purposes between e.g. flows of battery packs and flows of black mass and battery scrap. Choosing cell weights required the smallest number of calculation steps for the CES volumes for the MFA, and thus introduced few additional assumptions to the data. The "translation" was done by taking the average cell weight of LIBs with different cell chemistries in the GREET 2018 (Dai, Kelly, Dunn, & Beavides, 2018) bill-of-materials and dividing by their pack weight. Only certain categories of LIB-containing products went through this translation: Personal mobility, Light EV, Heavy EV, Industrial, ESS, Maritime, Portable and UPS LIBs were not translated from battery packs to cells.

- **The CES AfR volumes aggregate black mass with cell weights.** Although the volumes from pre-processors have been mapped, the volumes that they produced are near-impossible to extract from the AfR value. Black mass can include more than just mass from cells and is thus mixed with varying amounts of other metals.

- **Other networks are not considered in the optimization model.** This grand simplification is done due to the complexity of the LIB supply chain and uncertainty of how future networks will look in the future.

- **Battery cell producers are assumed to be the direct customers of the material from the facility.** Buyers can be **actors** outside the battery value chain or other actors within the battery value chain, e.g., cathode producers. However, the model design choice was made to limit the nodes to just the battery cell producers.

- The choice was made in our instance to keep the flows of EOL LIBs within Europe. This means that we assumed there to be **no exports of EOL products or imports of EOL LIB waste**. This is a big simplification.

Fixed Costs and Facility CO2 impact Assumptions

- A facility's fixed cost is a single value meant to represent all costs associated with the facility itself. **The fixed costs for the facilities geographical locations are calculated for three countries (Italy, Germany, Sweden) and all other countries are divided into one of the three country-regions based on their per-capita GDP and carbon intensity of the country's average energy mix.** For each of these countries, differences in raw materials, utilities, labor costs, emissions from the electricity mix, waste treatment, and other operational costs are accounted for. An improved model would include calculations for all countries. It could also include local, region-specific data such as lower CO2-impacts if the facility is located next to hydroelectric powerplant where it could source its electricity or areas where the plant is connected to district heating.

- **Fixed cost for each possible location is the sum of facility's CAPEX, OPEX, and carbon tax based on the country's average electricity mix and carbon tax rate** (The World Bank, 2022)**.**

- **The cost of each additional facility (while keeping the total volume the same) is estimated as the fixed cost of a single facility multiplied by the square root of the number of facilities in the new network.** The square root law of logistics is actually meant for warehouses, but it is used to estimate the additional hydrometallurgical facilities added with the assumption that the total processed volume for all facilities is constant. The same calculation is done for both monetary costs and CO2 emissions from the facility.

- **Costs for dismantling and transporting the batteries to the collectors is not included as costs in the model.**

Transportation Assumptions

- **The transportation costs for all roads are the same per ton-km freight.** A low and a high estimate is done to evaluate the effects of different transportation costs. The cost of transporting lithium-ion batteries has been shown to be high in a recent review article on the topic (Slattery, Dunn, & Kendall, 2021). However, it was found to be difficult to determine the cost-drivers in most of the literature. Since the additional costs of transporting EOL LIBs compared to other cargo likely do not increase linearly with transportation distance (as e.g., fuel costs do), the assumption could also likely be improved upon. Some of these costs may be due to transporting hazardous materials such as additional insurance requirements and the procurement of specialized equipment.

- **Delays from border controls are not considered as extra costs**. However, the expectation is that hazardous materials will require special agreements between countries that currently require foresight and significant waiting times, which in turn can cost the facility money. These rules are subject to change as the market matures.

- **The CO2-emissions from all transports are considered equal in all of Europe at 55 gCO2/ton-km** (Suzan, 2021)**.** However, different countries and regions have different transport vehicle fleets with trucks varying from carbon-neutral to carbon-heavy. Another aspect worth considering are the CO2 emission targets set out by the European Commission (European Commission, 2023) which aim to gradually decrease the overall emissions from trucks.

- **Full truckloads are assumed for all trips.**

Appendix B: Workshop on Factors Which Affect EOL LIB Flows

A digital workshop was done in 2022 in which all partners gave their inputs on the different factors that could affect EOL LIB flows in the coming years. The workshop served as a starting point to list and these factors and evaluate their potential impacts and the probability that they would be relevant in the future for the EU and for South Africa. It required the listing of all the factors, which is something that would need to be done to properly evaluate the results of the mapping, and to determine the parameters in the reverse logistics optimization problem. In this report, only the EU factors will be shown, although a similar scoring was done for the South African case.

Table 1 Results of the Workshop for the factors that affect the EU flows of EOL LIBs: 1-10 = low-high impact/probability. If both are high it means the factor has a significant effect on the EU EOL LIB flows. Note that the scores are subjective approximations and would likely change if they were to be repeated as more information becomes available and the LIB recycling industry matures.

Factor	Sub-Factor	(Predicted Impact)	(Predicted Probability)
Market Development	Disassembly, pre-treatment, and material recovery technologies.	10	10
	Assumptions regarding actors: Buyer locations, competitors, collectors.	3	8
	Supply and demand changes of flows of spent LIBs and recycled materials.	10	5
	Market price volatility of raw materials (commodity market).	6	N/A or no answer
	Ability to handle material which doesn't meet recycler's purity requirements.	N/A or no answer	N/A or no answer
Production and Consumption Flows	Supply risk of primary battery raw materials.	N/A or no answer	N/A or no answer
	Battery Demand.	N/A or no answer	N/A or no answer
	Battery chemistry changes and technical development.	N/A or no answer	N/A or no answer
EOL LIB Flows - Logistics	Hazardous Waste Classification, effect on imports/exports.	8	2
	Hazardous waste classification, effect on local distribution.	0	N/A or no answer
	Supply route changes.	7	6
	Distribution method options.	0	N/A or no answer
EOL LIB Flows - Processing	Production of undesirable/unmarketable products.	8	5
	Accumulation of waste from processing to waste treatment.	2	5
EOL LIB Flows - Collection of EOL Batteries	Scrap quality variations.	N/A or no answer	N/A or no answer
	Variations in types of battery products in EOL flows.	8	8
	Changes to legislature.	8	10
	EOL flow gatekeeping step.	6	N/A or no answer
	Batteries exported for EOL LIBs processing.	3	4
	Illegal Black Market.	8	8
	Collection strategy and collected amount.	9	3
Stocks	Battery reuse market, i.e., second-life batteries.	8	6
	Battery lifetime and use-phase.	9	2
	E-waste accumulated after e-waste disassembly.	5	8
Recycling Technology	Effect of upscaling.	N/A or no answer	N/A or no answer
	Variations of processing chemicals.	N/A or no answer	N/A or no answer

Table 2 Additional notes from the Workshop for the factors that affect the EU flows of EOL LIBs.

