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Life Cycle Assessment of Sustainable End-of-Life Management Operations for Electric Vehicle Battery Pack

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Declaration of Originality

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Abstract

As the global demand for sustainable transportation grows, Electric Vehicles (EVs) promise to address environmental concerns and reduce dependence on fossil fuels. Lithium-ion batteries (LIBs) have emerged as the leading technology in electric mobility due to their high energy density, reliability, and long cycle life. However, as the demand for Li-ion batteries increases, there are concerns regarding the availability and sustainability of the critical resources used for their production. This study investigates the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) of a specific Li-ion battery pack with a Nickel-Manganese-Cobalt (NMC) cathode chemistry. The battery pack considered in the analysis has a capacity of 95 kWh.
The LCA study involves the evaluation of the environmental impacts (i.e. greenhouse gas emissions, energy consumption, and resource depletion) associated with the entire life cycle of the battery pack, including raw material extraction, manufacturing processes, transportation, use phase, and End-of-Life (EoL) treatment. In parallel, the LCC analysis focuses on assessing the total cost associated with the Li-ion battery pack over its entire life cycle. This includes upfront costs, such as manufacturing and assembly, as well as operational costs and any potential end-of-life costs. The cost evaluation is based on secondary data derived from existing literature. The EoL is modeled analyzing three different scenarios : 1) simple disposal of the battery pack; 2) recycling of the battery pack; and 3) reconditioning the battery pack at the end of the first life followed by the recycling of the pack at the end of the second life.
This analysis uses Europe as the geographic location, based on the greater adoption of elective vehicles, more progressive current legislation, and availability of data. Based on the outcomes of the LCA analysis, the carbon footprint of simple disposal, recycling and reconditioning and recycling scenarios are respectively 131.3 kgCO_2 eq. , 119.7 kgCO_2 eq. and 81.1 kgCO_2 eq. The results of the LCC, highlights an economic impact of 151.1 €/ kWh for simple disposal, 147.3 €/ kWh for the recycling scenario and 89.5 €/ kWh for the reconditioning and recycling scenario. For completeness, two sensitivity analyses have been conducted on both the LCA and LCC of the battery pack. The first analysis considers the influence of the energy mix used in each stage of the battery pack's life cycle, by examining four distinct geographical locations, assuming the EoL stage is modeled as recycling. Finally, a sensitivity analysis for the EoL stage modeled as reconditioning is conducted, examining a range of different cell conversion rates (CCR) values used in previous studies.

To my family for always loving and supporting me.
To my grandma Rosalia.

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"I believe every human has a finite number of heartbeats. I don't intend to waste any of mine."

Neil Armstrong

Contents

Declaration of Originality **3**

Abstract **4**

Dedication **5**

Acknowledgment **6**

List of Tables **11**

List of Figures **13**

1 Introduction **1**

2 Literature review **4**

2.1 Li-Ion Battery Cell 4

2.1.1 Li-Ion Cell Structure and Materials 4

2.1.2 Battery Cell Manufacturing 7

2.2 Battery Module and Pack Assembly 10

2.2.1 Battery Module Assembly 10

2.2.2 Battery Pack Assembly 11

2.3 Battery Pack Integration in the Vehicle 13

2.4 Battery End of Life Assessment 13

2.5 Battery Disassembly 15

2.6 Recycling Processes for Li-Ion Battery 15

2.6.1 Pre-Treatment Methods for Battery Recycling 16

2.6.2 Pyrometallurgical Methods for Battery Recycling 17

2.6.3 Hydrometallurgical Methods for Battery Recycling 19
2.6.4 Pyro-Hydrometallurgical Method for Battery Recycling 21
2.6.5 Direct Methods for Battery Recycling 22
2.7 Life Cycle Assessment and Life Cycle Cost Assessment 23
2.7.1 Life Cycle Assessment 23
2.7.2 Life Cycle Cost Analysis 25

3 Methodology 27
3.1 Goal and Scope Definition 27
3.1.1 Battery Pack Under Analysis 27
3.1.2 Functional Unit 27
3.1.3 System Boundary 28
3.1.4 Allocation and Multifunctionality 28
3.1.5 Impact Assessment 29
3.2 Life Cycle Inventory 30
3.2.1 Battery Pack Manufacturing 30
3.2.2 Battery Pack Use Phase 33
3.2.3 Battery Pack Disassembly 34
3.2.4 Battery Pack EoL 35
3.3 Life Cycle Cost Inventory 38

4 Results and Interpretations 40
4.1 Life Cycle Impact Assessment 40
4.1.1 Battery Pack Manufacturing 40
4.1.2 EoL: Simple Disposal Scenario 44
4.1.3 EoL: Recycling Scenario 47
4.1.4 Sensitivity Analysis for Recycling Scenario 50
4.1.5 EoL: Reconditioning and Recycling Scenario 53
4.1.6 Sensitivity Analysis for Reconditioning and Recycling Scenario 57
4.2 Life Cycle Cost Analysis 60
4.2.1 Battery Pack Manufacturing 60
4.2.2 EoL: Simple Disposal Scenario 64
4.2.3 EoL: Recycling Scenario 66
4.2.4 Sensitivity Analysis for Recycling Scenario 67

4.2.5 EoL: Reconditioning and Recycling Scenario 70
4.2.6 Sensitivity Analysis for Reconditioning and Recycling Scenario 72
4.3 Comparison of the Three Baseline Scenarios 74

5 Conclusions **78**

6 Future Work **81**

Bibliography **84**

Vita Auctoris **91**

List of Tables

3.1 General Characteristics of the NMC622 Battery Pack. 28
3.2 EF 3.0 Impact Categories. 29
3.3 Bill of Materials for NMC622 Battery Cell. 32
3.4 Bill of Materials for NMC622 Battery Module. 33
3.5 Bill of Materials for NMC622 Battery Pack. 34
3.6 Additional Battery Pack Costs 38
3.7 Average prices of Electricity and Natural Gas for first half of 2022 39

4.1 Sensitivity analysis results for key environmental impacts in Recycling Scenario: electricity mix comparison. 50
4.2 Percentage of savings in environmental impacts with respect to EE electricity mix resulting from the adoption of RER, IT and SE electricity mix. 52
4.3 Percentage of savings in environmental impacts, with respect to the baseline scenario of CCR=50 %, by reducing the number of modules substituted 58
4.4 Percentage of growth in environmental impacts, with respect to the baseline scenario of CCR=50 %, by increasing the number of modules substituted 58
4.5 Costs breakdown in €/ kWh of the NMC622 battery pack. 61
4.6 Costs breakdown of the NMC622 battery cell in €. 63
4.7 Costs breakdown in €/ kWh of the NMC622 battery pack life cycle for Simple Disposal Scenario. 65
4.8 Costs breakdown in €/ kWh of the NMC622 battery pack life cycle for Recycling Scenario. 67
4.9 LCC sensitivity analysis for the complete life cycle of the battery pack: Recycling Scenario 68

4.10 Costs breakdown in €/ kWh of the NMC622 battery pack life cycle for Reconditioning and Recycling Scenario. 71
4.11 LCC sensitivity analysis for the reconditioning process of the battery pack [€/ kWh]. 73
4.12 Percentage of saving in environmental impacts and life cycle cost, with respect to the highest impact scenario 76
4.13 Comparison of the three scenarios under exam from the point of view of environmental impacts and total life cycle cost 77

List of Figures

2.1 Lithium Ion Battery Cell in Charge and Discharge Phase 6
2.2 Assembly Procedure of Pouch Cell 8
2.3 Assembly Procedure of Prismatic and Cylindrical Cell 9
2.4 Pouch Cell Module 10
2.5 Cylindrical Cell Module 11
2.6 Prismatic Cell Module 11
2.7 Battery Pack Integration in the Vehicle 13
2.8 LIBs EoL - Simple Disposal 14
2.9 LIBs EoL - Recycling 14
2.10 LIBs EoL - Repourpouse 15
2.11 LIBs EoL - Reconditioning 15
2.12 Disassembly Procedure of the Battery Pack 16
2.13 Overview of Pyro-Hydrometallurgical Recycling Process for LIBs 21
2.14 Schematic of Direct Recycling Process for LIBs 23
2.15 Schematic of Life Cycle Assessment 24

3.1 Pyro-Hydrometallurgic Process Implemented 36

4.1 Contributions of cells manufacturing and pack assembly to the impacts of the battery pack. 41
4.2 Contributions of each cell component and energy vector to the impacts of each battery cell. 42
4.3 EoL Simple Disposal Scenario: LCA results of the battery pack. 44
4.4 EoL Simple Disposal Scenario: LCA results of the battery pack for the six most relevant impact categories. 45

4.5 EoL Recycling Scenario: LCA results of the battery pack. 47
4.6 EoL Recycling Scenario: LCA results of the battery pack for the six most relevant impact categories. 49
4.7 Comparison of the life cycle environmental impacts of the battery pack with the use of different electricity mixes: RER, IT, EE and SE. 51
4.8 EoL Reconditioning and Recycling Scenario: LCA results of the battery pack. . . . 53
4.9 EoL Reconditioning and Recycling Scenario: LCA results of the battery pack for the six most relevant impact categories. 55
4.10 Comparison of the life cycle environmental impacts of the battery pack reconditioning scenario varying the number of modules. 57
4.11 LCC breakdown for a single NMC622 battery pack production 60
4.12 LCC breakdown for a single NMC622 battery cell manufacturing. 62
4.13 LCC breakdown for the complete life cycle of the battery pack : Simple Disposal Scenario. 64
4.14 LCC breakdown for the complete life cycle of the battery pack : Recycling Scenario. 66
4.15 LCC sensitivity analysis for the complete life cycle of the battery pack : Recycling Scenario. 68
4.16 LCC breakdown for the complete life cycle of the battery pack : Reconditioning and Recycling Scenario. 70
4.17 LCC sensitivity analysis for the complete life cycle of the battery pack : Reconditioning and Recycling Scenario. 72
4.18 Comparison of the three scenarios under exam for the six most relevant EF 3.0 impact categories and total life cycle cost 75

Chapter 1

Introduction

The Electric Vehicles (EVs) market is undergoing a rapid and continuous growth. In 2021, sales of electric vehicles doubled compared to the previous year, reaching a total of 6.6 million units sold, which accounted for nearly 10% of the global car sales [1]. The trend of rising sales has continued into 2022, with the first quarter alone seeing the sale of 2 million electric cars [1]. This represents a remarkable 75 % increase compared to the same period in 2021, indicating the accelerating transition towards electric mobility. Multiple factors are driving the diffusion of EVs in the automotive market. One of the primary influences is the increasing number of countries implementing policies that aim to phase out internal combustion engines or set electrification targets for the near future. Governments worldwide recognize the importance of reducing carbon emissions and promoting sustainable transportation alternatives. These policies have created a supportive environment for EV adoption, encouraging consumers and manufacturers to embrace electric vehicles. In this scenario, Europe leads the way in terms of climate and environmental policies, with the most ambitious framework among the continents [2]. This framework has undergone significant revisions through initiatives like the European Green Deal [2, 4] and Fit for 55 [4, 5]. The International Energy Agency (IEA) has released the Announced Pledges Scenario (APS), which projects that EVs will constitute more than 30% of global vehicle sales by 2030 [1]. This projection reflects the ongoing shift towards electric mobility and the ambitious commitments made by various countries to combat climate change and achieve decarbonization. As stated in [2, 6] the primary approach to meeting CO_2 regulation standards for passenger cars is by promoting the adoption of Battery

Electric Vehicles (BEVs). It is important to underline that although BEVs produce zero tailpipe emissions, their production phase, and in particular the manufacturing of the battery packs, can have significant environmental impacts [7, 8]. The continued growth of the EV market will result in a significant increase in demand for critical materials used in lithium-ion batteries (LIBs), such as lithium, cobalt and nickel. These materials are essential for the production of high-performance batteries, and their global demand is expected to grow at similar rates to meet the requirements of the expanding market [1]. As a consequence of this rapid market growth, 7.8 million tonnes of EV batteries per year are expected to reach the End-of-Life (EoL) stage by year 2040 [3]. Managing and treating these EoL batteries has become a pressing concern. Improper handling and disposal of EV batteries can have detrimental environmental impacts due to their complex composition and potentially hazardous materials. Therefore, it is essential to develop effective strategies for sustainably managing the EoL of EV batteries. One of the commonly used methodologies for assessing the environmental impacts of EV batteries is Life Cycle Assessment (LCA). LCA is a comprehensive approach that evaluates the environmental burdens associated with a product system throughout its entire life cycle. It considers all relevant stages associated with battery production, use, and disposals [43]. LCA considers various factors such as the production of raw materials, auxiliary and operating materials, energy consumption during use, and waste management practices during disposals. It incorporates the environmental burden of inputs from the extraction of ores and crude oil, as well as emissions to air, water, and soil, including pollutants like carbon dioxide and nitrogen oxides. By conducting LCA studies, the environmental impacts of EV battery packs can be thoroughly analyzed, helping to identify areas for improvement and guide the development of sustainable practices throughout the battery life cycle [50]. The upcoming Batteries Regulation will implement compulsory measures aimed at reducing the carbon footprint throughout the entire life cycle of batteries [9]. Battery manufacturers will have to report the carbon footprint associated with the entire life cycle of batteries that are made available in the market. The methodology for the carbon footprint assessment, and more in general the environmental impacts assessment, will be based on the principles of LCA [9]. The proposal for Battery Regulation also incorporates specific provisions regarding Critical Raw Materials (CRMs) used in the batteries. The increasing demand for CRMs in the production of EV batteries has raised concerns about the sustainability of their supply chains due to potential global shortages, geopolitical pressures, and the environmental and social impacts associated with mining and refining activities [8, 10]. Of particular concern in the coming decades are lithium, cobalt, and nickel, as their potential scarcity could hinder the widespread adoption of BEVs on a large scale [4, 10]. Regarding the economic aspect, the current integration of Life

Cycle Assessment (LCA) and Life Cycle Cost (LCC) analyses in existing literature has been limited. When assessing the economic aspects of BEVs, it is crucial to consider the cost implications of the battery component. [81] shows that the cost of the battery pack in a BEV can account for up to one-third of the total vehicle cost. The cost of battery packs has been decreasing over the years due to advancements in technology and increased production volumes. Through the combination of LCC and LCA analysis, researchers and policymakers can gain a comprehensive understanding of the economic and environmental implications of BEVs, identifying areas for cost reduction and environmental improvement, facilitating more sustainable and economically viable electric vehicle solutions [83]. The objective of this study is to present a comprehensive Life Cycle Assessment and Life Cycle Cost analyses for a specific case study battery pack, which is a very significant contributor to the environmental and economic footprint of a BEV. The software adopted for the analysis is GaBi by Sphera [92]. The analysis of the EoL of the battery pack is performed for three scenarios: 1) waste or simple disposal; 2) recycling; and 3) reconditioning operations for second EV use with recycling at the end of the second life. By evaluating and comparing the outcomes of the three scenarios, this research provides insights into which approach is the preferred in terms of both environmental sustainability and economic viability. The comprehensive assessment of the potential trade-offs and synergies between environmental and economic factors, will enable car manufacturers to make more informed choices regarding adopting and implementing sustainable practices in the context under investigation. While the primary emphasis of this study is the entire European Union, the potential impact of utilizing specific regional (i.e., country) electricity mixes and prices has been thoroughly examined and incorporated into a sensitivity analyses. Two sensitivity analysis are performed for both the LCA and LCC, covering different European countries. For the LCA sensitivity analysis, Italy (IT), Estonia (EE), and Sweden (SE) are the nations considered, representing the average, maximum and minimum impact on climate change, respectively, according to [11]. In the LCC sensitivity analysis, Italy (IT), Denmark (DK) and Netherlands (NL) are the nations under exam, representing the average, maximum and minimum cost of electricity, respectively, according to [87]. Considering the reconditioning scenario, in this study, the assumption is made that 50 % of the LIB cells can be effectively reused. This assumption is consistent with similar assumptions made in previous studies conducted by [63, 62]. However, it is worth noting that different LCA studies have taken into account different cell conversion rates (CCR), which is the percentage of LIB cells that are deemed viable for a second use, and range from 10% to 100% [58, 63, 62, 59]. To address the potential variability of the results associated with the CCR values, a sensitivity analysis is conducted, examining the same range of CCR values used in previous studies.

Chapter 2

Literature review

2.1 Li-Ion Battery Cell

2.1.1 Li-Ion Cell Structure and Materials

Lithium Ion Batteries have emerged as the dominant technology for BEVs due to their performances (energy density and power density), stability and long cycle life. Different combinations of cathode and anode chemistries have been investigated for LIBs, each with their advantages and disadvantages. Cells are designed in several shapes -cylindrical, pouch or prismatic- but all share similar main components. These are shown in Figure 2.1:

Shell: mainly of stainless steel or nickel-plated steel [12].

Cathode: the active materials are metal oxides containing lithium [12]. The first lithium-ion cathode material was $LiCoO_2$ (LCO) with a theoretical specific capacity of 274 mAh g $^{-1}$. Due to its structural instability at higher states of delithiation, its practical use is restricted at approximately 50% [14]. In general, LCO application is limited in the automotive industry due to thermal instability in the charged state, raw material cost and the availability of cobalt. $LiMn_2O_4$ (LMO) was introduced few years later, but due to its low theoretical capacity of 148 mAh g^{-1} and its thermal instability in the electrolyte is mainly used as additive in cathode blends [15]. $LiFePO_4$ (LFP) were introduced as a potential alternative to replace the structurally unstable LCO upon overcharge. Despite their wide use, the lithium cells resulting from

LFP cathodes are not able to achieve the same energy density due to their lower operating voltage, capacity and crystalline density [15]. $LiNiO_2$ (LNO) possess a similar theoretical energy as LCO. Contrary to cobalt, nickel and lithium can easily exchange their position in the lattice, affecting the performance and the accurate synthesis of the compound [14]. An effective approach to solve both problems is substituting part of the Ni by M=Co, Mn, Al, etc..., forming $LiNi_{1-x}M_x\ O_2$. The adjustment of the composition is beneficial for automotive applications as it balances the energy density, improves stability, safety and cost [15]. Lithium Nickel Cobalt Aluminum oxide $LiNi_{1-x-y}\ Al_x\ Co_y\ O_2$ (NCA) are obtained by the dual doping of Co and Al into the LNO structure. The addition of Al into $LiNiO_2$ improves the thermal stability.[14] In the automotive battery industry, one of the most successful Li-ion chemistries is the cathode combination of Lithium Nickel Manganese Cobalt oxide $LiNi_{1-x-y}Mn_x\ Co_y\ O_2$ (NMC). The first commercialized cathode from this family was the NMC_{111} with a composition of $LiNi_{1/3}\ Mn_{1/3}\ Co_{1/3}\ O_2$. However, the trend has moved towards compounds like NMC_{622} ($LiNi_{0.6}\ Mn_{0.2}\ Co_{0.2}\ O_2$) and NMC_{811} ($LiNi_{0.8}\ Mn_{0.1}\ Co_{0.1}\ O_2$). By increasing the Ni content to 80% and reducing the Co content to 10%, NMC_{811} possesses a specific capacity of 200 mAh g $^{-1}$, 25 % higher than that of NMC_{111} (163 mAh g^{-1}) [14, 15].

Anode: the active materials are carbonaceous compounds, mostly graphite [12]. The theoretical specific capacity of graphite is 372 mAh g $^{-1}$ when LiC_6 is formed [17]. The passivation film, referred as Solid Electrolyte Interphase (SEI), is a protecting layer formed on the negative electrode as a result of electrolyte decomposition, mainly during the first cycle. It kinetically protects the electrolyte from further reduction. Battery performance, charge loss, rate capability, cyclability, exfoliation of graphite and safety are highly dependent on the quality of the SEI [18, 14]. Conventional graphite anodes forms lithium dendrites upon overcharging, leading to internal short circuits and safety concerns, due to its flammable nature [15]. Titanium oxides, and in particular, lithium titanate $Li_4Ti_5O_{12}$ (LTO), presents a valid alternative to overcome the safety risks but at the cost of lower energy density to 175 mAh g $^{-1}$ [19]. Currently, the use of LTO is restricted only to niche market. Small improvements are possible for pure graphite electrodes, the next step is combining graphite with high-capacity active materials. Silicon is a promising candidate to replace graphite because of its abundance, non-toxicity and extremely high gravimetric capacity of 3579 mAh g $^{-1}$ [20]. Si anodes have some limitations, one of them is the large volume expansion ($> 280\%$) upon lithiation that cause significant structural strain [15], mechanical fracture and loss of active components from the current collector. The large volume expansion/contraction results in the repeated fracture/reformation of SEIs during charge/discharge cycles, which consumes lithium from the cathode materials, resulting in the loss of capacity. Using Si as a complete replacement for graphite is not possible currently. However, Si/graphite composite electrodes are a promising choice to increase the specific energy, while overcoming the electrode expansion issues upon charge/discharge cycles [14].

Electrolyte: allows the transfer of Li-ions between the cathode and anode in the cell. Some characteristic parameters of the battery, such as the specific capacity, the operating temperature range, the cycle efficiency and the safety performance, depend on the type of electrolyte adopted [12]. Current Li-ion batteries employ a liquid organic solution made of: lithium hexafluorophosphate ($LiPF_6$) as a conducting salt, a mixture of linear (Dimethyl Carbonate (DMC), Ethyl Methyl Carbonate (EMC)) and cyclic (Ethylene Carbonate (EC)) carbonates as solvents, and FluoroEthylene Carbonate (FEC) or Vinylene Carbonate (VC) as additives [14]. The major drawbacks of $LiPF_6$-based liquid electrolytes are the thermal decomposition at relatively low temperature (i.e. 105 °C) and the hazard of thermal runaway. A compromise between safety and performance is found in the Gel Polymer Electrolytes (GPEs) that include a certain portion of liquid components. With this solution, the risk of leakage is reduced if compared to the liquid electrolytes, and higher ionic conductivity is achieved compared to Solid Polymer Electrolytes (SPEs)[21].

Separator: prevents short circuits by separating the cathode and anode sides [12]. The most widely used separators currently are polyolefin-based materials such as PolyEthylene (PE) and PolyPropylene (PP) with relatively low cost, proper pore structure, excellent mechanical strength, and good overheat protection properties [12, 22].

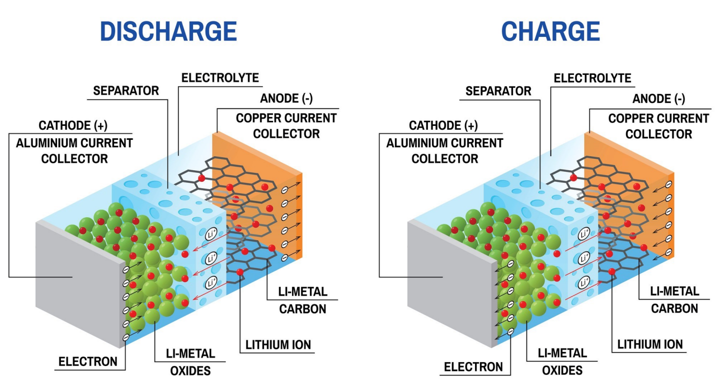

Figure 2.1: Lithium Ion Battery Cell in Charge (right) and Discharge (left) Phase [13]

2.1.2 Battery Cell Manufacturing

The production of the lithium-ion battery cell consists of three main steps: electrode manufacturing, cell assembly and cell finishing. Electrode production and cell finishing can be considered independent of the cell type, while in the cell assembly process there are differences between pouch cells, cylindrical cells and prismatic cells [35, 37]. As explained in detail in Section 2.1.1, regardless of the cell type, the unit cell consists of two electrodes and a separator with the ion-conductive electrolyte filling the pores of the electrodes and the remaining space inside the cell [35].

