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Modeling and simulating the evolution of circular economy for End-of-life e-mobility Li-Ion batteries

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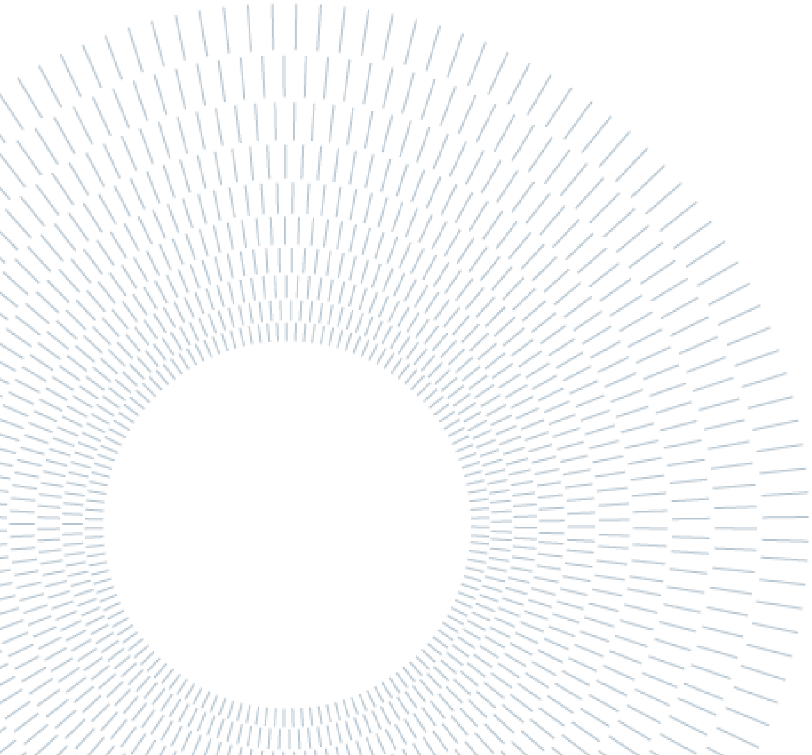


Abstract

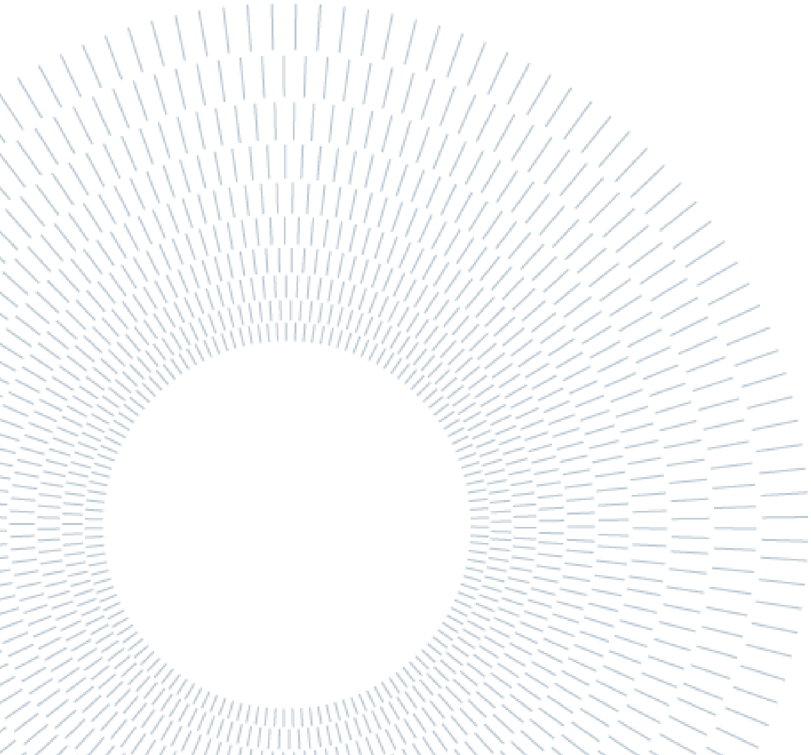
The commercialization of electrified vehicles (EV) has experienced a significant expansion worldwide in the last decade and it is expected to maintain this raising trend over the following years, driven by the need to reduce greenhouse gas emissions in the transportation sector. This trend boosts the demand for Li-ion batteries embedded in the vehicle, that will translate into an increase of batteries to be treated at their end-of-life. The thesis faces the issues and challenges of shifting from a linear to a circular value chain in the context of e-mobility batteries. It proposes a simulation model built on a systems dynamics tool, able to provide a comprehensive description of the return value chain, processes and second life applications. Furthermore, having determined all main factors influencing the development of circular economy strategies, the model captures their progress and interaction over time to see the effect on the results. The purpose is optimizing the evolution of return batteries flows and forecast their most likely distribution between the available circular economy strategies given a set of criteria. Data gathering of the real ecosystem together with a profitability analysis of the processes have been deepened to provide the required information to feed and run the model. The collected results have been analyzed and translated into recommendations to boost the development of those strategies, aiming at deriving the maximum gain from all of them.

Key-words: Electric vehicle, End-of-life Li-Ion batteries, Circular economy, Second life applications, Simulation model, System dynamics.

Abstract in italiano

Le vendite globali di veicoli elettrici e ibridi sono in forte crescita, confermando un trend che ha caratterizzato gli ultimi anni, in risposta alle esigenze di decarbonizzazione e riduzione di gas serra. Questa crescita impatta direttamente la produzione di batterie agli ioni di litio, che costituiscono il componente fondamentale della nuova tecnologia di veicoli, e pongono nuove problematiche sulla loro gestione una volta raggiunto il fine vita. Il presente elaborato si pone l'obiettivo di indagare questa tematica, e approfondire le sfide legate all'implementazione di un sistema di economia circolare per la gestione di queste batterie. Viene realizzato un modello di simulazione basato su un software di system dynamics, con lo scopo di fornire uno strumento che supporti il processo decisionale degli attori coinvolti nella filiera. Il modello è strutturato per garantire una descrizione completa della catena del valore, dei processi coinvolti e delle possibili applicazioni di seconda vita. Costruito su una serie di criteri e vincoli, il modello è finalizzato a stimare l'evoluzione dei flussi di ritorno delle batterie e prevedere la loro distribuzione tra le strategie di economia circolare disponibili. Sono stati raccolti dati e informazioni sull'ecosistema reale da usare come input per il modello, e è stata svolta un'analisi circa la redditività dei processi. I risultati raccolti hanno permesso di derivare conclusioni e spunti interessanti sul possibile sviluppo futuro di tali strategie applicate alle batterie agli ioni di litio.

Parole chiave: Veicoli elettrici, Batterie a fine vita, Economia circolare, Applicazioni di seconda vita, Modello di simulazione, System dynamics.



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List of Abbreviations

Al	Aluminium
BEV	Battery Electric Vehicle
BMS	Battery Management System
Co	Cobalt
Cu	Copper
DoD	Depth of Discharge
EoL	End of Life
ESS	Energy Storage System
EV	Electric Vehicle
Li	Lithium
LIB	Lithium-ion Battery
Mn	Manganese
Ni	Nickel
NMC	Nickel Manganese Cobalt
HVF	High Voltage Fragmentation
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
SDS	Sustainable Development Scenario
SoC	State of Charge
SoH	State of Health
SS	Storage system
STEPS	Stated Policies Scenario

1 Introduction and objectives

1.1. Circular economy introduction

Circular economy denotes an industrial economy that is restorative by intention and design. In a circular economy, products are designed for ease of reuse, disassembly and refurbishment, or recycling. The main concept behind circular economy states that reuse of vast amounts of material reclaimed from end-of-life products rather than the extraction of resources is the foundation of economic growth.[1]

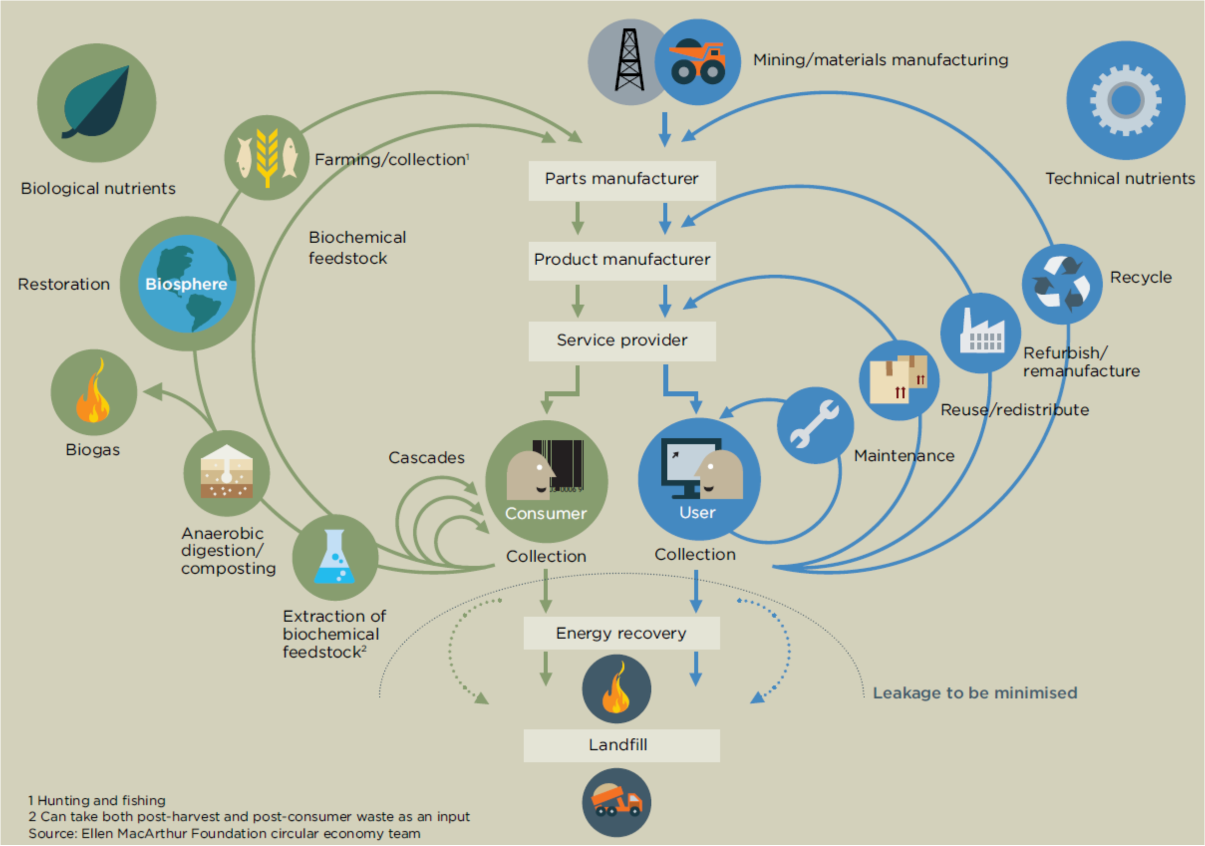
This paradigm overcomes the traditional model where the creation of value is achieved through a linear value chain based on a ‘take-make-dispose’ pattern. Companies extract materials, apply energy and labour to manufacture a product, and sell it to an end consumer—who then discards it when it no longer serves its purpose. While great strides have been made in improving resource efficiency, any system based on consumption rather than on the restorative use of resources entails significant losses all along the value chain. Moreover, linear systems increase companies’ exposure to risks, represented mainly by higher resource prices and harder-to-reach locations to extract. Overall, the linear “take-make-dispose” model relies on large quantities of easily accessible resources and energy, which is increasingly unfit the reality in which it operates. For these reasons, materializing the change of paradigm from consuming and discarding products to using and reusing them to the maximum extent possible is vital to ensure that continuing growth generates greater prosperity.[1]

Circular economy is strictly related to the management of materials flows. They are distinguished between biological nutrients, designed to re-enter the biosphere safely and build natural capital, and technical nutrients, which are designed to circulate at high quality without entering the biosphere.

Circular economy is based on a few simple principles:

- Design out waste. Biological and technical components of a product are designed by intention to fit within a biological or technical materials cycle, designed for disassembly and refurbishment. In particular, technical nutrients such as polymers, alloys, and other man-made materials are designed to be used again with minimal energy and highest quality retention.
- Build resilience through diversity. Modularity, versatility, and adaptivity need to be prioritized in an uncertain and fast-evolving world, in order to facilitate flexibility and face constant changes.
- Rely on energy from renewable sources. Systems should ultimately aim to run on renewable sources.
- Think in ‘system’. It is important to develop the ability to understand how parts influence one another within a whole, and the relationship of the whole to the parts, and derive possibility to build circular value chains.
- Waste is food. The ability to reintroduce products and materials back into the biosphere through restorative loops is at the heart of the idea.

The graphical description of how to close the loop and move from a linear to a circular value chain is represented in the Figure 1.1, where both biological nutrients and technical nutrients’ flows are depicted.



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input
Source: Ellen MacArthur Foundation circular economy team

Figure 1.1: The circular economy

The shift is embraced and accelerated by the development of efficient and effective take-back systems, the proliferation of business-model design practices that generate more durable products, facilitate disassembly and refurbishment, and consider product/service shift, where the product ownership and its control is retained by the manufacturer.

1.1.1. Circular economy processes

1.1.1.1. Second-life strategies

Under a circular economy perspective, the de-manufacturing processes include the set of technologies, tools and knowledge-based methods to recover and re-use functions and materials from industrial waste and post-consumer high-tech products. These processes can be distinguished between [2]:

- Reuse: reuse refers to the operations performed when a return product is put back into service, essentially in the same form, with or without repair or remediation
- Repair: Repair refers to actions performed in order to return a product or component purely to a functioning condition after a failure has been detected, either in service or after discard.
- Remanufacturing: Remanufacturing refers to the operations to return a used product to its original performance, usually with a warranty that is equivalent or better than that of the newly manufactured product. The product is processed using a standardized industrial process, in line with technical specifications. It implies performing disassembly activities.
    - Remanufacturing for function restore: The remanufactured product fulfills a function similar to the original part.
    - Remanufacturing for function upgrade: The remanufactured product is upgraded with new functionalities. Remanufacturing with upgrade aims to extend products' value life enabling the introduction of technological in order to satisfy evolving customers' preferences.
- Repurposing: Repurposing usually refers to reuse the end-of-life product in a new second life application, different from the one it has during its first life.

1.1.1.2. Recycling

Recycling systems are multi-stage systems including multiple size-reduction and separation stages. The objective of recycling systems is to process an incoming product and to obtain in output separated flows of pure materials to be re-used as secondary raw materials in the manufacturing process.

1.1.2. Circular economy in European context

Circular economy strategies can be a significant opportunity for Europe[3]. Indeed, the European economy is surprisingly wasteful in its model of value creation and continues to operate a take-make-dispose system. On the contrary, shifting toward a circular economy model in Europe would deliver better outcomes and yield annual benefits of up to €1.8 trillion by 2030 [3]. Indeed, leveraging on the wave of disruptive technologies, such as digitalization and automation, and new business models, like servitization, would allow to maximize value extracted from asset and material stocks by shifting to this new paradigm. Moreover, a circular economy could greatly benefit the environment and boost competitiveness and resilience. It reduces the need for primary processes such as raw materials extraction and treatment, that are the more energy intensive. Also, the local development of businesses based on circular economy can increase the system resilience, avoiding stop due to provision of materials. Finally, benefits would be achieved even considering the social implications. Equilibrium-modeling results suggest the circular economy could produce better welfare, GDP, and employment outcomes than the current development path. Indeed, this impact on employment is largely attributable to lower prices expected across sectors, led by the new model introduction. A circular model would mean a shift from the labour-scarce raw material sectors to the labour-intensive recycling sector. [3]

1.2. Introduction to the context

1.2.1. EV market

The electric car marker is characterized by a strong dynamism. The commercialization of electrified vehicles (EV), including battery, hybrid and plug-in hybrid electric vehicles (BEV, HEV, PHEV) has experience a significant expansion worldwide in the last decade and it is expected to maintain this raising trend over the following years. Even if the global pandemic shrank the market for conventional cars in 2020, for electric cars growth has been impressive, rising to 3 million global annual sales and representing 4.1% of total car sales and in 2021. [4]

1.2.2. Strategic roles of batteries

All around the world, vehicle manufacturers and policy makers are boosting their attention and actions related to electric vehicles (EVs), driving and enhancing this trend.

Indeed, the need for urgent and more intensive actions against climate change is broadly recognized and the electrification of the transportation sector allows to drastically reduce the greenhouse gas emissions, thanks to the completely new technology of the electric cars. The main component characterizing electric vehicles is represented by the battery, which is rechargeable and allows to power the electric motor. As a consequence, batteries are considered a systemic enabler of a major shift to bring transportation and power to greenhouse gas neutrality. Moreover, they play an important role in the energy sector, as they allow to shift from fossil fuel to renewable power generation as a dispatchable source of electricity. [5]

In Europe, this topic is even more critical, since the EU legislation is settings CO2 emission standards for carmakers. Since transport causes roughly a quarter of greenhouse gas (GHG) emissions and it represents the main cause of air pollution in cities. Given the role that batteries play in the roll-out of zero-emission mobility and the storage of intermittent renewable energy transition, the development of the battery market has been considered as an integral part of the Green Deal, the EU's new growth strategy that aims to transform the EU into a modern, resource-efficient and competitive economy. This plan and relative legislation set no net emissions of greenhouse gases by 2050 and economic growth decoupled from resource use. [6]

1.2.3. Evolution of the market and challenges

Given this central role of batteries, a circular and responsible battery value chain is one of the major near-term drivers to meet the Paris Agreement goals in the transport and power sectors. However, expanding the value chain related to this increasing role comes with several challenges that must be addressed. In particular, a fundamental change to produce these batteries responsibly and sustainably is needed, and this means lowering emissions, eliminating human rights violations, ensuring safe working conditions across the value chain, and improving repurposing and recycling. A solution to tackle these issues is moving from a linear to a circular value chain, because the shift can improve both the environmental and the economic footprint of batteries by getting more out of batteries in use, and by harvesting end-of-life value from batteries. [5] Focusing on this last point, the rapidly increasing demand for Li-ion batteries will translate into an increase of waste EV batteries after reaching first use in vehicles. These raising volumes are required to be treated in a sustainable way. [7]

The topic is particularly significant in Europe, where the extended producer responsibility states that producers of batteries and of products incorporating batteries are responsible for managing the waste generated by the batteries they place on the market. [6] While the end-of-life treatment of traditional internal combustion engine cars is established and mature, the transition toward a new product raises challenges on how to properly process batteries under a circular economy perspective. Moreover, even if European Directives (*End-of-Life Vehicles Directive 2000/53/EC and Batteries Directive 2006/66/EC*) states that batteries have to be collected and recycled, the technical characteristics of this technology creates new perspective for the end-of-life treatments. Once exiting their first life application, batteries usually have a residual capacity varying between 70% and 80%, that can be used in other applications before recycling. [7] Those applications may be represented by stationary systems, which provide energy storage and require less demanding performances if compared to the automotive use. Batteries may be removed from vehicles, tested, refurbished if needed and, after being recertified for performance and safety, used for another purpose. This allows to recover residual battery value at the end of life, but it can be considered as a short-term trade-off with battery recycling, as it may reduce the volumes directed to this strategy. Finally, benefits are achieved with recycling materials from end-of-life batteries and from manufacturing scraps during production, because it limits the need for virgin resources in the long terms. [5]

Applying circular economy strategy to improve the sustainability of the value chain and accomplishing this required change of paradigm is achieved by overcoming significant obstacles.

The development of information technology embedded within batteries, described as a battery passport, is needed to allow the sharing of key data derived from them. This enables to efficiently determine the state of health and chemistry of battery cells or help to manage them appropriately while determining the suitable second-life strategy to treat batteries. Moreover, design for disassembly strategies and technological development of processes have to be accomplished, in order to facilitate disassembly, improve the degree of automation and scale up production to significant volumes. Finally, challenges for the application of circular economy strategies are increased by the complexity of the battery technology. Indeed, batteries' technological innovation is driven by increasing energy density levels which is achieved by switching to more efficient chemistries, e.g. from NMC 111 to NMC 811. [5] However, this development is impacting the profitability of the recycling processes, mainly driven by the amount of Cobalt recovered, that is progressively decreasing in the new technologies. Indeed, Co is in greater demand than other metals because of their low relative abundance and high price. [8] Finally, specific type of cells assembled in the batteries may influence the effective application of remanufacturing strategies. Indeed, prismatic cells are more robust and larger than other types, which makes easier to properly handle during disassembly and testing. [9]

All these mentioned factors may be clustered according to different categories, whether they result from a regulation evolution (e.g. battery passport), a characteristic of the batteries (e.g. chemistry or cell type) or a technical feature of the circular economy process (e.g. technological availability or scrap rate). Their interaction and evolution will impact significantly the development of the end-of-life strategies in the near future and determine the future configuration of the value chain.

1.3. Main objective of the thesis and research questions

Given the complexity related to the value chain, the multiple factors to be considered and the need of tacking their evolution, a simulation analysis based on system dynamics and agent-based simulation is identified as the most suitable model to properly describe and capture these dynamisms. For this reason, the study has two main objectives.

1. The main objective of the thesis is to build a simulation model able to provide a comprehensive description of the value chain, capturing the previously mentioned factors and their progress over time. The aim is providing economic actors with a powerful tool to support decision making process. The representation is intended to be both vertical and horizontal.
    a. Horizontal description: The value chain is described from the input flows represented by the EV market, until the demand of second life applications.
    b. Vertical description: The value chain is described both considering a business layer and a process layer. Indeed, business representation does not allow to include significant technical factors influencing the system, so that a process layer to describe the phases of the circular economy strategies has been added.
2. The second objective of the thesis is running the developed model, predict and evaluate the evolution of the circular economy market related to the end-of-life EV Li-Ion batteries. Indeed, given defined input data, the model provides quantitative information forecasting the expected volumes related to the different strategies. Through this support, the main points the thesis is intended to address are:

a. The evolution of the End-of-Life batteries and influencing variables;
b. The comparison between different circular economy strategies for End-of-Life batteries;
c. The potential markets for second life applications;
d. The comparison between different recycling processes to recover materials from End-of-Life batteries.

2 Context and state of art

2.1. EV market

With 10 million of electric cars on the world road at the end of 2020, the electric vehicle market is gaining momentum globally. Electric car registrations increased by 41% in 2020, with battery electric vehicles (BEV) accounted for two thirds of them. For the first time, Europe led this change of paradigm and become the world's largest electric vehicle (EV) market, overcoming the annual Chinese EV sales. [4]

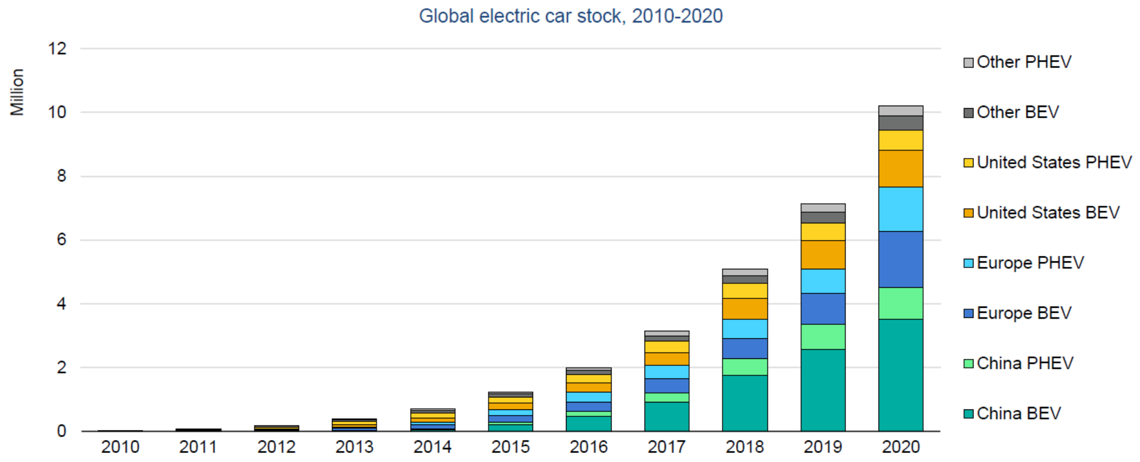


Figure 2.1: Global electric car stock, 2010-2020

The main drivers leading this change of paradigm are related to three main pillars. Supportive regulatory framework has strengthened key policies to reduce Co2 emissions. Additional incentives aimed at safeguard EV sales from the economic downturn, and the number of EV models expanded among all car manufacturers.

Despite the evidence of the increase of the EV market, it is still hard to define the expected future sales this market will experience. Indeed, two main distinctive scenarios may be identified to size the market. PLDs (passenger light-duty vehicles) represent the most significant share of vehicles, followed by LCVs (light-commercial vehicles), buses and trucks. Both battery electric cars (BEV), plug-in hybrid electric cars (PHEV) for all the different categories are considered.

The Stated Policies (STEPS) reflects all existing policies, policy ambitions and targets that have been legislated for or announced by governments around the world. It includes current EV related policies and regulations, as well as the expected effects of announced deployments and plans from industry stakeholders.

In the Stated Policies Scenario, the global EV stock across all transport modes (excluding two/three-wheelers) expands from over 11 million in 2020 to almost 145 million vehicles by 2030, an annual average growth rate of nearly 30%.

On the other hand, the Sustainable Development Scenario (SDS) estimates the required data to achieve net-zero emissions by 2050 and limit the global temperature rise to 1.5 °C as defined by the Paris Agreement. The SDS assumes that all EV-related targets and ambitions are met, even if current policy measures are not deemed sufficient to stimulate such adoption rates. In this situation, the global EV stock reaches almost 70 million vehicles in 2025 and 230 million vehicles in 2030. [4]

From the Figure 2.2, the gap between the two scenarios appears clear.

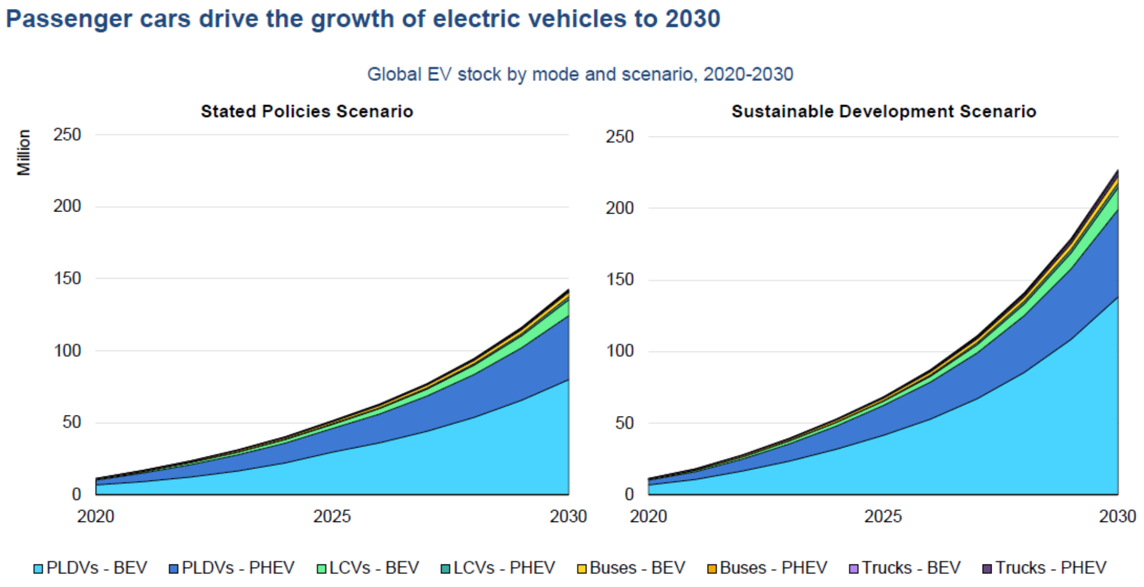


Figure 2.2: Global EV stock by mode and scenario, 2020-2030

Analysing the increase of annual sales divided by countries, it emerges that China and Europe are leading the electronification of the transport segment. Moreover, EV sales are expected to maintain Europe as one of the most advanced EV markets in the coming years and original equipment manufacturers are announcing are announcing their intention to only sell EVs in Europe from 2030. [4]

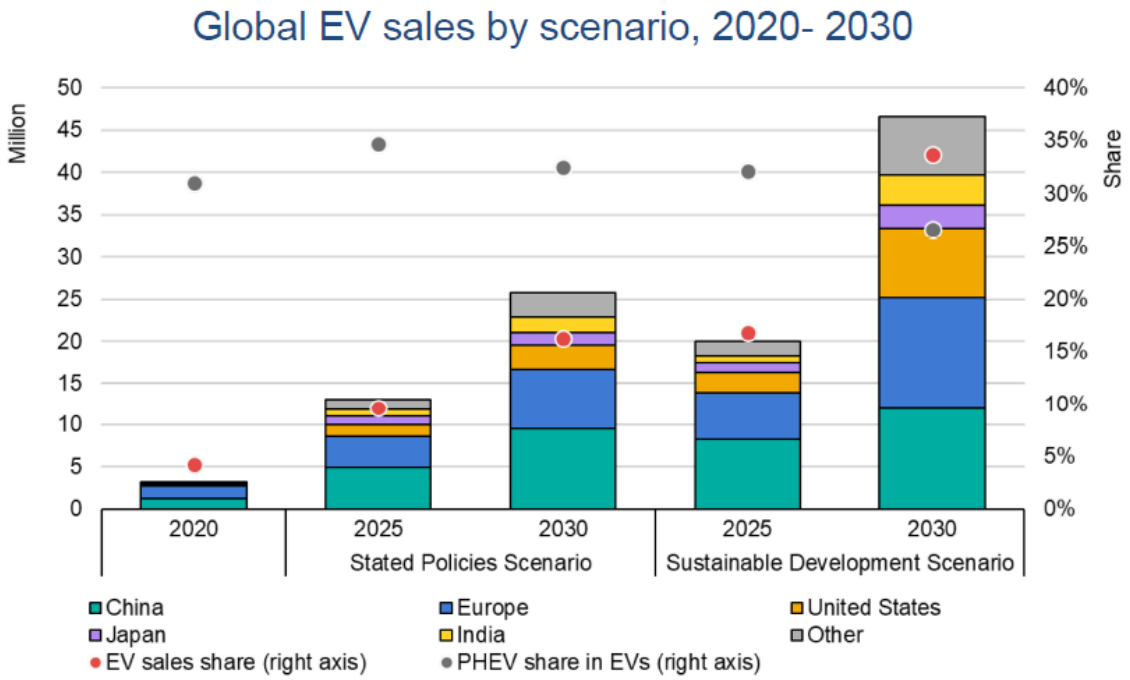


Figure 2.3: Global EV sales by scenario, 2020-2030

Considering the STEPS scenario, European EV sales share is similar to that of China 2030. On the contrary, the European market largely overtakes China in the sustainable development scenario. Indeed, the Europe's overall clean energy ambitions reflected in that scenario require higher electrification efforts to 2030, resulting in larger amount of vehicles sold. [4]

2.2. Li-Ion batteries for electric vehicles

Lithium-ion batteries are the key technology to drive decarbonization of the transportation sector. They are a complex product, composed by a modular architecture and a plurality of additional components ensuring their proper functioning.

2.2.1. Li-Ion batteries structure

The modular structure of the battery is composed by three main components so that the battery pack can be hierarchically broken down into three main levels. [10]

- Cell level: The lower one is represented by battery cells, the fundamental bricks of the battery pack.
- Module level: Cells are arranged in series and parallel, and held together by mechanical and/or physical joints.
- Pack level: Modules are arranged in series to composed battery pack, and are encased in a housing structure together with additional components.

The final voltage and capacity of the pack are obtained by the hierarchical assembly of single battery cells. Given the nominal voltage of 3.6 V – 3.8 V of the cell, the voltage value of the pack is achieved by connecting in series and parallel the cells, until reaching usually 300 V.

Figure 2.4: Schematic structure and components of a battery pack [10]

2.2.2. Cell functioning

A lithium-ion battery is made of a positive and a negative porous electrode, immersed in a liquid electrolyte, with a polymeric membrane called separator in between and two current collectors. The electrodes are electrically conductive, while the separator allows ions movement only. Lithium occupies active sites in both electrodes.

The chemical reactions needed to provide electric current involve the flow of electrons from one electrode to another, through an external circuit. During the operations, lithium ions are extracted from one electrode, pass through electrolyte and separator and are inserted into the other electrode. [11]

Considering the Figure 2.5, when these reactions occur from left to right side, the battery is being discharged. The opposite occurs during charge. When the electrode is experiencing a loss of electrons, meaning that an oxidation-reduction is occurring, it is called anode. On the other hand, a cathode is the material that undergoes an electrochemical reduction, meaning that it is gaining electrons. Therefore, both negative and positive electrodes can be anode or cathode, depending on charge or discharge. However, it is common to refer to the positive electrode as cathode because the reference case is the discharge of the battery.

The negative electrode (anode) is usually made of graphite, while the positive electrode is based on layered transition metal oxides. Li-ion batteries are named based on their cathode materials like, for instance, Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2), Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2) and Lithium Iron Phosphate (LiFePO4). The first one, also called NMC batteries cell, represent the most dominant chemistry for Li-Ion batteries, with around 71% of sales share. [4]

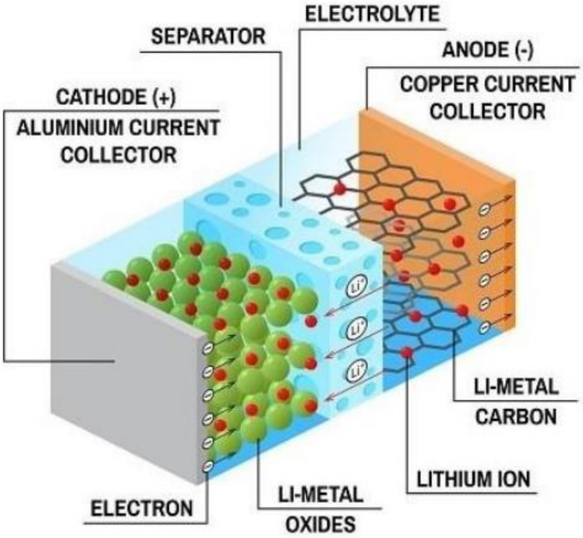


Figure 2.5: Li-Ion cell operation during the discharging process

2.2.3. Cell typology

Cells for EV applications are available in three main different shape: cylindrical, prismatic and pouch. [12]

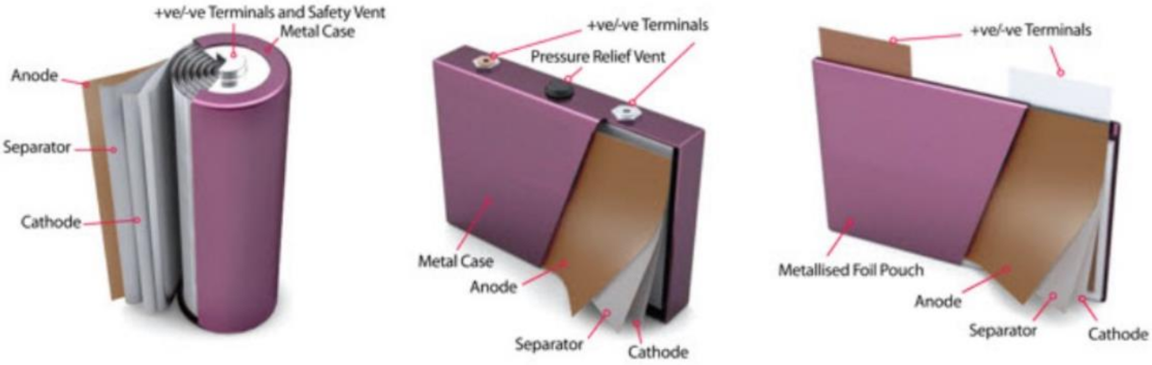


Figure 2.6:Cell typologies: cylindrical, prismatic and pouch (left to right) [12]

The cylindrical cell is the first one represented in the Figure 2.6. In this case, the cathode-anode double layer is rolled up and housed in a cylindrical steel case, which guarantees mechanical stability and strength. The negative electrode tab is welded on the bottom of the housing, making the entire case acting as a negative terminal. Instead, the positive electrode is located on the cell cap and is isolated from the rest of the case by a sealing gasket. The dimensions of Li-Ion cylindrical cells are highly standardized, with the same portfolio for automotive and general applications. Among the EV manufacturers, they are mainly used by Tesla EV models.

The second cell type is represented by Prismatic cell. The cathode-anode double layer is folded with a zig-zag pattern and housed in a prismatic rigid aluminum case. The positive and negative poles are made by pins exiting the upper face of the cell. Although there are some variations in the design, several industry groups have proposed standardized designs for prismatic cells. Also, they are bigger than the others, so that less number of prismatic cells are need to create a module. This simplifies both the assembly and disassembly activities.

The last type is represented by Pouch cells. The cathode-anode double layer is folded with a zig-zag pattern and housed in a soft plastic case. The positive and negative poles are made by lamellas transversally exiting the cell. There is no standardization in the pouch cells' dimensions and architecture. Generally speaking, pouch batteries are comparable in width and length to prismatic ones but much thinner.

The main pros and cons of the cell types are summarized in the following table. [13]

Table 2.1: Cell geometry pros and cons

Cell geometry	Pros	Cons
Cylindrical	Simple, low-cost production Highest energy density at cell level	High safety hazards in case of accident Complicated module integration Low energy density at pack level
Prismatic	Low safety hazards Low integration costs at the module and pack level High energy density at pack level	Cell production costs are slightly higher Energy density at cell level lower than that of cylindrical cells
Pouch	Low production costs	High integration costs

	High energy density at cell level	Energy density lost at module and pack level

Despite pouch and cylindrical cells have been more diffused in past EV modules, prismatic cells are expected to become more popular, because of the higher energy density at module and pack level. Moreover they tend to be safer than cylindrical ones. [13]

2.2.4. Cell/module connections

The voltage and capacity value of the battery pack are reached thanks to the electrical connections between cells and then modules. When connected in series, cells or module increase their voltage so that the resulting voltage is the sum of the voltage of the single elements connected in series. In this case, it is important to use cells with similar characteristic and equal capacity in order to avoid electrical imbalance during charging and discharging processes and the power of the battery pack is limited by the weakest cell. To form series and parallel connections, the cell terminals need to be electrically connected. This usually happens by cell-to-busbar connections. Busbars are strip-like metal couplers which allow the current flow between cell or module terminals.

2.2.5. Additional components

The figure explains how an EV battery is structured and which are their main components, besides the previously deepened cells and modules. The cooling system aims at managing temperature peaks and uniform thermal gradients across the battery pack. Indeed, the recommended operational range for Li-ion battery cells is generally between 25 °C and 40 °C. Other components are the battery junction block, which connects the battery and the external electrical system, and the service plug, a disconnect switch to be pulled out by hand in case of emergency.

Finally, the battery is composed of electronic devices and sensors, power cables, joins and a housing body, to protect the inner parts.