Factor	Sub-Factor	Additional notes (for both Europe and South Africa)
Market Development	**Disassembly, pre-treatment, and material recovery technologies.**	
	Assumptions regarding actors: Buyer locations, competitors, collectors.	
	Supply and demand changes of flows of spent LIBs and recycled materials.	
	Market price volatility of raw materials (commodity market).	
	Ability to handle material which doesn't meet recycler's purity requirements.	
Production and Consumption Flows	**Supply risk of primary battery raw materials.**	
	Battery Demand.	
	Battery chemistry changes and technical development.	
EOL LIB Flows - Logistics	**Hazardous Waste Classification, effect on imports/exports.**	• Transportation in and out of the EU can have a large effect. • Export of hazardous goods is not an issue from a mass restriction perspective, according to the IMDG.
	Hazardous waste classification, effect on local distribution.	• Between different countries there may be difference on legislation between EU countries, but it is unlikely to be a barrier to trade.
	Supply route changes.	• There are many actors, which does cause uncertainty about which ones will be present in the future. But the impact may be lower in EU than SA.
	Distribution method options.	•
EOL LIB Flows - Processing	**Production of undesirable/unmarketable products.**	• Undesirable products (from a circular economy perspective) are produced in the EOL LIBs processing steps. These flows are therefore diverted to waste flows or stocks. However, if alternative markets are identified the flows can flow to end users. The textile or alloy industry was identified as a secondary output source for a few of the products.
	Accumulation of waste from processing to waste treatment.	• The high number of actors in the recycling and production chain make it unlikely for accumulation to be too high. • It is standard to assume the low value metals (Cu, Al), along with the waste plastic etc. are sent to waste. • Possible beneficiation requires further processing or is still being researched and would therefore change material flows if considered, especially considering the large amount of this stream relative to the processed cathode material.
EOL LIB Flows - Collection of EOL Batteries	**Scrap quality variations.**	
	Variations in types of battery products in EOL flows.	• The input data (battery types) plays a large role in determining final quantitative material flows.
	Changes to legislature.	• Changes to the SA legislature will affect the flow of materials, although at this stage only the disposal of EOL LIBs to landfill is banned. No recycling, collection, or processing targets have been introduced. There is thus a large amount of uncertainty into the flows of collected LIBs.
	EOL flow gatekeeping step.	• It can be assumed that sufficient steps are taken to minimize batteries with life still in them. For example, ''testing'' steps at dismantling facilities.
	Batteries exported for EOL LIBs processing.	• It is currently unsure how much of this material is exported. It is out of the scope of my study, although e-waste recyclers can be contacted to estimate this quantity.
	Illegal Black Market.	
	Collection strategy and collected amount.	• Unless the legislature says so, this is unlikely to change much. Batteries already have intrinsic value, so large ones are unaffected, but portable batteries are still found in people's drawers.
Stocks	**Battery reuse market, i.e., second-life batteries.**	• The value of metals will be competing with second-life batteries. Depending on the price of recycling and the cost of primary raw materials, this can become a big factor. However, it is uncertain how much second-life will affect the total volume and when the second-life market is saturated
	Battery lifetime and use-phase.	• Battery lifetime models exist and although the consumer behavior may change, there is already real data showing good estimates.
	E-waste accumulated after e-waste disassembly.	• It will affect how much is smaller batteries are recycled, but also large to some extent. Design for recycling is important for batter recycling too. Not sure how much the legislature covers it in practice.
Recycling Technology	**Effect of upscaling.**	
	Variations of processing chemicals	

Appendix C: In-depth Methodology for Data Collection, Modelling, and Optimization

This chapter extends the description on the methodology for the project.

Data selection and management

Good management of the data was a priority to ensure that the results would be reproducible.

There are several challenges when modelling a large and varied region like the EU. One big challenge with modelling such a system is the access to data, occurrence of data gaps, and the quality, relevancy, and completeness of the available data. A second big challenge is choosing what the model should represent. And of course, the data available commands what is possible to model.

The answer to the first challenge was, for the EU part of WP3, to outsource most of the data collection process to a market analysis service Circular Energy Storage (CES) Research and Consulting (Circular Energy Storage, 2023), and to fill in gaps in data through our own desktop research and calculations. The main data from the market analysis service which was used was volumes of EOL LIBs that were (or are forecast to be) available for recycling (AfR), placed on the market (POM) for the years 2022, 2026, and 2030. For volumes processed by specific actors, a variety of sources were used.

For the optimization facility problem, the fixed costs of each facility location were required and the locations and the flows of all the supply and demand points for the facilities. By keeping the result in mind, the modelling choices could be made to fit the goal of having a relevant, complete, and transparent final dataset.

Some parts of the analysis were done in a bottom-up approach and some in a top-down approach. The locations and the processing volumes of each facility were done in a bottom-up approach. The collection volumes for collection points were done in a top-down approach (the total volumes for Europe came from the CES AfR volumes which were distributed along collection nodes). The authors of the CES data state that they obtained the volumes using a bottom-up approach themselves, but since only the aggregated volumes were available the simplification had to be made to use our own collection points.

How the data was stored

The data for the actor volumes and model parameters are collected in Excel files and sheets, see Table 3. The data collection process included performing mathematical operations on the CES volumes for the project's modelling purposes. It was also necessary to manually collect and compile data for the volumes of producers and enter data on volumes from different sources.

Table 3 The Excel files used to calculate values and store the data.