Electrode Production

The electrode production process starts with the production of slurry (composed by active materials, solvents and binders) by means of a rotating tool. The process of mixing is performed in two steps: a dry mixing of active materials, additives and binders; and a wet mixing (dispersion), with the addition of solvents (e.g., N-Methyl Pyrrolidone (NMP)) that are dispersed and homogenized [35]. The copper (for anode side) or aluminum (for cathode side) foil is coated with the previously made slurry. The foil coated on one side is transferred to the dryer and then fed back to the coating system to perform the same process on the other side [35]. During the drying process the solvent is removed from the material. The dryer is made of different chambers with different temperature zones. The foil is then cooled down to room temperature. The next step is the calendering process, where the copper or aluminum foil ,coated on both sides, is compressed by means of a rotating pair of rollers [35]. The calendered rolls are fed to a slitting station. For the slitting process, rolling knives are used to divide the initial wide electrode coil (mother roll) into small electrode coils (daughter rolls). The individual rolls are cleaned and then rewound (roll-to-roll process). The coils are then stored in a vacuum oven, where residual moisture and solvents are removed. Once the process is complete the coils are transferred to the dry room [37].

Cell Assembly

For the assembly process, the methodology depends on the type of cell considered.

Pouch Cell

For producing pouch cells, the separation of anode, cathode and separator sheets from the daughter rolls is needed [35]. The dried rolls are unwound and fed to the punching tool (that performs a shear cut) in a continuous process. After the separation process is over, the separated electrode sheets are stacked in a repeated sequence (anode, separator, cathode, separator). Different technologies patented by different companies are available, the most common one is the Z-folding [35]. For the Z-folding, the separator is used as an endless sheet that is folded into a z-shape with the anode and cathode sheets that are inserted from the left and right side, alternately. The separator is cut off after the stacking process is concluded and the stack is fixed with adhesive tape. To package the cell, the current collectors (copper for the anode and aluminum for the cathode) are welded (ultrasonic or laser) with the cell tabs [35]. The cell stack is then positioned in a pouched deep-drawn foil. With a sealing process the cell is sealed gas-tight on three sides only in order to fill the cell with electrolyte [37]. The electrolyte filling is performed under vacuum conditions by inserting a high precision needle into the cell. A pressure profile is applied to the cell to obtain a capillary effect, called wetting. After this process the pouch foil is sealed [35].

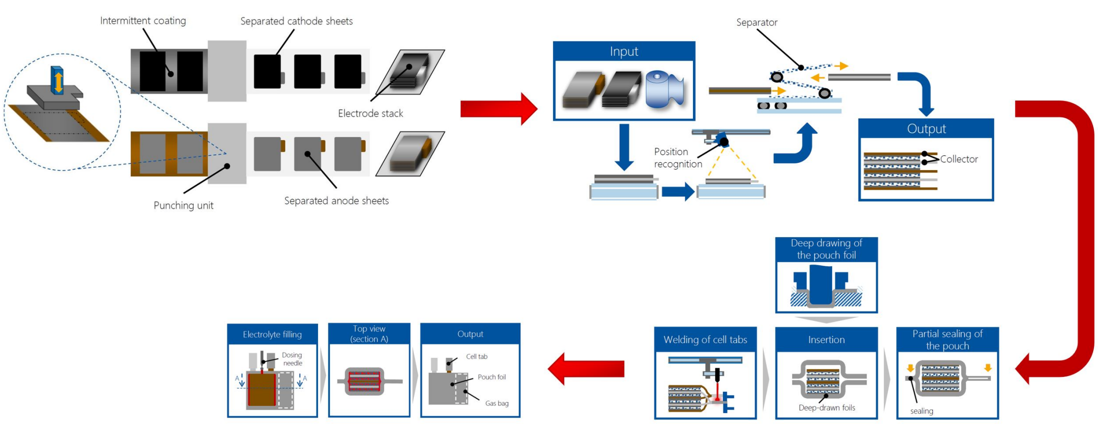

Figure 2.2: Assembly Procedure of Pouch Cell [35]

Prismatic and Cylindrical Cell

A winding process is needed in producing prismatic and cylindrical cells [35]. The electrode and separator foils are wound around a winding mandrel (prismatic cell) or a central pin (cylindrical cell). The final product is called a jelly roll and, to secure the position of the foils, an adhesive strip is used. Differently from the pouch cell, the jelly roll is inserted in a robust metal housing [35]. For a prismatic cell, an insulation foil for the protection of the jelly roll is used when the insertion is performed. The fist step is the welding of the edges of the jelly roll to the contact terminals, positioned on the lid of the cell assembly. After insertion, the housing is sealed though a welding process [35]. For the cylindrical cell process, a bottom insulator and the jelly roll and inserted in the cylindrical housing. After that, the current collectors of the anode and the cathode are welded respectively at the bottom and the lid of the housing. An insulation ring is used between the jelly roll and the lid [35]. The electrolyte filling is performed under vacuum conditions by inserting a high precision needle into the cell. A pressure profile is then applied to the cell to obtain a capillary effect,called wetting. After this process the cells are finally sealed.

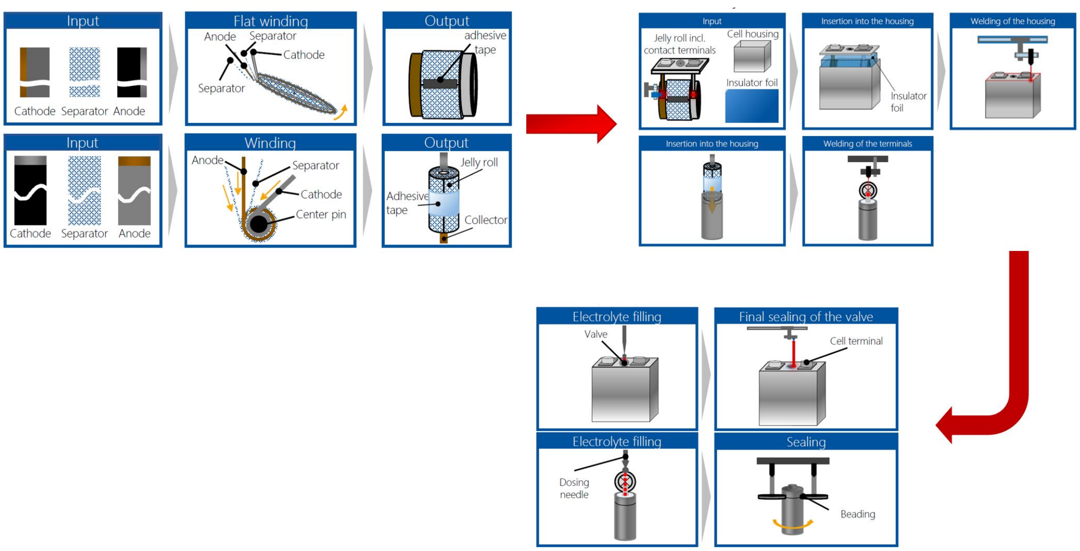

Figure 2.3: Assembly Procedure of Prismatic and Cylindrical Cell [35]

Cell Finishing

An additional operation of roll pressing can be performed for the pouch cells after the electrolyte filling, to ensure distribution and absorption of the electrolyte [37]. For all cell types, the formation procedure is the first charge and discharge cycle of the battery cell. The process is performed according to defined current and voltage curves. In the formation, Li-ions embed in the crystal structure of the graphite creating the interface layer between electrolyte and electrode [35]. In the pouch cell, during the first charging cycle there is a relevant formation of gases. The gases are pushed out of the cell into a gas bag that is pierced during the degassing process in a vacuum chamber. The cell is then sealed and the gas bag is separated and disposed. The aging process is the final step in the cell production, that ensure the quality of the cell [37]. The cell undergoes high and normal temperature aging. During this period, the open voltage circuit voltage of the cell is monitored. If no significant changes are experienced, over a period that depends on the manufacturer and the chemistry used, the cell is fully functional. An End-of-Life testing is performed before the cell leaves the factory. Once the tests like leakage tests, pulse tests, internal resistance measurements and optical inspections have been completed and passed the cell can be packed and shipped [35].

2.2 Battery Module and Pack Assembly

Vehicle manufacturers have adopted a variety of different physical configurations, cell types and cell chemistries for the design of the layout of the battery pack. At the state-of-the-art, the production of battery packs typically follows the cell-module-pack layout [51] where clusters of cells are arranged and interconnected within the module. The modules are then positioned within a housing which provides structural support, thermal management and protection from the external environment. Other auxiliary components (e.g., Battery Management System (BMS), cooling system) are implemented to ensure the proper functioning of the battery cells, creating the final battery pack.

2.2.1 Battery Module Assembly

The cells obtained after the manufacturing process described in Section 2.1.2 are connected serial and/or parallel in modules.

Pouch Cell Module

Pouch cells expand and shrink in thickness during charging and discharging cycles. Because of that, each cell is inserted into a frame that is stopped by means of springs. The cooling system can be implemented by adopting a liquid coolant or through convective means.

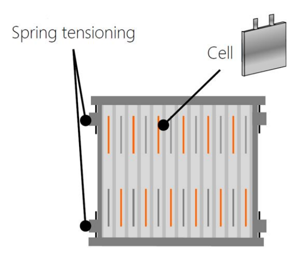

Figure 2.4: Pouch Cell Module [36]

Cylindrical Cell Module

The swelling of cylindrical cells is prevented by the module case. The cells can be connected in series and/or parallel and are contacted through a metal plate on both sides. The space available between the cells is used for cooling.

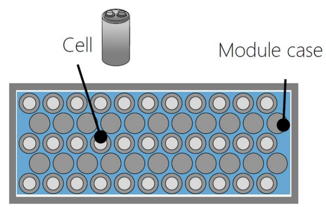

Figure 2.5: Cylindrical Cell Module [36]

Prismatic Cell Module

The installment of prismatic cells does not cause the formation of gaps, the cells are glued together and then clamped to the metal housing. The glue provides the double function of electrical and thermal insulator.

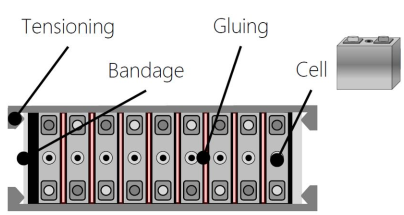

Figure 2.6: Prismatic Cell Module [36]

2.2.2 Battery Pack Assembly

Once the modules are assembled, they are positioned in the pack housing and connected to each other to form the complete battery pack.

Insertion and Attachment of the Cell Modules

In order to cool the modules during operation, cooling plates are positioned at the bottom of the battery pack tray [36]. The modules are then inserted at the bottom of the pack housing by grippers.

The process is repeated until all modules are inserted. To avoid vibrations during operation the modules are fixed to the pack housing by screw connections [36].

Electrical and Thermal Integration

The cooling system is positioned in the holder and connected to the elements in the pack housing. The high-voltage and low-voltage wiring and components are mounted. The Master Battery Management System (BMS Master) is installed to control the cooling system, modules, slave circuit boards and the high voltage module (relay, fuses, current measuring system) [36].

Sealing and Leak Test

Seals are applied to the edge of the housing before connecting the upper part by screwing. The housing is tested for leaks and a bursting disc is installed to secure the pressure and ensure the safety of the battery pack.

Charging and Flashing

The BMS Master is connected to a computer and is flashed through a system analysis program. The consistent State Of Charge (SOC) of the cells is established. In this phase, the thermal performance of the welded joints is monitored by the use of thermografic systems.

End of Line

A final inspection of the entire electronics components is performed. The charge and discharge of the battery is executed according to a defined profile and the SOC for storage or vehicle assembly is established [36]. The labels and warning marks are applied and the battery pack is packaged and transported.

2.3 Battery Pack Integration in the Vehicle

The placement of the battery pack in an electric vehicle is a critical design consideration from both a vehicle dynamics and thermal perspective [39]. From a vehicle dynamics standpoint, the battery pack should be placed so that the center of gravity of the vehicle remains low, minimizing mechanical stresses and fatigue on the mounting frame, and reducing the risk of structural failure. From a thermal perspective, heat dissipation is critical to prevent the battery from overheating with the potential damage of the cells and consequent thermal runaway. Therefore, the battery pack's placement should allow for appropriate air circulation to maximize heat dissipation [38]. This means positioning the battery pack in areas of the vehicle that have natural airflow, or incorporating active cooling systems, such as fans or liquid cooling. In order to protect the battery from potential impacts its position should be placed far off from the front or rear end of the vehicle [38]. Given these considerations the preferred space for storage is the center of the vehicle, beneath the vehicle floor.

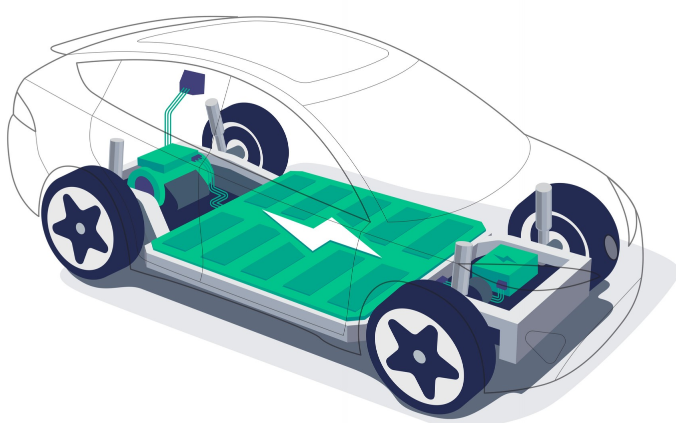

Figure 2.7: Battery Pack Integration in the Vehicle [39]

2.4 Battery End of Life Assessment

The State of Health (SOH) is the degree to which a battery meets its initial design specifications. Over time, as the battery degrades, its performance varies from its initial condition [24]. The Li-ion battery pack of an electric vehicle reaches the end of its useful first life when the total usable capacity drops to 80% of the initial one and the resting self-discharge rate is of about 5% over a

24-hour period [25]. Once the battery pack has reached the end of its first life, manufacturers have three different options [23]:

(1) Simple Disposal. The process is described in Figure 2.8. It usually occurs when battery packs are damaged or if the infrastructure or the market structure necessary for other options is not yet developed.

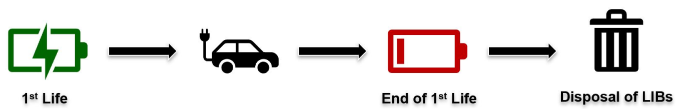

Figure 2.8: LIBs EoL - Simple Disposal

(2) Recycling. This is performed to recover the high value metals, such as nickel and cobalt contained in the cathode material of the battery cell. At the state-of-the-art, the main technologies available for battery recycling are the pyrometallurgic process, the hydrometallurgic process, and the direct method.

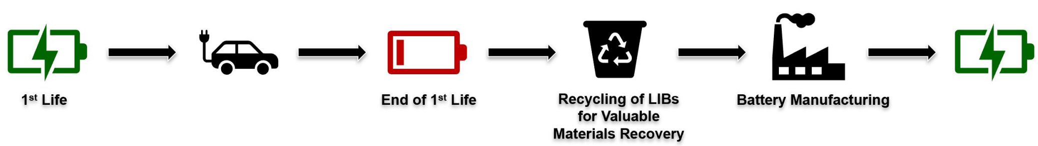

Figure 2.9: LIBs EoL - Recycling

(3) Reuse. The battery pack can be used in the second life for stationary energy storage applications or new mobility applications. At the end of the first life of the battery pack, second life applications can be considered before the recycling process, in line with circular economy principles and the waste management hierarchy [24]. In particular, two different alternatives are found to be adopted:

i. Repourposing. As shown in Figure 2.10, after collecting the battery packs, packs with suitable SOH and capacity requirements (as reported in Section 2.4) are selected and combined together. The assembly of battery packs is then used for stationary energy storage.

ii. Reconditioning. As described in Figure 2.11, after collection, the battery pack is reconditioned. The compromised modules are extracted and substituted with new ones to form

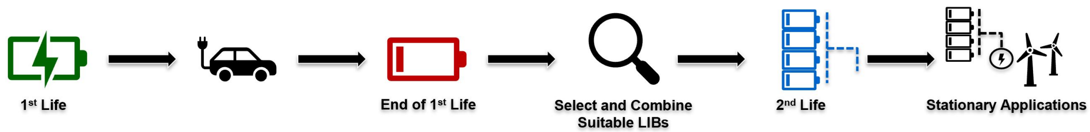

Figure 2.10: LIBs EoL - Repourpose

the new battery pack. The battery pack can be used again in EV applications (instead of a stationary application).

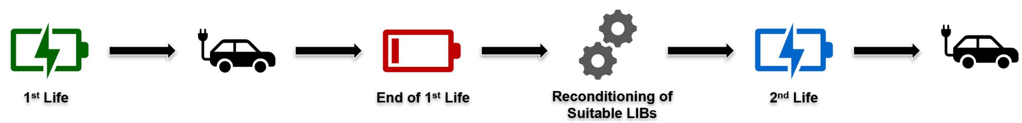

Figure 2.11: LIBs EoL - Reconditioning

Multiple studies can be found in the literature for second use in stationary storage systems [55, 56, 58, 57], while studies on refurbishing of battery packs for second EV applications are still limited [59].

Th recycle options after the end of its first life, will be described in details in the following sections.

2.5 Battery Disassembly

Vehicle manufacturers have implemented diverse approaches to power their vehicles, resulting in a broad range of electric vehicles available in the market that exhibit various design configurations, cell types, and cell chemistries. An example of a typical pack-module-cell configuration is shown in Figure 2.12. Different physical configurations and form factors of the battery packs require diversified approaches for the disassembly procedures, especially for automating the process [24]. For second life applications and recycling, the automotive battery pack is currently manually disassembled, to either reuse or recycle the modules. Due to the weight and high voltages involved in traction batteries, the safe dismantling process requires skilled personnel and specialized tools [24] .

2.6 Recycling Processes for Li-Ion Battery

The differentiation of the battery from both a chemistry and layout point of view presents a challenge for battery recycling. Recycling recovershighly valued metals such as cobalt and nickel from the

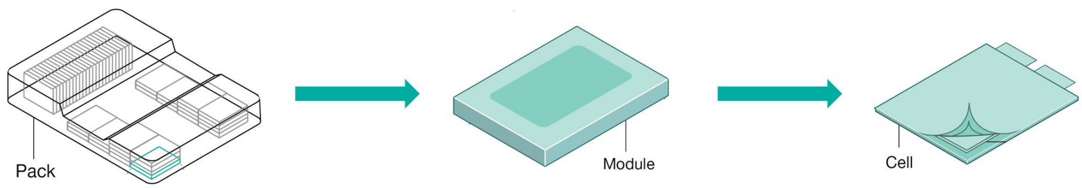

Figure 2.12: Disassembly Procedure of the Battery Pack

battery electrodes. The benefits can be seen if there is a sufficient gap between the procurement and recycling cost, caused by the predicted tight supply of nickel and potentially cobalt in the 2020s [23]. Battery manufacturers may find the idea of securing a supplementary source of battery metals, through recycling, appealing. However, for this approach to become widespread, it is crucial to develop a recycling process that is cost-competitive with traditional mining methods. Currently, the emerging processes that aim to improve the efficiency of materials recovery, from recycled batteries, are still in development and not fully matured [23]. In the following section, the state-of-the-art available technologies for LIBs recycling is described.

2.6.1 Pre-Treatment Methods for Battery Recycling

Pre-Treatment of Li-ion modules consists of two main processes: discharging and dismantling of battery modules, including disconnecting of major components (e.g. cables, battery cells, frames, electronics). After the cells are extracted from the modules,they undergo mechanical processing and separation. Mechanical separation techniques separate cell components based on their different physical properties (e.g. particle size, density, conductivity, magnetic properties). [28, 26].

Pre-Discharge

Before dismantling, batteries are discharged to release the residual charge, eliminating the risk of electric shocks. The possibility of sparks occurrence might cause the ignition of Volatile Organic Compounds (VOCs) during the crushing process causing a fire hazard [28]. Different methods for discharging are available: metal powder, low-temperature discharge, sodium chloride solution and controlled discharging via external circuits. Short-circuit discharge of metal powder is fast but with the side effect of high heat generation, that will result in a rapid rise of the cell temperature [29]. NaCl and alternative salts (Na_2 and $MgSO_4$) were tested to discharge portable batteries. NaCl provide the best discharge profile with low cost but the high concentrations of acid-base solution can corrode the battery casing, causing the loss of valuable metals. Solutions containing $MgSO_4$ are not capable to fully discharge the batteries. Currently, salt-water based discharge is the preferred method in the industrial environment, even if there is corrosion of the battery casing due to the acid-base solution [28, 12].

Mechanical Pre-Treatment

Mechanical pre-treatment separates specific components into several streams. The main objective is to separate the metallic particles (casing, copper and aluminum foils) and to concentrate the black mass. The black mass is the component with the highest value in the battery cell, consisting of a mixture of cathode and anode active materials. The sequence of processes involved are: crushing, sieving, magnetic separation, fine crushing, and classification [28]. The mechanical crushing can be wet or dry. The process removes the outer shell of LIBs, so that plastic and iron filings can be separated from the electrode material [27].

Thermal Pre-Treatment

Pyrolysis and incineration steps are applied for thermal pre-treatment. While similar to each other, these processes can be distinguished by the presence or absence of oxygen (or air). By adding oxygen, incineration can be used to remove the PVDF binder or carbon species. It is worth noticing that all plastic parts and the electrolyte are lost during the process. The appropriate temperature range has to be controlled carefully and should not exceed 600°C [28]. Pyrolysis is performed in an oxygen-free environment allowing the transformation of the organic compounds into lower molecular compounds or their recovery by recondensation [26].

Dissolution Process

The dissolution process separates the cathode active material from the cathode current collector (aluminum foil). The aluminum foil is recovered in the form of metal, and the organic solvent can be reused. The process cannot remove all impurities and the residue after separation needs to be treated urgently, restricting the applications in the industry [26, 28].

2.6.2 Pyrometallurgical Methods for Battery Recycling

Pyrometallurgic processes involve the thermal treatment of minerals, ores, and concentrates to recover valuable materials [12]. Two major approaches are used for the recycling of spent lithium ion batteries:

(1) Regeneration of electrode materials. It is conducted through a heat-treatment process in which a lithium salt is supplied to obtain the original constituent. The high temperature involved promote the re-crystallization of the electrode materials.

(2) Conversion of the spent lithium ion batteries into liquid alloys of Fe-, Co-, Ni- and Mn-. The process is performed at temperature higher than 1000°C.

In order to choose the appropriate pyrometallurgical conditions the physiochemical properties of the battery are of importance.

Calcination

Calcination is a technique for mineral processing that involves the decomposition of minerals to obtain the desired compound. For what concerns the treatment of materials derived from spent LIBs, a similar approach can be used. Lithium salts, organic binders and transition metal oxides can be decomposed by subjecting them to elevated temperatures either in presence of air or under vacuum conditions [12].

Roasting

Roasting is performed by subjecting the substances to heat in the presence of oxygen (or air). During the process, organic compounds, carbon and certain metals can be burned off. Because of this, the recycling of these materials have to be carried out prior to roasting [12]. Is is also possible to extract cathode materials, the result of the chemical reaction is a soluble compound that can be dissolved and separated in aqueous solution.

Smelting

Following the calcination and roasting procedures, after the metal scraps derived from outer casting and current collector are separated, the predominant substances remaining are lithium metal oxides. The smelting process involves melting the entire mixture, known as the charge, to achieve a molten state where multiple phases (such as slags, matte, speiss, and metal) coexist. The charge, consists of fluxes, reducing agents, and minerals. There are three types of smelting techniques: reduction smelting, matte smelting, and flash smelting. However, for the treatment of LIBs, the reduction smelting is the approach employed, since the feedstocks from these batteries primarily consist of oxides [12]. In reduction smelting the oxides are reduced by a reducing agents, in presence of a flux. The oxides are sourced from the cathode materials of the spent LIBs, while carbon, carbon oxide, and natural gas are commonly used as reducing agents. The flux employed usually contains CaO and SiO_2, capable of adjusting the fluidity and melting temperature of the slag. The process is typically carried out in a blast furnace. Once the reduction process is complete, the transition metals enter the liquid metal pool at the bottom of the furnace, while lithium oxide remains in the top slag layer. As the slag and liquid metals are immiscible, the liquid metals are extracted from the furnace, leaving behind the slag [12, 32].