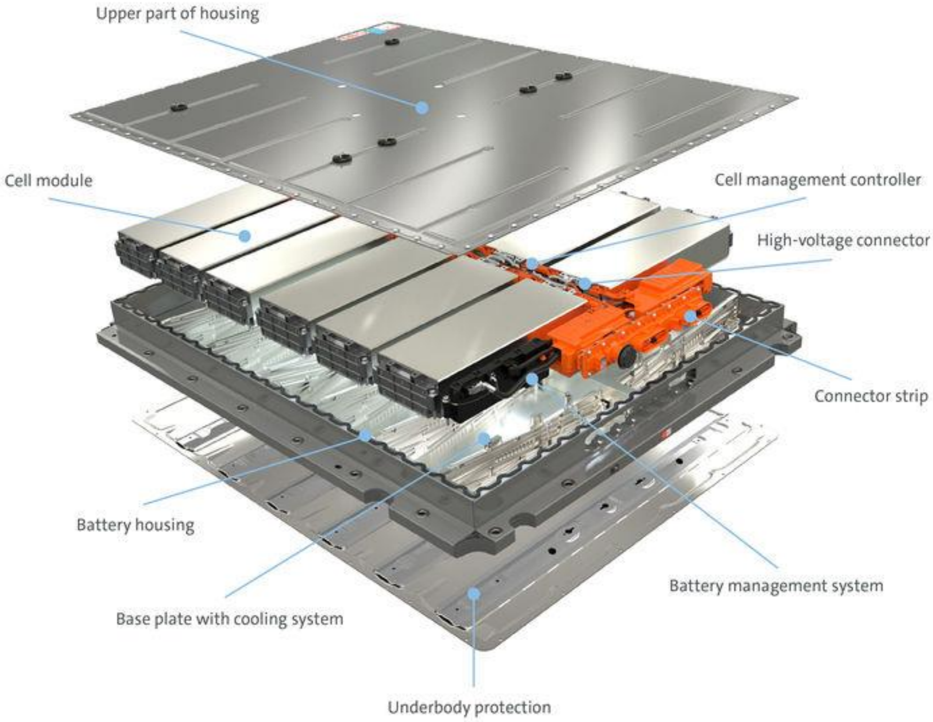


Figure 2.7: EV battery components

2.2.6. Battery management system

The Battery Management System (BMS) is an essential element of an EV battery pack dedicated to fulfilling three main tasks of a BMS:

- To ensure that the energy of the battery is optimized to power the product
- To ensure that the risk of damaging the battery is minimal.
- To monitor and control the charging and discharging process of the battery

Indeed, the BMS controls the functions of the battery to maximize its life, efficiency and safety, but also provides accurate estimations of the status of the battery such as the state of charge (SoC), defined as the ratio of the available capacity and the maximum possible charge that can be stored in the battery, and the state of health (SoH), a concept deepened later in the chapter. The main goal of the BMS, however, is to guarantee the passengers' safety and avoid any hazards like fire, thermal shock, short-circuits or over-charge/discharge. [14]

There are three main typologies of BMS, which differ because of hardware configuration. [14]

The distributed topology is characterized by having voltage monitors and discharge balancers with Printed Circuit Boards placed on each cell.

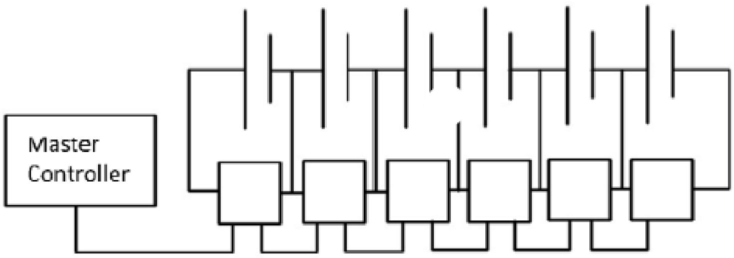


Figure 2.8: Distributed BMS topology [14]

In centralized topology, a unique master control unit is directly connected to every cell of the battery pack.

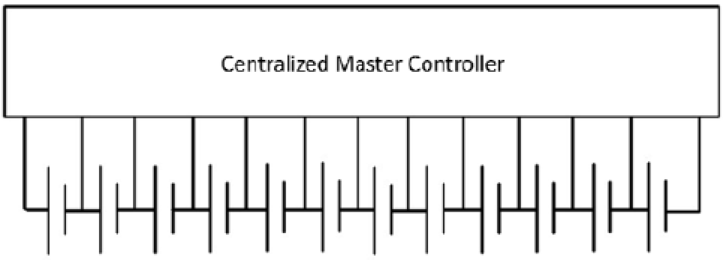


Figure 2.9: Centralized BMS topology [14]

In the modular structure, several slave controllers monitor modules or groups of cells and then consolidate the data to a master controller.

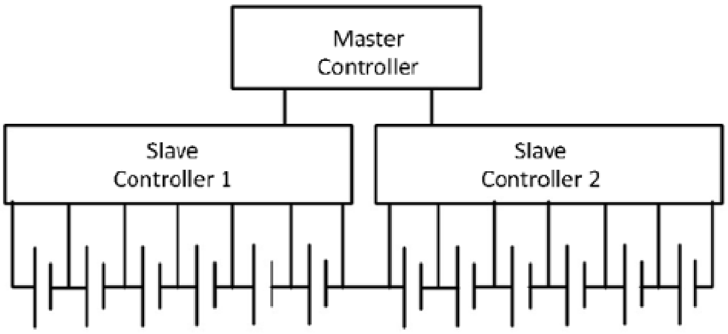


Figure 2.10: Modular BMS topology [14]

2.3. State of Health

2.3.1. Degradation mechanism

Lithium-ion batteries suffer from degradation. This topic becomes particularly significant when applied to electric vehicle batteries, because of the high performances required for this application. Degradation is commonly divided in two classes: calendar ageing and cycling ageing. [15] The first one refers to the refer to the irreversible loss of performance of the battery when not in operation. Indeed, within the battery, reactions evolve even if no current is flowing in the battery, triggered by a certain combination of electric potential, state of charge and temperature, in other words a certain thermodynamic state. The second degradation mechanism is called cycle ageing and occurs as a result of the complex relation between material properties, battery design, operating conditions and the loads the battery has to undergo during its usage phase. Moreover, charging and discharging cycles influence this phenomenon. Indeed, operations of the battery at voltage higher than the upper cut-off limit extends the range of exploitability of the battery at expense of shortening its useful lifetime. As a result, the operating zone is a trade-off between good exploitation of battery capability and keeping a satisfactory durability. Finally, the battery is influenced by depth of discharge (DoD), referring to the maximum fraction or percentage of a battery's capacity (given in Ah) which is removed from the charged battery on a regular basis. The higher the DoD, the larger the losses the battery experiences. [15]

2.3.2. State of health definition

Due to these degradation mechanisms, batteries experience a loss of performances when comparing their initial capacity to the one they have at the end-of-life. The battery state of health (SoH) is an indicator aimed at capturing this phenomenon and quantify the ageing level of the device. It describes the actual capability of the battery with respect to its beginning of life performance. However, there is no universal agreement on its definition and the way to compute it. The most common equation is the following.

$$SoH = \frac{Actual\ capacity}{Fresh\ cell\ capacity}\ [\%]$$

Nevertheless, it has some limitations. First, it does not take into account the application of the battery. [16] Without a definition more tailored on the application requirements, the value of SoH can be poorly indicative of the battery capability for the given use. Second, there is no link to the history of the cell. Batteries with the same SoH may have previously behaved differently, leading to differently behaviour in the future. Third, it provides limited information, being capacity fade just one of many critical aspects of a battery operation. Some batteries show a significant resistance increase, which turns out in power loss. [17] To tackle this problem, other definitions of SoH exist.

$$SoH_E = \frac{Actual\ deliverable\ energy}{Fresh\ cell\ deliverable\ energy}\ [\%]$$

$$SoH_P = \frac{Actual\ power\ capability}{Fresh\ cell\ power\ capability}\ [\%]$$

The same type of formula can be applied to the battery capacity, to determine the overall SoH of the pack. In this case, the result is influenced by the individual capacity of the cells. Indeed, a higher battery's SoH describes the fact the cells have similar residual capacity within the same module or pack, while lower values are caused by differences in their capacity. Depending on this condition, the state of the battery is determined to be homogeneous or heterogeneous.

There are two main factors influencing the phenomenon of the heterogeneous distribution of cell capacity within the pack. First of all, slightly different production parameters such as the fluctuation in the electrode film coating quality or the electrolyte filling leads to unavoidable difference in the cell performances. Moreover, the interconnection of the cells to form modules or packs implies that the individual cells are exposed to different contact resistances and are loaded differently accordingly. Different capacitances, self-discharge rates and internal resistances lead to a variation in cell performance. In addition to the factors just mentioned, there are other influencing variables such as extreme temperature effects. A typical case study is a non-homogeneously cooled battery pack. This causes the cells that are warmer on average to age more than the others. [18]

2.3.3. BMS data exploitation for second life diagnostics

The data which an automotive BMS typically collects are quite simple and are summarized in three main acquired values [19]:

- Operating temperature of the battery.
- Operating voltage of the battery cell groups.
- Current flow of the battery cells or cell groups.

These online acquisitions are used by the BMS software to estimate the battery SoC and SoH during battery first life and they are extremely valuable for a second life-oriented diagnostic.

On one hand, the time dependent acquisitions can be exploited to estimate the trend and slope of the ageing of the battery. This can unlock some first considerations about the remaining useful life of the battery under analysis.

Knowing the operating conditions of the battery in terms of temperatures and current flow rates, it is possible to estimate the electrochemical degradations phenomena occurred during its life. This is crucial for the concept of End-of-life decision, determining whether cores or components can be reused or must be recycled. It enables a pre-sorting of the optimal second-life application of the battery under analysis. [9]

However, determining the SoH still raises some issues to be addressed. The technical parameters required to determine the level of state of health are obtained with specific testing devices that usually require the battery to be present at a workshop, which may be time consuming. Current SoH determination procedures are complex and still have limitations regarding their confidence level. Additionally, the SoH does not allow for exact conclusions about the battery's true health and without further details, a profound analysis of the battery life expectancy is not possible. [20]

2.4. Current market scenario

To meet the expected volumes of the battery demand for the next years, driven especially by electrification in transportation sector, supply and production capacities need to increase along all steps of the value chain, considering both the linear and the reverse flows. This is a tremendous opportunity in terms of annual revenues, cumulative investment and job opportunities, but it also brings great challenges.

Moving from a linear to a circular value chain can improve both the environmental and the economic footprint of batteries by getting more out of them while in use, and by harvesting end-of-life value from batteries. [5]

The lithium battery value chain is analysed deepening the linear and reverse flows.

2.4.1. Lithium-ion batteries circular value chain

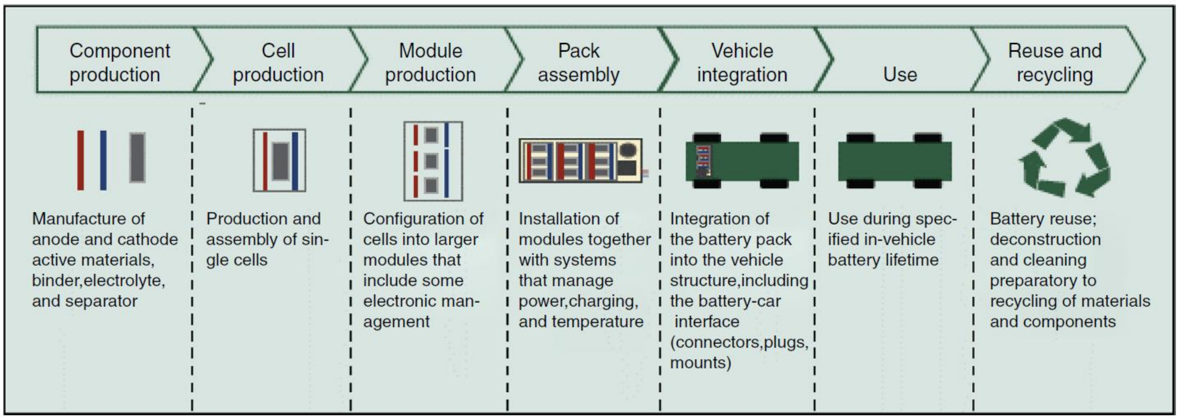


Figure 2.11: Lithium-ion batteries circular value chain

The first step describing the linear value chain is the extraction of minerals and raw materials used in lithium-ion batteries along with the processing of these materials, to be used in the production of various cellular components including anode, cathode, electrolyte and separator. [21]

Cells production is composed of three main steps. The first phase is dedicated to the production of the electrode components. Anodic and cathodic active materials are mixed with a conductive binder and coated on metallic foils which act as current collectors to transfer current in and out the cell. The coated foil undergoes a calendaring phase to control the electrodes thickness; a slitting phase to obtain foils with compliant width; and a drying phase, typically via oven heating. [13]

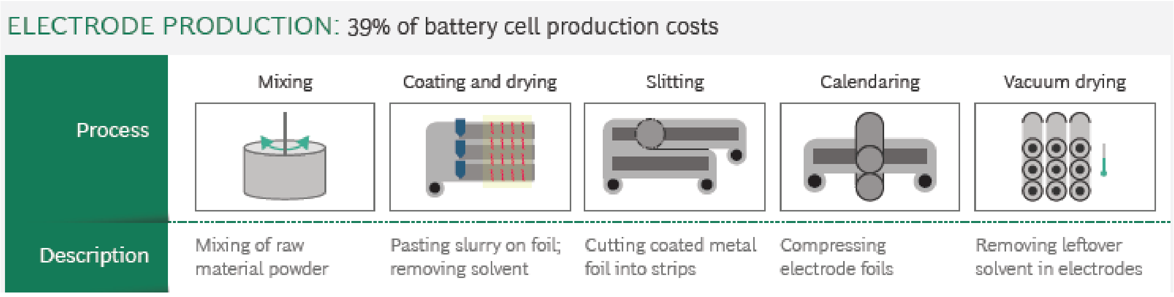


Figure 2.12: Cell production - electrode production

The cell assembly includes the foils folding inside the case properly separated via a polymeric separator. The connection between current collectors, terminals and eventually the safety-and-control electronic board; the enclosure of the case filled by the electrolyte.

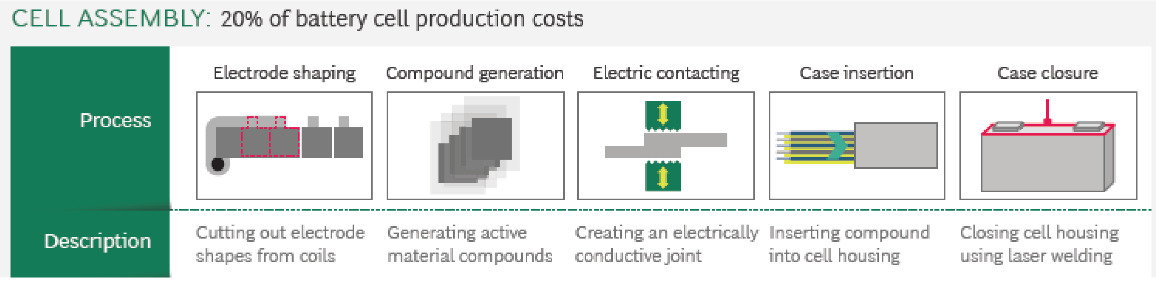


Figure 2.13: Cell production - cell assembly

Further testing steps finalize the manufacturing process. A specific formation process, namely, to charge the battery beginning with low voltage and gradually increasing, is the first mandatory electric cycle of the battery. The formation process is the main manufacturing defects identification stage.

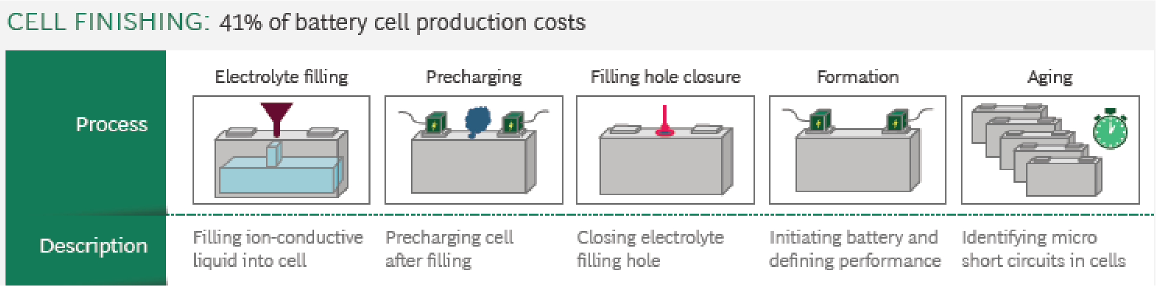


Figure 2.14: Cell production - cell finishing

The next stage of the process is battery-pack manufacturing, where cells are assembled in modules and then in pack, which represent the final element of the production chain of a battery. [22]

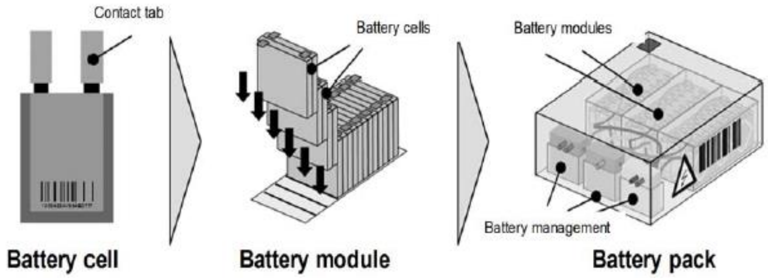


Figure 2.15: From battery cells to a battery pack

Finally, battery packs are integrated in the vehicles power train to be used for the first life application.

Figure 2.16: From a battery pack to an electric vehicle

Different elements of the value chain can be covered by the same companies, which decide to expand their research or production activities on different market segments. For example, some cell manufacturers also produce cellular components especially for cathode, while other players in the recycling industry are also active in the material processing sector.

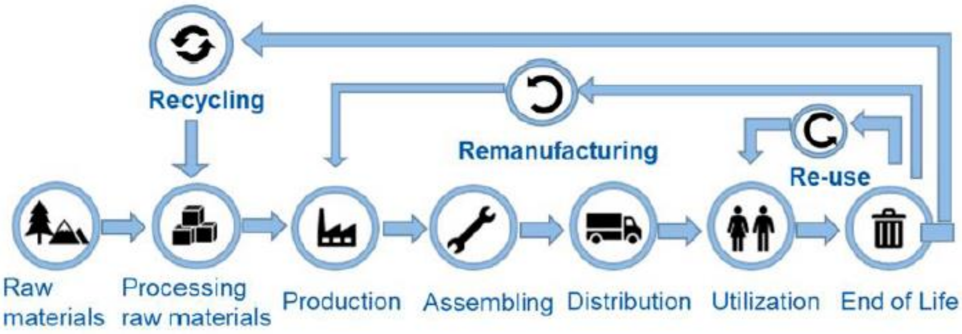


Figure 2.17: Lithium-ion batteries circular strategies

After the utilization phase, so at the end of the in-vehicle battery lifetime, batteries embark the return flow, which may include different steps. Generally, batteries need to be removed from the vehicle, collected and safely transported to suitable stakeholders able to treat them.

Because retired EV batteries contain a substantial electrical charge capacity, secondary utilization is a promising solution to reuse the remaining capacity and extract additional value from retired EV batteries. [23] The output of the return value chain is different depending on the type of second life strategy considered. In any case, the battery becomes the input of this new value chain, which is no more linear but circular since it brings to closing the loop.

2.4.2. EV Li-ion batteries end-of-life strategies

Processes that take advantage of the residual value of end-of-life batteries are summarized in a collective term, called circular economy strategies. Second use, remanufacturing and recycling all fall within this umbrella term.

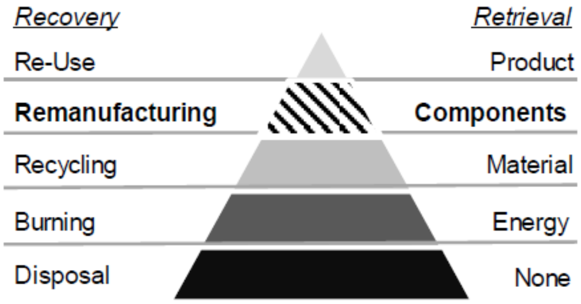


Figure 2.18: EV Li-ion batteries end-of-life strategies

The pyramid in Figure 2.18 shows the possible end-of-life strategies for EV Li-ion batteries and the element retrieved from that.

In particular, with the reuse a complete product is transferred to a similar application or used in a different function, while remanufacturing focuses on the retrieval of individual components of an end of-life product, and with the recycling raw material is retrieved. [22]

Post-vehicle-application Lithium-ion batteries have an economic value that can be reclaimed in one of the following ways [24] :

- Remanufacturing for reuse in vehicles;
- Remanufacturing for stationary storage application;
- Repurposing (reuse) for an off-road, stationary storage application;

- Recycling, disassembling each cell in the battery and safely extracting the precious metals, chemicals and other by products.

Repurposing represents the process with which the complete product, the end-of-life battery, is removed from an electric vehicle and re-used but for a different application, a stationary storage application. This option can be embarked when some requirements are respected. The residual value of used automobile batteries must be still significantly high, and the state of health needs to be defined as homogeneous, so no components have to be replaced.

Remanufacturing is an industrial process to transfer a used and worn component in a quasi-new condition or to an improved functional condition increases the resource efficiency.

Remanufacturing process focuses on comprehensive battery testing, disassembly of post-vehicle-application batteries as well as the reassembly of remanufacturing batteries. [24]

A prolongation of lifetime is enabled by modular designed battery packs, which allow a replacement of defective or outdated battery modules and cells. [22]

Once remanufactured, the pack can either return as a spare battery in the automotive sector or be commercialized in another sector as a stationary storage system. Typically, the after-sales-market offers a high potential for remanufacturing solutions. [25] Considering the fast developing technology of LIBs, the industry faces new challenges for the after series supply of suitable battery packs. Suitable remanufacturing solutions can help to establish a working spare part supply of LIBs. [22]

The remanufacturing scenario is probably the most interesting from the industrial point of view, because it is the path that captures and enhances most of the embedded value of end-of-life battery packs. However, it is also the most challenging. The efficient reorganization of units is a labour-intensive process driven by a deep knowledge of the products to estimate the best re-assembly configuration to satisfy the customer needs.

For its inner complexity, the lack of operating standards and the poor design for remanufacturing of automotive LIBs, remanufacturing is nowadays not an established practice at the industrial level.

Recycling is the most conservative end-of-life route for LIBs is recycling, namely a sequence of mechanical, thermal and / or chemical processes to recover the valuable materials embedded in the battery. Despite it is the less added value end of life perspective, recycling is unavoidable for the most compromised LIB cells and sooner or later mandatory for all LIBs.

Moreover, recycling plays an important role in the overall sustainability of future batteries and is affected by battery attributes including environmental hazards and the value of their constituent resources.[8]

LIBs contain several valuable materials. Among others, cobalt is the most valuable in e-mobility LIBs, especially in NMC LIBs used by most car brands. [26]

In particular, Cobalt is in greater demand than other metals because of its low relative abundance and high price. [8] Moreover, Cobalt production is concentrated in the Democratic Republic of Congo, which makes it unpredictable and highly susceptible to political risks. [27] This is the reason why it represents the main driver of most of the current industrially implemented recycling technologies, that do not valorise most of the other materials available or do not recover them as it happens for lithium in the pyrometallurgical processes.

An in-depth description of the activities constituting the main processes of remanufacturing and recycling has been performed in the following section.

2.4.3. Remanufacturing to enable e-mobility LIBs second life

Once the used battery packs are collected, their SoH is evaluated and in case it is good enough for starting a remanufacturing process, the following activities are performed:

- disassembling of the battery pack into modules or single cells level;
- testing the state of health of each unit;
- replacing the most compromised units to partially restore the performance of the pack.

It is also possible to store the disassembled units in a buffer in order to enable re-assembly of packs with atoms from different original EVs.

The disassembly process can be divided into two almost discrete and separated sub-processes:

- the disassembly from pack to module level;
- the disassembly from module to cell level.

The battery disassembly up to module level is quite the same for all the commercial models of automotive batteries. The main phases of the process are summarized here below.

- Covers removal
- Coolant removal
- Service plug removal
- Junction block removal
- (BMS removal)
- Modules removal

Covers removal: main covers of the pack are removed. Since they physically protect the pack components, they have to be removed at the beginning of every disassembly process.

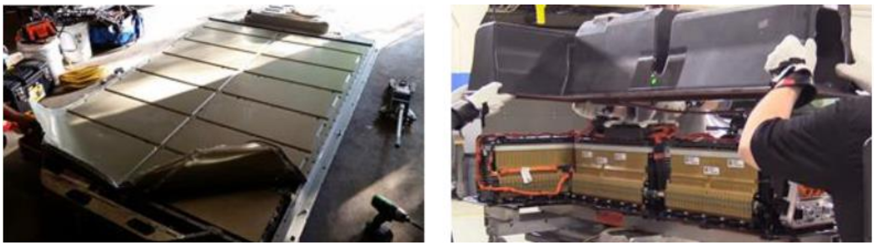


Figure 2.19: Covers removal from a battery pack

Coolant removal: if available, the cooling liquid has to be removed from the cooling pipes before continuing with any other disassembly operation.

Figure 2.20: Cooling liquid removal from a battery pack

Service plug removal: in every automotive battery pack there is a service plug or fuse which, if removed, cuts in two the modules series string, splitting in half the overall voltage. This operation is very useful to reduce the electric shock risk.

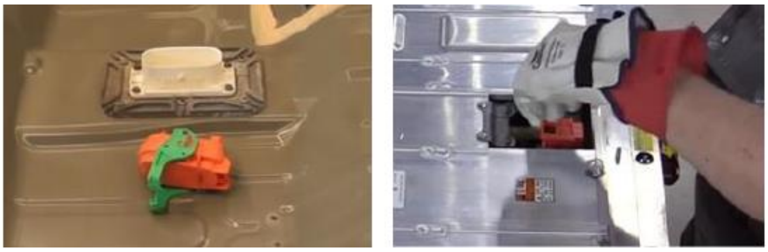


Figure 2.21: Service plug removal from a battery pack

Junction block removal: different modules use to be connected together by junction blocks, which are accessible at this stage of the disassembly process.

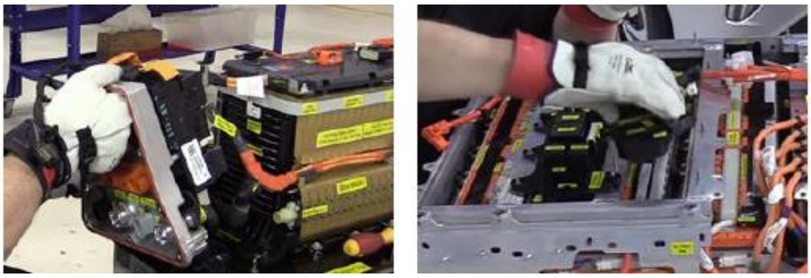


Figure 2.22: Junction block removal from a battery pack

Depending on the overall electronic architecture of the BMS of the battery, there might be the availability of a mother board (PCB) on top of the battery pack, which can be at this step disassembled.

Figure 2.23: BMS removal from a battery pack

Modules removal: at this point, single modules can be released from the battery pack case.

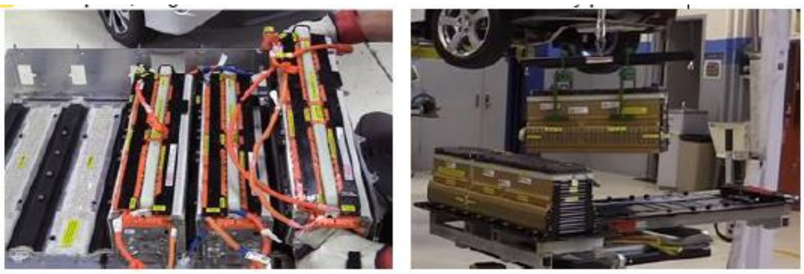


Figure 2.24: Modules removal from a battery pack

While for the pack disassembly into modules the process is somehow the same for every battery, for what concerns the disassembly from module to cell level, the differences between cell types, connection types, and module architecture don’t allow to generalize the description of this process.

However, among the cell types, the prismatic ones are the most suitable for the remanufacturing process with a disassembly up to the cell level. Compared to cylindric cells, the prismatic ones are bigger so inherently more valuable to be recovered, while compared to pouch cells, prismatic are less delicate and so it is easier to handle them with current technology. [9]

Since the second life battery reassembly process is expected to be like the first life battery assembly, the disassembly has to free the cells from all welds and glues to ensure that the cells could be reintroduced in an assembly process for first-life battery production.

After battery modules or cells are liberated from their housing, they need to be tested to decide whether to reuse or recycle them, based on abnormalities in their degradation. For this testing phase, standards and procedures need to be followed.

Once the scrap units are discarded, two cell reassembly processes have to be performed in series:

- Mechanical assembly;
- Laser welding.

Non-reversible mechanical joints can represent an issue during the reassembly phase.

For example, it is quite common that battery cells are glued together to increase the module stability. For this reason, after testing, the cells should be cleaned from old glue and then glued again.

In the mechanical assembly, it is reused the first life external case and the prismatic cells are joined with mechanical joints as screws, rivets, nut and bolt.

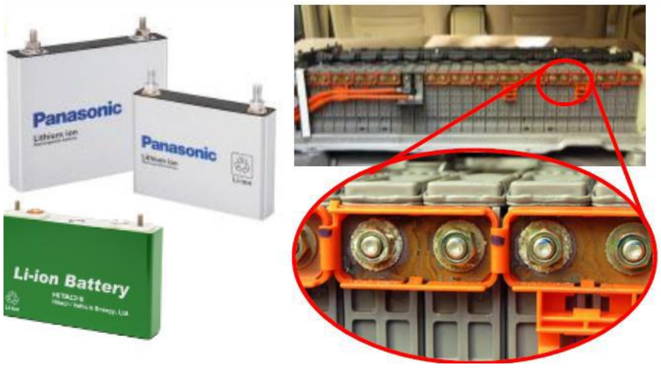


Figure 2.25: Mechanical assembly - prismatic cell nut and bolt configuration

Laser welding is then used for prismatic cells to busbar connection. It uses a focused laser beam as a point source of energy to create localised heating to join parts together. Laser welding has the ability to spot in an extremely localised and small surface area the energy beam, resulting in a low but effective heat exchange and dissipation within the product. To reassemble battery cells with welding technologies, a very precise and accurate process is needed. This can be manually, but of course this choice is very time consuming, or automatically, but the dimensions and peculiarities of welding spots as well welding technologies demand for very sophisticated ad hoc automatic stations.

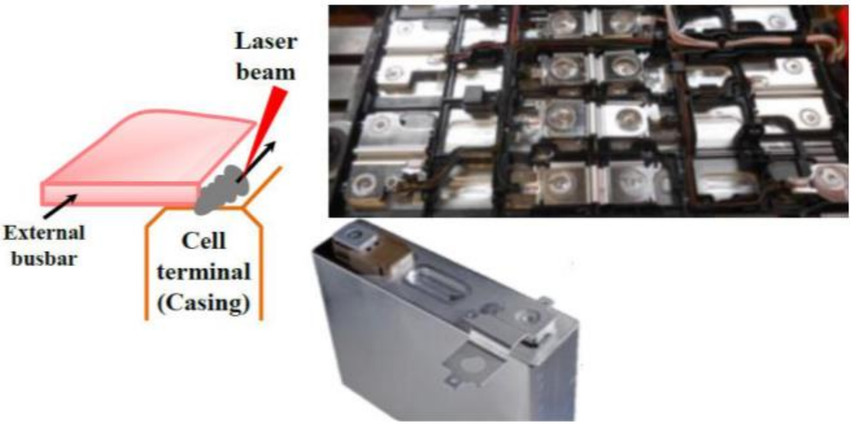


Figure 2.26: Laser welding for prismatic cell-to-bus bar connections

Finally, modules to pack reassembly is performed. In this case the activities are easier since is quite common to find reversible mechanical joints, as bolts/nuts, as well as reversible electrical joints, as plugs, keeping together the product.

2.4.4. Recycling to recover e-mobility LIBs metal

Recycling can be considered as a separate market from repurposing and remanufacturing. Recycling is a kind of commodity, since sooner or later it is necessary to close Lithium-ion batteries lifecycle. It is interesting analysing the processes related to the following recycling alternatives: Pyrometallurgical, Hydrometallurgical, and Direct recycling.

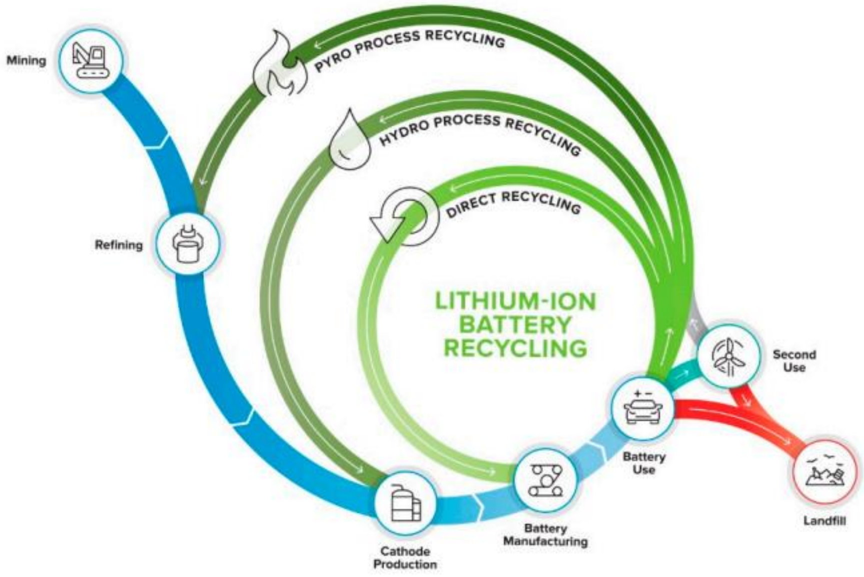


Figure 2.27: Lithium-ion batteries lifecycle

All the industrially appliable LIBs recycling processes are characterized by multiple steps, each one with a specific purpose. The main phases can be schematized according to Figure 2.28. [26]

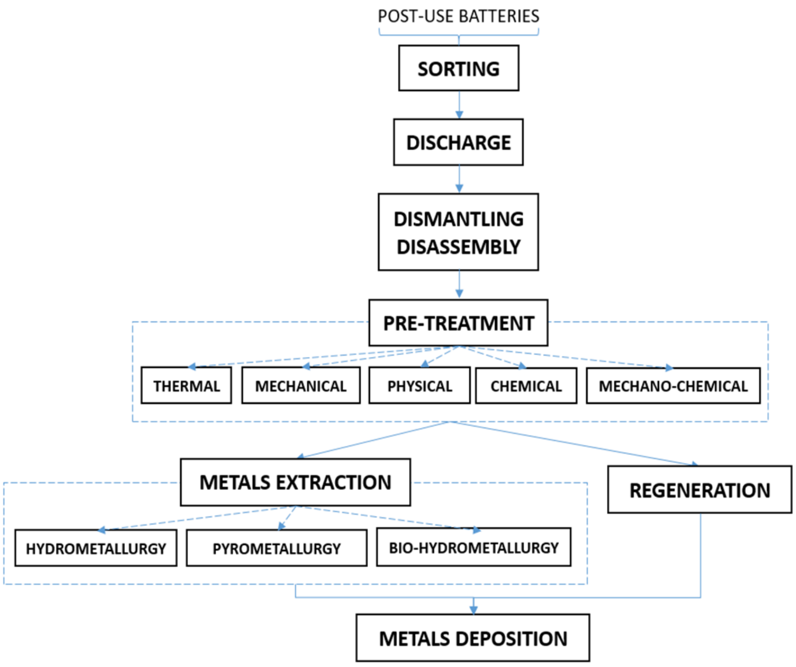


Figure 2.28: Typical LIBs recycling process. [26]

Sorting: LIBs need to be isolated from other energy storage devices, in order to not contaminate the recycling processes. Moreover, some selective recycling routes are optimized for specific LIB chemistries, for example the ones rich of Co.

Discharge: spent batteries discharging is necessary before undergoing any further process since residual charge of LIBs may lead to short circuit driven overheating and burn of batteries inside the recycling equipment.

Disassembly: complex modular batteries, as e-mobility ones, combine LIB cells with other components (cases, cables, printed circuit boards, cooling systems). Those components must be removed from the proper batteries through disassembly, otherwise they would compromise the overall recycling efficiency.

Pre-treatment: the different materials constituting LIBs have to be released and, when possible, mechanically separated, to facilitate downstream dedicated recycling processes.

Recycling (metals extraction and deposition): Thermal or chemical processes isolate and purify the target materials, obtaining secondary raw materials which can be introduced in new manufacturing processes.

Regeneration: as an alternative to conventional recycling, anode and cathode material are regenerated and reintroduced in new batteries without returning to precursor materials.

The following description of pre-treatment and recycling processes aims at highlighting their potential in terms of output, materials recovered and technological readiness.

2.4.4.1. Pre-treatment

Commercial battery systems are complex assemblies of multi-material and multi-layer products, in which each constituent material is strongly interconnected with other elements. For this reason, a pre-sorting of target materials is needed to facilitate recycling.

Moreover, most valuable constituents, such as the “black-mass” powder embedding the Co rich cathode, are enclosed into cell cases. Such materials must be released before recycling, otherwise no thermo-chemical deposition and isolation are possible.

Pre-treatment processes allow the proper selection and isolation of target materials, which impact the overall costs and therefore profitability of LIBs recycling.

In particular, the main objectives of pre-treatment processes are:

- The enrichment of metallic fraction.
- The reduction of scrap volumes and energy consumption.
- The improvement of recovery rate.
- The management of safety issues.

These aims are obtained by exploiting different chemical and physical properties of LIBs components. [26]

Many pre-treatment technologies exist, both at laboratory and industrial scale. The main distinction is between mechanical, chemical, and thermal pre-treatment.

2.4.4.2. Conventional mechanical pre-treatment

The combination of mechanical and physical pre-treatments is the most used technique at the industrial level.

As reported in Figure 2.29, a first crushing step is performed to remove the external steel case by magnetic separation. This is followed by a fine grinding that segregates current collector foils (Cu and Al layers) and organic materials from the active leachable powder. Coarser fractions are then subjected to Eddy Current technologies to separate Al and Cu and to a densiometric table to remove plastics. The fine fractions of valuable metals are then directed to the subsequent hydrometallurgical process. [26]

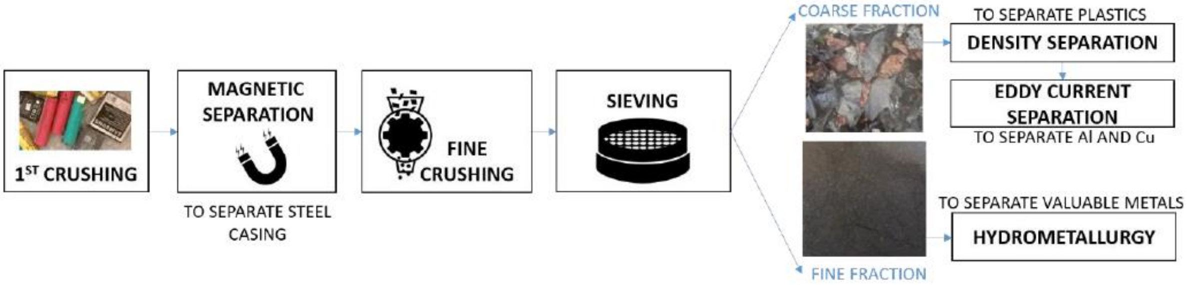


Figure 2.29: Combined mechanical and physical pre-treatments [26]

2.4.4.3. Innovative mechanical pre-treatments

More elaborated and optimized solutions exist at different technology readiness levels. Among them, the most promising are External case removal and High Voltage Fragmentation.