Recyclers.xlsx	• Recycler coordinates and volumes for 2022, 2026, and 2030.
Producers.xlsx	• Producer coordinates and volumes for 2022, 2026, and 2030.
Collectors.xlsx	• City and country populations and properties (list) • Total volumes of EOL LIBs available for CES AfR volumes in Europe for 2022, 2026, and 2030. • Total volumes of EOL LIBs CES POM volumes in Europe for 2022, 2026, and 2030. • Material composition for pack-to-cell translation. • Battery pack-to-cell weight ratio
Fixed_costs.xlsx	• CAPEX, OPEX, CO2e and carbon tax costs for each battery technology and for 2022, 2026, and 2030 calculated based on and CO2 tax.

Collectors data

The CES AfR volumes are used to represent the total supply of EOL LIBs for collectors. CES AfR is broken down into different product categories for years up to 2030, meaning it was possible to distinguish between battery packs and cells for each year. However, since the volumes were expressed in tons for each category the weights had to be converted to a common denominator to aggregate the flows for the optimization model. Cell-weight equivalents were used for this and a bill-of-materials from Argonne National Laboratory (Dai, Kelly, Dunn, & Beavides, 2018). The total volumes of EOL LIBs from these sources were then distributed between countries based on their relative populations. Thereafter each country's volume was distributed along the cities with populations greater than half a million inhabitants.

The initial plan was to map out all of Europe's collectors in a bottom-up approach and then distribute the CES AfR volumes for all of them. However, no database for the data was found in our exploration. A test on Swedish collectors was done to see how much effort it would be to collect the data from different community websites. As there were more than 200 centralized collectors, this showed itself to be a considerably tedious and lengthy task. Thus, the decision was done to instead distribute the CES AfR volumes over Europe's larger cities instead as a proxy to the many smaller and actual centralized collection points.

The CES AfR volumes also include the weights of black mass aggregated into the AfR weights as part of its estimate. Since it was impossible to distinguish the flows from the data, they were all assumed to be "cells" for the optimization part of the analysis.

Producers and cell producer scrap data

Cell producer locations and production volumes were found through a combination of (at the time) limited data on CES with the addition of several other sources[1] such as company-reported volumes, websites, and news articles. The locations and the volumes were then used to represent the customer demands in a bottom-up approach.

Cell producers also produce cell scrap, which is why the locations were also used to represent additional supply nodes in the optimization (in addition to the collector nodes). The cell scrap estimate was based on literature values (Circular Energy Storage, 2022) and a very rough estimate was set to 10 percent the annual production capacity of the cell producer.

Recyclers data

Other recycling actors were only part of the mapping and were not considered in the optimization part. The data came from a combination of CES and from various company reported volumes, websites, and news articles[1].

[1] (Battery-News, 2023), (Freyr, u.d.), (Verkor, 2022), (Northvolt, 2022), (Batteries News, 2021), (electrive, 2020), (electrive, 2022), (INSIDEEVS, 2022), (Batteries News, 2023), (Argus, 2019), (Italvolt, 2023), (electrive, 2020), (DSD, 2023), (Freyr, 2023), (CNEVPost, 2022), (Ramey, 2022), (Mihalascu, Volkswagen Delays Decision On Eastern Europe Battery Gigafactory, 2022), (Reuters, 2021), (Davies, 2022), (Britishvolt, 2023), (ACC, 2023), (Customcells, 2021), (Svolt-EU, 2023), (Flaherty, 2020), (Kane, 2022), (hipa, 2019), (Battery Industry, 2022), (Energy Watch, 2021), (equinor, 2020), (Randall, CALB to build battery plant in Europe, 2022), (Randall, InoBat to build battery factory in Serbia, 2022), (BASQUEVOLT, 2023), (Northvolt, 2022), (Mihalascu, VW Breaks Ground On First Cell Plant, Shows Prismatic Unified Cell, 2022), (Manthey, 2022), (CES, 2022), (Glencore, 2022), (Morrow, 2023), (Italvolt, 2021), (Altilium Metals, 2023), (Benitez, 2022), (Veolia, 2022), (Battery News, 2023), (Aurubis, 2022), (Fortum, 2023), (CES Online, 2023), (Northvolt, 2022), (Fortum, 2021), (Mete, 2022), (Veolia, 2021), (Ecobat, 2023), (Gigamine, 2022), (Volkswagen Group, 2019), (SungEel HiTech, 2023), (RSBruce, 2023), (Reconi, 2023), (librec, 2023), (endesa, 2021), (ecobat, 2023), (electrive, 2023), (Velázquez-Martínez, Valio, Sanasalo-Aarnio, Reuter, & Serna-Guerrero, 2019), (Decena, 2021)

Fixed costs & facility CO_2 emissions data and modelling

Fixed costs are costs representative of all expenses for a facility. The costs were created from a combination of a facility's CAPEX, OPEX. A carbon tax was also added based on the facility's CO_2-emissions from energy usage.

The fixed costs were broken down by technology: 2 current technologies (HCl-NMC & H_2SO_4-NMC) and 2 novel technologies (H_2SO_4 & MSA). The accumulated fixed costs from constructing a facility in 2023 were also calculated for the years 2023, 2026, 2030, and 2034. However, in the optimization only the 2030 scenario is analyzed.

Fixed cost price will likely vary by the region where the facility is located. Since Europe is a large and varied region for an optimization problem, there was merit to including some regional variability for the fixed costs in the optimization model. In a best-case-scenario, the fixed cost value would have been approximated for each country, based on differences in wages, electricity costs, waste management expenses, and so on. However, a simplification was done due to the limited size of the project. Three countries were chosen to be representative countries for which the fixed costs were calculated based on national data. All other countries were grouped into one of these three "country-categories" based on a more-or-less arbitrary scoring system: countries were scored based on GDP per capita and electricity mix carbon intensity. Figure 12 and Table 4 show the regions and how each case used different values as fixed costs.

In a similar manner to the fixed costs, the CO_2-emission for each facility was calculated based on the emissions from the electricity mix in the region where the facility was located. The same simplification was done with Germany, Sweden, and Italy as representative nations to which each other country was grouped.