Metal Refining

Metals obtained from the smelting process inevitably contain impurities from the air (oxygen and nitrogen) and from the battery scrap, like carbon [12]. Three typical metal-refining methods are metal-slag process, metal-metal process, and metal-gas process.

2.6.3 Hydrometallurgical Methods for Battery Recycling

Hydrometallurgical recycling of LIBs is based on the dissolution of metallic components, mostly coming from the cathode and anode active materials , preferably with mineral acids, followed by metal separation (by solvent extraction, ion exchange, and precipitation) [28]. Hydrometallurgy is considered the preferable process due to its ability to recover larger amounts of battery components while achieving very high purities of the metal salts. Compared to the pyrometallurgical process, advantages are: high recycling efficiency, high metal selectivity, low energy consumption, little hazardous gas emission, and low capital cost [30]. The pre-treatment steps include discharging, removing of the plastic shell, release of the electrolyte and peeling off procedure of cathode and anode to remove the attached Al and Cu foils. Fine particles of waste cathode materials (like Co, Li) are obtained after calcination and grinding. The obtained particles will be used as raw materials for the following leaching process [12]. The main process consists of : leaching (e.g. acid leaching, alkaline leaching), purification (e.g. solvent extraction, chemical precipitation, electrochemical deposition) and recovery procedures.

Leaching Mechanism

During the leaching process, one or more solutes are extracted from a solid through the application of a liquid solvent. The metal in the cathode material, obtained by the pretreatment, is converted into ions in the solution. For the dissolution leaching, the process is performed as follows: 1) the leaching method directly dissolves all metals with the acid; 2) where the leaching method first leaches aluminum with alkali, and then leaches other metals with acid. The leaching of the anode material is usually performed by the leaching medium, which contains inorganic acid, organic acid, alkali, or bacterial solution [27]. The leaching media are usually mineral acids (H_2SO_4, HCl and HNO_3). Inorganic acids are highly effective for the recovery of metals ($> 99\%$) when applied under optimal conditions [28].

Inorganic Acid Leaching

Strong inorganic acids, such as sulfuric acid (H_2SO_4), nitrate acid (HNO_3) and hydrochloric acid (HCl) are commonly used as leaching agents for the leaching of positive active materials. HCl and H_2SO_4 present the highest leaching efficiencies and they are capable to complete dissolute different metals (Co, Li, Mn, Ni) from different kinds of waste cathode materials. HNO_3 and H_3PO_4 (weaker acid) have good performances during the leaching of some simple waste cathode materials, such as $LiCoO_2$. The dissolution characteristics of the strong mineral acids and the selectivity characteristic of the weaker acid are both necessary to achieve satisfied recovery results during the leaching processes [12, 30]. The leaching efficiency of Co without reducing additives follows the order of HCl $> H_2SO_4 \approx HNO_3$. The leaching generates some harmful gases such as Cl_2, SO_3 and NO_x, harmful for the environment and for the human health. To avoid secondary pollution, the waste-water, which is rich in strong acids , needs to be post-treated.

Organic Acid Leaching

Organic acids have the ability of degrading under aerobic and anaerobic conditions, with the generation of limited environmental pollution [28]. High leaching efficiencies can be achieved with organic acids when a reduction agent (H_2O_2) is applied. The function of the reducing agent is to convert the metal in the cathode material into a valence state that is more soluble in the acid solution [30, 27].

Alkaline Leaching

If compared with acid leaching, the leaching of cathode materials in alkaline solution is rare. However, Alkali leaching with an ammonia-based system is quite selective for specific elements, such as Ni, Co, and Li, because of the formation of stable metal ammonia complexes [12].

Bioleaching

Bioleaching is a process of mineral bio-oxidation, assisted by microorganisms, which transforms insoluble metal sulfates into water-soluble metal sulfates. The principle is to use the acid produced by the decomposition of microorganisms to dissolve the LIBs components [27]. The biological metabolic function can separate target components and impurity, recovering metals

[12]. Up to date, biotechnologies are not commonly applied in battery recycling due to slow process kinetics, leading to long processing times.

Purification and Recovery of Valuable Metals

After the leaching step, the different metal ions need to be separated for recovery. The solution from the leaching processes consists of valuable metal elements (such as Li, Co, Ni, Mn, Fe, Cu, and Al) and different techniques are adopted for the metals separation. Chemical precipitation is commonly used for the removal of impurities metal like Al, Fe and Cu [31, 12]. Solvent extraction is a liquid-liquid extraction that exploits the different solubilities of compounds in two immiscible liquids to separate them from each other. An important parameter to take into account is the equilibrium pH of the solution [30, 12]. Solvent extraction is frequently used in combination with a precipitation process to produce high-purity metal salts [27]. In the regeneration process the cathode material is synthesized directly from the leaching liquor with the addition of certain chemical compounds to obtain the right amount of metal ions [12]. Currently, the main technologies adopted are the sol-gel method (organic acids leaching solution) and the co-precipitation [12].

2.6.4 Pyro-Hydrometallurgical Method for Battery Recycling

Pyrometallurgical and hydrometallurgical methods are usually employed in combination with additional pre-treatment or post-treatment techniques. A schematic process flow diagram depicting the pyro-hydro metallurgical process for LIBs recycling is shown in Figure 2.13. In this recycling

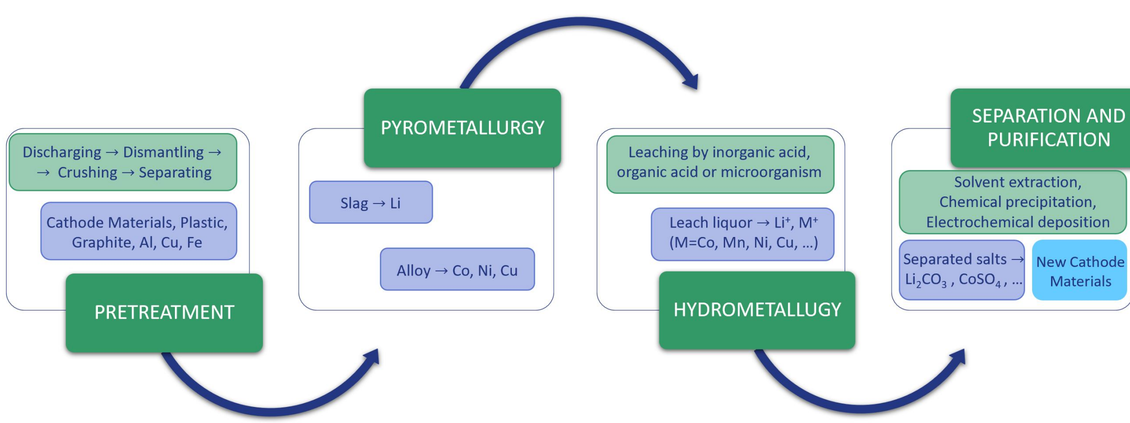

Figure 2.13: Overview of Pyro-Hydrometallurgical Recycling Process for LIBs

strategy, spent LIBs are first discharged and then dismantled through a series of steps to enable the recovery of the electrolyte and separation of the electrodes. Following electrolyte recovery, the LIBs are crushed and screened to separate the plastics, graphite, and various metallic components such as aluminum, copper, iron, and others [32]. In the following stage, a pyrometallurgical process, that involves high-temperature smelting, is utilized to recycle and recover valuable metals like nickel, cobalt, and copper. During smelting, the materials are transformed into a molten state, allowing the metals to be selectively extracted. The resulting metal-rich product undergoes a hydrometallurgical process. In this stage, leaching or dissolution techniques are utilized to extract the desired metals from the molten or solid form obtained from the smelting process. The metals are dissolved in appropriate chemical solutions, and subsequent purification and separation techniques are employed to obtain high-purity metal compounds [32]. The Pyro-Hyrometallurgical process combines the advantages of both pyrometallurgical and hydrometallurgical methods, maximizing metal extraction and promoting sustainable resource utilization.

2.6.5 Direct Methods for Battery Recycling

The direct recycling approach consists of several steps, including discharging and dismantling, electrolyte recovery, separation and regeneration of electrode materials. The schematic description of the process is depicted in Figure 2.14. Unlike pyro- and hydrometallurgical processes, that break down the cathode to recover chemical products through thermal or solution-based methods, direct recycling aims to recover and regenerate the active cathode materials while preserving their original structure. The goal is to reuse these materials in the production of new batteries, without compromising their morphology [33, 32]. NMC cathode material is estimated to be almost ten times more valuable than the equivalent amounts of the constituents pure metals [34]. By avoiding energy-intensive refining and resynthesis processes, the direct recovery of cathode materials can ensure efficient resource utilization while promoting environmental sustainability. Currently, direct recycling approach faces numerous challenges that limit its implementation to the laboratory scale. One significant obstacle is the wide variety of cathode chemistries found in lithium-ion batteries. To achieve high-purity cathode powder, it is preferable to have a single type of cathode input. The presence of multiple cathode chemistries makes more complex the direct recycling process and hinders the efficient recovery of cathode materials [32]. It is still a relatively new technology that requires further development and optimization to improve the efficiency and scalability of the processes.

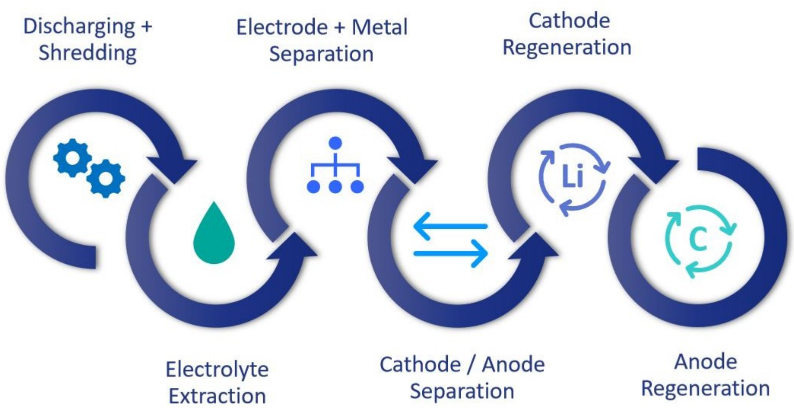

Figure 2.14: Overview of Direct Recycling Process for LIBs

2.7 Life Cycle Assessment and Life Cycle Cost Assessment

2.7.1 Life Cycle Assessment

The International Organization for Standardization (ISO) provides guidelines and requirements for conducting a Life Cycle Assessment according to ISO 14040 and 14044 [40, 41]. ISO 14040 defines LCA as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle [40]. As shown in Figure 2.15, the environmental impacts of a product or service are assessed across its complete life cycle, including stages such as production, distribution, use, and end-of-life.

The LCA methodology is based on 4 main steps [42]:

(1) Goal and Scope Definition. In this phase the aims of the study are defined. The intended application, the reasons for carrying out the study and the intended audience. Methodological decisions are explained, including the definition of the functional unit, establishment of system boundaries, determination of allocation procedures, selection of the impact categories for study and the choice of the appropriate Life Cycle Impact Assessment models.

(2) Life Cycle Inventory (LCI). This phase includes data collection and calculation procedures required to quantify the inputs and outputs of the system under study. Inputs and outputs involve various elements such as energy, raw materials, physical inputs, products, co-products, waste, and emissions to air/water/soil. The data collected includes information on foreground processes as well as background processes.

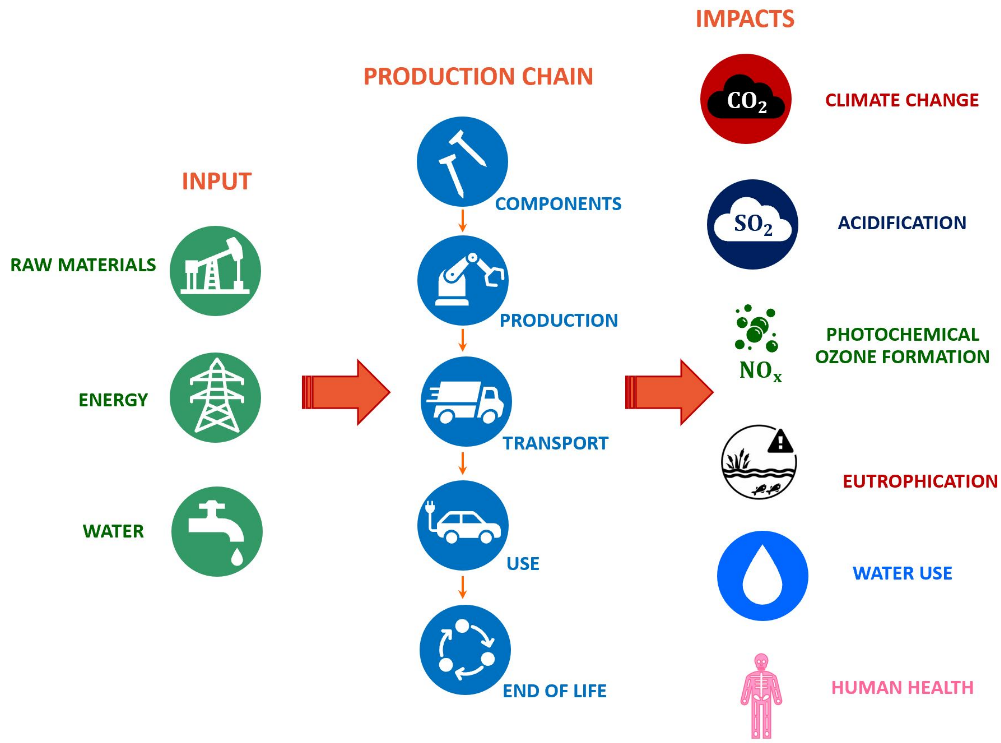

Figure 2.15: Schematic of Life Cycle Assessment

(3) Life Cycle Impact Assessment (LCIA). In this phase, LCI results are associated to the environmental impact categories and indicators.

(4) Life Cycle Interpretation. The collected data and calculated environmental impacts are examined and evaluated to draw meaningful conclusions. The goal is to provide a comprehensive understanding of the environmental performance of the product, system, or process being assessed.

Life Cycle Assessment is used to understand the overall energy and environmental performances of Li-ion batteries for EV applications. Because of their transparency and completeness, the majority of existing LCA studies on automotive LIBs rely on data from four specific studies [68]: Notter et al. (2010) [64] , Majeau-Bettez et al. (2011) [65] , Dunn et al. (2012) [67] , and Ellingsen et al. (2014) [66]. Nevertheless, it is important to consider that these studies were conducted during the early stages of commercialization of LIBa. During this period, industry data were often proprietary, and if accessible, may not have reflected current practices [68]. Because of the dynamic nature of the industry, evolving technologies, and changing manufacturing practices, there could be significant differences between the data utilized in these studies and the current state of commercial-scale production. As stated in [69], a limited number of publications consider the end-of-life stage in the LCA of LIBs. Furthermore, among those studies that do include the EoL stage, few evaluate environmental impact categories beyond global warming potential (GWP), yielding unrealistic conclusions [70], since other impact categories may bear significant contributions, primarily in the EoL stage [71]. In Chapter 3, the LCA approach for this study will be explained in detail.

2.7.2 Life Cycle Cost Analysis

Life Cycle Cost Assessment does not have an ISO standard, unlike LCA. Different definitions can be found in the literature. [80] defines LCC as a cradle-to-grave economic model of the total cost of acquiring and utilizing a system over its entire life span. LCC considers the costs incurred during various stages, including manufacturing, operation and disposal. The state-of-the-art literature reveals a lack of substantial research for the integration of cost analysis in the LCA analysis [81]. When comparing the cost of BEVs with conventional internal combustion vehicles (ICEVs), the battery pack is a key component. Up to one-third of the total vehicle costs can be attributed solely to battery expenses [82]. The cost per kWh registered in the 2010 to 2011 time frame was of 500 €/kWh to 1200 €/kWh [83]. However, the cost of batteries is rapidly declining. In 2014 the price reported was around 450 €/kWh [84].At the present time, the cost applied by market leading manufacturer is estimated to be from 150 €/kWh to 325 €/kWh [85, 83]. There is a wide understanding among manufacturers that for BEVs to achieve cost-competitiveness, the cost of battery packs needs to decrease below 150 €/kWh [83, 85]. Recycling plays a crucial role in achieving environmental sustainability, but its significance extends beyond that. It is equally essential for ensuring a sustainable supply of raw materials and managing costs effectively. As the demand for LIB batteries continues to grow, recycling presents an opportunity to recover valuable materials and reintroduce them into the supply chain reducing the dependence on the market of new raw material. In China the estimated recycling costs for batteries are approximately 32 €/ kWh. While the profit generated depends on the battery size, it averages around 10 €/kWh [93]. On the other hand, in Europe, the current recycling costs are reported to be around 62 €/ kWh, as reported in [93]. However, according to [93] there are expectations of a decline in the recycling costs by 2025, with an anticipated reduction to approximately 40 €/kWh with a projected revenue of 2 €/kWh. As described in Section 2.4 the main approaches for the use of second life batteries are refurbishment and repurposing. The reconditioning process requires significant labor, resources, and time investment for the replacement of damaged or aged parts in the LIB. Repurposing for less-demanding applications, such as stationary energy storage, could be a more cost-effective approach. According to the findings from [94], the approximate cost of reconditioning an EV battery is estimated to be 160 €/kWh, while repurposing the same battery for alternative applications is reported to have a lower cost of 120 €/kWh. Based on [23], it is projected that by 2030, the costs of both reconditioning and repurposing second life batteries will decrease to a cost of 53 €/kWh and 77 €/kWh, respectively.

Chapter 3

Methodology

3.1 Goal and Scope Definition

The goal of this study is to perform both an LCA and LCC cradle-to-grave assessment of a 95kWh NMC622 battery pack, suitable to be implemented on a passenger car, to evaluate its potential environmental and economic impacts. Three different scenarios for the end-of-life stage of the battery back are compared: 1) simple disposal; 2) recycling; and 3) reconditioning and recycling.

3.1.1 Battery Pack Under Analysis

The NMC622 battery pack under analysis is designed with a cell-module-pack configuration. The rated energy capacity of the battery pack is 95kWh. The battery cell is of prismatic design, the cathode active material is composed of a lithium compound ($LiNiCo_{0.6}Mn_{0.2}O_2$) while the active anode material is made of graphite (Gr). The characteristics of the NMC622 battery pack are reported in Table 3.1. The primary data for the battery pack (i.e., nominal energy storage capacity, Bill of Material of the pack, number of cells and modules) used in this study have been provided by the vehicle manufacturer.

3.1.2 Functional Unit

The Functional Unit (FU) is a key concept adopted in the LCA process. The FU is used to facilitate the comparison of different products or systems that fulfill the same ultimate function. The selection

Parameter	Value	Unit	Source
Battery Pack Nominal Energy Storage Capacity	95	kWh	Primary Data
Battery Pack 1^{st} life lifetime	160000	km	Primary Data
Cell Weight	0.6945	kg	Secondary Data[1]
Cell Nominal Voltage	3.6	V	Secondary Data[1]
Cell Nominal Energy Storage Capacity	0.1680	kWh	Secondary Data[1]

[1] Data taken from [44]

Table 3.1: General Characteristics of the NMC622 Battery Pack.

of an appropriate functional unit is crucial as it serves as a fundamental component for meaningful assessments and evaluations [45]. The FU is defined by the ISO 14040 standard as the quantified performance of a product system, and is used as a reference unit [40]. In this study, the functional unit established is 1 kWh of the nominal energy storage capacity of the battery pack.

3.1.3 System Boundary

The system boundary encompasses the entire life cycle of the product, from cradle to grave. In detail, the phases included are the following: raw material acquisition and preprocessing, component production, cell manufacturing, module and pack assembly, use phase and End of Life. Three scenarios are considered for the EoL phase: simple disposal, recycling, reconditioning and recycling of the battery back at the end of the fist life. As a consequence, the methods for the materials disposals are: incineration, landfill, and recycling.

3.1.4 Allocation and Multifunctionality

The allocation procedure is defined by ISO 14040 and ISO 14044 as the partitioning of input and output flows of a product system between the system under study and one or more other product systems, produced simultaneously [40, 41]. Regarding the battery pack manufacturing process, no cases of product produced with the use of the same process have been identified and no allocation procedure is necessary. Allocation is needed for the use and the EoL phases. In the use phase, "main function approach" or "delta approach" is employed, in order to allocate to the battery only the vehicle energy consumption related to the charging/discharging inefficiency [46]. Concerning the EoL stage, the "avoided burden" or "0:100" approach is used so that, the first life cycle takes the burden of the recycling process but at the same time benefits of the credits for the avoided virgin material production [47]. Since only virgin materials are considered as inputs, the benefits are credited at the EoL stage of the life cycle [71].

3.1.5 Impact Assessment

The assessment of potential environmental impacts is carried out with the use of a predetermined set of impact categories. For this study, the Environmental Footprint 3.0 (EF 3.0) impact assessment method, described in [48] is adopted, in accordance with the ILCD handbook [48] and the PEFCR for rechargeable batteries [76]. The list of the impact categories included in the methodology is reported in Table 3.2.

Impact Category	**Unit**
Acidification	Mole H^+ eq.
Climate Change	CO_2 eq.
Ecotoxicity, freshwater	CTUe
Eutrophication - freshwater, marine	kg P eq.,kg N eq.
Eutrophication - terrestrial	Mole N eq.
Human toxicity, cancer	CTUh
Human toxicity, non-cancer	CTUh
Ionizing radiation, human health	kBq U^{235}
Land Use	Pt
Ozone Depletion	kg CFC-11 eq.
Particulate Matter	Disease incidences
Photochemical ozone formation, human health	kg NMVOC eq.
Resource use, fossils	MJ
Resource use, minerals and metals	kg Sb eq.
Water Use	m^3

Table 3.2: EF 3.0 Impact Categories.

3.2 Life Cycle Inventory

The creation of the inventory that is used for the implementation of the life cycle model on the GaBi Software involves collecting and analyzing the data for quantifying the material and energy inputs and outputs of the product system under study [50]. The literature was comprehensive reviewed to analyze the life cycle assessments of battery cells and packs. The data collection process undertaken for this purpose is described in detail in the subsequent paragraphs. The whole battery pack life cycle (from manufacturing to the end of life) for the baseline scenario, is assumed to take place in Europe using the European (RER) electricity mix. As mentioned in Section 1, a sensitivity analysis is performed to assess the variability of the results with the use of different electricity mix.

3.2.1 Battery Pack Manufacturing

The production of battery packs currently follows the typical cell-module-pack layout. Clusters of cells are arranged and interconnected within the module. The modules are then assembled within a housing, that provides structural support, thermal management and protection from the external environment [51].

Battery Cell Manufacturing

The Bill of Materials for the NMC622 prismatic battery cell is derived from the EverBatt 2020 database, published by the Argonne National Laboratory [44]. The active cathode material of the cell, responsible for the determination of the energy density of the cell, is a ternary lithium compound that contains : nickel, cobalt and manganese ($LiNiCo_{0.6}Mn_{0.2}O_2$). The active anode material is graphite. The cathode and anode material are then mixed with carbon black, used as conductive agent, and polyvinylidene fluoride, as binder [15]. The mixtures of cathode and anode materials are then coated on a collector foil made of aluminum and copper, respectively [14]. The electrodes are separated by the separator (i.e., a porous membrane), composed of polyethylene and polypropylene [15]. The electrolyte fills the cell. It is composed of lithium hexafluorophosphate, a conductive salt, with the addiction of cyclic and linear carbonates (solvents) and additives, for the improvement of the performance and of the life of the cell [14].

