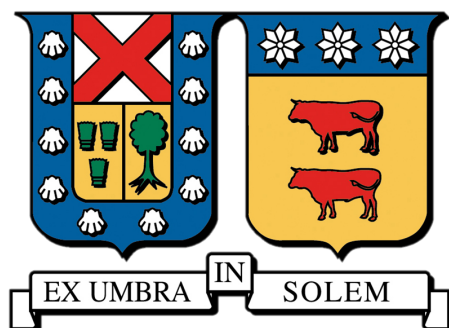




UNIVERSIDAD TÉCNICA FEDERICO SANTA MARÍA
INDUSTRIES DEPARTMENT

**COMPREHENSIVE FEASIBILITY STUDY FOR THE
IMPLEMENTATION OF A LITHIUM-ION BATTERY RECYCLING
PLANT IN CHILE**

THESIS TO OBTAIN THE DEGREE OF INDUSTRIAL ENGINEER

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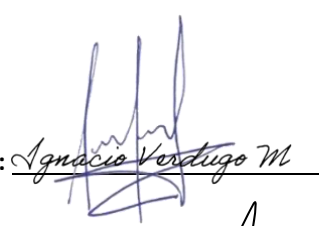
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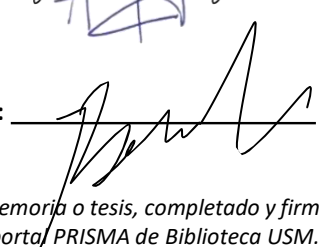
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1 Investigation Problem

From the beginning of the first industrial revolution, the use of fossil fuels has produced the emission of large quantities of pollutants, causing the greenhouse effect and climate change, which has been a great challenge for humanity [1].

Electrification of transportation is one of the most effective strategies to reduce pollutant emissions. Unlike fossil fuels, which irreversibly disappear from vehicles' tanks while leaving behind pollution, lithium batteries contain valuable materials that can be recovered and reused, creating a circular cycle of utilization [9].

In 2018, there were approximately 5.1 million electric vehicles (EVs) operating around the world, a number that has increased exponentially in the last decade [4]. It is estimated that sales of these vehicles will be 245 million dollars by 2030 based on current and expected policies, which corresponds to a 41% annual increase in sales [5].

The global market for these batteries reached nearly 250 GWh in 2020 and is projected to increase tenfold by 2030 [8]. This kind of growth, combined with Chile's significant lithium reserves, presents a strategic opportunity to develop a recycling industry that could establish the country as a leader in the zone in the circular economy of critical minerals.

A key feature of lithium-ion batteries is their high circularity potential. When recycled, approximately 95% of their components can be recovered for alternative uses or transformed into new batteries [8]. This characteristic not only reduces environmental impact but also represents significant economic opportunities.

Chile holds a privileged position in the global lithium market, concentrating substantial reserves of this strategic mineral [11]. This natural advantage provides an exceptional starting point

for developing a recycling industry that complements primary extraction, creating an integrated resource utilization model.

Currently, lithium-ion battery recycling is not conducted in Chile; discarded batteries are handed over to waste management companies and subsequently deposited in concrete landfills [12]. This situation represents both a challenge and an opportunity to develop technical and business capabilities within the country.

Lithium-ion battery manufacturing involves substantial operational costs that vary from 20 to 50 million dollars yearly depending on location, production scale, and technology used [10]. Understanding this cost structure is essential for evaluating the economic feasibility of recycling.

Lithium prices have risen by 400% in recent years due to increased demand from the EV sector [10]. This highlights how battery recycling offers a strategic advantage by recovering components like copper, graphite, and lithium salts [12]. This creates economic circularity by reintroducing materials into production, reducing raw material costs, creating business opportunities, and decreasing dependence on both volatile markets and primary resource extraction.

To capitalize on this opportunity, it is essential to develop technical capabilities, establish appropriate regulatory frameworks, and promote applied research efforts. The proposed study's detailed analysis of recycling methods, production costs, and market projections will provide valuable insights for strategic decision-making in this field.

2 Objectives

2.1 General Objective

- Determine the feasibility to implement a lithium-ion battery recycling plant in Chile.

2.2 Specific Objectives

1. Conduct a PESTLE analysis for contextual understanding.
2. Establish potential facility locations that meet technical and operational requirements to determine the optimal battery recycling plant location.
3. Develop an integrated estimation model for EV battery lifecycle projections incorporating sales volumes, end-of-life quantities, and chemistry-specific mass distributions for accurate forecasting of recycling facility capacity requirements applied to Chilean markets.
4. Identify technical equipment requirements and flow charts for recycling alternatives.
5. Recognize the best recycling alternative considering economic and environmental benefits on the whole, with feedstock adaptability.
6. Conduct an economic analysis of battery recycling operations examining critical material recovery plant investments, stage-specific operational costs, and per-kilowatt-hour metrics for optimizing investment decisions.
7. Develop a risk assessment model incorporating sensitivity analysis and Monte Carlo simulations for uncertainty quantification in battery recycling processes.



8. Compare environmental impacts between the production of batteries with recovered and virgin materials to assess significant changes in emissions and energy use.

3 Scope

- This study focuses on cathode recycling from end-of-life lithium-ion batteries. The emphasis is placed specifically on the recovery processes and technologies for cathode materials. The analysis concentrates on the economical impacts to address an effective cathode material recovery.
- The research is exclusively focused on the Chilean context. The study examines the feasibility and implementation of cathode recycling within Chile's specific market conditions, existing infrastructure, and regulatory framework. All analyses, projections, and recommendations are tailored to the Chilean operating environment.
- The study considers only Battery Electric Vehicles (BEV) and Hybrid Electric Vehicles (HEV) for battery recycling analysis, excluding other types of electric vehicles such as PHEVs, MHEVs, EREVs, and FCEVs. This focused approach allows for a more precise analysis of the two main electric vehicle categories that represent the majority of the recyclable lithium-ion battery market in Chile.
- The evaluation horizon extends to 2045, allowing for a comprehensive long-term analysis of market development, technological evolution, and infrastructure requirements for cathode recycling operations in Chile.
- The scope is limited to lithium-ion batteries (LIBs) specifically from electric vehicles, excluding other applications such as consumer electronics or stationary energy storage systems.

4 Glossary

- **Anode:** An electrode through which the conventional current enters into a polarized electrical device.
- **Capacity:** The total amount of electrical charge that a battery can store, typically measured in ampere-hours (Ah) or milliampere-hours (mAh).
- **CAPEX:** Capital expenditure - the funds used by a company to acquire, upgrade, and maintain physical assets such as property, industrial buildings, or equipment.
- **Cathode:** An electrode through which conventional current leaves an electrical device.
- **Electric Vehicle (EV):** Vehicle that uses one or more electric motors for propulsion.
- **Energy density:** Amount of energy that a battery can store relative to its mass. Measured in Wh/kg.
- **EOL:** End of Life - refers to the point when a battery or system reaches the end of its useful operational life, typically when capacity drops below 80% of original capacity for EV batteries.
- **EVB:** Electric Vehicle Batteries - specialized battery systems designed for electric vehicle applications, typically lithium-ion based with high energy and power density requirements.
- **ICE:** Internal Combustion Engine - a heat engine in which the combustion of a fuel occurs with an oxidizer in a combustion chamber that is an integral part of the working fluid flow circuit.

- **Leaching:** Is a process widely used in extractive metallurgy where ore is treated with chemicals to convert the valuable metals within into soluble salts while the impurity remains insoluble.
- **LFP:** Lithium Iron Phosphate ($LiFePO_4$) - a type of lithium-ion battery cathode material known for its safety, thermal stability, and long cycle life.
- **LIB:** Lithium-Ion Battery - a type of rechargeable battery in which lithium ions move from the negative electrode through an electrolyte to the positive electrode during discharge, and back when charging.
- **NCA:** Nickel Cobalt Aluminum oxide ($LiNiCoAlO_2$) - a cathode material for lithium-ion batteries offering high energy density but with thermal stability concerns.
- **NMC:** Nickel Manganese Cobalt oxide ($LiNiMnCoO_2$) - a popular cathode material for lithium-ion batteries that balances energy density, power capability, and safety.
- **OPEX:** Operating expenditure - the ongoing costs for running a product, business, or system, including maintenance, utilities, and operational staff costs.
- **Outliers:** Data points that differ significantly from other observations in a dataset, potentially indicating measurement errors, exceptional conditions, or novel phenomena.
- **Overfitting:** A modeling error in machine learning where a model learns the training data too specifically, including noise and fluctuations, resulting in poor performance on new, unseen data.

- **POM:** Put On Market - refers to the act of introducing a product or technology to the commercial market for sale or distribution.
- **Power:** The rate at which energy is transferred or converted, measured in watts (W). In battery context, it refers to how quickly energy can be delivered or accepted.
- **Power density:** Amount of power it can generate relative to its mass. Measured in W/kg.
- **Relithiation:** The reincorporation of lithium into an electrode in a lithium-ion battery.
- **Slag:** Stony waste matter separated from metals during the smelting or refining of ore.
- **SOH:** State of Health - a measure of the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery, typically expressed as a percentage.

5 Theoretical Framework

Several frameworks have been developed to evaluate lithium-ion battery (LIB) recycling methods and its facilities. These frameworks provide structured approaches to assess the viability, impact, and sustainability of different recycling technologies and processes. This structured assessment perspective helps stakeholders make informed decisions about recycling investments while advancing the circular economy goals crucial for sustainable battery management.

- **Environmental:** evaluates impacts, assessing the ecological footprint of recycling processes.

These assessments typically measure air emissions, wastewater discharges, energy intensity, reagent consumption and secondary waste generation. Recent research demonstrates that converting mixed-stream LIBs into battery-grade materials through recycling reduces environmental impacts by at least 58% compared to conventional mining supply chains [73].

- **Technical-procesual:** evaluates recycling methods based on efficiency metrics and indicators such as recovery percentage, technical feasibility, specific conditions, and adaptability to local conditions. Three primary technical approaches dominate LIB recycling: hydrometallurgical, pyrometallurgical, and direct physical recycling processes [74].

- **Socio-economic:** examines broader societal impacts of recycling initiatives beyond direct financial returns. This framework helps to explain how recycling plants create employment opportunities and develop specialized skills in areas like robotics and chemical safety [72].

- **Circular economy:** emphasizes closed-loop systems where products and materials maintain their value through multiple life cycles. It prioritizes design considerations that facilitate end-of-life recovery and reintegration of materials can be use to examine how circular economy principles in EV battery recycling contribute to sustainable development goals [72].

- **Economic:** employs financial modeling to assess the viability projects. This framework centers on metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and payback periods to determine investment attractiveness. This model serves as a framework for recycling cost optimization in an international battery recycling economy, accounting for the entire recycling chain from battery collection through material recovery [75].

Using mainly a techno-economic approach provides a robust assessment methodology for evaluating the feasibility of a lithium-ion battery recycling plant in Chile. This integrated approach balances financial viability with technical performance.

Based on the technical framework, the assessment should evaluate which recycling technologies (hydrometallurgical, pyrometallurgical, or direct recycling) are most suitable for Chile's specific context. On the other hand, a comprehensive economic model should incorporate Chile-specific parameters including: transportation distances from collection points, local wages and operating costs, energy prices and sources, capital equipment costs, material recovery values in local markets and scale economies at different processing volumes.

Modeling should include sensitivity analyses for critical variables specific to Chile's market condition such as metal price volatility. These analyses should identify key economic thresholds that would trigger shifts in operational strategy or technology deployment.

It is also important to consider political and regulatory constraints. Chile's political landscape significantly impacts the viability of recycling operations through policies governing collection rates and end-of-life battery supply chain disposal.

5.1 Batteries

Batteries function as electrochemical devices that convert chemical energy into electrical energy through controlled redox reactions. At their core, batteries store energy in the form of chemical potential, similar to how other energy sources like fossil fuels store energy in chemical bonds [13]. This energy storage mechanism involves the transfer of electrons through an external circuit while ions move through an internal medium. The fundamental principle lies in the controlled conversion between chemical potential energy and electrical energy, allowing batteries to serve as portable energy sources [13].

In all batteries, the energy storage process requires the conversion of electrical energy into a chemical form that can be readily stored. This conversion is achieved through electrochemical reactions that occur at the interface between electronic conductors (electrodes) and ionic conductors (electrolytes). During discharge, the stored chemical energy is converted back to electrical energy that powers external devices. In rechargeable batteries, like lithium-ion, this process is reversible, allowing multiple charge-discharge cycles over the battery's lifetime [13].

5.2 Lithium-Ion Batteries

5.2.1 Basic Architecture

Consist of five essential components: positive electrode (cathode), negative electrode (anode), separator, electrolyte, and current collectors [3]. The positive and negative electrodes are where the electrochemical reactions occur, while the separator prevents direct contact between electrodes while allowing ion transport. The electrolyte facilitates ion movement between electrodes, and current collectors efficiently transfer electrons to and from the external circuit [3].

5.2.2 Charge and Discharge

When the battery is in a discharge state and providing electrical current, the anode releases lithium ions towards the cathode, generating an electron flow from one side to the other. When it is in a charging state, the opposite occurs, lithium ions are released by the cathode and received by the anode, generating an electron flow in opposite direction [14].

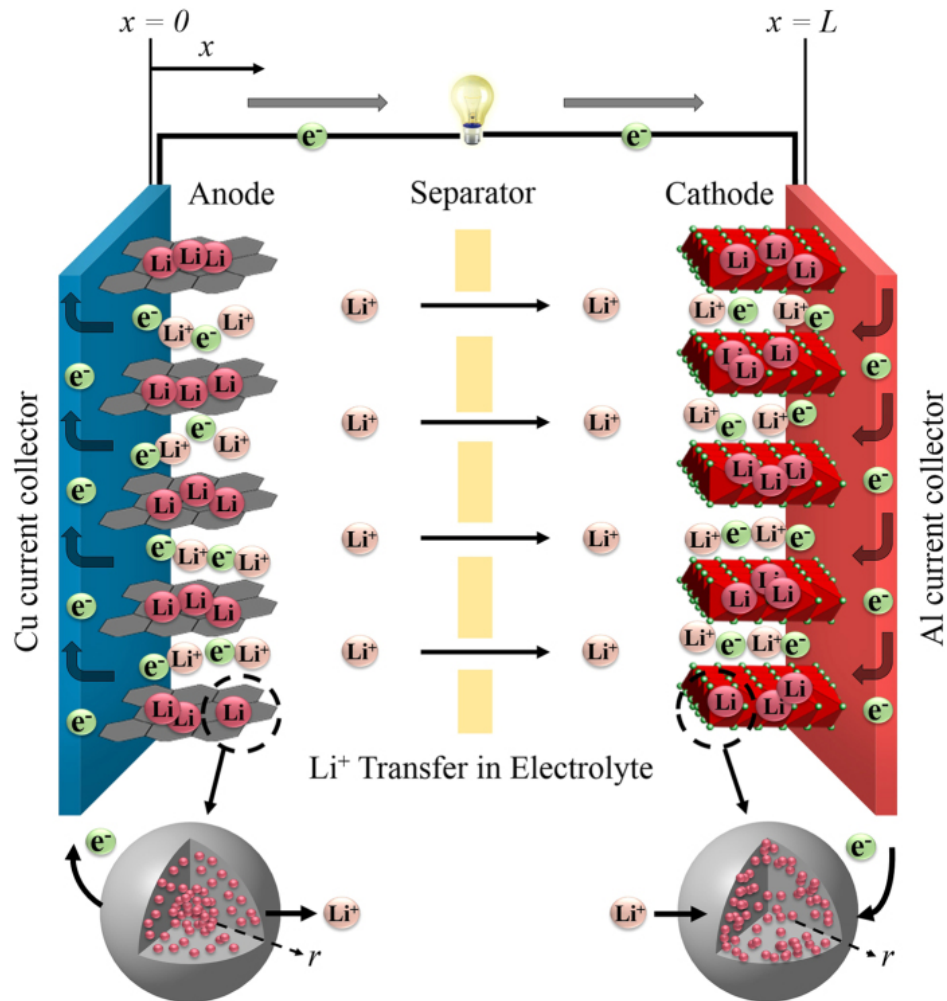


Figure 1: Involved Lithium-Ion Battery Components Schema (Discharge) [2].

5.2.3 Lithium Battery Demand: Current Trends and Future Projections

The demand for lithium batteries is increasing at an annual rate of 32%, with projections indicating a significant expansion across various sectors by 2030 [47]. This growth is driven by advancements in EV technology, the proliferation of renewable energy infrastructure, and the rising adoption of consumer electronics [47].

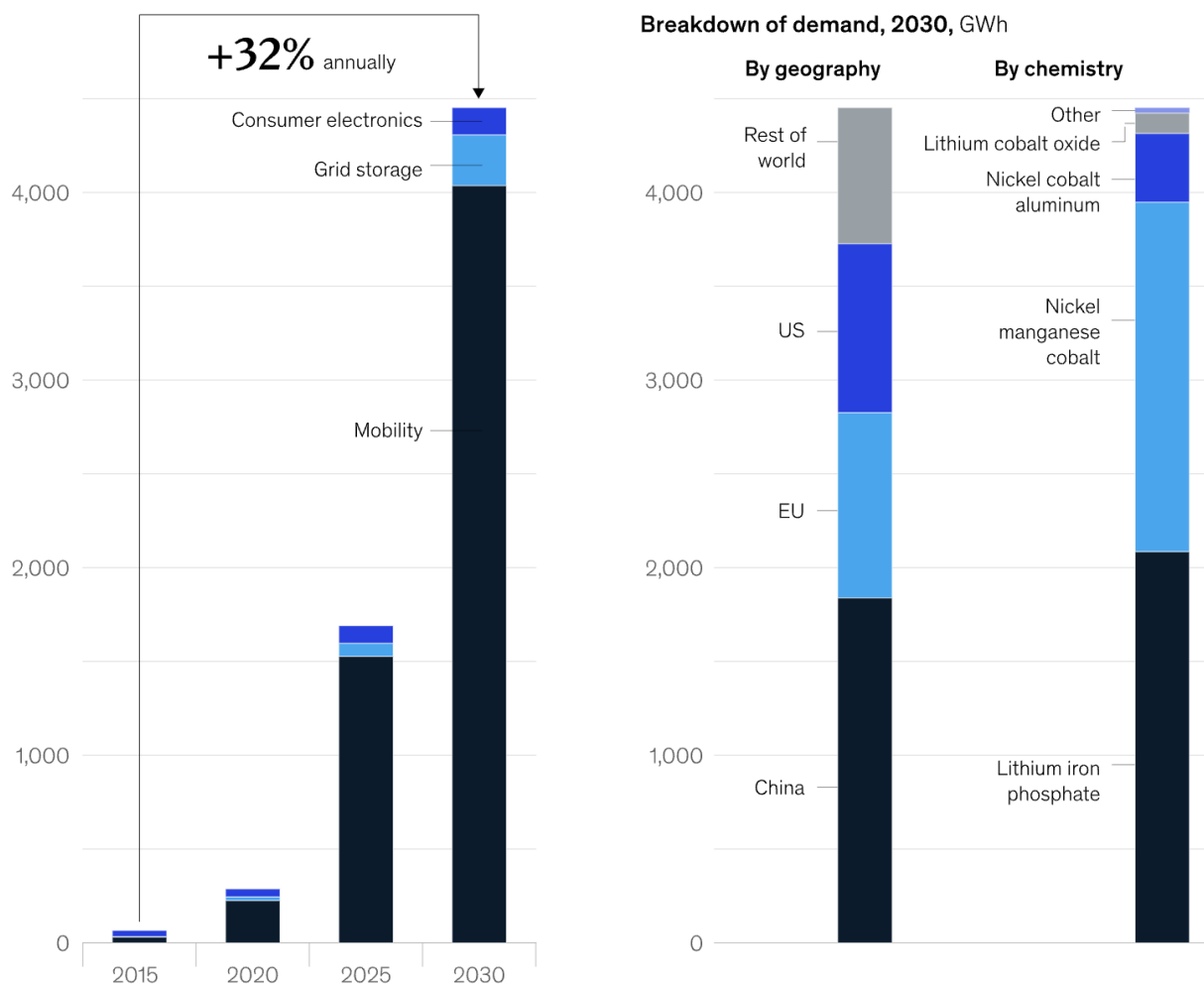


Figure 2: Projected Demand for Lithium-Ion Batteries (2030) [47].

Note: Values in GWh.

China's announced cell production capacities corresponded to 84% of global totals in 2023

but are projected to decline slightly by 2030 as other regions ramp up production [49]. The EU expansion may only cover 72% of regional demand by 2030 unless additional projects are realized [49]. The US is well-positioned to meet domestic demand through operational facilities that correspond to 103% of projected needs by 2030 [49]. Regions like India and Indonesia face challenges in scaling up production capacities due to limited infrastructure investments. Their announced capacities correspond to less than half of domestic vehicular battery demand by 2030 [49].

In terms of chemistry, lithium iron phosphate (LFP) batteries are gaining traction due to their cost-effectiveness and safety, while nickel manganese cobalt (NMC) and nickel cobalt aluminium (NCA) batteries remain popular for high-performance applications [48] [50]. LFP batteries typically have lower energy density, which can impact performance in certain conditions [51]. This performance differential explains why manufacturers often reserve LFP batteries for their entry-level models. NCA batteries offer high specific energy and power, making them suitable for long-range EVs like Tesla models. NMC batteries, on the other hand, balance energy density with safety and are widely used by manufacturers such as Nissan, Chevrolet, and BMW [50].

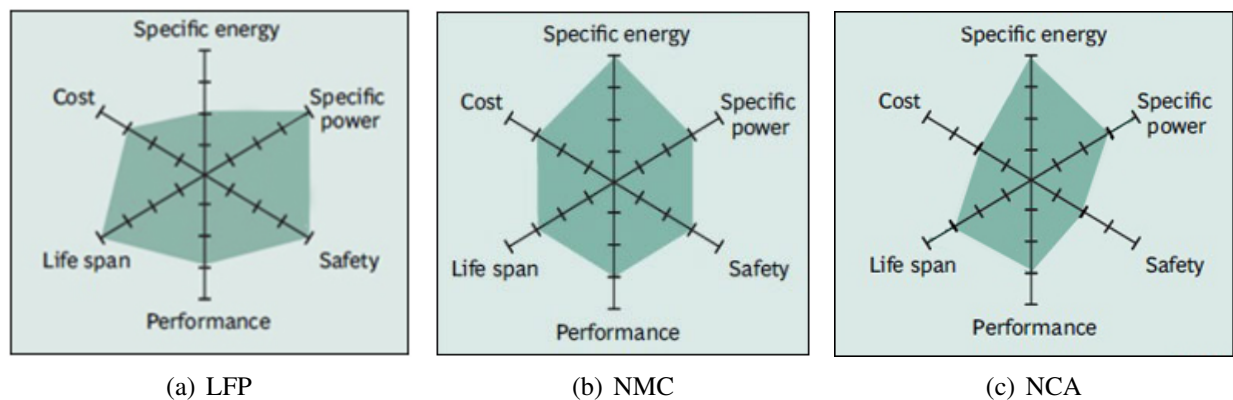


Figure 3: Battery Characteristics [33].

Note: The farther the colored shape extends along a given axis, the better the performance along that dimension.

5.2.4 Battery Value Chain: Market Breakdown

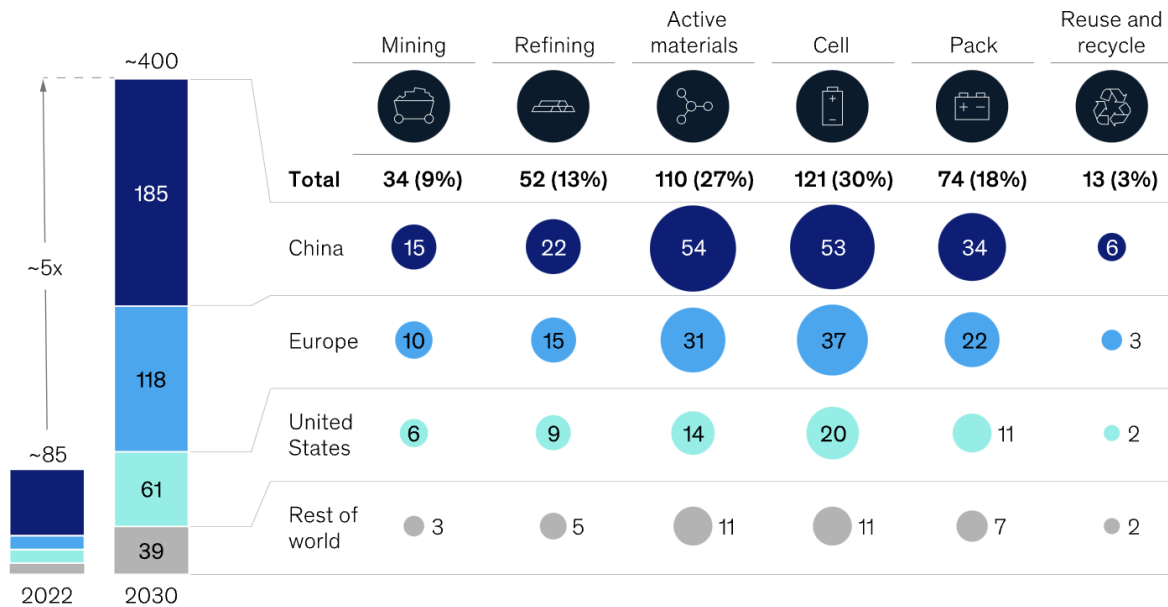


Figure 4: Battery Value Chain Revenues by 2030 [52].