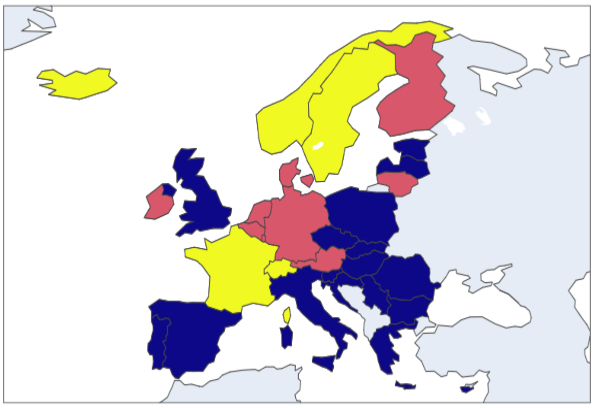

Figure 12 Country categories based on GDP per capita and carbon intensity. Countries received scores for GDP per capita (low score = low GDP per capita), and electricity mix carbon intensity (low score = high carbon

intensity). Blue countries (Italy-based) = lowest scores, red countries (Germany-based) = medium, yellow countries (Sweden-based) = high. Table 4 provides the values used in the modelling.

Table 4 Country-category assumptions for EU countries for 2030

Country Category	Technology	Annual fixed cost [Euro]	Carbon tax [Euro]	CO_2-emissions [ton CO_2]
Germany	H2SO4 – Novel1	1,074,944,304	5,892,235	157,977
Germany	MSA – Novel2	2,661,839,260	19,992,275	536,013
Germany	HCl-NMC – Current1	1,230,878,461	1,184,925	31,769
Germany	H2SO4-NMC – Current2	1,826,120,647	820,696	22,004
Sweden	H2SO4 – Novel1	1,045,262,727	516,723	3,537
Sweden	MSA – Novel2	2,722,600,230	1,753,234	12,000
Sweden	HCl-NMC – Current1	1,284,435,079	103,913	711
Sweden	H2SO4-NMC – Current2	1,797,827,510	71,971	493
Italy	H2SO4 – Novel1	1,063,109,261	9,447,200	97,065
Italy	MSA – Novel2	2,875,294,903	32,054,226	329,341
Italy	HCl-NMC – Current1	1,329,111,251	1,899,826	19,520
Italy	H2SO4-NMC – Current2	1,819,196,181	1,315,847	13,520

Transportation costs and CO2-emissions of transportation data

For the transportation costs used in the optimization, the values between two nodes were determined by the product of the transportation distance, the weight of the cells being transported, and the transportation rate (Euro per ton-km or tons of CO_2 per ton-km). For the monetary costs, a low and a high estimate were used. The low estimate is closer to what the costs would be of transporting generic goods in Europe. The high estimate was calculated to about 40% of the total cost (fixed + transport costs) based on literature estimates on transporting lithium-ion batteries. The extra costs are associated with infrastructure and services connected to safety and health considerations of transporting cells which may e.g. catch fire or explode if not handled with care. For the transportation CO2-emissions, the same values were used which are an average of European transports in 2022. Table 5 shows the input parameters to the model.

Table 5: Transportation costs and emission values

Transportation Rate	Value	Unit

Transport cost (low estimate)[2]	6.4762E-2	Euro / ton-km
Transport cost (high estimate)[3]	7.7146	Euro / ton-km
Transport emissions[4]	5.5E-5	tons CO_2 / ton-km

Data modelling for mapping and optimization

All the modeling (except for a few bar graphs in Excel) was done using the Python programming language in Jupyter Notebooks using several packages. Visualizations include the GIS (Geographic Information System) visualizations, the optimizations, and the Sankey charts. Figure 13 shows an overview of how Excel and Python is used to build local data pipelines, build the models, perform the optimizations, and visualize the results.

[2] (Della, 2023)
[3] (Slattery, Dunn, & Kendall, 2021)
[4] (Suzan, 2021)