The manufacturing process of the cell is the one described in Section 2.1.2 for a prismatic cell, with reference to [35]. The total amount of energy necessary for the cell manufacturing is taken from [73]. This study focuses solely on the impacts related to the large-scale production of NMC622 cells in a research factory in Germany, excluding considerations on raw material production, use phase, and recycling. The findings of [73] reveals that a total of 41.48 kWh/kWh of cell capacity is required for the production of the battery cells. Among these, 52 % (equivalent to 21.38 kWh/kWh of cell capacity) are attributed to thermal energy utilization for drying and operating the drying rooms. The remaining 48 % (equivalent to 20.10 kWh/kWh of cell capacity) are consumed as electricity, primarily during the formation process and the operation of the machines [73]. The value in [73] does not account for the energy required for producing the active cathode material and the recycling of the N-Methyl-Pyrrolidone (i.e., solvent used in the mixing stage of cell manufacturing). Therefore, the energy consumption value for producing the active cathode material has been included according to [44] considering a value of 28.94 kWh/kWh of cell capacity for electricity and a value of 48.96 kWh/kWh of cell capacity for natural gas. The electricity required for the recycling process of the NMP solvent is added considering [74] that identifies a value of 10.2 kWh/kg of NMP vaporized. The complete material inventory for the cell manufacturing is reported in Table 3.3.

Modules Assembly

The modules in the battery pack are composed of NMC622 prismatic battery cells. The BoM of the module housing is modeled according to [66], as shown in Table 3.4. The protection of the battery cell is guaranteed by a cassette made up of an inner and outer case, composed of aluminum and nylon 66, glass filled materials. Busbars, made of aluminum and copper, are welded to the cells tabs, a process that is considered to be a part of the battery assembly sequence [66]. Additionally, a lid, made of ABS material, is placed on top of the tabs and busbars.

Battery Management System

The Battery Management System plays a critical role in monitoring, managing and protecting the cells within the battery pack to maximize their efficiency and lifespan. The estimation of the mass share of the BMS is based on [44]. The components that are included in the system are: the Battery Module Boards (BMBs), the Integrated Battery Interface Systems (IBIS), fasteners, High Voltage (HV) system and Low Voltage (LV) system [66]. There is one BMB for each module, placed under the module lids, between the rows of busbars. The BMBs are responsible for monitoring the voltage and temperature of the battery cells, ensuring that they remain within predefined limits. The IBIS acts as the master controller for the BMBs, supervising their operation and managing the battery's charging and discharging strategies [75].

Mass of NMC622 cell	0.695 kg
Material	**Value**
Cathode	
Active Cathode Material ($LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$)	36.00 %
Conductive additive (Carbon Black)	0.375 %
Binder (PVDF)	0.750 %
Current collector (Aluminum)	9.090 %
Anode	
Active Anode Material (Graphite)	21.60 %
Conductive additive (Carbon Black)	0.375 %
Binder	0.440 %
Current collector (Copper)	18.08 %
Separator	
Polypropylene (PP)	1.710 %
Polyethylene (PE)	0.400 %
Polyethylene-terephthalate (PET)	0.280 %
Electrolyte	
Lithium-hexafluorophosphate ($LiPF_6$)	1.660 %
Ethylene Carbonate (EC)	4.620 %
Dimethyl Carbonate (DMC)	4.620 %

Table 3.3: Bill of Materials for NMC622 Battery Cell [44].

Battery Pack Assembly

The data collection process for the battery pack assembly includes the production of the modules (along with all the required materials), the Battery Management System, the cooling system and other auxiliary components. The inventories for the modules assembly and BMS are described in Section 3.2.1 and Section 3.2.1, respectively. The liquid cooling system has the role of controlling and maintaining the cells temperature within their optimal operating range. The composition of the cooling liquid is a mixture of Water and Ethylene Glycole (WEG) [52]. Gap fillers are commonly used in battery packs to safely dissipate excessive heat and provide structural stability. The composition

NMC622 Battery Module	
Components	**Value**
NMC622 Battery Cells	64.02 %
Module Housing Components (Aluminum)	21.44 %
Module Packaging Components	10.62 %
Gap Filler (Silicon-based)	1.817 %
Cooling Liquid (WEG)	1.220 %
Busbars (Copper)	0.881 %

Table 3.4: Bill of Materials for NMC622 Battery Module.

of the thermally conductive gap fillers can be polyurethane- or silicone- based. For this study, a silicon-based gap filler is modeled. This provides low variability of properties with temperature and time [53]. The battery assembly procedure is the one described in Section 2.2.2 with references to the manufacturer data provided and [36]. To complete the assembly of the battery pack a determined amount of energy is required. The energy consumption value is closely related to the level of automation implemented in the plant and, as a consequence, divergent data are encountered in the literature [64, 67, 65]. In this study, the total amount of energy required for the assembly process, that includes the assembly of the modules, is estimated based on [67] for medium level automation of the plant. [67] assumes an energy consumption of 0.75 kWh/kg of battery pack , of which 62% is required as natural gas and 38% is required as electricity. The complete material inventory for the cell manufacturing is reported in Table 3.5.

3.2.2 Battery Pack Use Phase

The use phase is modeled according to the Product Environmental Footprint Category Rules (PERCR) for Rechargeable Batteries [76], taking into account the electricity lost during the recharging phase over the total lifespan of the vehicle. The lifespan of the vehicle (i.e., the first life of the battery pack) is assumed to be 160000 km. The energy that the battery pack delivers during its life cycle is defined by [76] as "Application Service Energy"and is computed as the energy consumption along a given drive cycle multiplied by the lifespan of the battery.

$$Application \quad Service \quad Energy \quad = \quad WLTC_{ec} \cdot lifespan \tag{3.1}$$

NMC622 Battery Pack	
Components	**Value**
NMC622 Battery Cells	42.86 %
Pack Housing Components (Aluminum)	27.82 %
Module Packaging Components	24.09 %
Gap Filler (Silicon-based)	2.857 %
Cooling Liquid (WEG)	0.714 %
Busbars (Copper)	0.577 %
BMS	0.511 %
Screws (Steel)	0.357 %
Plumbing (ABS)	0.214 %

Table 3.5: Bill of Materials for NMC622 Battery Pack.

For this study, in compliance with the European legislation [60], the drive cycle adopted as reference is the Worldwide Harmonized Light Vehicle Test Cycle (WLTC). The value of energy consumption along the drive cycle considered is 14.9 kWh/100 km. The losses are computed as [76, 72]:

$$Losses \quad = \quad (1 - \eta_{charger} \cdot \eta_{batt,c} \cdot \eta_{batt,d}) \cdot Application \quad Service \quad Energy \tag{3.2}$$

$\eta_{charger}$ is the efficiency of the charger, assumed to be 0.89.
$\eta_{batt,c}$ is the efficiency of the battery during charging, assumed to be 0.98.
$\eta_{batt,d}$ is the efficiency of the battery during discharge, assumed to be 0.98.
The energy losses that results from the approach described, over the battery lifespan, are 3462.6 kWh.

3.2.3 Battery Pack Disassembly

Disassembly is an integral part of the recovery process, and it is necessary to partially or fully dismantle the battery pack before its components or parts can be reused, remanufactured, or recycled. Prior to the disassembly process, the state-of-charge of the battery is measured and a discharging operation is performed [61]. The initial step of the process involves breaking down the battery packs into their primary components, which include the materials of the battery pack packaging, battery modules, BMS and cooling system. Given the limited volume of batteries recycled and the wide variety of battery designs, with the relative problems described in Section 2.5, manual dismantling is currently the preferred method [61]. The energy requirements for manual disassembly are generally minimal, and because of this are not accounted for in this study.

3.2.4 Battery Pack EoL

The description of the EoL inventory for the three different scenarios analyzed in this study, Section 2.4, is described in the following.

Waste - Simple Disposal Scenario

The impact of the EoL stage, modeled as a Waste or Simple Disposal process, includes the impacts associated with the disposal of non-cells and cells materials. It is assumed that no recycling process is performed for the battery pack components. The simple disposal of cells materials includes wastewater treatment, incineration of graphite, PVDF, carbon black and plastics. Aluminum is disposed in landfills [72]. Disposing non-cell materials, including components of the BMS, cooling system and battery packaging, and copper and steel parts, are modeled with the specific "Market for Scrap"in Ecoinvent 3.8. The aluminum is assumed to be disposed in landfills. Electronic components and plastics materials are treated as waste.

Recycling Scenario

Following the guidelines outlined in the PEFCR on rechargeable batteries [76], it is assumed that the battery pack undergoes dismantling at its EoL to separate the main components and maximize the recovery of the different material fractions. In this analysis, as stated in Section 3.1.4, all the input materials of the manufacturing process are considered to be 100% primary materials, not considering any environmental credits associated with recycled material content [77]. However, the potential benefits derived from material recycling are credited to the EoL stage, in terms of "avoided primary materials". The impact of the EoL stage, modeled as a recycling process, on both the cells materials and the non-cell materials is categorized into two segments:

(1) Disposals, that includes the impacts of the recycling process and the impacts associated with the disposal of non-recycled materials. Non-recycled materials for the cells materials are associated with activities like wastewater treatment, incineration of graphite, PVDF, carbon black, and plastics, as well as landfilling of aluminum, lithium, and the remaining slag [72].

(2) Credits, that are a measure of the savings achieved by substituting some of the virgin materials with recovered ones. The attribution of credits for cell materials primarily arises from the

recovery of nickel, manganese, cobalt, and copper. Concerning the non-cell materials, the credits mainly account for the recovery of copper, aluminium, and steel, considering their respective recovery rates.

In this study, the recycling of the battery cells is simulated through a combined pyro-hydrometallurgical process, described in Section 2.13 and depicted in Figure 3.1, in accordance with the guidelines of PEFCR for rechargeable batteries [76]. During the Pyrometallurgical process, the batteries are introduced into a furnace where they undergo smelting (high-temperature procedure), resulting in the recovery of an alloy of cobalt, copper, nickel, and iron. Some materials cannot be recovered due to the high temperature of the process: graphite, plastic materials and the electrolyte (that are burned), aluminum (that is oxidized) and also manganese. Lithium exits the furnace in a slag, with aluminum, but is not recovered because not economically convenient [67, 72]. After the pyrometallurgical process, a hydrometallurgical step is needed to recover the metals from the alloy. The inventory for the process is assessed considering the recovery rates of [76] and adapting them to the case study. The inventory in [76] is also applied for the recycling of non-cell materials, namely the BMS, cooling system, and battery packaging. The recovery rate as pure metals is set to 90% for copper and aluminum and 85% for steel [76, 44, 72]. The EoL stage is assumed to occur in Europe for the baseline scenario with the use of the average European (RER) electricity mix. As shown in Figure 2.15, the environmental impacts of a product or service are assessed across its complete life cycle, including stages such as production, distribution, use, and end-of-life.

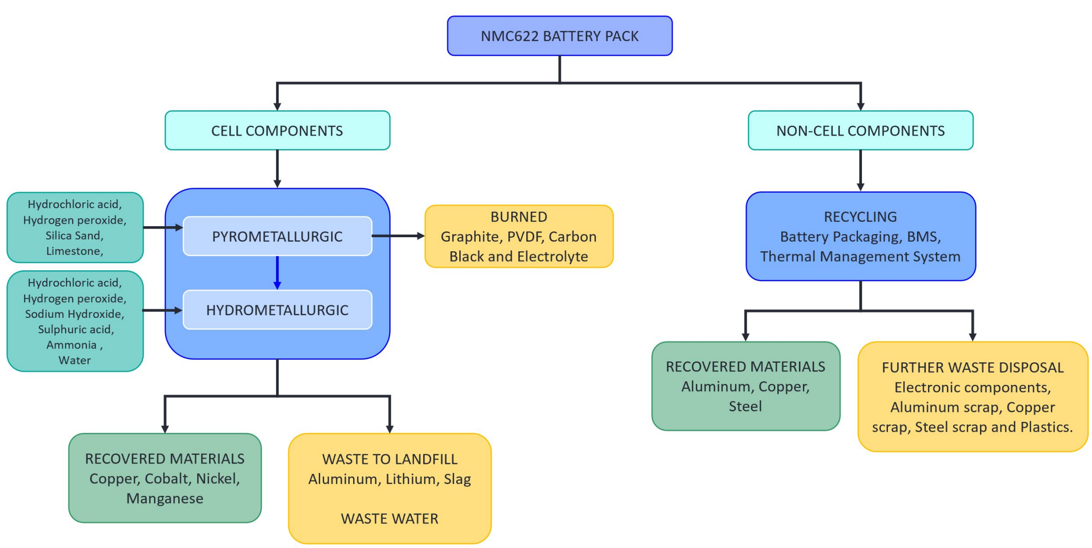

Figure 3.1: Pyro-Hydrometallurgic Process Implemented

Reconditioning and Recycling Scenario

When the battery pack reaches the end of its fist life it undergoes a reconditioning process. During this process, any modules that are found to be compromised or damaged are removed and replaced with new ones, resulting in the formation of a new battery pack. This reconditioned battery pack is then suitable for reuse in EV applications [59]. For the modeling of the reconditioning phase, according to [59] the electricity consumption needed for the reconditioning process is estimated to be 26.04 kWh for each module that is substituted. The module substituted is assumed to undergo the same production process as the one described in 3.2.1. With the swapping of the modules, other components like busbars, plumbings and screws needs to be substituted and a new BMS is implemented. Not all lithium-ion battery cells are suitable for reuse at the end of the battery first life. Therefore, this study assumes that 50% of the LIB cells can be effectively reused, which aligns with a similar assumption made by [63, 62]. However, various LCA studies have considered different cell conversion rates (CCRs) (i.e. representing the percentage of LIB cells viable for a second use), ranging from 10% to 100% [58, 63, 62, 59]. To account for the potential variability in CCR, a sensitivity analysis is performed in this study, analyzing the same range of CCR values.

With the creation of a reconditioned battery pack, that can be reused for traction application, the production of a new battery pack is avoided. However, the credits assigned for the avoided battery production are decreased by a factor that depends on the State of Health (SoH) of the battery at the end of the first life and on the round trip efficiency of the battery in the first and second life. The mass of the avoided battery pack is based on [78], accurately modified for the case study, and is modeled through:

$$M_{av,bat} = M_{2nd} \cdot SoH \cdot (1 - \eta_{rt1} + \eta_{rt2}) \tag{3.3}$$

M_{2nd} is the mass of the second-life battery, SoH is the state of health at the end of the first life and η_{rt1},η_{rt2} are the round-trip efficiency of the first and second use, respectively. In this study the mass of the second-life battery is assumed equivalent to the one of the first life. The value of the SoH is based on [54, 79] and is assumed to be 80 %. The values of the round-trip efficiencies are based on [58] and are respectively $\eta_{rt1} = 0.98$ and $\eta_{rt2} = 0.95$. The mass of the avoided battery pack resulting after the previous assumptions is 543.2 kg and the credits are assigned according to this value. The second use phase is the one described in Section 3.2.2. At the end of the second life it is assumed that the battery pack undergoes a recycling process equivalent to the one described in Section 3.2.4.

3.3 Life Cycle Cost Inventory

The LCC analysis includes all the phases of the battery pack's life cycle, in accordance with the cradle-to-grave system boundary. This approach ensures that the boundaries of the LCA and LCC are consistent and cover the same scope of evaluation. The inventory data employed in this analysis are estimates intended for large scale production scenarios. The sources considered in this study refer to publications that provide data from plants with varying annual production capacities, ranging from 883 MWh [73] to 32.9 GWh [49, 44]. The study considers the expenses associated with raw materials, ancillary materials, processing, electricity, and fuels. These cost assessments are based on information obtained from reputable secondary sources [49, 44, 86, 87, 88]. To account for the overall pricing of components, additional expenses related to capital equipment, labor costs, Value Added Taxes (VAT), and manufacturer profit margins have been taken into consideration. This ensures that the analysis incorporates all relevant costs and accurately reflects the selling prices of the individual components, going beyond the mere costs of materials and energy. In Table 3.6 is shown the complete inventory of the additional costs considered.

Additional Cost	RER	ITA	DK	NL	Source
Capital Equipment	2.1 %	2.1 %	2.1 %	2.1 %	[89]
Human Labor	14 %	11 %	16 %	14 %	[91]
VAT	21 %	22 %	25 %	21 %	[90]
Profit Margin	6 %	6 %	6 %	6 %	[89, 82]

Table 3.6: Additional Battery Pack Costs

According to [89], there is a 2.1% increase in cost due to capital equipment. Additionally, [91] indicates a range between 3% and 17% increase resulting from human labor costs, depending on the nation considered. [90] suggests an increase due to the Value Added Taxes (VAT) that is dependent on the nation considered. [89] and [82] propose respectively a 6.5% and a range between 5% and 9% increase attributed to the profit margin. Regarding the costs of raw and ancillary materials, they are based on commodity prices from May 2023, which have been adjusted for inflation. The exchange rates utilized in this study for the conversion of the prices into a unified currency are: 1.1128 USD to 1 €, 151.69 JPY to 1 €, 7.62 CNY to 1 €, and 90.06 INR to 1 €. For what concerns electricity and natural gas, this study considers the European (RER), Italian (IT), Danish (DK) and Dutch (NL) average costs for the first half of 2022, inclusive of taxes. The specific average prices are presented in Table 3.7.

	RER	IT	DK	NL	Source
Electricity [€/ kWh]	0.2525	0.27	0.4559	0.0595	[87]
Natural Gas [€/ kWh]	0.0861	0.129	0.16	0.1293	[88]

Table 3.7: Average prices of Electricity and Natural Gas for first half of 2022

The use phase cost incorporates the retail price of electricity, assuming an AC home charging scenario. This choice is based on the current preference and affordability of home and work recharging options among European EV consumers. For the battery EoL stage, the costs of recycling are included, while revenues are considered for the sale of secondary materials, aligned with the avoided burden approach adopted for the LCA. Costs, such as general transport services and material processing, rely on the Ecoinvent 3.8 database and GaBi software [92].

Chapter 4

Results and Interpretations

4.1 Life Cycle Impact Assessment

The following sections present the Life Cycle Impact Assessment of the NMC622 battery pack, which was previously described in Section 3.2.1. The impacts resulting from the baseline scenario, using the European (RER) energy mix, are detailed in terms of Battery Pack Manufacturing, Simple Disposal Scenario, Recycling Scenario, and Reconditioning+Recycling Scenario. To gain insights into the impact variability associated with different national energy mixes, a sensitivity analysis, assuming a recycling scenario, is conducted. For the Refurbishing and Recycling scenario, the sensitivity analysis is performed to evaluate the variability of the results when different numbers of modules are substituted to create the new, regenerated battery pack.

4.1.1 Battery Pack Manufacturing

With reference to the baseline scenario, Figure 4.1 exclusively focuses on the production stage of the complete battery pack to illustrate the relative contributions of cell manufacturing, represented by the blue bars, and pack assembly, represented by the orange bars. The results are shown for all the impact categories of the EF 3.0. Notably, cells manufacturing emerges as the primary contributor across all the examined categories, ranging from a 55 % share for Climate Change to a significant 90 % for Ionising radiation. Additionally, the contribution of cells manufacturing for the resource use, mineral and metals is substantial, accounting for 86 % of the overall impact. This is mainly attributed to the utilization of rare metals during the production stage of the cells.

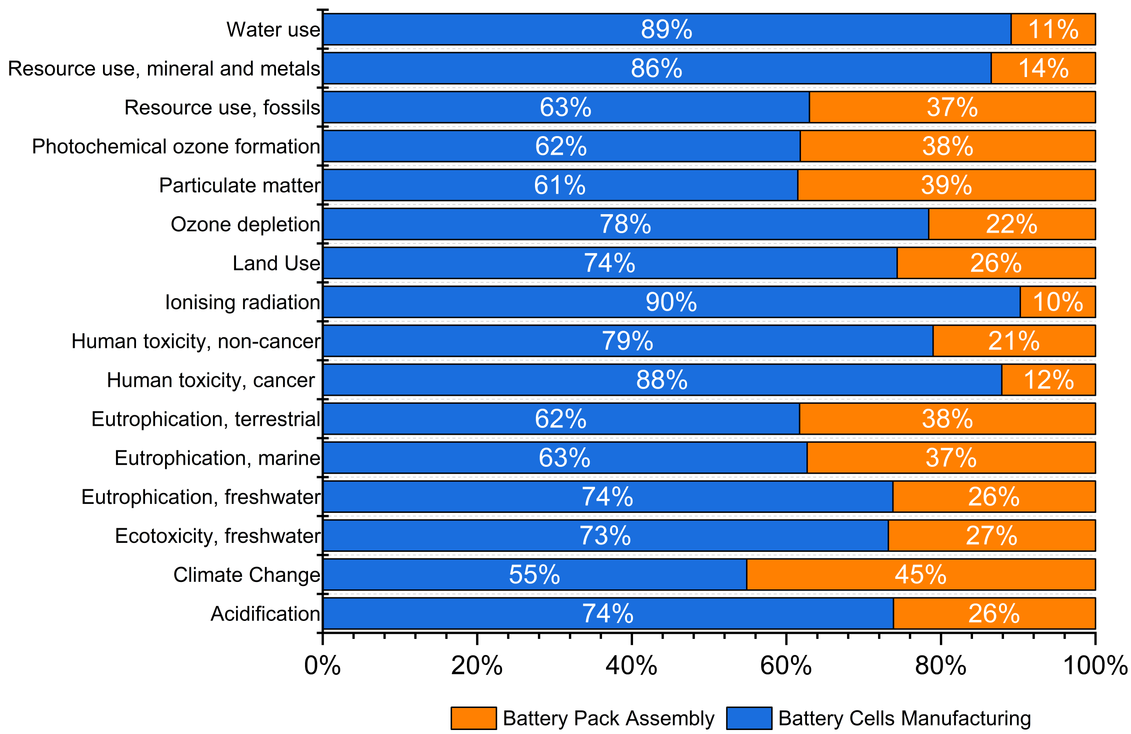

Figure 4.1: Contributions of cells manufacturing and pack assembly to the impacts of the battery pack.