Note: Revenue in billions.

The market for battery cells will grow, on average, by more than 20 percent per year until 2030, reaching at least \$360 billion globally. There is also a realistic scenario in which the market accelerates and hits \$410 billion by 2030 [53]. That could happen if the industry follows the path of other renewable technologies such as solar and wind and enters a virtuous cycle in which increased scale drives down costs, which would accelerate growth in the market for electric vehicles [53].

The value chain is segmented into six key components, each representing a distinct phase in battery production and lifecycle:

- **Mining (9%):** Representing \$34 billion of the projected market, mining operations form the foundation of the battery supply chain, extracting raw materials needed for production [52].
- **Refining (13%):** With projected revenues of \$52 billion, refining processes convert raw

materials into battery-grade materials.

- **Active Materials (27 %):** This segment, valued at \$110 billion, involves the production of cathode and anode materials that are critical components of battery cells [52].
- **Cell Manufacturing (30 %):** The largest segment at \$121 billion, cell manufacturing represents the core of battery production [52].
- **Pack Assembly (18 %):** At \$74 billion, this segment involves assembling cells into battery packs suitable for various applications [52].
- **Reuse and Recycling (3 %):** Though currently the smallest segment at \$13 billion, battery recycling is expected to play an increasingly important role in creating a circular economy for batteries [52].

China leads in all segments with an established position in the battery supply chain, where as of 2019, it controlled 23% of mining, 80% of chemical refining, 66% of cathode/anode production, and 73% of battery cell production [54]. Europe is gradually becoming the second-largest lithium-ion battery producer, with more than 1,000 GWh of cell manufacturing capacities announced as of March 2021 [54]. The United States has a smaller but growing presence, with its strongest position in cell manufacturing [52]. Other regions contribute minimally across all segments, highlighting the concentrated nature of the global battery supply chain [52].

5.2.5 Battery Components: Costs Breakdown and Historical Trends

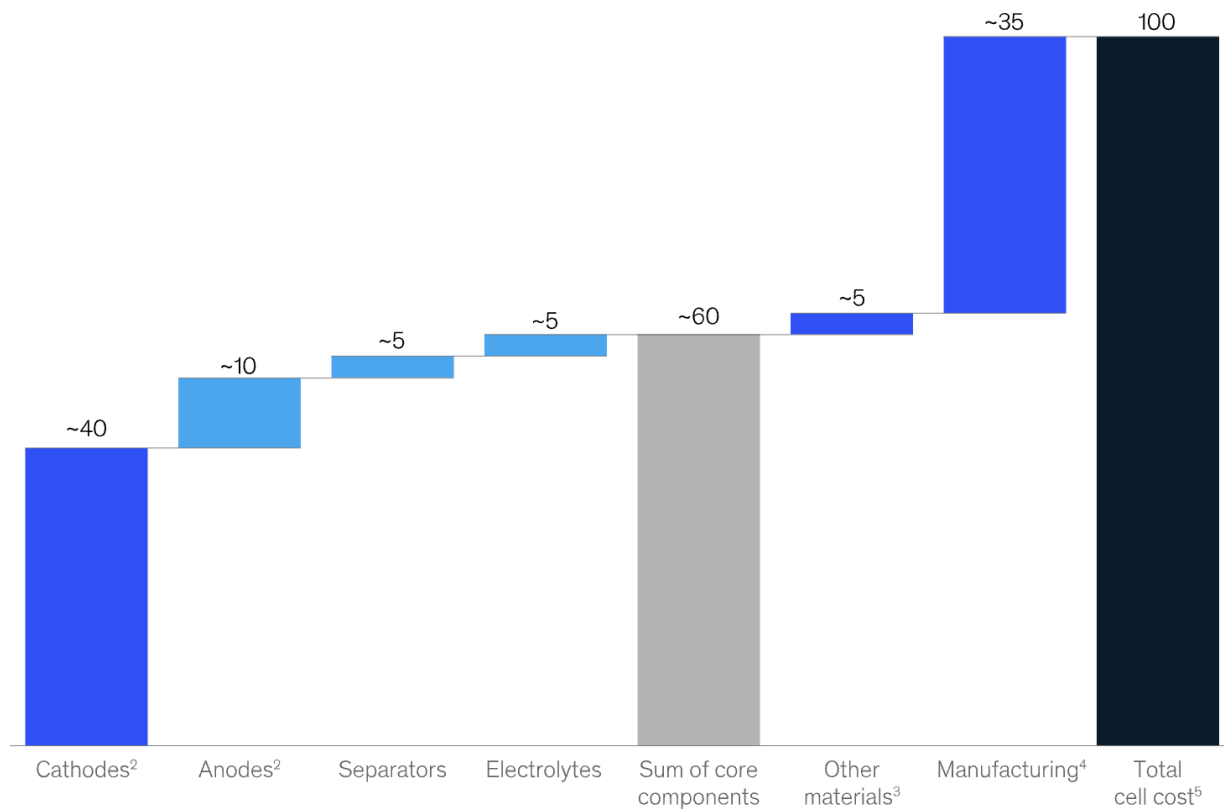


Figure 5: Cost Breakdown of a Typical Lithium-Ion Battery Cell [55]

Note: Values in percentage.

Cathodes represent the single largest cost component in lithium-ion batteries at approximately 40% of the total cell cost [55]. Cathodes are typically made from lithium combined with other metals such as cobalt, nickel, or manganese, materials whose prices fluctuate based on availability and demand [56]. On the other side, anodes contribute approximately 10% to the total cost of lithium-ion batteries [55]. Traditionally made primarily from graphite, anodes represent a smaller but still significant cost factor [56].

Manufacturing accounts for approximately 35% of the total cost of lithium-ion battery cells [55]. This substantial portion covers expenses related to production facilities, equipment, labor,

quality control, and assembly processes.

Lithium-ion battery costs have seen remarkable reductions over time. In 2008, battery costs were approximately \$1,355 per kWh, falling to around \$400/kWh by 2012 as reported by Tesla [56] [57]. By 2017, the average cost had decreased to approximately \$209/kWh, and by 2021-2022, costs ranged between \$132-153/kWh for EV battery packs [56]. This represents an approximately 90% reduction in costs over a 14-year period.

The proportion of costs attributed to different components has changed significantly over time. Materials represented only about 10% of lithium-ion battery costs in 2012 but increased to approximately 50% by 2019 and as much as two-thirds during commodity price spikes in 2022 [58]. This shift highlights how raw material prices have become increasingly dominant in determining overall battery costs.

5.2.6 Recycling: Available Material Projections and Context

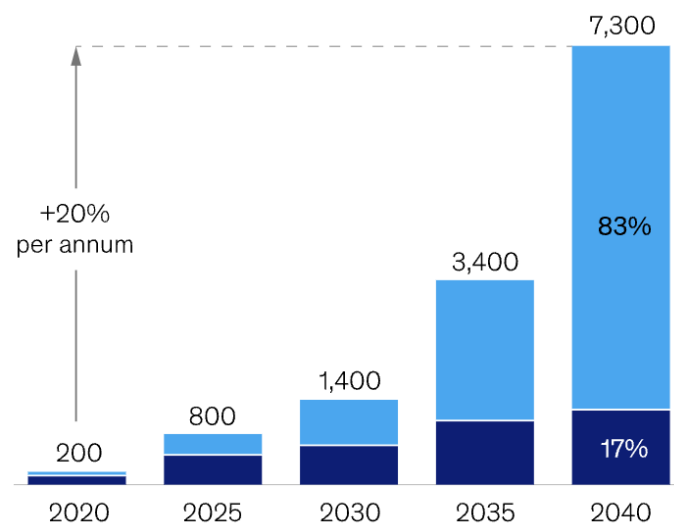


Figure 6: Available Material Projection for Recycling [52].

Note: Sky blue represents material coming from end of life batteries. Dark blue material coming from scrap. Values in kilotons.

The rapid expansion of battery recycling capacity is being driven by multiple factors, including the exponential growth in electric vehicle adoption, regulatory pressures, and technological innovations in recycling processes. As illustrated in the chart, the volume of available materials is expected to more than double every five years, reaching 800 kilotons by 2025, 1,400 kilotons by 2030, 3,400 kilotons by 2035, and 7,300 kilotons by 2040 [52].

An estimated 1.2 million batteries from light- and heavy-duty battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) will reach their end of life in 2030 globally, rising dramatically to 14 million in 2040 and 50 million by 2050 [59]. This exponential growth in end-of-life batteries represents both a challenge and an opportunity for the recycling industry.

Currently, there is a significant imbalance in global battery recycling capacity. As of December 2023, China leads with more than 500,000 metric tons of recycling capacity, while the United States and Europe each have approximately 200,000 metric tons [60]. Leading companies in this space include CATL, Umicore, Redwood Materials, Li-Cycle, and Cirba [61] .

Recent technological breakthroughs have significantly improved the economics and efficiency of battery recycling. Modern recycling facilities can now recover nearly all of the cobalt and nickel and over 80% of the lithium from used batteries and manufacturing scrap. Projections suggest that recycling could reduce the combined annual demand for new lithium, cobalt, nickel, and manganese mining by 3% in 2030, 11% in 2040, and 28% by 2050 [59].

The economic benefits are compelling. Beyond creating a more stable and secure supply chain for critical battery materials, recycling operations create local jobs and economic value. This is particularly important given the geopolitical tensions and supply chain vulnerabilities that have affected critical mineral markets in recent years.

5.3 EverBatt: Battery Recycling Process and Supply Chain Model

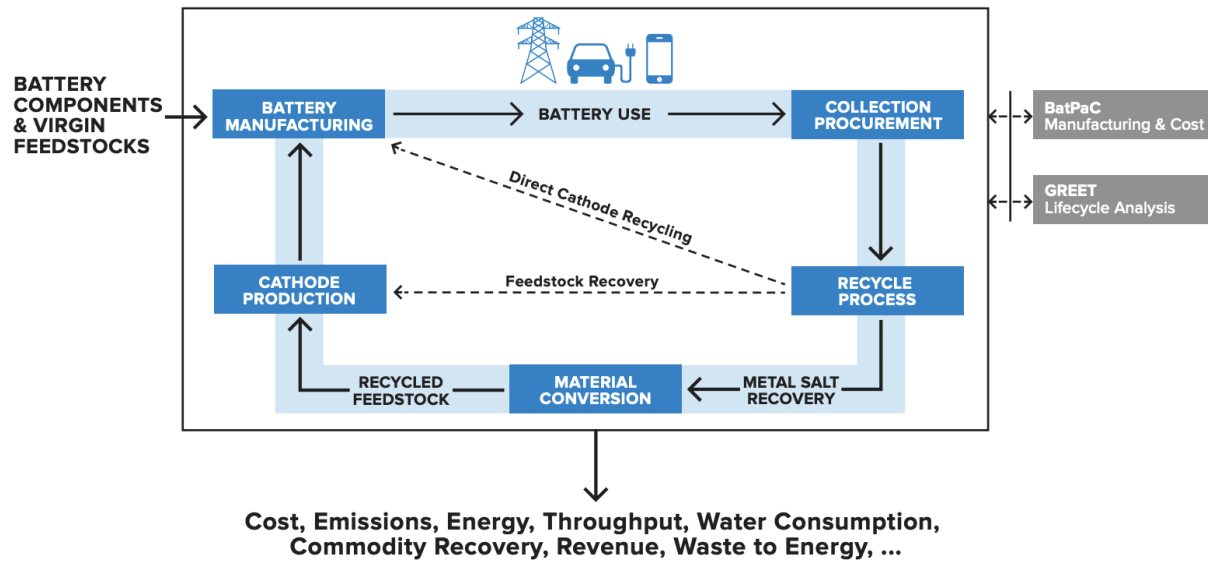


Figure 7: Everbatt's Recycling Model [63].

EverBatt is a closed-loop battery life-cycle model [63]. It provides techno-economic analysis of different recycling pathways and adapts to differing battery chemistries and formats and cathode/cell production methods [63]. It allows users to benchmark production with recycled materials against production with virgin materials to provide a holistic picture of the benefits and tradeoffs of battery recycling, estimate the cost and environmental impacts of existing industrial practices along the battery supply chain [62].

This is done with the integration of two other models: BatPaC and GREET. BatPaC is a software modeling tool designed for users who are interested in estimating the cost of lithium-ion batteries after they have reached a mature state of development and are being manufactured in high volumes [107]. On the other hand, GREET do a life cycle analysis to assess the environmental impacts associated with technologies, fuels, products, and energy systems across various stages of the supply chain [108].

It is possible to benchmark three different types of recycling routes after preprocessing through the model: pyrometallurgy, hydrometallurgy and direct recycling. Each alternative has its own series of steps to complete the process in which there are specific equipment involved.

5.3.1 Pyrometallurgy

Also known as smelting, is a thermal-based recycling process that treats EV batteries as if they were traditional metal ores. This method has been widely used in metallurgical industries and has been adapted for battery recycling.

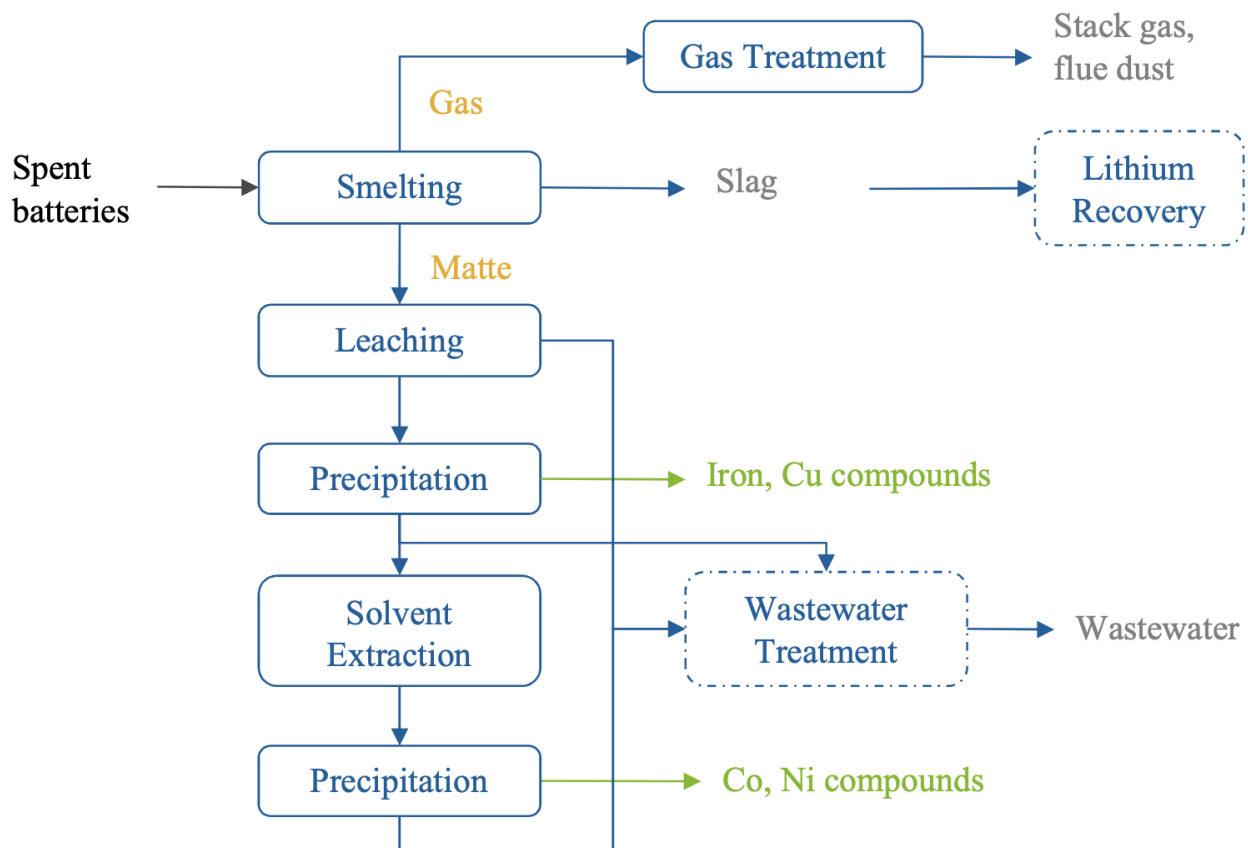


Figure 8: Generic Pyrometallurgical Recycling Process [62].

Note: Solid boxes denote common unit operations; dashed box denotes optional unit operation; green denotes products; grey denotes wastes.

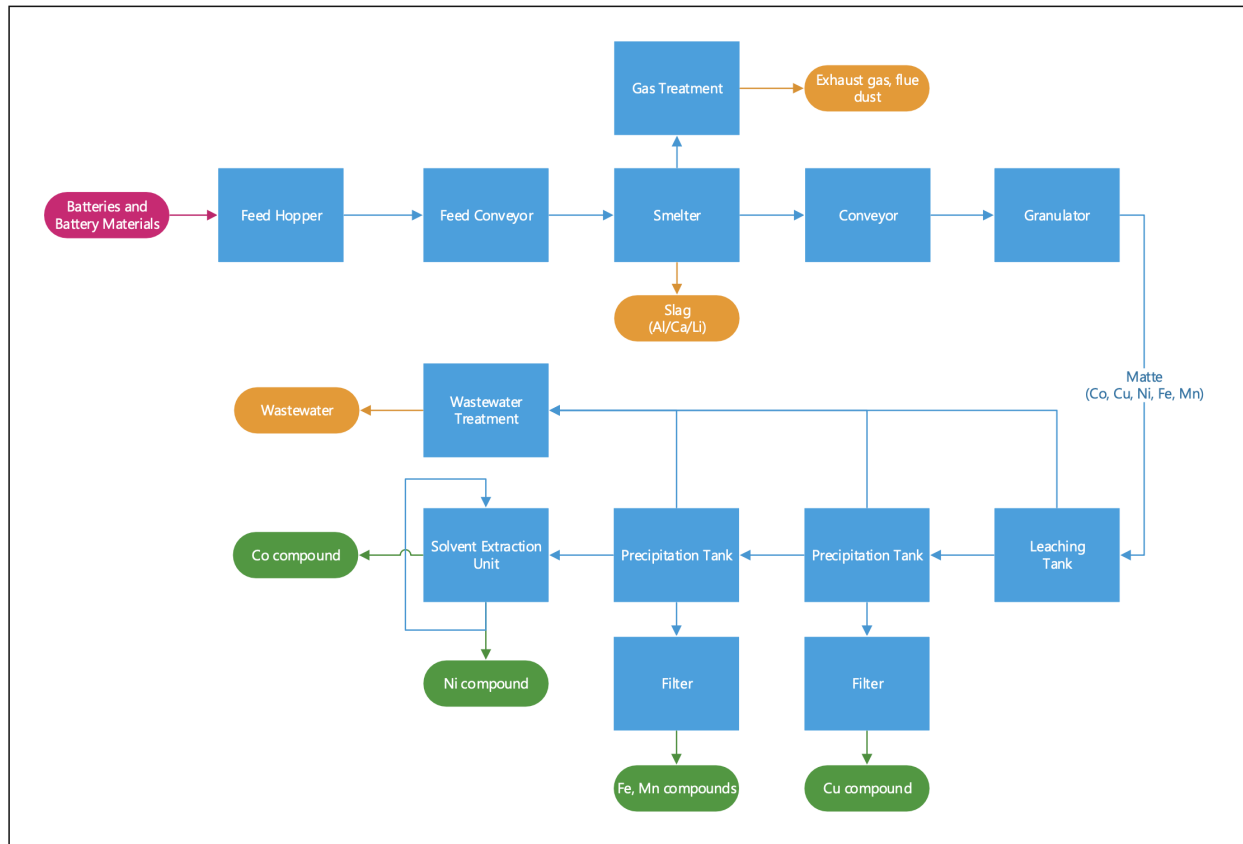


Figure 9: Equipment Assumed for Generic Pyrometallurgical Recycling [62].

Note: Green denotes products. Orange denotes wastes.

The pyrometallurgical approach exposes batteries to extremely high temperatures to melt or burn the components of the cell [64]. At temperatures above 700°C, the lithium metal oxide of the cathode and anode react to form lithium carbonate (Li_2CO_3) and various metal oxides [65].

The process begins with minimal pre-treatment of batteries, followed by the high-temperature smelting phase. During this phase, the plastic components and electrolytes are burned off as fuel or slag, while the valuable metals form an alloy that can be further processed. Lithium typically ends up in the slag phase, which requires additional processing to recover [64].

However, this method has significant drawbacks. It requires a significant amount of energy, loses a substantial amount of lithium and produces severe secondary pollution [1].

5.3.2 Hydrometallurgy

Consists of three main steps: pretreatment, leaching, and metal deposition [64]. The pretreatment phase begins with discharging the battery to prevent short circuits and hazards. The battery is then dismantled, and materials are sorted and crushed to expose valuable components.

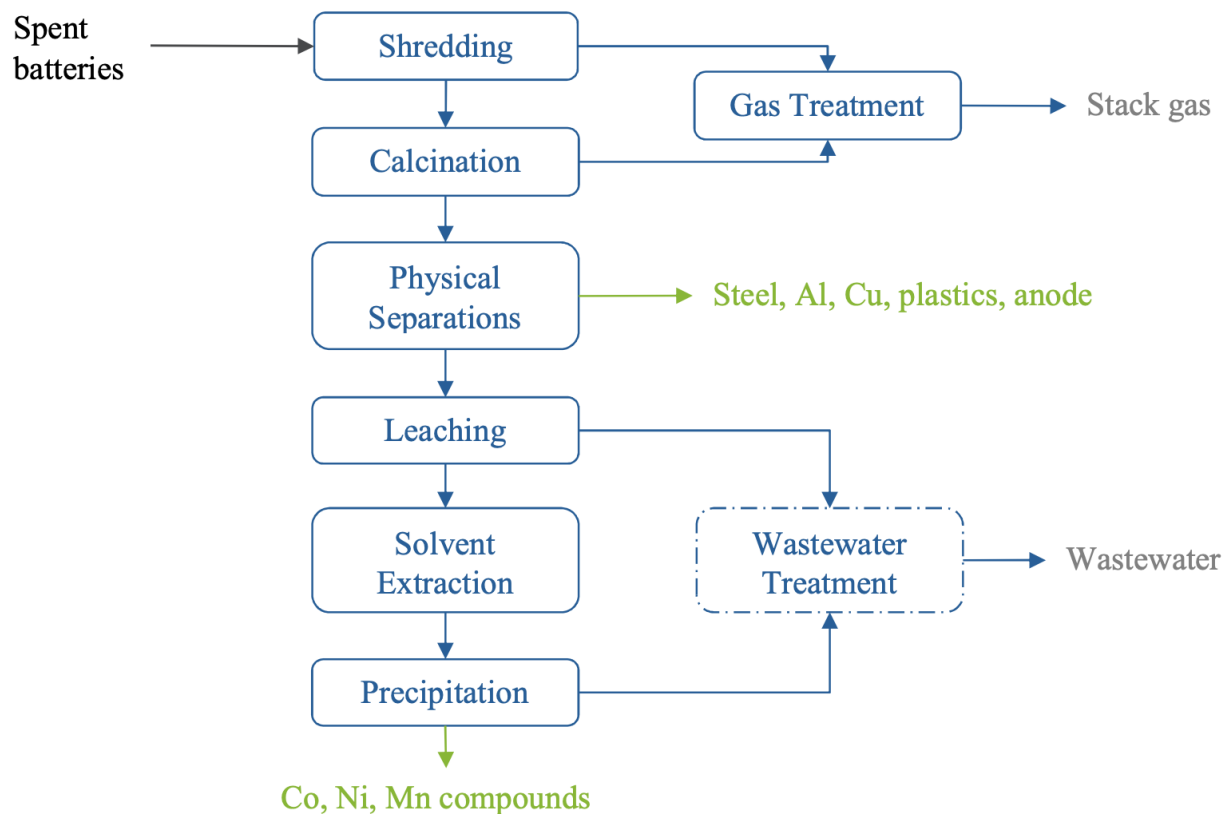


Figure 10: Generic Hydrometallurgical Recycling Process [62].

Note: Solid boxes denote common unit operations; dashed box denotes optional unit operation; green denotes products; grey denotes wastes.