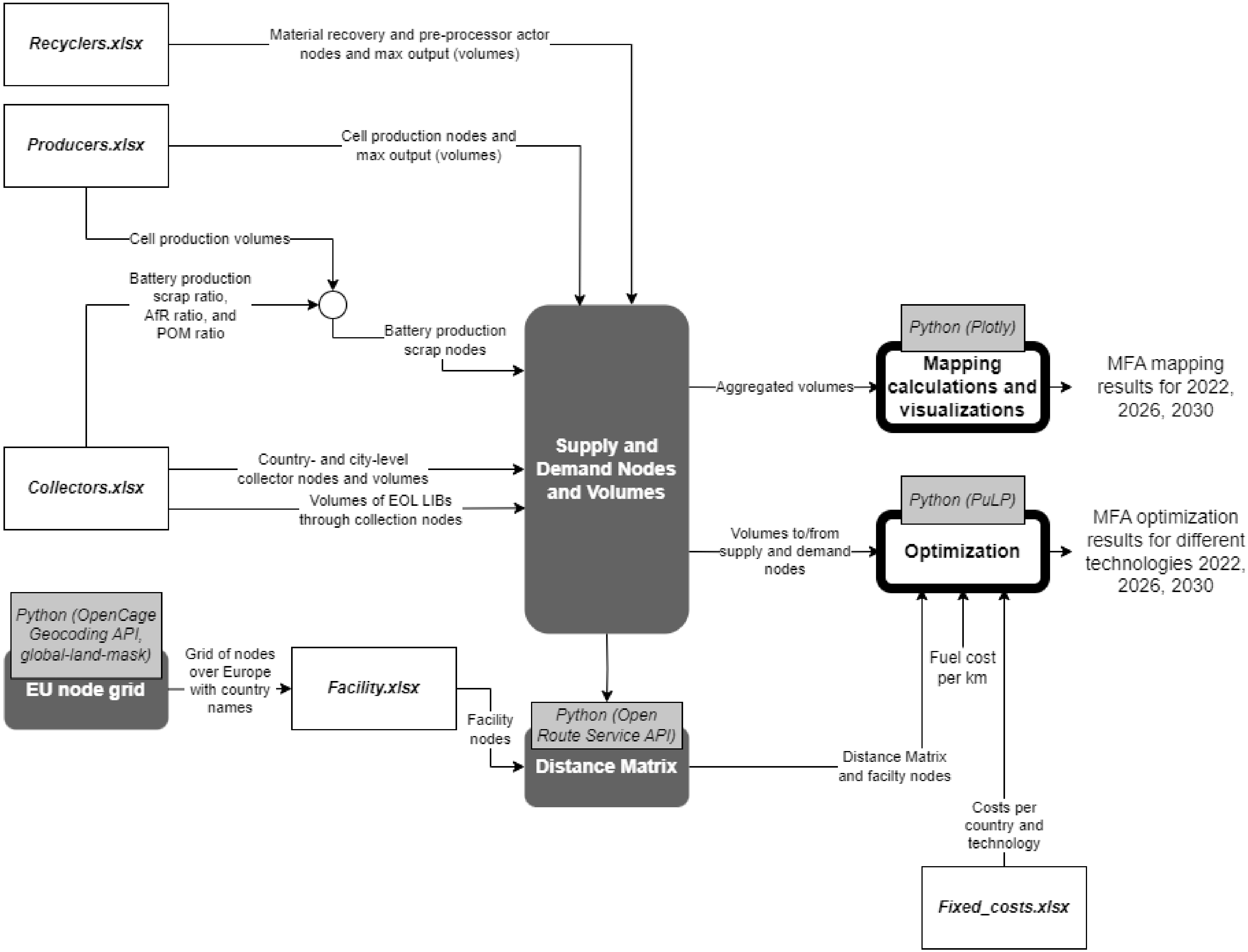

Figure 13 Data flow from .xlsx files (to the left side and bottom) to the results (on the right side). Python packages used (other than NumPy/Pandas) and APIs (Application Programming Interfaces) are shown in the light-gray boxes that sit on top of other boxes.

Supply and Demand Nodes and Volumes

In Python, the data from several data sources was combined in a data pipeline. From this data the optimization model obtained the values for the different optimizations it performed. Table 6shows what goes into the Supply and Demand nodes. Figure 2 shows a conceptual diagram of how the selection of different combinations of nodes happen in the optimization model.

Table 6 EOL EU LIB flows and the optimization parameters they be used in. Collected EOL LIBs/BM = the CES AfR weight for that year.

Flow	How much of the flow represents the supply/demand flow from the actor	Node class
Pre-processors	100% of annual capacity	Supply node
Collectors	100% of annual capacity	Supply node
Producers	10% of annual capacity	Supply node
Producers	100% of annual capacity	Demand node

GIS visualizations and Sankey Charts

Mapping the flows was effectively done with GIS and Sankey Charts. For the mapping, the coordinates, type of flow, and the volumes of those flows were fed to scatter plots API on Mapbox maps in the Plotly visualization library. Registering an account grants access to some cleaner-looking maps through an access token. Sankey charts were created using the Plotly Python package (Plotly Technologies Inc., 2015).

Facility Grid and Distance Matrix

To calculate distances between nodes, a grid was created to cover all the countries modelled from which distances to all the Supply and Demand nodes could be calculated. After placing a square grid over the area of interest, the global land mask API was used to remove candidate nodes that were under water. Thereafter the OpenCage Geocoding API (OpenCage, 2023) was used to match the coordinate to a country. With the country information the fixed cost of the node could be determined.

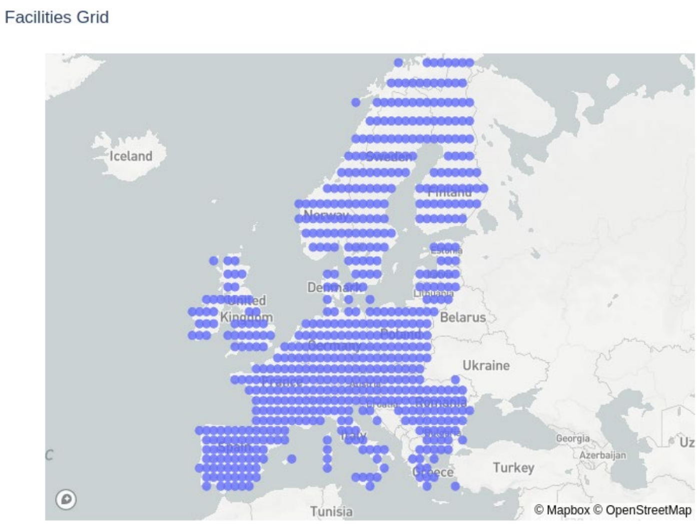

Figure 14 A grid of nodes over the chosen countries in Europe. All nodes are candidate locations for the facility location optimization.

After the candidate locations had been determined, the Openrouteservice API (Openrouteservice, 2023) was used to create a distance matrix[5], which is essentially a dictionary with all the combinations of distances between the candidate facility locations and the Supplier/Demand nodes. The distances could then be multiplied by the tonnage and the rate (Euro or CO_2-emission) per ton-km to determine the transportation costs (Euro or CO_2-emission) needed for the optimization.

[5] More specifically, the dataframes from facilities/suppliers/customers were first split into chunks to handle the Openrouteservice maximum limits. Thereafter through iterations, each chunk was fed to the API and the output was aggregated into a dictionary which was consequently converted to a dataframe (i.e., a data table).

Background on the optimization methodology

The optimization of facility locations in a geographically complex region like Europe made the transport distance more important than with a more homogenous region. The variations of landmass and water regions make it more important to use "real" mapped distances rather than a simplified approach like geometric averages.

After the model for the optimization problem was developed, it needed to be solved. The PuLP package for solving Linear Programming problems was used as an interface to the standard open-source PuLP solver CBC (Coin-or branch and cut) (COIN-OR, 2023).

The facility fixed costs, the supply-node Supply volumes of EOL LIBs, and the customer-node Demand volumes are also input data that would be considered in the optimization model. The facility location problem with linear programming was thus used to optimize the reverse logistics network.

The optimization model will follow the general problem structure of a capacitated facility location optimization. Additionally, the model will:

- calculate the best location for a specified number of facilities,
- use actual mapped distances travelled on road,
- use linear programming as the mathematical modelling technique.

The location problem is meant to minimize the total cost of placing a material processing plant in Europe. Since the plant require both transportation from a collection point to the facility and transportation from the facility to a buyer, both routes must be included in the objective function.

Problem Statement for optimization

The objective for the optimization is to model the reverse logistics problem such that the total cost of the system can be minimized through the geographical placements of the material recovery plants (facilities). The "cost" can be in this case be either the monetary cost or the CO_2-emissions produced. The same model can be used to optimize both by simply changing the parameter values to either Euro-cost or tons-CO_2 emitted.