External case removal

Cylindrical and prismatic cells have a metallic external case. The weight of this case can account for more than 20% of the total weight of the cell for cylindrical batteries and 18% for prismatic ones. [26]

If the cell case undergoes the crushing phases together with the rest of the battery, three main issues arise:

- The hard metallic fraction of the external case, which is not the black mass material target, contributes to energy consumption and equipment tool wear, lowering the economic efficiency of the process.
- Part of this metal fraction contaminates the black mass powder. Therefore, less efficient downstream recycling processes can be applied.
- The case itself is a mono-material component that might be destinated to a dedicated recycling stream, instead of being aggregated with other components while undergoing shredding.

If this cutting case process is integrated at the beginning of a pre-treatment stream, the following stages could focus only on the internal components of the battery, with a pre-concentrated availability of target materials.

Figure 2.30: Preliminary case removal (left, prismatic; right, cylindrical)

High Voltage Fragmentation

In recent years High Voltage Fragmentation (HVF) has been applied for the recycling of complex and high added-value products such as LIBs. In particular, this technology shows promising results in the almost complete separation of the black mass from the Al current collector foil in the lower dimensional fraction.

The product is put in a grounded metallic vessel and is covered by a dielectric liquid in order to feel a pulsing fast-rising voltage up to 40 – 200 kV, generated through a couple of electrodes. When reached the dielectric voltage breakdown, a plasma channel is created and the product is crushed by the resulting shockwaves.

Compared to conventional recycling, HVF technology does not need high temperatures or critical chemicals and it is very energy efficient. Nevertheless, the high costs related to the current equipment make HVF process less convenient than a traditional crushing. [26]

2.4.4.4. Thermal pre-treatments

High-temperature treatments principally act on LIBs organic components. Among them, Polyvinylidene Fluoride (PVDF) binder is responsible of the active powder adhesion on current collector foils and it could represent the major challenge for materials separation.

The optimal temperatures range to decompose it, was found at 500-600°C leading to the spitting of Carbon chains into shorter units and allowing the easy material detachment from Al and Cu layers. [26]

Moreover, high temperature thermal treatments improve Li recovery efficiency up to 90% thanks to carbon removal, but requires air-filtering systems and gas scrubbers due to significant toxic gaseous emissions (e.g. dioxins, HF, CO, CO2, etc.).

2.4.4.5. Chemical pre-treatment

Chemical pre-treatments use organic solvent and supercritical fluids (e.g. CO2) to extract the electrolyte or dissolve the binder.

Different substances have been tested to dissolve PVDF binder and it has been proved that organic solvents such as N-methyl pyrrolidone (NMP) or N, Ndimethylformamide (DMF) show a good solubility (200 g/kg) at moderate temperature (≈100°C).

Chemical pre-treatments can not be performed without the combination of another pre-treatment strategy, for example, mechanical pre-treatment for the liberation of active material. For this reason, they are not often used for industrial applications.

2.4.4.6. Recycling

In this paragraph are described the main recycling strategies to purify and recover single secondary raw materials from pre-treated LIBs.

A general scheme to recycle spent LIBs is shown in Figure 2.31 below.

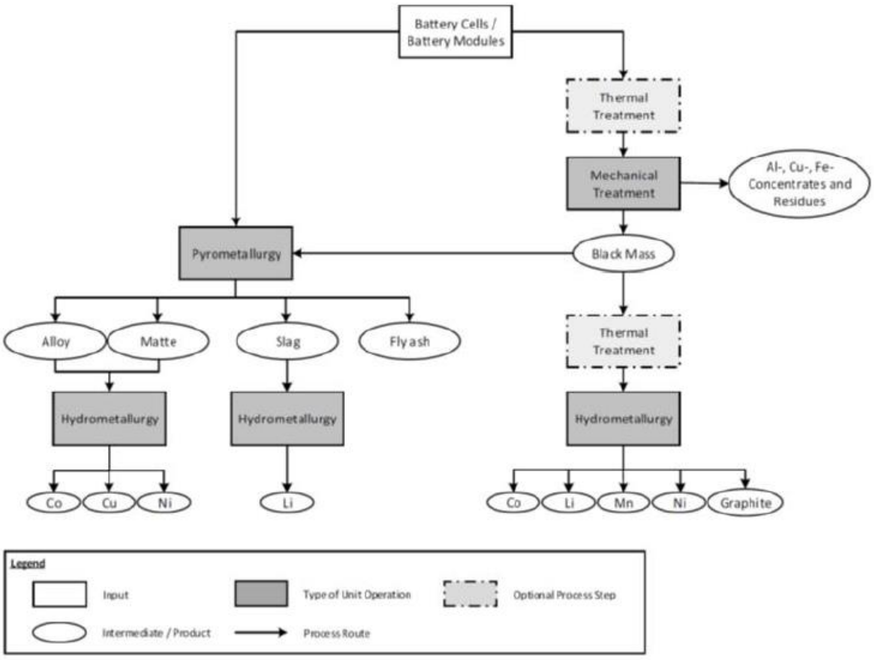


Figure 2.31: General LIBs recycling scheme

2.4.4.7. Pyrometallurgical metal recovery

Pyrometallurgy is a mature recycling technology largely established at an industrial scale. Pyrometallurgical metal recovery uses a high-temperature furnace to reduce the component metal oxides to an alloy of Co, Cu and Ni, which can be furtherly separated through hydrometallurgical treatments.

This technique has some important advantages, such as quick and high productivity of the metal phase and large treatment capacity, since usually designed for large volumes of raw materials. It can be used with whole cells or modules, without the need of prior passivation and mechanical pre-treatment steps.

However, Li, Al, and Mn are normally lost in the slag, and for this reason, this process is suitable for Co and Ni rich batteries.

Moreover, pyrometallurgical processes display environmental drawbacks, such as the production of toxic gases, and high energy costs.

2.4.4.8. Hydrometallurgical metal recovery

Hydrometallurgical processes are the most suitable methods for the recovery of metals, in particular Li and Co, from spent Li-Ion batteries.

Generally, the overall recycling process begins by mechanical treatment, that is shredding LIBs previously submerged in a brine solution to deactivate the cells.

Through a hammer mill, three types of material fractions are produced:

- metal solids;
- metal-enriched liquid;
- plastic fluff.

The metal solids are separated by screening since they contain various amounts of copper, aluminum, and cobalt (depending on the type of Li-Ion battery processed), which can all be used as raw materials in new products.

Instead, the metal-enriched liquid, mainly rich in Li, is subjected to hydrometallurgical process (chemical treatment) that consists of three main steps:

- leaching;
- leaching solution purification;
- precipitation of Co and Li.

The aim of leaching is to solubilize metal oxides present in the cathode active materials in a solution. The leaching of cathode active materials at industrial scale is usually carried out by using inorganic acid such as HCl, H2SO4 and HNO3.

The metals solubilized in the obtained solution are recovered in the purification step consisting of a series of chemical methods such as chemical precipitation, solvent extraction and electrolytic deposition. The presence of aluminum and copper foils has a negative effect on the purification process, especially when solvent extraction is to subsequently be used to remove metals such a nickel and cobalt. Hence, those metals have to be removed first to prevent coextraction for example by electrolysis. Then solvent extraction of nickel can be performed.

After filtration of the leaching solution to remove impurities, precipitation of cobalt is performed, followed by precipitation of lithium.

Hydrometallurgical processes bring some main advantages. A reduced energy consumption thanks to lower temperatures, the recovery of Li in the carbonate form, the leaching of metals to be reused for LIBs new cathodes and a good efficiency on different battery chemistries.

2.4.4.9. Direct recycling

Direct recycling is a novel approach to recover the cathode and anode materials as proper components and reinsert them in the manufacturing loop of new batteries without an actual hydrometallurgical reduction into constituent materials. [28]

There is no specific pre-treatment technology suitable for direct recycling. Nevertheless, at the end of the pre-treatment phase, high purity black mass must be available, with poor contamination of current collector foils and polymeric fraction. For this reason, conventional shredding technologies are not suitable to begin a direct recycling stream, while the innovative mechanical pre-treatment technologies able to detach the black mass from current collectors with poor contamination, as HVF, are more suitable alternatives.

Once the high-grade black mass is obtained, it is necessary to sort the cathodic and the anodic material, to enable dedicated downstream recovery. The froth flotation technology is considered the most suitable option to satisfy this need. Froth flotation is a process for selectively separating of hydrophobic materials from hydrophilic. In a vessel where water is sometimes enriched with chemical reagents, water bubbles lift hydrophobic particles. Being graphite hydrophobic and cathode hydrophilic, they are suitable to be sorted by forth flotation.

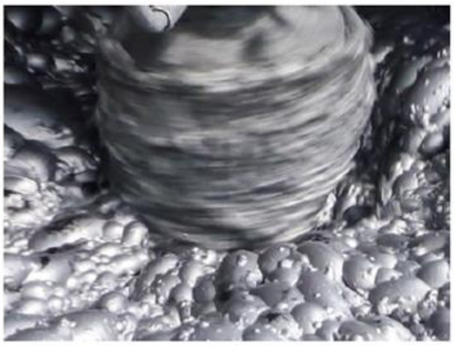


Figure 2.32: Froth flotation at industrial level

Re-Lithiation

Once the electrode powers are sorted into anode and cathode fractions, a re-lithiation process heals the material before its reintroduction into the manufacturing stream.

2.4.5. Barriers for the development of remanufacturing

The future development of remanufacturing process is influenced by some barriers that need to be overcome. They can be summarised as the lack of available information to ease the treatment of EoL batteries, the need of a technological process development of machines and equipment and the absence of shared standards to certify processes and remanufactured products.

2.4.5.1. Information issue

Information on several aspects of batteries is still not provided. This issue is related to different batteries, it can be extended to the electric vehicles' ones, and it refers to both static and dynamic information. [6]

The former one usually includes data about the model and the type of chemistry, which are constant throughout the life of the battery. The lack of this information impacts multiple stakeholders of the value chain. For example, end users of smartphones and laptops are unable to orient their purchase to the batteries that have better performance in the characteristics of interest to them. [29] For recycling companies instead, missing information about the chemistry type makes the sorting activity difficult to perform and the cell classified as not identifiable can be lost for appropriate recycling and sent to dedicated landfills. Finally, knowledge of the cell chemistry is essential in the remanufacturing processes to properly perform the replacement of the cells in the remanufactured battery. [18]

Dynamic information instead, changes along battery's lifecycle and evolves over time depending on the quality, composition and use. This type of information is critical to identify the right second life strategy to treat the end-of-life vehicle and therefore is relevant especially for industrial operators, retailers and recyclers.

The scheme provided by German aerospace center records data divided in master, transaction and status categories. [18]

They are described in the Table 2.2.

Table 2.2: Data category and parameters

Category	Parameter
Master data	- Cell chemistry - Design of the cells - Number of cells per module - Number of modules - Information on the BMS - Information on the thermal management

Transaction data	- Number of cycles to date - Calendar life - Known problems - Holder of extended producer responsibility - Circulation strategies already implemented
Status data	- Residual capacity (SoH) - Internal resistance - State of charge (SoC) - Depth of Discharge (DoD) - Operating temperature

Master data contains general information about the structure of the battery system and is made mainly of static information. Transaction data provide information about the usage history of the battery system while dynamic information is represented by the status data, which record the current state of health of the battery system along the entire life cycle. This last information is a decisive parameter for the selection of a suitable second-life strategy, since it has a direct impact on the remaining service life of the battery system.

Finally, historical information about the recycling strategies that have already been run can save time-consuming tests. If the battery systems have already been reconditioned or used in a second-life application, they may be directly sent for material recycling. If this data structure is not available, the required information must be determined manually using electrical tests, which impact time and costs of the circular economy strategies.

A corresponding system for recording such data is already in use for all battery systems produced in China since 2018. There, each battery system is coded with a unique ID. The coding is then used by all participants along the value chain to update the data in the event of further processing/modification and to upload it to the traceability management platform. This unique coding of the battery systems can also open up further potential in the recycling of battery systems, for example with regard to targeted and automated dismantling. [18]

2.4.5.2. Technology availability

Traditional remanufacturing is characterized by disassembly of a core up to an optimal disassembly level and by the replacement of some parts in order to achieve the specifications and reliability of the original product. For EV batteries, remanufacturing activities can be performed up to module or cell level, depending on the depth of disassembly. In this latter case, reaching a depth of disassembly up to cell level leads to better performances of the remanufactured products if compared to the one subject to remanufacturing activities up to model level. However, increasing the depth of disassembly is problematic to perform technically, because of inconvenient battery design features. Moreover, the development of remanufacturing activities on a large scale is slowed down by technological barriers, related to the testing, disassembly and reassembly steps of the process. Indeed, the process of remanufacturing up to module level should be ideally made by replacement old, out of specifications modules with ones having similar useful life expectancy to the ones staying in the battery pack. Even if life expectancy is often difficult to predict, modules can be individually tested by capacity measurement, internal resistance and self-discharge current. Therefore, it is possible to build battery packs of homogeneous modules, thus optimizing reliability and performance and the value of the used modules. [9] The critical point of this process is that some modules can seem functional after a first analysis but might have some cells with signs of deteriorating fast. Those cells need to be known and a diagnostic method to identify the modules with deteriorated cells is required, because most modules with few degraded cells could still have a high residual value.

The testing procedures at cell level can be very long and require expensive equipment, so that some research is needed in reducing the testing time to achieve a meaningful sorting of the cells. [9] Some feasibility studies have already been implemented, but they need to be validated outside the laboratory conditions. On the other hand, the selective removal of cells is often critical because it may damage the cells contacts, thus impacting the quality of the remanufactured product. *Kampker et alias* addresses widespread cells contacting technology of welding and proposes a method for contacting and separating battery cells and to overcome this problem. Finally, the study highlights the fact that both the assembly and disassembly activities must be capable of automation. Indeed, automatized production technologies can be scaled to industrial relevant quantities and may allow to overcome safety problems related to the handling of used cells. [9] All these factors are nowadays critical for the development of remanufacturing activities up to cell level and some of their aspects must be deeply addressed and solved.

2.4.6. Second-life EV batteries in stationary applications

This part of the chapter is dedicated to an overview of the opportunities related to the reintroduction on the market of second life automotive batteries in stationary applications that have been already implemented. Also, a description of the stationary applications of batteries is provided.

2.4.6.1. Stationary energy storage systems

Stationary energy storage systems can be used in electricity grid integration under two main circumstances: private installations or main grid regulation.

Private installations are usually combined with renewable energy sources, and they can further be segmented according to their application, whether they are used in residential, commercial and industrial energy context. The difference in the needed capacity storage for each segment justify significant diversified dimensions for the systems. The residential storage segment is couple with photovoltaic (PV) power generators, characterized by system smaller than 10 kW and storage capacity that vary between 3 and 15 kWh. Commercial applications refer to energy storage systems with a capacity that varies from 20-30 kWh to 200 kWh, paired with PV systems between 10 and 100 kW but nowadays constitute a niche in the European Market. [30]

The trend of coupling residential storage system with solar panel installations can be applied also to large utility-scale application (industrial). Indeed, due to the intermittent nature of renewable energy source, large storage systems are often used in renewable energy parks, and they serve also as grid regulators. Thanks to their capability of fast response to short-term fluctuations of the grid frequency, storage systems can provide ancillary services to the grid ensuring the balance of electricity supply and demand. When supply exceeds demand, the electric grid frequency increases and vice versa. [31] The capacity and power of these systems can be sized to values greater than *100 MWh* and *100 MW* respectively. In this case, automotive battery packs need to be rearranged in bigger architectures in order to provide major capacity and power.

2.4.6.2. Pilot project for second life EV batteries in stationary applications

Given the increasing interest in second life applications, EV companies have begun to form partnerships with battery manufactures and recycling companies to develop a market around second-life batteries. There has been plenty of research and pilot projects for repurposing used EV batteries into grid-scale stationary energy storage. [27] *Bloomberg business news* provides examples of second-life batteries application developed globally. Lots of them have been realized in Europe.

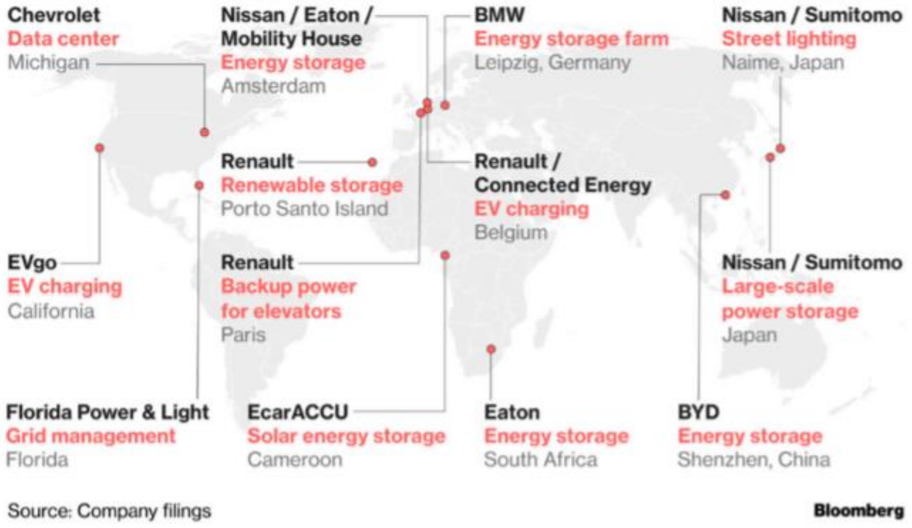


Figure 2.33: Examples of second-life batteries application

The pilots project are deepened in the following section and they are summarized in Table 2.1.

Table 2.3: Pilot projects for second-life batteries applications

OEM	Partner /service provider	Capacity	Application
Renault	*n.a.*	2,5 – 7,5 KWh	Residential storage system
Nissan	Eaton	4,2 KWh	Residential storage system
Nissan	Eaton, The mobility house	4 MWh	Peak shaving, back-up power
Daimler	GETEC, the mobility house, Remondis	13 MWh	Renewable energy
BMW	Vatrenfall & Bosch	2,8 MWh	Renewable energy
Renault	*n.a.*	60 MWh	Renewable energy

Second life e-mobility batteries for residential applications

The direct reuse of post-use automotive batteries as stationary residential energy storage system is the most developed second life application for e-mobility batteries. Two examples of products available on the market are the Powervault 3eco produced by Renault and the Eaton xStorage, derived from Nissan return batteries. Regarding second life batteries, the characteristic which most affects the willingness to buy of these products is the warranty. Residential storage systems made with new LIB cells are marketized with a warranty of 10 years, while the warranty for second life applications batteries is set to cover 3 or 4 years.

Figure 2.34: Two examples of residential storage systems from return batteries

It is important to highlight that European Standards to certify the remanufactured products have not been introduced yet. For this reason, Nissan certifies its products according to the "UL 1974 Standard for Evaluation for Repurposing Batteries" developed in 2018 by the UL standardization company.

Second life e-mobility batteries for utility-scale applications

BMW Bosch and Vattenfall

BMW, Bosch, and Vattenfall formed a joint venture in 2016 to form a large storage facility in Germany producing a total capacity of 2 MW using 2600 retired batteries from more than 100 BMW EVs to stabilize the grid and reduce the impact of peak demand. [32]

BMW, Northvolt and Umicore

BMW is collaborating with Northvolt, Europe's largest EV battery factory and Umicore, a mineral processing and battery recycling company, to develop battery reuse and recycling systems. They announced to reuse most of the retired EV batteries in the renewable energy storage sector [135].

Daimler

Aiming at demonstrating a "complete sustainable lifecycle" for automotive batteries, Daimler has built in 2015 the world's largest secondary use stationary storage, made from approximately 1,000 used vehicle batteries with a 13 MWh output. [8]The Mobility House and GETEC have been in charge of repurposing the batteries to be used at the site of REMONDIS, a recycling, service and water company in Lünen, Germany. [7] German car manufacturer Daimler also joined its subsidiary, Mercedes-Benz Energy, to launch projects using EV battery packs for stationary energy storage. In total, three energy storage plants made of retired EV battery systems were connected to the grid in Germany. One project turned a retired 330 MW of installed capacity (9.8 MWh of energy capacity) using 1920 battery modules from EV battery packs. [27]

Nissan and Eaton

A significant public demonstration of the ability of repurposed batteries to provide energy storage and grid service has been carried out in the Netherlands, where a 3 MW (nominal power)/2.8 MWh (nominal capacity) energy storage system was installed for the Johan Cruyff Arena (Amsterdam) in 2018.

Renault

Finally, Groupe Renault, the European leader in electric mobility, announced in 2018 the launch of Advanced Battery Storage, a stationary storage system for energy developed exclusively from EV batteries. Developed in early 2019 on three sites in France and Germany, this stationary storage system uses EV batteries compiled in containers and its capacity will be gradually expanded over time to reach 60 MWh, equivalent to 2,000 EV batteries. The purpose of this system is to manage the difference between electricity consumption and production at a given time, in order to increase the proportion of renewable sources in the energy mix. [33]

2.5. European policy framework

Finally, an analysis of the current and under development regulation is provided, aiming at identifying the future mandatory requirements and obligations related to the EoL batteries.

2.5.1. Proposal for a regulation of the European Parliament and the Council concerning batteries and waste batteries

The *Proposal for a regulation of the European Parliament and of the Council concerning batteries and waste batteries* is designed to modernise the EU's regulatory framework for batteries and to replace the *Directive 2006/66/EC on batteries and accumulators* (Batteries Directive). [6]

It is part of the *European Green Deal* and related initiatives, including the new circular economy action plan and the new industrial strategy, which identify batteries among resource-intensive sectors with high potential for circularity to be addressed as a matter of priority.

The *Proposal* has three interlinked objectives:

- strengthening the functioning of the internal market, by ensuring a level playing field through a common set of rules
- promoting circular economy
- reducing environmental and social impacts throughout all stages of the battery lifecycle

Batteries are classified according to three categories, diversified mainly because of variations in chemical composition, construction, and size:

- portable batteries, used in laptops or smartphones
- automotive batteries, excluding traction batteries for electric cars
- industrial batteries, for energy storage or for mobilising electric vehicles or bikes. EV batteries belong to this last category.

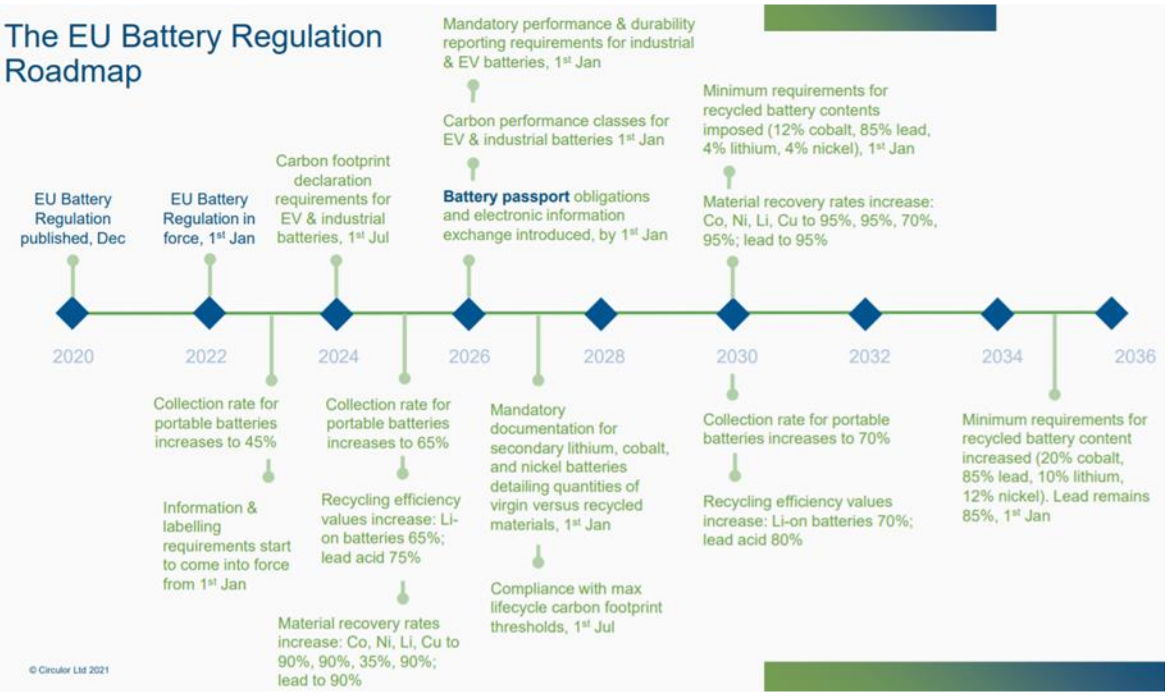
The previous defined Batteries Directive already aimed at minimising the negative impact of batteries and waste batteries on the environment, while ensuring the smooth functioning of the internal market. It laid down rules to limit the amount of hazardous substances and improve the environmental performance of batteries and activities of actors involved in their lifecycle, such as producers, distributors, end-users and recyclers. It also required Member states to ensure appropriate collection scheme. Indeed, under the extended producer responsibility principle, producers of batteries and producers of other products that incorporate a battery became responsible for the waste management of batteries that they placed on the market, in particular the financing of collection and recycling schemes. Finally, it set out requirements for the labelling of batteries and their removability from equipment.

Overall, the proposed regulation concerning batteries and waste batteries replace the Batteries Directive, by establishing requirements for sustainability, safety and labelling to allow the placing on the market and putting into service of batteries, as well as requirements for their end-of-life management.

Concerning industrial and EV batteries, the main innovations envisaged by the Commission proposal include:

- The introduction, in the battery classification, of a dedicated category of electric vehicle batteries, alongside the existing portable, automotive and industrial battery classes
- Progressive requirements to minimise the carbon footprint of EV batteries and rechargeable industrial batteries
- Supply chain due diligence obligations for economic operators that place rechargeable industrial batteries and EV batteries on the market with mandatory third-party verification through notified bodies;

- Mandatory minimum levels of recycled content for EV batteries and automotive batteries containing cobalt, lead, lithium or nickel in active materials, set for 2030 and 2035
- Mandatory recycling efficiencies for lithium-based batteries: 65 % by 2025, 70 % by 2030.
- Mandatory material recovery targets
    - 2025: 90 % for cobalt, copper, lead and nickel, and 35 % for lithium
    - 2030: 95 % for cobalt, copper, lead and nickel, and 70 % for lithium.
- Labelling and information requirements, leveraging on data available and stored on the battery management system:
    - Provision of basic information, technical parameters, end-of-life information and general compliance with EU legislation (as labels, technical documentation or online) through label or QR (quick response) code
    - Provision of specific information to end-users and economic operators (end-of-life, refurbishment and repurposing, energy efficiency) through label or QR (quick response) code
    - Realisation of an electronic information exchange for batteries and a battery passport for each industrial and EV battery placed on the market from 2026
- Electrochemical performance and durability requirements for portable batteries of general use (applying from 1 January 2027), as well as for rechargeable industrial batteries (from 1 January 2026).
- Safety requirements for stationary battery energy storage systems;
- Requirements relating to the operations of repurposing and remanufacturing for a second life of industrial and EV batteries


The EU Battery Regulation Roadmap

EU Battery Regulation published, Dec

EU Battery Regulation in force, 1st Jan

Carbon footprint declaration requirements for EV & industrial batteries, 1st Jul

Mandatory performance & durability reporting requirements for industrial & EV batteries, 1st Jan

Carbon performance classes for EV & industrial batteries 1st Jan

Battery passport obligations and electronic information exchange introduced, by 1st Jan

Minimum requirements for recycled battery contents imposed (12% cobalt, 85% lead, 4% lithium, 4% nickel), 1st Jan

Material recovery rates increase: Co, Ni, Li, Cu to 95%, 95%, 70%, 95%; lead to 95%

Collection rate for portable batteries increases to 45%

Information & labelling requirements start to come into force from 1st Jan

Collection rate for portable batteries increases to 65%

Recycling efficiency values increase: Li-on batteries 65%; lead acid 75%

Material recovery rates increase: Co, Ni, Li, Cu to 90%, 90%, 35%, 90%; lead to 90%

Mandatory documentation for secondary lithium, cobalt, and nickel batteries detailing quantities of virgin versus recycled materials, 1st Jan

Compliance with max lifecycle carbon footprint thresholds, 1st Jul

Collection rate for portable batteries increases to 70%

Recycling efficiency values increase: Li-on batteries 70%; lead acid 80%

Minimum requirements for recycled battery content increased (20% cobalt, 85% lead, 10% lithium, 12% nickel). Lead remains 85%, 1st Jan

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Figure 2.35: The EU Battery Regulation Roadmap

All these innovations have been deepened in the Proposal, with the development of 13 measures and relative sub-measures to properly address them.

Finally, the last three listed measures have led to the definition of a so-called *Standardization request to the European standardisation organisations (ESOs) as regards performance, safety and sustainability requirements for batteries*. Standardization requests are emanated from the European Commission (EC) in order to ask for specific actions from the ESOs to support and complement European policy objectives. [34]

2.5.2. Standardization Request

The European standardization organizations are represented by CEN and CENELEC, officially recognized by the European Union as being responsible for developing and defining voluntary standards at European level. More in detail, CEN is the European Committee for Standardization and brings together the National Standardization Bodies of 34 European countries. It supports standardization activities in relation to a wide range of fields and provides a platform for the development of European Standards and other technical documents in relation to various kinds of products, materials, services and processes. On the other hand, CENELEC is the European Committee for Electrotechnical Standardization, and prepares voluntary standards in the electrotechnical field, which help facilitate trade between countries, create new markets, cut compliance costs and support the development of a Single European Market. [35]

Drafting new European standards in support of the Proposal for a regulation for batteries and waste batteries has the main policy objective to improve the environmental performance of batteries. The *Standardization request* includes four deliverables, which have been coupled with deadlines.

Standards are developed by a technical committee, which is made of a table of experts of different fields related to the subject under analysis. The CEN has the role of supervising the development of the work performed by the defined technical committee. In particular, it manages to find the trade-off between respecting the timeliness defined by the European Commission and achieving the consensus within the technical committee to approve the new standards. The standard development process is public and the progress of the work is available for consultancy by the interested economic actors. For this reason, setting the deadline at the end of 2025, it is assumable to have some actors already equipped with the required testing procedures to obtain the certification compliant to the new standard for their products' warranty. [34]

Standards are listed in the Table 2.4.

Table 2.4: Standards mentioned by the *Standardization Requests*

Reference information	Deadline for the adoption

1.	European standard(s) on performance and durability aspects of portable rechargeable and non-rechargeable batteries	07 December 2025
2.	European standard(s) on performance and durability aspects of rechargeable batteries with internal energy storage	07 December 2025
3.	European standard(s) on the re-use and repurposing of rechargeable batteries with internal energy storage: • Design • Diagnostic and determination of the SoH • Battery evaluation for repairing and repurposing	07 December 2025
4.	European standard(s) on the safety aspects o stationary battery energy storage systems with internal energy storage	07 December 2025

First of all, the proposal for a regulation on batteries and waste batteries requires that general-purpose non-rechargeable and rechargeable industrial and electric vehicle batteries placed in the Union market are durable and high performing. For this reason, European standards on capacity, minimum average duration, delayed discharged performance and leakage testing for the general-purpose non rechargeable batteries are required. Also, capacity fade, internal resistance increase, energy round-trip efficiency and expected lifetime for the rechargeable ones have to be defined to verify the performance and durability requirements of batteries.

The third deliverable aims at facilitating the reuse and repurposing of rechargeable industrial and electric vehicle batteries. According to it, the standard shall include informative guidance on design and assembly techniques, so that they do not prevent the remanufacturing activities applied on battery cells and modules. It shall explain how disassembly operations should be performed, including targeting certain components, and provide guidelines to use standardised tools to facilitate such disassembly. Also, the standard shall describe the procedure for the determination of the SoH of batteries, which may be used for the certification of batteries at the end of their first life with a view to providing a reliable estimate of their remaining capacity and expected behaviour. Such diagnostic is likely to require access to certain data on battery usage and history, which is normally stored in the Battery Management System (BMS). The test procedure shall evaluate the parameters that are specifically related to performance in the intended second life application. Also, the substitution of failing components of a battery performed during remanufacturing operations requires a detailed assessment of individual battery modules and cells. The standard shall describe the necessary steps, conditions and protocols for the safe repair, re-use and repurpose of batteries and battery packs, modules and cells originally designed for electro-mobility applications.

Finally, the last deliverable describes necessary steps and conditions to test stationary battery energy storage systems related to the safety parameters included in the proposal, in order to ensure that these batteries are safe during their operations.

3 Methodology

3.1. Introduction

The primary goal of the study is providing economical actors a useful tool able to properly describe the overall circular economy value chain and support the decision-making process. Furthermore, the research presents multiple insights and analysis about the business development of EV second life strategies derived by the application of the mentioned tool.

With this purpose, the research develops a model to forecast the EV batteries return volumes considering a time horizon from 2020 until 2040. It describes how these flows are expected to be distributed between diversified second life strategies, based on three main criteria, such as the batteries' state of health, the profitability of the process and second-life applications' demand constraints. To achieve this aim, the study needs to be able to capture multiple factors influencing the development of the entire value chain and to keep track of their progress during the time horizon under analysis. Moreover, a comprehensive description of the value chain needs to be represented, both horizontally and vertically. On the one hand, the steps included in the analysis covers the overall value chain, from the electric vehicles market, until the demand of second-life applications. On the other, business layer representation does not allow to include significant technical factors influencing the system, so that a process layer has been added to describe circular economy strategies. Finally, the study wants to provide the decision makers with quantitative results and data.

The complexity of the value chain represented, the multiple factors to be described, the dynamism of the elements under analysis and the willingness to provide quantitative outputs lead to choose a simulation based on system dynamics and agent-based modeling as the most appropriate mode to represent the system, run the model and collect results. In particular, the software *Anylogic* has been selected as the support tool.

The development of the current study has been structured in two main parts. The first step has been related to the creation of the simulation model itself, which represents the first significant output of the thesis. The second one instead, refers to the collection of all the required data to feed the model and get the desired results. The following section illustrates the adopted methodology and focuses on the theoretical description of simulation, in order to properly explain the drivers that led to choose *Anylogic*.

3.2. Modeling

Modeling is a way used to solve real-world problems as it is not always affordable to experiment with real objects to find the right solutions. In this case, models can be built to represent real systems, following a modeling language. This process assumes abstraction so that the model is always less complex than the original system. Among different models, the present study is developed relying on a simulation one, which is executable and able to describe the trajectory of the system's state changes. Indeed, simulation is the imitation of the operation of a real-world process or system over-time and it is often used to predict their behaviors under certain conditions. Simulation usually follows a set of rules that provides information about how the system evolves from a current to a future state. The rules can take many forms, including differential equations, state charts, process flowcharts, and schedules. The model's outputs are produced and observed as the model runs.

3.2.1. Simulation phases

Building and running a simulation model to get the desired results is achieved following a defined path. The first step relates to the understanding of the real-life environment and system, in order to identify the problem that has to be addressed and the key factors to be represented in the model. This becomes the basis to develop the conceptual model, which maps and describes the real systems through a certain level of abstraction. It includes the definition of variables, constraints, buildings block of the system and the performances to be measured. The last step is building the computational model, that describes the system through encoding and uses computer programs to perform simulations and analysis. Running the computational model fed with the right data allows to perform experiments and derive results and solutions. Depending on the type of system under analysis, the obtained solution may be compared with the real system functioning in order to collect feedbacks.

3.2.2. Simulation modeling

Simulation models may differ the one from the others because of different levels of abstraction, depending on the level of description of the represented system. The more models are abstract, the higher the usage of aggregates and statistics rather than individual objects.

Modern simulation modeling uses three methods and associates them to different abstraction levels: discrete event, agent based, and system dynamics.

This latter assumes very high abstraction, and it is typically used for strategic modeling. Discrete event modeling represents discrete events systems, which update their values only at discrete time point, and supports low-medium abstraction. In the middle are agent-based models, which can vary from very detailed models where agents represent physical objects to the highly abstract models where agents represent competing companies or governments. These simulation models may be sometimes used in overlapping, meaning that different parts of the models are described using different methods.

In particular, agent-based models are often combined with system dynamics or discrete event simulation, because it is the best way to capture the agent's internal dynamics. For this reason, the presented study has been developed integrating some elements of agent-based simulation in a system dynamics model. The choice of Anylogic as software tool lies on the need to combine different types of models and create a multi-method one.

In the following part, entities belonging to the different types of simulation used by *Anylogic* are displayed, focusing on the ones that have been included in the model under analysis.

3.2.3. System dynamics

System dynamics (SD) can be defined as a perspective and set of conceptual tools that enable to understand the structure and dynamics of complex systems. System dynamics is also a rigorous modeling method that enables to build formal computer simulations and use them to design more effective policies and organizations. [36]

Due to its high level of abstraction, SD is able to will suited for strategic modelling and it is built on different elements that allow to create simulation models.

3.2.3.1. Stocks

Stocks are accumulations that characterize the system state and represent sources of disequilibrium of the system. The model works only with aggregates so that stock’s items are indistinguishable, and they are expressed in quantities.

3.2.3.2. Flows

Flows are the rates at which these system states change, and they are measured in quantities in a given time period. Flow may flow out of one stock and flow in another, but they may also come from nowhere. In this case they are denoted by a cloud shape, that usually represents the starting point. Symmetrically, flow may flow out from a stock to "nowhere", expressing the end point of the flow.

The picture shows an incoming flow, a stock and an output flow leaving the system through the cloud.

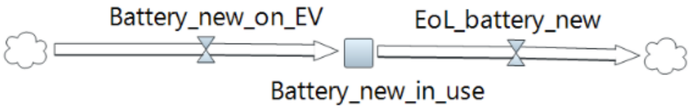


Figure 3.1: Flows and stock

3.2.3.3. Parameters and Dynamic variables

Parameters are static element used to store values that remain fixed during the simulation run. On the contrary, dynamic variables are defined by a formula, so that they change their values according to the elements described in a function or an equation. They are significant for the simulation model because they are able to capture and store changes of the overall system. In Anylogic, parameters are displayed as shows in the right picture, while dynamic variables are represented with a circle.

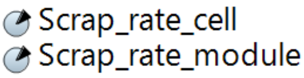


Figure 3.2: Parameters examples

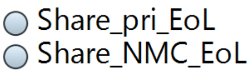


Figure 3.3: Dynamic variables examples

3.2.3.4. Formula

Anylogic generates a stock's formula according to the incoming and outgoing flows and the formulas related to the stocks cannot be changed. On the other hand, the one describing the flows behavior can be defined when building the model. This has been significant to create the tool, because it has allowed to send incoming flows in different directions, depending on a set of variable loaded in the system. An example of formula is shown below. The code returns the value of Share_substitution_reman, which is a dynamic variable of the system, depending on the value of EV_battery_subtitution. As long as this latter equals zero, the dynamic variables is set again equal to zero, otherwise it is the result of the ratio displayed.