All the metals in an EV battery cell are dissolved in an inorganic acid [66]. Materials such as aluminum and copper are removed, followed by the selective recovery of valuable metals like cobalt, nickel, manganese, and lithium [66]. This selective precipitation or extraction process is conducted by adjusting pH levels, using solvent extraction, or through electrowinning.

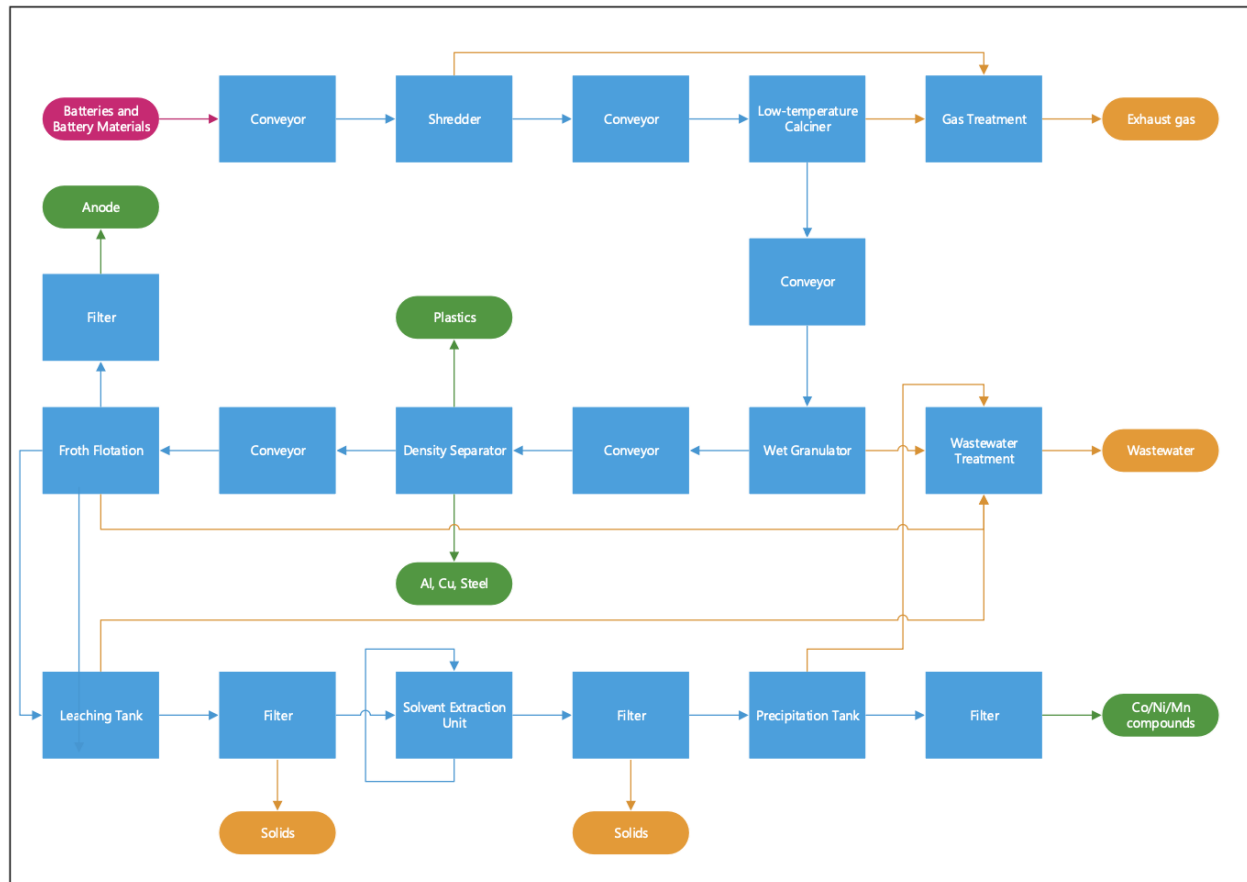


Figure 11: Equipment Assumed for Generic Hydrometallurgical Recycling [62].

Note: Green denotes products. Orange denotes wastes

The advantages of hydrometallurgical processes are the high purity of the materials obtained, their low operating temperature and lower amounts of carbon produced compared to pyrometallurgical processes [22].

This process can be scaled to fit different operational sizes, making it suitable for implementation in developing countries [64]. Furthermore, materials flow analysis predicts that by 2040, recycled batteries processed via hydrometallurgy could supply 60% of cobalt, 53% of lithium, 57% of manganese, and 53% of nickel globally, significantly reducing the need for primary resource extraction [67].

5.3.3 Direct Recycling

Direct recycling focuses on the recovery, regeneration, and reuse of battery components without breaking down their chemical structure [64]. It enables the production of cathodes that can be directly used in assembly, eliminating the need to resynthesize from precursors [45].

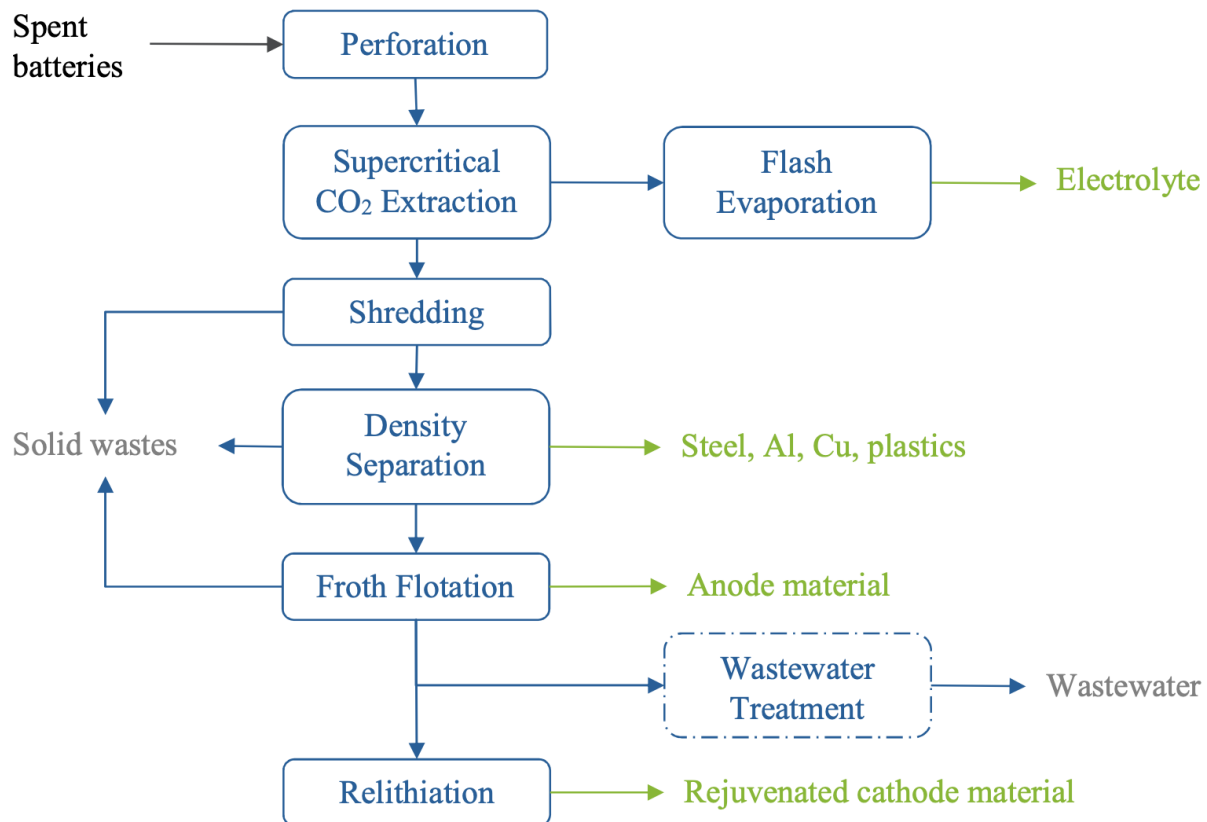


Figure 12: Generic Direct Recycling Process [62].

Note: Solid boxes denote common unit operations; dashed box denotes optional unit operation; green denotes products; grey denotes wastes.

Direct recycling offers compelling advantages in terms of energy consumption, safety, cost, flexibility, and economic returns [68]. From an environmental perspective, it is generally considered superior to other alternatives because it requires less energy and fewer chemical reagents while preserving more of the value embedded in the original battery materials.

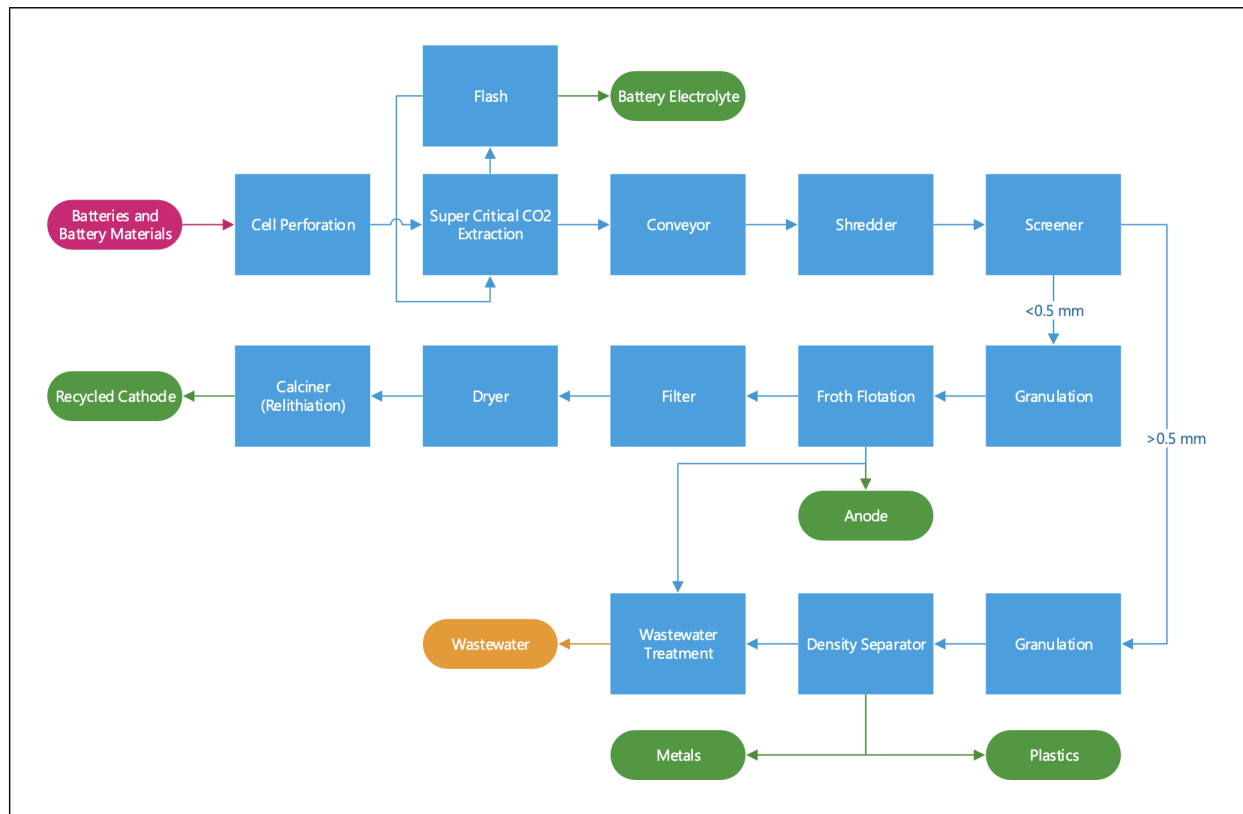


Figure 13: Equipment Assumed for Generic Direct Recycling [62].

However, direct recycling faces significant challenges that have hindered its commercial implementation [45]. These obstacles include difficulties in disassembling battery packs designed for performance rather than recyclability, sorting mixed battery chemistries, separating components effectively, and addressing technological limitations [68].

5.3.4 Recoverable Materials

Different recycling technologies can recover various materials from spent lithium-ion batteries. While pyrometallurgical processes mainly recover basic metal compounds, hydrometallurgical methods can extract a wider range of materials including lithium carbonate and electrolyte components. Direct recycling stands out for its ability to recover specific cathode materials.

Pyrometallurgical	Hydrometallurgical	Direct
• Copper compounds • Iron compounds • Co²⁺ in output • Ni²⁺ in output • Lithium compounds* • Aggregate (from slag)*	• Copper • Steel • Aluminum • Graphite • Plastics • Lithium carbonate • Co²⁺ in output • Ni²⁺ in output • Mn²⁺ in output • Electrolyte solvents • Electrolyte salts*	• Copper • Steel • Aluminum • Graphite • Plastics • LCO • NMC(111) • NMC(622) • NMC(811) • NCA • LMO • LFP • Electrolyte solvents • Electrolyte salts*

Figure 14: Recoverable Materials Through Different Recycling Technologies [62].

*Note: * not currently included in EverBatt.*

5.4 Types of Electric Vehicles

Some definitions for different types of electric vehicles are:

- **Hybrid electric vehicle (HEV):** Vehicle that combines two power sources, with a primary combustion engine and a battery and electric motor that provide support in various situations [35].
- **Battery electric vehicle (BEV):** Vehicles that operate solely on batteries and are recharged by connecting them to the electrical grid [35].
- **Plug-in hybrid electric vehicle (PHEV):** A vehicle that combines a combustion engine with an electric motor and higher-capacity batteries, which are recharged by plugging the vehicle into the electrical grid [35].
- **Mild hybrid electric vehicle (MHEV):** A mild hybrid vehicle that combines a combustion engine with a small electric motor, which assists driving in specific moments and also serves as a starter motor [35].
- **Extended range electric vehicle (EREV):** A vehicle powered exclusively by one or more electric motors, with an internal combustion engine to generate electricity for the storage system or battery [35].
- **Fuel cell electric vehicle (FCEV):** A vehicle that uses hydrogen as the main energy source to power the vehicle. These are electric vehicles, either light or medium, with a fuel cell and an electric motor that act as converters of propulsion energy [35].

5.5 Electric Vehicle Sales: Market Forecast

The accurate forecasting of electric vehicle sales represents a critical challenge. Several established methodologies are commonly employed to predict future sales, each with distinct characteristics and applications.

An important alternative is use an existing forecast. Reviewing literature for Chile, there are projections in short and medium term. For example, in short term, EV sales (PHEV + BEV) were expected to be 4.982 units in 2024 and are expected to be 9.863 at the end of 2025 and 17.753 at 2026 [35]. On the other hand, at 2030 there are projections expecting more than 93.000 cars in Chile's total EV fleet [76] . However there are no forecasts that predict behaviour in more than 20 years from now.

Commonly used forecasting techniques are:

- **Linear regression:** a statistical method that models the relationship between a dependent variable and one or more independent variables using a linear equation [77].
- **Polynomial regression:** An extension of linear regression where the relationship between the dependent and independent variables is modeled as a polynomial equation. This allows for capturing non-linear patterns in the data by including higher-order terms of the independent variable(s) [78].
- **Time series:** A technique that uses historical, time-stamped data to predict future values. By analyzing trends, seasonality, and patterns in past data, it provides insights for strategic decision-making [79].
- **Machine learning:** Machine learning models analyze large datasets to identify patterns and

relationships, enabling accurate predictions. These models can handle complex, non-linear relationships and adapt to new data over time [80].

- **Difussion/S-Curve:** This approach models the adoption of technologies or products over time using an S-curve. The curve represents initial slow adoption, rapid growth during the middle phase, and eventual saturation. It is often used in technology forecasting [81].

In this particular context there are two key considerations:

1. It is required an effective methodology for both short and long timeframes.
2. Chile represents a scenario with limited annual data, given its recent electric vehicle adoption which only began in 2015 [35].

Table 1: Forecasting Models Comparison [82][83][84].

Model	Characteristics	Suitability for Chile
Linear Regression	+ Simple, interpretable. - Assumes linear growth. - Ignores external shocks.	Limited utility due to market volatility; best for early-stage baseline estimates.
Polynomial Regression	+ Captures non-linear trends. - Overfits with sparse data. - Struggles with abrupt policy shifts.	Moderate for short-term, stable periods; less reliable amid policy uncertainty.
Machine Learning	+ Handles complex interactions. + Adapts dynamically to new data. - Requires large datasets. - Black-box interpretation.	High potential for 2025–2030 forecasts as data grows; dependent on infrastructure/policy inputs.
Time Series	+ Effective for historical pattern analysis . - Fails during structural shifts. - Cannot integrate external variables.	Limited use unless combined with adaptive techniques.
Diffusion/S-Curve	+ Matches adoption lifecycle. + Strong for long-term trends . - Overlooks short-term disruptions . - Assumes stable adoption rates.	Best post-2030 if market stabilizes; underestimates near-term risks like charging infrastructure delays.

5.5.1 Simulating EV Sales: An Hybrid Approach

An innovative approach to EV sales forecasting combines projection equations with S-curve dynamics to optimize both short-term and long-term predictive accuracy. This methodology employs "a polynomial function together with a logistic function" with the combination weighted according to a time-dependent function [34]. The polynomial component provides detailed short-term estimates while the logistic function establishes the appropriate long-term adoption curve.

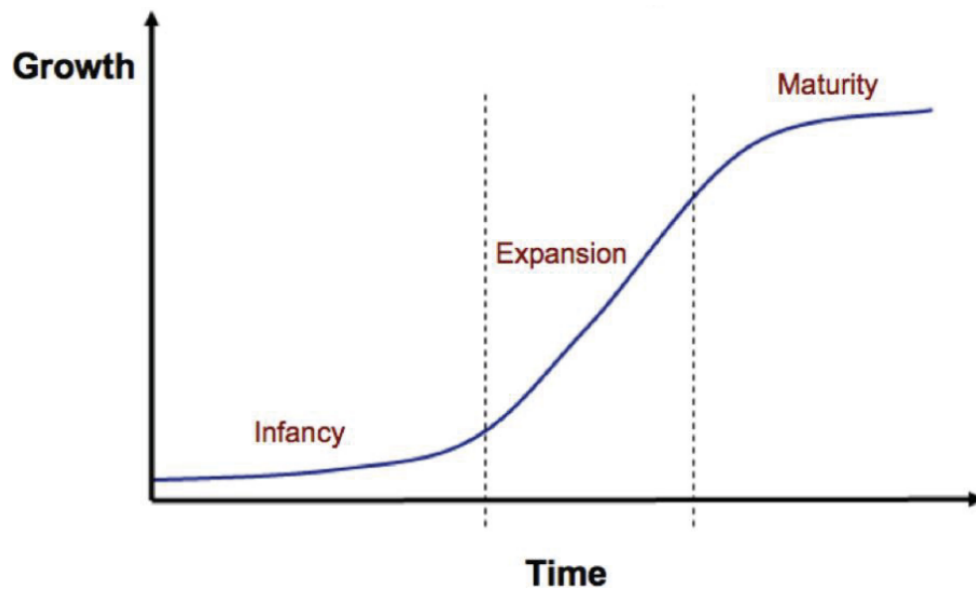


Figure 15: S-Curve (Business Life Cycle) [86].

The S-curve represents three different stages. Stage 1 is initial growth, followed by stage 2, exponential growth, and the final stage is characterized by deceleration [85]. The sales are low, and after some time, the increase is more rapid, and finally, when reaching close to maximal volume, the growth is reduced, and finally, the increase is zero. In the case of EVs, the sales are a part of the total car sales. So, the theoretical maximal sales are reached when all sold cars are EVs [34].

In order to be able to adjust the curve, a more complex version of the S-curve function must be used. When adding α and T_0 to the function, it is possible to adjust the curve.

$$f(t) = \frac{1}{1 + e^{-\alpha(t-T_0)}} \quad (1)$$

- α : changes the derivative of the function when $f(t) = 0,5$
- T_0 : shifts the timeline (T_0 is the time when $f(t) = 0,5$)

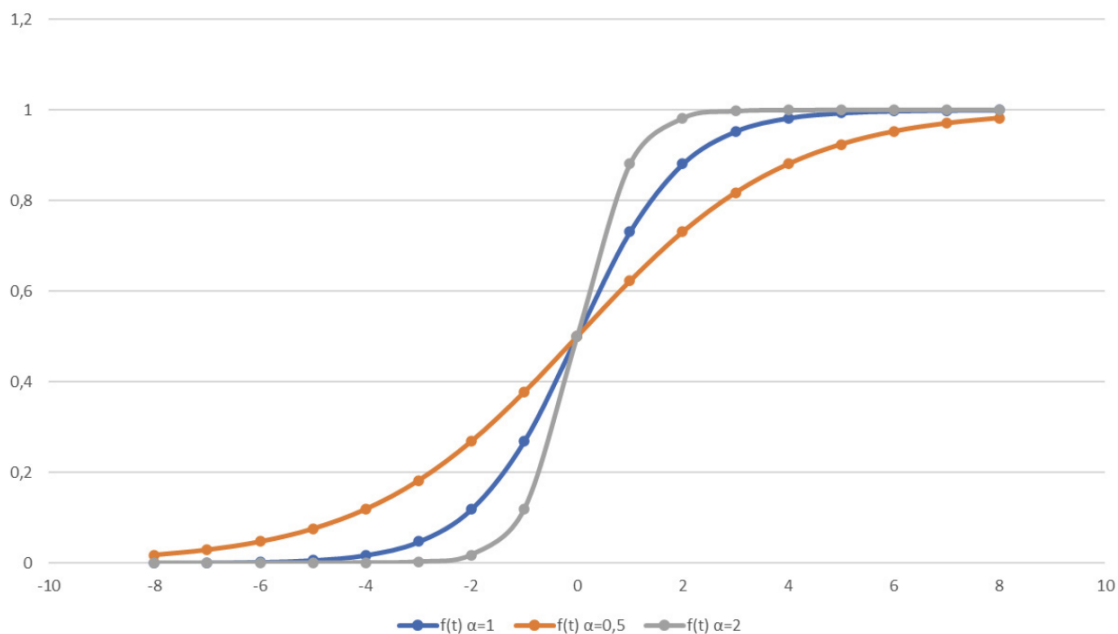


Figure 16: Logistic Function [34].

In calculation, a modified version of Equation (1) will be used:

$$FC_S(t) = \frac{Sales_{tot}}{1 + e^{-\alpha(t-T_0)}} \quad (2)$$

- $Sales_{tot}$: maximum number of EVs that will be sold in the future.
- T_0 : year when the sales reach 50% of the final sales.

The cons of this formula are that it is not so easy to get good early values. The pros are that the curve will be S-curve shaped, and it can be used to forecast the sales several years from now. The conclusion is that a combined polynomial and logistic model is better to forecast [34].

$$FC(t) = \omega \cdot FC_{pol}(t) + (1 - \omega) \cdot FC_S(t) \quad (3)$$

The weight function is raised to 5 to shift the weight from the polynomial to the logistic function fast [34].

$$FC(t) = \left(\frac{T_f - t}{T_f - T_i} \right)^5 \cdot FC_{pol}(t) + \left(1 - \left(\frac{T_f - t}{T_f - T_i} \right)^5 \right) \cdot \frac{Sales_{tot}}{1 + e^{-\alpha(t-T_0)}} \quad (4)$$

where

- $FC(t)$: forecasted value of a particular year t .
- t : particular forecast year.
- $FC_{pol}(t)$: trend line equation of the polynomial function obtained from the historical data
- T_f : final year of evaluation horizon.
- T_i : first year of recorded historical data

The results show that the forecasting equations give good results when sales per year are used in all combinations [34].

5.6 End-Of-Life Electric Vehicle Batteries

While the diffusion of EVs in the market is a matter of preference of one technology over the others, their EOL generation flow is not a choice but rather depends on their survival age [38].

Several approaches have been used by authors to simulate electric vehicles EOL battery distribution. Ai et al. (2019) simulation examines uniform, Weibull, and truncated distribution functions while taking this assumption that the lifespan of EVBs is expanding over time [87]. The results confirmed that the type of distribution function is not as important as the parameters of the distribution themselves [87]. Yano et al. (2016) developed a model to predict the replacement probability of batteries in the Prius model HEVs using Weibull distribution and found the parameters for each of the three generations by fitting the model to the historical EOL data [88]. Wu et al. (2020) carried out a spatial analysis to determine the value of retired batteries for recovery utilization in several provinces in China, considering a Weibull function for battery retirement probability and average specific energy of batteries at EOL [89].

The calculation for compliance with lithium-ion battery targets in Chile is also based on Weibull's formula [32]. Weibull is a probability distribution that allows estimating the waste generation rate of different goods, being primarily useful for products with long useful lives, in which it is known that each product has a different useful life and the parameters differ depending on the geographic/climatic region [32].

In this study, it is adopted a two-parameter Weibull distribution: scale and shape. The scale parameters stand for the relative magnitude of lifespans, which is commonly equal to the average EV lifespan [95]. Whereas the shape parameters describe the contrariness of a product retired pattern, and they rarely change over time [96].