To estimate the additional costs for building more facilities in the network with the same total capacity, the square root law of operations management (Wilson Peruman & Company, 2020) is utilized. For the simple case of doubling the facilities in the network, the total cost becomes the product of the original total cost and $\sqrt{2}$. Using this expression, a generalized solution for the cost of each facility is created:

$$FC_{n\_facilities} = \frac{\sqrt{n}}{n} FC_{original} \tag{3}$$

Where $FC_{original}$ is the cost of one facility with the capacity of the 98,667 tons used to calculate the fixed cost in the technoeconomic assessment and $FC_{n\_facilities}$ is the fixed cost per facility with n representing the total number of facilities. An optimal network and total cost are calculated for different values of the number (and resulting fixed cost) and the absolute lowest cost is considered the absolute minimum for the problem. Next, the objective function and constraints to find the optimal network and total costs of n facilities are shown.

Objective Function for Supply-to-Facility-to-Demand (S2F2D) for optimization

$$Minimize\left(\sum_{i=1}^{S}\sum_{j=1}^{F} t_{S2F,ij}x_{ij} + \sum_{j=1}^{F} f_j y_j + \sum_{j=1}^{F}\sum_{k=1}^{D} t_{F2D,jk}z_{jk}\right) \tag{4}$$

where:

- *S*, *F*, and *D* are the sets of suppliers, facilities, and customers, respectively.
- *i*, *j*, and *k* represent single suppliers, facilities, and customers, respectively.
- t_{S2F} and t_{F2D} are transport costs [€ per ton-km or tons CO_2 per ton-km] for the supplier-to-facility route, and the facility-to-customer route, respectively.
- x_{ij} and z_{jk} are continuous variables that can take any value over and including 0. They represent the cell-weight equivalents volumes [tons] of goods from supplier-to-facility (supplier *i*, facility *j*) and the facility-to-customer (facility *j*, customer *k*), respectively.
- f_j is the cell-weight equivalents capacity [tons] of the facility *j.*
- y_j is a binary variable which is 0 if the facility is inactive or 1 if the facility is active.

Constraints for S2F2D for optimization

$$\sum_{j=1}^{F} y_j = number\_of\_facilities \qquad \forall i \in Supply \tag{5}$$

(5) fixes the number of facilities that are active to an integer value greater than 0.

$$\sum_{j=1}^{F}(x_{i,j}) \leq supplier\_supply_i \qquad \forall i \in Supplier \qquad \textbf{(6)}$$

$$\sum_{j=1}^{F}(z_{j,k}) \leq customer\_demand_k \qquad \forall k \in Customer \qquad \textbf{(7)}$$

(6) and (7) state that only supply and demand routes to facilities that are active (where the continuous variables are more than 0) allow goods to pass through. They also set the higher of the limit the goods that can pass through supply and demand routes.

$$x_{i,j} \leq facility\_capacity_i * y_j \qquad \forall i \in Supplier, \forall j \in Facility \qquad \textbf{(8)}$$

$$z_{j,k} \leq facility\_capacity_i * y_j \qquad \forall k \in Customer, \forall j \in Facility \qquad \textbf{(9)}$$

(8) and (9) state that goods from/to suppliers/customers are only passed to/from facilities if the facilities are open.

$$\sum_{i=1}^{S} x_i = facility\_capacity_i * y_j \qquad \textbf{(10)}$$

$$\forall j \in Facility$$

$$\sum_{k=1}^{C} z_k = facility\_capacity_i * y_j \qquad \textbf{(11)}$$

(10) and (11) state that the sum of the flows from and to each facility is equal to its capacity, and these equations also imply the conservation of flows from suppliers to customers.

Scenarios for optimization

Each of the four technologies (two current and two novel) will undergo the same methodology for optimization outlined above for 2030. Additionally, a sensitivity analysis is performed on the transportation costs by choosing an average cost for transporting goods and a much higher cost (about 60% of the fixed cost) that is more in line with current research for lithium-ion batteries (Slattery, Dunn, & Kendall, 2021).

Appendix D: Additional Data and Visualizations of European LIB Actors and Volumes

Code

The project code is long and is has been uploaded to a public repository: github.com/erikemilsson/ELiMINATE_EU_MFA

Actors and volumes

Table 7 to Table 9 show volumes in tons of cell equivalents for several actors. References for the data is a collection of several websites, news sites, and Circular Energy Storage.[1]

Table 7: EOL LIB volumes attributed to collectors, their coordinates, and tons of collected EOL LIBs in cell-weight equivalents.

Country	City	Latitude	Longitude	Year_2022	Year_2026	Year_2030
Austria	Vienna	48.21219552	16.37659903	630	1050	2020
Belgium	Antwerp	51.21218312	4.408770295	815	1358	2613
Bulgaria	Sofia	42.6966725	23.33497505	495	825	1587
Croatia	Zagreb	45.79497465	15.97996172	289	481	925
Cyprus	Nicosia	35.1667	33.3667	85	142	273
Czech Republic	Prague	50.0756649	14.43016804	757	1261	2428
Denmark	Copenhagen	55.67110276	12.577485	413	688	1324
Estonia	Tallinn	59.42419703	24.7861544	94	157	303
Finland	Helsinki	60.22303213	24.9085641	392	653	1256
France	Paris	48.79637185	2.344447532	2790	4650	8949
France	Marseille	43.34048347	5.376756833	1967	3278	6309
Germany	Berlin	52.46975637	13.38552309	1607	2679	5155
Germany	Cologne	50.94073707	6.938699112	434	723	1391
Germany	Düsseldorf	51.21517785	6.801462963	253	421	810
Germany	Munich	48.14076689	11.53464567	657	1094	2106
Germany	Frankfurt am Main	50.11494995	8.670901159	295	491	946
Germany	Stuttgart	48.80947666	9.184137439	262	436	839
Germany	Leipzig	51.34408823	12.37026562	228	380	732
Germany	Dortmund	51.49898287	7.46906929	248	413	795
Germany	Essen	51.45491743	7.043338947	245	408	784
Germany	Hanover	52.34593854	9.718802419	224	374	719
Germany	Nuremberg	49.42806214	11.06311724	218	363	698