Algorithm

```
if (EV_battery_substitution==0){
Share_substitution_reman=0;
} else {
Share_substitution_reman=flow_reman_cell_auto_eff/EV_battery_substitution;
}
return Share_substitution_reman;
```

3.2.3.5. Feedback loops and delay

System dynamics is particularly useful to study causal dependency in the systems. Causal loop diagrams are composed of variables that are interconnected by arrows with defined polarities that can be positive or negative. The arrows represent the causal links (cause-effect relations) between variables, while their polarity displays whether they vary in the same direction.

Moreover, dependency links allow to graphically describe existing relationships between the system stocks, flows, or parameters. Each time an element is mentioned in another ones' formula, a link must be added to the model.

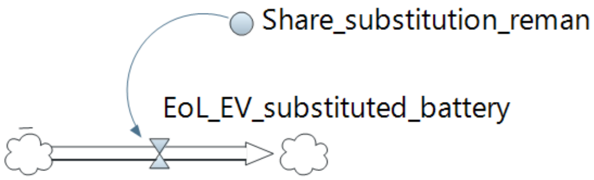


Figure 3.4: Dependency link between dynamic variable and flow

Links are divided in:

- Positive links
- Negative links

If following a sequence of causal links, the variable of origin can be reached as destination, a loop is established. The important loops are emphasized using loop identifiers that display whether it is a reinforcing/positive (R) or balancing/negative (B) feedback.

- Reinforcing loops, determined by an even number of negative links, that result in nurturing a certain behavior.
- Balancing, determined by an uneven number of negative links, that result in halting a behavior.

Another significant feature of system dynamics is the incorporation of time delays, an element required to describe the behavior of the system. Material delays refer to delays to physical flow of materials, which do not leave the stock immediately but wait for the time defined by the associated delay. Time delays are elements whose output laggardly trails the input, hence, inside every delay there is an embedded stock, in which the difference between the output and the input accumulates.

3.2.4. Agent-based simulation

Agent-based simulation is a relatively new method and allows to identify objects (agents) in the model and to define their behaviour. There are many ways to specify an agent’s behavior. Frequently agent has a notion of state and its actions and reactions depend on the state. In the realized tool, agent-based simulation has been used to modify parameters’ characteristics through state charts and to define the flows orientation according to some functions.

3.2.4.1. Statecharts

Statecharts have state and transition, which leads to a state change of a defined parameter. This is particularly useful when some parameters have to be updated during the run, because of changes in the external factors influencing the system.

3.2.4.2. Functions and table functions

Anylogic is able to gives input to the model using functions, that rely on a Java language. In particular, they have been used mainly to include if statement to direct flows. Indeed, based on the values of parameters, dynamic variables, or other flows, the model is able to define where to send a specific flow according to specifications of the function.

Finally, the model has been fed with the necessary data to run the simulation. In Anylogic, this is possible using table functions, which are made of several argument-value pairs. The data collected in the table are called using a function call, that returns a value given a specific argument.

3.3. Data collection

The second output of the thesis has been related to the results gained by running the simulation model. With this purpose, appropriate data has been gathered and then used to feed the model. Moreover, collecting and analyzing data about the profitability of the second life strategies has led to realize a cost-benefit analysis and derive conclusions even before the run of the simulation itself.

The data required belongs to multiple categories and contexts. It refers to expected electric vehicle sales, second-life application demand, technical information about the processes, external factors related to regulations and market development. Moreover, a comprehensive description of the revenues and costs structured has been developed. All these elements have been deepened in the '*Data collection*' part of this document.

Regarding the adopted methodology, the primary source has been the review of academic articles and companies' and organizations' reports. These papers provide information that have been fed in the model or used as starting point to make reasonings and derive the data needed. In parallel, the involvement of experts has been significant to understand the as-is situation and raise awareness about the most critical points and expected evolutions of the external environment. In particular, interviews have been realized with Marco Ottaviani and Nicoletta Picone. The former is an independent consultant on regulatory, environmental and safety aspects applicable to the production, transport and marketing of batteries. As an active member of European and National committees, he supports battery industry (EUROBAT, EPBA, ANIE CEI), and has a specific competence in transport of dangerous goods and wastes management. The latter works for COBAT, a service platform that guarantees an efficient collection, storage and recycling of waste and waste batteries and it offers services to enhance and support the companies' choice to be the protagonists of the circular economy. As R&D expert, she oversees activities focused on the development of innovative technologies, processes, and products as well as the related business model evaluation in order to strategically set the COBAT's roadmap.

Finally, conspicuous data has been collected thanks to the collaboration with CIRC-eV laboratory of the Mechanical Engineering department of Politecnico di Milano. The CIRC-eV is the first European Lab dedicated to the concept of Circular Factory, integrating disassembly, testing, reassembly and material recycling functions in the same facility, to design and demonstrate new sustainable circular economy solutions for the e-mobility sector. It integrates the key enabling technologies to implement these functions, focusing, in its first configuration, on the most critical component for sustainable e-mobility, namely Li-Ion Batteries. It has provided studies and results carried out by researchers and this data has been particularly useful to structure and realize the profitability analysis. Overall, it has supported the thesis development during its overall process and validated the data collection and results monitoring phases.

4 The Model

4.1. Conceptual model

The present chapter aims at describing how the simulation model has been structured and built on the *Anylogic* software. The overall system provides a description of the value chain from the introduction of the new EV battery in the market, until the extraction of the raw materials from the end-of-life batteries. The figure below summarizes the expected life cycle of the battery, highlighting the different paths than can be taken.

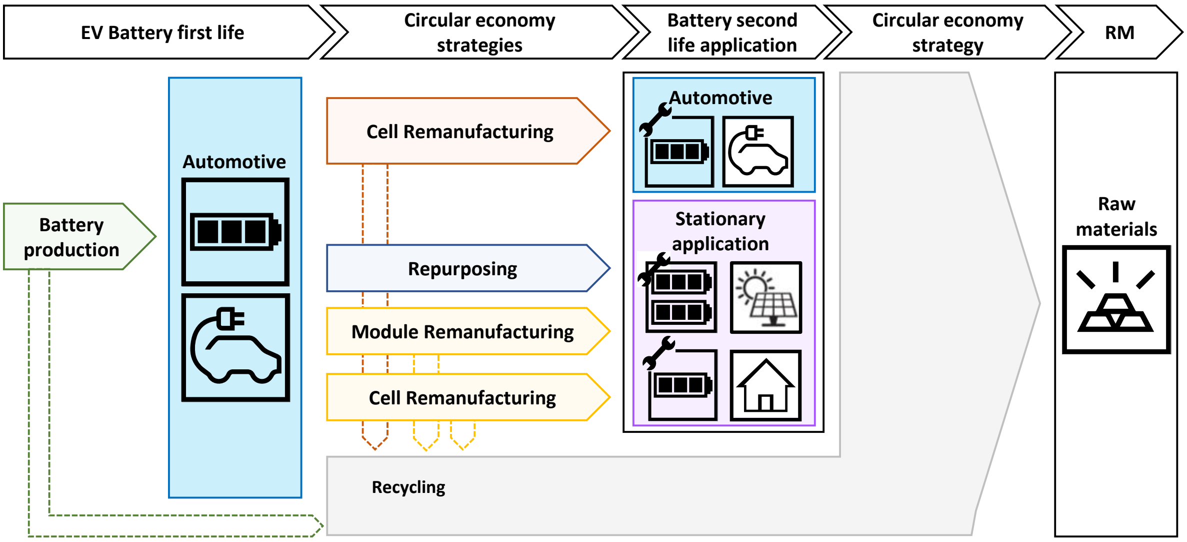


Figure 4.1: Expected battery lifecycle

Once assembled in the electric vehicle, the battery begins its first life cycle. The time related to the usage phase of the battery depends on different factors that are deepened later in the analysis. Once it is retrieved from the vehicle, it can be treated according to four main circular economy strategies:

- Repurposing

- Remanufacturing up to module level
- Remanufacturing up to cell level
- Recycling

Outputs are classified as:

- Battery for automotive application
- Batteries for stationary applications
  - Small storage system for residential applications
  - Large storage system for stationary applications in utility-scale power system, i.e. solar parks.
- Raw materials.

Those output obtained from different strategies.

Table 4.1: Strategies and Output represented in the model

Output	**Strategy**
Battery for automotive application	Remanufacturing up to cell level
Large storage system	Repurposing Remanufacturing up to module level Remanufacturing up to cell level
Small storage system	Remanufacturing up to module level Remanufacturing up to cell level
Raw materials	Recycling

Large storage systems are the only one realized also through repurposing strategies. Indeed, the larger size of the battery allows to manufacture the SS by assembly multiple EV battery pack. On the contrary, small storage system requires modules to be assembled in a different direction if compared to ones in the electric vehicles batteries. For this reason, disassembling at least until reaching the module level is necessary. Finally, batteries to be used as spare parts for automotive need to be remanufactured up to cell level, because the higher performances required for such application necessitates testing and removal of damaged cells.

The following assumption has been defined when building the model.

Table 4.2: Assumptions of the model

Assumption	Reasons
Remanufacturing up to cell level performed on prismatic cells	Prismatic cells are suitable for remanufacturing activities up to cell level because of their larger dimensions and lower number of connections.
Second-life market estimated as the portion of customer willing to buy a second-life application product	The demand of the second-life products is represented by the customers that need a certain product, and are willing to satisfy their needs with one resulted from a second-life strategy.
Batteries obtained by different second life strategies assumed to satisfy different categories of customers	Repurposing, remanufacturing up to module level or remanufacturing up to cell level impacts the final quality of the second life products, thus satisfying needs of diverse customers.
Battery for automotive applications more profitable than batteries for storage systems	Batteries for automotive applications are more performing, justifying higher prices and higher margin.
Batteries for small storage system more profitable than large storage system ones	Being large storage system made by multiple second-life batteries, the product is quite expensive, leading to reduce the unitary price and to obtain lower margin (€/KWh) if compared with small storage system.
Batteries sent to recycling after second life application	All batteries reaching their second life EoL are considered to have a low residual value and thus sent to recycling
Infinite demand for raw materials	Demand for raw materials is considered infinite in order not to limit the flows direct to recycling

4.2. Causal relations

After having described the value chain to be represented in the model, the causal relations connecting the different entities of the system have been deepened. This step has been significant because the model's runs and results rely on the communication between the different parts of the ecosystem. The representation in the figure X highlights how the development of the EV markets boost the production of batteries, that fuels the second life markets after a certain period of time (delay), represented in the diagram by the signed arrow. Both the first and second applications batteries positively impact the development of recycling strategies.

The diagram demonstrates how connection links result in the creation of three causal loops. Two of them are balancing loops (B) and the last one is reinforcing (R).

1. Red balancing loop: it emerges a negative relationship between the production of new batteries and the development of a second-life market for spare parts. Indeed, the higher the batteries recovered from remanufacturing activities, the lower the need of producing new batteries to be devoted as spare parts, assuming a fixed demand of battery substitution.
2. Yellow balancing loop: it emerges a negative relationship between the production of virgin materials and the development of recycling strategies, providing in output recycled materials. Indeed, the higher the amount of materials recovered from the battery, the lower is the need to source virgin material, assuming that the two types of products are comparable.
3. Green reinforcing loop: this last loop wants to highlight the potentiality of closing the loop and building a circular value chain. Starting from the production, batteries may undergo a first and the second life, be processed

through recycling, serving as input to produce recycled materials to be used as raw materials of the battery production.

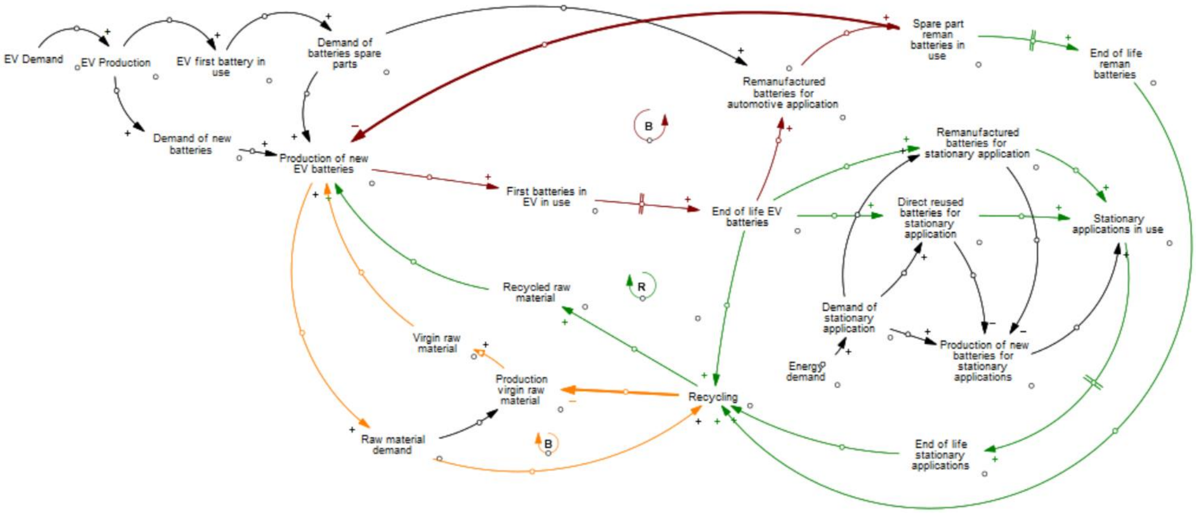


Figure 4.2: Causal relations between entities in the model

This representation aims at highlighting the relations between entities and prove the potentiality of circular economy value chain development.

4.3. Simulation model

4.3.1. Introduction

The computational model in *Anylogic* has been built in order to describe all the steps previously depicted. Moreover, a dedicated part has been realized to represent the steps characterizing the circular economy strategies. This section constitutes the process layer of the model.

The overall model is represented in the figure and is made of seven different macro-parts, connected thanks to multiple dependency links. The overall functioning of the model is achieved thanks to the communication between all its parts.

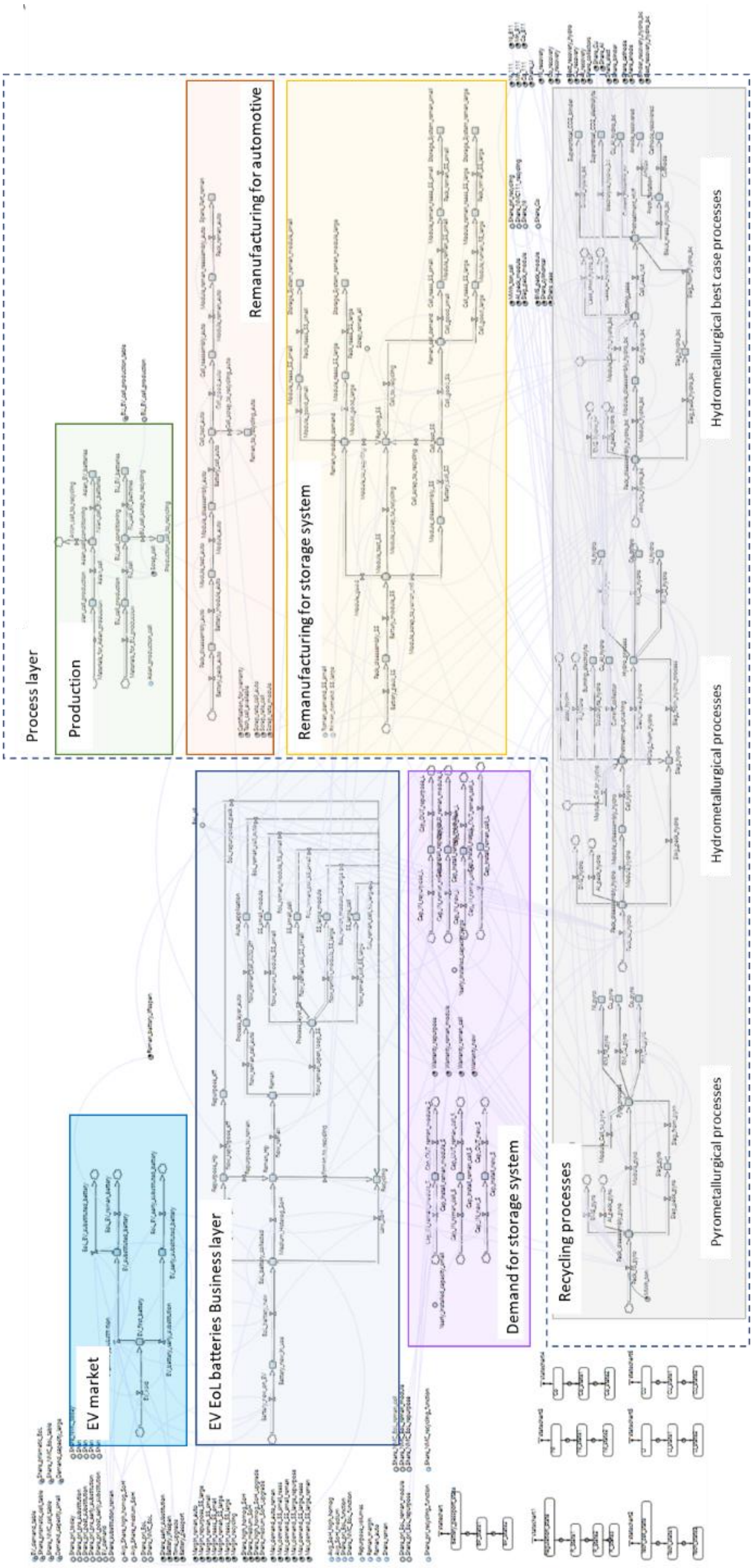


Figure 4.3: The simulation model on Anylogic

The input of the model is mainly related to the electric vehicles annual sales, represented by the EV market block. Then, the business layer is responsible for the main directions taken by the flows based on multiple criteria. The process layer describes the way flows are processed. This part is significant to map all the output steams considered as a scrap for the remanufacturing or manufacturing, that can be treated by recycling. A final part is totally dedicated to this last strategy. In particular, recycling processes are characterized by one or two input flows, and multiple output flows, which are determined by a set of factors. The only strategy not deepened at the process level is repurposing, because it does not imply any disassembly activity, neither the presence of scrap.

Generally speaking, *Anylogic software* allows to achieve a dynamic representation of the system, and to capture development characterizing the environment, the technological progress and changes in batteries features.

The main strength of using a system dynamic simulation is that all these changing mechanisms are described by the model, that provides results on the basis of these dynamisms. A static modelling would not be able to derive such accurate analysis.

All the building blocks describing the model are deepen in this chapter. A last paragraph is dedicated to the variables determining the evolution of the system.

4.3.2. EV market

The electric vehicle market tracks the stock of EV batteries from their introduction in the market until the moment they are removed from the vehicle. Both battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) are considered. Since the average life of a battery is shorter than the one of the vehicles, each car is estimated to be subject to one substitution of the battery during its usage phase. The removal of the battery occurs because of two different reasons:

- The battery is substituted because it has reached the end of life, estimated to occur on average after 8 years;
- The battery is substituted because it is underperforming if compared with new generation of batteries. In this case, the battery is subject to an early substitution, estimated to occur on average after 4 years.

Moreover, considering the first option, it is assumed that a car owner may decide to substitute the end-of-life battery with a remanufactured product, instead of a new one. This impacts the cost of the battery and its expected life duration.

This part is significant because it represents the input of batteries in the model, and allows to compute the return flows. Data is fed in MWh, and it represents the total annual amount of energy provided by batteries inserted in the market, both from BEV and PHEV. A more detailed estimation of volumes is explained in the *Data collection* section. Moreover, tracking the EV that need a battery substitution allows to estimate the potential market for second-life products as the portion of clients willing to buy a remanufactured battery over the total customers that need a spare part. Flows and stocks describing the EV market are depicted in the following figure.

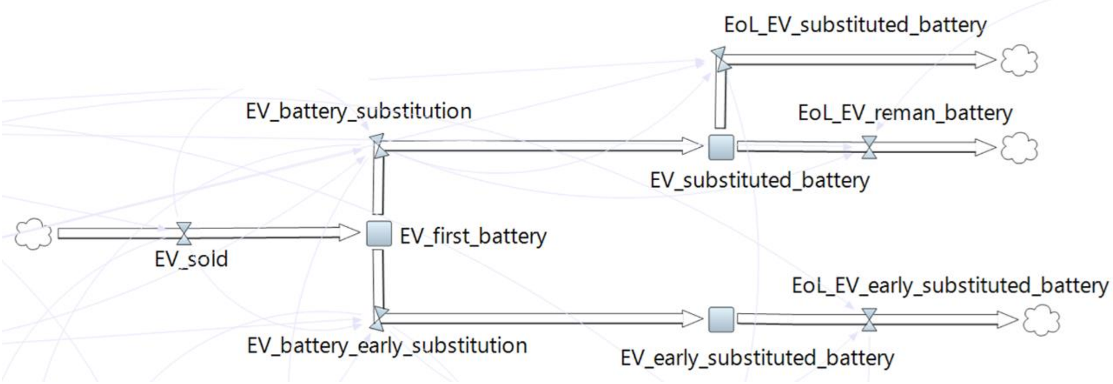


Figure 4.4: EV market represented on the model

4.3.3. Business layer

The second block displayed in the figure is the more complex one, because of the plurality of factors and criteria considered while directing flows. The aim of the system is to optimize the flows of batteries, assigning them to strategies according to their state of health, prioritizing the more profitable process and satisfying the demand for second life applications.

The first step computes the annual amount of batteries exiting their first life. This is done relying on data provided by the EV market block, considering all batteries that are retrieved from cars in the year under analysis.

The direction assigned to flows is determined based on three major criteria:

- Battery state of health
- Profitability of the strategy
- Availability of a second life market

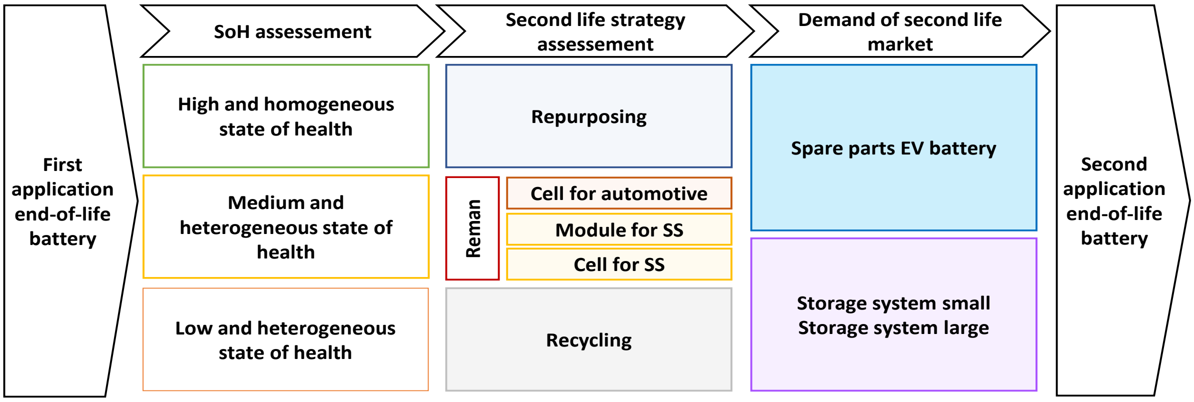


Figure 4.5: Business layer representation

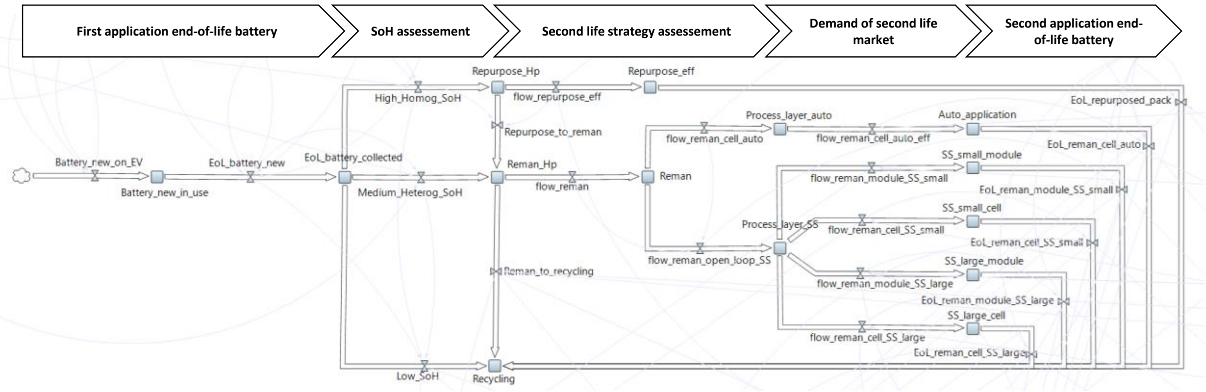


Figure 4.6: Business layer on the model

The business layer results derived from the constant interaction with blocks describing the process layers.

At the beginning, flows are directed on the basis of their state of health, knowing that this value is associated with a theoretically more suitable strategy. The higher the SoH of the battery, the higher its value embedded and lower is the need to deeply process the product. For this reason, high level of state of health batteries are sent to repurposing strategies, medium and heterogenous batteries to remanufacturing and low SoH batteries to recycling.

After that, the diversified flows of batteries SoH are re-assigned to the different strategies depending on the profitability of the strategy. The objective is maximizing the overall system margins.

Finally, the actual flows exiting the strategy correspond to the one needed to satisfy the second market demand. This estimation of flows is more complex than the previous ones and requires the interaction with the process layers to achieve the right result. Indeed, circular economy processes are characterized by some features that modify the final value of flows and need to be taken into consideration.

Finally, the business layer keeps track of the amount of second-life batteries reaching the end-of-life each year. This information is stored because those flows are sent to recycling. Depending on the application of the battery, the product is characterized by a different duration of the second-life.

The business layer is structured in such a way to allow that supply flows of batteries exceeding the demand flows for remanufacturing are re-direct to other strategies, in order not to get lost. Batteries should be used to satisfy the demand of the more profitable strategy based on their quality level until reaching the saturation of the market. In case of oversupply of batteries, they need to be treated according to other strategies. For this reason, flows connecting the three major strategies have been introduced in the business layer.

4.3.4. Process layer

In this part, remanufacturing up to cell level, remanufacturing up to module level and recycling strategies are deepened in order to properly explain the way processes have been depicted and their interactions with the business layer. Moreover, the production of the battery cells has been represented in the model, even if it is an activity belonging to the linear value chain of the battery manufacturing.

4.3.4.1. Cell production

The European production of cells have been represented in the model, together with the Asian production of cell. This has two main purpose. On the one hand it aims to keep track of the cells discarded by the process and sent to recycling. Being the announced installation of capacity in Europe expected to be quiet significant before 2025 and 2030, the expect volumes of scrap should be interesting to be computed. Moreover, the European union has the goal of achieving a production capacity able to cover then demand of batteries before 2030. The system is able to compare the volumes of batteries requires given the annual expected sales with the production capacity already installed in Europe. As long as the demand exceeds supply, cars manufacturers are obliged purchase batteries from Asian manufacturers. On the contrary, they should be able to rely on the European production capacity, if the announced investment in capacity will materialize.

In the figure, the scrap from the European production is sent to recycling.

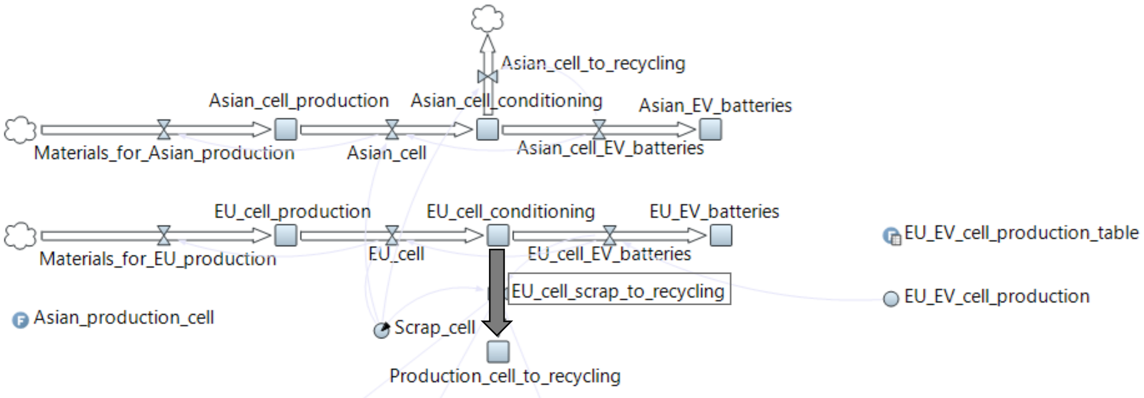


Figure 4.7: Cell production on the model

4.3.4.2. Remanufacturing

When entering the remanufacturing flows, the directions to be taken differ depending on the demand of the second-life application market to satisfy. The first option is represented by the automotive application, where the battery serves as a spare part for a vehicle, and the second one by the stationary application, divided in residential or utility-scale application.

Remanufacturing for automotive application

As previously explained, flows entering the remanufacturing activities are direct to satisfy the demand for remanufactured product in the automotive application, until reaching its limit.

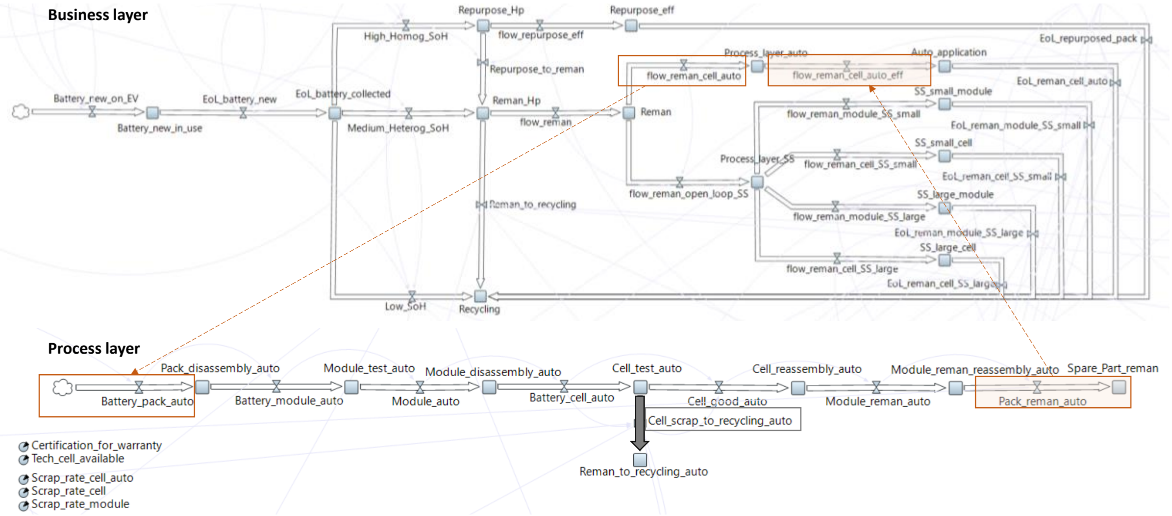


Figure 4.8: Remanufacturing for automotive application on the model

As shown in the Figure 4.8, the flow enters the process, passes through the different stages and reaches the end after having been reduced by the amount of scrap. The flow representing the scrap is sent to recycling.

The demand is represented by the share of car-owner that decide to substitute their batteries with a remanufactured product.

Variables influencing the output flows:

- Certification for warranties
- Tech available
- Scrap rate
- Share prismatic
- Max demand for automotive application

Remanufacturing for storage system

The system describing strategies to treat batteries for storage systema is more complex than the previous one. Indeed, both remanufacturing up to module level and remanufacturing up to cell level is performed to obtain the product. Moreover, both small and large storage systems are considered.

This part of the model is connected also with the demand for storage system application, as it is explained later in the chapter.

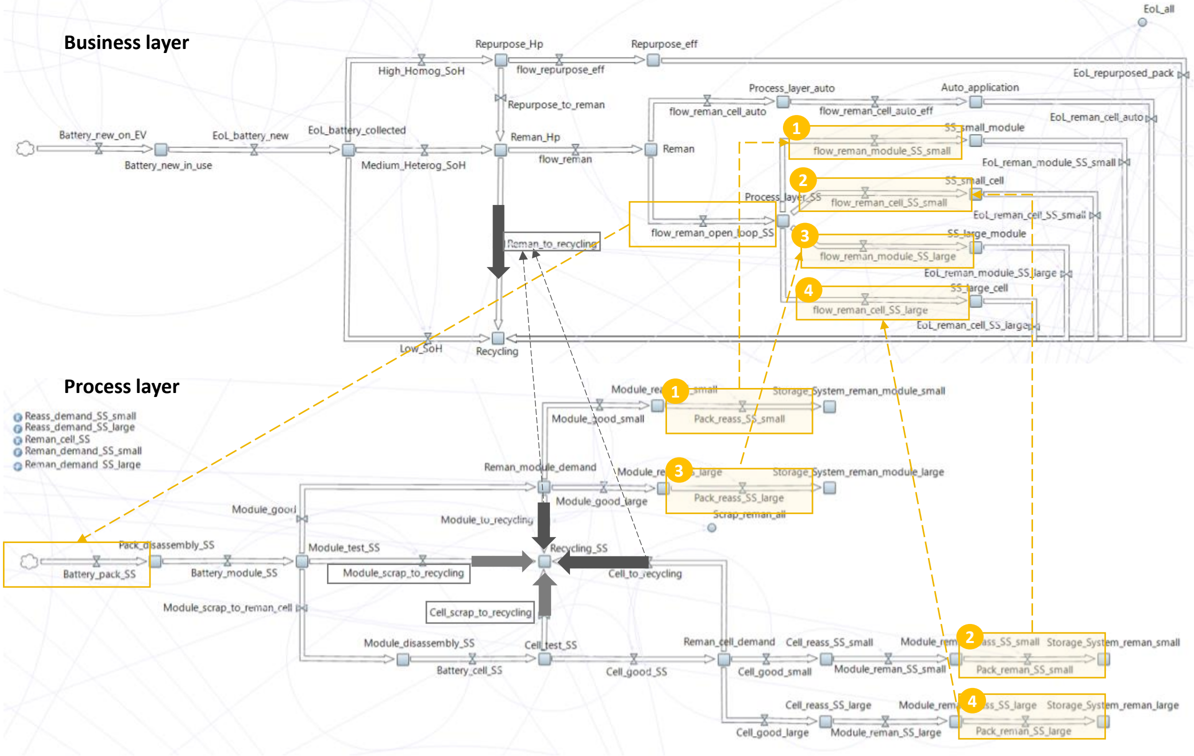


Figure 4.9: Remanufacturing for storage system on the model

Entering as a unique flow, a first step aims at testing modules and dividing the good one from the discarded ones. The good ones are then processed in order to create storage application and satisfying the demand for residential and utility-scale applications. As previous explained, precedence is given to the batteries used to build small storage system, because of their higher unitary margin.

Considering instead the scrap of modules, the ones characterized by prismatic cells are processed again to reach the cell level. Again, cells are tested and the good ones are used to satisfy the demand.

Four flows are sent to recycling, but they are a result of different mechanism.

Parameters:

- Certifications for warranties
- Scrap rate of remanufacturing up to module level process
- Scrap rate of remanufacturing up to cell level process

- Demand for small storage system that depends on the maximum acceptance rate for the remanufactured products
- Demand for large storage systems that depends on the maximum acceptance rate for the remanufactured products

4.3.4.3. Recycling

Once entering the recycling process, MWh of batteries are converted into tons using energy density.

Income flows:

- Pack
- Cells and modules

Income flows of pack: (collected from the business layer)

- Flows of low state of health
- Flows of oversupply from remanufacturing and repurposing strategies if compared with the demand
- Flows of end of life

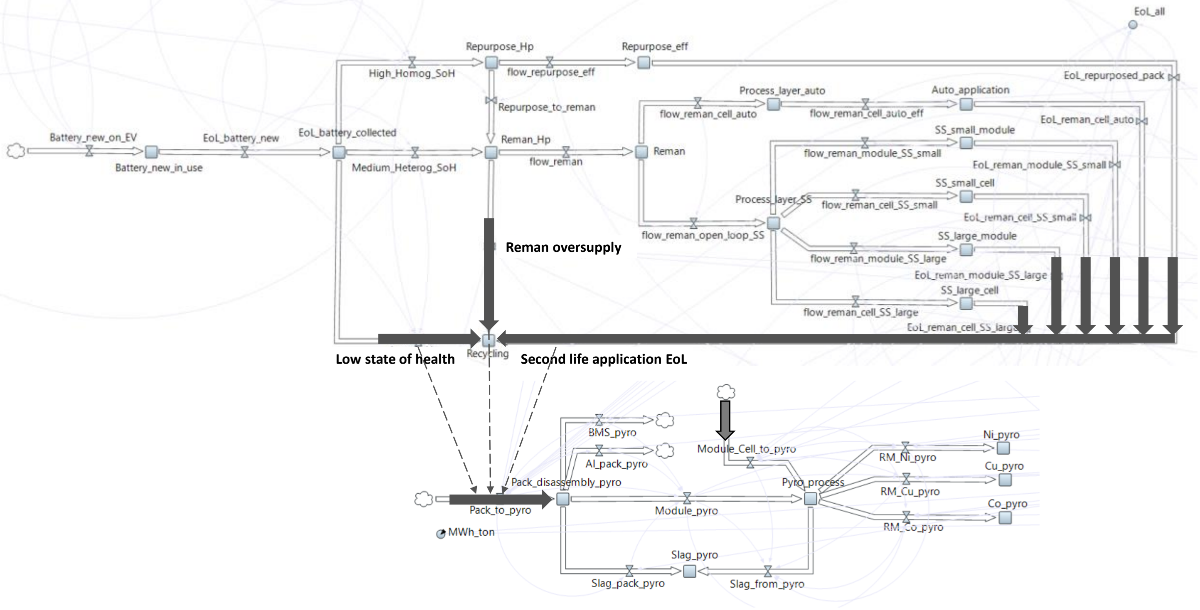


Figure 4.10: Recycling input flows on the model

Income flows of cells and modules: (process layer)

- Scrap from production
- Scrap from remanufacturing for automotive applications (up to cell)
- Scrap from remanufacturing for storage system application (up to module and up to cell)

4.3.4.4. Recycling processes

The system analyses and compares three different recycling scenarios: a conventional pyrometallurgical process, a conventional hydrometallurgical process and a hydrometallurgical best-case scenario. The last one is comprehensive of the most innovative technologies, not always available on an industrial scale such as:

- External cell case removal through a cutting case process to avoid the contamination of the black mass powder;
- High Voltage Fragmentation for the separation of the black mass from the Al current collector foil;
- Chemical pre-treatment to extract the electrolyte or dissolve the binder through the use organic solvent and supercritical fluids (e.g. CO2);
- Direct recycling to recover the cathode and anode materials as proper components.

The model assigns flows directed to recycling to all the three processes, in order to give evidence of the different outputs obtained given the same amount of input. To compute the exact quantity of materials recovered from the process, the share of materials embedded in the battery and the recovery rate of the process are fed into the model. Moreover, given the dynamism of the external environment, recovery rate values are updated at definite instant of time to keep track of the regulation development.

