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EXECUTIVE SUMMARY OF THE THESIS

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

TESI MAGISTRALE IN MANAGEMENT ENGINEERING – INGEGNERIA GESTIONALE

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1. Introduction

Li-Ion batteries are becoming a crucial product due to the role they play in the roll-out of zero-emission mobility and the storage of intermittent renewable energy transition. Their demand is mainly fueled by the expansion of electrified vehicles, driven by the need to reduce greenhouse gas emissions in the transportation sector. This trend will translate into an increase of return batteries to be treated once they reach the end of life in the vehicle.

Given these raising expected volumes, the present study tackles the issues and challenges of shifting from a linear to a circular value chain in the context of e-mobility batteries. Information availability, technological improvement of the industrial processes, development of suitable standards about circular economy strategies and second-life products, expected technological upgrades, and the complexity of the battery itself are the main significant factors. Starting from the plurality and interconnections of these elements, the thesis pursues two main objectives.

The first focuses on building a simulation model able to present a comprehensive description of the value chain, capturing the previously mentioned factors and their evolution over time. The contribution of the study is providing economic actors belonging to this value chain with a powerful tool to support their decision-making process. Indeed, the novelty of the model is including in a unique platform a plurality of markets and strategies to quantitative highlight how the different macro-area representing the ecosystem are intertwined and the effects of their relations.

The second objective is to predict the evolution of the circular economy markets related to the end-of-life (EoL) electric vehicle (EV) Li-Ion batteries, by running the mentioned simulation model.

The results obtained clearly highlight the importance of having a comprehensive knowledge of the overall development of the ecosystem to properly take decisions about a given second life strategy.

It appears that on the one hand, second-life markets cannibalize one another, and on the other, their development limits the flows to recycling.

Moreover, it emerges 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 could be exploited, and efforts should be devoted to raise the willingness of the customers to buy a remanufactured product. Moreover, deepening other applications fields for second-life batteries not included in the presented study may reveal new business models opportunities related to the end-of-life batteries. Finally, future recycling processes should be developed relying on the most innovative technologies in order to gain the maximum benefits and reduce the dependency on raw materials price fluctuations.

2. The context

Li-Ion batteries are complex products characterized by a modular structure. Cells are the fundamental bricks of the battery and are arranged in series and parallel to form modules, which are then assembled in the pack together with electronic devices, cooling systems, cables, and joins. The final voltage and capacity of the pack are obtained by the hierarchical assembly of single battery cells.

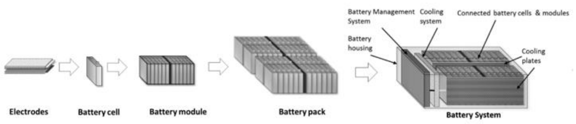

Figure 1: Schematic structure of a battery pack

Once reaching the end-of-life, batteries undertake the return flow. Generally, they have a residual capacity varying between 70% and 80%. [1] For this reason, secondary utilization is a promising solution to extract additional value from retired EV batteries. Processes that take advantage of the residual value of end-of-life batteries are distinguished in repurposing, remanufacturing and recycling, and all fall within the circular economy strategies term. Repurposing represents the process with which the complete product is removed from an electric vehicle and re-used for a different application.

Remanufacturing is an industrial process to transfer a used and worn component into a quasi-new condition. The process includes a comprehensive battery testing, disassembly of as well as the reassembly activities. 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. 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 labor-intensive process driven by a deep knowledge of the products to estimate the best re-assembly configuration to satisfy the customer needs. Remanufacturing can be performed up to module or cell level, depending on the depth of disassembly. This latter case is more suitable to be applied on prismatic cells types, as they are easier to be properly handled during the disassembly and testing phases because of their large size. [2]

Recycling recovers the valuable materials embedded in the battery following a sequence of mechanical, thermal and/or chemical processes. Despite it is the less adding value among all processes, it is unavoidable for the most compromised battery cells and sooner or later mandatory for all end-of-life batteries. Conventional recycling technologies, such as pyrometallurgical and hydrometallurgical ones, are mainly driven by cobalt, the most valuable material embedded in the battery because of its low relative abundance and high price. [3] However, an alternative to conventional recycling has been developed. Direct recycling is a novel approach that allow to recover the cathode and anode materials as proper components and to reinsert them in the manufacturing loop of new batteries.

A further development of these described strategies is enabled by few crucial initiatives.