Germany	Dresden	51.00800362	13.72864468	226	377	725
Germany	Hamburg	53.54925606	9.900617565	768	1281	2465
Germany	Bremen	53.11652119	8.81227831	234	389	749
Greece	Athens	38.04116109	23.80382439	760	1267	2438
Hungary	Budapest	47.46622623	19.01613305	693	1155	2223
Iceland	Reykjavik	64.1472	-21.9424	26	43	82
Ireland	Dublin	53.3441	-6.2675	355	592	1139
Italy	Rome	41.95803158	12.57990682	2097	3494	6724
Italy	Milan	45.51601106	9.120360751	683	1138	2190
Italy	Naples	40.84840002	14.31399795	472	786	1513
Italy	Turin	44.97099232	7.702444574	413	689	1326
Italy	Palermo	38.09367447	13.33917937	330	550	1058
Italy	Genoa	44.43275263	8.96068049	283	472	908
Latvia	Riga	56.84630921	24.39618709	136	226	435
Liechtenstein	Vaduz	47.15543221	9.510356931	3	4	9
Lithuania	Vilnius	54.66879513	25.2375731	198	329	634
Luxembourg	Luxembourg	49.81903764	6.09836397	46	76	147
Malta	Valletta	35.8983	14.5126	36	59	114
Netherlands	Amsterdam	52.33869339	4.842158161	530	883	1698
Netherlands	Rotterdam	51.95075027	4.52945701	380	633	1218
Netherlands	The Hague	52.06228993	4.375340573	320	534	1027
Norway	Oslo	59.90202837	10.78129293	379	632	1217
Poland	Warsaw	52.13880564	20.9892915	1091	1819	3500
Poland	Krakow	50.08629452	19.95495591	487	811	1561
Poland	Łódź	51.72682801	19.44777737	404	673	1294
Poland	Wrocław	51.16567709	17.02806393	391	651	1253
Poland	Poznań	52.35058217	16.76019218	322	536	1032
Portugal	Lisbon	38.72320526	-9.175560443	729	1214	2336
Romania	Bucharest	44.42885094	26.10398193	1373	2289	4404
Serbia	Belgrade	44.79776245	20.45058388	493	821	1580
Slovakia	Bratislava	48.13098303	17.13001534	387	645	1241
Slovenia	Ljublana	46.01379786	14.55725331	148	247	475
Spain	Madrid	40.39491229	-3.70466513	1597	2661	5121
Spain	Barcelona	41.44963044	2.198489964	791	1319	2538
Spain	Seville	37.37172976	-6.015618352	338	563	1084
Spain	Zaragoza	41.6799069	-0.877591625	333	556	1070
Spain	Málaga	36.71306733	-4.457762135	280	467	899
Sweden	Stockholm	59.30190765	18.02080784	456	760	1462
Sweden	Gothenburg	57.69772574	11.99554222	274	456	878

Switzerland	Zürich	47.41204621	8.574376947	608	1014	1951
United Kingdom	London	51.5002	-0.1262	3647	6079	11698
United Kingdom	Birmingham	52.4829	-1.8935	435	725	1396
United Kingdom	Manchester	53.4807	-2.2344	224	373	717
United Kingdom	Leeds	53.7997	-1.5492	209	349	671
United Kingdom	Sheffield	53.3836	-1.4669	226	376	724

Table 8: Cell producers capacities, their coordinates, and tons of produced EOL LIBs in cell-weight equivalents.

Name	Country	Latitude	Longitude	Year_2022	Year_2026	Year_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

Table 9: European battery recyclers, their coordinates, and tons of processed EOL LIBs in cell-weight equivalents.

Name	Type	Latitude	Longitude	Year_2022	Year_2026	Year_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

There were several battery projects with insufficient information available that could thus not be included in the data for the mapping and optimizations. Table 10 includes all of them from the search.

Table 10 Battery projects either not included in the mapping and optimization, or where educated guesses have been done to approximate the production volumes. See the Producers.xlsx for more specific details on the volumes used in the modelling.

Name	Country	City	Notes
Avesta Battery and Energy Engineering	Belgium	Seneffe-Manage	202X 3GWh
Magna Energy Storage MES	Czech Republic	Horní Suchá	20XX 15GWh
BlueSolutions	France	Quimper	1.5GWh 20XX
Customcells	Germany	Itzehoe	40GWh + 3.5GWh 20XX
Tesla Gigafactory Berlin-Brandenburg	Germany	Brandenburg	20XX but I marked 2026 as it should have a considerate impact on the model
SVOLT	Germany	Lauchhammer	202X 16GWh
Farasis	Germany	Bitterfeld-Wolfen	DELAYED 16GWh
VARTA	Germany	Ellwangen	ON PAUSE 20XX 3GWh
EAS	Germany	Nordhausen	202X 0.5GWh
Samsung	Hungary		TBD X GWh
GS Yuasa Hungary	Hungary		Assembles LIBs but is also considering manufacturing lithium-ion cells at the plant in the future.
EVE	Hungary		202X XGWh
ACC	Italy	Termoli	202X 40GWh, guessing 2026 because it has large impact
Anodox	Latvia	Riga	202X XGWh
Eurocell	Netherlands	Amsterdam	City tba, but guess is Amsterdam.
Elinor Batteries	Norway	Trondheim	X GWh
Panasonic, Equinor, Norsk Hydro	Norway		CANCELLED
Volkswagen	tba		202X 7.6GWh
BYD	tba		By 2030, the Volkswagen Group intends to operate six cell factories with a total volume of 240 GWh throughout Europe together with partners.
Inobat	tba		
PowerCo	tba		202X X GWh
Prologium	tba		X GWh
Tata Motors	tba		120 GWh
AMTE Power	United Kingdom	Dundee	10GWh + X

Britishvolt	United Kingdom	Northumberland	CANCELLED
Nanotech Energy	United Kingdom		X GWh

There were several maps that were not included in the main report to condense it. Below are the maps for 2022, 2026, and 2030 for the tons of cell-weight equivalent flows of materials from different sources:

- Figure 15 to Figure 17: Material Recovery actors and volumes
- Figure 18 to Figure 20: Pre-processors
- Figure 21 to Figure 23: Collectors
- Figure 24 to Figure 26: Producers