Finally, a significant part of the system is related to the computation of the revenues gained by each process, which is more complex than the other strategies because of the plurality of output. System dynamics simulation is suitable for such complex system.

The three processes are represented below. The first one serves as a reference to understand how the model is structured and the parameters influencing the system are depicted in the figure.

Overall, the following variables determine the output flows:

- Material share (e.g. Share of Ni in the cathode)
- Material recovery
- Share of NMC
- Share of prismatic, cylindrical and pouch

Finally, the variables needed to compute revenues are:

- Output flows
- Material price
- Share NMC
- Share prismatic

The formulas to compute flows and revenues are:

- $Output\ flow_i = ShareMaterial_i * Recovery_i * Input\ flow$
- $Revenues = \sum_i Output\ flow_i * Price_i - Slag * cost_{slag}$

Pyrometallurgical process and variables

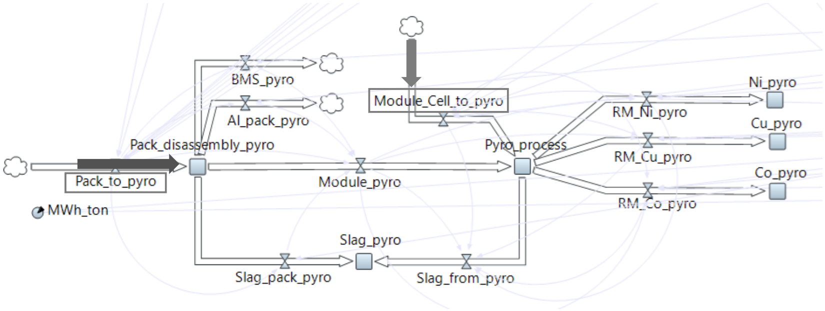


Figure 4.11: Pyrometallurgical process on the model

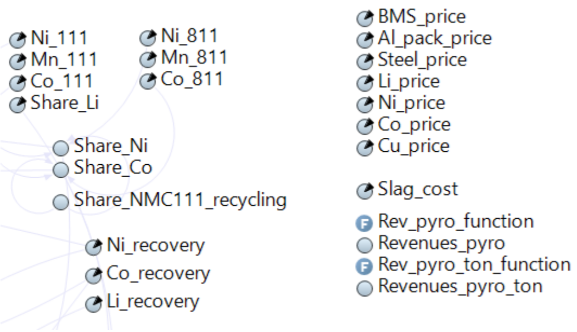


Figure 4.12: Recycling variables on the model

Hydrometallurgical process

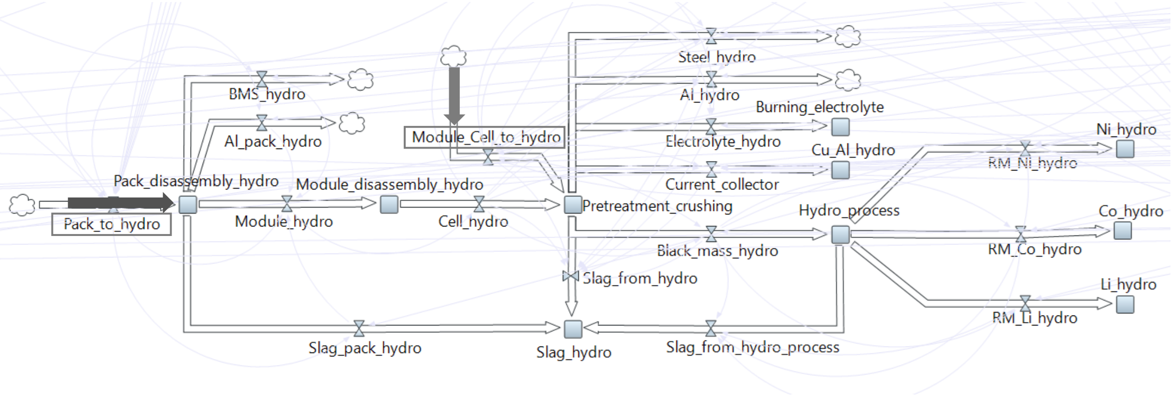


Figure 4.13: Hydrometallurgical process on the model

Hydrometallurgical best case process (direct recycling)

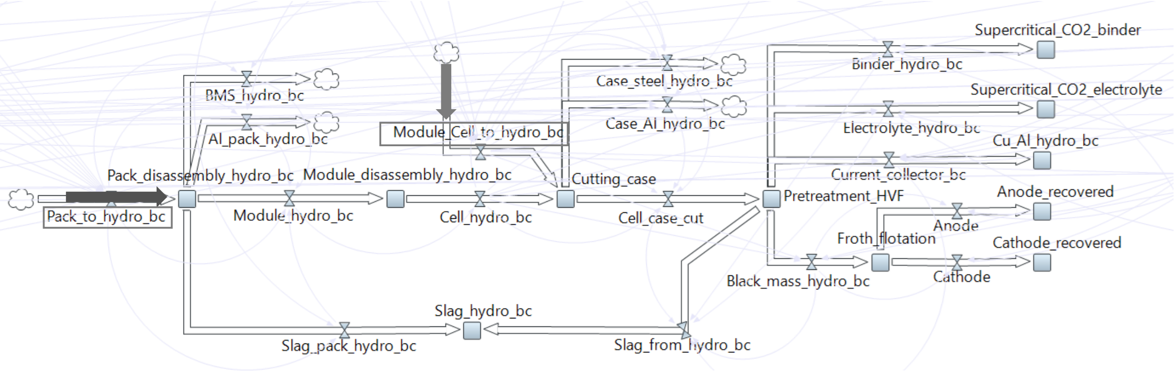


Figure 4.14: Hydrometallurgical best case (direct recycling) on the model

Recycling Outputs

As it appears from the graphical representation, each recycling process is able to recover multiple and diversified materials, which are listed in the Table 4.3. Pyrometallurgical process generates lower number of flows it generates so that the slag derived from the not-recovered material is expected to be larger than the ones of the other processes.

Table 4.3: Output streams of the represented recycling processes

Pyrometallurgical	**Hydrometallurgical**	**Hydrometallurgical best case**
BMS	BMS	BMS
Al_pack	Al_pack	Al_pack
RM_Cu	Steel_case	Steel_case
RM_Ni	Al_case	Al_case
RM_Co	Al_current_collector	Al_current_collector
Slag	Cu_current_collector	Cu_current_collector
	RM_Ni	Binder
	RM_Co	Electrolyte
	RM_Li	Anode
	Electrolyte	Cathode
	Slag	Slag

4.3.5. Second life application demand for storage system

This part of the model aims at determining the annual value of demand satisfied by remanufactured products. As previously explained for the automotive applications, the demand is computed as the total demand multiplied by the maximum share of clients willing to buy a second-life product. Given data about the annual installed capacity of storage systems, the model devotes a maximum share to products derived from the circular economy strategies, distinguishing the one obtained from remanufacturing up to cell level from remanufacturing up to module level as explained in the assumptions.

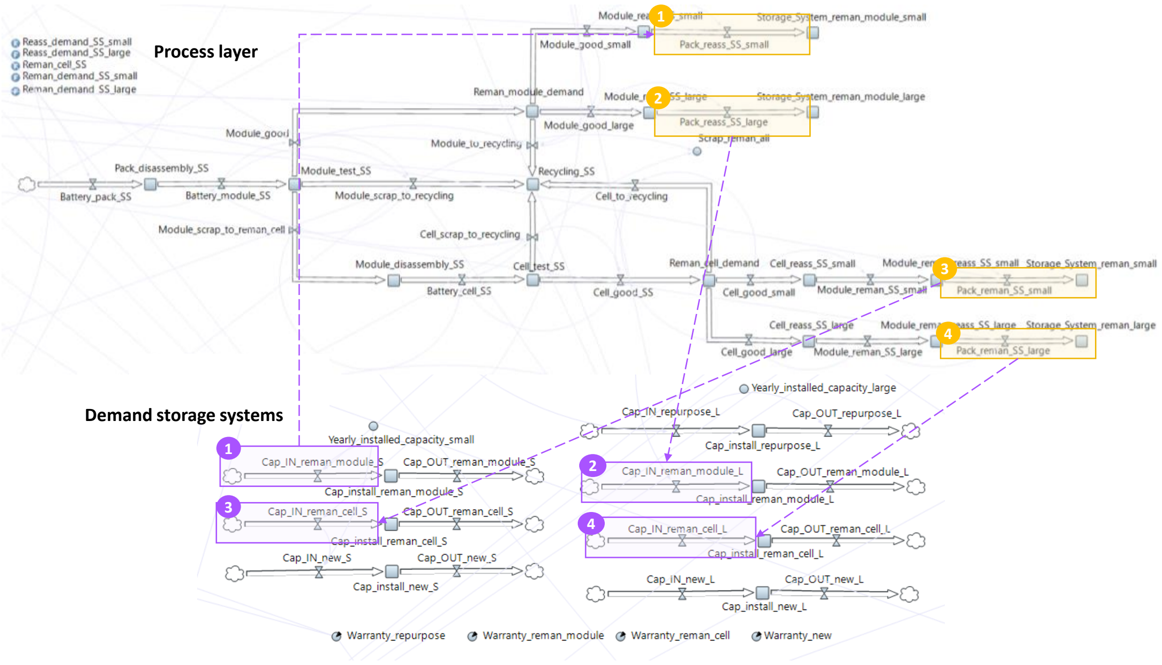


Figure 4.15: Second life application demand for storage system on the model

4.3.6. Variables

Given the capability of the simulation to capture changes in the system's parameters, the most significant variables are represented by the ones influencing the direction of flows because of their development during the simulation run. They are listed below, highlighting their impact on the model and the implications of their introduction in the system.

The introduction of these standard allows to set warranties compliant to the same set of rules and to make comparison between the different remanufactured products.

As explained in *Chapter 2*, the progress of the work item realized by the technical committee and supervised by the CEN organization is available for consultancy by the interested economic actors.

For this reason, soon after the deadline, some actors can be considered to be already equipped with the required testing procedures to obtain the certification compliant to the new standard for their products' warranty. It is clear that these standards are enabler for performing remanufacturing activities, both at module and cell level.

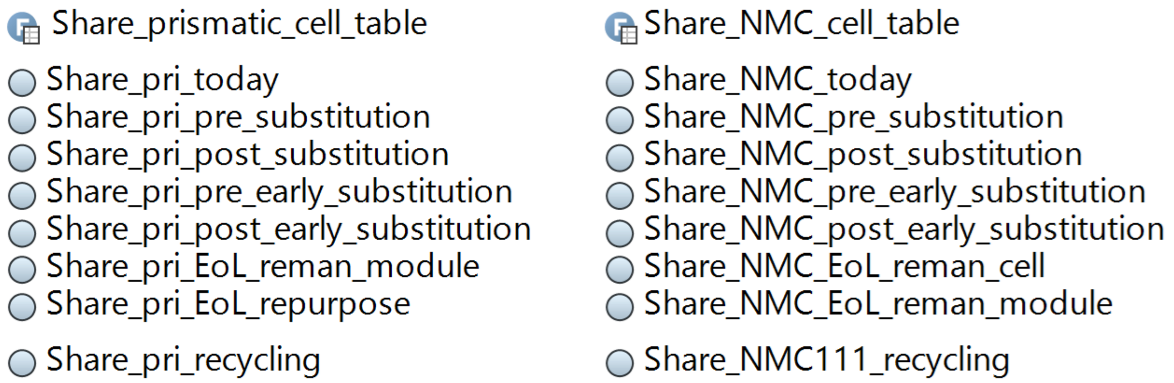
Table 4.4: Most significant variables of the model

	Variable name	Description	Flows impacted	Business implications
Technology	Technology available	Variable describing the development of technology to perform remanufacturing activities up to cell level	Flows of remanufacturing up to cell level	Overcoming technological limitations related to the process allows to automatize activities and to scale up production to industrial relevant quantities
Regulation	Certification for warranties	Variable describing the evolution of European standard on the re-use and repurposing of rechargeable batteries	Flows of remanufacturing up to module and up to cell level	Treating the products according to a unique and commonly approved set of European standards allows to obtain the certification for its warranty and to make it comparable with the other certified products available on the market.
Regulation	Battery passport	Variable describing the evolution of regulations related to the provision of specific information to end-users and economic operators and the realization of an electronic information exchange for batteries and a battery passport.	Flows of the State of health	Providing economic operators with specific information regarding the end-of-life batteries, such as the residual capacity, in order to facilitate the choice of second-life strategy to treat the battery
Regulation	Recovery rate	Variable describing the minimum recovery rate to be achieved from the recycling process and applied to a specific material.	Amount of primary materials recovered from recycling	Minimum required recovery rate set by European regulations allowing to recovery significant amount of materials embedded in the battery

Battery feature	Share of Prismatic cells	Dynamic variable keeping track of the share of prismatic cell type processes, in order to know how many cells to be sent to remanufacturing up to cell level	Remanufacturing up to cell level Aluminum recovered from the recycling	Share of batteries characterized by prismatic cell type influencing the amount of volumes that can be remanufactured up to cell levels and the amount of aluminum recovered through recycling
Battery feature	Share of NMC 111	Dynamic variable keeping track of the share of NMC cells processed by recycling	Amount of cathode material recovered from Recycling	Share of batteries characterized by NMC 111 influencing the quantity recovered through recycling, because of the different materials in the cathode, and determining the profitability of the process, driven by price of Cobalt

4.3.6.1. Prismatic and NMC111 Variables

The share of batteries characterized by prismatic cells and those with NMC111 as cathode have been described by the model. Indeed, having information about the value of share at a given year, it has been important to compute how the distribution of these shares evolve during the simulation. Their progress depends on the way flows are directed during the run, based on the defined criteria and parameters. For this reason, a dynamic variable has been associated to each flow of the model to associate a value describing its share of prismatic and NMC111 cell type. The figure displays the table functions and dynamic variables added in the model to perform the computation.



Share_prismatic_cell_table
Share_pri_today
Share_pri_pre_substitution
Share_pri_post_substitution
Share_pri_pre_early_substitution
Share_pri_post_early_substitution
Share_pri_EoL_reman_module
Share_pri_EoL_repurpose
Share_pri_recycling

Share_NMC_cell_table
Share_NMC_today
Share_NMC_pre_substitution
Share_NMC_post_substitution
Share_NMC_pre_early_substitution
Share_NMC_post_early_substitution
Share_NMC_EoL_reman_cell
Share_NMC_EoL_reman_module
Share_NMC111_recycling

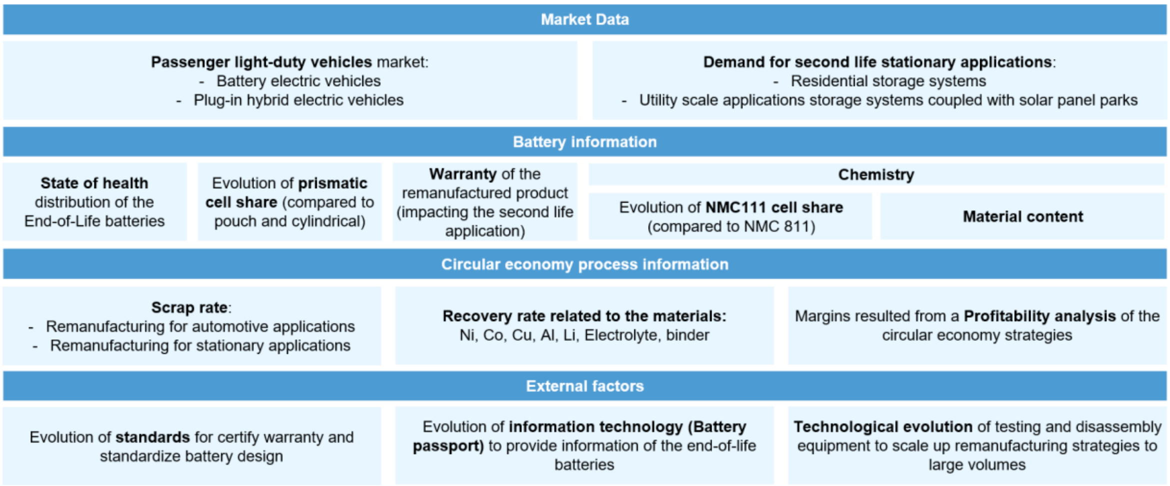
Figure 4.16: Prismatic cell typology and NMC chemistry on the model

Only by keeping track of these values for all the considered flows, it is possible to know the exact number of batteries that can undergo remanufacturing up to cell process. At the same time, the share of NMC111 batteries characterizing all the different flows entering the recycling strategy allows to compute the exact quantities of materials recovered.

5 Data Collection

This section explains how the data used to feed the model for the simulation has been gathered. Overall, an analysis of the existing literature and reports has been carried out to collect the required information. Moreover, the collaboration with the CIRC-ev laboratory of Politecnico di Milano has been crucial to define data, especially the one related to the circular economy processes.

The data deepened in the section is loaded in the simulation model as parameters or table functions. Their category schematized in the following figure.



Market Data

Passenger light-duty vehicles market:
- Battery electric vehicles
- Plug-in hybrid electric vehicles

Demand for second life stationary applications:
- Residential storage systems
- Utility scale applications storage systems coupled with solar panel parks

Battery information

State of health distribution of the End-of-Life batteries

Evolution of **prismatic cell share** (compared to pouch and cylindrical)

Warranty of the remanufactured product (impacting the second life application)

Chemistry

Evolution of **NMC111 cell share** (compared to NMC 811)

Material content

Circular economy process information

Scrap rate:
- Remanufacturing for automotive applications
- Remanufacturing for stationary applications

Recovery rate related to the materials: Ni, Co, Cu, Al, Li, Electrolyte, binder

Margins resulted from a **Profitability analysis** of the circular economy strategies

External factors

Evolution of **standards** for certify warranty and standardize battery design

Evolution of **information technology (Battery passport)** to provide information of the end-of-life batteries

Technological evolution of testing and disassembly equipment to scale up remanufacturing strategies to large volumes

Figure 5.1: Data categories and names

5.1. Market data

5.1.1. Electric Vehicle Market

The data describing the evolution of the electric vehicles market relies on the analysis provided by IEA, the international energy agency. IEA is an organization committed to shaping a secure and sustainable energy future, by ensuring energy security, tracking clean energy transitions, collecting data, or providing training around the world.

In particular, information has been gathered from the Global EV Outlook, the annual publication that identifies and discusses recent developments in electric mobility across the globe. [4] As explained in *Chapter 2*, The outlook for electric mobility takes a scenario-based approach and explores two different scenarios built on the latest market data, policy drivers and technology perspectives: the Stated Policies and Sustainable Development scenarios. The SDS assumes that all EV-related targets and ambitions are met, even if current policy measures are not deemed sufficient to stimulate such adoption rates. For this reason, the data chosen to feed the model relies on the estimation of the stated policies scenario. Moreover, for the purpose of the study, the electric vehicles under analysis belong to the categories of battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) of cars.

The EV outlook provides information about the historical data of European EV sales, from 2010 to 2020, which are displayed in the graph. The market under analysis includes all countries belonging to the European Union, Norway, Iceland, Switzerland and United Kingdom.

Table 5.1: Historical European BEV and PHEV sales

	BEV	PHEV
2010	2.632	44
2011	10.134	433
2012	18.341	9187
2013	32.521	26.094
2014	61.571	34088
2015	87.167	100643
2016	104.405	116.561
2017	138.342	155.791

2018	201.869	179.337
2019	363.404	204.297
2020	746.819	625.459

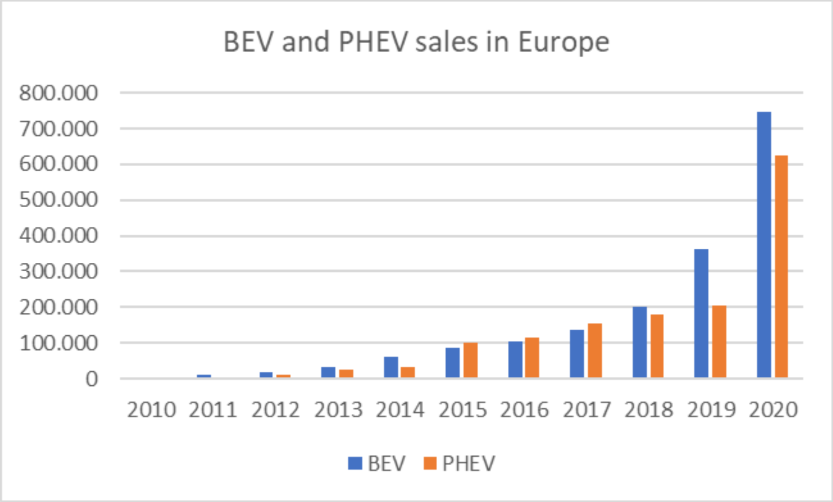


Figure 5.2: Historical European BEV and PHEV sales

The IEA provides also projections about the future development of the EV market. In particular, data of the expected sales in 2025 and 2030 has been gathered following the STEPS scenario and they equal overall 3200K and 5900K units sold respectively.

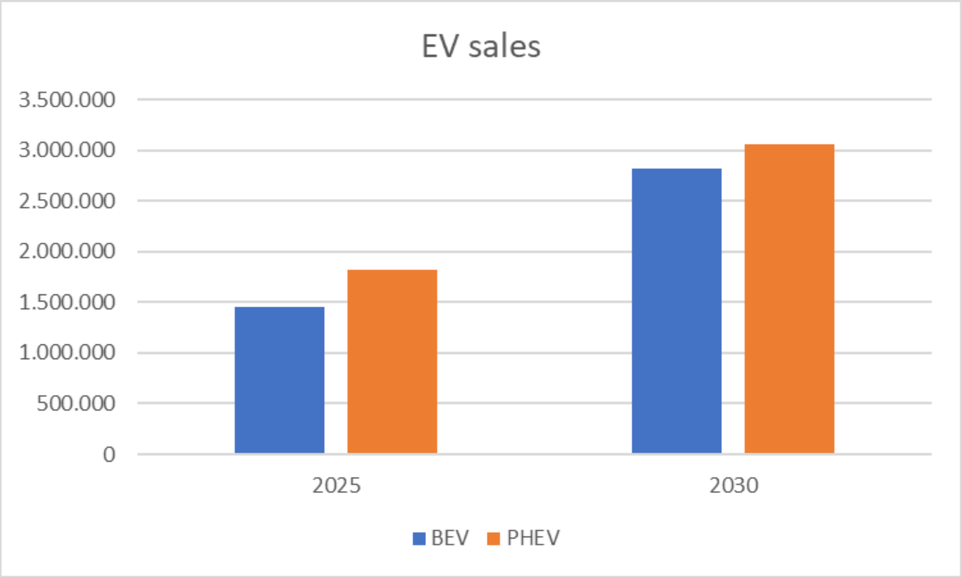


Figure 5.3: Forecast of European BEV and PHEV sales

Assuming a linear growth, yearly sales have been derived from the collected data.

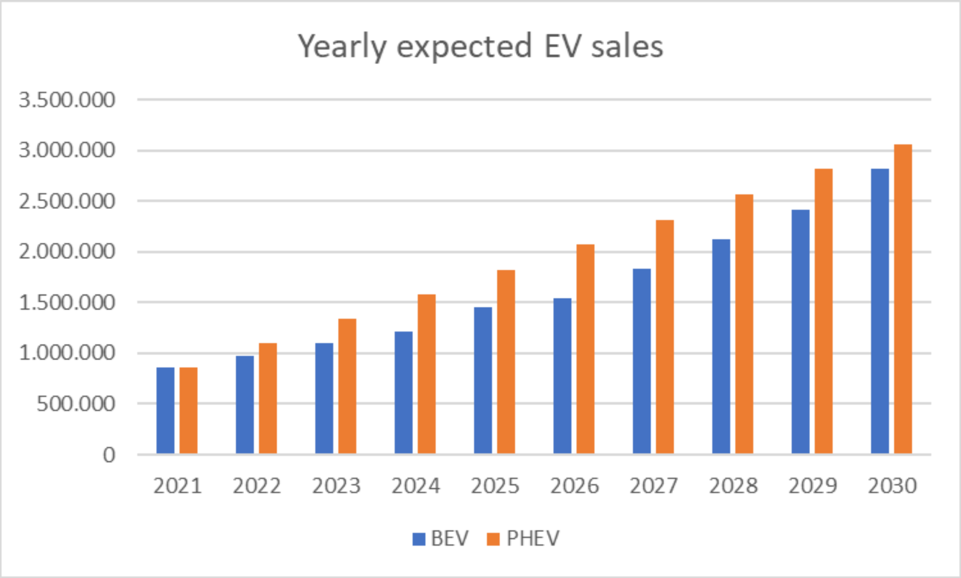


Figure 5.4: Expected distribution of European EV sales

The simulation model has been built in order to allow the interaction between different parts of the overall value chain. For this reason, the unit moving in the system represents the energy and are describe in MWh. To properly feed the model, the previously described sales of cars have been multiplied by the energy each single EV is able to provide, depending on its type, whether it is a BEV or an PHEV. According to the EV Outlook, a constant average battery capacity of 55 kilowatt-hours (kWh) can be set for BEVs, while PHEV are able to provide on average 14 kWh of energy.

Table 5.2: Battery capacity

Type of car	Battery capacity (KWh)
BEV	55
PHEV	14

The following Table 5.3 describes the data collected, and the results obtained in terms of overall energy the new batteries put on the market can provide each year.

Table 5.3: Annual energy provided (MWh)

	Yearly sales	Annual energy provided

	BEV	PHEV	BEV	PHEV	Total (MWh)
2010	2.632	44	145	1	145
2011	10.134	433	557	6	563
2012	18.341	9.187	1.009	129	1.137
2013	32.521	26.094	1.789	365	2.154
2014	61.571	34.088	3.386	477	3.864
2015	87.167	100.643	4.794	1.409	6.203
2016	104.405	116.561	5.742	1.632	7.374
2017	138.342	155.791	7.609	2.181	9.790
2018	201.869	179.337	11.103	2.511	13.614
2019	363.404	204.297	19.987	2.860	22.847
2020	746.819	625.459	41.075	8.756	49.831
2021	863.150	864.312	47.473	12.100	59.574
2022	979.481	1.103.165	53.871	15.444	69.316
2023	1.095.811	1.342.017	60.270	18.788	79.058
2024	1.212.142	1.580.870	66.668	22.132	88.800
2025	1.450.402	1.819.723	79.772	25.476	105.248
2026	1.537.426	2.069.039	84.558	28.967	113.525
2027	1.828.349	2.318.354	100.559	32.457	133.016
2028	2.119.273	2.567.670	116.560	35.947	152.507
2029	2.410.196	2.816.985	132.561	39.438	171.999
2030	2.822.682	3.066.301	155.248	42.928	198.176

The data of the last column is plotted in the following graph. The rapid growth characterizing the EV market emerges even when considering the energy provided by EV batteries in the future.

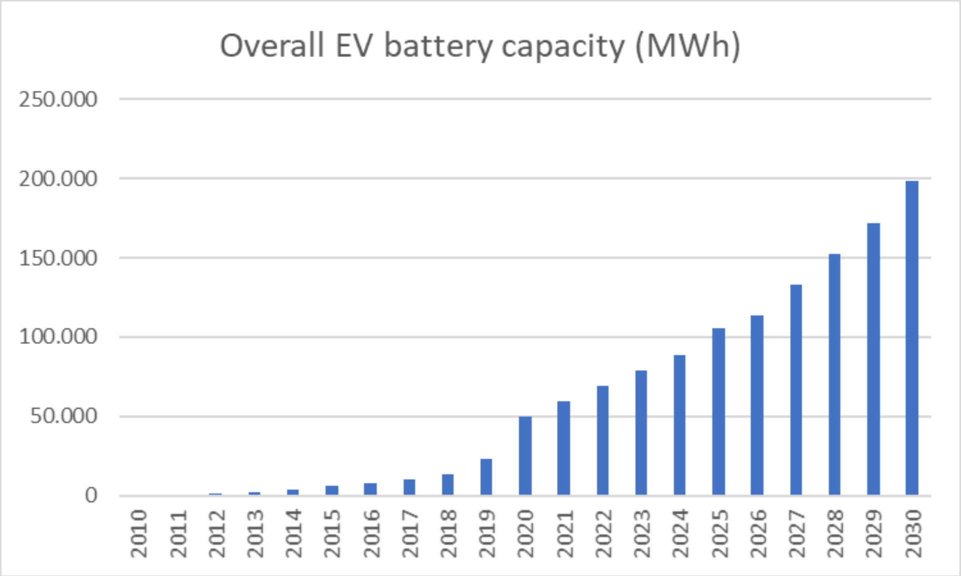


Figure 5.5: EV battery annual energy provided

In the model, these values have been used to feed the EV demand table.

5.2. Demand of stationary applications

The demand side in the model is represented by the users of small and large storage systems. The former refers to the residential storage systems usually installed in houses, while the latter are represented by the energy storage systems used in solar parks. Indeed, this section explains how their related markets have been sized. In both cases, data have been gathered by the public reports of SolarPower Europe, a member-led association that aims to ensure that more energy is generated by solar than any other energy source by 2030. Data collected represent the overall demand, that, in the model, is multiplied by a percentage representing the share of customers willing to buy a second-life battery rather than purchasing a new storage system.

5.2.1. Small storage system demand

According to the annual European Market Outlook for residential battery energy storage (BESS) of SolarPower Europe, solar-and-battery is probably the greatest couple in the energy transition.

Indeed, BESS are often coupled with residential solar photovoltaic (PV) systems to optimise the local use of the energy produced. Small-scale solar PVs are attractive because they allow homeowners to produce their own clean and cheap electricity but 75-80% of the electricity generated is exported to the grid instead of being self-consumed. In fact, the solar PV system's peak production is reached around midday, whereas the home load is high either in the morning or in the evening, outside of work-time hours. Coupling of solar and storage at a residential level allows to store excess electricity produced during the day in order to consume it at night. It increases the self-consumption rate of the installation up to between 60–90% and leads to substantial savings on the electricity bill. [30]

For this reason, in Europe the evolution of home storage is closely related to the development of residential solar markets. The battery energy storage system business started to gain traction in 2013, when German government introduced a premium to buy excess electricity produced by renewable energy plants of private individuals. Since then, the market has only experienced a positive trend, driven by strong public support schemes in most European countries.

Considering the BESS annual market, in 2017 approximately 2% of all residential solar PV systems across Europe were coupled with a battery, resulting in 350 MWh of total residential storage capacity installed. The following year 65,500 residential BESS systems were commissioned, and the doubling of demand for solar systems led residential storage installations to reach 747 MWh in 2019. The strong growth path continued in 2020, with a 44% year-on-year increase in annual installed capacity. For the first time, the European residential battery market reached the landmark GWh scale, totalling 1,072 MWh of storage capacity installed, equivalent to about 140,000 battery systems.

The growth in cumulative installed storage capacity is even more pronounced. The residential BESS fleet jumped from less than 2 GWh in 2019 to over 3 GWh in 2020.

Such high growth in cumulative capacity gives an even better perspective of the speed of adoption of BESS technologies. [30]

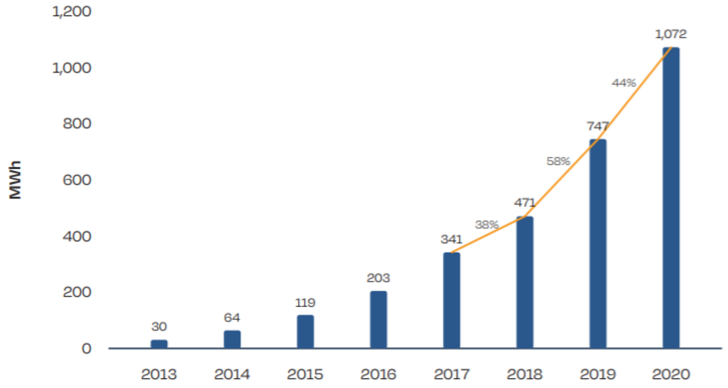


Figure 5.6: European residential BESS annual market

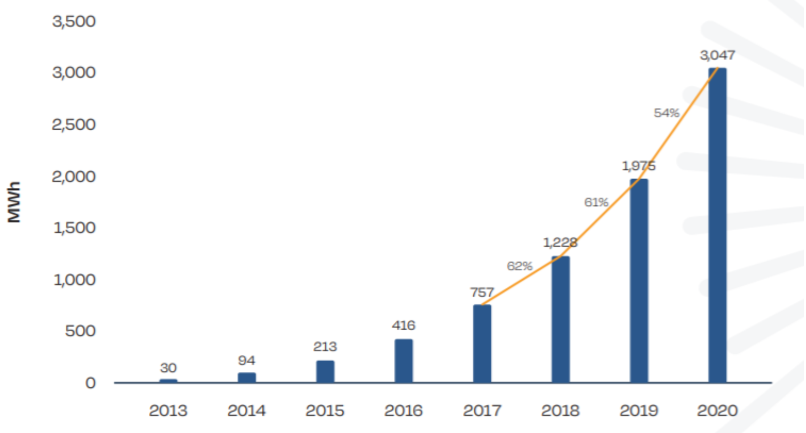


Figure 5.7: European residential BESS cumulative market

Today, residential BESS accounted for approximately 8% of the total residential PV systems in operation in Europe.

Going on with the report, SolarPower Europe's five-year forecast has been structured according to Low, Medium and High Scenarios. Overall, the estimation states that the residential BESS market will maintain its upward path, as many European countries see the first tangible results of the recovery packages and other measures put in place to back their economies. Moreover, the high growth rates are justified by the fact that the market is considered to be in the first stage of its lifecycle and huge market potential may derived by future development of the solar

European market. Indeed, over 90% of European buildings are still without solar systems.

The Medium Scenario describes the most likely development given the current state of play of the market and the values defined for the volume equal the 1.37 GWh in 2021, 1.67 GWh in 2022, 1.96 GWh in 2023, 2.21 GWh in 2024 and 2.51 GWh in 2025. The Outlook foresees a stagnating market in 2021 in case of Low Scenario forecast. This one is based on the assumption that policymakers halt solar and storage support and other issues arise, including interest rate hikes and severe financial crisis situations. By contrast, further advancement in EU member states' ambition towards renewable energy and decarbonisation goals, paired with improved policy frameworks and other positive effects on markets could lead to 1.82 GWh of installed capacity in 2021, as depicted in the High Scenario.

Overall, the estimation shows very high growth rates over the coming years, as the market is considered to be in the first stage of its lifecycle. Indeed, last year's 54% annual growth is expected to be followed by a 45% increase in 2021.

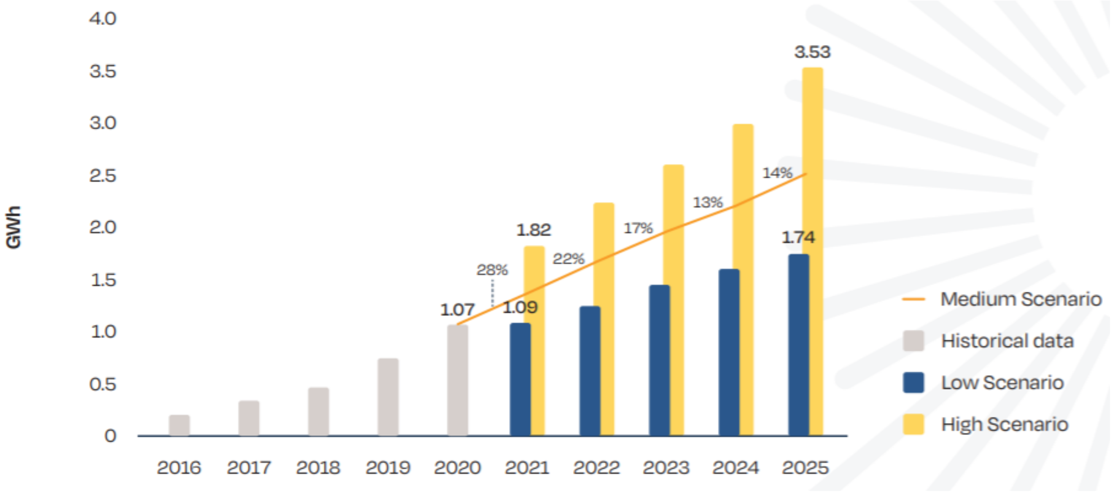


Figure 5.8: European residential BESS expected annual installations

For the purpose of the analysis, the values estimated according to the Medium Scenario have been taken into consideration. On the one hand, the European Market Outlook for BESS states the High Scenario to be too optimistic. On the other, it highlights the potential of the battery market due to its early growth stage and the possibility of further development because of the interconnection between the BESS and solar market. Indeed, in Europe 90% of European buildings are still without solar systems: a rise of PV installation may have a positive impact on the energy storage market. These factors may offset the negative impacts resulted from trade conditions or new COVID-related restriction. [30] For this reason, the Low Scenario has been excluded to describe the future evolution of the market. The growth of the market is expected to reach 7500 MWh installed in 2030. [37] To determine data from 2030 to 2040, a linear growth has been assumed, leading to 22 GWh installed. The Table 5.4 summarises the values of the BESS market, that has been used to describe the demand for the small storage system.

Table 5.4: Annual residential BESS capacity installed

	Storage Capacity (MWh)
2020	1072
2021	1370
2022	1670
2023	1960
2024	2210
2025	2510
2026	3200
2027	4000
2028	4998
2029	5996
2030	7500
2031	8625
2032	9919
2033	11407
2034	12547
2035	13802
2036	15182
2037	16700

2038	18370
2039	20207
2040	22228

5.2.2. Large Storage system demand

In order to size the demand of large storage systems, an analysis of the solar photovoltaic (PV) European market has been realized. The trend of coupling residential storage system with solar panel installations can be applied also to large utility-scale application. Indeed, due to the intermittent nature of renewable energy source, large storage systems are often used in renewable energy parks. Thanks to their capability of fast response to short-term fluctuations of the grid frequency, storage systems can provide ancillary services to the grid ensuring the balance of electricity supply and demand. When supply exceeds demand, the electric grid frequency increases and vice versa. [31]

The annual EU Market Outlook for Solar Power published by the SolarPower Europe has been the starting point to derive the data required for the simulation. [38] The historical data about the annual installation of solar power in Europe has shown a peak in 2011, followed by several year-long market slump. After that, due to the needs of the EU to boost solar capacity in order to succeed in reaching the 1.5°set by the Paris agreement, improvements in national policy conditions have led to reach a new record and to experience a new increasing trend.