An improvement of information technology embedded within batteries, described as a battery passport, is needed to allow the sharing of key data. This enables to efficiently determine the chemistry of EoL battery and its state of health (SoH), described as the actual capability of the battery with respect to its beginning of life performance. The availability of this information facilitates sorting of batteries and helps identifying the most suitable second-life strategy to treat them. Moreover, the technological improvements of machines and equipment to perform disassembly and testing during remanufacturing activities is required to be in a mature phase in order to ensure its feasibility and economic sustainability on a large scale.

Deepening the evolution of regulation, the definition of European standards is crucial as it enables economic actors to put on the market a product compliant to a same set of regulations, and to get common certifications for warranty. Also, the Proposal for a regulation of the European Parliament and of the Council concerning batteries and waste batteries aims at modernising the EU's regulatory framework for batteries. In particular, it sets new mandatory recycling efficiencies, material recovery targets, and labeling and information requirements. [4]
Finally, challenges for the application of circular economy strategies are fueled by the complexity of the battery technology.
Indeed, batteries' technological innovation is driven by increasing energy density levels. This is achieved by switching to more efficient chemistries, e.g from NMC 111 to NMC 811, characterized by a lower amount of Cobalt and thus impacting the profitability of recycling. [5]
In addition, prismatic cells are expected to become the dominant design used in EV battery packs and influence the effective application of remanufacturing strategies.

3. Methodology

The complexity of the value chain to be represented, the multiple factors involved, 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 method to represent the system, run the model and collect results. The software *Anylogic* has been selected as the support tool.
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. This is used as the basis to develop the conceptual model, and to design the causal relations, that highlight the interconnections between the systems' entities.
The last step is building the computational model, i.d. the simulation model.
Finally, the model is fed with data derived through a review of the available information in the existing literature and reports, and a cost-benefit analysis developed to identify the profitability of the circular economy strategies.

4. The model

Conceptual model

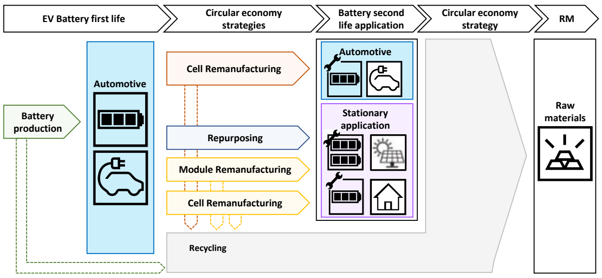

Figure 2: Main entities of the system

According to the conceptual model, at the end of its first life, the battery can be treated according to four main circular economy strategies, which lead to diversified outputs.

Table 1: Strategies and Output of the system

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

Causal relations diagram

The causal relations diagram highlights the potentiality of building a circular value chain. The development of the EV market boosts the production of batteries, which fuels the second life markets after a certain period of time. First and second applications of batteries positively impact the development of recycling strategies, that provide recycled materials to be used for battery production. Finally, negative relationships between the production of new batteries and the development of a second-life market for spare parts, and between the production of virgin materials and the development of recycling strategies are highlighted.

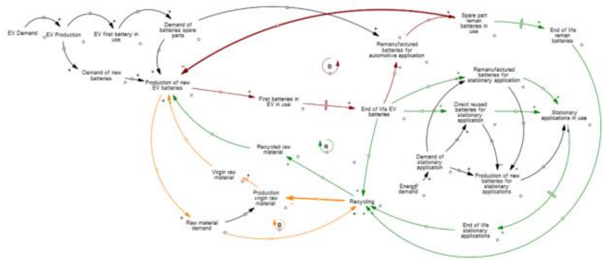

Figure 3: Causal loop diagram

Simulation model

The simulation model is built to optimize the overall value chain by directing the return batteries flows according to their state of health, prioritizing the more profitable strategies, considering losses due to the scrap in the processes and aiming at satisfying the demand for second life applications. The overall model is made of seven different interconnected macro-parts: EV sales market, demand for storage application, business layer, and the processes incorporated into the process layer. The input is the electric vehicles annual sales, represented by the EV market block.
The business layer is responsible for the main directions taken by the flows based on SoH, profitability criteria and second life product demand. The process layer graphically represents how remanufacturing for the different applications (second life battery for automotive, small storage system, large storage system) and the three recycling alternatives are structured.