Battery Cell

Through the application of a weighting operation, six impact categories are been identified as the most significant at the present time: Resource use - mineral and metals, Climate Change, Resource use - fossils, Ecotoxicity - freshwater, Particulate matter, and Acidification. Figure 4.2 presents the distribution of contributions of components and energy vectors to the impacts of cells manufacturing, for the most relevant categories. In general, the results are noticeably influenced by cathode production, which accounts for a significant portion ranging from 28 % to 65 %. This can be attributed to the production of the active cathode materials and the extraction of aluminum. Similarly, anode production also emerges as a prominent contributor, ranging from 15 % to 69 %, primarily due to copper extraction. In terms of resource use of minerals and metals, the contributions from the

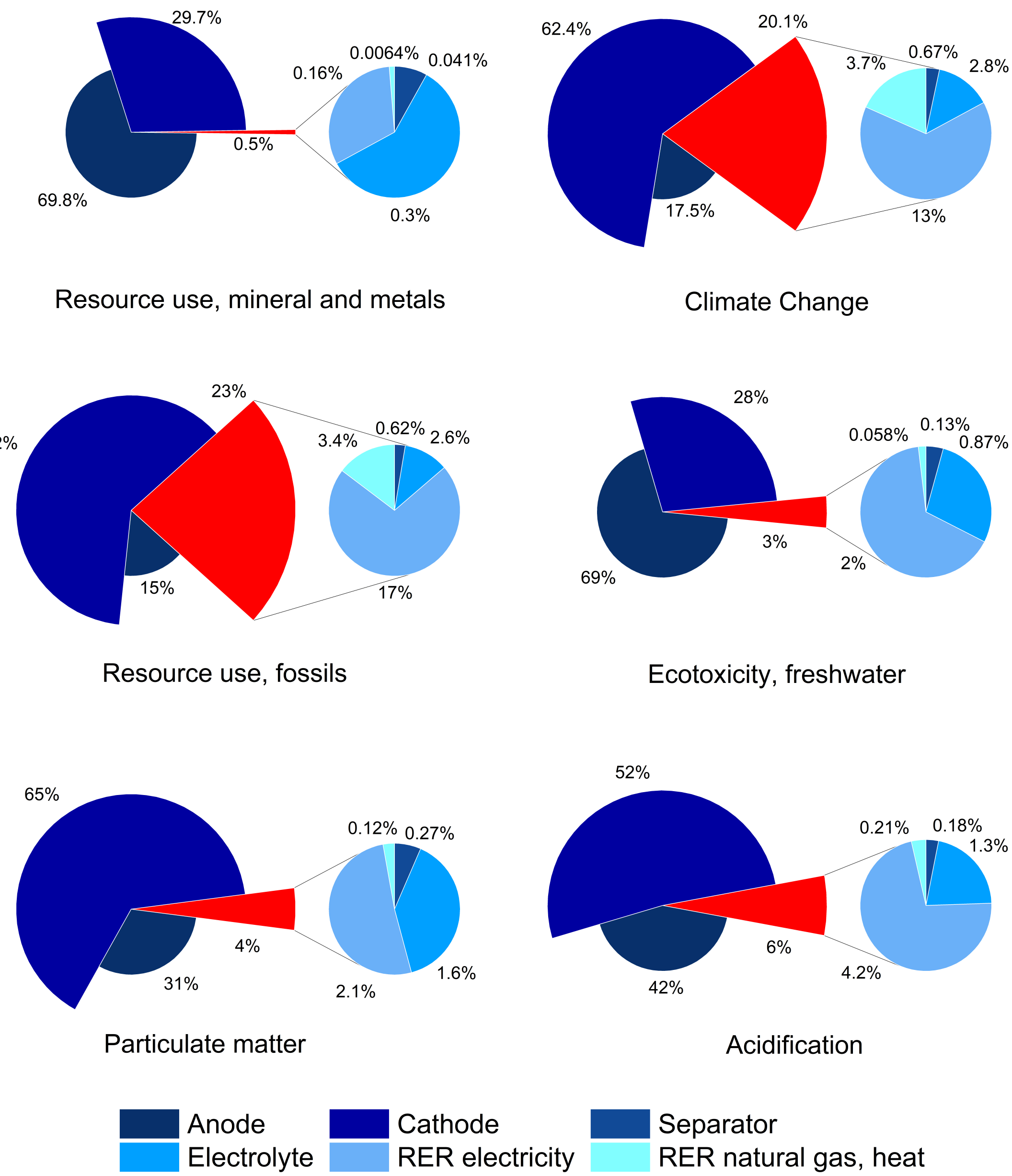

Figure 4.2: Contributions of each cell component and energy vector to the impacts of each battery cell.

anode (69.8 %) and cathode (29.7 %) are significant. These contributions are strongly influenced by copper extraction for the anode and the production of active cathode materials for the cathode. The other contributions accounts for about 0.5 % with the electrolyte share of 0.3 % while the electricity represents the 0.16 %. The contribution of the separator and natural gas are limited.

Climate change impacts can primarily be attributed to the cathode, accounting for 62.4 % of the total impact. This is primarily due to the extraction of metals such as cobalt and nickel, as well as the energy consumption associated with their production. Additionally, the extraction of aluminum for the collector foil is also a significant contributor. Anode production contributes to 17.5 % to the climate change impact, primarily due to copper extraction. The energy consumption associated with cell manufacturing itself accounts for 16.7 % of the total impact.

In terms of resource use of fossils, the impact is heavily influenced by cathode production, which represents the largest contribution at 62 %. Additionally, the energy required for cell manufacturing plays a significant role in the overall impact, accounting for 16.7 % as electricity and 3.4 % as heat. Anode production represents the 15 %, mainly due to the extraction of copper.

When considering the ecotoxicity of freshwater, the impact is primarily driven by anode production, which accounts for 69 % of the total, because of, the extraction of copper during the production process. The extraction of metals such as cobalt and nickel for the cathode production plays a key role in the ecotoxicity impact of cell manufacturing, representing a share of 28 %. The other contributions are limited to the 3 % of the overall impact.

For particulate matter, the main contributors are cathode production, accounting for 65 %, and anode production, accounting for 31 %. The impacts of cathode production are primarily associated with the extraction of cobalt, nickel, and aluminum. The contribution of energy consumption to the particulate matter is not significant, as it represents less than 3 % of the overall impact.

Lastly, in terms of acidification, the impact is primarily attributed to cathode production (52 %) and anode production (42 %). The primary driver of the impact in cathode production is the extraction of nickel, while the secondary contributor is the extraction of aluminum. The impacts due to electricity consumption accounts for 4.2 % of the total impact, while the natural gas contribution is limited to about 0.21 %.

4.1.2 EoL: Simple Disposal Scenario

In relation to the reference scenario (RER energy mix), Figure 4.3 presents the results of the comprehensive life cycle impact assessment conducted for the specific EoL, modeled as Simple Disposal. The contribution of battery pack production is segmented into two elements: cells manufacturing, shown as light-blue bars, and the production of battery pack components and assembly, depicted by the orange bars. The yellow bars represent the impact of the battery losses during the use phase. At the end of its life, the battery's impact (green bars) comprises the simple waste disposal of the components of the battery (i.e, landfill, incineration) as described in Section 3.2.4.

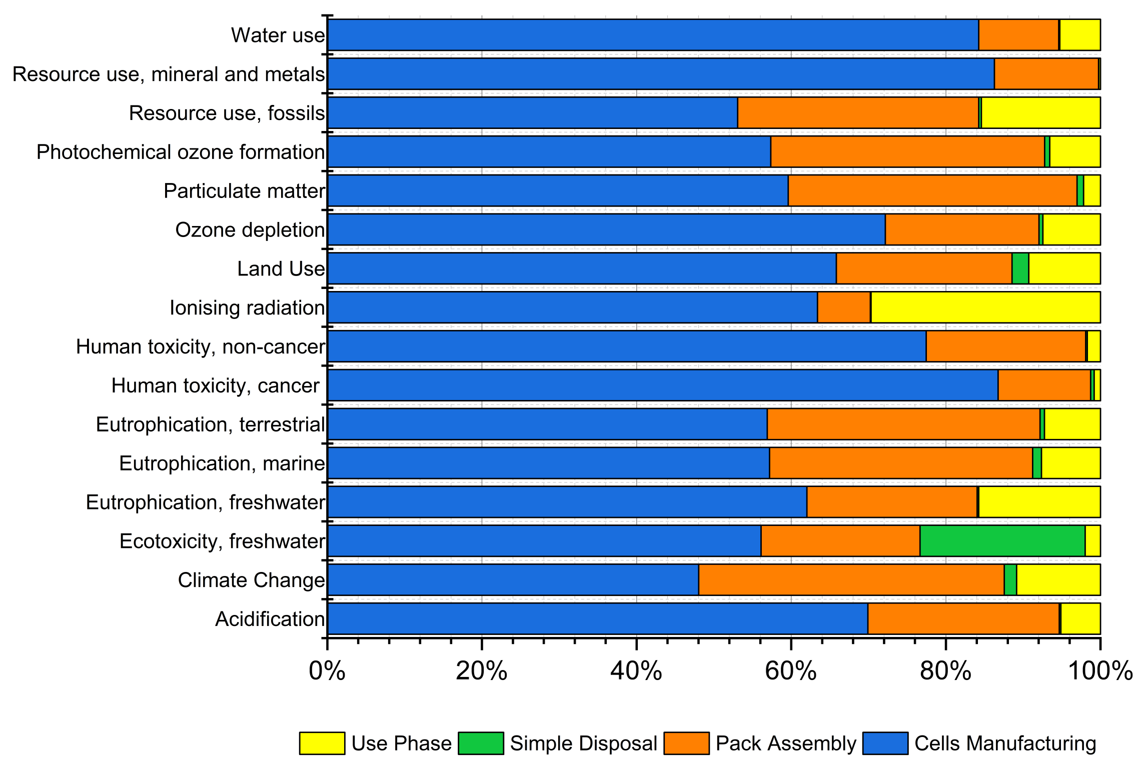

Figure 4.3: EoL Simple Disposal Scenario: LCA results of the battery pack.

The highest contribution to the impacts is given by the production process of the battery pack (70 % to 99 %), followed by the use phase (0 % to 30 %) and simple disposal (0 % to 21 %).
Figure 4.4 provides a detailed overview of the six most significant impact categories. The results are presented in relation to the functional unit, which represents 1 kWh of rated energy capacity of

the battery pack. The contributions of the battery pack production phase is divided into cells manufacturing (light-blue bars) and the production of battery pack components and assembly (orange bars). The impact during the use phase is represented by the yellow bars, which account for battery losses. Additionally, the impact of the EoL of the battery (green bars) includes the disposal of the battery components without recycling operations.

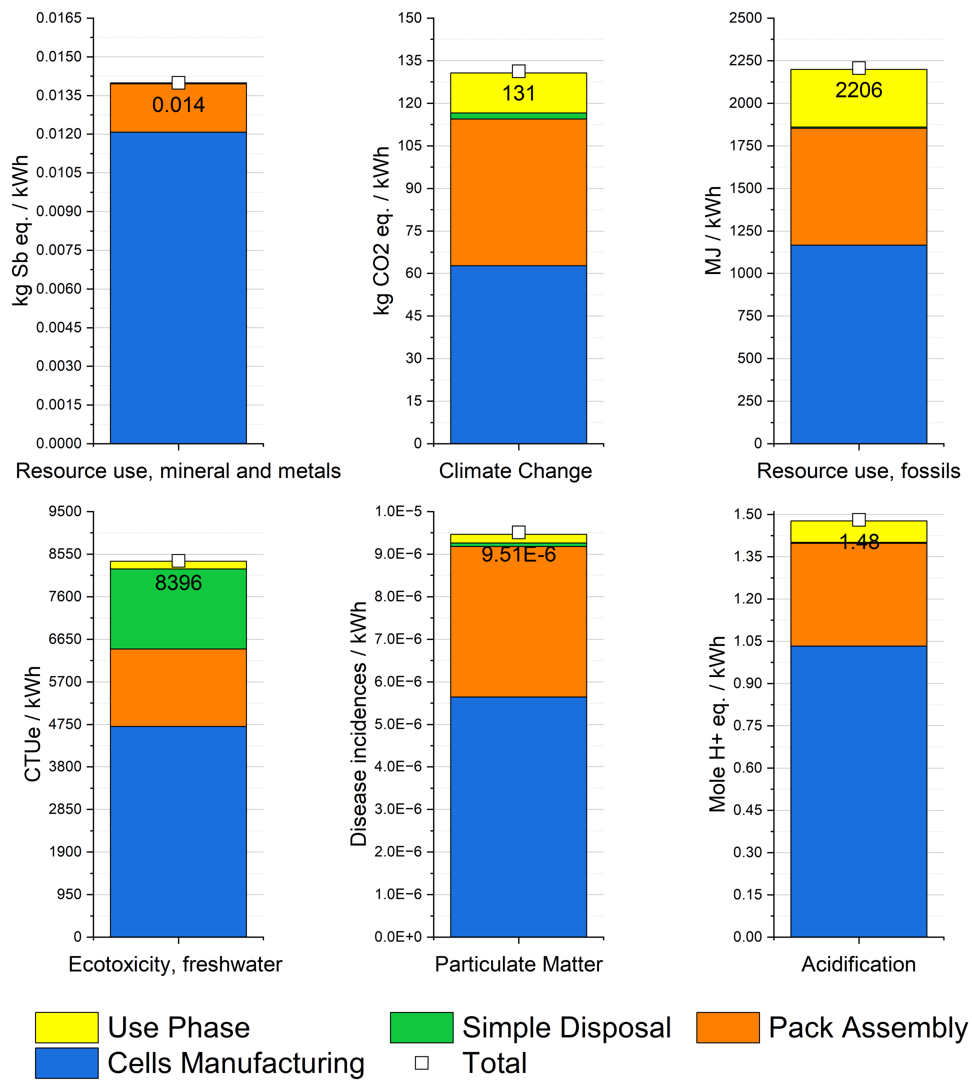

Figure 4.4: EoL Simple Disposal Scenario: LCA results of the battery pack for the six most relevant impact categories.

The impact category of resource use, minerals and metals is almost solely influenced by the battery pack production (99 %). Cells manufacturing (light-blue bar), plays an important role as it accounts for 86 % of the total impact, which can be mainly attributed to the extraction of nickel, copper, and cobalt for the active cathode material production. In contrast, the impact of end-of-life simple disposal (green bar) is almost null, representing 1% of the total. The use phase (represented by the yellow bar) does not contribute significantly to this specific impact category.

In terms of climate change, the main driver of the impact is the production of the battery pack, representing 88 % of the total impact (indicated by the orange and light-blue bars). Within the production phase, cell manufacturing accounts for 55 % of the overall impact. The use phase of the battery pack contributes 10 % to the climate change impact (shown by the yellow bar). In the end-of-life phase, the disposal process slightly increases the climate change impact by 2 % (depicted by the green bar).

In analyzing the resource use of fossils, the impact is greatly influenced by the battery pack manufacturing, accounting for 84 % of the total impact (indicated by the orange and light-blue bars), primarily attributed to the energy consumption and raw material extraction involved. The use phase contribution of the battery pack to the overall impact is relevant and around 15 % . End-of-life disposal (green bar) has a negligible contribution to the overall value.

The impact of ecotoxicity on freshwater is predominantly attributed to the production of the battery pack, accounting for 77 % (orange and light-blue bars). Specifically, cells manufacturing contributes 56 % (represented by the light-blue bar) due to the production of anode and cathode materials. The impact of the use phase is limited, accounting for approximately 2 % (yellow bar). The simple disposal (green bar) have a relevant effect, representing 21 % on the overall impact, mainly attributed to the incineration of cell materials.

When considering the impact category of particulate matter, the battery pack's production phase (represented by the orange and light-blue bars) has the highest contribution, accounting for 97 %. Within the production phase, cell manufacturing (light-blue bar) contributes 60 % to the overall impact, primarily due to the production of the active cathode material. The impact of the use phase is negligible, representing around 2 % of the total. Simple disposal operations (shown by the green bar) contributes to 1 % to the overall impact. The acidification category is primarily influenced by cell manufacturing (light-blue bar), contributing significantly with 70 % . The production of cathodes, with its energy consumption and raw material extraction, plays a crucial role in this impact category. The use phase accounts for 5 % of the total acidification impact. On the contrary, the contribution of end-of-life is very limited.

4.1.3 EoL: Recycling Scenario

Referring to the baseline scenario (RER energy mix), Figure 4.5 illustrates the outcomes of the impact assessment conducted on the analyzed battery throughout its complete life cycle. The contribution of battery pack production is divided into two components: cells manufacturing represented by the light-blue bars, and the production of battery pack components and assembly represented by the orange bars. The yellow bars depict the contribution of the use phase. The impact of the battery at the end of its life includes the impacts associated with cells, modules, and other pack components, and is divided into two parts: disposals represented by the green bars, and environmental credits depicted by the red bars. Disposals accounts for the recycling process and further waste disposal of the materials.

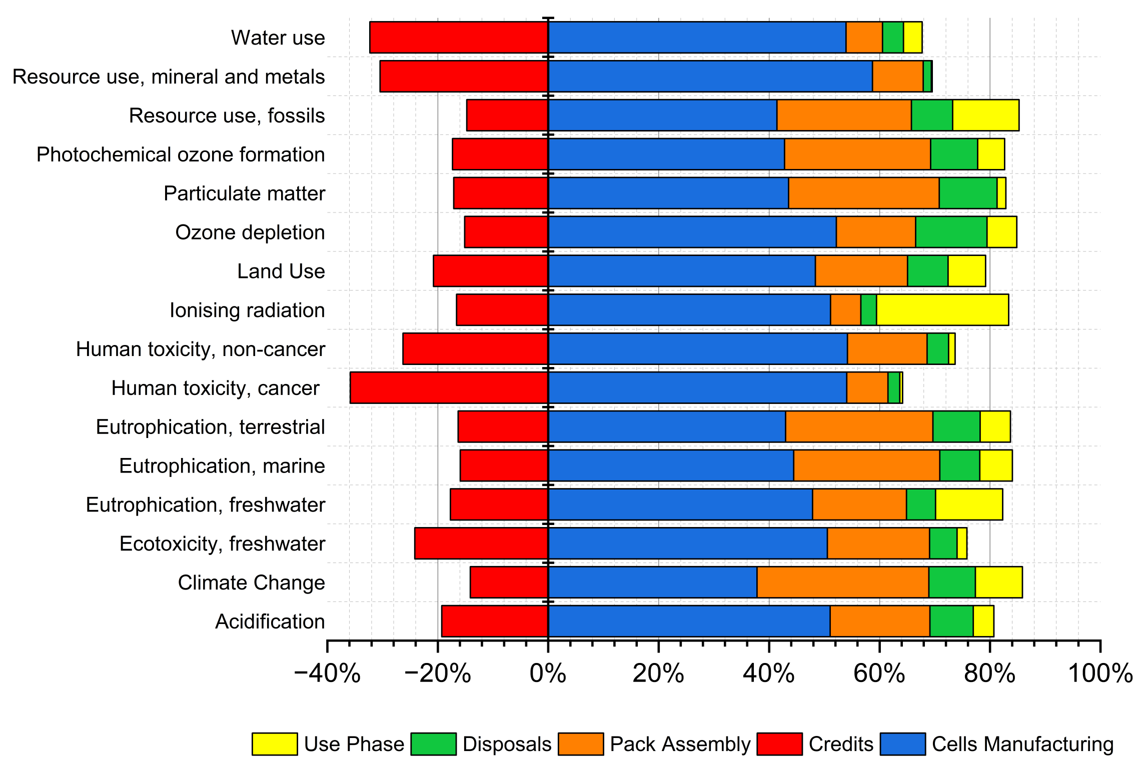

Figure 4.5: EoL Recycling Scenario: LCA results of the battery pack.

The most substantial contribution to the impacts is attributed to battery pack manufacturing (57 % to 71 %), followed by disposals (1 % to 13 %), and the use phase (0 % to 24 %). However, it is important to note that the overall impact is mitigated by the inclusion of environmental credits (14 % to 36 %). The six most relevant impact categories, are shown in detail in Figure 4.6. The results are presented per functional unit, or 1 kWh of rated energy capacity of the battery pack. Cells manufacturing is represented by the light-blue bars, and the production of battery pack components and assembly represented by the orange bars. The yellow bars depict the contribution of the use phase. The impact of the battery at the end of its life is divided into two parts: disposals represented by the green bars, and environmental credits depicted by the red bars. The solid white squares indicate the net impact in each category.

In the resource use category for minerals and metals, the impact is predominantly driven by cells manufacturing (light-blue bar), accounting for 59 % of the total impact. This is primarily attributed to the production of anodes and cathodes. On the other hand, the impact of end-of-life disposals is relatively minor, representing less than 2 % (green bar). The inclusion of -31 % for the credits (red bar) significantly reduces the overall impact. The use phase (yellow bar) is not relevant for this specific impact category.

When considering climate change, the primary contributor to the impact is the production of the battery pack (69 %) (represented by the orange and light-blue bars), with cell manufacturing accounting for 38 % of the total impact. The use phase of the battery pack contributes 9 % to the climate change impact (yellow bar). In the end-of-life phase, the disposal process (green bar) increases the climate change impact by 8 % due to the consumption of chemicals and energy during recycling. However, the inclusion of -14 % credits (red bar) helps to reduce the overall climate change impact.

Examining the resource use of fossils, the impact is significantly influenced by the battery pack assembly (65 %) (represented by the orange + light-blue bars), primarily due to the energy consumption and raw material extraction involved in the process. The use phase of the battery pack contributes 13 % to the total impact. End-of-life disposals (green bar) contribute 7 % to the overall value. The inclusion of credits (red bar) leads to a saving of 15 %.

The impact of ecotoxicity on freshwater is primarily associated with the production of the battery pack (70 %) (orange and light-blue bars), specifically cells manufacturing (51 %) (light-blue bar) due to anode and cathode production. The impact of the use phase (yellow bar) is not relevant at about 1 %. End-of-life disposals (green bar) have a negligible effect on the total impact, accounting for 7‘% of the overall value. The inclusion of credits (red bar) reduces the overall impact by 24 %.

Regarding the impact category of particulate matter, the production of the battery pack (orange and light-blue bars) has the highest contribution (71 %). Within the production phase, cell manu-

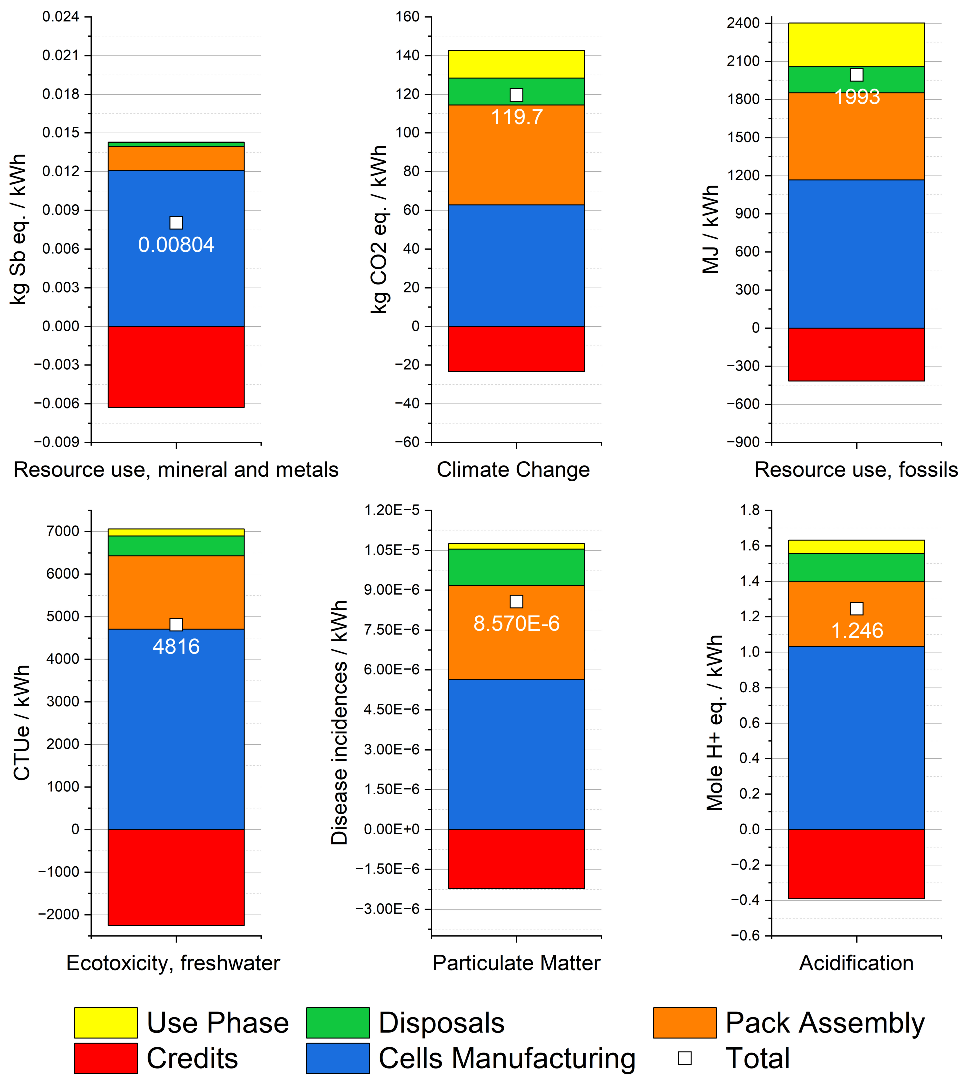

Figure 4.6: EoL Recycling Scenario: LCA results of the battery pack for the six most relevant impact categories.

facturing (light-blue bar) accounts for 44 % of the overall impact, primarily due to the production of cathodes and anodes. The impact of the use phase is negligible and less than 2 %. The contribution of end-of-life disposals (green bar) to the overall impact is 11 %. The inclusion of credits leads to a saving of approximately 17 %, as it avoids the extraction of materials such as copper, aluminum, cobalt, and manganese. In terms of acidification, the acidification category is primarily influenced by cell manufacturing (light-blue bar), with a significant contribution of 51 %. In particular, the production of cathodes plays a crucial role in this impact category. End-of-life disposals (green bar) increase the overall impact by 8 %. However, by including credits (red bar), a substantial saving of 19 % is achieved due to the avoided extraction of nickel, copper, and cobalt.