In 2021, demand has grown significantly, reaching around 25.9 GW of new solar PV capacity connected to their grids, an increase of 34% over the 19.3 GW installed the year before. The growth rate from one year to another are slightly different. In particular, 2020 only experienced a growth of 15%, surely due to the impact of Covid-19 Pandemic. [38]

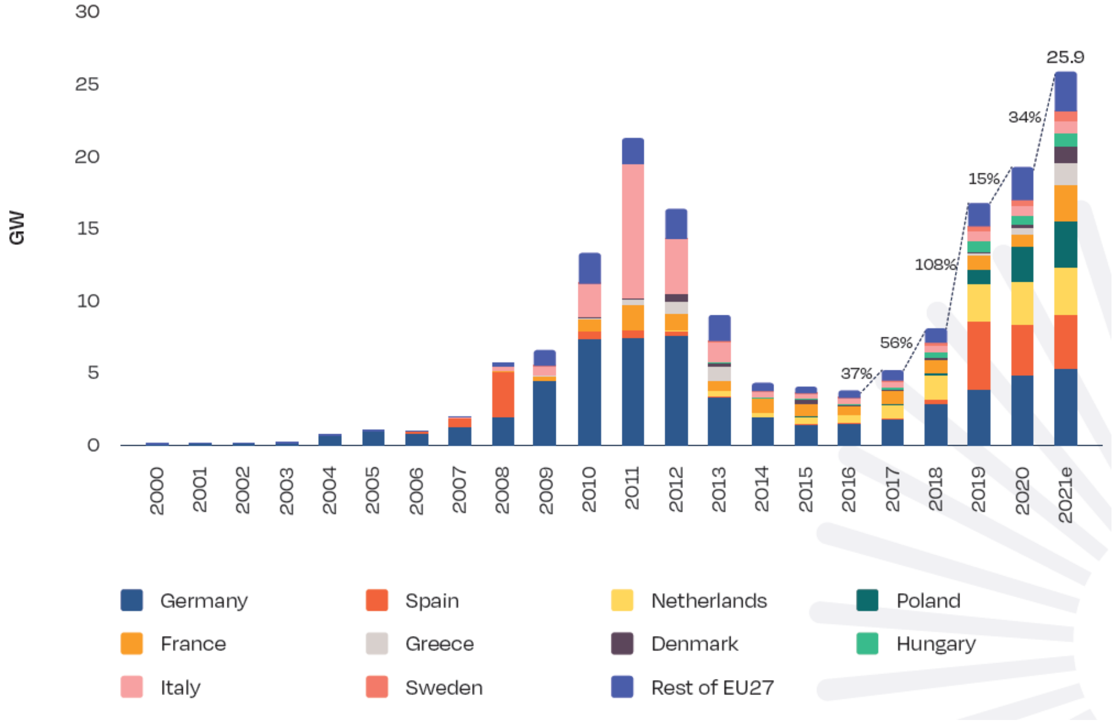


Figure 5.9: European solar PV installed power capacity

Again, the forecasts on which the simulation rely follow the Medium Scenario, that anticipates the most likely development given the current state of play of the market. According to this, the coming 4 years until 2025 will be characterised by further strong growth. Overall, new solar installations will account for 38.5 GW in 2023, 44.6 GW in 2024 and 49.7 in 2025. Moreover, a strong growth in the second half of the decade is expected due to improved policy conditions and further technology cost reductions. The Medium Scenario projections foresee an 85 GW annual solar market in 2030 increasing 72% from 2025 levels and 230% compared to 2021. [38] For the purpose of the analysis, this growth is considered to be equally distributed between the different years.

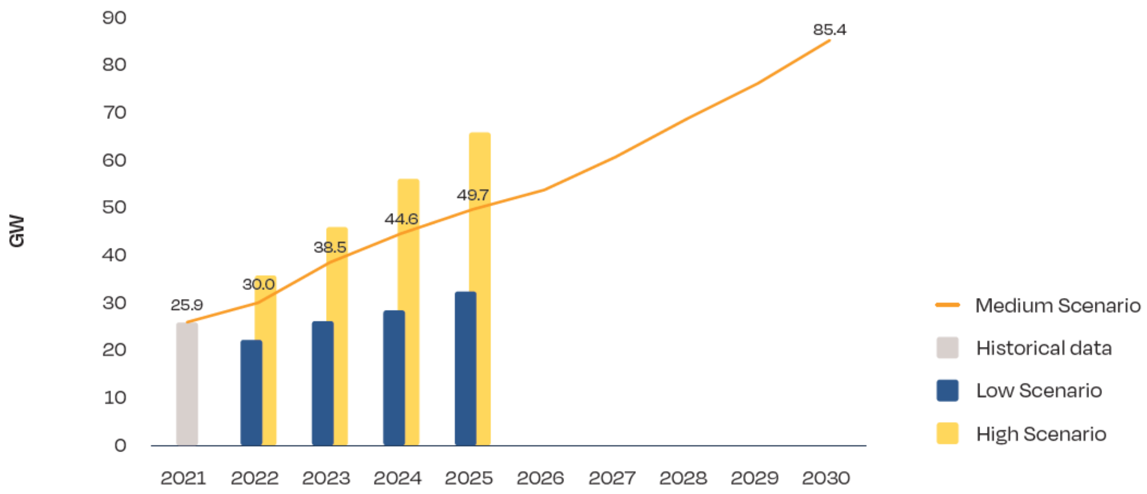


Figure 5.10: European annual solar PV expected power capacity installations

Finally, after 2030 the annual growth rate is expected to stabilize at 5%, assuming that the market will enter its mature phase, but incentive will remain high in order to meet the Paris agreement conditions.

The values presented in the report refer to various systems size, divided in residential (<10kW), commercial (<250kW), industrial (<1000kW) and utility-scale (>1000kW) segment. For the purpose of the analysis, the last type of system has been considered, which typically represent the 75% of the overall power installed.

To set the right percentage describing the number of solar parks coupled with storage system, the study relies on data provided by the USA GTM research [39] Focusing on the USA market, GTM estimates that solar-plus-storage have accounted for about 4% of distributed PV by the end of 2018 and could reach 27% by 2023. [40] Despite being related to the US market, this information can properly fit the analysis under development, since data is similar to the one evaluated by SolarPower Europe to the residential storage systems market. Overall, the share is set to be equal to 5% in 2020 and it increased every five years until reaching 30%.

Finally, a reasonable value of the capacity associated to the storage systems has been evaluated, given the amount of power provided by the renewable energy source.

With this purpose, some examples of solar parks coupled with storage systems have been identified globally.

In Japan, SB Energy, a subsidiary of multinational holding company SoftBank, has developed two large-scale-solar-plus-storage projects. The 64.6 MW solar farm of Tomatoh Abira has been combined with 19MWh of onsite battery energy storage and the 102.3 MW solar park near the town of Yakumo, has been linked to 27 MWh of lithium-ion storage capacity. [41] [42] In Europe, examples are the Wykes' Solar PV plant at the Chelveston Renewable Energy Park or the Akuo Energy project developed in Corsica, where a part of the produced solar energy is converted into DC power to be stored in three batteries on hand. [43] [44] Finally, the Spanish inverter manufacturer and storage system provider Ingeteam has connected to the grid a 40MW solar plant coupled to 9MWh of storage in town of Almaraz. [45]

In general, the MW describing the solar park power are three times higher than the storage capacity of the battery system. This value is considered to be fix in the time horizon under analysis.

Given all these values, the following data for the new installation of storage systems has been defined. The last column represents the demand for large storage system, under the assumption that they are made by Li-ion batteries.

Table 5.5: Computation of Large storage system annual capacity installed

	Solar panel (MW)	Growth	Utility-scale (MW)	Share of solar-plus-storage	Solar-plus storage (MW)	Rate MW/MWh	Storage capacity (MWh)
2013	9000		6750	5%	338	3	113
2014	4000	-56%	3000	5%	150	3	50
2015	4000	0%	3000	5%	150	3	50
2016	3775	-6%	2831	5%	142	3	47
2017	5172	37%	3879	5%	194	3	65
2018	8069	56%	6051	5%	303	3	101
2019	16783	108%	12587	5%	629	3	210
2020	19300	15%	14475	5%	724	3	241

2021	25900	34%	19425	10%	1943	3	648
2022	30000	16%	22500	10%	2250	3	750
2023	38500	28%	28875	10%	2888	3	963
2024	44600	16%	33450	10%	3345	3	1115
2025	49700	11%	37275	15%	5591	3	1864
2026	56840	14%	42630	15%	6395	3	2132
2027	63980	13%	47985	15%	7198	3	2399
2028	71120	11%	53340	15%	8001	3	2667
2029	78260	10%	58695	15%	8804	3	2935
2030	85400	9%	64050	15%	9608	3	3203
2031	89670	5%	67253	20%	13451	3	4484
2032	94154	5%	70615	20%	14123	3	4708
2033	98861	5%	74146	20%	14829	3	4943
2034	103804	5%	77853	20%	15571	3	5190
2035	108994	5%	81746	20%	16349	3	5450
2036	114444	5%	85833	25%	21458	3	7153
2037	120166	5%	90125	25%	22531	3	7510
2038	126175	5%	94631	25%	23658	3	7886
2039	132483	5%	99363	25%	24841	3	8280
2040	139108	5%	104331	25%	26083	3	8694

5.3. Battery information

Several types of information related to the battery pack have been gathered to feed the model. Indeed, most of the results this study is focus on depends on the characteristics of the batteries. For this reason, this part deepens the features of the return batteries in terms of state of health, type of cells and chemistry. Moreover, it defines the warranties associated to the battery depending on the circular economy strategy adopted. This last information has been significant to derive the usage time of the second life application.

5.3.1. State of health

An important factor influencing the applicability of the second-life strategies is their dependence to the State of Health (SoH) value of a battery system, which is defined as the ratio between the current capacity and the initial capacity of a battery.

According to car manufacturer, common electric vehicles' batteries reach the end of life when they loss around 20% of their capacity, falling below a SoH of 80%. This limit is mainly fixed for marketing reasons in front of real impediments, since the reduction of the battery capacity directly impact the mileage an EV may run. [46]

However, the SoH of the EoL batteries does not always equal 80% since clients do not return the vehicle at this precise moment for several reasons. Indeed, it is not always possible to have awareness of this value, as most of the EV models do not show the SoH level. Season weather, temperature changes and the use of auxiliary loads (as heater, cooler, etc.) affect the battery performance, making it difficult for the owner to precisely know whether the 80% is reached. Moreover, it may happen that the limit criterion still fulfil the necessities of the majority of EV owners and they may extend car's lifespan well beyond this limit. [47] This would impact and reduce the SoH value of the return battery.

Despite these elements make more difficult to estimate the exact distribution of SoH for the end-of-life batteries, Casals have realized an analysis aiming at defining the one that better describes the return battery SoH. In the study, only functionally correct batteries have been considered as part of the sample while damaged batteries or batteries from cars that suffered important accidents are excluded. According to them, battery SoH can be estimated by using a normal distribution centred at 80%, with the 95th percentile set at 90% and the 5^{th} ones at 70% value of SoH. As explained in *Chapter 2*, a higher SoH describes the fact the cells have similar residual capacity within the same module or pack, while lower values are caused by differences in their capacity. Depending on this condition, the state of the battery is determined to be homogeneous or heterogeneous.

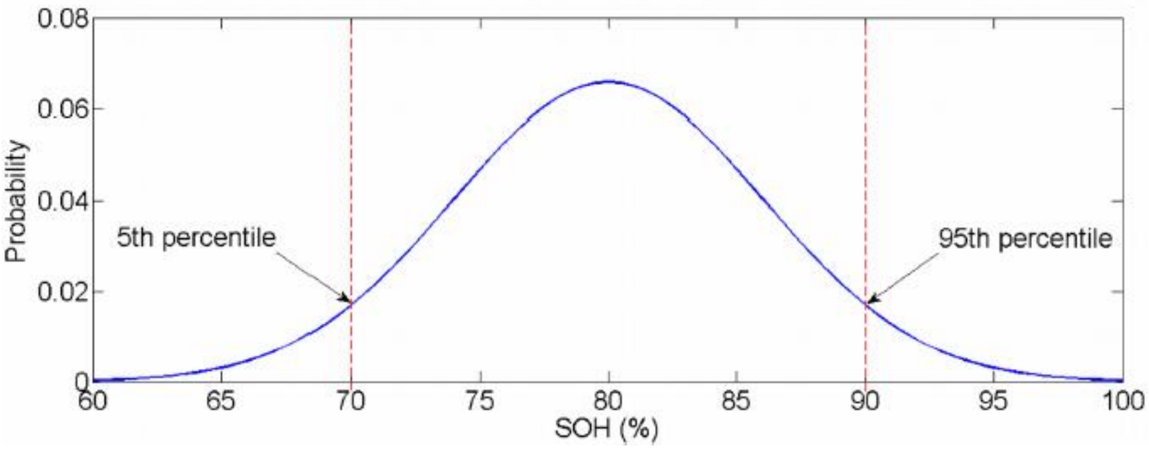


Figure 5.11: Normal distribution of EoL battery SoH

According to the survey conducted by German aerospace centre, the average lifetime of an EV battery in 2030 is estimated to be increase from a value of 8 to 12.2 years in a technically advanced scenario. [18] Indeed, with higher energy and power densities, batteries will offer longer vehicle ranges around 300 km or more. Under this assumption, the SoH value of the forthcoming EV generations may be revised to a lower average value (70-60%) of the normal distribution, since a longer usage phase will impact the quality state of the return battery. However, this significant change will not be included in the simulation as the return batteries with higher average lifetime would reach the end-of-life after the end of the simulation run.

Focusing instead on the share of batteries too damaged, this value is set at 15%, and includes all the batteries too deteriorated for a second life application and that are sent directly to recycling. [48]

Table 5.6: Portion of damaged batteries

	Share of batteries	Strategy
Damaged batteries	15%	Recycling
Not damaged batteries	85%	Second-life application

After having identified that the 85% of return batteries may be suitable for a second life application, each range of the SoH level has been associated to different strategies following the experts' opinions of the German aerospace centre survey. Indeed, they have been asked how high the lower SoH threshold should be for the applicability of the respective second-life strategy. According to them, the levels for repurpose range from 100 % to 75 % while remanufacturing of battery systems is possible up to a limit of 65%. The results are summarised in Figure 5.12.

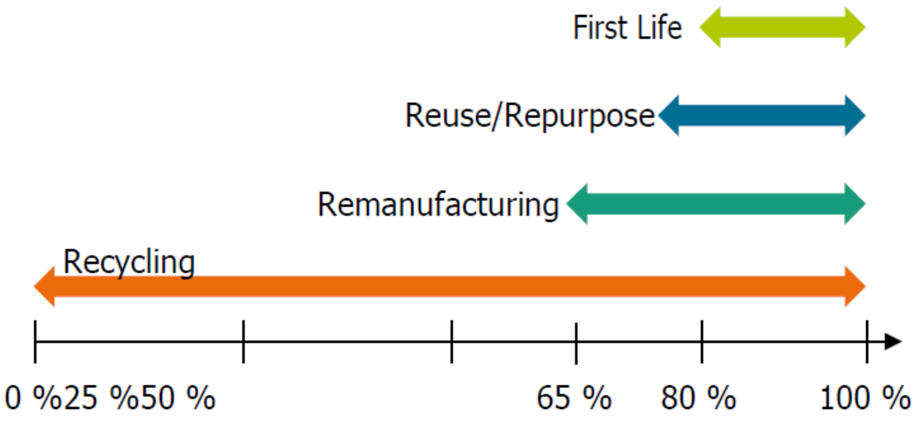


Figure 5.12: SoH limit value for the circular economy strategies

Table 5.7: SoH range applied to the strategies

	Lower bound	Upper bound
Repurpose	75%	100%
Remanufacturing	65%	100%
Recycling	0%	100%

Even if following the expert's opinions battery packs can be recycled regardless of their condition, in the simulation model only the previous defined share of 15% of the overall batteries is sent to recycling, in order to exploit the residual value of the reusable ones.

Merging the information about the SoH distribution and the ranges suitable for the different strategies, the following share of batteries describes the percentage of batteries that can be sent to the different strategies.

Table 5.8: Share of batteries divided by strategies based on their SoH

SoH	Strategy	Lower	Upper	Share of batteries
High and Homogeneous	Repurpose	75%	100%	72.5%
Medium and Heterogeneous	Remanufacturing	65%	75%	27.5%

For sake of simplicity, the amount of batteries with high and homogeneous SoH is set equal to 70% that can be suitable for repurposing, and to 20% the others. Finally, since these shares represent the 85% of the overall return batteries, each value is multiplied by 0,85 to get the right percentage of the overall return batteries.

Table 5.9: Share of batteries and relative SoH

SoH	Values
High and Homogeneous	60%
Medium and Heterogeneous	25%
Low and Heterogeneous	15%

It is remarkable that, if the second-life processes are economically profitable and the demand is sufficiently high, there is a large space for a second-life application considering the SoH of the return batteries.

After that, the SoH values for the batteries that have been subjected to an early substitution have been estimated, meaning that they are removed form the vehicle only after four years of operation. In that case, the average value of the battery SoH can be increased up to a 90% level. Under this assumption, none of the early substituted batteries should be sent to the recycling strategy and a relatively small percentage is considered to be characterized by a medium and heterogenous SoH.

Table 5.10: Share of batteries and relative SoH for early substitution

SoH of early substituted batteries	Values	Strategies
High and homogenous	70%	Reuse
Medium and heterogenous	30%	Remanufacturing

5.3.2. Prismatic cell

Determining which type of end-of-life battery cell is used in the EV models is essential for the study as remanufacturing activities that reach the cell levels are performed only on batteries made of prismatic cells. Indeed, there is a lower number of cells in each module when dealing with prismatic ones, due to their bigger dimension. This implies less connections are present and makes the disassembly at the cell level easier. Moreover, cells differ the ones from the others because of the materials used for the case. This information must be recorded when simulating the recycling process, in order to quantify the amount of steel or aluminium recovered. An analysis of the most popular car models has been realized to estimate the share of prismatic, cylindrical and pouch cell available on the market. Information about the type of cells embedded in the battery of the major automakers has been merged with the volumes of EV sold by each car maker. The German market has been taken as a reference point for the values of sales, as it is the larger in Europe. [4]

Table 5.11: EV German car model sales and relative cell types

OEM	CAR MODEL	EV sales	CELL GEOMETRY
AUDI	PHEV: A3 sportback E-tron, A8 hybrid, Q5 Hybrid, Q7 E-tron	50923	Prismatic cell
BMW	EV: i3	56930	Prismatic cell
	PHEV: i3 REX, i8, 330e, X5, etc.		Prismatic cell
BYD	PHEV: F3DM	-	Prismatic cell
CHEVROLET	EV: Bolt	-	Pouch cell
	PHEV: Volt		Pouch cell
CITROEN	EV: C-zero, E-Berling multispace, E-Mehari	-	Prismatic cell
FIAT	EV: 500e	-	Prismatic cell
FORD	EV: Focus electric	18565	Pouch cell
HYUNDAI	EV: Ioniq Electric	35435	Pouch cell
	PHEV: Ioniq Plug-in hybrid		Pouch cell
JEEP	PHEV: Renegade; Wrangler	-	Prismatic cell

KIA	EV: Soul electric	21302	Pouch cell
	PHEV: Niro, Optima, Xceed		Pouch cell
MERCEDES	EV: Classe B	76200	Pouch cell
	PHEV: C350e, E350e, S500, GLC 350e		Pouch cell
MINI	EV: e		Cylindrical cell
MITSUBISHI	EV: iMiEV	-	Prismatic cell
	PHEV: Oulander		Prismatic cell
NISSAN	EV: Leaf, EVALIA	-	Pouch cell
OPEL	HEV: Ampera	23629	Pouch cell
RENAULT	EV: Zoe	39464	Pouch cell
SMART	EV: ED	24019	Cylindrical cell
TESLA	EV: model S, model X, model Y, model 3, Roadster	39714	Cylindrical cell
TOYOTA	PHEV: Prius Plug-in	-	Prismatic cell
VOLKSWAGEN	EV: e-Golf, e-Up	108280	Prismatic cell
	PHEV: Golf GTE, Passat GTE		Prismatic cell
VOLVO	PHEV: V60, XC60 T8, XC90 T8, S90	21319	Pouch cell

Thanks to this data, the shares of the different types of cells are computed as follows.

Table 5.12: Distribution of cell types in 2021

	EV sales 2021	Share 2021
Cylindrical cell	63733	12%
Pouch cell	235914	46%
Prismatic cell	216133	42%
Total	515780	100%

These values refer to the year 2021. [49] There are no available forecasts about the EV sales distinguished by automakers, neither it is possible to know exactly the type of cells OEM will decide to place in the battery. However, prismatic cells are expected to become the dominant design used in EV battery packs. Energy density on the module and pack levels is highest for this type of cells and constitutes the driver for the adoption of prismatic. [13]

Due to the lack of quantitative data related to the percentage of the cells, the estimation is based on the following assumptions. Cylindrical cells will remain stable as they are represented mainly by the Tesla EV models, which are expected to cover a large portion of the market share even in the future. Therefore, the raise of prismatic cells will gradually impact and reduce the share of pouch ones. New values of share have been set for 2025, and they are considered fixed until the end of the simulation.

Finally, knowing that prismatic are experiencing an increasing trend, lower shares have been set for year 2014, when the simulation starts. Indeed, since the focus is on the end-of-life batteries reaching the end-of-life, even the values related to the EV models placed on the market before 2022 must be recorded.

Overall, the Table 5.13 describes the distribution of type of cells on the electric vehicles.

Table 5.13: Actual and expected distribution of cell types

	Share 2014	Share 2021	Share 2025
Cylindrical cell	12%	12%	12%
Pouch cell	68%	48%	28%
Prismatic cell	20%	40%	60%
Total	100%	100%	100%

5.3.3. Chemistry

In order to estimate the amount of material recovered by the different recycling processes, data about the components and chemical elements embedded in a battery pack has been gathered.

5.3.3.1. NMC content

It is important to mention that the manufacturing capacity expected in Europe will primarily target lithium-ion cells with cathodes employing nickel, manganese and cobalt (NMC) in different proportions, and anode mainly graphite. Indeed, an increasing number of car makers are choosing full NMC chemistry to achieve higher energy density and thus extend vehicle battery autonomy. [6] According to the

Global EV outlook, Nickel-manganese-cobalt already represents around 71% sale share, while nickel-cobalt aluminium accounting for most of the rest. For this reason, the developed study is focused on batteries characterised by NMC chemistry. [4]

Today NMC exist with different mass proportions and corresponding individual advantages and disadvantages. NMC 111 are characterized by a quantitatively equal composition of the elements Nickel (Ni), Manganese (Mn) and Cobalt (Co) and usually have a high chemical stability. On the other hand, NMC 811 have highest theoretical performances due to higher energy density, lower costs due to the lower share of Cobalt, but also potential safety concerns. Finally, NMC532 and NMC622 are in between the previous types described. [18]

The study conducted by the German aerospace allows to define the factors influencing the development of the NMC chemistry and set the expected future share of NMC111 and NMC 811 in the market. [18]

According to the experts' opinion, the decision on the cathode chemistry mainly depends on the rising raw material prices. As most battery manufacturers currently do not have long-term fixed price contracts with suppliers of critical materials such as cobalt, fluctuations in the prices of the corresponding metals would ultimately lead to increased battery production costs. On the contrary, nickel is characterized by a higher availability and is more widely distributed geographically. Also, a higher nickel content results in higher capacity and higher energy.

The experts interviewed strongly believe that the market share of NMC 111 will decrease drastically and that of NMC 811 will increase accordingly. However, according to the current state of the art, the increase in nickel content reduces the stability of a battery, which means that NMC 532 and NMC 622 will nevertheless remain competitive alternatives to NMC 811. The experts' opinion are translated in the following quantitative values of shares.

Table 5.14: NMC share distribution in 2020 and 2030

Battery chemistry	NMC 111	NMC 532	NMC 622	NMC 811
2020	45%	35%	20%	5%
2030	9%	14%	30%	47%

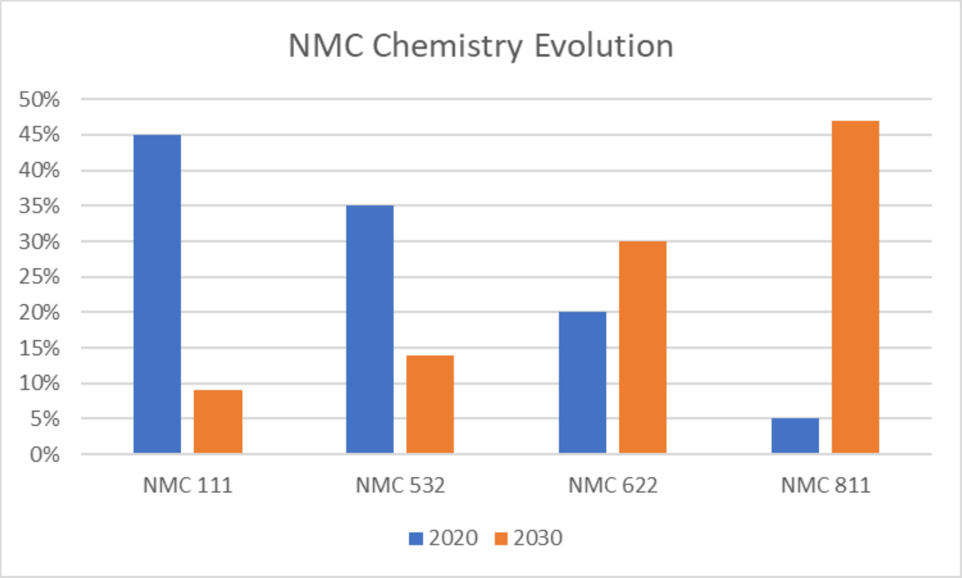


Figure 5.13: NMC share distribution in 2020 and 2030

In order to simplify the analysis, only the NMC111 and NMC811 have been included in the model and their shares have been re-computed by excluding the other types.

Table 5.15: NMC111 and NMC811 share in 2020 and 2030

	NMC111	NMC811
2020	90%	10%
2030	16%	84%

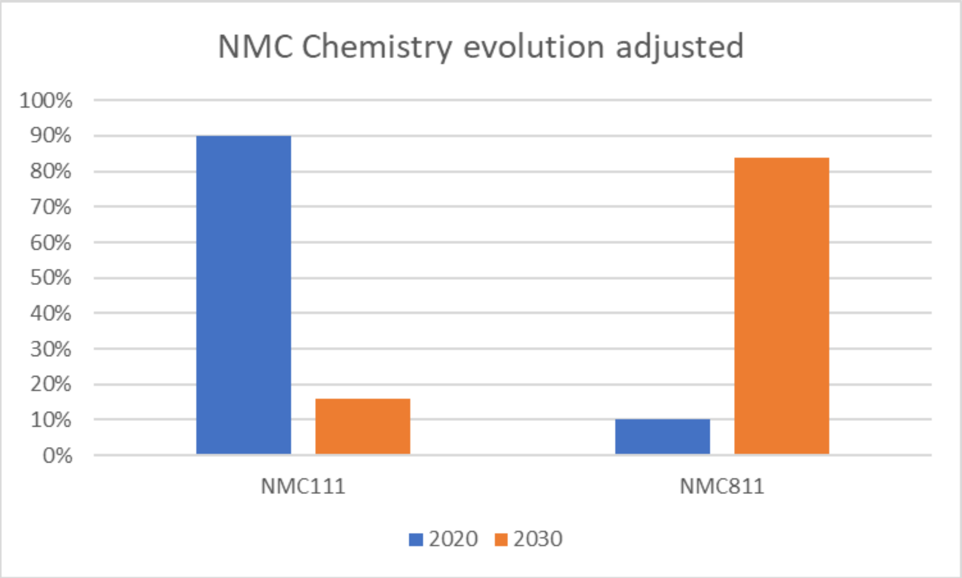


Figure 5.14: NMC111 and NMC 811 share in 2020 and 2030

Once defined the limit values for 2020 and 2030, the NMC111 shares have been linearly distributed in order to set the data needed to feed the model. Overall, an annual growth of 7% has been calculated, while after 2030 their shares are assumed to stabilize at 16%.

Table 5.16: NMC111 annual expected share

Year	NMC111
2020	90%
2021	83%
2022	75%
2023	68%
2024	60%
2025	53%
2026	46%
2027	38%
2028	31%
2029	23%
2030	16%
2031	16%
2032	16%
2033	16%

2034	16%
2035	16%
2036	16%
2037	16%
2038	16%
2039	16%
2040	16%

5.3.3.2. Material content

With the purpose of defining the material content embedded in the battery, the analysis relies on the information provided by *Q Dai et Al.* [50] The authors describe the quantity in weight of every component of several type of batteries, which differ from each other for the cell chemistry that characterize the pack. The type of cell considered in the study has been the pouch type.

Given the focus on the NCM111 and NMC 811 as previously explained, pack with this type of chemistry has been analysed.

This initial information provided referred to the pouch cells types and it has been the starting point for computing the share of materials in a battery characterized by cylindrical and prismatic cell, since type of cell differ for the material of the case. As explained previously in *Chapter 2* for the pouch type, the cathode-anode double layer housed in a soft plastic case. Instead, cylindrical cell's case is made of steel and prismatic ones of aluminium. They represent the 20% of the overall weight of the cell for the former and 18% for the latter. [26]

Through this information, the weight of each component for the three types of cells has been computed with its relative percentage. Then, these values allow to derive the information needed to feed the model according to the steps of the recycling process the battery was subject to. Indeed, each of them would lead to the removal of one or more components, and the shares of those components to properly describe the real process have to be defined.

The data is summarised in the Table 5.17.

Table 5.17: Components weight and percentage divided by cell types

	Pouch				Cylindrical				Prismatic			
	Weight		Percentage		Weight		Percentage		Weight		Percentage	
	111	811	111	811	111	811	111	811	111	811	111	811
Cell	120	112			144	136			136	128		
Active cathode	42	35	25%	22%	42	35	22%	19%	42	35	23%	20%
Active anode	26	25	16%	16%	26	25	14%	14%	26	25	14%	14%
Binder (PVDF)	4	4	2%	3%	4	4	2%	2%	4	4	2%	2%
Current collectors	29	27	17%	17%	29	27	15%	15%	29	27	16%	16%
Electrolyte	18	19	11%	12%	18	19	9%	11%	18	19	10%	11%
Plastic Case	3	2	2%	2%	-	-	-	-	-	-	-	-
Steel Case	-	-	-	-	27	26	14%	14%	-	-	-	-
Aluminium Case	-	-	-	-	-	-	-	-	19	18	11%	10%
Pack and module	45	45			45	45			45	45		
Aluminium	30	29	18%	19%	30	29	16%	16%	30	29	16%	17%
Slag	10	10	6%	6%	10	10	5%	5%	10	10	5%	6%
BMS	6	6	4%	4%	6	6	3%	3%	6	6	3%	3%
Total: Pack	165,0	157,7	100%	100%	189,7	180,8	100%	100%	181,5	173,2	100%	100%

It emerges that the percentage are similar. For this reason and to avoid having useless exponential increase in the data collected, unique values describing the share of the component have been set, regardless of the type of cell and its chemistry. An average value represented by 10% has been chosen for the case of the cells. However, to know the type of material of the case, the model is feed with information related to the share of prismatic, cylindric and pouch cell.

Table 5.18: Share of components on the total battery weight

	Percentage
Cell components	
Active cathode material	22,0%
Active anode material	15,0%
Binder (PVDF)	2,0%

Current collectors	16,0%
Electrolyte	10,0%
Plastic Case	10,0%
Steel Case	
Aluminium Case	
Pack and module components	
Aluminum	16%
Slag	6%
BMS	3%
Total: Pack	100%

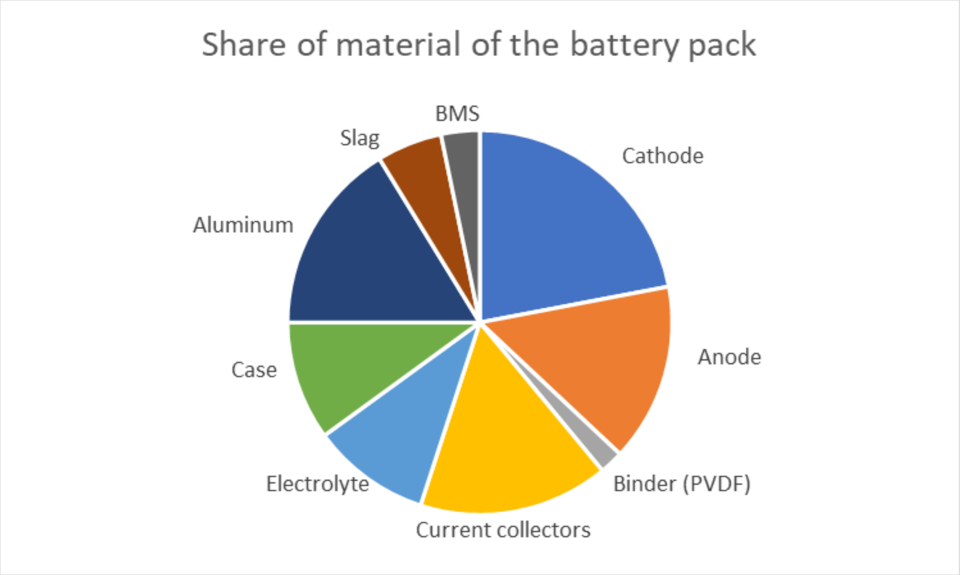


Figure 5.15: Share of materials of the battery

Finally, additional data related to the chemical elements embedded in the cathode and in the current collectors has been gathered. Current collectors are often made of copper at the anode and aluminium at the cathode.

Table 5.19: Share of Al and Cu on the total Current collector weight

Copper	65%
Aluminim	35%
Current collectors	100,0%

Instead, the share of Nickel, Manganese and Cobalt of the cathode depends on the chosen type of chemistry. The weight of elements has been identified as follows. [51]

Table 5.20: Material weight of cathode

Cell type	Stoichiometry	Molar Mass [g]	Lithium [g]	Cobalt [g]	Nickel [g]	Manganese [g]	Oxygen [g]
NMC111	$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$	95,9	6,9	19,6	19,6	18,3	31,4
NMC811	$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$	97,3	6,9	5,9	47,0	5,5	32,0

From these values, the needed shares for the model have been derived.

Table 5.21: Share of material weight of cathode

Cell type	Lithium	Cobalt	Nickel	Manganese	Oxygen
NMC111	7%	20%	20%	20%	33%
NMC811	7%	6%	48%	6%	33%

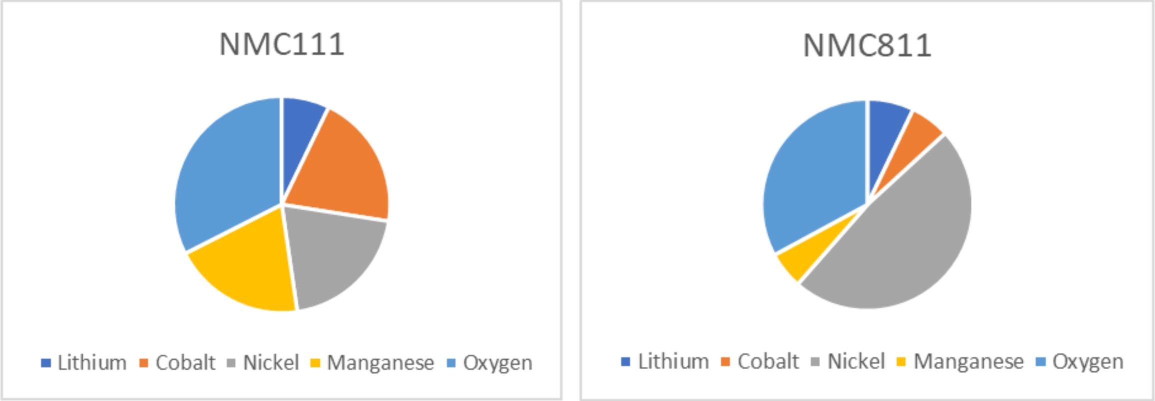


Figure 5.16: Share of materials in the cathode NMC 111 and NMC 811

5.3.4. Warranty

Warranty of battery is a significant factor because it sets the maximum operating life of the product and it is the characteristic that most effect the willingness to buy of the clients.

Residential storage systems made with new LIB cells are marketized with a warranty of 10 years. On the contrary, batteries that have been remanufactured and repurposed cannot be associated to a 10 years warranty, because their quality is not comparable to the one of a new product. Powervault 3eco and xStorage are two examples of energy storage system coming from a EoL EV batteries, realized respectively by Renault and Nissan. They have both set the warranty of the product at 3 years. [52] This energy storage systems are realized through a remanufacturing process up to the module level.

In case of remanufactured batteries down to cells level, the presence of a cell by cell diagnostic, quality oriented reassembly and certification would increase the warranty appliable to remanufactured batteries and therefore increase the market competitiveness of these products.

For this reason, in case of remanufactured batteries for stationary application, the warranty has been set to 5 years. On the other hand, 4 years has been assigned to remanufacturing batteries for automotive application, due to the higher performances required in this case.

Finally, no data have been found related to possible warranty applied to repurposed batteries for utility-scale application. However, since in this case the EoL battery is characterized by a higher SoH, its expected lifetime is considered to be at least 3 years.

Table 5.22: Second-life product and associated warranty time

Second life Strategy	Warranty time
Repurposing	3 years
Remanufacturing up to module level	4 years
Remanufacturing up to cell level for stationary application	5 years
Remanufacturing up to cell level for automotive application	4 years

5.4. Process

5.4.1. Scrap rate

When deepening the remanufacturing processes, a significant parameter is related to the scrap rate of the system, representing the percentage of cells or modules that are discarded because there are considered as too damaged. Indeed, the whole idea of repurposing and remanufacturing activities is based on the concept that only few cells are actually degraded when the battery reaches its end of life. The analysis performed by *Mathew et Al*. simulates the reliability properties of battery cells. [53] They have demonstrated that the replacement of 5–30% of the cells can bring a battery system at a state of health higher than 95% and it is justified by the presence of differences in the state of charge (SoC) between individual battery cells in a module or in a pack. The low percentage of damaged cells implies that most of them are worth recovering. The work presented by *Kampker et Al* aims at confirming the result of the simulation of Mathew et al. [9]

They have developed a research project called *BatteReMan*. The study consists in the analysis of Modules from the battery of a StreetScooter vehicle, used for six month, with two deep cycles per day and six days per week. The cells of the 18,650 type recovered from a module have been separated and tested by means of cycling between safe voltage limits.

The sample considered is made by 196 nominally rated between 2800 mAh 4.2 V and 2.7 V. According to the test, 89% of cells from a battery module are still reusable, while 9% show either low capacity and cannot be charged to the nominal voltage because of aging. This implies they have an insufficient capacity for reuse. The remaining small part shows no continuity between positive and negative terminals, or unsteady measurement values. Probably these last group of cells have been either damaged during the disassembly process or suffered severe failures in use. According to the authors, 11% of cells analysed should be sent to recycling.

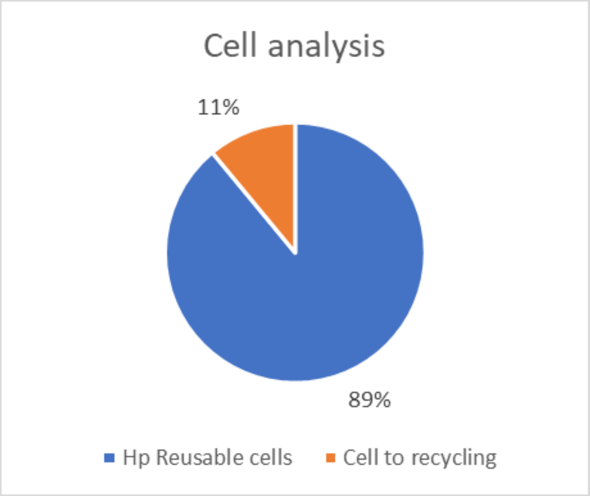


Figure 5.17: Result of the cell analysis

However, in order to get proper values for the simulation, additional considerations must be considered. Among the reusable cells, a distinction has to be made considering the second-life application of the cell under analysis. Indeed, not all the reusable cells may be suitable for the automotive applications because their SoH is not high enough fit the requirements of performance. The suitable ones correspond to the 68% of the overall sample. On the contrary, the stationary applications are less demanding and a higher share of cells, equals to 84%, may fit their requirements. Finally in both cases, a 5% of the reusable cells are probably not worth being reused, increasing share of cells for recycling.