It can be mathematically described as:

$$W(n) = \sum_{t=t_0}^n POM(t) \cdot L^{(p)}(t, n) \quad (5)$$

$$L^{(p)}(t, n) = \frac{\alpha(t)}{\beta(t)^{\alpha(t)}} \cdot (n - t)^{\alpha(t)-1} \cdot e^{-[(n-t)/\beta(t)]^{\alpha(t)}} \quad (6)$$

- $W(n)$: waste generated in year n .
- $POM(t)$: put on market batteries in year t .
- $L^{(p)}(t, n)$: Weibull distribution.
- $\alpha(t)$: shape parameter of the probability distribution, which can vary over time t .
- $\beta(t)$: form parameter of the probability distribution, which can vary over time t .
- n : year of waste evaluation.
- t : year of put on market batteries.

Matsuno et al. (2012) analysis of Ni-Cd battery lifetime distribution function is often used for parameter adoption. The shape parameter (α) is described as 3.5 and it is used in different EV's EOL battery projections such as the US, EU and China [97] [87] [98] [89] . In these forecasts a combination of constant and assumed dynamic lifespans for the form parameter (β) is also used, ranging in between 8 to 17 years [98] [87] [89]. As more empirical data becomes available, more complex three-parameter Weibull distribution shall be developed to better capture battery discard probabilities [87].

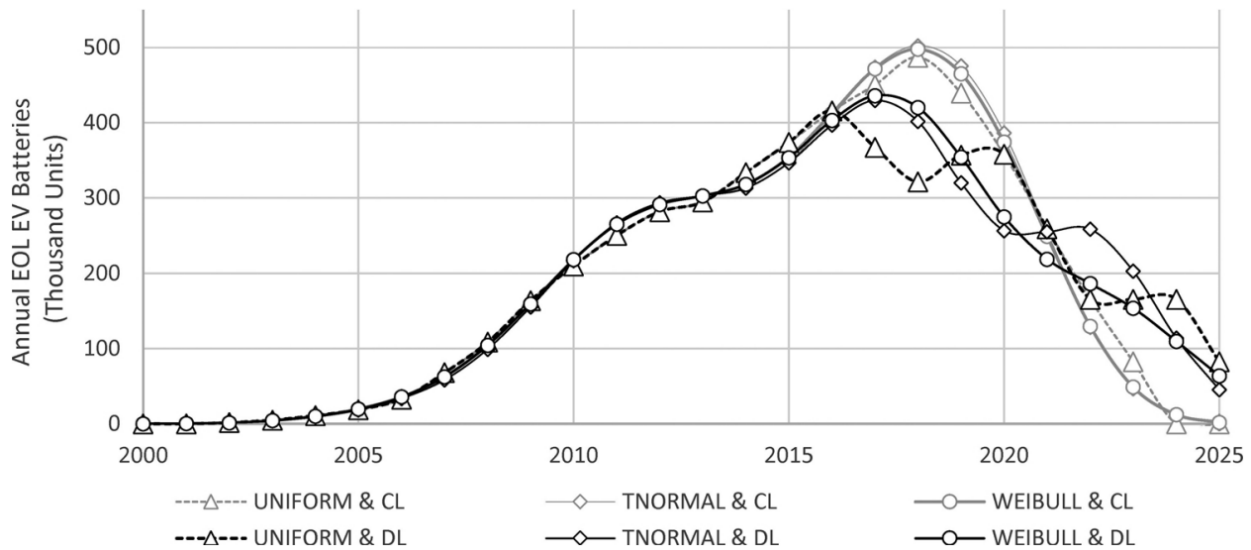


Figure 17: U.S. EOL Batteries from Existing EVs by Different Scenarios (2000–2025) [87]

Note: UNIFORM: Uniform distribution function for discard probabilities; TNORMAL: Truncated normal distribution function for discard probabilities; WEIBULL: Weibull distribution function for discard probabilities; CL: Constant lifespan scenarios; DL: Dynamic lifespan scenarios.

Ai et al. (2019) results from Figure 17 shows that incorporating a dynamic lifespan approach versus using a constant lifespan produced minimal differences in model outcomes. This suggests that the additional complexity introduced by the dynamic approach may not be justified by appreciably improved results.

To estimate the EOL distribution of EVs in Chile, it will be used Fallah's et al. (2021) approach, which learned from EOL's distribution pattern in a larger market in which EV sales started earlier [38]. In this study, the authors selected UK's market to estimate Ireland's EOL battery stock due to its similar availability of vehicle models, environmental conditions as well as ELV legislation [38]. However, no country has similar climate conditions due to Chile's large geographical distribution and due to the lack of information, this seems as the best approach.

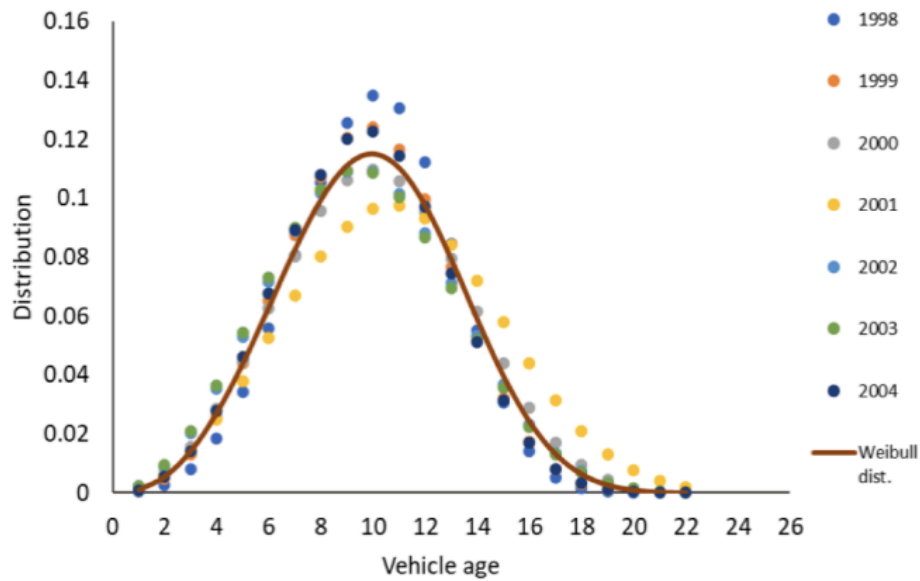


Figure 18: Weibull Distribution of EOL Electric Vehicles in UK [38]

Note: The parameters of the Weibull distribution are $\alpha = 11$ and $\beta = 3, 2$.

5.7 Reuse and Recycle Rate

The aforementioned studies explored the estimation of the stockpile generation from EOL EVBs, whereas the second-use applicability of these EOL batteries is unsettled due to their inconsistency in terms of cycling age and SOH [38]. This burden could be reduced by incorporating an enabling battery management system in newly manufactured EVs and monitoring the SOH of batteries during their whole lifetimes [90] [91].

Yet, there are other financial burdens among which some relates to the uncertainties in economic priority between recycling and reuse due to unclear financial dynamic in the second-hand EVB market in terms of marginal cost and demand in the market, specifically when EOL batteries are a valuable secondary resource for critical materials in the battery supply chain [92].

Recent studies considered different rates of reuse in their estimation. For example, Moore et al. (2020) considered a recycling rate of 37% and 50% in scenarios with a high and low advance-

ment in battery capacity technology for estimating the available energy capacity of EOL EVBs for second-use applications [93]. Bobba et al. (2019) assumed an annual linear increase from 0% in 2010 to 20% in 2030 for battery repurposing as a low second-use scenario, whereas, in a high second-use scenario, 80% of EOL EVBs are considered to be eligible for repurposing [94]. Yet, these assumptions are not based on actual figures, as the EV sector is still in its infancy and rapidly developing [38]. Monitoring and testing the SOH of EOL batteries are not currently efficient. This uncertainty in along with other socio-economic burdens leads to a low rate of reuse to date [38].

Currently, the installed capacity for second-life batteries in Europe is less than 100 MWh and in North America less than 10 MWh, which indicates that reuse represents a small fraction compared to the total number of discarded batteries [24]. With this data and the fact that this zones are more advanced in recycling policies, its suggests that the effect of the reuse rate in Chile's modeling would be difficult to assume or even, not significative to consider in the assesment timeframe.

5.8 Economic Indicators

5.8.1 Net Present Value (NPV)

Difference between the present value of cash inflows and the present value of cash outflows over a period of time. It is used in capital budgeting and investment planning to assess a project's profitability. A positive NPV indicates that the projected earnings exceed the anticipated costs, making the project potentially worthwhile [101].

$$NPV = \sum_{t=0}^n \frac{C_t}{(1+r)^t} + C_0 \quad (7)$$

- C_t : Net cash flow at time t
- r : Discount rate (minimum acceptable return or cost of capital)
- n : Total number of periods
- C_0 : Initial investment ($t = 0$)

5.8.2 Internal Rate of Return (IRR)

Discount rate r at which the net present value of all cash flows (both incoming and outgoing) from an investment equals zero. In other words, it is the annualized effective compounded return rate that makes the present value of future cash flows equal to the initial investment. IRR is commonly used to evaluate the attractiveness of a project or investment; the higher the IRR, the more desirable the investment [102].

$$NPV = \sum_{t=0}^n \frac{C_t}{(1+r)^t} + C_0 = 0 \quad (8)$$

5.8.3 Payback Period

Length of time required to recover the initial investment in a project. A shorter payback period is generally preferred, as it means the investment's cost is recovered more quickly [103].

$$\frac{\text{Cost of Investment}}{\text{Average Annual Cash Flow}} \quad (9)$$

6 Methodology

1. Make a PESTLE analysis, this includes political, economic, sociological, technological, legal and environmental aspects considering only Chile's information and general disposition of electric vehicle's battery recycling.
2. Calculate annual electric vehicle sales using Equation (4).
 - (a) Estimate evaluation horizon T_i and T_f in time weighting formula.
 - (b) Calculate FC_{pol} using historical data.
 - (c) Determine $Sales_{tot}$ through adjusted vehicle yearly sales.
 - (d) Identify α and T_0 through an iterative method with a test training and cross-validate it with a test set using historical data.
3. Estimate EOL EV batteries using Equations (5) and (6).
4. Calculate collected batteries based on collection targets.
5. Estimate final mass or raw material entering the recycling plant based on system capacity, battery chemistry proportions, and energy density using the EverBatt model.
6. Define a place for the recycling plant that minimizes transportation costs dependent on the place with more EOL batteries.
7. Obtain the amount of potential recovered mass in the disassembly stage using the EverBatt model.
8. Determine CAPEX, OPEX and production amounts for each stage in the value chain using the EverBatt and BatPaC models.

9. Extract cost and revenue per kilogram of processed raw material in the recycling plant using the EverBatt model.
10. Define the number of simulations for the Monte Carlo risk analysis that represents historical material prices.
11. Calculate economic indicators distributions of the recycling plant project such as net present value, internal rate of return, and payback, though the development of a cash flow and the use of simulated material prices with a Monte Carlo analysis.
12. Define a battery chemistry to produce in the battery factory that aligns with projected market share relevance.
13. Define a place for the battery factory that works as an strategic place to acquire and sell materials, while minimizing transportation costs.
14. Collect the cost allocation per stage in the production of cathode cathode production per kWh with recovered materials using the EverBatt model.
15. Calculate battery production cost distribution per kilowatt-hour for recovered and virgin materials using the EverBatt model and simulated material prices with a Monte Carlo analysis.
16. Calculate material price correlations with NPV using Python.
17. Estimata environmental impacts using the GREET model.

7 Assumptions

- As shown in Figure 5.2.3 the vast majority of the market belongs to NCA, NMC and LFP batteries. The high prices of the materials have made efforts towards innovation in LFP batteries, which are not cobalt or niquel dependant, impacting in market share. In 2019 this represented 5% while in 2022 represented 40% of the total market [24]. Nevertheless, nowadays the production of the other chemistry type batteries does not stop, so it will be used the demand breakdown for 2030 provided by the Mckinsey Battery Demand Model to estimate the fraction of feedstock corresponded to each battery type.
 - **Lithium iron phosphate (LFP)**: Approximately 47% of the total.
 - **Nickel manganese cobalt (NMC)**: Approximately 42% of the total.
 - **Nickel cobalt aluminum (NCA)**: Approximately 11% of the total.
- By 2045, it is assumed that 100% of vehicle sales in the country will consist of electric vehicles (EVs). This assumption aligns with the goals outlined in the National Electromobility Strategy, which aims to promote a complete transition to electric mobility. The strategy includes a series of government policies and incentives designed to gradually phase out Internal Combustion Engine (ICE) vehicles, making way for EVs to eventually dominate the market. This assumption underpins our projections, positing that by 2045, electric vehicles will achieve a full market share, reflecting the intended impact of the National Electromobility Strategy on consumer demand and regulatory standards.

8 Results

8.1 PESTLE Analysis

8.1.1 Political

Chilean government has shown a strong commitment to environmental sustainability and renewable energy. Initiatives such as the National Electromobility Strategy aims to increase the use of electric vehicles [27], which will increase the demand for EV battery recycling facilities.

- **By 2035:**

100% of sales for light and medium vehicles, public transport (buses, taxis, and shared transport vehicles), and major mobile machinery (including extraction trucks and heavy mining machinery) must be zero emissions [36]. This will transform both urban mobility and industrial sectors through sustainable, zero-emission technologies.

- **By 2040**

The zero-emission requirement will expand to include 100% of sales for minor mobile machinery, such as construction, agricultural, and forestry equipment [36]. This ensures that smaller but essential mobile machinery used across various industries also aligns with the country's sustainable energy goals.

- **By 2045:**

The government aims for all cargo transport and intercity buses to be zero emissions by 2045, completing the transition of all major transportation sectors [36].

8.1.2 Economical

- **Growing EV Market:** Increasing adoption of EVs in Chile suggests a future surge in used Li-ion batteries, providing a steady supply of raw materials for recycling plants.
- **Stable Economy:** Chile's relatively stable economic conditions favor long-term investments and project financing.
- **Tax Credits for R&D Investment:** Fiscal incentives for companies investing in research and development of new recycling technologies. There is a 35% tax credit on research and/or development expenses. The remaining 65% can be considered as necessary expenses to generate income, regardless of the company's line of business. The annual tax credit cap has been increased to 15,000 Monthly Tax Units (UTM) per company [29].
- **Tariff Reductions:** Exemptions for importing advanced recycling machinery and technology. Specifically, this type of machinery reduce tariff from 6% to 0% [30].

8.1.3 Social

- **Environmental Consciousness:** Growing public concern for environmental issues may lead to increased support for recycling initiatives.
- **Employment Opportunities:** Establishing a recycling plant can create jobs, contributing to local economic development and social welfare.

8.1.4 Technological

The current recycling processes for used lithium-ion batteries (ULIB) in Latin America and the Caribbean (LAC) mostly reach only the mechanical treatment phase (crushing) and the subsequent separation of the different fractions (black mass, plastic, copper, aluminum). Recycling companies continue to depend on smelters in the Global North (Europe, North America, Asia) to export and recover the valuable materials [24]. However, this challenge presents a significant opportunity for technological transfer and advancement.

- **Advanced Recycling Technologies:** While such technologies exist globally, they have not yet been implemented in Latin America. Technology transfer is feasible with collaboration among investors, companies with expertise, and government support.
- **Smart Label:** It will be required that batteries contain a label providing the following information: identification of the manufacturer, country and date of manufacture, battery weight, battery capacity, composition (including chemical composition of the electrolyte, hazardous substances, among others), usable extinguishing agent [31].
- **Traceability:** The manager who collects batteries from mechanical workshops must declare the generation of this waste for those workshops that are not declaring them due to not being obligated or not complying with regulations. The recovery of batteries for which adequate traceability cannot be demonstrated (from the generator to the recovery plant) cannot be counted towards meeting the targets in recycling matter [31].

8.1.5 Legal

- **Extended Producer Responsibility (EPR) Law:** Chile's EPR law mandates that producers and importers are responsible for the end-of-life management of their products, including batteries. Compliance with this law creates a legal obligation for companies to ensure proper recycling, increasing demand for local recycling facilities. The government has initiated the process of drafting the Supreme Decree that establishes collection and recovery targets and other associated obligations for batteries as a priority product [25].
- **Temporary Reduction in Circulation Permits for Electric Vehicles (EVs):** As part of the new Energy Transition Bill, a temporary discount on circulation permits for EVs will be introduced. This measure, expected to take effect in 2045, aims to encourage the adoption of electric vehicles by reducing the financial burden on consumers, making EVs more accessible and appealing [36].
- **Basel Convention Compliance:** Chile's commitment to the Basel Convention imposes strict regulations on importing and exporting hazardous wastes like used lithium-ion batteries. Companies must obtain prior consent from authorities and provide detailed documentation for any cross-border movement of these materials.

8.1.6 Environmental

- **Circular Economy Promotion:** Recycling batteries conserves valuable resources like lithium, nickel, and cobalt, contributing to a circular economy.

8.2 Feedstock Estimations

To calculate the amount of batteries that will reach the end of their life, it is necessary to estimate the sales volume of electric vehicles. Sales volume directly impacts the number of batteries put on market, as each EV typically contains a lithium-ion battery pack. This estimation serves as the basis for projecting how many batteries will eventually need to be recycled or disposed. Once the volume is determined, the battery life cycle distribution can be modeled to estimate the number of batteries that will reach the end of their life each year.

8.2.1 EV Sales Projection

Using Equation (4) and Chile's historical data of EV sales as seen in Table 8, the parameters were obtained. The time frame was calculated through the first year of recorded historical data in EV sales (T_i) and the last year (T_f) through the fact that national policies determined that in 2045 the transition process from ICE vehicles to EVs is complete [36]. Due to established goals from the policies, the vast majority of vehicles should transition in 2035, however it is highly unlikely that the market will achieve this goal, which has been proven overly optimistic in various developed markets [36] [99]. The polynomial function (FC_{pol}) was obtained through the historical data shown in Table 8. On the other hand, the logistic function was determined by starting with the calculation of sales in the final year, using an adjustment that relates the average of the last three years of vehicle sales (371.851) with population growth (8,04%) giving a result of 401.748 vehicle sales in 2045 [35] [37]. Finally, to estimate the slope (α) and the year where EV market share reaches 50% (T_0) an iterative approach was used. Using the already known parameters and the historical data to cross-validate the results, giving values of 0,3892 and 2036,18 respectively.

$$FC(t) = \omega(t) \cdot FC_{pol}(t) + (1 - \omega(t)) \cdot FC_S(t)$$

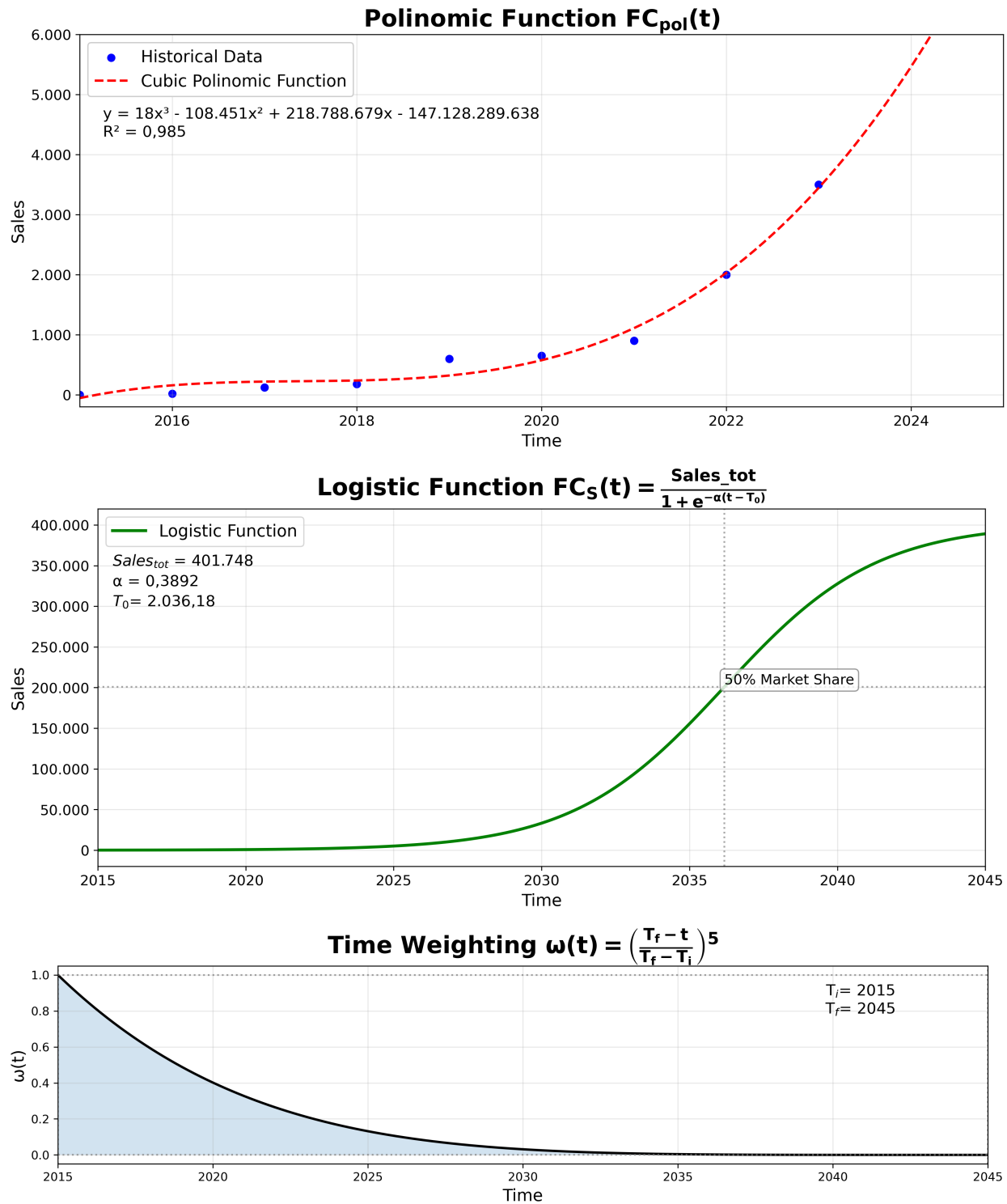


Figure 19: Components of the Electric Vehicle Sales Forecasting Model.

It can be seen that the polynomial function fits almost perfectly the historical data, with an $R^2 = 0,985$ and the logistic function has the typical adoption curve of new technologies. The time weighting function is responsible for giving relative value to the components of the model. It can be seen in Figure 19 that in 2030 the polynomial function loses its value almost completely, declining significantly from 2025. The function shows its ability to consider the polynomial function in the short term and the logistic function in the medium and long term.

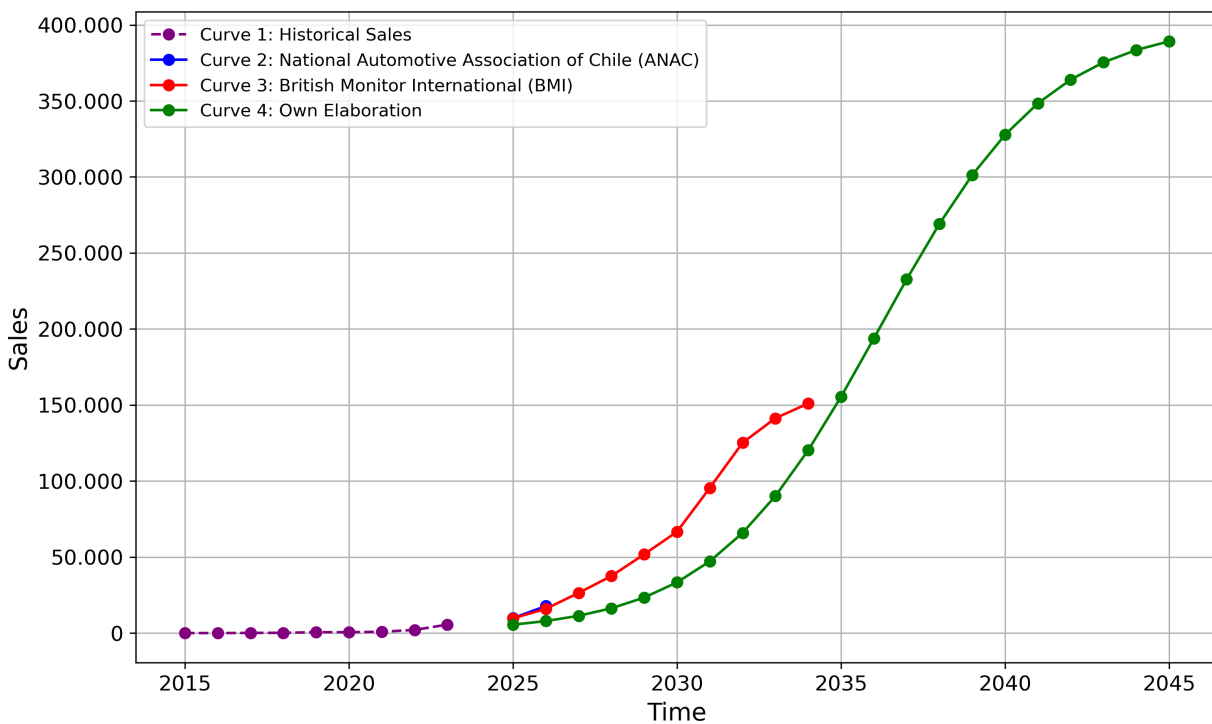


Figure 20: Projected EV Sales Comparison by Model [35] [99].