4.1.4 Sensitivity Analysis for Recycling Scenario

The assumption made about the electricity mix plays a crucial role in determining the environmental impacts. This assumption affects various stages of the battery pack life cycle, representing the 13.6 % in cell manufacturing, 2.6 % in battery pack assembly, 100 % in battery use, and 7.4 % in recycling. As mentioned in Section 1, the baseline scenario assumes that battery production, use, and recycling occur in Europe, with the use of the average European (RER) electricity mix. To compare the baseline recycling scenario with alternative scenarios, a sensitivity analysis is conducted, considering three different regions: Italy (IT), Estonia (EE), and Sweden (SE). The variation in the electricity mix is applied throughout the entire lifecycle of the battery pack.
In Table 4.1 are reported the results of the total impact for the six most relevant environmental categories.

Impact Category [Unit/kWh]	**RER**	**IT**	**SE**	**EE**
Resource use, mineral and metals [kg Sb eq.]	8.037E-03	8.034E-03	8.026E-03	8.044E-03
Climate Change [kg CO_2 eq.]	119.66	120.89	94.40	157.07
Resource use, fossils [MJ]	1993.4	1797.6	1749.6	2251.7
Ecotoxicity, freshwater [CTUe]	4816.4	4777.2	4638.0	5263.2
Particular Matter [Disease incidence]	8.57E-06	8.64E-06	8.42E-06	1.34E-05
Acidification [Mole H^+ eq.]	1.2461	1.2279	1.1134	1.7066

Table 4.1: Sensitivity analysis results for key environmental impacts in Recycling Scenario: electricity mix comparison.

The outcomes of the sensibility analysis show that the highest impacts are achieved with the use of the Estonian energy mix. The climate change impact for the baseline scenario is assessed to be 119.7 kg CO_2 eq. / kWh. This result reduces to 94.4 kg CO_2 eq. / kWh if the SE energy mix scenario is considered. With the EE energy mix the total climate change increases up to 157.1 kg CO_2 eq. / kWh. For the Italian energy mix, the value obtain is in between the one achieved with the Estonian and Swedish one and is 120.9 CO_2 eq. / kWh.

The results of the sensitivity analysis for the most relevant impact categories are displayed in Figure 4.7 where the environmental impacts are normalized relatively to the scenario with the highest impact in each category.

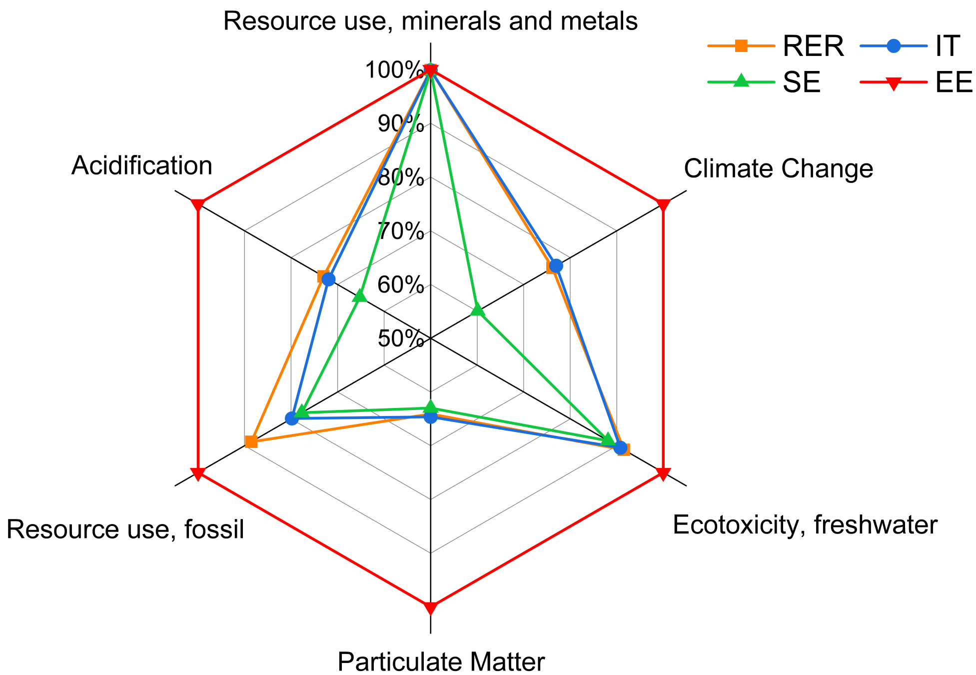

Figure 4.7: Comparison of the life cycle environmental impacts of the battery pack with the use of different electricity mixes: RER, IT, EE and SE.

The scenario with the use of EE electricity mix (red spider) resulted in the highest values across all impact categories, followed by RER (orange spider), IT (blue spider), and finally SE (green spider). Table 4.2 provides the percentage of reduction of environmental impacts achieved by adopting other electricity mixes compared to the EE electricity mix.

Compared to the baseline scenario, the adoption of the EE energy mix resulted in a significant increase in impacts, ranging from 0.09 % to 26.9 %. On the contrary, the adoption of the SE and IT energy mixes resulted in a significant reduction in impacts compared to the baseline scenario. The SE energy mix achieved the greatest reduction in the range 0.23 % to 39.9 %. Similarly, the adoption of the IT energy mix resulted in a reduction ranging from 0.13 % to 35.4 %.

Impact Category	EE–RER	EE–IT	EE–SE
Particular Matter	35.9 %	35.4 %	37.0 %
Acidification	26.9 %	28.1 %	34.8 %
Climate Change	23.8 %	23.0 %	39.9 %
Ecotoxicity, freshwater	8.49 %	9.24 %	11.9 %
Resource use, fossils	11.5 %	20.2 %	22.3 %
Resource use, mineral and metals	0.09 %	0.13 %	0.23 %

Table 4.2: Percentage of savings in environmental impacts with respect to EE electricity mix resulting from the adoption of RER, IT and SE electricity mix.

When it comes to climate change, the choice of electricity mix has a crucial impact. In this case, adopting the SE energy mix results in a reduction of 39.9 % while for the IT energy mix the impact sees a limitation of 23 %, finally the RER energy mix leads to a reduction of the climate change impact of 23.8 %. Even if not directly addressed in this study, a further lowering of the environmental impacts with respect to the SE would be experienced if the Canadian energy mix is considered. Indeed, more than half (60 %) of the electricity in Canada is generated from hydro-sources with the remaining produced from a variety of sources [95], while for Sweden only 47 % is generated by hydro-sources.

4.1.5 EoL: Reconditioning and Recycling Scenario

The results of the comprehensive life cycle impact assessment for the specific end-of-life of the baseline scenario are presented in Figure 4.8. The end of life is modeled as the Reconditioning process, described in Section 3.2.4, followed by a second use stage and the final Recycling process, described in Section 3.2.4.

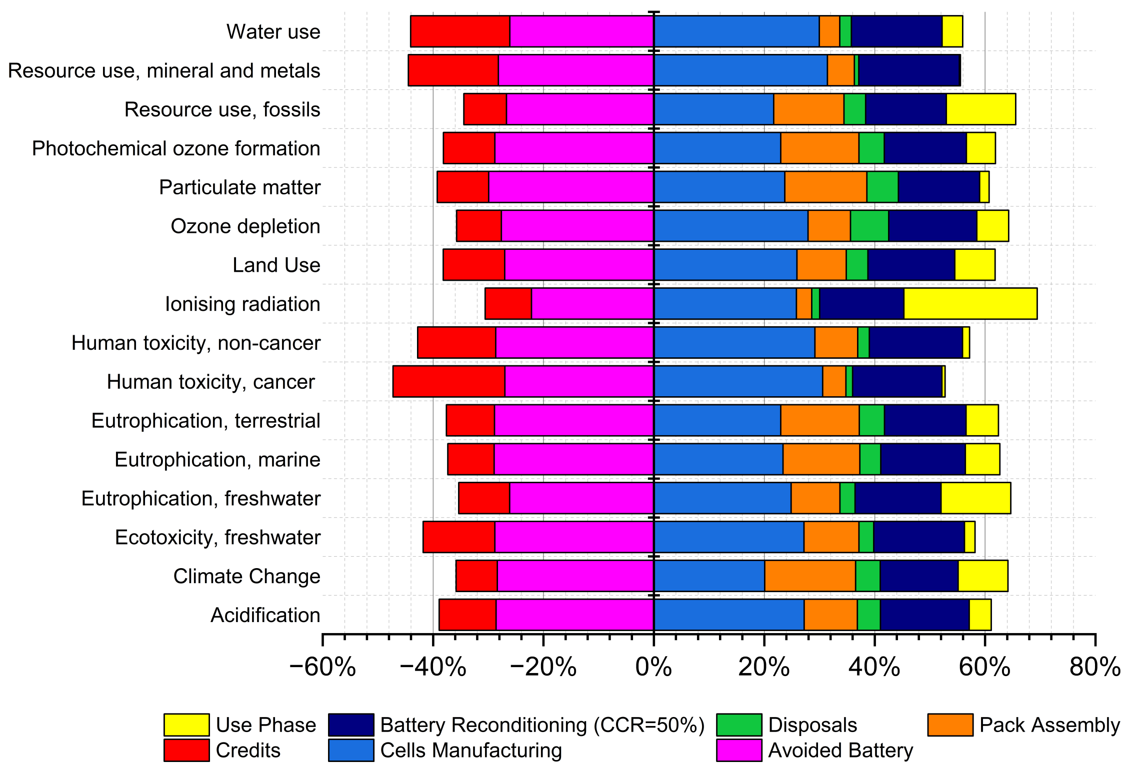

Figure 4.8: EoL Reconditioning and Recycling Scenario: LCA results of the battery pack.

The contribution of battery pack production is divided into two components: cells manufacturing, indicated by the light-blue bars, and the production of battery pack components and assembly, represented by the orange bars. The impact of battery losses during the two use phases is shown by the yellow bars. The reconditioning process of the battery pack is analyzed in terms of two distinct contributions. The impact associated with battery reconditioning is represented by the navy bars, while the benefits arising from the avoided manufacturing of a new battery pack are depicted in magenta. At the end of its second life, the environmental impact of the reconditioned battery pack is divided into two components: disposals, represented by the green bars, and environmental credits, depicted by the red bars. Disposals account for the recycling process and any subsequent waste disposal activities related to the materials of the battery. The environmental credits represent the positive contributions or benefits derived from the recycling and recovery processes during the end-of-life treatment of the battery.

As shown in Figure 4.8 the largest contribution to the overall impacts is primarily attributed to battery pack manufacturing, accounting for 39 % to 29 % of the total impact. The reconditioning process of the battery pack at the end of its first life has an important share of 14 % to 18 %. Disposals constitute a smaller portion, ranging from 1 % to 7 %, while the use phase accounts for 0% to 24% of the impacts. The total impact is mitigated by the inclusion of environmental credits, which contribute 7 % to 20 % to offsetting the total environmental burden. The use in a second life of the reconditioned battery avoids the production of a new battery pack producing a benefit that ranges between 26 % to 30 %.

Figure 4.9 provides a detailed representation of the six most relevant impact categories. The impacts are presented per functional unit, which refers to 1 kWh of rated energy capacity of the battery pack. The manufacturing of cells is illustrated by the light-blue bars, while the production of battery pack components and assembly is represented by the orange bars. The yellow bars indicate the contribution of the use phase. The navy bars in the figure represent the impact associated with battery reconditioning and the magenta bars depict the benefits that arise from avoiding the manufacturing of a new battery pack. The impact of the battery at the end of its life is divided into two parts: disposals, shown by the green bars and environmental credits, the red bars. The solid white squares represent the net impact in each category.

The resource use category for minerals and metals is primarily influenced by cells manufacturing, as depicted by the light-blue bar, which contributes to 31% of the total impact. This can be attributed to the production of anodes and cathodes. The use phase (yellow bar) does not have a significant relevance in this impact category. The reconditioning procedures (navy bar) contributes with the 18 % to the overall impact, due to the substitution of the 50% of modules and the electronics components of the BMS. The avoided production of a new battery pack (magenta bar) gives a credit of -28 %. At the end of the second life, the impact of end-of-life disposals is relatively minor, accounting for around 2 % (green bar). The inclusion of environmental credits at -16% (red bar) significantly mitigates the overall impact.

In terms of climate change, the primary driver of impact is the production of the battery pack

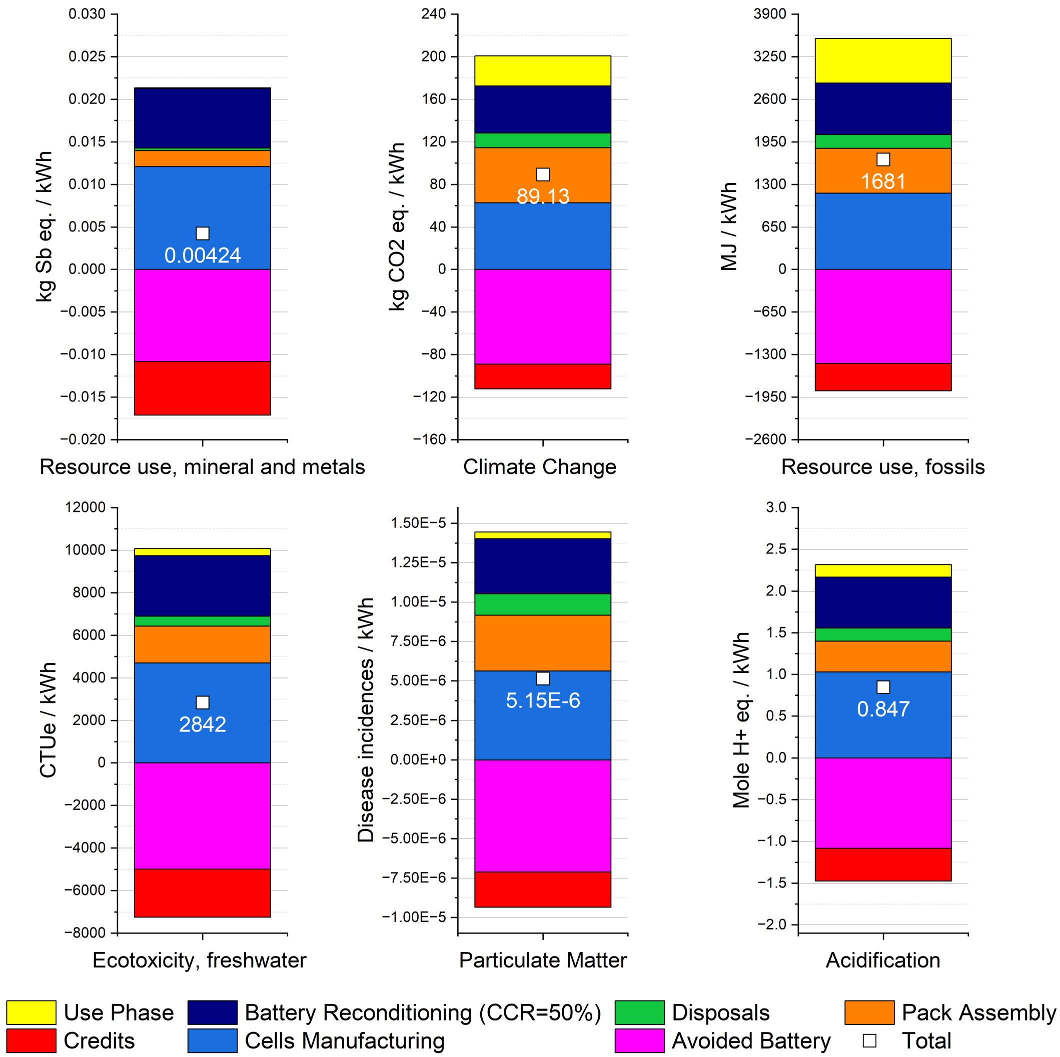

Figure 4.9: EoL Reconditioning and Recycling Scenario: LCA results of the battery pack for the six most relevant impact categories.

(orange and light-blue bars), which accounts for 37% of the total impact. Within this category, cell manufacturing contributes 20 % to the overall impact. The use phase of the battery pack contributes 9 % to the climate change impact (yellow bar). The reconditioning procedures, indicated by the navy bar, account for 14 % of the overall impact. Additionally, the avoided production of a new battery pack (magenta bar), provides a credit of -28 % to the overall impact. During the end-of-life phase, the disposal process (green bar) increases the climate change impact by 4 % due to the consumption of chemicals and energy during recycling. However, the inclusion of -8 % credits (red bar), helps to reduce the overall climate change impact.

When examining the resource use of fossils, the impact is primarily due to the battery pack assembly (orange and light-blue bars), accounting for 35 % of the total impact. This is mainly attributed to the energy consumption and raw material extraction involved in the assembly process. The use phase of the battery pack contributes 13% to the overall impact (yellow bar). The reconditioning process (navy bar), contribute to 14 % of the overall impact. The avoided production of a new battery pack, depicted by the magenta bar, provides a benefit of 26 % to the total. End-of-life disposals (green bar) provide 4% to the total value. The inclusion of credits (red bar), results in a saving of 8 %.

The impact of ecotoxicity on freshwater is associated with the production of the battery pack (orange and light-blue bars), which account for 37 % of the total impact. Specifically, cells manufacturing (light-blue bar), contributes 27 % to the overall impact due to the production of anodes and cathodes. The use phase (yellow bar), is not relevant and contributes only about 2% to the impact. The impact due to the reconditioning (navy bar) of the battery pack is 16 %, with a benefit due to the avoided new battery pack (magenta bar) of 29 %. In terms of end-of-life disposals (green bar), it has a limited effect, accounting for 3 % of the overall impact. The inclusion of credits (red bar), reduces the overall impact by 13 %.

For particulate matter, the highest contribution (39 %) is attributed to the production of the battery pack (orange and light-blue bars). The impact of the use phase (yellow bar) is minimal, amounting to less than 2 %. Reconditioning (navy bar) accounts for 15 % of the total impact, with a 30 % benefits (magenta bar) given by the avoided impacts of the production of a new battery pack. The contribution of end-of-life disposals (green bar) to the overall impact is 6 %. With the including credits, approximately 9 % of the impact is saved, as it avoids the extraction of materials such as copper, aluminum, cobalt, and manganese.

In the context of acidification, cell manufacturing (light-blue bar) has a significant influence, contributing 27 % to the overall impact, because of the production of cathode materials. The impact of the use phase is limited to 4 %. The process of reconditioning the battery pack increases the impact to about 16 %. The avoided manufacturing of a new battery pack results in a saving of 29 % in the impact. End-of-life disposals (green bar) increase the overall impact by 4 %. Credits (red bar) leads to a substantial saving of 10 %, attributed to the avoided extraction of nickel, copper, and cobalt.

4.1.6 Sensitivity Analysis for Reconditioning and Recycling Scenario

As mentioned in Section 3.2.4, not all LIB cells are suitable for reuse at the end of their initial lifespan. For the baseline scenario, this study assumes that 50 % of LIB cells can be effectively reused. However, different cell conversion rates can be applied and the values range from 10% to 100%. To account for this potential variation in CCR, a sensitivity analysis is conducted, analyzing the same range of CCR values, modified accordingly to our study. The results of the analysis for the most relevant impact categories are shown in Figure 4.10, normalized relative to the scenario with the highest impact in each category.

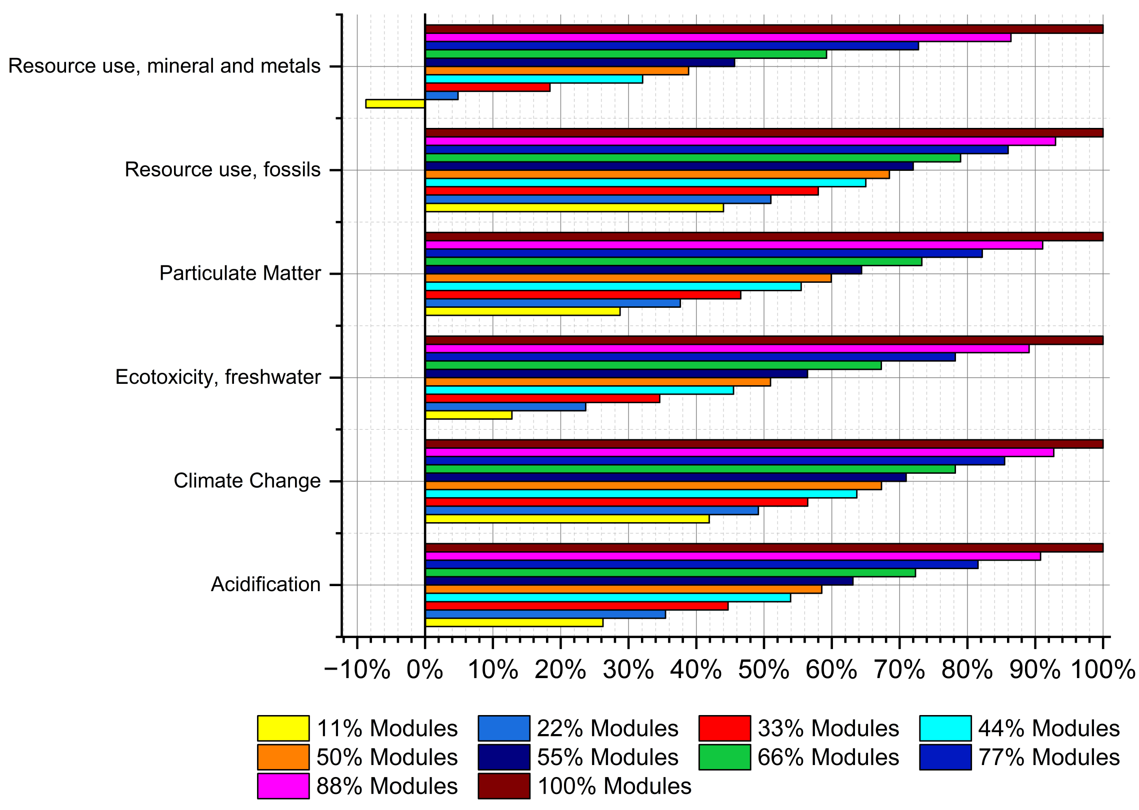

Figure 4.10: Comparison of the life cycle environmental impacts of the battery pack reconditioning scenario varying the number of modules.

The scenario in which 100 % of the modules, corresponding to all the battery cells in the pack, are replaced (represented by the dark-red bars), results in the highest impacts. As the number of compromised modules decreases, a subsequent reduction in impact is observed. Specifically, the substitution of 11 % of the modules (indicated by the yellow bars), which corresponds to approximately CCR=10%, yields the lowest impact. Table 4.3 and Table 4.4 provides the percentage of reduction and increase of environmental impacts by implementing different level of reconditioning for the battery pack with respect to the baseline scenario of 50 % of modules substituted.