This leads to define the following percentages characterising the cell status and allows to set the proper value of scrap rate for the remanufacturing process up to the cell level for both automotive and stationary applications.

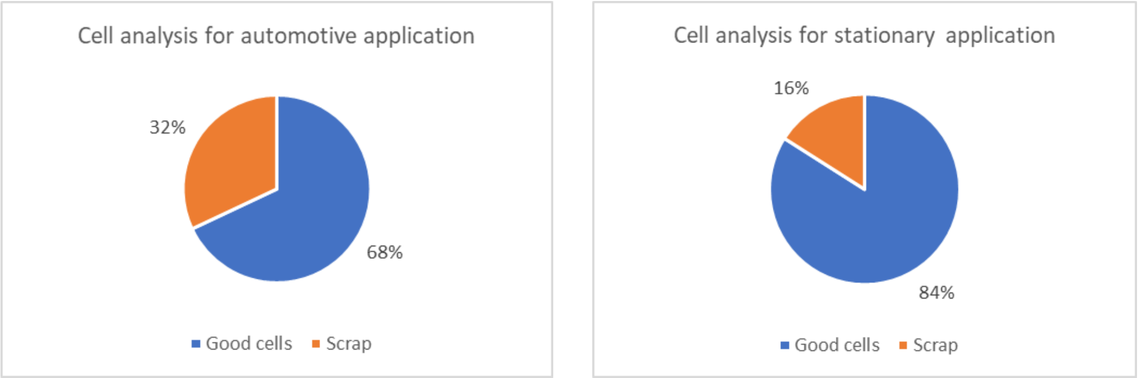


Figure 5.18: Remanufacturing process scrap rate for different applications

Considering instead the scrap rate required for the remanufacturing activity up to the module level, no papers have been found in the literature with a similar analysis that provided experimental data. However, the state of health of the modules depends on that of their embedded cells and on how these cells are positioned within the battery pack. It is worth mentioning that for this process only stationary systems are considered as second-life applications, which implies that the number of deteriorated cells just derived is low. Moreover, they can be assumed to be uniformly distributed within the battery pack, especially considering that the deteriorated cells are usually the ones close to the border, as they are exposed to higher contact resistance. Based on this reasoning, the share of failed modules has been set at a relatively low value of 30%.

Overall, the values are summarised in the table below.

Table 5.23: Scrap rate associated to the process

Process	Scrap rate
Remanufacturing up to module level	30%
Remanufacturing up to cell level for automotive	32%
Remanufacturing up to cell level for stationary application	16%

5.4.1.1. Recovery rate

The last step to compute the exact quantity of materials extracted from the battery is collecting information about the recovery rate of the recycling process. Despite this value usually depends on the type of technological process considered, this study has been structured to give priority to the target set by the European Parliament and the council. Indeed, the *Proposal for a regulation concerning batteries and waste batteries* has defined both values for minimum recycled content in the new battery pack and the recovery rate. These percentages are strictly related, as the target level of recycled materials can be achieved if mandatory recovery rates for the critical raw materials are set. [6]

Table 5.24: Recovery rate baseline and target

	Recovery rates		
	Baseline 2020	Target 2030	Target 2035
Nickel	80%	90%	95%
Cobalt	80%	90%	95%
Lithium	10%	35%	70%
Copper	80%	90%	95%

Moreover, according to the EU regulations, processes not able to satisfy these requirements may be put to a halt. These values are supposed to encourage the development of high-quality and cost-efficient recycling technologies to treat lithium batteries and they have been chosen to describe the recovery rate of the processes within the simulation model.

5.4.1.2. Cell Production capacity

The last table function of the model describes the European production capacity of lithium cells. Today European manufacturing capacity of lithium-ion cells for electric cars and energy storage is roughly 35 GWh per year and the main battery factories are located in Poland and Hungary. The EU does not have yet a large-scale production capacity, but this is rapidly changing since consolidating an EU battery value chain is particularly important for the EU automotive sector due to the high share of EV sales. [6]

Supported by EU-centralized initiatives as the European Battery Alliance and the European Investment Bank, the European Li-ion cell production capacity is estimated to reach 370 GWh/year in 2025 and furtherly increase by 2030 to more than 800 GWh/year. [54] The main ongoing and planned battery cell factories are reported in the Figure 5.19.

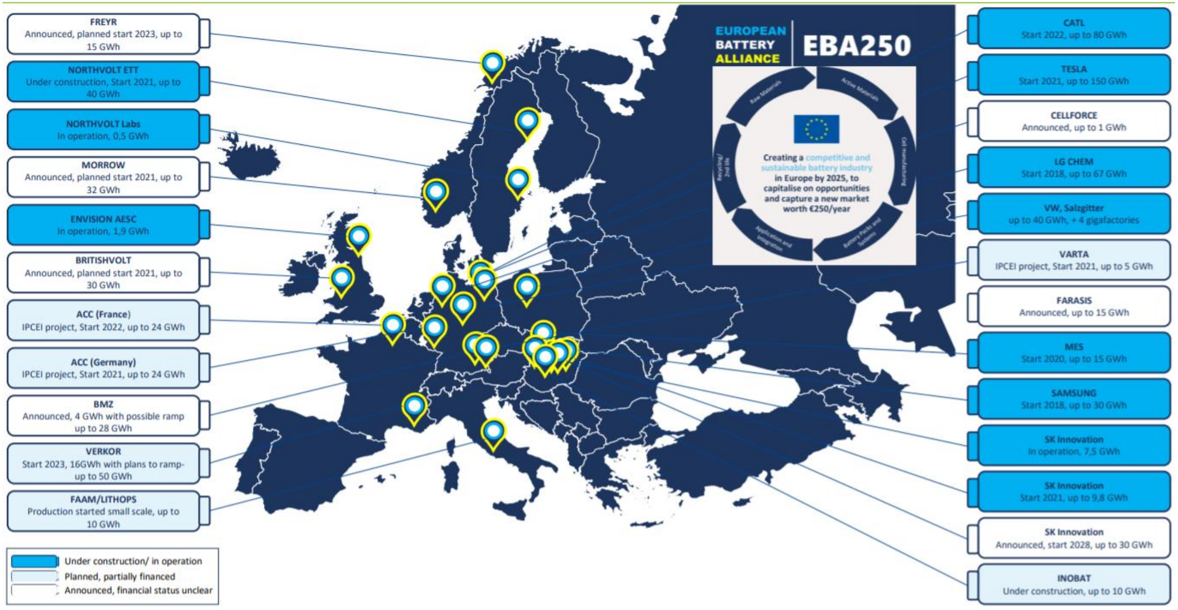


Figure 5.19: Announced production capacity installation in Europe

If these levels of production materialise, this capacity could serve the demand in Europe in 2025 considering both electric vehicles and storage applications and it would make the EU the second highest region of production worldwide. [6]

Uncertainty about the expected demand of batteries rises in the medium and long terms, making the levels of production after 2030 difficult to be know. It is estimated that the minimum and a maximum scenario for battery capacity demand generated by electric vehicles and energy storage solutions will cover respectively 1500 GWh and 2400 GWh in 2049. [55] Assuming that the new installed production will follow the demand curve, these values have been considered as a reference to maintain the raising trend of cell production from 2030 to 2040 and feed the model with reliable data.

Moreover, they have provided information about the average percentage considered to cover the cell production devoted to the automotive application, which is set at 80%. Indeed, the study considers the production of the EV batteries and excludes the ones manufactured for storage system because it is focused only on the automotive sector for what concerns the first life application of the battery.

Table 5.25: Cell production destinated to automotive battery application

	Total production	EV Battery production
2020	35	28
2021	102	81,6
2022	169	135,2
2023	236	188,8
2024	303	242,4
2025	370	296
2026	456	364,8
2027	542	433,6
2028	628	502,4
2029	714	571,2
2030	800	640
2031	880	704
2032	960	768
2033	1040	832
2034	1120	896
2035	1200	960
2036	1280	1024
2037	1360	1088
2038	1440	1152
2039	1520	1216
2040	1600	1280

5.5. External factors

The implementation of second-life strategies to treat EV batteries is strongly related to two external factors. On the one hand, the technological development of machines and equipment to perform remanufacturing activities is required to be in a mature phase in order to ensure its feasibility and its economic sustainability. On the other, the definition of European regulation and standards is crucial for the market. Thanks to them, economic actors are enabled to put on the market a product compliant to a same set of regulations, and to get a common certification for warranty. Indeed, introducing standards on the testing procedures is significant because it ensures the safety of the battery for the end user, introduces a shared methodology to measure the performances of the remanufactured products and enables the comparison between different products.

Given this considerations, three parameters have been introduced in the model to describe these external factors. Their values have been modified during the simulation run, in order to capture the development of the market and the expected changes in terms of technological progress and regulation updates.

5.5.1. Certification for warranty

The certifications for warranty are related to the development of the CEN and CENELEC standards, which have been required by the European Commission. As deepened in *Chapter 2*, a so-called 'Standardization request' has been formalized to the CEN and CENELEC organizations in order to introduce standards on four specific deliverables. [34]

Table 5.26: Standards mentioned in the *Standardization Request*

Reference information	Deadline for the adoption

1.	European standard(s) on performance and durability aspects of portable rechargeable and non-rechargeable batteries	07 December 2025
2.	European standard(s) on performance and durability aspects of rechargeable batteries with internal energy storage	07 December 2025
3.	European standard(s) on the re-use and repurposing of rechargeable batteries with internal energy storage: • Design • Diagnostic and determination of the SoH • Battery evaluation for repairing and repurposing	07 December 2025
4.	European standard(s) on the safety aspects of stationary battery energy storage systems with internal energy storage	07 December 2025

Particularly significant for the purpose of the simulation is the third point, related to the standards on the re-use and repurposing of rechargeable batteries within internal energy storage. This point relates to the definition of guidance on the design and assembly techniques, to the description of procedures for the determination of the SoH of batteries, and to protocols for the safe repair, re-use and repurpose of battery packs, modules and cells. The introduction of these standard allows to set warranties compliant to the same set of rules and to make comparison between the different remanufactured products.

As explained in *Chapter 2*, the progress of the work item realized by the technical committee and supervised by the CEN organization is available for consultancy by the interested economic actors.

For this reason, soon after the deadline, some actors can be considered to be already equipped with the required testing procedures to obtain the certification compliant to the new standard for their products' warranty. It is clear that these standards are enabler for performing remanufacturing activities, both at module and cell level.

Focusing on the simulation model, this progress has been described by a parameter called 'Certification for warranty'. Set equal to zero at the beginning of the run, it is then changed in 30% in 2026 in order to describe the percentage of actors ready to perform remanufacturing activities and be compliant to the legislation. In 2028 is turned in 70%, to include new possible actor and, it is finally changed into 100%, in order not to limit anymore the amount of batteries that can hypothetically be sent to remanufacturing.

Table 5.27: Values of Certification for warranty variable over time

Year	Certification for warranty
Initial value	0
2026	0,3
2028	0,7
2030	1

5.5.2. Availability of information

One of the critical factors for the business development is the possibility to access information about the state of health of the batteries, because it sets the optimal strategy for the specific battery depending on its quality. As previously explained, this information is stored in the BMS of the battery but it is not easily accessible, because nowadays automakers are not willing to provide this type of data.

Having recognise the limitation coming from the lack of information, the commission of the European Union has dedicated a specific measure to tackle this problem in the *Proposal for a regulation on batterie and waste batteries*. [6] The measure number 12 concerns the availability of reliable information and has the objective to guarantee suitable data to end-users and economic operators for the safe and sustainable use of batteries and the relevant activities within related value chains.

The introduction of the measure is supposed to be described through three different sub-measures. [6]

- Provision of basic information, technical parameters, end-of-life information and general compliance with EU legislation (as labels, technical documentation or online);
- Provision of specific information to end-users and economic operators (end-of-life, refurbishment and repurposing, energy efficiency);
- Realisation of an electronic information exchange for batteries and a battery passport (for industrial and electric vehicle batteries only);

The first one is mainly impacting the sorting and recycling activities, as it allows to provide specific information about the battery types and cells. Moreover, it aims at reducing the fire risks of from lithium-ion batteries during collection, storage, removal and recycling.

The others are much more interesting for the purpose of the study, because they concern the accessibility to the information of the state of health of the battery once it reaches its end-of-life. In particular, the second one extends the types of data provided by the label and obliges producers to generate and make available to end-users information regarding both the initial and usage phase of the battery. This implies having access to data about the remaining capacity, considering both individual cells and module degradation. This information would be provided as part of the technical documentation accompanying the battery or the appliance where the battery is incorporated and, in any case, via online, accessible through bar and QR codes. These two sub measures are expected to be introduced in 2023.

Finally, the last step states the introduction of a battery dataspace and a battery individual ‘passport’ with a unique digital ID for each EV battery placed on the market. Each battery has an individual digital record fed by the static information, and updated with the dynamic information generated throughout its lifecycle. This mainly includes important transactions such as date of placing on the market, repurposing actions and second life. Having data about the ageing of the battery directly impacts the choices for potential second lives. This last submeasure is defined to be introduced in 2026. [6]

These regulation developments have been incorporated in the system through the parameter called battery passport. Following a similar logic for the one adopted to the certification previously described, the value of the parameters has been multiplied for the flows of batteries with high and medium state of health, in order to limit the amount of batteries in the channel. Indeed, even if hypothetically the share of products in good condition is known to be high, not having access to the battery data is expected to impact the collection and sorting of the battery. For this reason, this parameter has set equal to 0 at the beginning of the run, meaning that all the battery types are sent to recycling due to the lack of data, regardless of their state of health. Then, it has been changed during the simulation run in following the evolution of the regulation. The introduction of mandatory information for the end-users is assumed to increase the visibility on the state of health of the battery, reaching a 50% while the setting up of the data exchange system and the battery passport allow to set the parameter equal to 100%, meaning that all the data about the SoH are available and the battery are properly distributed depending on their state. The values are summarized in the table.

Table 5.28: Values for Battery passport variable over time

Submeasure	Year	Battery passport value
Baseline	Initial value	0
Provision of specific information to end-users and economic operators	2023	0.5
Realisation of an electronic information exchange for batteries and a battery passport	2026	1

5.5.3. Technology available

In *Chapter 2*, the main criticalities related to the development of the remanufacturing activities up to cell level on a large scale have been deepened. In particular, the testing procedures at cell level can be very long and require expensive equipment. Moreover, reassembly and disassembly activities need to be properly designed in order not to damage cells and their feasibility analysis must be properly assessed from an economic and safety point of view. [9]

For all this reason, it is unlikely to consider remanufacturing processes up to cell level to be implemented on a large scale in the short run. This limitation needs to be translated in the model, and a specific parameter has been introduced to capture this external factor.

The tech_cell_availability parameter is multiplied for the flows sent to remanufacturing activities up to cell level, in order to limit their quantities. At the beginning of the simulation, this parameter is set equal to zero to describe the lack of actors properly equipped with machineries to perform the remanufacturing process. Later, it has been modified according to the experts' opinions. In particular, in 2025 its value has been changed in 50%, to capture an initial development of the industry and describe the presence of some remanufacturers. Finally, it is supposed to reach 100% of technological availability in 2030, when it is reasonable to assume that all flows directed to remanufacturing up to cell level can be treated. The following table summarizes this value.

Table 5.29: Values of technology available for cell over time

Year	Technology available for cell
Initial value	0
2025	0.5
2030	1

5.6. Data for profitability

A supplementary analysis has been performed to assess the profitability of the second-life strategies and the recycling processes included in the model.

For this purpose, a business plan drawn up by experts of CIRC-ev laboratory of Politecnico di Milano has been taken as reference for most of the OPEX values in the following evaluations.

Since for this project has been signed a non-disclosure agreement, only aggregated data are reported. The cost items have been declined in detail in the tables available in the Appendix A. They have been computed considering the following fixed parameters.

Table 5.30: Operator annual cost computation

	Quantity	**Unit**
Working days	250	day/year
Hours / shift	7,5	h/day
Operator annual cost	75000	€/year

Table 5.31: Average energy density of battery and cell

	Pack energy density (Wh/kg)	kWh	kg	Modules/ pack (%mass)	Modules/ pack (kg)	Module Energy density (Wh/kg)
EV battery	155	55	355	75%	266	206,7
PHEV battery	140	14	100	75%	75	186,7
Avg battery	148		227	75%	171	196,7

5.6.1. Cost - Repurpose and remanufacturing processes activities

Cost–benefit analyses are essential to evaluate the economic profitability of secondary use of retired EV batteries. This section provides the data considered for establishing some priorities in the distribution of volumes in the model.

Firstly, for each second life strategy has been identified the all the processes and activates involved, as it shown in the table below.

Table 5.32: Activities involved in each second life strategy

	Repurpose	**Remanufacturing up to module level**	**Remanufacturing up to cell level**
Testing pack	X	X	X
Disassembly pack to module (manual)		X	X
Testing module		X	X
Disassembly module to cell (manual)			X
Testing cell			X
Reassembly cell to module			X
Reassembly module to pack		X	X
Testing after remanufacturing to certificate battery state		X	X
Pack assembly	X (SS large)	X (SS large)	X (SS large)

Then, each process has been evaluated in terms of OPEX, expressed in €/ton.

Table 5.33: Opex estimation for Repurposing

Repurposing	(€/ton)
Testing pack	/
Pack assembly	132
OPEX	**132**

Table 5.34: Opex estimation for Remanufacturing up to module level

Remanufacturing up to module level	(€/ton)
Testing pack	/
Disassemby pack to module	355
Testing module	/
Reassembly module to pack	176
Testing to certificate battery state	/
OPEX	**531**
Pack assembly	132
OPEX	**663**

Table 5.35: Opex estimation for Remanufacturing up to cell level

Remanufacturing up to cell level	(€/ton)
Testing pack	/
Disassemby pack to cell	591
Testing module	/
Testing cell	/
Reassembly cell to module	1041
Reassembly module to pack	176
Testing to certificate battery state	/
OPEX	**1808**
Pack assembly	132
OPEX	**1940**

It is important to highlight that it has not been possible to estimate testing costs due to unavailability of information. However, they can be considered negligible since testing is performed on stations in parallel that can be overseen simultaneously by one operator that must not be present during the whole test, which lasts at least one hour.

For what concerns disassembly and reassembly activities, in most of them the operator cost is predominant since lots of operations are performed manually.

The disassembly of the modules and cells is time-consuming but can be performed by different trained and specialized operators at the same moment, thus decreasing the total amount of time needed for the disassembly.

Remanufacturing of pack and module with a disassembly and reassembly up to cell level is characterized by a total OPEX much higher than the other strategies one. This is due to the high cost of reassembling cell into a new module. However, this is the main adding value activity with which EoL batteries are restored to a product with specifications near to the original one.

In particular, the reassembly cell to module level is the result of two in series activities the mechanical assembly and the laser welding. The former lasts five minutes per module and requires new busbar as consumables. The latter lasts twenty minutes per module and ring a significant cost due to inert gases consumption.

The reassembly module to pack is performed with manual operations that last one hour per battery pack. No consumables are needed since the components removed during the disassembly are here reused.

The pack assembly activity has to be added in the computation of the total OPEX only in case of storage systems large as second life application.

5.6.2. Benefit - Battery price for second-life strategies

The market price for a secondary battery has been defined considering the battery pack alone to be able to compare the different second life products.

The prices for second-life application batteries have been set starting from the average price of a battery pack for Electric vehicles, residential storage systems (small) and storage systems large.

Table 5.36: Price of new batteries in different applications

Price (€/kWh)

EV battery new	500
Storage system small battery new	370
Storage system large battery new	150

Then, it has been assumed that a customer will be willing to pay for a secondary battery if it has a price-warranty ratio that is at least equal to the new batteries one.

Price new battery: Warranty new battery = Price second-life battery: Warranty second-life battery

Table 5.37: Warranty time of batteries obtained through different processes

Warranty time			
	EV	**Storage system small**	**Storage system large**
Battery new	8	10	10
Battery from remanufacturing up to cell level	4	5	5
Battery from remanufacturing up to module level	-	4	4
Battery from repurposing	-	-	3

Table 5.38: Price reduction in percentage according to the different strategies

Percentage price reduction	
Battery new	100%
Battery from remanufacturing up to cell level	50%
Battery from remanufacturing up to module level	40%
Battery from repurposing	30%

Matching the second life strategies with the automotive and storage systems applications, the following prices has been obtained.

Table 5.39: Prices of different batteries obtained through different processes

Price (€/kWh)			
	EV	**Storage system small**	**Storage system large**
Battery new	500	370	150
Remanufacturing up to cell level	250	185	75

Remanufacturing up to module level	-	148	60
Repurpose	-	-	45

Once defined the accepted prices, they have been compared with the previous OPEX in order to determine what has been called the partial margins.

To do so, the processes OPEX expressed in €/ton has been converted in €/kWh considering an energy density of an average battery pack.

Table 5.40: Opex in euro per ton

OPEX (€/ton)			
	EV	**Storage system small**	**Storage system large**
Remanufacturing up to cell level	1808	1808	1940
Remanufacturing up to module level	-	531	663
Repurpose	-	-	132

Table 5.41: Average battery energy density

Energy density	
	Wh/kg = kWh/ton
Battery full electric	155
Battery hybrid	140
Average battery pack	**148**

Table 5.42: Opex in euro per KWh

OPEX (€/kWh)			
	EV	**Storage system small**	**Storage system large**
Remanufacturing up to cell level	12,2	12,2	13,1
Remanufacturing up to module level	-	3,6	4,5
Repurpose	-	-	0,89

Table 5.43: Partial margin in euro per KWh

Partial margin (€/kWh)			
	EV	**Storage system small**	**Storage system large**
Remanufacturing up to cell level	238	173	62
Remanufacturing up to module level		144	56
Repurpose			44

The estimations made are useful to highlight how attractive different strategies could be and to compare the profitability of the same second life product coming from different processes. However, there is a limitation due to the data available today. The above second-life strategies margins are overestimated since they do not take into account the residual value of EoL batteries that could turn into a price to be paid to the upstream actor in the supply chain and that could be different in case of a EoL battery with different SoH.

5.6.3. Cost - Recycling processes activities

For recycling has been followed the same scheme seen above. Each recycling alternative has been associated with all the processes and activates involved, as it is shown in the table below.

Table 5.44: Activities involved in each recycling process configuration

	Recycling Pyrometallurgical	**Recycling Hydrometallurgical**	**Recycling Hydrometallurgical best case**
Testing Pack	X	X	X
Disassembly pack to module (manual)	X	X	X
Disassembly module to cell (manual)			X
Mechanical pre-treatment	X	X	

High Voltage Fragmentation pre-treatment			X
Pyrometallurgical treatment	X		
Hydrometallurgical treatment		X	
Cell cutting mix Cylindrical and Prismatic			X
Froth flotation			X
Re-Lithiation			X

The pyrometallurgical, the hydrometallurgical and the best case of hydrometallurgical (direct recycling) recycling process has been evaluated in terms of OPEX, expressed in €/ton.

Table 5.45: Opex estimation for Pyrometallurgical recycling

Pyrometallurgical Recycling	(€/ton)
Testing pack	/
Disassemby pack to module	355
Mechanical pretreatment	166
Pyrometallurgical treatment	1626
OPEX	**2147**

Table 5.46: Opex estimation for Hydrometallurgical recycling

Hydrometallurgical Recycling	(€/ton)
Testing pack	/
Disassemby pack to cell	591
Mechanical pretreatment	166
Hydrometallurgical treatment	1500
OPEX	**2257**

Table 5.47: Opex estimation for Hydrometallurgical best case recycling

Hydrometallurgical best case Recycling	(€/ton)
Testing pack	/
Disassemby pack to cell	591
Cell cutting mix Cylindrical and Prismatic	1168
High Voltage Fragmentation pretreatment	212
Froth flotation	/
Re-Lithiation	800
OPEX	**2771**

5.6.4. Recycled raw material price

The market value analysis of virgin and recycled LIBs constituent materials and precursors is provided in Table 5.48.

Table 5.48: Prices of recycled materials

Recycled re-usable output fraction	**Cost of the recycled re-usable output fraction**	**Sources**
Lithium Hydroxide	< 13,0 €Kg)	https://www.lme.com/Metals/EV
Lithium Carbonate	< 13,0 €Kg)	https://tradingeconomics.com/
		https://www.lme.com/Metals/EV
Ni-BASED	< 25,00 €/Kg	https://www.alibaba.com
Al-Based	< 0,30 €/Kg	https://www.alibaba.com
Co-BASED	< 20,00 €/Kg	https://www.metalbulletin.com/
Mn-Based	< 0,50 €/Kg	https://www.indiamart.com/ https://www.alibaba.com
Graphite	< 0,40 €/Kg for Internal Application	https://www.focusgraphite.com/
	If re-synthetized: < 12,00 €/Kg	https://westwaterresources.net/
Polymers/Separators	< 8,00 €/m²	https://www.indiamart.com/ https://www.alibaba.com
Al supports foils	< 2,50€/Kg	https://www.mtixtl.com/ https://www.alibaba.com
Cu supports foils	< 3,00 €/Kg	https://www.mtixtl.com/ https://www.alibaba.com
Electrolytes	< 3,50 €/Kg	https://www.chemicalbook.com/
		https://www.mtixtl.com/
Fluorinated Binders, PVDF	< 25,00 €/Kg	https://www.mtixtl.com/
		https://www.alibaba.com

6 Model simulation and results

The main benefit of the model is the overall view of the value chain that it provides. This is enabled by the multiple aspects that the model considers and ties together, resulting in a complex ecosystem composed of:

- The volumes that are placed on the first market, that after some years reach the end of their life and constitute a possible offer for second life applications.
- The demand of second-life applications that channels these volumes into different strategies.
- The representation of the production, the remanufacturing processes, and the recycling processes.

The model allows making forecasts to many actors in the value chain since it is able to give outputs on different aspects they can be interested in. Those outputs are the result of several factors that evolve over time and interact with each other.

For this reason, the model can be useful to define multiple scenarios that users can get by setting different values associated to variables and parameters.

In this way, the users can evaluate how the outputs change when inputs are modified and also better understand the role that each variable plays on the overall results.

Here below are displayed the data and plots provided by the model during the simulation run.

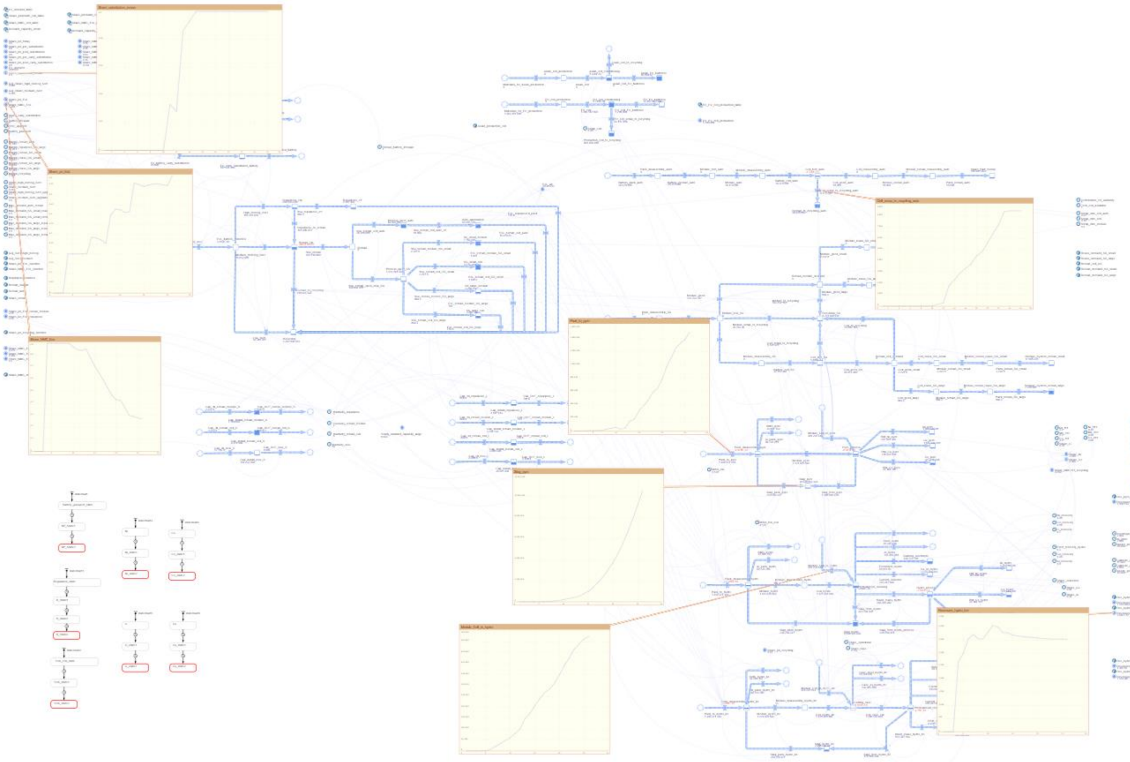


Figure 6.1: Plots provided by the model during the simulation run

The macro-areas of findings get from the simulations performed are the following:

- Estimation of End-of-life EV return flow over the years;
- Evaluation of remanufacturing impact on return volumes;
- Estimation of volumes to recycling over the years;
- Comparison between three recycling processes based on profitability analysis.

6.1. End-of-life EV Li-Ion batteries

Given the raising volumes of EV sales, the end-of-life Li-Ion batteries are forecast to increase in the next years until reaching almost 3 million batteries in 2030, representing 480K tons. These values are based on the chosen STEP scenario (iea), which is more conservatives in terms of volumes sold if compared to the SDG one.

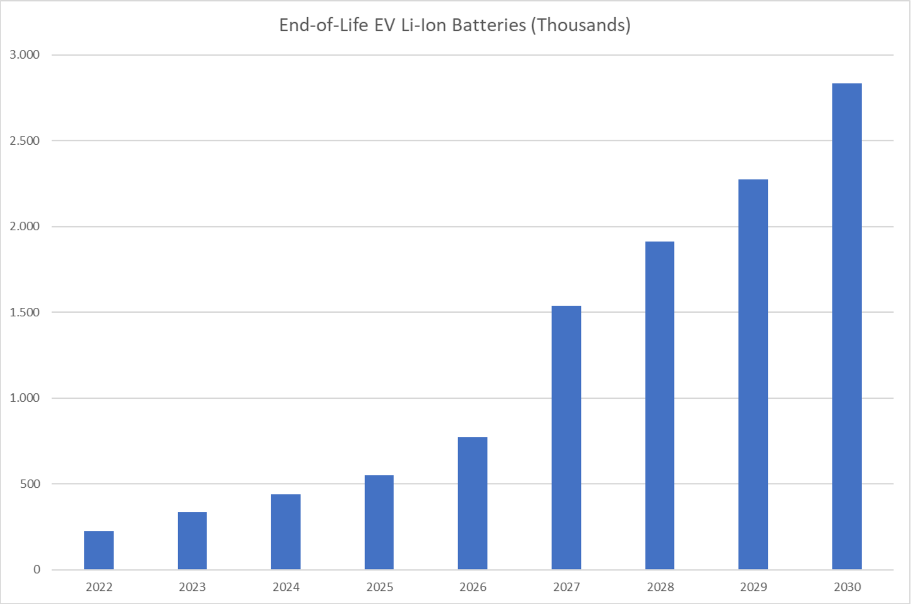


Figure 6.2: End-of-Life EV Li-Ion Batteries

Thanks to the evolution of the information availability, the classification of batteries according to the state of health is expected to be feasible and simplify the sorting of the products at the end of the first life. According to the analysis, the majority of end-of-life batteries are characterized by high residual capacity that could be exploited through second life. Indeed, only a small share of batteries is considered to be so damaged to be sent directly to recycling.

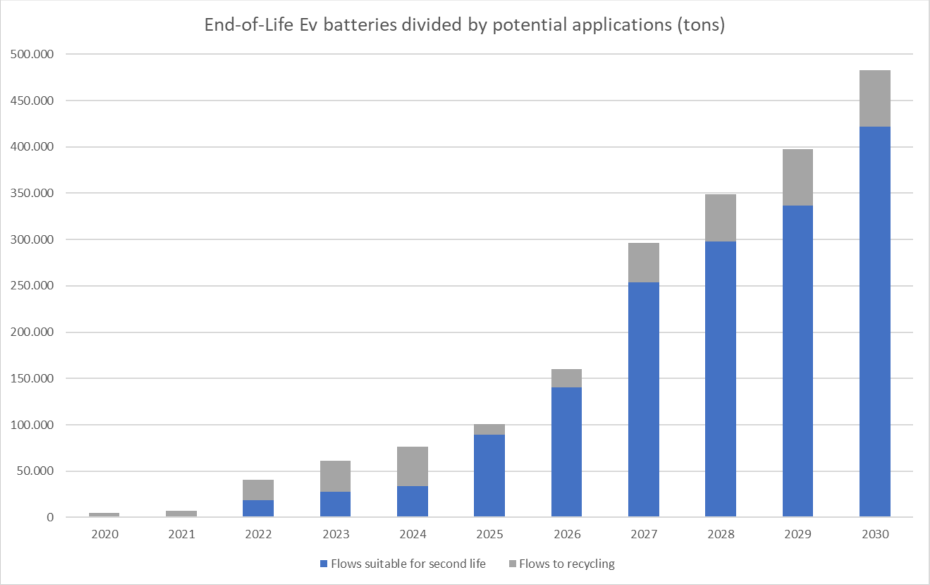


Figure 6.3: End-of-Life EV Li-Ion Batteries by potential applications

Given the high volumes of potential supply for second life application, further analyses have been developed to understand the real evolution of the circular economy strategies.

For what concern the supply side, the analysed barriers are expected to be overcome in the following years, leading to a development of the remanufacturing activities. On the other hand, the demand side is mainly constrained by the maximum willingness of the customers to buy a second life product. Indeed, the potential demand market for remanufactured product has been described as the portion of customers interested in a second-life product within all the potential customers.

In order to properly quantify the potentiality coming from second life market applications, different scenarios have been run, setting different value for the maximum willingness of the customer to buy a second life product in the different markets.

Table 6.1: Customer willingness for second life products in Scenario 1 and 2

	Scenario 1	Scenario 2
Customer willingness for automotive application	10%	50%
Customer willingness for residential stationary application	20%	60%
Remanufacturing up to module level	10%	30%
Remanufacturing up to cell level	10%	30%
Customer willingness for utility-scale stationary application	30%	60%
Repurposing	10%	20%
Remanufacturing up to module level	10%	20%
Remanufacturing up to cell level	10%	20%

It is hard to predict how customers will behave and a more detailed analysis of customers' preferences may be required.

As explained in *Chapter 4*, the demand of storage systems obtained through different strategies are considered separately. Indeed, given the different quality performances expected by the batteries, they are assumed to satisfy different types of customers, classified in distinctive clusters. As a consequence, for the storage system applications, the overall portion representing clients willing to buy a second-life products results by summing up the maximum demand covered by each single strategy.

When considering the automotive applications, the potential market is represented by the customers who need a battery substitution at a given year. Limiting the demand by the percentage describing the willingness of the clients allows to derive the available market, so the customers interested in the product. However, only users of prismatic cells batteries can really purchase a remanufactured product, since the substitution of the battery is assumed to be done with a battery having the same cell types of the previous one.

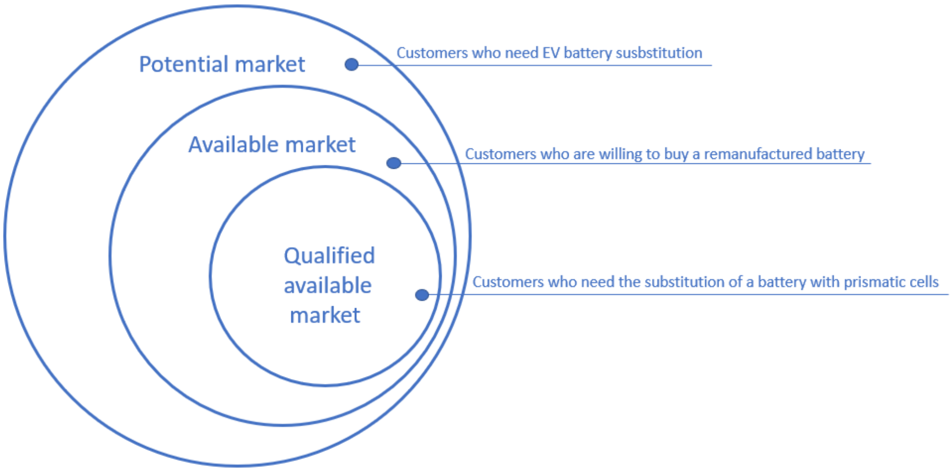


Figure 6.4: Description of potential, available and qualified available market

The following paragraphs describe the results obtained and show a comparison between the two scenarios.

6.2. Second life strategies

The first output to be analysed is the evolution of the share of batteries with prismatic cells reaching the end-of-life. Indeed, this information is extremely useful to determine the availability of batteries for the automotive sectors and the possibility to perform remanufacturing activities up to cell level.

The shape of the curve is influenced by the fact that input data follow a growing step curve. The data of the end-of-life batteries are determined by considering the vehicles performing a battery substitution at a given year.

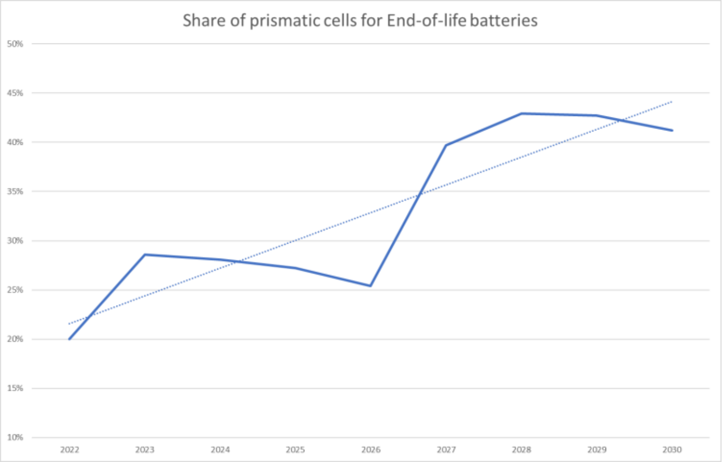


Figure 6.5: Evolution of share of prismatic cells for EoL batteries

6.2.1. Automotive applications

Supply is constrained by technological evolutions, development on the standards for certification for warranties and the portion of prismatic cells available from end-of-life batteries. Indeed, remanufacturing for automotive applications required reaching a cell disassembly level, which is assumed to be performed only on prismatic cell types.

The improvement in the gradual reduction of this barriers leads to the increase of volumes processed with remanufacturing.