The available developed projections account only for the short and medium term. ANAC's and BMI's model are very close in short term (2025-2026) with a little gap between the elaborated one. On the other hand, in the medium term, it seems that BMI's model is more aggressive with values surpassing a gap of 50.000 sales in some years, finally converging in year 2034. Unfortunately, there is no model to compare with in the long term.

The final model presents a clear infancy, expansion and maturity phase:

- **Infancy phase (2015-2030):** During this period, EV adoption in Chile is relatively low, as the technology is still new, and the market was nascent. Consumers are still learning about and gaining awareness of EV options.
- **Expansion phase (2030-2040):** This is the period where we would expect to see a rapid increase in EV sales and market share, as the technology becomes more mainstream, charging infrastructure improves, and consumer adoption accelerates. The EV market would be experiencing significant growth during this phase.
- **Maturity phase (2040- 2045):** As the EV market reaches a higher level of saturation, the growth rate may start to slow down, and the market share of EVs may stabilize or experience more gradual increases. In 2045 it is expected around 400.000 electric vehicles sales.

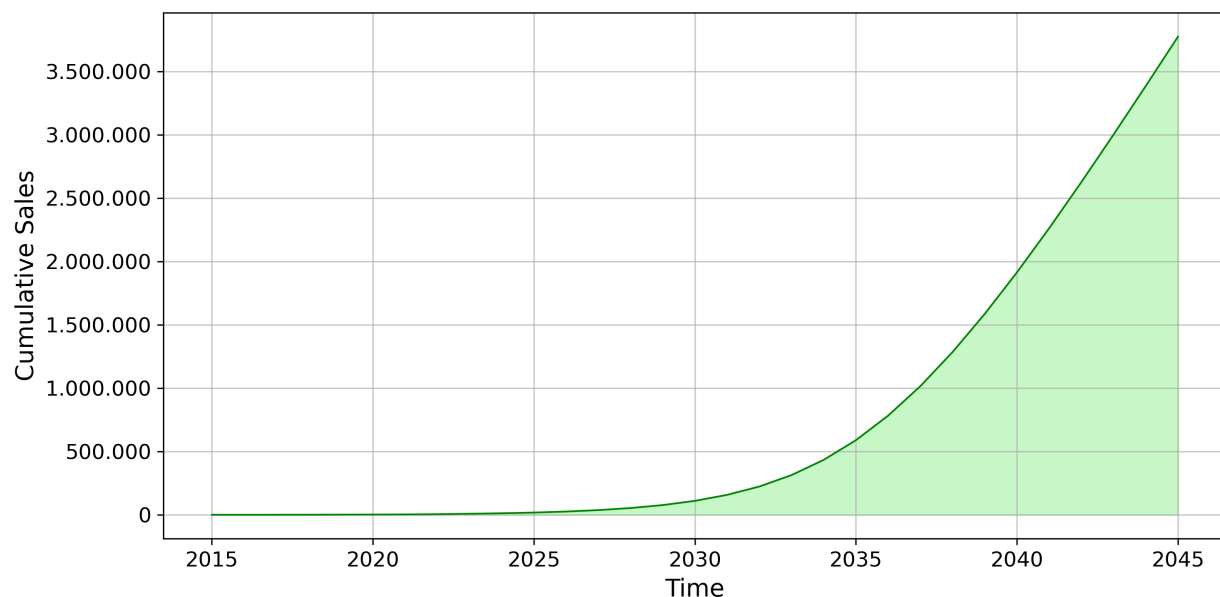


Figure 21: Cumulative EV Sales in Chile.

Up until 2030, cumulative EV sales growth is relatively moderate, with 109.796 EVs projected to be in circulation by that point. This value is very near to what the Latin American Energy Organization projected by 2030, with an EV fleet of around 93.000 [76]. From 2030 onwards, the rate of EV accumulation accelerates dramatically.

By 2040, the cumulative EV sales are projected to reach 1.790.709 units - a nearly 19-fold increase from 2030 levels. This period of rapid EV adoption, from 2030 to 2040, will be a critical time of transformation for the country's transportation landscape.

During this period of exponential EV growth, the country will need to make substantial investments and improvements to its EV charging infrastructure to support the surging number of electric vehicles. This will require coordinated efforts between the government, automakers, and energy providers to ensure the necessary charging capacity is deployed across the nation.

8.2.2 EOL EV Battery Estimations

As suggested by the Committee responsible for establishing the Extended Producer Responsibility Goals in Chile, it can be mathematically described the way batteries end their useful lifes using a Weibull distribution described in Equation (5) and (6) [32].

With due regard to the limitations of the parameters, and following Fallah's et al. (2021) approach, the parameters ($\alpha = 11$ & $\beta = 3,2$) to develop the Weibull distribution described in Equation (6) came from a larger market in which sales started early. Once having the distribution, the amount of EOL EV batteries is calculated through Equation (5) and the already known sales values from Figure 20.

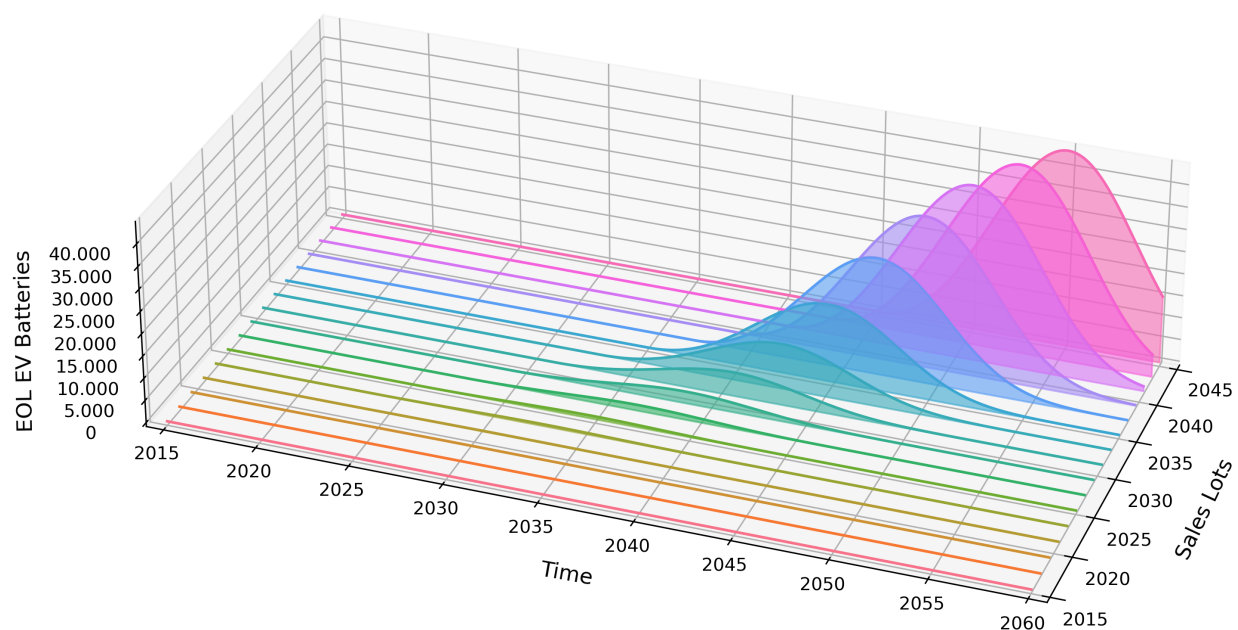


Figure 22: Applied Weibull Distribution Behaviour in Equation (5).

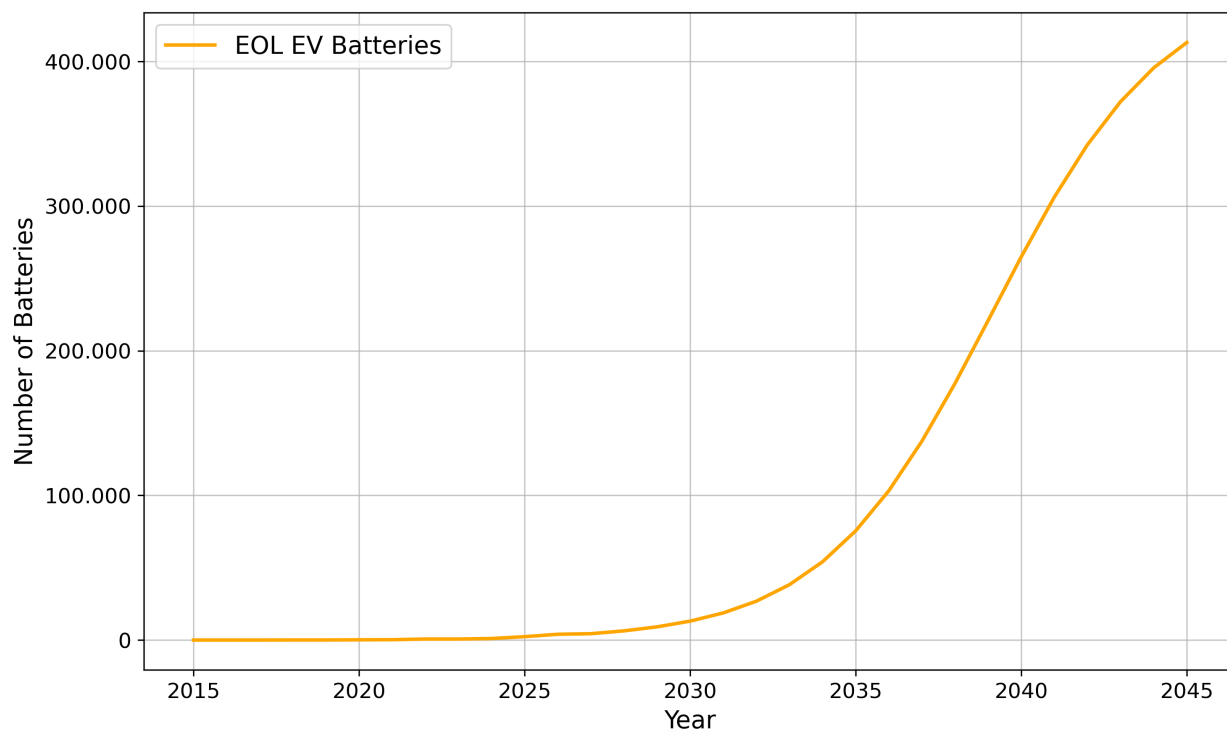


Figure 23: Projected EOL EV Batteries by Year.

In Figure 22 it can be seen how batteries end their useful life depending on the year of sale (sale lot). Using Equation (5) to add the batteries of each lot, it is possible to determine the amount of batteries that end their useful life in a specific evaluation year.

The amount of EOL EV batteries in Chile starts to become significant in 2030 as seen in Figure 23 with 13.066 units. At this time, 42.118 batteries will be discarded. In 2045, the rate of EOL EV batteries will be 413.130 with an accumulation of 2.989.051 units if no action is taken.

8.2.3 Collection Rate

While Chile leads Latin America in electric mobility adoption, it currently lacks specific collection targets for electric vehicle lithium batteries. It would be reasonable to adopt Colombia's established targets (Table 10) as a benchmark due to their development of a comprehensive framework for battery collection that aligns with international standards [39].

The collection rate is indispensable to make any projections because it gives the final battery mass collected which can be used to recycle. This rate depends on the effort of many agents in the system, such as regulators and the private sector.

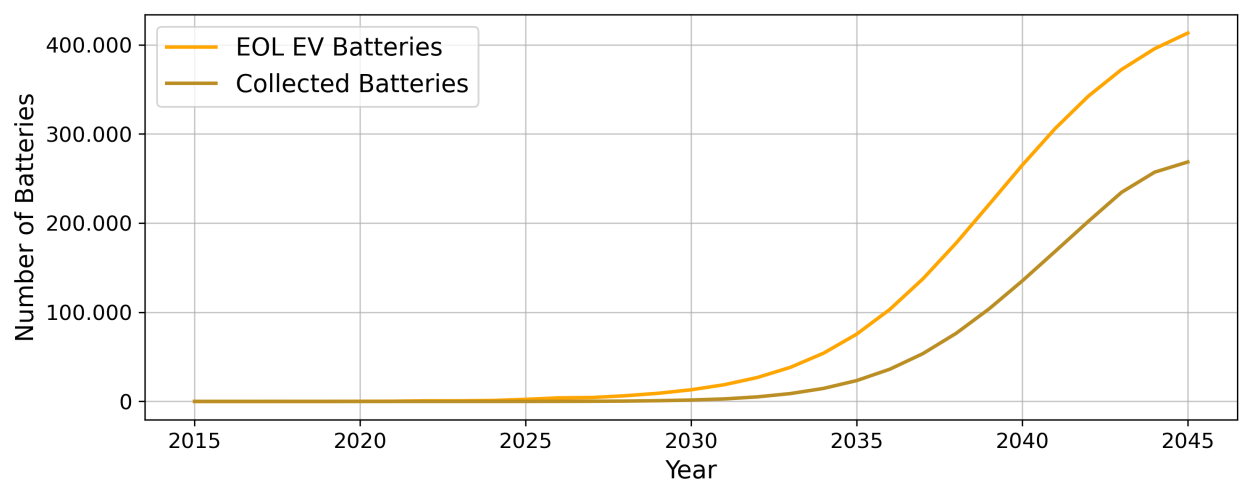


Figure 24: Proposed Regulatory EV Battery Collection Targets in Chile.

8.2.4 Mass Estimation

To estimate the mass that could enter the recycling plant three type of data was used: vehicle distribution (Table 9 and Figure 10), battery capacity (Figure 10), battery market share by chemistry (Figure 5.2.3) and energy density (Table 11).

$$\sum_j^m \sum_i^n \frac{\text{Battery Capacity}_i \cdot \text{Collected EOL Batteries}_i \cdot \text{Battery Market Share}_j}{\text{Battery Density}_j} \quad (10)$$

- $i = \text{vehicle type}$
- $j = \text{battery chemical composition}$

The mathematical procedure considers that vehicle types market share will be constant. It starts with the estimation of collected EOL batteries by vehicle type, multiplying the corresponding market share with the total amount of collected EOL batteries. Once having this value, it is possible to calculate the total amount of battery capacity specific to the vehicle. This quantity is in kWh and then is multiplied by the expected battery market share by chemical composition to then be divided for its respective battery density (kWh/ton) to finally have the particular ton measurement. This process is done for every vehicle type i and every battery chemical composition j until m vehicles and n battery chemistry types are considered.

The results seen in Figure 25 indicates that in 2036 the annual battery mass collected from EOL batteries will reach 10.000 tons in various chemistry types, having different types of critical materials in them. From this year the amount of waste increases dramatically until 2045, where EV market share reaches 100%. The country could be producing around 80.000 tons of EOL EV

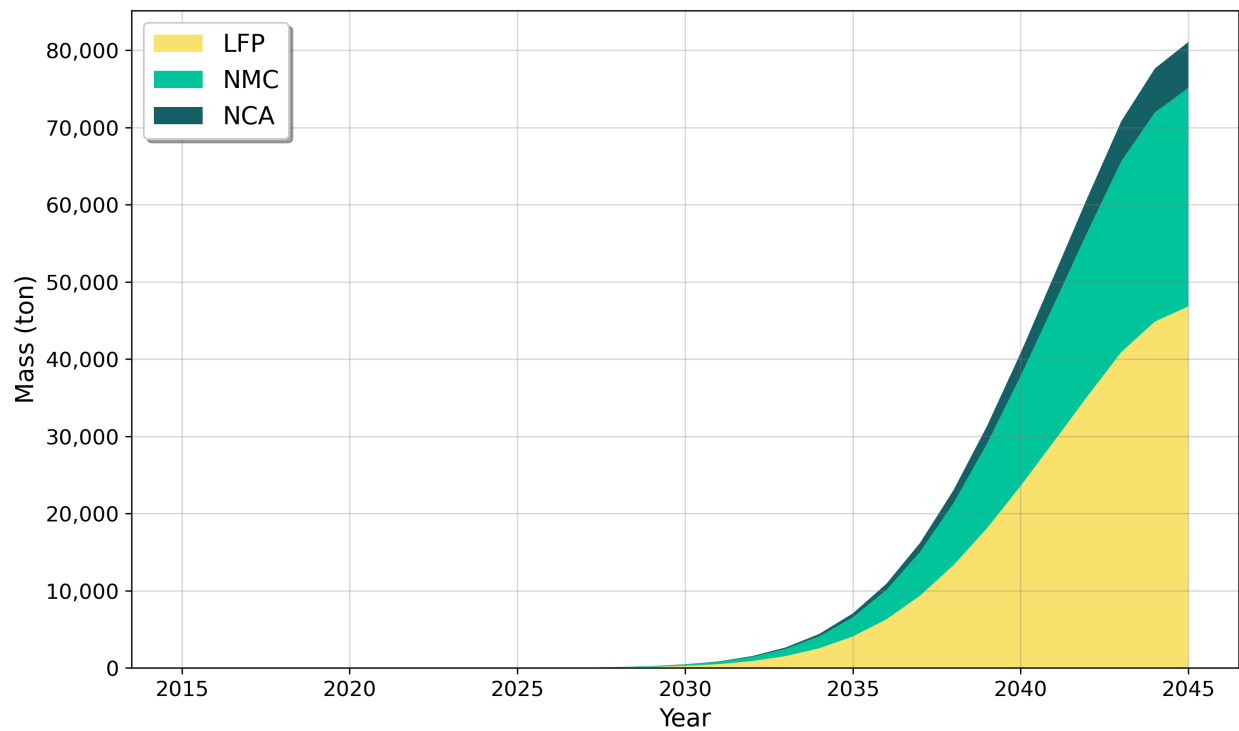


Figure 25: Annual Battery Mass by Chemistry Type.

batteries each year. LFP dominates the field with 46.838 tons, coming second is NMC with 28.281 tons and finally NCA with 5.958 tons. In total, if the situation is left unaddressed, the country could be collecting 481.096 tons of batteries in collection centers until this date.

8.3 Model Analysis

The model analysis will be divided into two main facilities: a recycling plant and a battery factory, each one having its own process. It should be noted that each facility could work individually and that if the recycled feedstock is not sufficient for battery production, the factory can buy materials at market price.

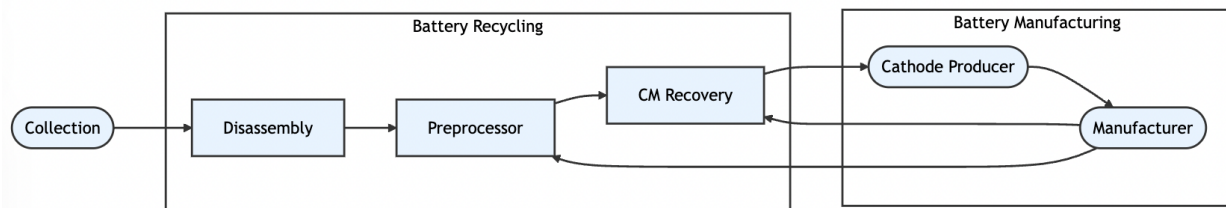


Figure 26: Battery Recycling and Manufacturing Process Flow.

8.3.1 Time of Evaluation

The recycling plant is expected to start working in 2045 due to the constant feedstock volume from EOL EV batteries, which gives the plant an almost constant feedstock to process, facilitating evaluation procedure.

Battery factory is assume to already be builded when the recycling plant is finish its construction, making manufacturing calculations easier to obtain and understandable.

8.3.2 Collection and Transportation

The recycling plant's location selected is Santiago due to its proximity to the highest supply of EOL batteries. There is a distance from the collection center(s) to the plant considered as the radius of Santiago city (24,86 miles) since there are no type of this facilities yet.

On the other hand, the battery factory's location is Antofagasta, since there are already projects of this matter in the zone and due to its proximity to material. The distance between the recycling plant and the battery factory is considered as 898 miles.

8.3.3 Recycling Plant Characteristics

The analysis will focus solely on hydrometallurgy as a result of its environmental and economic superiority, which processes per year as seen in Figure 25: 5.958 tons of NCA, 46.838 tons of LFP and 28.281 tons of NMC(811) batteries individually or jointly.

8.3.4 Factory Production Capacity and Chemistry

It is considered a production of 80 GWh/year, which is derived from a Tsingshan Holding Group reference plant investment case of 120.000 ton/year cathode material production [100].

The analysis focuses merely on NMC(811) battery manufacturing because it is expected an important market share in the future. Also, the current model is not able to analyze the fabrication of LFP batteries, which is another type worth analyzing due to its projected market share.

8.3.5 Processes Involved

- Dissassembly: vehicle battery pack removal and disassembly into modules and cells.
- Preprocessing: treatment of battery cells to produce black mass and other products.
- Critical Material Recovery: extraction of valuable metals from black mass.
- Cathode Production: synthesis of new cathode using recovered metals or virgin materials.
- Battery Production: assemble battery packs ready for installation in vehicles.

8.4 Battery Recycling Results

Different types of recycling plants can be made. The alternatives consider volume and type of stock to feed the plant and the recycling method, which directly affects in plant capacity. However, the main objective is to recycle the most amount of batteries while being profitable, so full feedstock will be evaluated.

The following analysis takes into account various indicators to determine whether an alternative is economically feasible or not, following model specific suggestions and metal market cost of capital rates for emerging countries, considering a cost of equity of 13,81% and a cost of debt of 7,38% in USD [106]. It starts with CAPEX and OPEX estimation followed by a micro-analysis of feedstock recycling per kilogram (average material prices). It also takes into consideration risk, addressing specific material price volatility with Table 16 values to calculate economic indicators such as NPV, IRR and Payback. The income statement considers a plant life of 10 years.

Recyclers may also be required to pay for batteries they process. The battery fees to the recyclers assumed for NCA and NMC (solicited from industry sources) are 1/3 of its market value in nickel and cobalt [62]. Due to the lack of these materials in LFP batteries, a suggested assumed static payment to recyclers of 2,00 \$/kg is needed to make the return more attractive [62].

This case presents a plant capacity of 122.000 tons to operate 81.077 tons annually. Feedstock combination corresponds 58% to LFP, 35% to NMC(811), and 7% to NCA batteries. Required investment of each individual item is obtained using Table 17 as a reference to build a detailed breakdown in Table 2, giving a total of \$165.625.132 in CAPEX.

On the other hand, OPEX ascends to \$60.997.664, which varies slightly depending on price material change and considers raw materials, labor cost, maintenance, etc.

Table 2: Capital Expenditures Breakdown for Recycling Plant.

Item	Cost
A. Inside battery limits (ISBL) plant cost	\$ 76.404.167
Purchased Equipment	\$ 23.876.302
Equipment erection	\$ 11.938.151
Piping	\$ 14.325.781
Instrumentation and control	\$ 7.162.891
Electrical	\$ 4.775.260
Civil	\$ 7.162.891
Structures and buildings	\$ 4.775.260
Lagging and paint	\$ 2.387.630
B. Offsite battery limits (OSBL) cost	\$ 30.561.667
C. Design and Engineering Cost	\$ 26.741.458
D. Contingency	\$ 10.314.563
E. Working Capital	\$ 21.603.278

Transportation costs ascends to \$0,94 per kilogram of feedstock and involves the use of a medium-duty truck to move the batteries from the collection center to the recycling plant. Considering the hazardous material classification that makes transportation more expensive than usual, the goal is to have the minimum distance between these two facilities. Disassembly costs of \$0,17 per kilogram of feedstock comes from labor required to remove the packs from the vehicle, disassembly down to modules and then to individual cells. There is also revenue in this process, which comes from the mass left when cells are completely detached, having around 180 kilograms of available material to be recovered mainly in steel, copper and aluminum as seen in Figure 27 and although steel is the material to be possible to recover the most amount of mass (107,82 kg), aluminum (49,28 kg) and copper (12,38 kg) are the ones that significantly drive the revenue with their relative higher market price per kilogram.