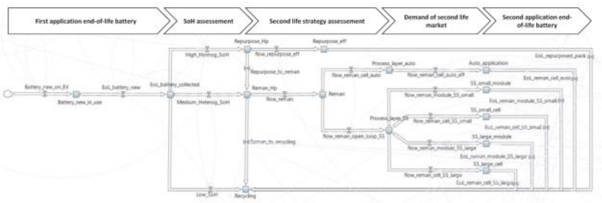

Figure 4: Business layer of the *Anylogic* model

5. Results

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 millions batteries in 2030, representing 460K tons. The majority of them are characterized by high residual capacity that could be exploited through second life, while a small share of batteries is considered to be so damaged to be sent directly to recycling.

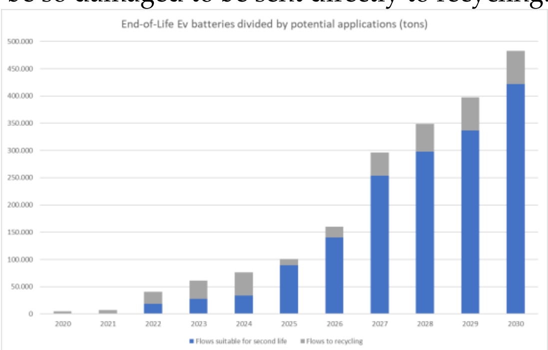

Figure 5: EoL batteries by potential application

The simulation demonstrates that the barriers impacting the supply of second-life batteries are expected to be overcome in the following years, leading to a development of the remanufacturing activities. On the contrary, the demand side of the different analyzed applications is mainly constrained by the maximum willingness of the customers to buy a second life product. For example, in the case of low willingness of the clients (estimated as 10% of total customers – Scenario 1) in the automotive sector, the available supply of remanufactured batteries sold as spare parts can totally cover the customer demand in 2028. On the contrary, in case of high customer willingness (estimated as 50% of total customers – Scenario 2), the available supply is not able to completely satisfy the market before 2030.

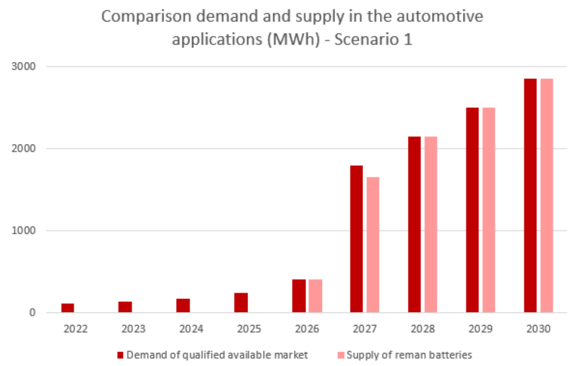

Figure 6: Comparison demand and supply - Scenario 1

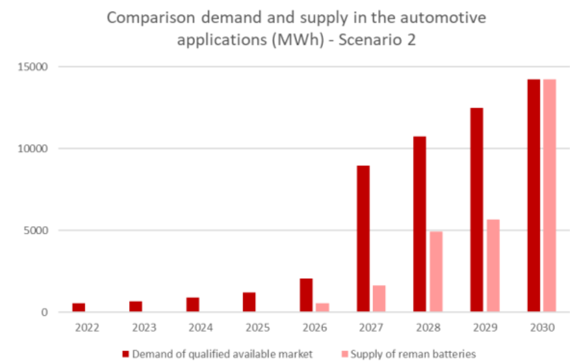

Figure 7: Comparison demand and supply - Scenario 2

The development of spare parts batteries market cannibalizes storage systems obtained through remanufacturing up to cell level. 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.

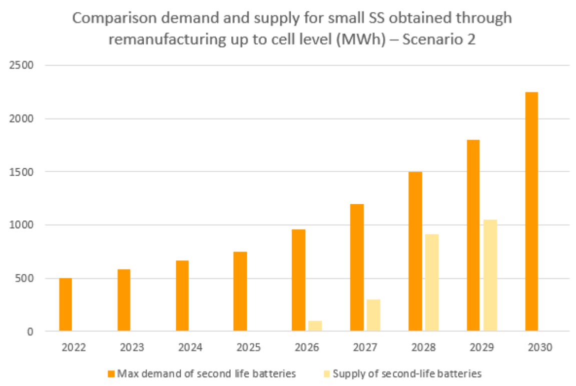

Figure 8: Comparison demand and supply for small storage system - Scenario 2

By comparing the second life application of the return flows estimated in the two scenarios with the potential application due to batteries SoH, it emerges that the high residual capacity of batteries previously displayed in Figure 5 is not completely exploited.