Impact Category	**11% – 50%**	**22% – 50%**	**33% – 50%**	**44% – 50%**
Acidification	-47.6 %	-34.0 %	-20.4 %	-6.78 %
Resource use, mineral and metals	-41.1 %	-23.0 %	-13.8 %	-4.61 %
Particular Matter	-38.2 %	-27.3 %	-16.4 %	-5.45 %
Ecotoxicity, freshwater	-31.2 %	-22.3 %	-13.4 %	-4.45 %
Resource use, fossils	-25.4 %	18.2 %	-10.9 %	-3.63 %
Climate Change	-24.5 %	-17.5 %	-10.5 %	-3.50 %

Table 4.3: Percentage of savings in environmental impacts, with respect to the baseline scenario of CCR=50 %, by reducing the number of modules substituted

When considering the reduction in the number of substituted modules, the Acidification impact category shows the highest percentage of saving compared to the baseline scenario, decreasing from 47.6 % to 6.78 %. On the other hand, the Climate Change impact category experiences the smallest reduction in impact, decreasing from 24.5 % to 3.50 %. Lowering the number of substituted modules results in savings in all the impact categories analyzed.

Impact Category	**55%–50%**	**66%–50%**	**77%–50%**	**88%–50%**	**100%–50%**
Acidification	6.78 %	20.3 %	33.9 %	47.6 %	61.1 %
Particular Matter	5.45 %	16.4 %	27.3 %	38.2 %	49.1 %
R. use, mineral and metals	4.61 %	13.8 %	23.0 %	32.3 %	41.5 %
Ecotoxicity, f.	4.45 %	13.4 %	22.3 %	31.2 %	40.1 %
Resource use, fossils	3.63 %	10.9 %	18.2 %	25.4 %	32.7 %
Climate Change	3.5 %	10.5 %	17.5 %	24.5 %	31.5 %

Table 4.4: Percentage of growth in environmental impacts, with respect to the baseline scenario of CCR=50 %, by increasing the number of modules substituted

Examining the cases where a larger number of modules need to be substituted compared to the baseline scenario, the Acidification impact shows the highest increase, rising from 6.78 % to 61.1 %.

In contrast, the Climate Change impact experiences the smallest change, increasing from 3.5 % to 31.5 %. An increase in the number of substituted modules leads to higher environmental impacts across the analyzed categories.

4.2 Life Cycle Cost Analysis

The subsequent sections provide a detailed Life Cycle Cost Analysis (LCCA) of the NMC622 battery pack, as described in Section 3.3. The impacts associated with the baseline scenario, utilizing the European (RER) energy mix, are presented for Battery Pack Manufacturing, Simple Disposal Scenario, Recycling Scenario, and Reconditioning+Recycling Scenario. To further understand the variations of costs of the battery pack resulting from different national energy mixes, a sensitivity analysis is conducted assuming a recycling scenario. Additionally, for the Refurbishing and Recycling scenario, a sensitivity analysis is performed to assess the variability of costs when different numbers of modules are substituted to create the second life battery pack.

4.2.1 Battery Pack Manufacturing

Figure 4.11 illustrates the breakdown of the costs associated producing a single battery pack for the baseline scenario. The costs related to cell manufacturing (in light-blue) are shown separate from the pack assembly components (in orange) and module assembly components (in green).

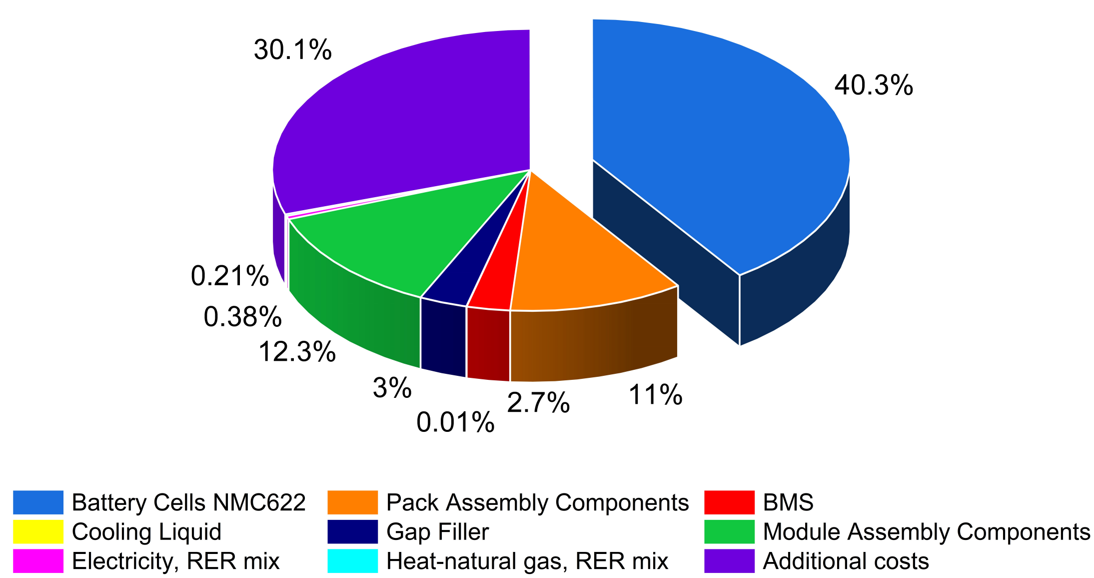

Figure 4.11: LCC breakdown for a single NMC622 battery pack production

The largest cost driver in battery pack manufacturing is the cost of cell manufacturing (in light-

blue), accounting for 40.3% of the total. Additional costs make up 30.1 % of the overall expenses. The production costs of modules (in green) and pack (in orange) assembly components contribute 12.3 % and 11 %, respectively. The cost of the BMS is responsible for 2.7 % of the total cost (red portion). The cost shares of the gap filler (in dark-blue) and cooling liquid (in yellow) are relatively small and not significant, constituting 3 % and 0.01 % of the total cost, respectively. In terms of energy requirements for the assembly procedures, electricity (depicted in magenta) and natural gas (depicted in cyan) play a minor role, accounting for 0.38 % and 0.21 %, respectively.
The costs breakdown €/ kWh for the production of the battery pack are listed in Table 4.5.

Contributor	**Cost**
Battery Cells NMC622	55.9 €/ kWh
Pack Assembly Components	15.2 €/ kWh
Module Assembly Components	17.1 €/ kWh
Cooling Liquid	0.02 €/ kWh
Gap Filler	4.17 €/ kWh
BMS	3.77 €/ kWh
Electricity, RER mix	0.53 €/ kWh
Heat-natural gas, RER mix	0.30 €/ kWh
Additional costs	41.8 €/ kWh
NMC622 Battery Pack	138.7 €/ kWh

Table 4.5: Costs breakdown in €/ kWh of the NMC622 battery pack.

The total production cost of the NMC622 battery pack amounts to 138.7 €/ kWh. This figure represents the cumulative expenses incurred throughout the entire manufacturing process, including the costs of extraction and production of raw materials, cell manufacturing, pack assembly components, module assembly components, and other associated expenses. The additional expenses, as explained in detail in Section 3.3, include other elements such as labor, capital equipment, VAT and the revenue generated from the sale of the battery pack. Taking into consideration all the assumptions made, for the battery pack under exam, with a rated energy capacity of 95 kWh , the cost of the resulting battery pack is 13177 €.

Battery Cell

Battery cells emerge as a crucial component that significantly influences the overall cost of the battery pack. In Figure 4.12 a detailed description of the manufacturing costs for each individual cell, for the baseline scenario (RER energy mix), is shown.

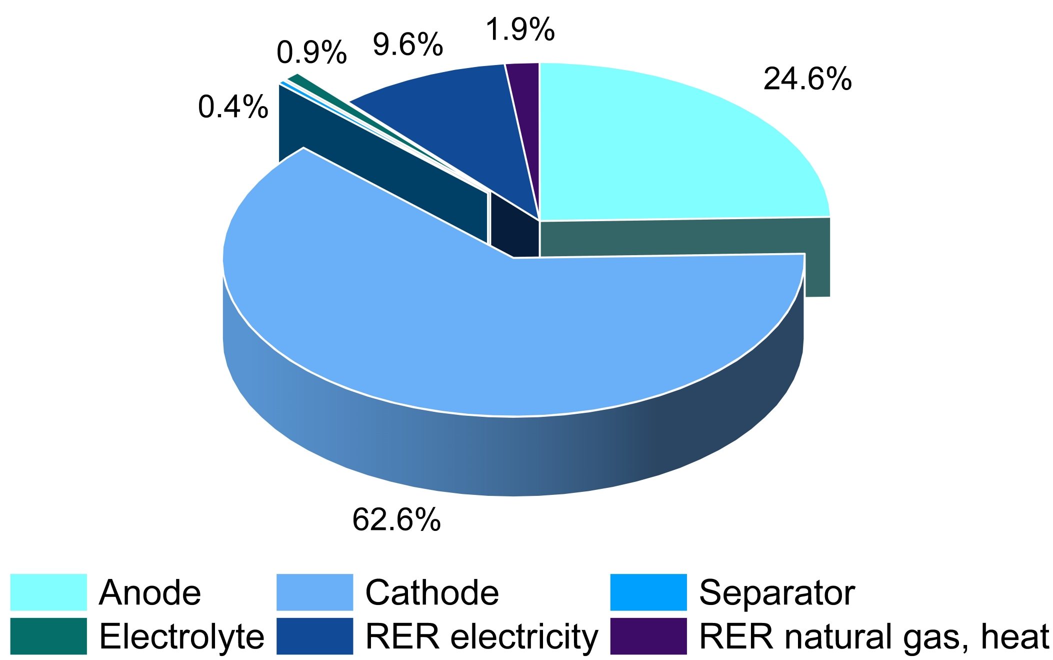

Figure 4.12: LCC breakdown for a single NMC622 battery cell manufacturing.

The production of the cathode alone constitutes 62.6 % of the total cost. This substantial share is primarily attributed to the use of high-value materials such as cobalt, nickel, lithium, and aluminum. The production of the anode also holds a significant cost share, accounting for 24.6 %. The electricity required for the cell formation process represents 9.6 % of the overall cost, while the heat necessary for the drying rooms contributes a limited share of 1.9 %. The remaining components make up less than 2 % of the total cost, in particular 0.4 % for the separator and 0.9 % for the electrolyte.

The costs breakdown to produce of a single battery cell is listed in Table 4.6.

The manufacturing of the NMC622 battery cell has a total cost of 12.2 €. This value includes the total expenses involved throughout the entire production process, including the costs associated with sourcing and processing raw materials.

Contributor	Cost
Anode Component	2.99 €
Cathode Component	7.61 €
Separator	0.05 €
Electrolyte	0.11 €
Electricity, RER mix	1.16 €
Heat-natural gas, RER mix	0.23 €
NMC622 Battery Cell	12.2 €

Table 4.6: Costs breakdown of the NMC622 battery cell in €.

As expected, due to the presence of high-value materials (nickel, lithium, cobalt, manganese), the cathode component is the key contributor to the total cost of the battery cell.

4.2.2 EoL: Simple Disposal Scenario

Considering the baseline scenario, with the utilization of the European energy mix, Figure 4.13 presents the results of the complete life cycle cost analysis conducted for the specific EoL, modeled as Simple Disposal. The contribution, to the overall life cost of the battery, of the battery pack manufacturing is represented by the dark-red portion. The detailed breakdown of the costs of the battery pack production are shown in Section 4.2.1. For the use phase, the energy losses are accounted for and are represented by the yellow section. The cost of the end of the lifespan of the battery (represented by the green portion) primarily consists of the straightforward disposal of its components, such as landfilling or incineration, as outlined in Section 3.2.4.

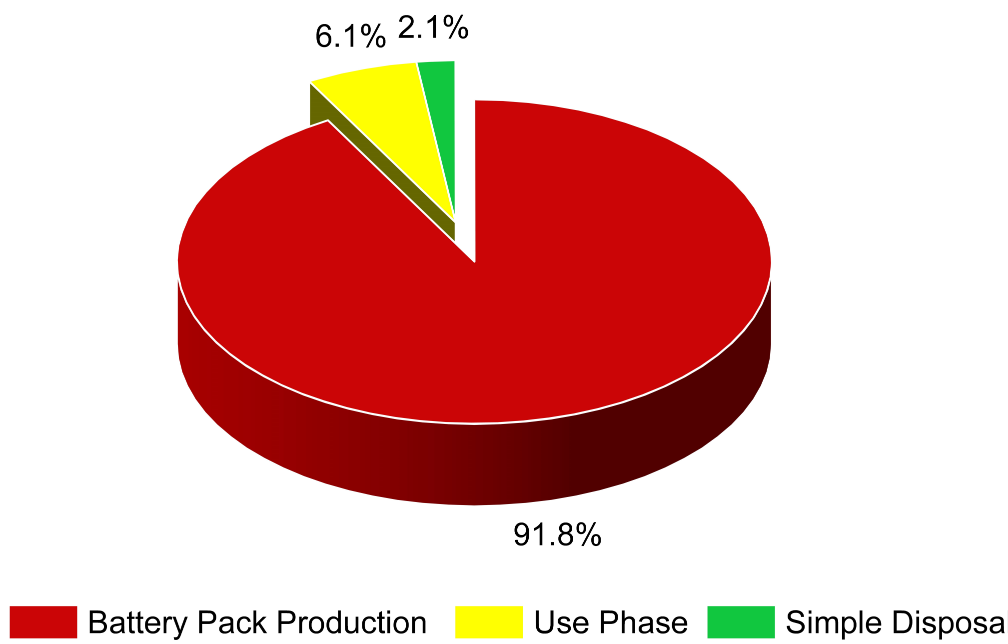

Figure 4.13: LCC breakdown for the complete life cycle of the battery pack : Simple Disposal Scenario.

The production of the battery pack stands out as the primary contributor to the overall cost, accounting for 91.8 % of the total. The cost associated with the use phase of the battery is limited, comprising only 6.1 % of the total cost. The cost of the simple disposal represents a relatively small 2.1 % of the overall life cycle cost.

Table 4.7 lists the costs contribution in €/kWh of the complete life cycle of the battery pack.

Stage	**Cost**
Battery Pack Production	138.7 €/ kWh
Use Phase	9.185 €/ kWh
Simple Disposal	3.195 €/ kWh
Battery Pack Complete Life Cycle	151.1 €/ kWh

Table 4.7: Costs breakdown in €/ kWh of the NMC622 battery pack life cycle for Simple Disposal Scenario.

The complete life cycle of the battery pack, with the assumption of a Simple Disposal model for the End-of-Life stage, is 151.1 €/ kWh. For this case it is assumed that no revenues are generated from the EoL disposal of the battery pack.

4.2.3 EoL: Recycling Scenario

For the specific End-of-Life scenario, modeled as Recycling of the battery pack, Figure 4.14 presents the results of a comprehensive life cycle cost analysis. These outcomes are depicted in relation to the reference scenario characterized by the RER energy mix.
The dark-red section of the diagram represents the cost associated with the production of the battery pack, which includes cell manufacturing, module production, and pack assembly, as described in Section 4.2.1. The yellow section represents the cost of the battery's energy losses during the use phase. The green portion represents the cost associated with the End-of-Life disposals, in particular recycling and further waste disposal. The red section, indicted with a negative value contributes to the reduction of the overall cost. Credits represents the benefits obtained from avoiding the production of virgin materials such as copper, aluminum, nickel, and cobalt and the revenues coming from the sale of the materials recovered through the recycling process.

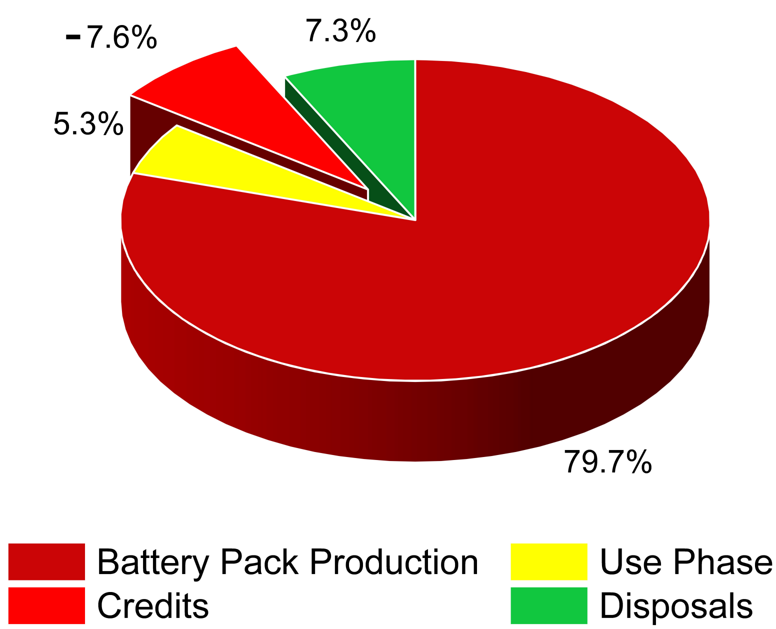

Figure 4.14: LCC breakdown for the complete life cycle of the battery pack : Recycling Scenario.

Based on the data presented, the production of the battery pack is the primary factor driving the overall cost, constituting 79.7 % of the total. The cost attributed to the use phase of the battery is relatively minor, amounting to 5.3 %. End-of-Life disposals contributes with a share of 7.3 % to the overall cost. However, there is a reduction of 7.7 % of the total cost due to credits, which are derived from the avoided production of virgin materials such as copper, aluminum, nickel, and cobalt and the revenue of the selling of the recovered materials. The costs breakdown €/ kWh for the whole life cycle of the battery pack, assuming a recycling scenario, are listed in Table 4.8.

Stage	**Cost**
Battery Pack Production	138.7 €/ kWh
Use Phase	9.185 €/ kWh
Disposals	12.76 €/ kWh
Credits	-13.30 €/ kWh
Battery Pack Complete Life Cycle	147.3 €/ kWh

Table 4.8: Costs breakdown in €/ kWh of the NMC622 battery pack life cycle for Recycling Scenario.

The complete life cycle cost of the battery pack, taking into account all stages from production to EoL, is calculated to be 147.3 €/ kWh. This cost includes the raw materials, manufacturing processes, transportation, use, and final recycling with further disposal. Notably, it is assumed that revenues are generated in the form of credits during the Recycling stage. These credits effectively offset a portion of the overall cost, thus contributing to a more economically viable life cycle for the battery pack.

4.2.4 Sensitivity Analysis for Recycling Scenario

The assumption made about the electricity mix plays a crucial role in determining the cost of the complete life cycle of the battery pack. As described in Section 1, the baseline scenario implies that battery production, use, and recycling occur in Europe, with the use of the average European (RER) electricity mix. To compare the baseline recycling scenario with alternative scenarios, a sensitivity analysis is conducted, considering three different regions: Italy (IT), Denmark (DK), and Netherlands (NL). The variation in the electricity mix is applied throughout the entire lifecycle of the battery pack. Human labor prices and VAT taxes are changed according to the nation in consideration, as in Section 3.3.

Figure 4.15 shows the results as €/ kWh of the rated energy capacity of the battery pack. As mentioned above, the nations considered are Italy (green bar), Denmark (red bar), Netherlands (light-blue bar).

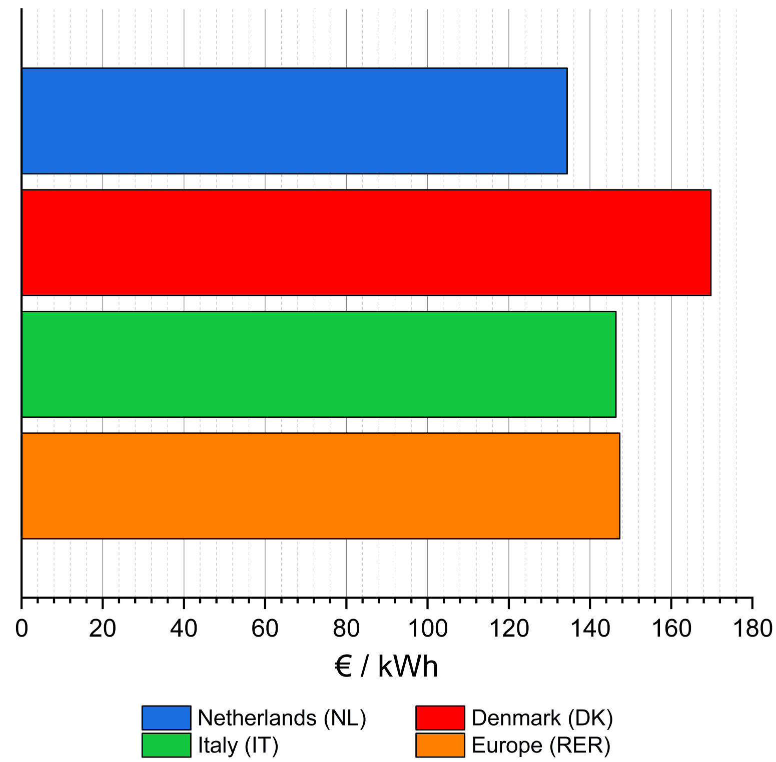

Figure 4.15: LCC sensitivity analysis for the complete life cycle of the battery pack : Recycling Scenario.

The baseline scenario (RER) yields a cost of 147.3 €/ kWh, which reduces when regional-dependent prices such as electricity and human labor decrease, as observed in the Netherlands scenario (134.4 €/ kWh). Italy prices results in a cost of 146.4 €/ kWh. Meanwhile, Denmark has the highest prices for electricity, natural gas and human labor, resulting in a final cost of 169.8 €/ kWh. In Table 4.9 are reported the costs of each stage of the life cycle, assuming different geographic locations.

	RER	**ITA**	**DK**	**NL**
Battery Pack Production [€]	9703.1	9249.2	9703.1	8788.4
Use Phase [€]	872.58	934.91	1578.61	206.03
Disposals [€]	1212.2	1231.9	1269.3	1203.8
Credits [€]	-1263.4	-1263.4	-1263.4	-1263.4
Battery Pack Complete Life Cycle [€]	13997	13908	16129	12766

Table 4.9: LCC sensitivity analysis for the complete life cycle of the battery pack: Recycling Scenario

As displayed in Table 4.9, credits are not related to energy consumption and consequently are equal for all the four geographic locations. Battery production is influenced by the additional national costs (i.e. VAT and cost of human labor) and the local energy prices, as detailed in Section 3.3. Indeed, taking into exam the case of Denmark, the highest human labor pay and energy prices brings to the highest cost of the battery pack production. The same considerations can be done for the use phase and the disposals phase, where electricity consumption is a crucial factor.

4.2.5 EoL: Reconditioning and Recycling Scenario

The results of the complete life cycle cost analysis conducted for the specific end-of-life scenario, modeled as Reconditioning followed by second use and Recycling, are presented in Figure 4.16. These results are based on the baseline scenario, which assumes the European energy mix.

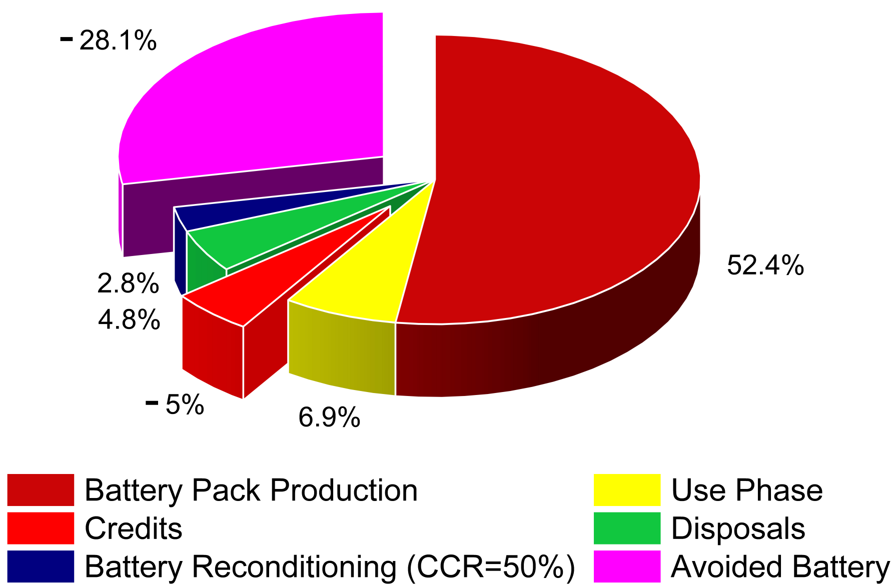

Figure 4.16: LCC breakdown for the complete life cycle of the battery pack : Reconditioning and Recycling Scenario.