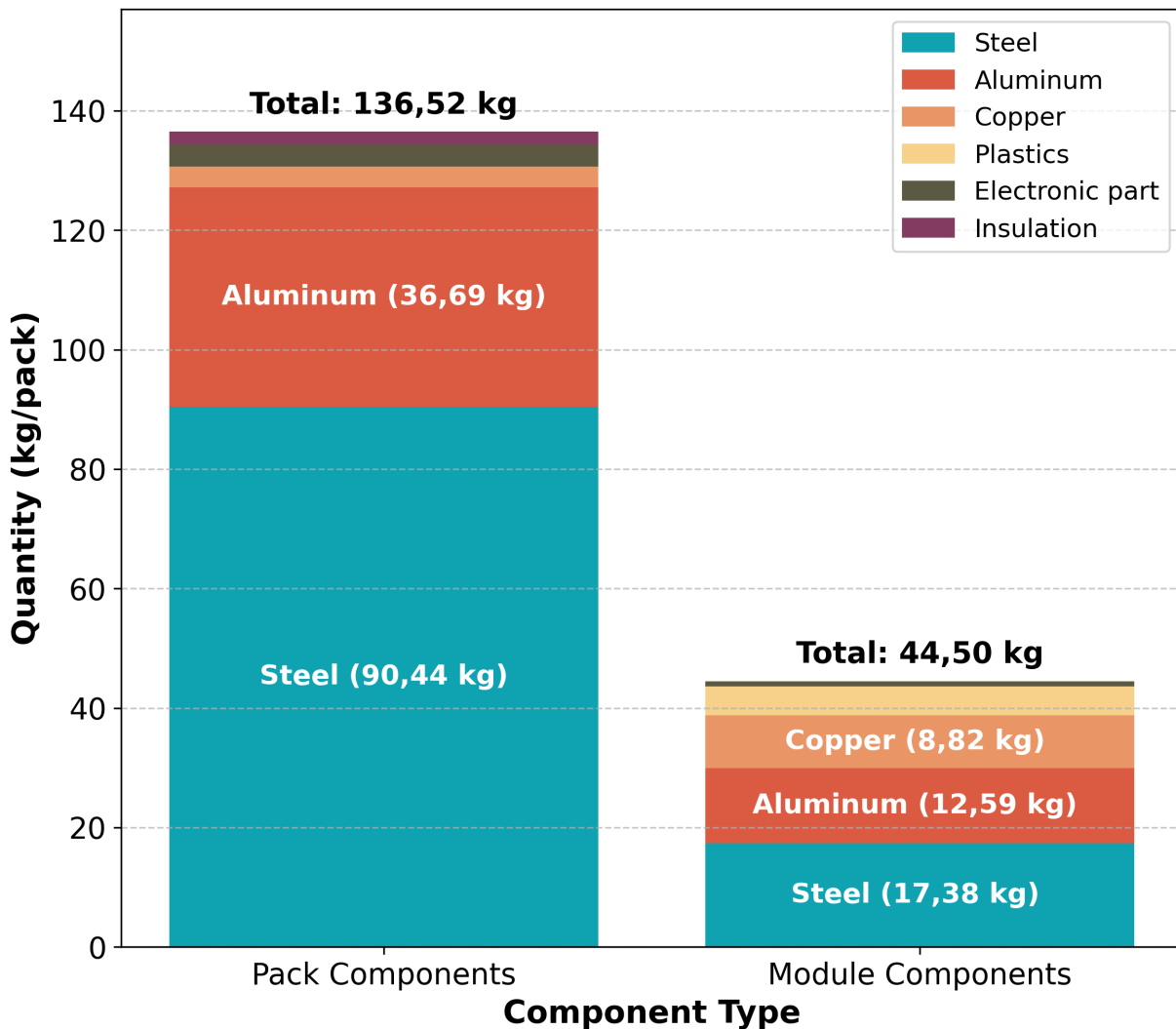


Figure 27: Recovered Components in Disassembly.

The main part of the analysis consists in the use of simulations to evaluate various scenarios. In this case, historical data and code is used to develop possible material prices and then apply them to the model to determine probability distributions of key economic indicators, sensitivity of outcomes and risk assessments. A particular minimum number of simulations is needed to give the results statistical significance, allowing the data generate a clear normal distribution in results. However, there must be a balance between the results and computational usage to minimize the simulation time. This equilibrium is reached at 5000 simulations, as seen in Figure 28.

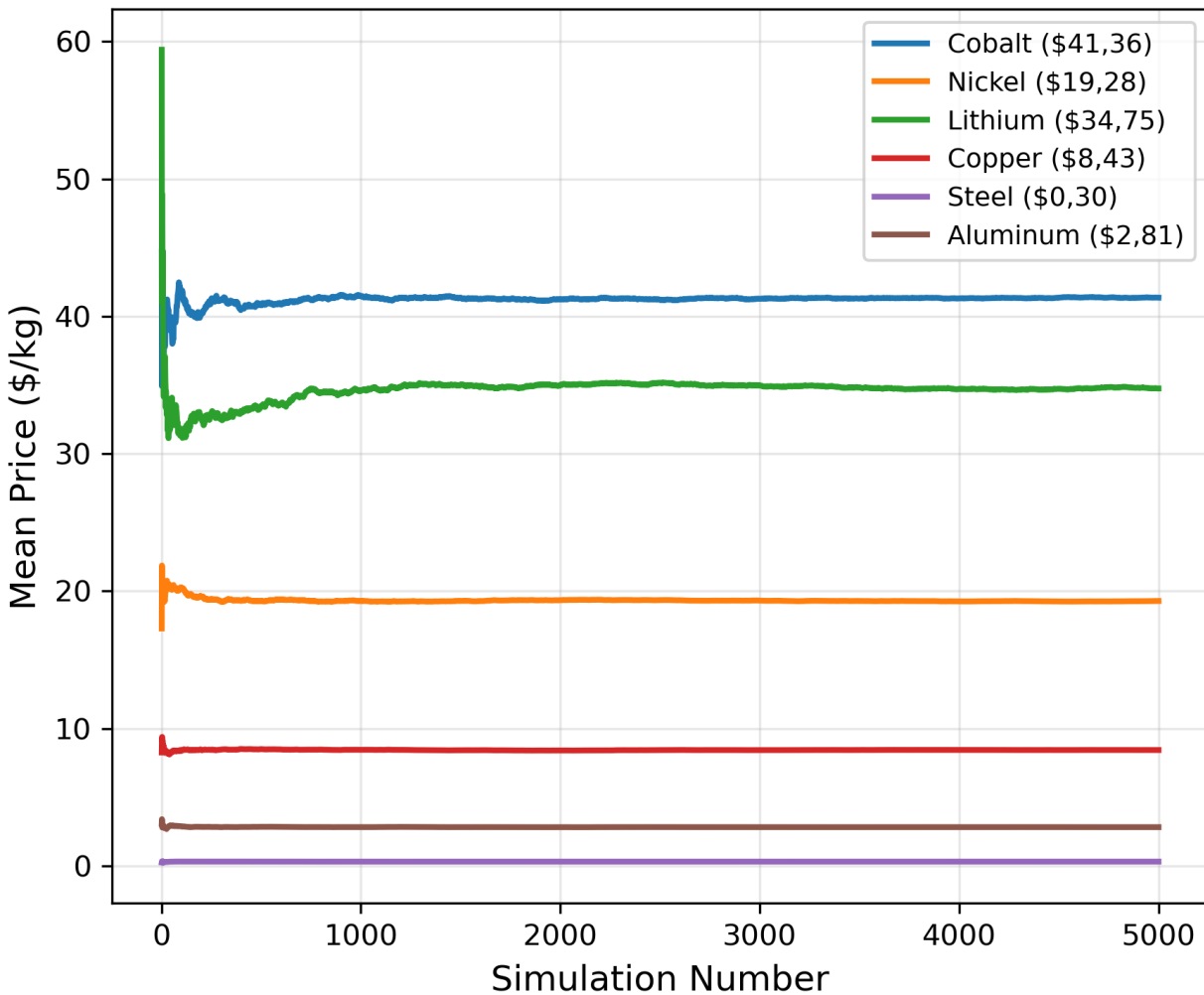


Figure 28: Mean Material Prices Evolution Across Simulations.

Expected results considers the convergence of the mean of simulated prices in Figure 28 with the historical ones in Table 16, which happens in almost every material with less than 1% error. A particular case occurs with lithium carbonate price simulations due to its high standard deviation. Raw prices do not have an upper limit, but have a lower limit from the minimum selling price close to \$0, and this is noticeable in Figure 29. Due to this, higher raw price simulations deviate the mean price relatively higher ($\approx 15\%$). To solve this problem, median prices are used (as in symmetric distributions should be similar), reducing lithium prices error to around 10%.

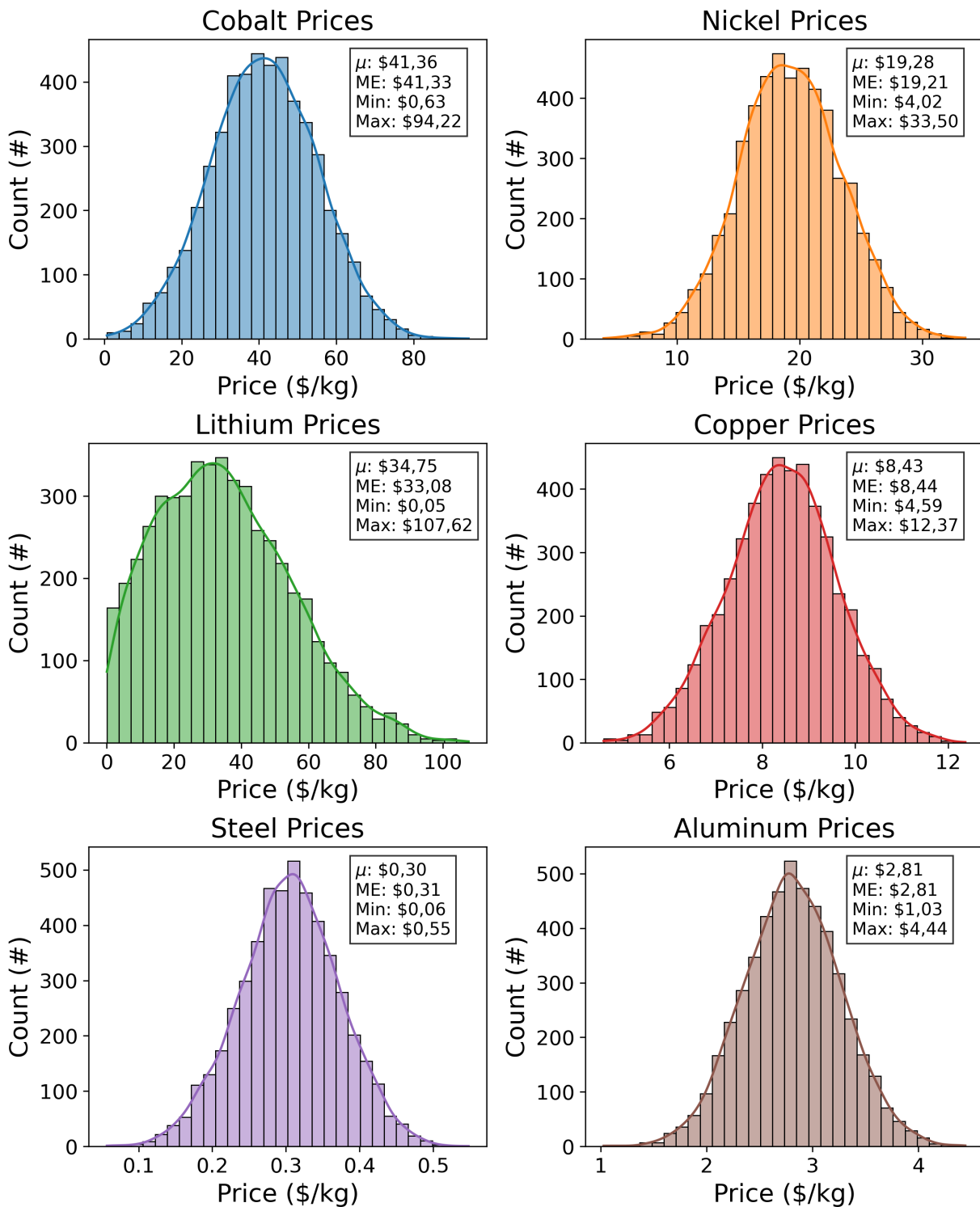


Figure 29: Material Prices Distribution.

The final operational revenue is primarily generated from the sale of materials recovered through the recycling process. For this specific feedstock, processing 1 kilogram yields approximately 12,1% crude lithium carbonate, 1,2% cobalt (Co^{2+} in product), 8,6% nickel (Ni^{2+} in product), 0,8% manganese (Mn^{2+} in product), and 22,7% graphite, leaving the rest in solid and water waste. Based on the total processed tonnage, this corresponds to a potential recovery of approximately 9.813 tons of crude lithium carbonate, 957 tons of cobalt (Co^{2+}), 6.995 tons of nickel (Ni^{2+}), 671 tons of manganese (Mn^{2+}), and 18.442 tons of graphite.

The economic allocation of the recycling revenue varies depending on the actual market prices of the materials and can be modeled as shown in Figure 30. The data show that, in most cases, the overall revenue is primarily driven by the sale of lithium carbonate, followed by nickel and, lastly, cobalt.

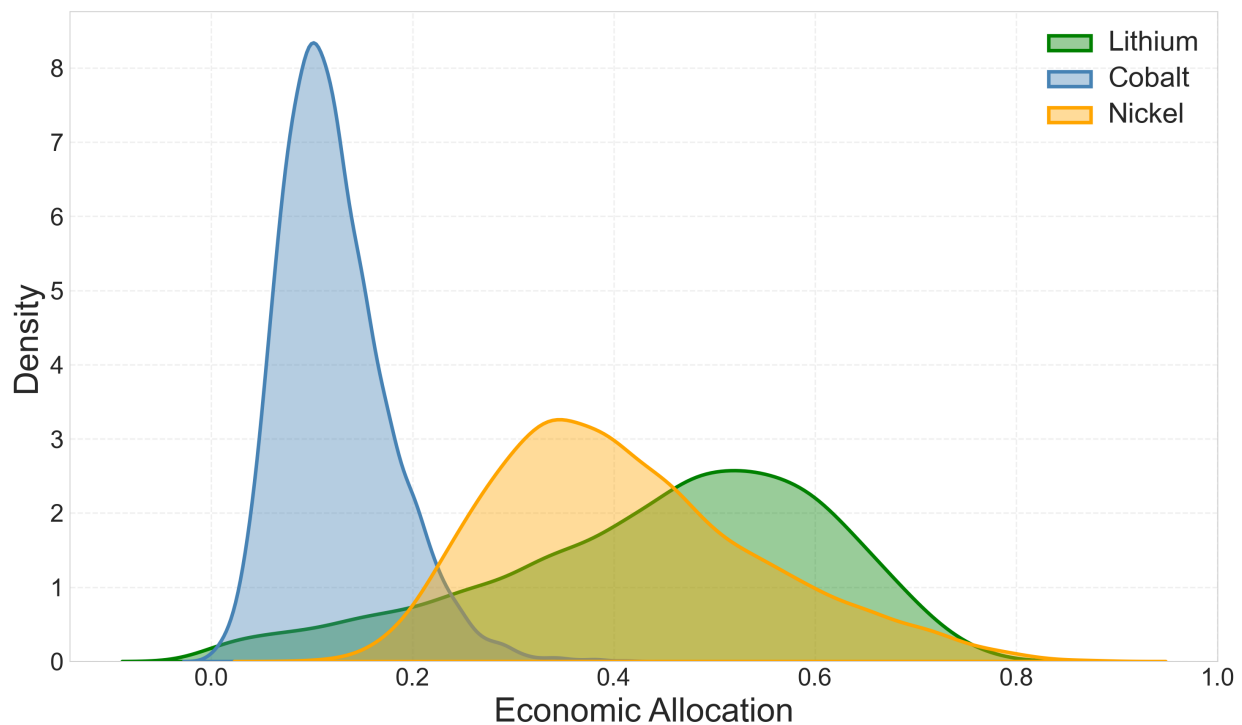


Figure 30: Economic Allocation From Recycling Revenue.

Cash flow development considers 5 years in plant construction, starting in 2040, and the beginning of the operation at year 6 (or 2045). Two cases were evaluated, a debt-free scenario and another with debt as can be seen in Figure 42 and Figure 43. The second subject to a maximum debt-equity ratio of 75%, so first two years of construction are completely done with own capital. As a result of the access to cash flow, economic indicators can be determined.

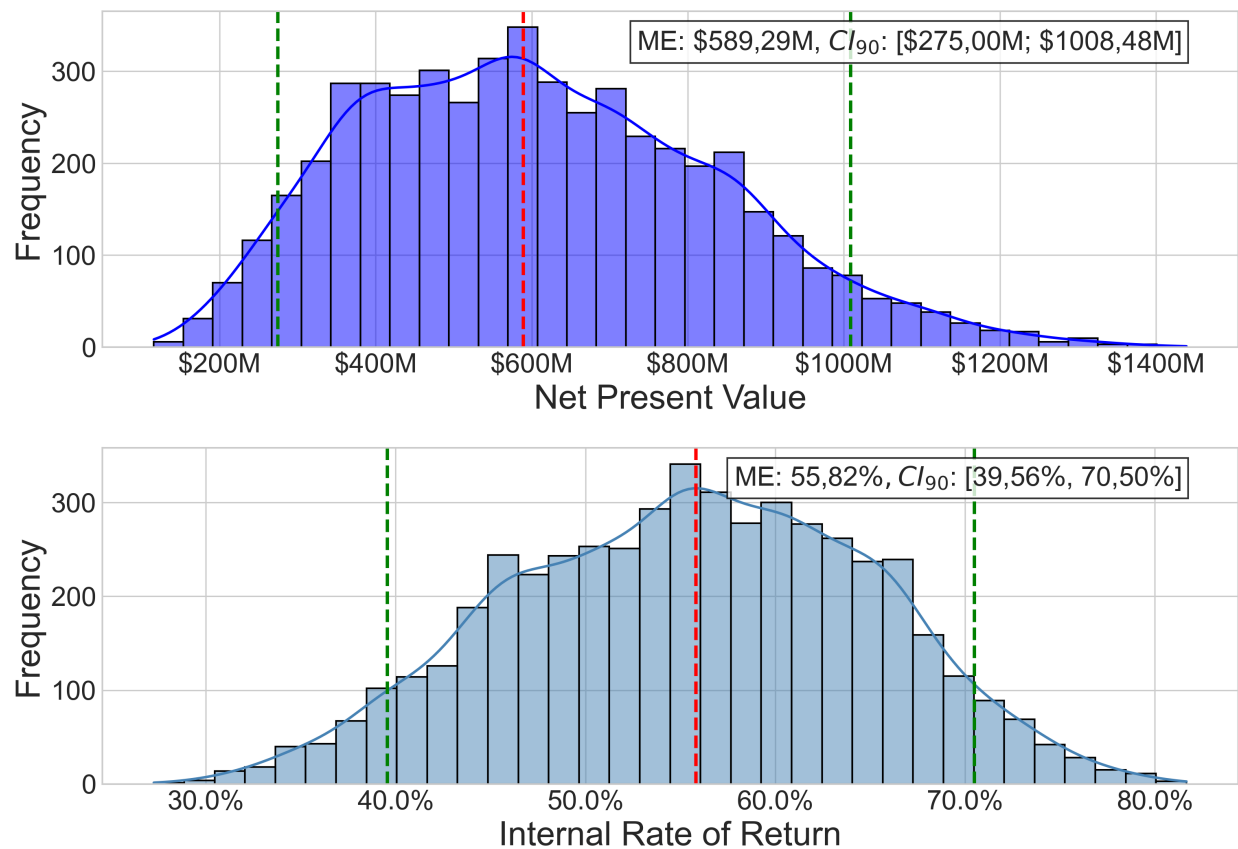


Figure 31: Risk Analysis of NPV and IRR in a Debt-Free Scenario.

The results obtained in Figure 31 and Figure 32 show that in both cases (equity and debt use scenarios) the 90% confidence interval of the NPV is always positive, which translates into a profitable project regardless of material prices. The use of debt makes the median NPV and IRR ascend in \$63,78M and 13,54% respectively, which indicates that the use of this tool brings a significant improvement in the project's financial performance. Calculated present value index

median of 3,60 and 3,98 presents a healthy profitability-investment ratio for both cases. On the other hand, payback oscillates between year 6 and 7 for the debt-free scenario and is maintained at year 6 with the use of debt, which indicates that the investment is recovered a year or two years into the operation of the plant.

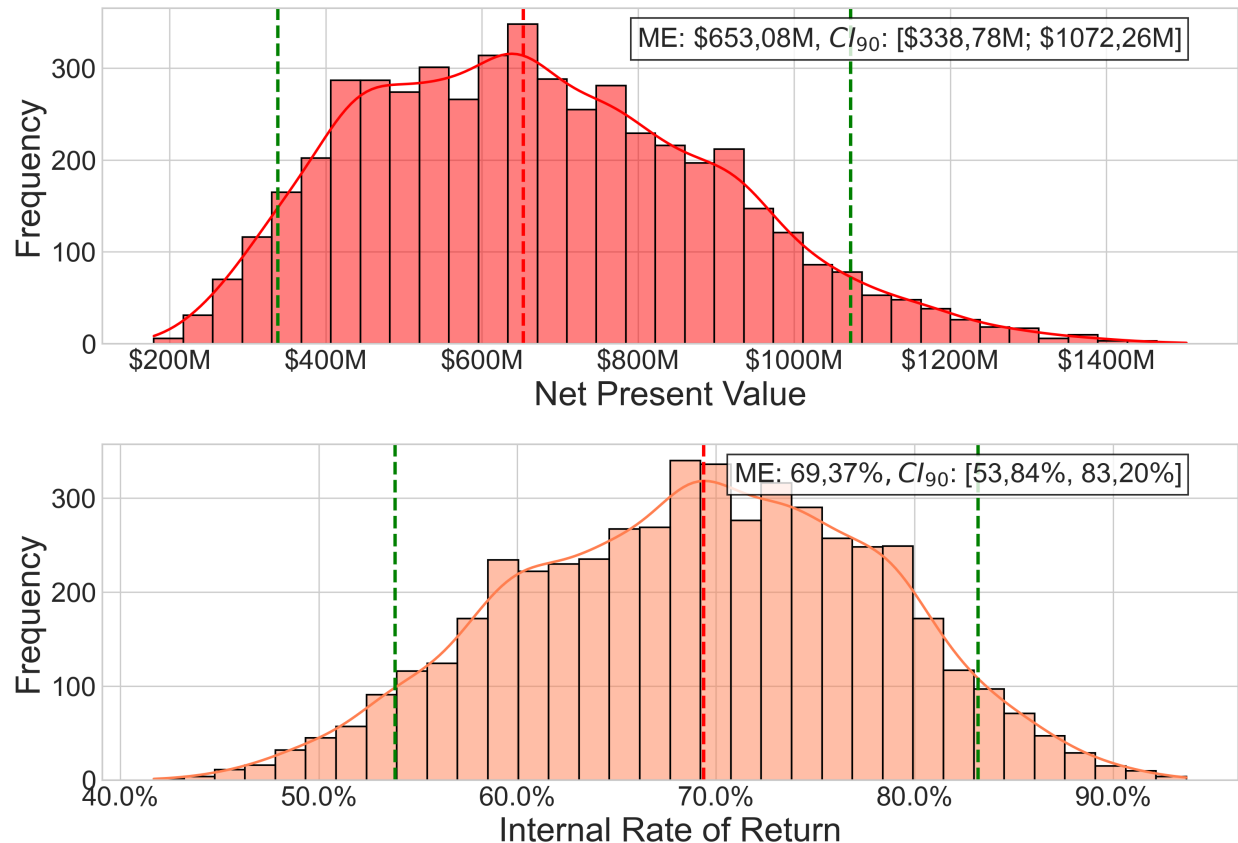


Figure 32: Risk Analysis of NPV and IRR in a Debt Scenario.

In summary, this project has strong fundamental financial indicators that present the project as a good investment option regardless of material price volatility. IRR values exceed in various digits the average return on the industry, adding this with the lack of risk, the only worry is where to find the money with strategic partners that can allow this project become a reality. The set of these must have the capital and the knowledge to build the plant and to operate an hydrometallurgical process with desired efficiency to maximize return on investment.