Figure 15: Material recovery nodes and processing volumes for 2022

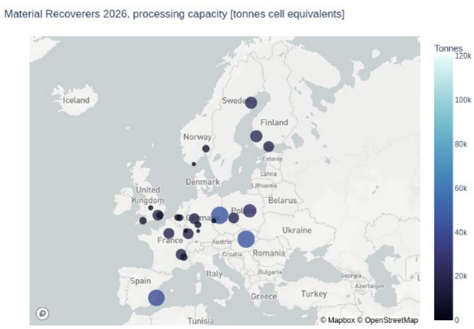

Figure 16: Material recovery nodes and processing volumes for 2026

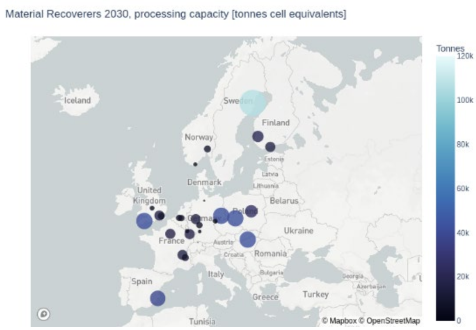

Figure 17: Material recovery nodes and processing volumes for 2030

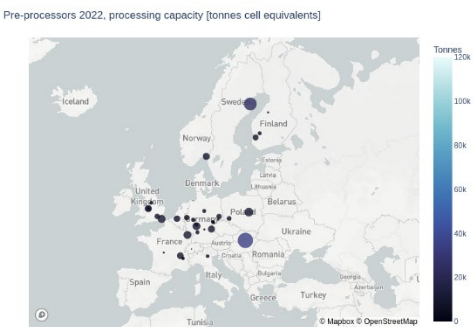

Figure 18: Pre-processor nodes and processing volumes for 2022

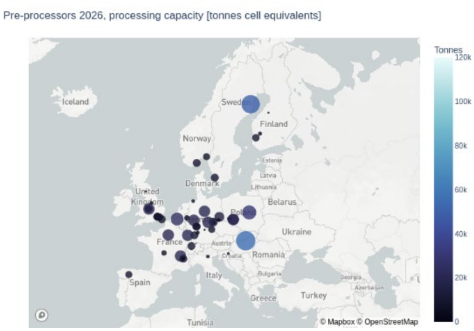

Figure 19: Pre-processor nodes and processing volumes for 2026

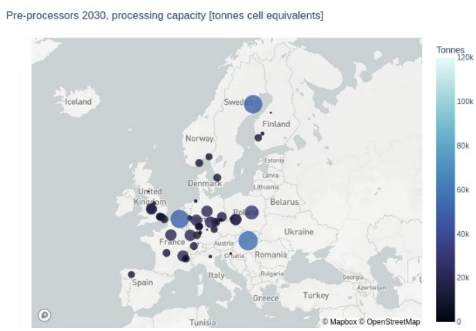

Figure 20: Pre-processor nodes and processing volumes for 2030

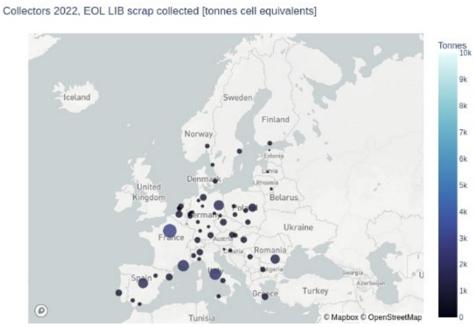

Figure 21: Collector nodes and collection volumes for 2022

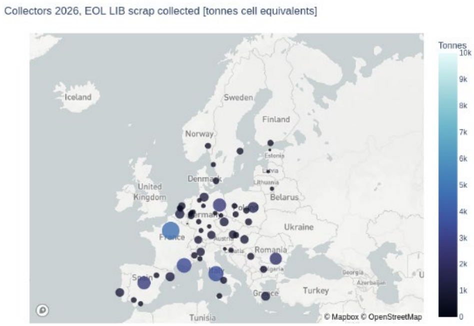

Figure 22: Collector nodes and collection volumes for 2026

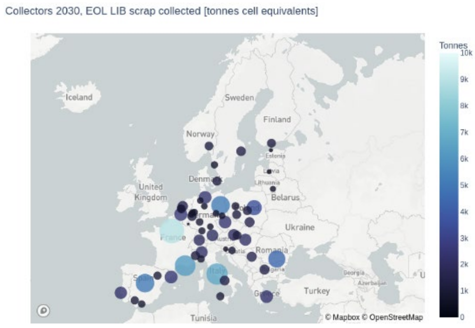

Figure 23: Collector nodes and collection volumes for 2030

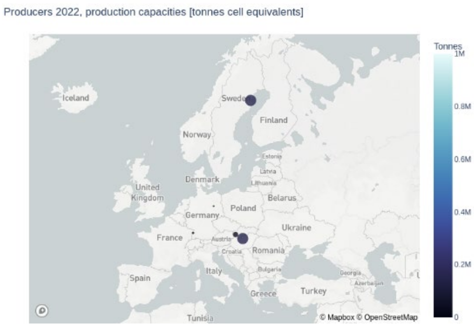

Figure 24: Producer nodes and production volumes for 2022

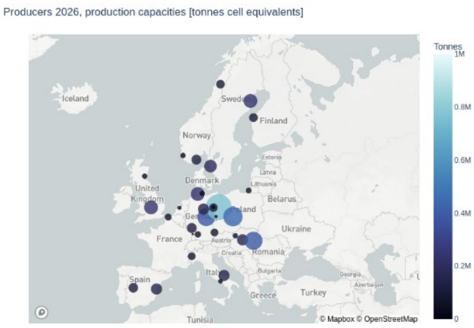

Figure 25: Producer nodes and production volumes for 2026

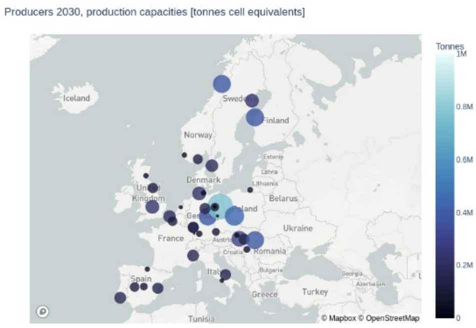

Figure 26: Producer nodes and production volumes for 2030

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