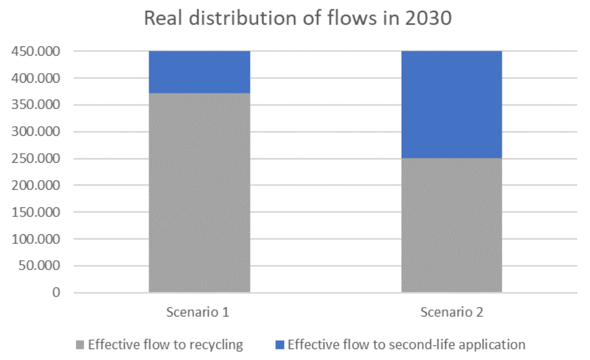

Figure 9: Distribution of flows between second life application and recycling

Indeed, in 2030 the barriers for the development of the remanufacturing activities are overcome but, in both scenarios, only a portion of high residual capacity batteries are dedicated to second life applications.

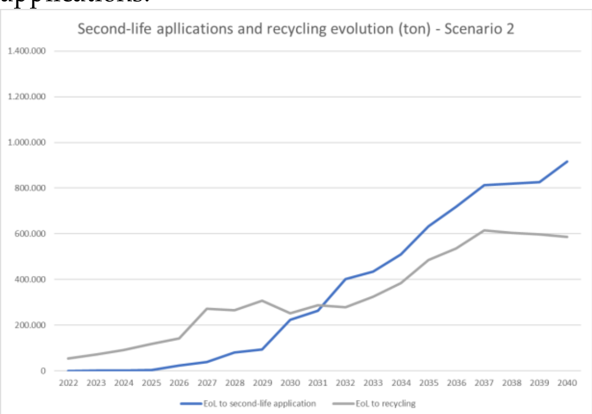

Figure 10: Second-life applications and recycling evolution

The Figure 10 highlights the inverse relation between second-life strategies and recycling. Assuming high volumes directed to second life applications (Scenario 2), the end-of-life batteries volumes directed to recycling experience a growth slowdown from 2030.

Finally, the main results on the three recycling processes included in the model show a significant difference in the materials and components obtained as output. Indeed, the hydrometallurgical best case turns out to be the most efficient, due to the low amount of slag produced. The direct recycling embedded in this process configuration is able to regenerate battery components instead of precursors.

Moreover, the quantity per tons of each material recovered from batteries is computed by the model, as well as revenues obtained from their selling.

The most significant insight comes from the expected drop of cobalt obtained due to the decreasing trend of NMC 111, in favor of NMC 811. This means lower quantities of valuable material recoverable from recyclers and in turn lower revenues in case of pyrometallurgical and hydrometallurgical conventional processes.

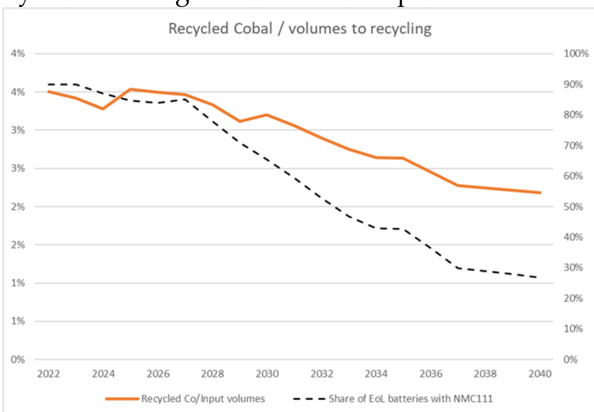

Figure 11: Recycled cobalt per ton of batteries

6. Conclusions

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.

The simulation model has the novelty to capture all the relevant mentioned factors and describe their expected progress over time. Moreover, all the different parts of the model are intertwined and influence one another.

The results obtained clearly 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.

It emerges 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. If volumes higher than the ones considered in this study will materialize, the announced European production capacity may not be enough to satisfy the battery demand and the availability of end-of-life batteries to be remanufactured may represent even a bigger opportunity. Moreover, deepening other applications fields for second-life batteries not included in the presented study may reveal new business models related to the end-of-life batteries. 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 order to gain the maximum benefits and reduce the dependency on raw materials price fluctuations.

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