The dark-red section represents the cost of producing the battery pack, including cell manufacturing, module production, and pack assembly, as explained in Section 4.2.1. The yellow section represents the cost attributed to energy losses during the two battery's use phase. The navy portion in the diagram represents the cost associated with the reconditioning procedure of the battery pack at the end of its initial life. The magenta section, indicated by a negative value, represents the savings achieved through the avoided production of a new battery pack. This includes material costs, energy costs, and other associated expenses that would have been incurred if a new battery pack had been manufactured instead of reconditioning the existing one. The green section represents the cost associated with end-of-life disposals, specifically recycling and waste disposal. The red section,

indicated by a negative value, contributes to reducing the overall cost. These credits represent the benefits derived from avoiding the production of new materials like copper, aluminum, nickel, and cobalt, as well as the revenue generated from selling the materials recovered through the recycling process. According to the data provided, the production of the battery pack emerges as the primary cost driver, accounting for 52.4 % of the total cost. The reconditioning process account for 2.8 % with the benefit of the avoided battery pack producing a saving of 28.1 %. The two use phases of the battery incurs a relatively minor cost, representing 6.9 % of the overall expenses. End-of-life disposals contribute 4.8 % to the total cost. However, the inclusion of credits results in a cost reduction of 5 %, due to the avoided production of new materials such as copper, aluminum, nickel, and cobalt, as well as the revenue generated from selling the recovered materials.
The breakdown of costs in euro per kilowatt-hour for the entire life cycle of the battery pack, considering the reconditioning and recycling scenario, is presented in Table 4.10.

Stage	**Cost**
Battery Pack Production	138.7 €/ kWh
Use Phase	18.37 €/ kWh
Battery Reconditioning	7.36 €/kWh
Avoided Battery	-74.34 €/ kWh
Disposals	12.76 €/ kWh
Credits	-13.30 €/ kWh
Battery Pack Complete Life Cycle	89.55 €/ kWh

Table 4.10: Costs breakdown in €/ kWh of the NMC622 battery pack life cycle for Reconditioning and Recycling Scenario.

The total life cycle cost of the battery pack, which considers all stages from production to end-of-life, is calculated to be 89.55 €/kWh. This cost includes expenses related to raw materials, manufacturing processes, use, reconditioning at the end of the first life and the final recycling and disposal phase at the end of the second life. Thanks to the avoided manufacturing of a new battery pack and the generation of credits during the recycling stage, revenues are generated that offset a portion of the overall cost. This inclusion of credits significantly contributes to a more economically viable life cycle for the battery pack.

4.2.6 Sensitivity Analysis for Reconditioning and Recycling Scenario

The assumption made regarding the number of modules, and so cells, substituted in the battery pack is a critical factor in evaluating the final life cycle cost. The number of modules replaced during the battery pack's life cycle has implications for the materials and manufacturing processes involved. A higher substitution rate would require a larger quantity of new modules and cells to be produced, leading to an increase in the material costs, energy consumption, and manufacturing expenses. The sensitivity analysis, varying the number of battery modules substituted is shown in Figure 4.17. The baseline scenario, with 50 % substitution of modules leads to life cycle cost of 89.55 €/ kWh.

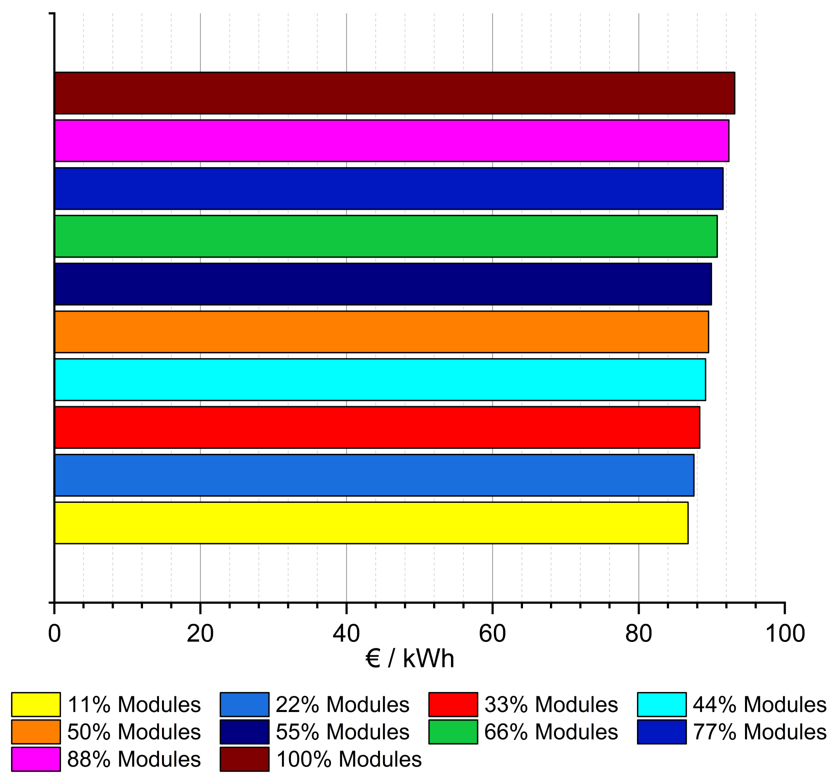

Figure 4.17: LCC sensitivity analysis for the complete life cycle of the battery pack : Reconditioning and Recycling Scenario.

Increasing the number of modules up to 100 %, the cost reaches the value of 93.15 €/ kWh. With a lower number of modules substituted, at a minimum of 11 %, the price decreases to 86.75 €/ kWh. The reconditioning process is crucial for the sensibility analysis of the life cycle cost, as it is the only variable under exam. The cost resulting from the study are reported in Table 4.11. However, the cost associated with the avoided battery pack does not dependent on the number of modules substituted.

Reconditioning	**11%**	**22%**	**33%**	**44%**	**50%**	**55%**	**66%**	**77%**	**88%**	**100%**
Cost [€/ kWh]	4.57	5.37	6.17	6.97	7.36	7.76	8.56	9.36	10.16	10.96

Table 4.11: LCC sensitivity analysis for the reconditioning process of the battery pack [€/ kWh].

According to the data provided in Table 4.11, the cost of the reconditioning process for the battery pack ranges from 4.57 €/ kWh to 10.96 €/ kWh. The baseline scenario for the reconditioning cost is stated to be 7.36 €/ kWh.

4.3 Comparison of the Three Baseline Scenarios

In this section, the three baseline scenarios -the simple disposal scenario, recycling scenario, and CCR=50 % reconditioning + recycling scenario- are compared.

1. The simple disposal scenario, revolves around the conventional approach of waste management. It primarily involves disposing of waste materials through methods such as landfilling or incineration as explained in Section 3.2.4. In this scenario, waste is not subject to any recycling or reconditioning processes, leading to a potentially significant environmental impact and a missed opportunity for resource reuse.

2. The recycling scenario involves collecting, sorting, and processing of the battery pack materials as mentioned in Section 3.2.4. By diverting the materials from landfills and incinerators, the recycling scenario aims to mitigate environmental harm, reduce waste accumulation, and promote the efficient utilization of resources.

3. The third scenario, CCR=50 % reconditioning + recycling, combines two EoL management strategies, as described in Section 3.2.4. It includes the process of remanufacturing of the battery pack to the original state, to be used for a second application. The integration of reconditioning aims to extend the lifespan of the product, thereby reducing the need for new production. At the end of the second life, a recycling process is applied.

Figure 4.18 compares the most relevant impact categories and the life cycle cost of the battery pack, where the values are normalized relative to the scenario with the highest impact in each category. The red spider diagram represents the simple disposal scenario; the blue spider is associated with the recycling scenario; and finally, the green spider is linked to the reconditioning scenario. Table 4.12 lists the percentage of saving with respect to the highest impact scenario of Figure 4.18, that is the Simple Disposal scenario (red spider). The recycling scenario offers significant benefits in terms of environmental impacts compared to the simple disposal scenario. Specifically, recycling can lead to environmental savings ranging from 9.9 % to 42.6 %. Moreover, the recycling scenario also brings an estimated cost reduction of approximately 2.5 % compared to the simple disposal scenario . This cost savings is attributed to the reduced waste management expenses, avoided landfill fees, and potential revenue generated from selling recycled materials. The range of environmental savings resulting from the implementation of the reconditioning scenario is estimated to be between 23.8 % and 69.7 %. In addition, the reconditioning + recycling scenario also offers an estimated cost reduction of the 40.7 % when compared to the simple disposal scenario. The reconditioning + recycling scenario offers notable benefits compared to the recycling scenario. The range of environmental savings is estimated to be between 14.2 % and 35.9 % while the cost reduction resulting is approximately 38.3 %, compared to the recycling scenario alone.

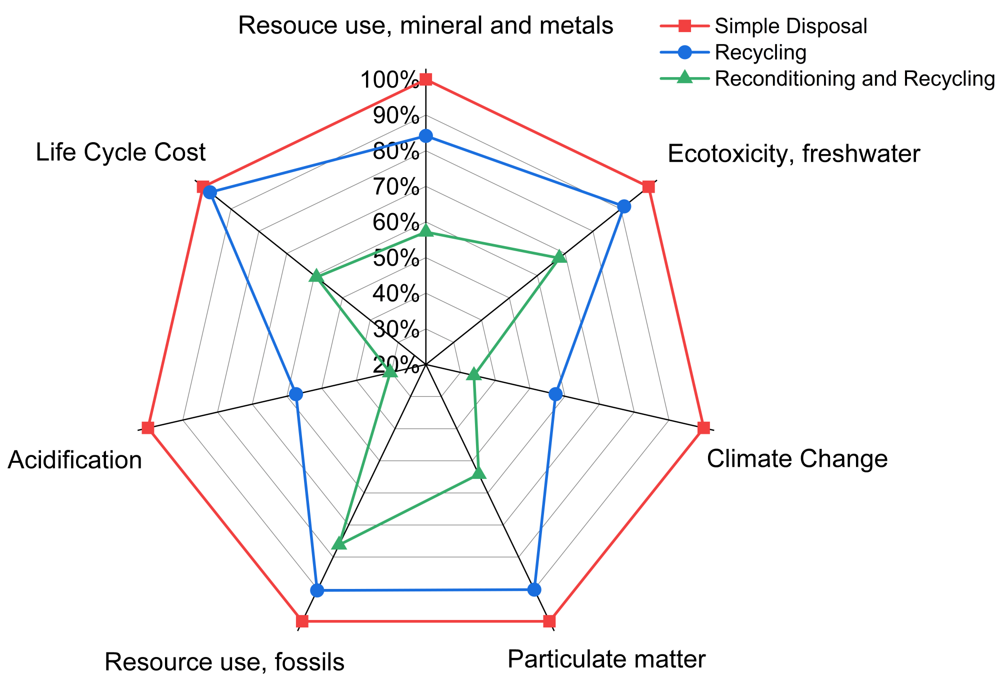

Figure 4.18: Comparison of the three scenarios under exam for the six most relevant EF 3.0 impact categories and total life cycle cost

In Table 4.13 the summary of all the total environmental impacts and the cost of the life cycle of the battery pack for the three scenarios are listed.

In the life cycle analysis, the simple disposal scenario is found to have the highest environmental impacts and life cycle costs compared to the recycling and reconditioning + recycling scenarios. Simple disposal does not recover any materials, resulting in the loss of valuable resources and increased environmental burden. The recycling scenario offers significant benefits by recovering components and avoiding the extraction of high-value materials, leading to lower emissions and cost savings. The recycling process allows for the efficient utilization of materials, reducing the need for virgin resources and minimizing environmental impacts associated with extraction and manufacturing. The

Impact Category	S. D. - Recy.	S. D. - Recond.	Recy. - Recond.
Acidification	15.9 %	42.8 %	27 %
Climate Change	8.8 %	32.1 %	23.3 %
Ecotoxicity, freshwater	42.6 %	66.2 %	23.5 %
Particulate matter	9.9 %	45.8 %	35.9 %
Resource use, fossils	9.6 %	23.8 %	14.2 %
R. use, mineral and metals	42.6 %	69.7 %	27.1 %
Life Cycle Cost	2.5 %	40.7 %	38.3 %

Table 4.12: Percentage of saving in environmental impacts and life cycle cost, with respect to the highest impact scenario

sale of recovered materials generates revenues, which further contributes to the reduction of the overall cost. In the reconditioning + recycling scenario, the reconditioning process plays a key role by extending the lifespan of the battery pack. By replacing the compromised modules, the battery pack can be given a second life and used anew. This approach reduces the overall need for the manufacturing battery packs, resulting in significant cost and emission reductions.

Impact Category / kWh	Simple Disposal	Recycling	Reconditioning
Acidification [Mole H^+ eq.]	1.48	1.25	0.847
Climate Change [kg CO_2 eq.]	131.3	119.7	89.13
Ecotoxicity, freshwater [CTUe]	8396.5	4816.4	2842
Eutrophication, freshwater [kg P eq.]	0.0892	0.0747	0.0652
Eutrophication, marine [kg N eq.]	0.174	0.152	0.108
Eutrophication, terrestrial [Mole of N eq.]	1.59	1.42	0.98
Human toxicity, cancer [CTUh]	5.42E-07	2.46E-07	8.47E-08
Human toxicity, non-cancer [CTUh]	8.81E-06	5.97E-06	3.37E-06
Ionising radiation [kBq U^{235} eq.]	27.88	23.10	26.6
Land Use [Pt]	493.3	393.3	298.6
Ozone depletion [kg CFC-11 eq.]	9.46E-06	9.12E-06	7E-06
Particular matter [Disease incidences]	9.51E-06	8.576E-06	5.15E-06
P. ozone formation [kg NMVOC eq.]	0.48	0.42	0.29
Resource use, fossils [MJ]	2206	1993	1681
R. use, mineral and metals [kg Sb eq.]	0.0139	0.0080	0.0042
Water Use [m^3 world eq.]	208.9	115.6	69.76
Life Cycle Cost [€]	151.1	147.3	89.5

Table 4.13: Comparison of the three scenarios under exam from the point of view of environmental impacts and total life cycle cost

Chapter 5

Conclusions

A Life Cycle Assessment and Life Cycle Cost evaluations have been conducted to assess the environmental and economic effects of a standard 95 kWh NMC622 battery pack. Three different scenarios have been examined for the end-of-life phase: Simple Disposal, Recycling and Reconditioning and Recycling. The study primarily examines the overall impact in Europe, but a sensitivity analysis, assuming the case of recycling scenario has been performed to evaluate the variability of the results considering the environmental impacts for Italy (IT), Estonia (EE), and Sweden (SE), and cost impacts for Italy (IT), Denmark (DK) and Netherlands (NL). Considering the reconditioning scenario, in this study, the assumption for the baseline scenario has been that 50 % of the LIB cells can be effectively reused.

In terms of environmental impact, focusing on the production of the battery pack, the cell manufacturing process is identified as the primary contributor in all the examined environmental impact categories. When analyzing the split between cell manufacturing and pack assembly, cell manufacturing alone accounts for 55 % of the climate change impact and 86 % of the resource use, minerals and metals. For cell manufacturing, the production of cathode and anode materials emerges as the main drivers of the environmental impacts. Cathode production ,in particular the production of active cathode materials, is identified as the primary contributor for the following impacts: climate change, fossil resource use, particulate matter emissions, and acidification. Anode production, namely the extraction of copper, is the main contributor to impacts such as mineral and metal resource use, as well as freshwater ecotoxicity. Concerning the whole life cycle of the battery pack, the three different scenarios examined brings to different results in terms of environmental impacts. However, for all three of them, the battery pack production results as the highest contributor to the impact categories. Assuming the Simple Disposal scenario, the battery pack results in a climate change of 131.3 kg CO_2 eq. / kWh. The use phase of the battery pack contributes with approximately 10 % to the total climate change impact. However, the significance of the battery use phase is a subject of ongoing debate, and further analysis is required to assess the overall validity of this finding. EoL impacts accounts for a small percentage in all the impact categories, around 2 % for climate change. Recycling the battery pack at the end of its first life results in decrease of the climate change to 119.7 kg CO_2 eq. / kWh. The use phase of the battery pack contributes approximately 10 % to the total climate change impact. Credits play a crucial role in the study, as they substantially reduce the impacts across all the examined categories, from -14% for climate change to -36% for human toxicity. In relation to climate change, the electricity mix used during different phases of the battery's life cycle has a significant influence on the results. Specifically, the electricity mix accounts for 13.6 % of the climate change impact in cell manufacturing, 2.6 % in battery pack assembly, 100 % in battery use, and 7.4 % in battery recycling. The sensitivity analysis conducted on the LCA with the recycling scenario, highlighted notable variations in the environmental impacts depending on the electricity mixes employed. The electricity mix in Estonia resulted in the highest impact values across all examined categories, followed by Italy and Sweden.

Reconditioning the battery pack after its first life (for second use) and recycling the battery at the end of the second life brings to a climate change result of 89.1 kg CO_2 eq. / kWh , which is 32 % lower than the one obtained with the simple disposal scenario. The total impacts are mitigated by including the environmental credits and the avoided production of a new battery pack that produces a benefit from 26 % for Ionising radiation to 30 % for particulate matter (28 % for climate change). The sensitivity analysis performed on the number of modules substituted, and as a consequence on the number of cells substituted, showed that the increase in the number of modules substituted brigs to a substantial rise of the environmental impacts for all the impact categories.

In terms of costs, the production cost of the battery pack is primarily influenced by cell manufacturing, which accounts for 40.3 % of the total cost. Additionally, there are other additional costs that contribute 30.1 % to the overall production cost. The costs associated with the module and other components of the battery pack are also significant, collectively accounting for over 20 % of the production cost. Within the cell manufacturing, the main contributor is the cost of cathode production, which represents 62.6 % of the total cost. This can be attributed to the high-value materials such as cobalt, nickel, lithium, and aluminum used in cathode production.

In terms of life cycle analysis, for the simple disposal scenario of the EoL, the compete life cycle cost is of 151.1 €/ kWh with the battery production accounting for 91.8 % of the total. Considering the recycling scenario, the battery pack manufacturing accounts for a share of 79.7 %, the credits from recycling reduce the total life cost of the battery pack to the value of 147.3 €/ kWh. The sensitivity analysis conducted on the LCC revealed that if the manufacturing, use and recycling of the battery pack occurs in DK the battery pack LCC results in 169.8 €/kWh, because of the high price of electricity, natural gas and human labor. For the NL scenario the life cycle cost reduces to a value of 134.4 €/kWh, this is mainly dependent on the lower electricity and human labor price.
The reconditioning and recycling scenario offer the highest life cycle cost benefits. For the baseline scenario, i.e. with 50 % of modules substituted and RER energy consumption, the battery pack cost is around 89.6 €/ kWh. This decrease is mainly due to the avoided manufacturing of a new battery pack because of the second use of the reconditioned battery. The sensitivity analysis shows that with the increase in the number of modules substituted, also the life cycle cost of the battery increases to a value of 93.2 €/kWh for 100 % substitution. However, even in in this situation the life cycle cost of the battery pack remains lower than the one obtained assuming a recycling or simple disposal scenario.
Comparing the three scenarios, reconditioning the battery back after the fist life and performing a recycling operation at the end of the second life apparently emerges as the best option. Nevertheless, the reconditioning operations of the battery pack presents some challenges that needs to be taken into account. Because of the many configurations found in the battery market, the manual disassembly presents a key point in terms of cost and hours of work needed for the operations. The reconditioning process is complicated not only by the diverse designs of battery components (modules, and packs) but also by the varying State of Health of used batteries and the increased cell-to-cell variability found in second-life batteries compared to new ones. The second-life business model for lithium-ion batteries is still in the early stages of development, primarily because of the relatively new nature of the electric vehicle market and the lifetimes of BEVs. Based on the circumstances examined, recycling is the preferred option, able to promote circular economy, enabling the conservation (recovery and reuse) of high value resources such as lithium, cobalt, nickel, copper and aluminum. Recycling provides a viable solution to comply to the number of regulations and directives established by any many countries concerning the responsible disposal of batteries, thereby preventing potential legal and financial consequences.

Chapter 6

Future Work

The focus of this study has been the analyses of the LCA and LCC of a NMC622 Li-ion battery pack for automotive applications. To conduct the assessments and obtain significant results some aspects of the model have been simplified. In the future developments of this study, the following aspects are worth addressing:

1. *Analysis of different design and chemistry of the Li-ion battery cells.* The chemical composition of the battery cells used affects the overall environmental and cost impact of the battery pack. New chemistries for the ternary battery have been developed to address the need for use reduction of high value metals such as Cobalt. The investigation of the impacts associated with the use of new technologies is crucial to understand their viability. Moreover, the use of different design for the cell, such as pouch or cylindrical needs to be investigate. The design of the cell greatly affects the manufacturing process, a key contributor for both environmental and cost impacts.

2. *Analyzing different EoL allocation method.* In this study, benefits and burdens associated with the EoL are allocated implementing the avoided burden method. However, within the PEF method, the CFF formula was introduced to define the specifications for the modeling of the EoL stage. The avoided burden scenario and the CFF scenario have in common some parameters, such as the amount of material recycled, the amount of material used for energy recovery and the specific emissions and resourced depleted. Comparing the impacts resulting fro two

allocation methodology is of interest, as the CFF is able to account for multifunctionality in recycling, re-use processes.

3. *Including implementations and disassembly procedures of the battery pack in the vehicle.* This study does not accounts for the energy and additional costs, such as labor, required for the mounting of the battery pack on the vehicle or any disassembly operations required at the End-of-Life. The reliability of data on these processes is currently low. For future studies, the implementation of more reliable data on these subjects will give a complete assessment of the environmental burden and cost impact of the life cycle of the battery pack.

4. *Analyzing the variability of LCC results with the use of different costs.* For this assessment, the cost inventory of the components of the battery pack is taken from secondary data, applicable to a generic study case. Costs are not constant, in particular for high value metals, and their variation can deeply affect the final results of the LCC. Future works aimed to assess the variability of the LCC results can provide a broader picture of the overall life cost of the battery pack.

5. *Including a sensitivity analysis for China.* China's EV sales are close to 50 % of the overall EV stock. As described in the cited literature, the energy mix adopted for all the life stages of the battery pack is a key element when assessing the environmental and cost impacts. China is one of the largest energy consumer and producer. Coal supplies about 55 % of the total energy consumption with petroleum and natural gas being the major secondary sources [96]. Relying on coal as the main source might bring to an increase in the climate change impact, but at the same time reducing the overall life cycle cost. Another factor to consider is that China is currently a leader in battery recycling technology research. Future work that assesses the performances of the life cycle of the battery pack in China can improve the understanding of the variability of some parameters such as energy mix and recovery rate of recycled materials.

6. *Analyzing the impact of recycling regulations for the EoL of battery packs.* Although different analysis can be performed for the EoL of the battery pack at the end of its first life, the lack of regulation leaves the matter in the hands of the carmakers. Investments will have to be made from the automotive companies to match the expected volume of batteries to be recovered. Currently, the investments are strictly tied to the revenues arising from the recycling operations. In this scenario, policymakers can provide solutions that might have less impact, but serve as a crucial starting point for the generation of a new net of collection and recycling plants.

These additional studies will allow for a more complete and accurate view of the environmental burdens and costs associated with the life cycle of a Li-ion battery pack.

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