Even the demand side is influenced by the amount of batteries with prismatic cells that need to be substituted in a given year, since they are the only substitutable with remanufactured batteries.

The customer willingness is the main driver on the demand side for the remanufacturing strategies, as the two scenarios shows different distribution of flows.

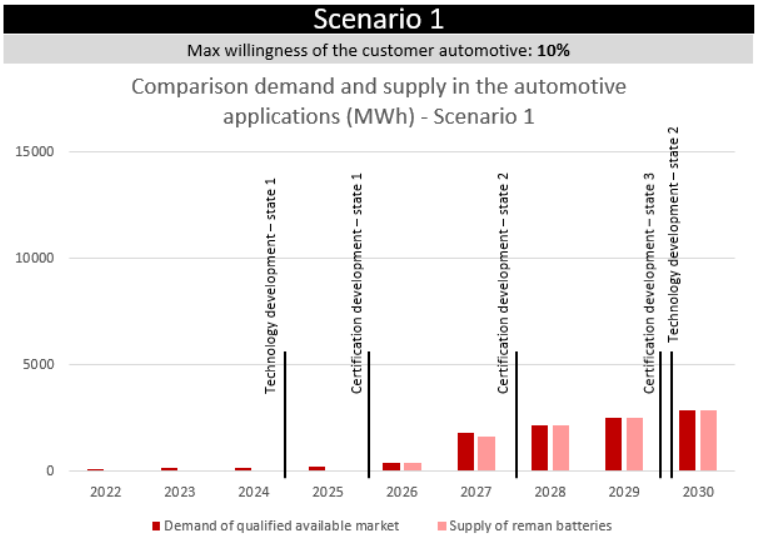


Figure 6.6: Remanufacturing for automotive application in Scenario 1

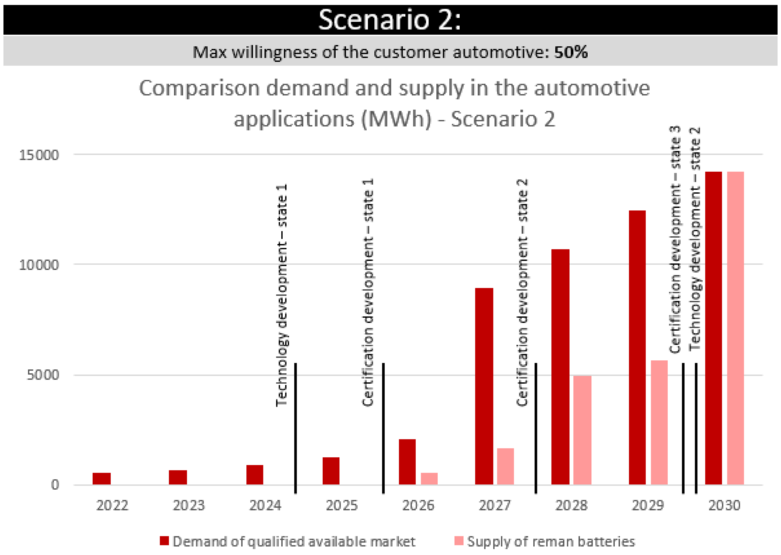


Figure 6.7: Remanufacturing for automotive application in Scenario 2

In the case of low value of willingness of the clients, the possible share of market to be covered with remanufactured products are totally reached in 2028. On the contrary, increasing the value of maximum customer willingness raises the demand, so that the total available supply is not able to completely satisfy the market before 2030.

6.2.2. Residential stationary systems applications

Similar reasonings can be developed for the stationary applications. Insights have been derived focusing on the stationary application for residential storage systems because of the higher reliability of data on the demand related to this application. Diversified analyses have been realized for products resulting from remanufacturing up to module level and remanufacturing up to cell level strategies. Indeed, customers are assumed to be different, and supply is constrained by the availability of prismatic cells only in the latter case.

6.2.2.1. Remanufacturing up to module level

The former case shows that the maximum share of market to be covered with remanufactured up to module level products are totally reached in 2026 for both scenarios. As soon as standards improvement in relation to the certification of warranties materialize, the return flows of end-of-life turn out to be high enough to satisfy this demand. The only constraint is related to the willingness of the clients.

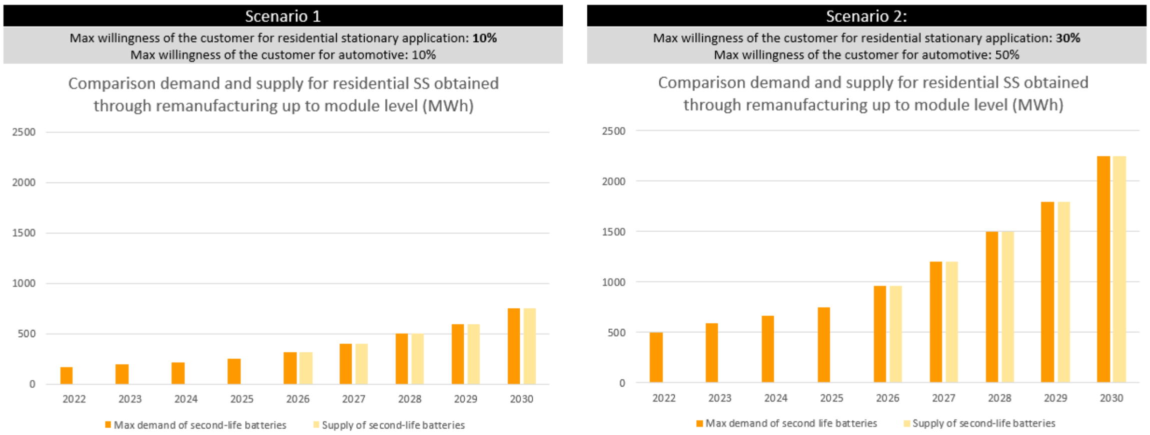


Figure 6.8: Remanufacturing up to module level, Scenario 1 and 2 in small SS

6.2.2.2. Remanufacturing up to cell level

For remanufacturing up to cell level the situation is different. In this case, it is important to note that the model priorities the remanufacturing for automotive sector when directing flows, because of a higher expected profitability of this application. For this reason, when the demand of automotive spare parts increases, less batteries are available for residential storage systems. This translates into a shortage of batteries available for storage application in scenario 2, which shows an offset of supply in 2030. Indeed, prismatic batteries' flows have been already used to cover the high demand represented by automotive applications, that in 2030 furtherly increases because of technological and regulation enablers are assumed to improve.

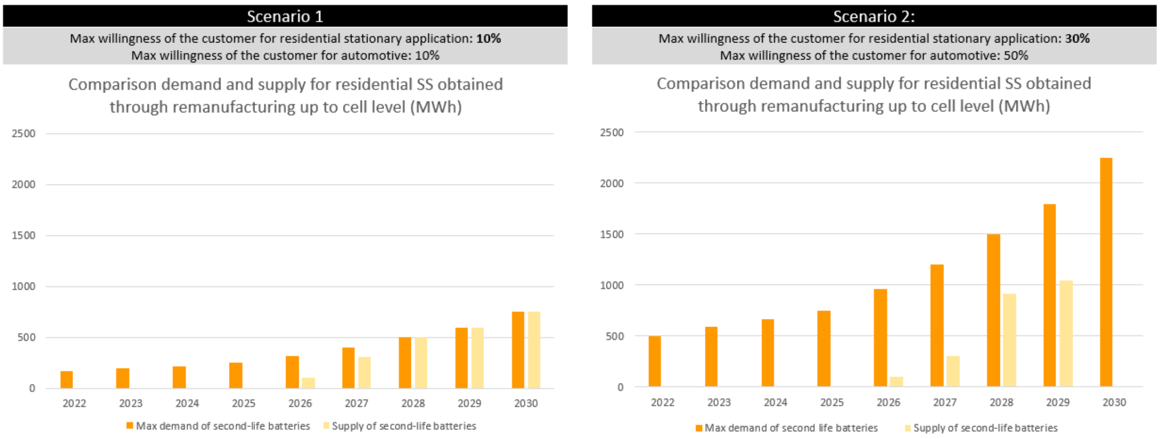


Figure 6.9: Remanufacturing up to cell level, Scenario 1 and 2 in small SS

Even if the case of 50% of customers being willing to buy a remanufactured spare part battery is hard to materialize, results quantitative display how second life markets are intertwined, and how one market can cannibalize the other. It is significant to understand how a certain market is more likely to behave in order to properly quantify the possible available return flows of batteries.

6.2.3. Recycling and second life strategies

By comparing the actual applications of the return flows with their potential application previously computed, it emerges that the high residual capacity of batteries is not completely exploited. In 2030 the barriers for the development of the remanufacturing activities are assumed to be overcome. However, in both scenarios only a portion of the available batteries are dedicated to second life applications.

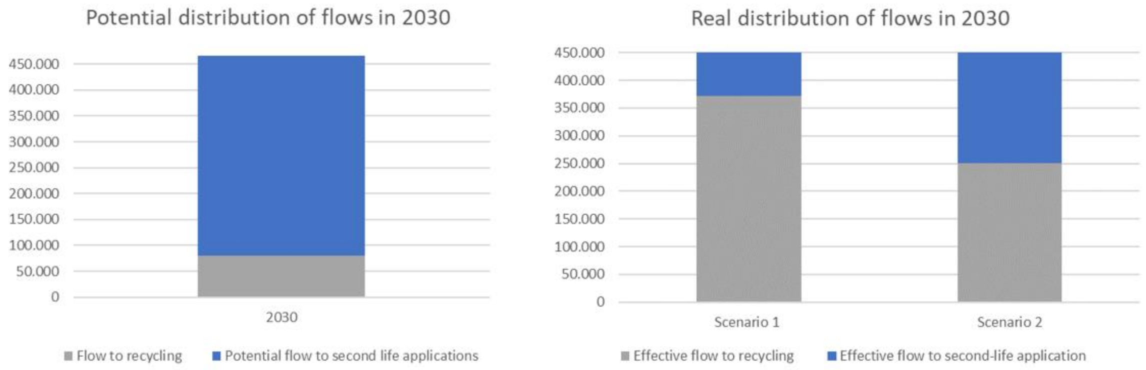


Figure 6.10: Potential and real distribution of flows in 2030

This limitation results from the constraints posed by the prismatic cells to performed remanufacturing activities, but it is also a consequence of the limits on the demand side. Indeed, scenario 2, that is characterized by a higher willingness of the clients for all the applications, shows that more than a half of total flows are directed to second-life strategies instead of recycling, representing a much larger share if compared to the scenario 1. As previously shown, demand for residential storage systems from remanufacturing up to module level is immediately saturated and demonstrates that even other flows may be available. This part of the analysis suggests that deepening other applications fields for second-life batteries not included in the presented study may be interesting to identify new business opportunities related to the end-of-life batteries.

Comparing the evolution over time of repurposing and remanufacturing for second life and recycling strategies gives raise to other considerations. In following graphs, only flows coming from return of end-of-life batteries are considered, so that any scrap derived from production and remanufacturing processes is excluded by the computation of recycling tons.

It is interesting to notice the difference in the flows distribution when comparing the scenarios.

The limitation of flows caused by the demand side in Scenario 1 results in a significant increase of volumes to be treated by recycling, reaching 900 K tons in 2035 and almost 1400K in 2040.

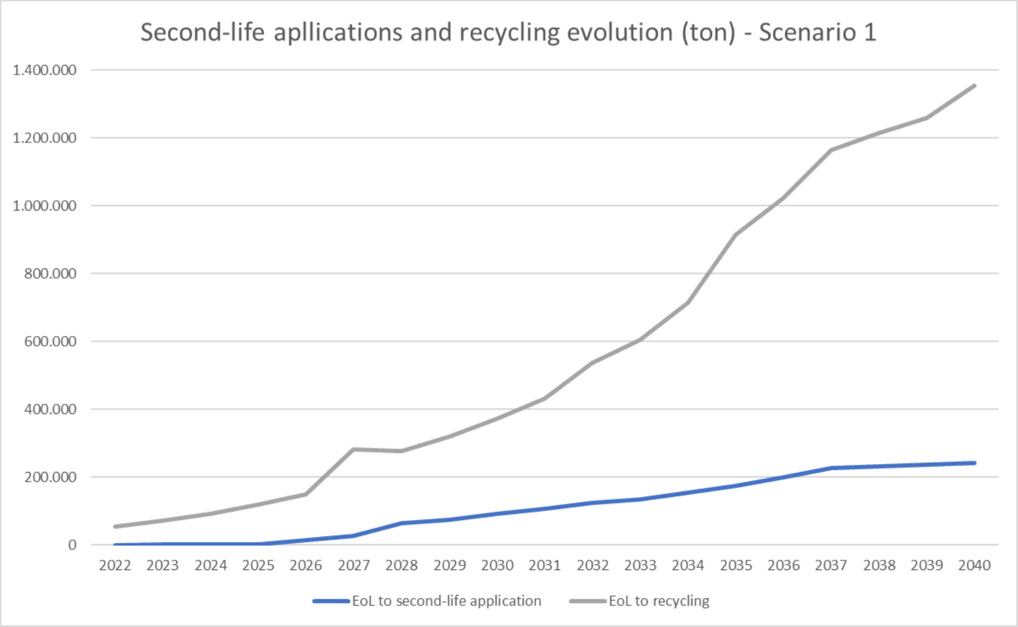


Figure 6.11: Second-life application and recycling evolution in Scenario 1

The second scenario provides insights about the relationship between second-life market and recycling. Given the high volumes directed to the former application, in 2031 flows are expected to be almost equal. In 2032, second life applications overtake recycling volumes, and their constant growth leads to a decrease of batteries to be directly treated through recycling. For this reason, only around 500K tons are recycled in 2035, and 600K in 2040. It is clear that an estimation of the possible future configuration of the second life market is necessary to compute the tons to be recycled and properly sizing the capacity of future recycling plants.

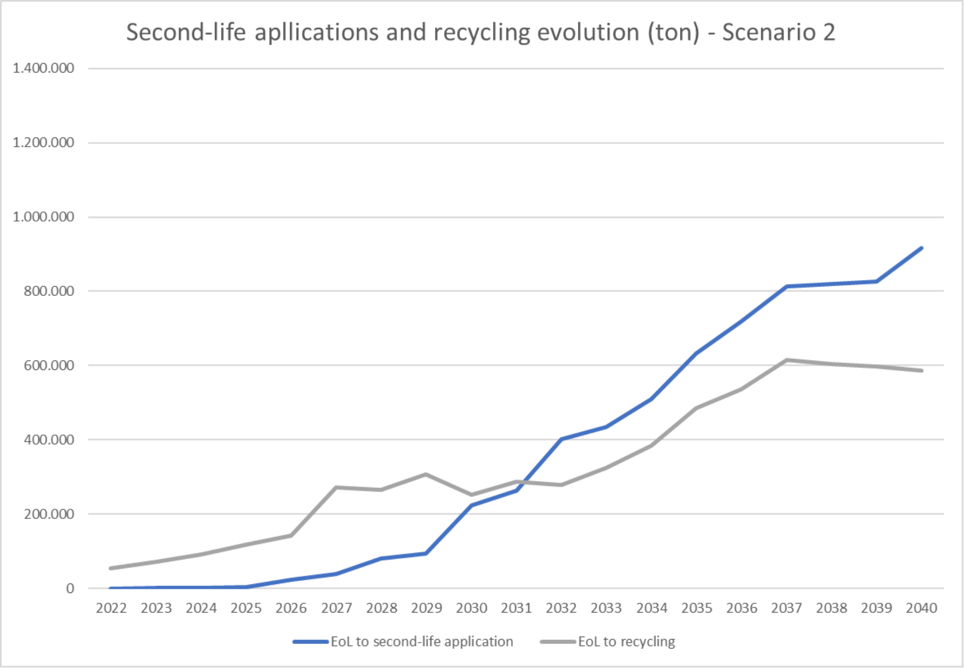


Figure 6.12: Evolution of second-life application and recycling in Scenario 2

6.2.4. Recycling

6.2.4.1. Recycling volumes

Analysing recycling from a broader perspective, it is interesting to estimate the overall volumes that will reach this stage of the circular value chain.

The main flows identified are the scraps coming from European production plants of Li-Ion batteries cell, end-of-life EV batteries not used for second life applications, batteries reaching end-of-life after a second life application, and scraps coming from remanufacturing processes.

Comparing the two scenarios previously described, some important insights can be derived. Firstly, a higher exploitation of second life opportunities reduces the overall tons of material that need to be recycled in future years. Volumes are about the same until 2030, while after that year the values start increasing with a different growth rate in the scenarios 1 and 2. In particular, in scenario 1 volumes are about

1400K in 2035 and 2000K in 2040, while in scenario 2 they are below 1200K in 2035 and about 1700K in 2040.

Moreover, the scenario 2 shows how the batteries that entered a second life delay the volumes sent recycling of about the warranty time of that specific second life application.

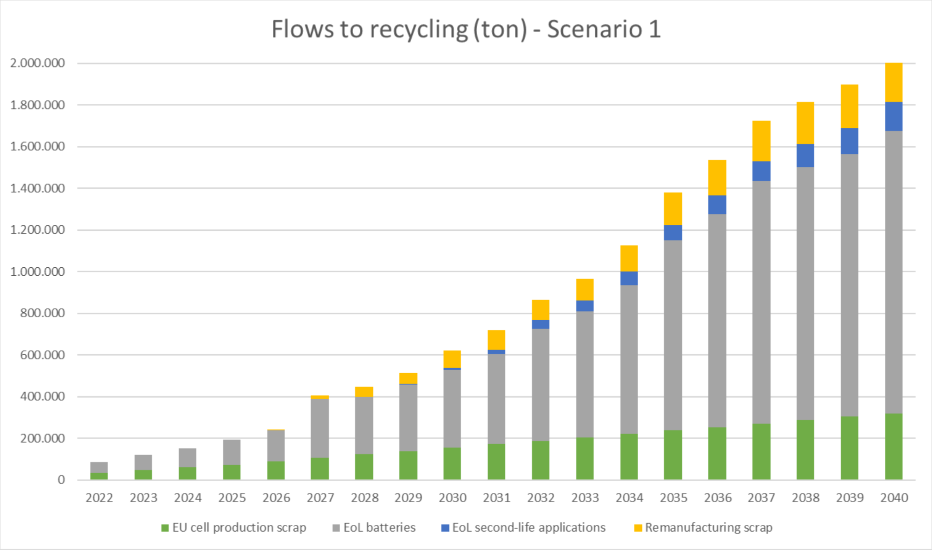


Figure 6.13: Diverse flows directed to recycling in Scenario 1

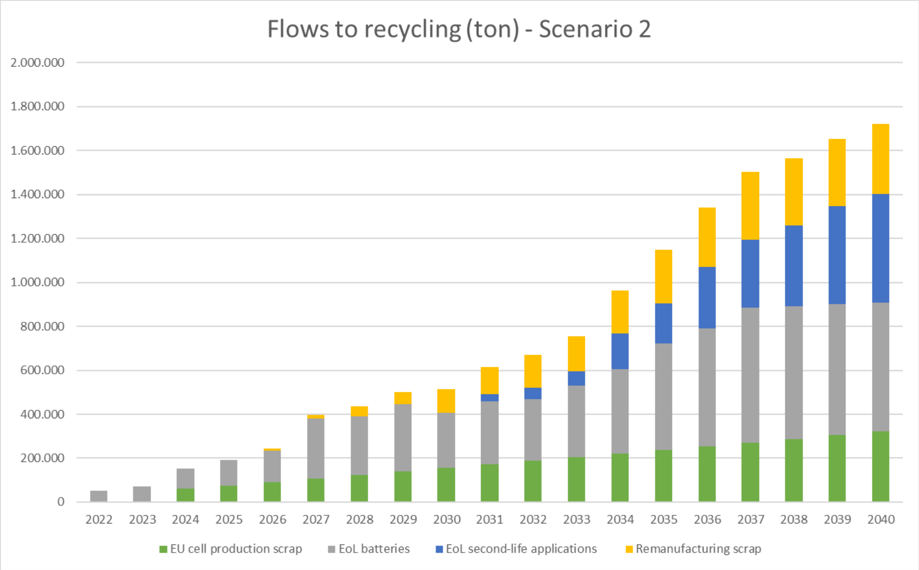


Figure 6.14: Diverse flows directed to recycling in Scenario 2

6.2.4.2. Recycling processes and revenues comparison

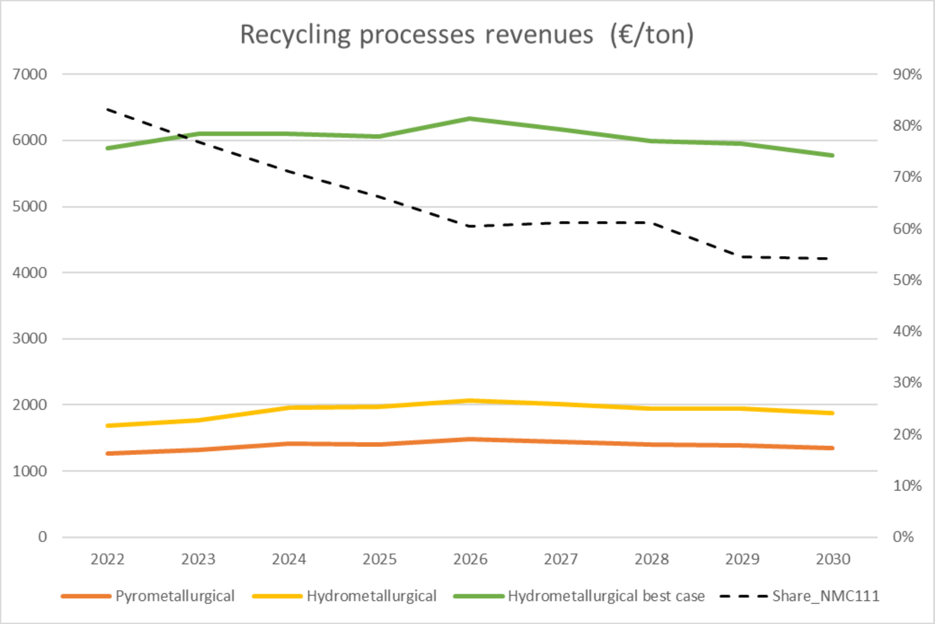


Figure 6.15: Recycling process revenues

One of the key benefits of the model is the possibility to estimate and compare the revenues coming from the different recycling configurations. The assessment is performed in a dynamic way, considering the evolution of batteries cell chemistry and typology.

Those values are the result of the selling of the recovered materials and of all the components obtained from the disassembly of batteries and pre-treatment processes, such as BMS and external case, that can be destinated to a dedicated recycling stream.

The prices taken into account for the computation of revenues are shown in Figure 6.15, so the maximum prices for recycled reusable output fraction.

This means that the results obtained may be overestimated and they represent the revenues upper bound that a recycler can get.

The huge difference in revenues between the three configurations is due to the different materials and components obtained as output from the processes. This leads also to different quantities of slag produced, that turns out into a cost for the recyclers. It has been estimated a cost of 500 €/ton for the disposal of the slag.

In the pyrometallurgical process only Ni and Co are recovered, and a huge slag is generated, equal to 70% of the total input.

The hydrometallurgical process highlights the possibility to recover lithium and get aluminium or steel from the case, Al form the current collector, and the electrolyte. In this alternative the slag produced is lower and equal to 54% of the total input.

From the hydrometallurgical best case other benefits appear. Firstly, the possibility to obtain the binder and the electrolyte in higher quantities compared to the conventional hydrometallurgical process. Moreover, the anode and cathode are get from the direct recycling process. Finally, the slag that originates from this process is much lower than the one coming from conventional pyrometallurgical and hydrometallurgical processes and it represents only 21% of total input.

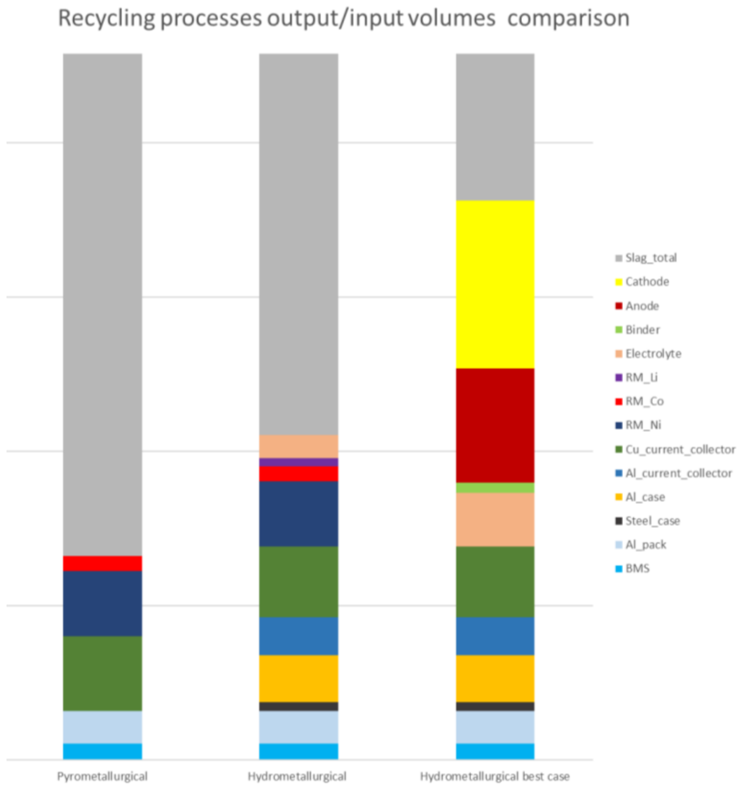


Figure 6.16: Comparison of recycling process output/input volumes

The Figure 6.16 shows the disruptive revenues that can be reached exploiting the most innovative technologies in terms of both pre-treatment and recycling processes that characterizes the hydrometallurgical best case.

In particular, being direct recycling able to regenerate battery components instead of precursors, it allows reducing revenues dependency on battery chemistry and on raw material price fluctuations.

Cobalt represents the main driver for the profitability of pyrometallurgical and hydrometallurgical conventional recycling process. The overall quantity of cobalt recovered is expected to increase in the future years as shown in Figure 6.17. This is mainly due to the increase of volumes that will need to be processed. In addition, the cobalt increasing recovery rates set out in the *Proposal for a Regulation on batteries and waste batteries* will have a positive impact on those values.

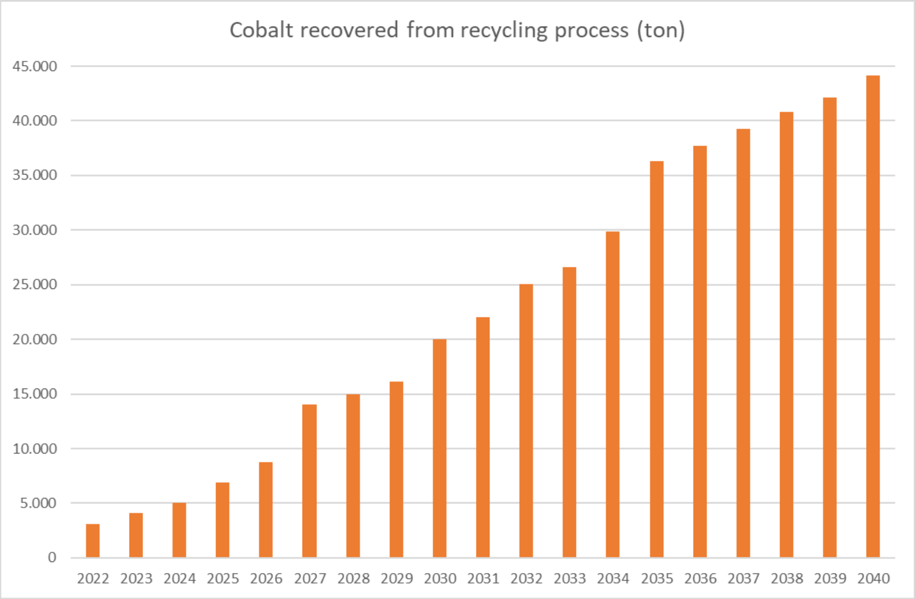


Figure 6.17: Volumes of Cobalt recovered from Pyrometallurgical recycling

However, the quantity of cobalt per tons of end-of-life Li-ion batteries that could be recovered will decrease as shown in Figure 6.18.

The graph represents two main outputs of the simulation:

- The share of end-of-life batteries that need to be recycled in a given year that are characterised by chemistry NMC 111;
- The quantity of cobalt (tons) that a recycler would be able to recover from each ton of those batteries entering the recycling process.

The graph shows how the decreasing trend of NMC 111, in favour of NMC 811, impacts on the amount of cobalt available in the battery cells. This means lower quantities of material recoverable from recyclers and in turn lower revenues.

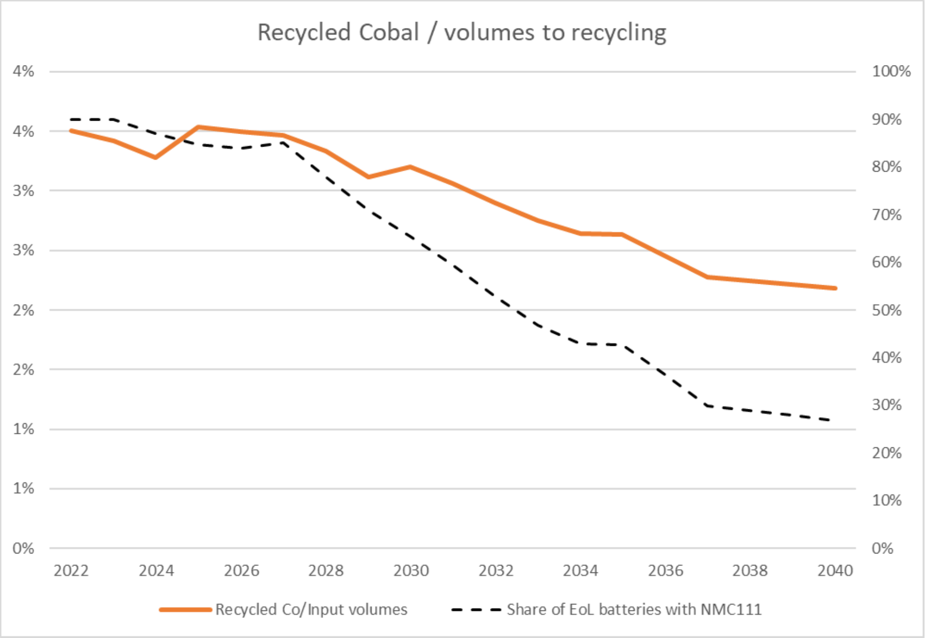


Figure 6.18: Recycled Cobalt on total input batteries

7 Conclusions

7.1. Business implications and recommendations

The presented thesis is intended to provide economic actors of the battery value chain with a powerful tool to support their decision-making process in the context of end-of-life batteries. Given the high expected return flows volumes of EV batteries, a structured approach to improve the sustainability of the battery value chain and move to a circular model is needed but comes with significant challenges. Information availability, technological improvement of the industrial processes, development of suitable standards about circular economy strategies and second-life products, expected technological upgrades, and complexity of the battery itself are the main significant factors influencing the development of the circular economy applied to the e-mobility sector.

The presented study deepens and tackles all these mentioned issues, with the aim of providing a clear understanding of their impact on the different phases of the circular economy value chain.

The simulation model has the novelty to capture all these relevant factors and include them in a unique platform. The simulation tool allows to describe their expected progress over time. In some cases, factors have been translated into parameters that gradually change their value at a given time or event. In other, the data describing the variable's evolution has been fed as input tables into the model. Moreover, all the different parts of the model are intertwined and influence one another. Indeed, when dealing with a circular model, steps are not distributed in a linear way and two different strategies may result to be both an alternative and placed in sequence. The need to estimate the relationships between all these parts translates into the development of a simulation model.

The results obtained clearly show this dependence and highlight the need to have a comprehensive knowledge of the circular economy evolution to properly take decisions about a given strategy. With this perspective, it is not possible to properly compute the expected flows to be recycled without knowing the potential market for second-life applications. This is a critical point to properly size the capacity of future recycling plants and estimate the right expected values of revenues.

At the same time, when estimating the demand for EV battery spare parts it is necessary to size the possible storage system market and vice versa, since one market can cannibalize the other.

Moreover, linking demand and supply sides leads to identify the need to focus on the demand side. Once the barriers that constrain the supply side are overcome, high volumes of batteries with significant residual capacity are expected to be available. This potentiality should be exploited, and efforts should be devoted to raise the willingness of the customers or on in deepening other applications fields for second-life batteries applications not included in the presented study. New business opportunity may arise.

Moreover, the thesis focuses on the more conservative scenario provided by IEA (STEPS scenario). However, if higher volumes will materialize as assumed in the SDS scenario, the announced European production capacity may not be enough to satisfy the battery demand. In this context, the availability of end-of-life batteries to be repurposed or remanufactured may represent an even bigger opportunity to be taken.

Finally, the dynamic computation of recycling revenues allows to link the profitability of the process with changes in the battery technology and recovery requirements. Due to the evolution of batteries' chemistry toward a lower quantity of Cobalt, future recycling processes should be developed relying on the most innovative technologies. In this way, the maximum benefits from the cathode and anode materials recovered as proper components can be get, and a reduction in the dependency on raw materials price fluctuations can be obtained.

7.2. Limitations and future improvements

The presented model has been developed starting from the analysis of the current markets and ecosystem with the aim of describing the most significant factors and steps of the value chain.

However, some possible improvements have been identified and may be implemented.

Firstly, the model may be furtherly expanded, by linking parts of the value chain that are currently not related. The representation of production capacity has been functional to the computation of scrap to be recycled. However, their flows may be linked to the annual sales of electric vehicles, in order to describe the relations between cell battery production and EV battery demand. Moreover, the estimated flows of recovered material from the recycling process may become an input to cells production. As shown in the causal loop diagram of *Chapter 4*, the system is interconnected and creates a reinforcing loop that starts from the battery production and goes back to the battery production, passing by first and second applications and recycling treatments. Linking the recycling processes output with cell production would enable the comparison between the total amount of raw materials needed for production and the recovered materials available. In this way, it would be possible to understand how the evolution of the recycling process could reduce the need of virgin materials extraction and production.

Secondly, to manage the trade-off between the willingness of representing the real world and the constraints posed by the *Anylogic* software, some assumptions have been developed. For example, having estimated that the applications of small storage systems are more profitable than the one in the utility-scale application, the model prioritizes flows for residential applications. However, this assumption may be removed if the user may decide to give a different perspective to the analysis.

In addition, the model has been developed and tested with data about available forecasts that are uncertain by definition. For this reason, as soon as the uncertainty related to the analysed markets decreases, the input data should be updated by economic actors to get the most accurate and reliable outputs.

Moreover, the model could host a wider range of input data about Li-ion batteries in use in other markets, as well as the demand for different types of second-life applications.

Finally, the flexibility of the tool would enable the user to easily modify the scope of analysis, in terms of geographical regions. The results shown in *Chapter 6* have been obtained from an aggregated analysis related to the European context. However, it will be sufficient to enter country-specific data about Li-ion batteries production capacity, e-mobility volumes, and second life application demand to get a comparison between different countries.

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A Appendix A

A.1. OPEX

Repurpose and remanufacturing processes OPEX

Disassembly pack to cell OPEX	**Unit**
Maintenance	€/ton/y
Maintenance	*% investment cost*
Maintenance cost	*€*
Operator	€/ton/y
Operators	*# FTE*
Unitary operator cost	*€/FTE/y*
Total operator cost	*€/y*
Energy	€/ton/y
Unitary energy cost	*€/kWh*
Energy consumption	*kW/y*
Total energy cost	*€/y*
Floorspace	€/ton/y
Unitary floorspace cost	*€/m2/y*
Floorspace needed	*m2*
Total floorspace cost	*€*
Consumable	€/ton/y
Consumables	*% investment cost*
Consumables cost	*€*
Capacity	**ton/y**
Total OPEX	**€/ton/y**

Reassembly cell to module OPEX	**Unit**
Mechanical assembly	

Operator	€/ton/y
Operators	*# FTE*
Unitary operator cost	*€/FTE/y*
Total operator cost	*€/y*
Laser Welding	
Operator	€/ton/y
Operators	*# FTE*
Unitary operator cost	*€/FTE/y*
Total operator cost	*€/y*
Consumable	€/ton/y
Consumables	*€/module*
Consumables cost	*€*
Capacity	**ton/y**
Assembly time	*min/module*
Throughput	*Kg/h*
Hours/day	
Working days	
Total OPEX	**€/ton/y**

Reassembly module to pack OPEX	**Unit**
Operator	€/ton/y
Operators	*# FTE*
Unitary operator cost	*€/FTE/y*
Total operator cost	*€/y*
Capacity	**ton/y**
Assembly time	*min/pack*
Throughput	*Kg/h*
Hours/day	
Working days	
Total OPEX	**€/ton/y**

Assembly packs in storage systems large OPEX	**Unit**

Operator	€/ton/y
Operators	*# FTE*
Unitary operator cost	*€/FTE/y*
Total operator cost	*€/y*
Capacity	**ton/y**
Throughput	*pack/day*
Throughput	*Kg/day*
Working days	
Total OPEX	**€/ton/y**

Recycling processes OPEX

Mechanical pre-treatment OPEX	**Unit**
Equipment wear & consumables	€/ton
Tool wear costs	*€/y*
Equipment maintenance	€/ton
Equipment maintenance	*% equipment cost*
Equipment maintenance cost	€
Manpower	€/ton/y
Shifts/day	
Unitary operator cost	*€/y*
Total operator cost	*€/y*
Energy	€/ton/y
Throughput machine	*Kg/h*
Shifts/day	
Unitary energy cost	*€/kWh*
Energy consumption	*kWh/y*
Total energy cost	*€/y*
Capacity	**ton/year**
Throughput machine	*Kg/h*
Shifts/day	
Hours/shift	
Working days	
Total OPEX	**€/year**

High Voltage Fragmentation pretreatment OPEX	**Unit**
Equipment wear & consumables	€/ton
Tool wear & consumable costs	*€/year*
Equipment maintenance	€/ton
Equipment maintenance	*% equipment cost*
Equipment maintenance cost	*€*
Manpower	€/ton
Shifts/day	
Unitary operator cost	*€/y*
Total operator cost	*€/y*
Energy	€/ton
Throughput machine	*Kg/h*
Shifts/day	
Unitary energy cost	*€/kWh*
Energy consumption	*kWh/y*
Total energy cost	*€/y*
Capacity	**ton/year**
Throughput machine	*Kg/h*
Shifts/day	
Hours/shift	
Working days	
Total OPEX	**€/ton**

Cell cutting (cylindrical and prismatic) OPEX	**Unit**
Maintenance	€/ton/y
Maintenance	*% investment cost*
Maintenance cost	*€*
Operator	€/ton/y
Operators	*# FTE*
Total operator cost	*€/FTE/y*

Energy	€/ton/y
Unitary energy cost	*€/kWh*
Working hours	*h/y*
Power	*kW*
Energy	*kWh*
Total energy cost	*€/y*
Floorspace	€/ton/y
Unitary floorspace cost	*€/m2/y*
Floorspace needed	*m2*
Total floorspace cost	*€*
Consumable	€/ton/y
Consumables	*% investment cost*
Consumables cost	*€*
Capacity	**ton/y**
Total Opex	**€/ton**