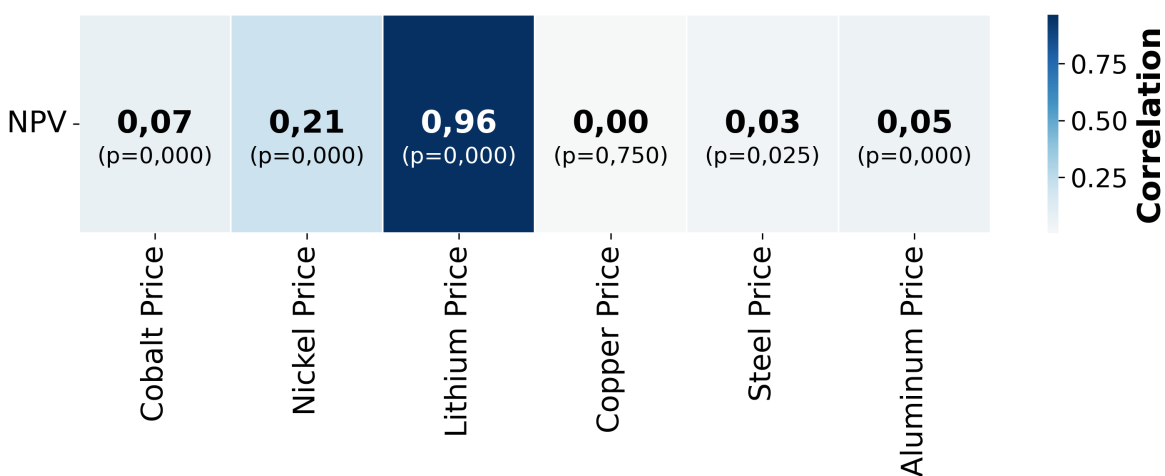


Figure 33: NPV Correlation with Material Prices.

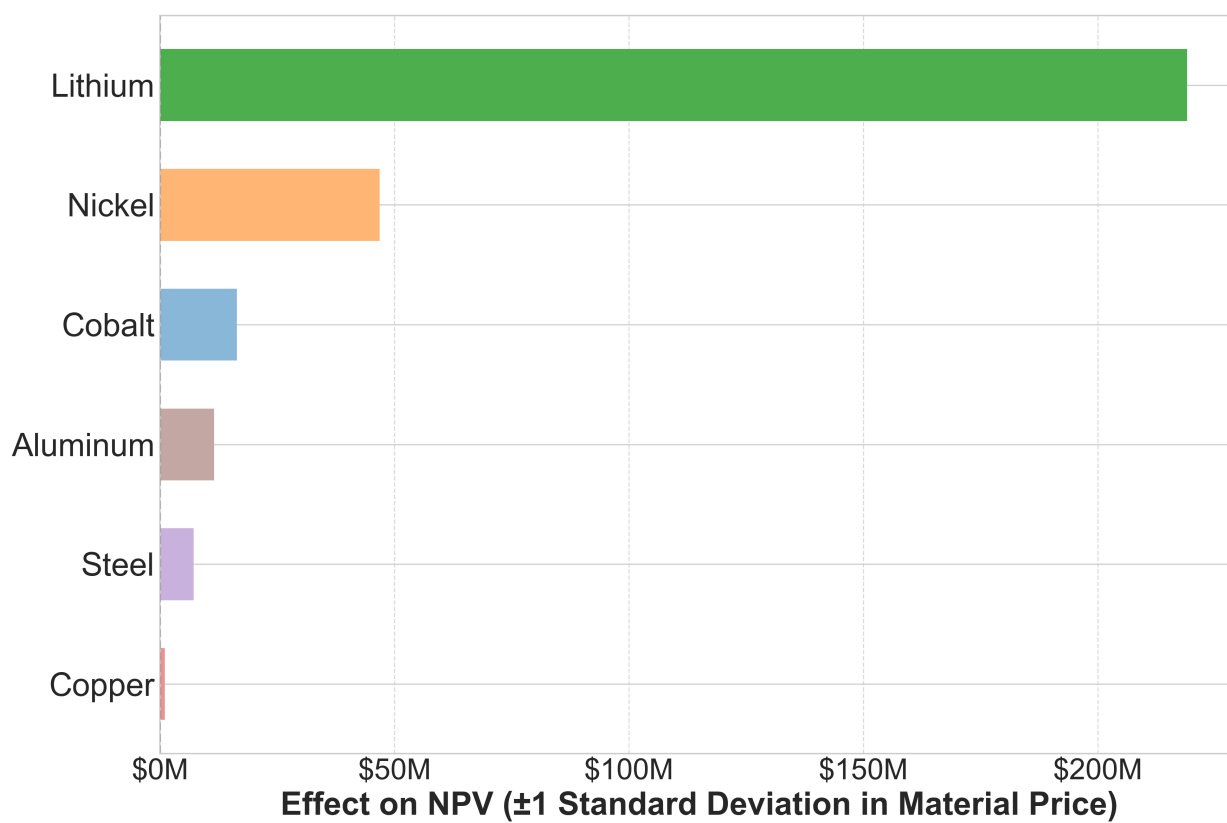


Figure 34: Impact of Material Price Variability on NPV.

The correlation is an important indicator to measure the strength and direction between two variables and can be seen in Figure 33 considering material prices effect on NPV. On the other hand, it is important to address statistical significance to dismiss a correlation value given due to randomness. Only cobalt, nickel, lithium and aluminum prices present a p-value under 0,05, so the correlation is statistically significant in these cases.

There is combination of two factors that make the correlation between material prices and NPV strong or weak, which are: price volatility and yield from feedstock through hydrometallurgy. The effect on price volatility can be seen directly in the tornado chart in Figure 34. The effect of lithium prices moving into its standard deviation can make an impact of around \$230M, while the impact of the following material, nickel, reaches a fifth of this value, with almost \$50M.

The interpretation of the results in Figure 33 indicates that NPV increases significantly and predictably when lithium prices rises ($corr = 0,96$) in its historical normal range, followed by nickel prices ($corr = 0,21$).

8.5 Battery Manufacturing Results

8.5.1 Cathode Production

The facility is able to produce annually 15.793 tons of NMC 811 cathode powder. The above assuming the complete use of cobalt sulfate amounts.

Table 3: Capital Expenditures Breakdown for Cathode Production.

Item	Cost
A. Inside battery limits (ISLB) plant cost	\$28.368.130
Purchased Equipment	\$8.865.040
Equipment erection	\$4.432.520
Piping	\$5.319.024
Instrumentation and control	\$2.659.512
Electrical	\$1.773.008
Civil	\$2.659.512
Structures and buildings	\$1.773.008
Lagging and paint	\$886.504
B. Offsite battery limits (OSBL) plant cost	\$18.912.086
C. Design and Engineering Cost	\$11.820.053
D. Contingency	\$4.728.021
E. Working Capital	\$9.574.243

The investment in CAPEX ascends to \$73.402.533, in which purchased equipment stands out as the most costly item. On the other hand, it is possible to make a comparison in OPEX considering material origin: virgin or recycled. Thanks to savings in raw material costs, manufacturing costs present and general expenses present a significant decrease. The effect of using recovered materials from hydrometallurgy reduces OPEX in 72,30%, from \$75.933.174 to \$21.037.218 a net difference of \$54.895.956 in annual savings.

The battery factory can transform the recovered materials and use them directly into cathode powder production to continue with battery manufacturing, greatly reducing the need to reach to the market. Annually, available materials for battery production are: 2.516 tons of cobalt sulfate, 18.434 tons of nickel sulfate, 9.813 tons of lithium carbonate and 1.845 tons of manganese sulfate.

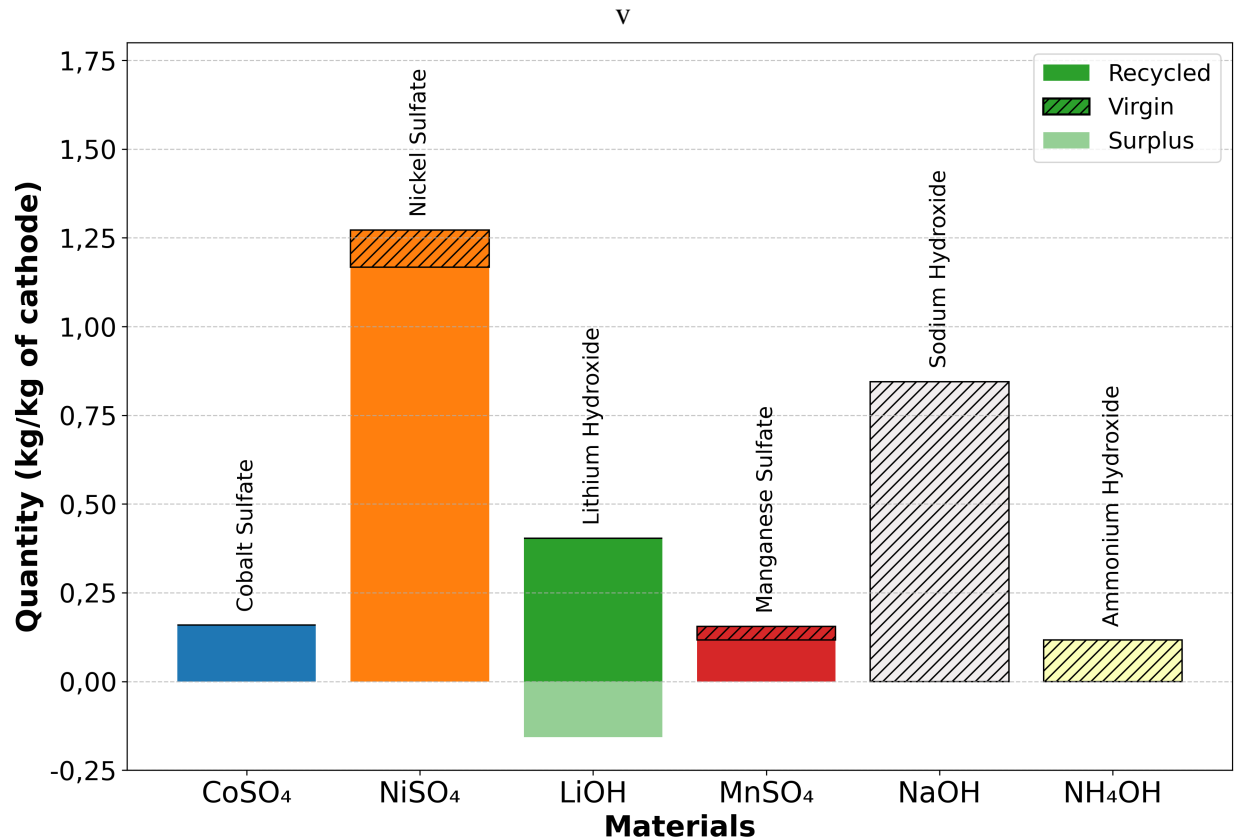


Figure 35: Required Material to Produce Battery Cathode.

The quantities of material required to produce one kilogram of cathode can be seen in Figure 35, where three categories are stacked into the bar for each material. It is noted that most of the material needed to fabricate batteries are available from recycling, also that nickel and manganese sulfate recovered quantities are not sufficient to produce a kilogram of cathode by itself, so market reach is required along with sodium and ammonium hydroxide. On the other hand, there is a considerable surplus of lithium hydroxide that can be directly sell to the market.

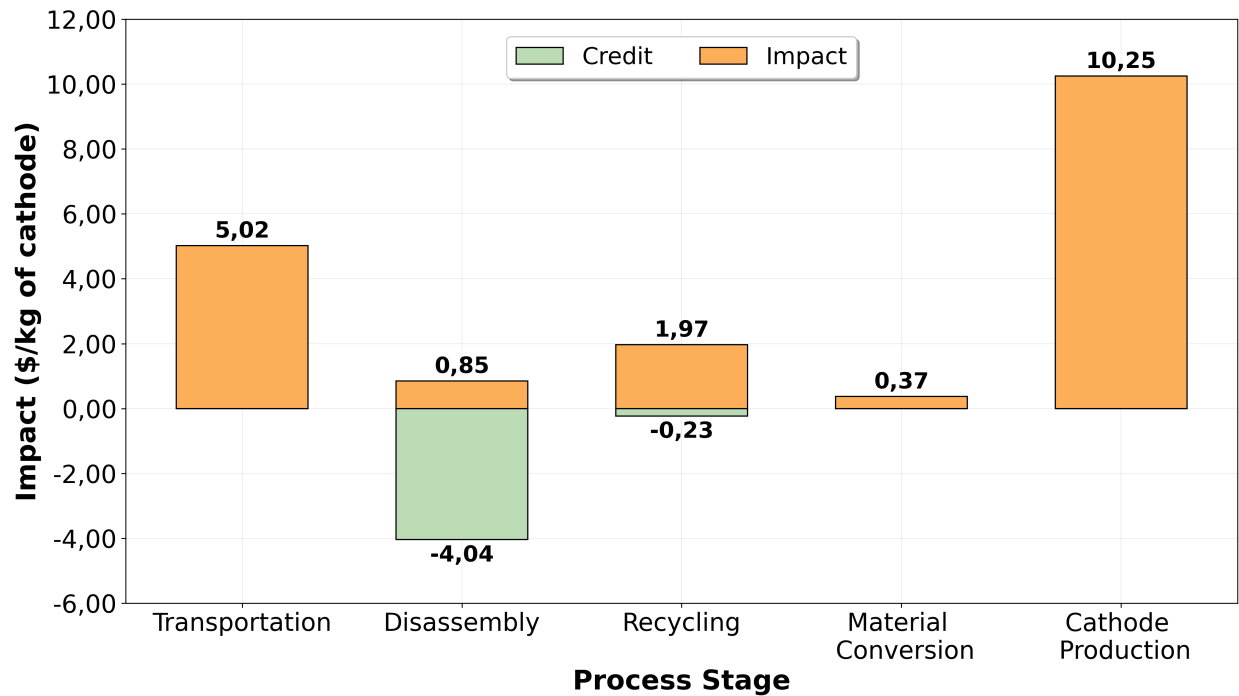


Figure 36: Closed-loop Recycling Impact Breakdown of Costs for Cathode Production.

Note: Recycling credits are given to materials that are recovered but not used to produce new cathode powder, such as Al and Cu.

The final cost to produce cathode powder, adding impact values and subtracting credits, is \$14,19 per kilogram of cathode. As shown in Figure 36, the processes contributing most significantly to this cost are transportation and cathode production. Disassembly, on the other hand, plays a crucial role by generating significant revenue, which effectively lowers the final production cost.

8.5.2 Battery Production

Using all the cathode powder produced in the previous stage, the battery factory can annually produce 32.241 tons of NMC 811 cells.

Table 4: Expenditures Breakdown for Battery Manufacture.

Capital Expenditures	\$909.181.665
Launch cost	\$26.464.393
Working capital	\$75.628.978
Capital equipment	\$777.434.084
Building	\$29.654.210
Operational Expenditures	\$641.183.260
Materials	\$479.093.514
Direct labor	\$6.606.680
Depreciation	\$79.225.292
Variable overhead	\$18.487.730
General, sales and administration	\$26.079.925
Research and development	\$31.690.116

Thanks to Table 4, it can be said that the stage of more investment involvement corresponds to the manufacture of batteries. CAPEX ascends to \$909.181.665, more capital than all the value chain together, and OPEX maintains at \$641.183.260, with raw materials being the main contributor to the last with 70.86% in allocation.

The effect between the use of virgin or recycled materials in cost can be seen in Figure 37. Considering the median, it reduces the fabrication cost of batteries in 46,0%. On the other hand, analyzing each distribution individually, the confidence interval of the batteries produced from recovered material is 37,3% smaller than the one who uses virgin materials, indicating that the use of recovered materials creates a kind of shield in the face of material volatility.

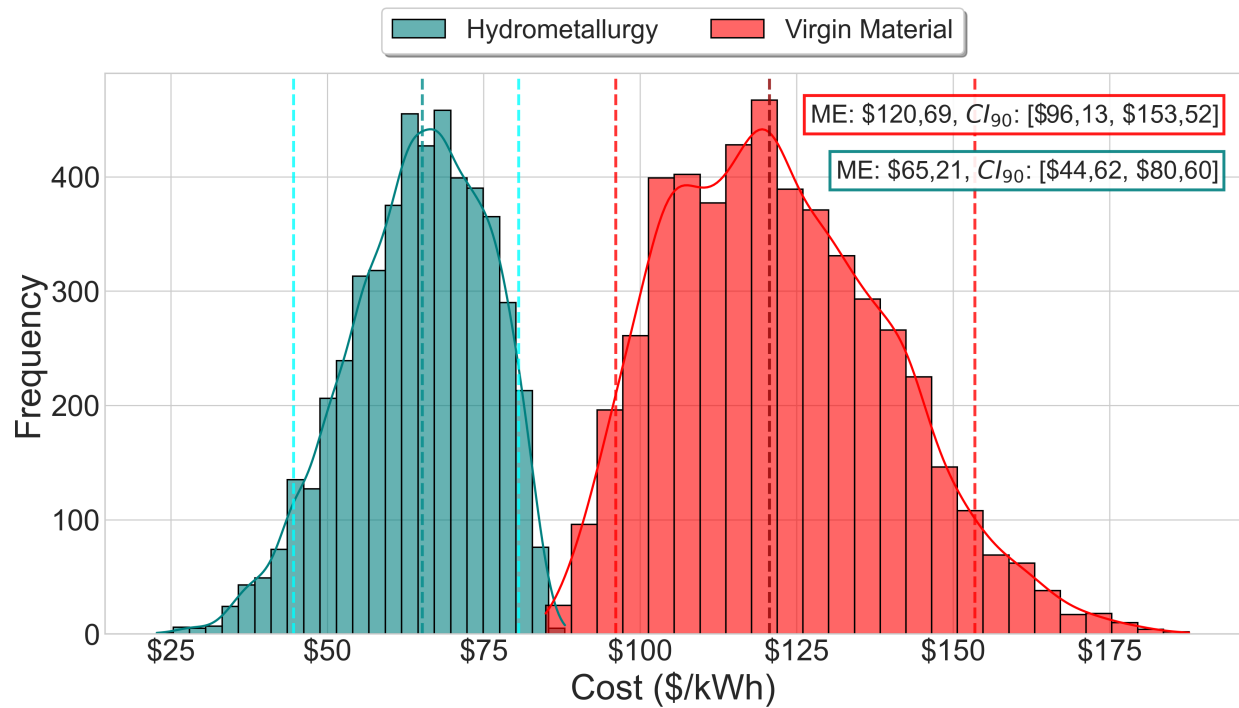


Figure 37: Battery Cost Distribution per kWh.

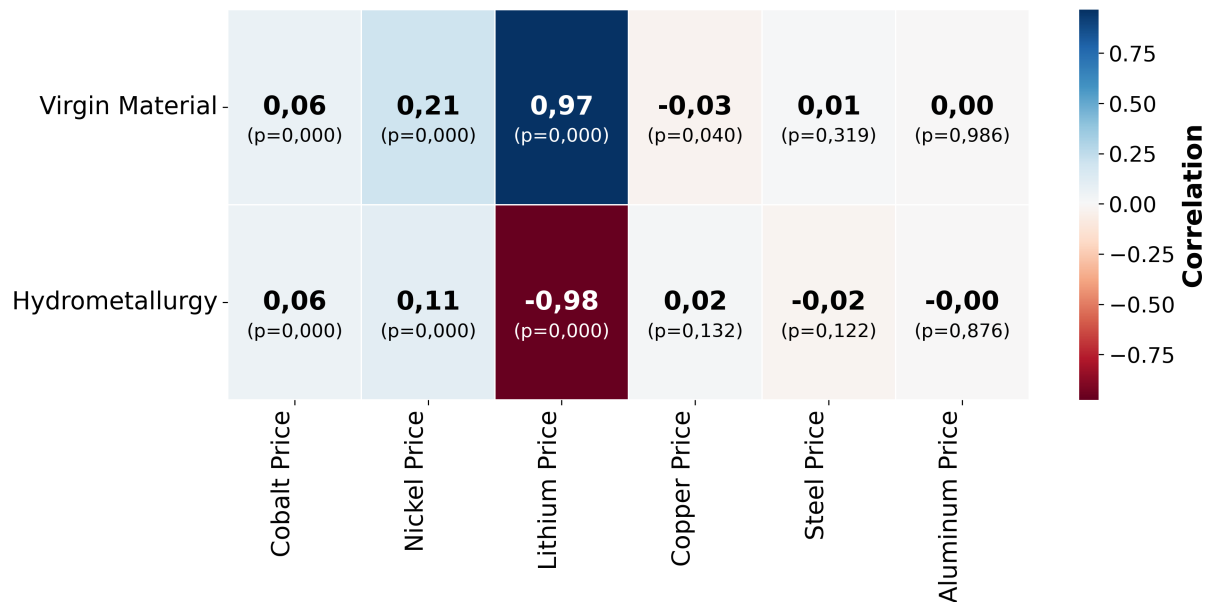


Figure 38: Battery Cost Correlation with Material Prices.

The correlation between the battery cost and material prices seen in Figure 38 shows something counterintuitive specifically with lithium price. While production with virgin materials has a

strong direct relationship with lithium price, production with recovered materials has a strong inverse relationship due to the surplus of material in cathode production as seen in Figure 35, which is finally sold to the market and counts as an earning. Nickel correlation also manifest changes, specifically, it reduce its value because of the reduction in the need of it. Other correlations are not relevant due to their low correlation value or its p-value above 0,05.

As seen in Table 5 the production of batteries from recovered materials reduce the use of fossil fuels in 24,39%. The energy use is calculated considering the generation mix of electricity in Chile seen in Table 15, where renewable energy accounts for more than 50% of the mix but does not translates into battery production energy demand. This behaviour is produced by the current disposition of plants to produce the materials (or pieces) that batteries use in their fabrication, such as an electronic part or proper insulation.

Table 5: Energy to Produce a Battery.

Type	Virgin Manufacture	Hydrometallurgy
Fossil Fuels ($\frac{MJ}{kWh}$)	873,160	683,370
Coal ($\frac{MJ}{kWh}$)	176,729	100,127
Natural Gas ($\frac{MJ}{kWh}$)	536,281	485,730
Petroleum ($\frac{MJ}{kWh}$)	160,150	97,513
Other ($\frac{MJ}{kWh}$)	83,020	90,278
Total Energy ($\frac{MJ}{kWh}$)	956,180	773,648

The production of batteries make some significant dangerous emissions, which can be reduced using recovered materials as seen in Table 6. The most important reduction consider sulfur oxides (SO_x), responsible for acid rain and respiratory problems, present an emission decrease of 77,98%. Nitrogen oxides (NO_x), PM10 and PM2,5 also present a considerable reduction.

On the other hand, as seen in Table 7, greenhouse effect gases also present a reduction of

Table 6: Dangerous Emissions in Battery Production.

Type	Virgin Manufacture	Hydrometallurgy
$SO_x \left(\frac{g}{kWh}\right)$	235,134	51,781
$NO_x \left(\frac{g}{kWh}\right)$	82,743	55,044
$PM_{10} \left(\frac{g}{kWh}\right)$	14,250	5,029
$PM_{2.5} \left(\frac{g}{kWh}\right)$	6,940	3,785
$BC \left(\frac{g}{kWh}\right)$	0,639	0,457
$OC \left(\frac{g}{kWh}\right)$	1,465	0,969

22,3%. The calculation is done by comparing methane (CH_4), nitrous oxide (N_2O), volatile organic compounds (VOC) and carbon monoxide with how much heat each gas traps in the atmosphere compared to CO_2 amounts to obtain final $GHGs$ amounts.

Table 7: Greenhouse Gases Emission in Battery Production.

Type	Virgin Manufacture	Hydrometallurgy
VOC	13,452	9,256
CO	84,866	70,775
CH_4	318,017	290,187
N_2O	1,605	1,304
CO_2	54.964	41.367
$GHGs$	65.082	50.539

Hydrometallurgy offers many benefits, such as efficient metal extraction with lower environmental impact. However, one of its drawbacks is its high water consumption compared to virgin manufacture. Specifically, it increases the use of water by 28,3%, from 68,6 to 88,3 gallons per kWh of NMC 811 battery cell produced.

9 Conclusions

In Chile, political initiatives through the national electromobility strategy are a determining factor for an aggressive transition towards electromobility, with ambitious goals such as having 100% of medium and light vehicle sales be electric. Additionally, there are economic incentives along with technological capabilities to develop recycling plants in the country. From a legal perspective, mandatory collection of a large portion of discarded batteries will be enabled once collection targets for electric vehicle lithium-ion batteries are determined under the EPR Law.

There is an inevitable transition from ICE vehicles to EVs as a step to develop a sustainable world. Specifically, in Chile, this type of vehicles will reach 50% market share in 2036 with around 200.000 sales according to the developed model reviewed with other insititutions projections.

The effect of EOL batteries will start to become significant in 2035, as the country will start to dispose around 10.000 tons of these annually and will reach 80.000 tons in 2045. At 2035, it is important to already have developed an hydrometallurgy pilot plant and therefore, at minimum, a small size recycling plant, otherwise, the country is going to face an exponential increase in dangerous waste.

For this to be possible, some public policies must be established:

1. The definition of collection rates are indispensable to actually force companies to dispose EV batteries in a responsible and safe way. This can be done through the extended producer responsibility law and will incentivize business models directly related to the matter.
2. The development of a framework that defines when, how and where the batteries must be disposed for companies to be aware of the steps to follow when EVBs reach their end of life.

3. The elaboration of a digital passport that can show specific battery characteristics such as: manufacturer identification, country and date of elaboration, weight, energy capacity, battery chemistry, current responsible, etc. This will ease handling during the lifetime and at the end of their life, also letting the regulatory entity know the traceability of the product and the current responsible if accounting is necessary.

In the value chain, transportation is one of the most costly stages, with a cost of \$0,98 per kilogram of feedstock and \$5,02 per kilogram of cathode produced, considering the movement of feedstock from the collection center to the plant in Santiago and then to the battery factory in Antofagasta (if applies), which minimizes final transportation cost. On the other hand, disassembly can drive an important amount of revenue to operational income, being able to recover around 180 kilograms of material. In the latter, the cost per kilogram of feedstock processed is \$0,17 and the revenue \$0,79. When taking into account values per kilogram of cathode processed, these values turn into \$0,85 and \$4,04 respectively.

The best recycling technology considering material recovery, environmental impacts and feedstock adoption is hydrometallurgy. Comparing this process to other availables, hydrometallurgy is superior to pyrometallurgy in first two items and superior to direct recycling in the last. It is worth highlighting that this type of recycling is already used in developed countries, so technological transfer is possible.

The amount of investment to start operating the plant is \$165.625.132 in CAPEX and \$60.997.664 in OPEX, with most of the economic allocation generally belonging to lithium. The plant can recover annually: 9.813 tons of crude lithium carbonate, 957 tons of cobalt, 6.995 tons of nickel, 671 tons of manganese and 18.442 tons of graphite. Analyzing results, it can be said

that this project is very low risk, considering a confidence interval of 90% for economic indicator, NPV is always positive. Median values of \$596,23M and 56,11% for IRR without financing and \$660,01M and 69,65% for IRR with financing, indicates the attractiveness for public or private investment.

The chemistry chosen for battery production is NMC 811 due to its significant projected market share and model scope. The cathode production stage for this chemistry type battery involves a CAPEX of \$73.402.533 and an OPEX of \$21.037.218. In this stage, annually, it can be produced 15.793 tons of NMC 811 cathode powder with a substantial surplus in lithium hydroxide.

The battery production stage is the last and most costly stage, with a CAPEX of \$909.181.665 and an OPEX of \$641.183.260. The factory can produce 32.241 tons of NMC 811 cells, and using the value chain of recovered materials through hydrometallurgy, it can potentially reduce its cost in 46,0%. An aspect to highlight is the negative correlation between battery cost and lithium price due to existence of a surplus in this material.

The use of recovered materials can reduce the use of fossil fuels in 24,39%, dangerous emissions by 65,70% and greenhouse gases by 22,30%. However, it uses more water than conventional manufacture, increasing from 68,6 to 88,3 gallons per kWh of NMC 811 battery cell produced.

To conclude, results indicate that the manufacture of NMC 811 battery cells from recovered materials from hydrometallurgy is economic, technical and environmentally-friendly feasible option. Nevertheless, the construction of the facilities requires considerable investment and collective efforts to develop a complete framework for disposal.

10 Annex

Table 8: Historical EV Sales in Chile [35].

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023
Light & Medium	36	31	140	197	302	236	856	1.769	2.094
Buses	0	0	0	5	307	367	26	200	1.383
Trucks	0	0	0	0	0	0	12	45	29
Total	36	31	140	202	609	603	894	2.014	3.506

Table 9: Vehicle Distribution Analysis by Category in Chile [35].

Category	2021	2022	2023	Average	Average % of total
Light & Medium	415.581	426.777	313.865	385.408	97,17%
Buses	1.868	3.122	3.073	2.688	0,68%
Trucks	16.898	16.038	12.650	15.195	3,83%

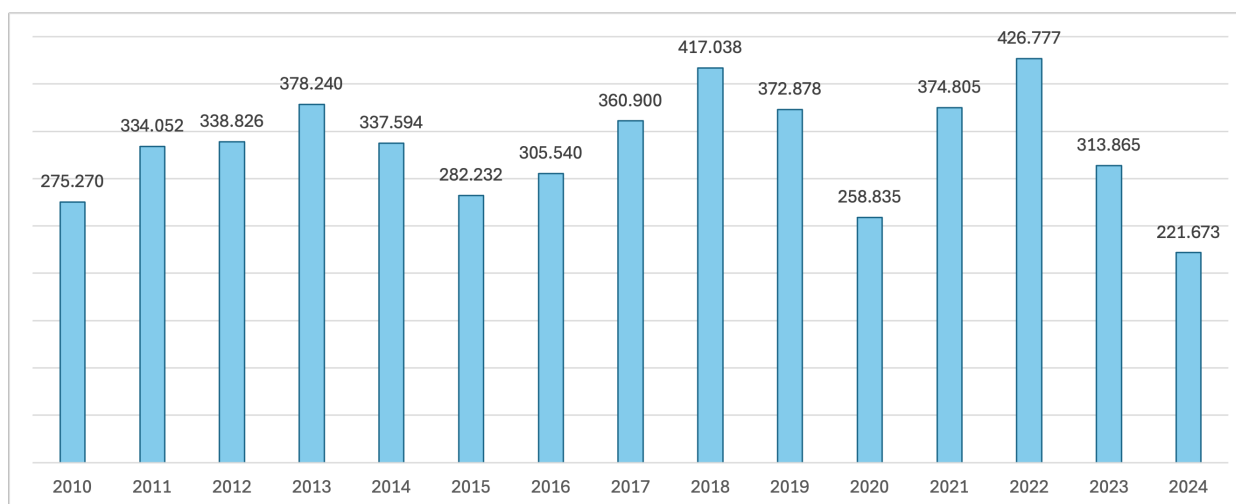


Figure 39: Historical Vehicle Sales in Chile [35].

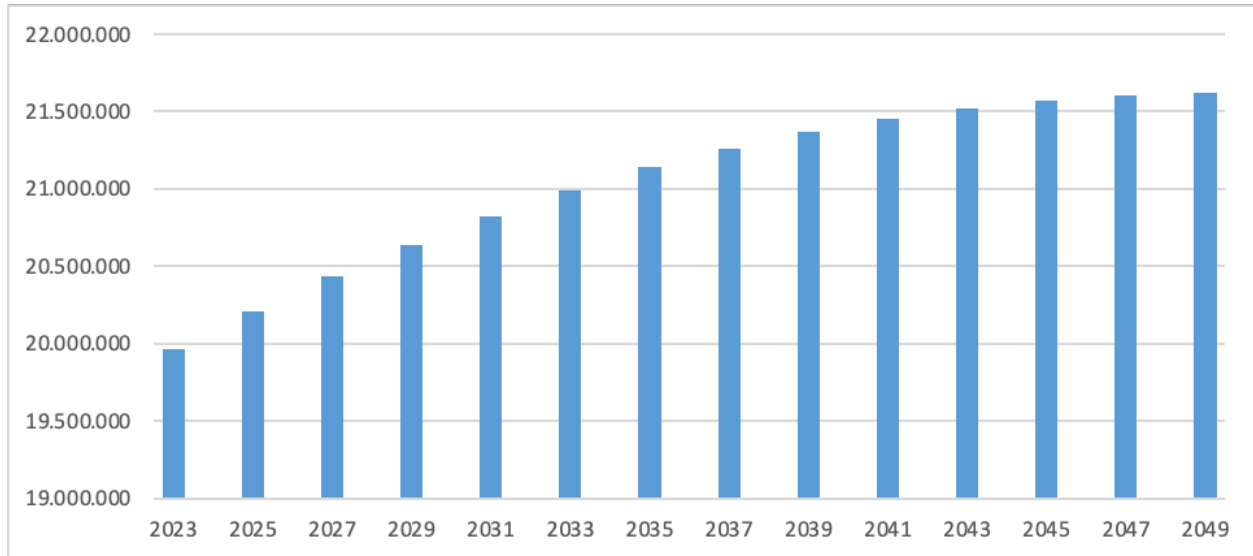


Figure 40: Population Growth in Chile [37]

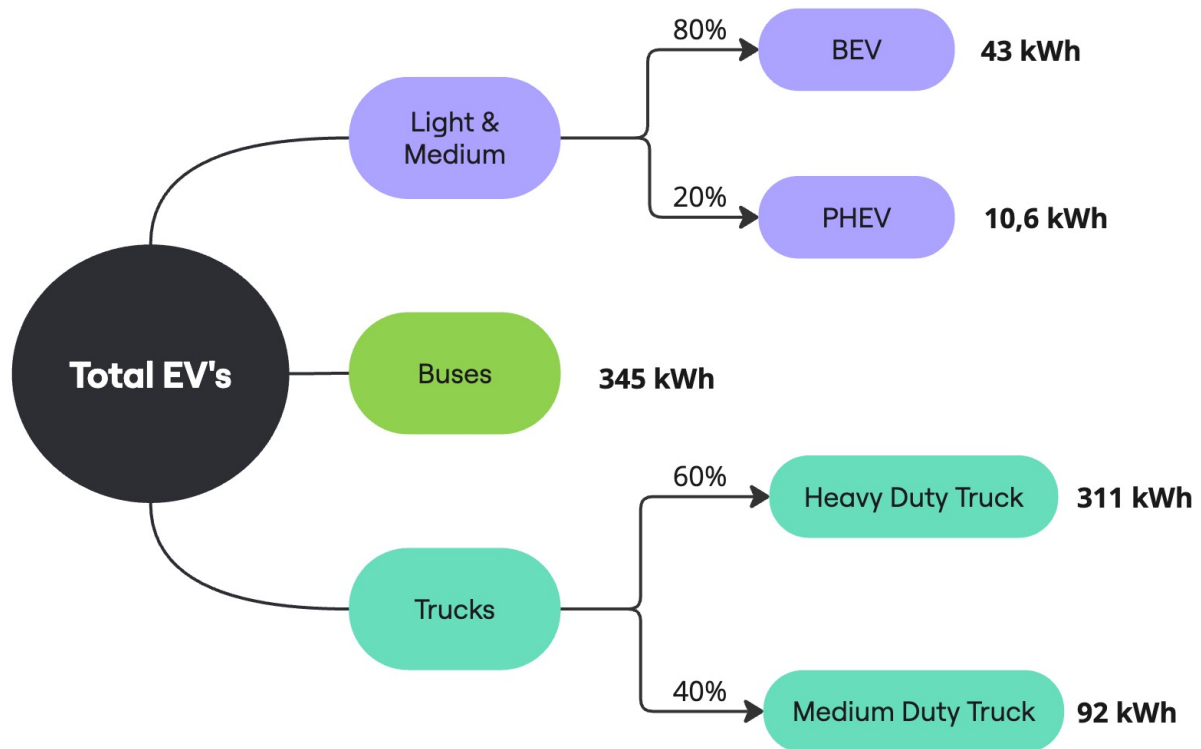


Figure 41: EV Market Segmentation Model and Battery Capacity [40] [35].

Table 10: Proposed Collection Rate Targets for EV Batteries in Chile [39].

Year	Collection rate (CRi)
2023	0%
2024	0,5%
2025	1%
2026	2%
2027	4%
2028	6%
2029	9%
2030	12%
2031	15%
2032	19%
2033	23%
2034	27%
2035	31%
2036	35%
2037	39%
2038	43%
2039	47%
2040	51%
2041	55%
2042	59%
2043	63%
2044	65%
After 2044	65%

Table 11: Battery Energy Density by Chemistry [42] [43].

Chemistry	Ranges (Wh/kg)	Average (Wh/kg)
LFP	90-160	125
NMC	150-220	185
NCA	200-260	230

Table 12: Projected EV Sales and EOL Batteries.

Year	Sales	Sales Cumulative	EOL	EOL Cumulative	Collected
2015	36	36	0	0	0
2016	31	67	0	0	0
2017	140	207	1	1	0
2018	202	409	41	42	0
2019	609	1.018	39	81	0
2020	603	1.621	161	242	0
2021	894	2.515	242	484	0
2022	2.014	4.529	690	1.174	0
2023	3.506	8.035	693	1.867	0
2024 (p)	3.814	11.849	1.049	2.916	5
2025 (p)	5.521	17.370	2.330	5.246	23
2026 (p)	7.937	25.307	3.985	9.231	80
2027 (p)	11.387	36.694	4.378	13.609	175
2028 (p)	16.331	53.025	6.336	19.945	380
2029 (p)	23.395	76.420	9.107	29.052	820
2030 (p)	33.376	109.796	13.066	42.118	1.568
2031 (p)	47.219	157.015	18.738	60.856	2.811
2032 (p)	65.898	222.913	26.839	87.695	5.099
2033 (p)	90.179	313.092	38.277	125.972	8.804
2034 (p)	120.264	433.356	54.125	180.097	14.614
2035 (p)	155.408	588.764	75.480	255.577	23.399
2036 (p)	193.761	782.525	103.194	358.771	36.118
2037 (p)	232.636	1.015.161	137.466	496.237	53.612
2038 (p)	269.208	1.284.369	177.418	673.655	76.290
2039 (p)	301.278	1.585.647	220.926	894.581	103.835
2040 (p)	327.715	1.913.362	264.939	1.159.520	135.119
2041 (p)	348.423	2.261.785	306.272	1.465.792	168.450
2042 (p)	364.002	2.625.787	342.268	1.808.060	202.055
2043 (p)	375.373	3.001.160	372.268	2.180.328	234.529
2044 (p)	383.490	3.384.650	395.593	2.575.921	257.135
2045 (p)	389.193	3.773.843	413.130	2.989.051	268.535

Note: projected values are indicated with (p).

Table 13: Projected EOL Battery Mass.

Year	LFP	NMC	NCA
2015	0	0	0
2016	0	0	0
2017	0	0	0
2018	0	0	0
2019	0	0	0
2020	0	0	0
2021	0	0	0
2022	0	0	0
2023	0	0	0
2024 (p)	1	1	0
2025 (p)	4	2	1
2026 (p)	14	8	2
2027 (p)	31	18	4
2028 (p)	66	40	8
2029 (p)	143	86	18
2030 (p)	273	165	35
2031 (p)	490	296	62
2032 (p)	889	537	113
2033 (p)	1.536	927	195
2034 (p)	2.549	1.539	324
2035 (p)	4.081	2.464	519
2036 (p)	6.300	3.804	801
2037 (p)	9.351	5.646	1.189
2038 (p)	13.307	8.034	1.693
2039 (p)	18.111	10.935	2.304
2040 (p)	23.568	14.230	2.998
2041 (p)	29.381	17.740	3.737
2042 (p)	35.243	21.279	4.483
2043 (p)	40.907	24.699	5.203
2044 (p)	44.850	27.080	5.705
2045 (p)	46.838	28.281	5.958

Note: projected values are indicated with (p).

Table 14: Cost Parameters.

Description	Cost
Building cost (\$/m ²)	565
Direct labor (\$/hr)	7.00
Capital cost adjustment (%)	119
Electricity cost (\$/kWh)	0.12
Natural gas cost (\$/MMBTU)	53.30
Water cost (\$/gal)	0.003
Wastewater discharge cost (\$/gal)	0.004
Landfill cost (tip fee \$/ton)	39.13

Table 15: Electricity Generation Mix [109].

Energy Source	Percentage
Residual oil	10%
Natural gas	15%
Coal	13%
Biomass	2%
Nuclear	0%
Hydro	22%
Others	37%
T&D Loss	6%

Table 16: Mineral Commodity Prices [46].

Material	$\bar{x}$ (\$)	σ (\$)
Copper	8.41	1.16
Steel	0.31	0.068
Aluminum	2.81	0.46
Cobalt	41.31	13.87
Nickel	19.31	4.09
Lithium	30.14	23.32

Table 17: Capital Expenditures Model for Generic Chemical Plants [62] [71].

Item	Cost
I. Inside battery limits (ISLB) plant cost	$I.1 + I.2 + I.3 + I.4 + I.5 + I.6 + I.7 + I.8$
1. Purchased Equipment	
2. Equipment erection	50% of I.1
3. Piping	60% of I.1
4. Instrumentation and control	30% of I.1
5. Electrical	20% of I.1
6. Civil	30% of I.1
7. Structures and buildings	20% of I.1
8. Lagging and paint	10% of I.1
II. Offsite battery limits (OSBL) plant cost	15% of I
III. Design and Engineering Cost	25% of (I + II)
IV. Contingency	10% of (I + II)
V. Working Capital	15% of (I+II+III+IV+V)

	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054
INFLOWS															
I. Operational income	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675
A. Disassembly	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675
B. Recycling	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202
Niquel	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473
Lithium Carbonate	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552
Cobalt	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409
Maghemite	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681
Graphite	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 2,114.389	\$ 2,114.389	\$ 2,114.389	\$ 2,114.389	\$ 2,114.389	\$ 2,114.389	\$ 2,114.389	\$ 2,114.389	\$ 2,114.389	\$ 2,114.389
II. Non-operational income	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000
LFP collection	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000
OUTFLOWS															
I. Operational expenditures	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 197,910.844	\$ 197,910.844	\$ 197,910.844	\$ 197,910.844	\$ 197,910.844	\$ 197,910.844	\$ 197,910.844	\$ 197,910.844	\$ 197,910.844	\$ 197,910.844
A. Disassembly	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664
B. Variable costs of production	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387
Raw Materials	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 33,344.270	\$ 33,344.270	\$ 33,344.270	\$ 33,344.270	\$ 33,344.270	\$ 33,344.270	\$ 33,344.270	\$ 33,344.270	\$ 33,344.270	\$ 33,344.270
Utilities	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374
Consumables	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064
Operating expenses	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311
Freight and shipping	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 2,392.322	\$ 2,392.322	\$ 2,392.322	\$ 2,392.322	\$ 2,392.322	\$ 2,392.322	\$ 2,392.322	\$ 2,392.322	\$ 2,392.322	\$ 2,392.322
C. Fixed costs of production	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007
Labor costs of production	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400
Supervision and management	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080
Direct salary overhead	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 107.520	\$ 107.520	\$ 107.520	\$ 107.520	\$ 107.520	\$ 107.520	\$ 107.520	\$ 107.520	\$ 107.520	\$ 107.520
Maintenance	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800
Property taxes and insurance	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208
Rent of land and/or buildings	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658
General plant overhead	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317
R&D costs	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855
Selling and marketing costs	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785
General and administrative (G&A) c	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910
Allocated environmental charges	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160
Running license fees and royalty pay	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658
II. Non-operational expenditures	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824
NM&A collection	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771
NM&A collection	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892
Transportation	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161
III. Interest	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
IV. Depreciation	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356
V. Loss from previous periods	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Pre-tax profit	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 287,732.831	\$ 287,732.831	\$ 287,732.831	\$ 287,732.831	\$ 287,732.831	\$ 287,732.831	\$ 287,732.831	\$ 287,732.831	\$ 287,732.831	\$ 287,732.831
After-tax profit	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 76,613.795	\$ 76,613.795	\$ 76,613.795	\$ 76,613.795	\$ 76,613.795	\$ 76,613.795	\$ 76,613.795	\$ 76,613.795	\$ 76,613.795	\$ 76,613.795
III. Depreciation	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356
IV. Loss from previous periods	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
VII. Amortization	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
VIII. Paid capital investment	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Buildings	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Equipment	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Equipment erection	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Piping	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Instrumentation and control	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Civil	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Structures and buildings	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Landing and parking	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
B. Offsite battery limits cost	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
C. Design and Engineering Cost	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
D. Contingency	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
VIII. Working Capital	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Cash flow	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392
Financing	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Net cash flow	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392
Cumulative net cash flow	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392	\$ 218,355.392

Figure 42: Expected Cash Flow in a Debt-free Scenario.

	CONSTRUCTION PERIOD										OPERATION PERIOD									
	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054					
INFLOWS																				
I. Operational income	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675	\$ 485,643.675					
A. Disassembly	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675	\$ 391,967.675					
B. Recycle	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202	\$ 63,689.202					
Niquel	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473	\$ 328,278.473					
Lithium carbonate	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552	\$ 135,078.552					
Cobalt	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409	\$ 147,877.409					
Graphite	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681	\$ 39,523.681					
II. Non-operational income	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000					
LFP collection	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000	\$ 93,676.000					
OUTFLOWS																				
I. Operational expenditures	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 212,977.491	\$ 206,461.082	\$ 205,942.015	\$ 205,169.881	\$ 204,340.763	\$ 197,242.617	\$ 196,286.606	\$ 195,560.041	\$ 194,157.715	\$ 192,974.038					
A. Disassembly	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664	\$ 60,977.664					
B. Variable costs of production	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387	\$ 13,493.387					
Raw Materials	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 33,444.270	\$ 33,444.270	\$ 33,444.270	\$ 33,444.270	\$ 33,444.270	\$ 33,444.270	\$ 33,444.270	\$ 33,444.270	\$ 33,444.270	\$ 33,444.270					
Utilities	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374	\$ 20,710.374					
Consumables	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064	\$ 9,206.064					
Effluent disposal	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311	\$ 621.311					
Packaging and shipping	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 2,392.312	\$ 2,392.312	\$ 2,392.312	\$ 2,392.312	\$ 2,392.312	\$ 2,392.312	\$ 2,392.312	\$ 2,392.312	\$ 2,392.312	\$ 2,392.312					
C. Fixed costs of production	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007	\$ 14,140.007					
Labor costs	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400	\$ 806.400					
- Operating labor	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080	\$ 430.080					
- Supervision and management	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 107,520.5	\$ 107,520.5	\$ 107,520.5	\$ 107,520.5	\$ 107,520.5	\$ 107,520.5	\$ 107,520.5	\$ 107,520.5	\$ 107,520.5	\$ 107,520.5					
- Direct salary overhead	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800	\$ 268.800					
Maintenance	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208	\$ 3,820.208					
Property taxes and insurance	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658					
Rent of land and/or buildings	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317	\$ 2,139.317					
General plant overhead	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855	\$ 4,520.855					
- R&D costs	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785	\$ 3,282.785					
- Selling and marketing costs	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910					
- General and administrative (G&A) c/s	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160	\$ 524.160					
Allocated environmental charges	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658	\$ 1,069.658					
Running license fees and royalty pay/s	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910	\$ 713.910					
II. Non-operational expenditures	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824	\$ 129,696.824					
NMC collection	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771	\$ 43,030.771					
NCA collection	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892	\$ 10,418.892					
Transportation	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161	\$ 76,247.161					
III. Interest	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900					
IV. Depreciation	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 9,419.886	\$ 9,419.886	\$ 9,419.886	\$ 9,419.886	\$ 9,419.886	\$ 9,419.886	\$ 9,419.886	\$ 9,419.886	\$ 9,419.886	\$ 9,419.886					
V. Loss from previous periods	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356					
Pre-tax profit	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762					
Tax (2%)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 113.500	\$ 113.500	\$ 113.500	\$ 113.500	\$ 113.500	\$ 113.500	\$ 113.500	\$ 113.500	\$ 113.500	\$ 113.500					
After-tax profit	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 5,533.262	\$ 5,533.262	\$ 5,533.262	\$ 5,533.262	\$ 5,533.262	\$ 5,533.262	\$ 5,533.262	\$ 5,533.262	\$ 5,533.262	\$ 5,533.262					
III. Depreciation	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356	\$ 7,236.356					
IV. Loss from previous periods	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900	\$ 1,561.900					
V. Amortization	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762	\$ 5,646.762					
VII. Amortization	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 21,663.954	\$ 21,663.954	\$ 21,663.954	\$ 21,663.954	\$ 21,663.954	\$ 21,663.954	\$ 21,663.954	\$ 21,663.954	\$ 21,663.954	\$ 21,663.954					
VIII. Amortization	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 32,824.573	\$ 32,824.573	\$ 32,824.573	\$ 32,824.573	\$ 32,824.573	\$ 32,824.573	\$ 32,824.573	\$ 32,824.573	\$ 32,824.573	\$ 32,824.573					
IX. Inside battery limits plant cost	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 16,388.694	\$ 16,388.694	\$ 16,388.694	\$ 16,388.694	\$ 16,388.694	\$ 16,388.694	\$ 16,388.694	\$ 16,388.694	\$ 16,388.694	\$ 16,388.694					
X. Inside battery limits plant cost	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 14,325.781	\$ 14,325.781	\$ 14,325.781	\$ 14,325.781	\$ 14,325.781	\$ 14,325.781	\$ 14,325.781	\$ 14,325.781	\$ 14,325.781	\$ 14,325.781					
Equipment erection	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 22,876.402	\$ 22,876.402	\$ 22,876.402	\$ 22,876.402	\$ 22,876.402	\$ 22,876.402	\$ 22,876.402	\$ 22,876.402	\$ 22,876.402	\$ 22,876.402					
Piping	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 11,938.151	\$ 11,938.151	\$ 11,938.151	\$ 11,938.151	\$ 11,938.151	\$ 11,938.151	\$ 11,938.151	\$ 11,938.151	\$ 11,938.151	\$ 11,938.151					
Instrumentation and control	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891					
Electrical	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 4,775.260	\$ 4,775.260	\$ 4,775.260	\$ 4,775.260	\$ 4,775.260	\$ 4,775.260	\$ 4,775.260	\$ 4,775.260	\$ 4,775.260	\$ 4,775.260					
Oil	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,162.891	\$ 7,16						

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