Battery recycling: The economics of a multi-billion Euro circular economy in the making

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Abstract

Supply chain disruptions and raw material shortages have led to a price hike for Li-ion batteries. Concerns around humanitarian conditions and the environmental impact of mining essential battery raw materials are fueling skepticism about electromobility. Raw material sourcing is becoming increasingly geopolitical – with governments and corporations alike pushing for the localization of supply chains.

A new circular economy with battery recycling as its cornerstone is promising to help solve all these problems at once. A multi-billion Euro industry is emerging. However, many of the fundamental questions of this industry have yet to be answered:

- What is the right technology for battery recycling?
- When is the right time to invest?
- How do successful business models for EoL-batteries look like?
- What about 2nd-life applications?

FEV has collaborated with players from across the battery recycling value chain – from dismantlers to metal extractors to OEMs. Along the way we have accumulated a deep technical and economic understanding of the industry and built a suite of models we call CycleBat, allowing us to make predictions about the future of recycling. This presentation will share FEV's vision of the future circular economy in the automotive industry and explain what it takes to succeed in it.

Content

1 Introduction 2
2 Methodology 3
2.1 Oversimplified approach 3
2.2 Advanced approach – enabled by CycleBat 4
3 Results 5
3.1 Battery cell chemistry choice 6
3.2 Battery Pack Design 8
3.3 Utilization of Vehicle-On-Board (VOB) data 10
3.4 Logistics network design 11
4 Limitations 12
5 Conclusion 12
6 References 13
7 Acknowledgement 13

1 Introduction

As global efforts to combat climate change intensify, the role of Li-ion batteries in powering electric vehicles (EVs) has become increasingly important. With projections indicating that over 1 billion tons of end-of-life (EoL) batteries will need managing by 2040, the dual imperatives of environmental sustainability and economic viability have never been more critical. Regulatory frameworks such as the extended producer responsibility (EPR) in the EU's Battery Regulation have already begun to affect the financial landscape for Original Equipment Manufacturers (OEMs). These regulations are prompting OEMs to accrue significant financial reserves today, even before recycling scales up, to account for future responsibilities tied to vehicle and battery recycling.

Utilizing FEV's CycleBat, a robust suite of forecasting and cost models, this paper offers an exhaustive analysis of the EoL battery value chain. CycleBat enables a nuanced examination of various factors including design-for-circularity, second-life battery applications, cell chemistry choices, and the costs associated with typical recycling routes. The suite also provides insights into machine, labor, and processing costs as well as future recycling demand and scales, allowing for a comprehensive view that balances both environmental stewardship and immediate as well as long-term financial imperatives.

This research aims to guide the automotive industry in making informed decisions that are both environmentally sustainable and financially prudent. By adopting a multi-faceted approach to battery design, OEMs can navigate the complexities of current regulatory and market pressures, thereby unlocking a multi-billion Euro business opportunity while fulfilling their extended producer responsibilities.

2 Methodology

To quantify the immediate and long-term financial and environmental impacts of design-for-circularity approaches on end-of-life (EoL) batteries, this study employs FEV's CycleBat suite of forecasting and cost models. Developed through the amalgamation of insights from multiple projects across the entire battery value chain, CycleBat serves as a robust tool for assessing the complexities involved in battery design, usage, and disposal. CycleBat comprises two core components: the CycleBat Market and the CycleBat ValueChain, each addressing different aspects of the EoL battery scenario.

One of the critical objectives of this research is to elucidate the methodologies for calculating the projected EoL battery disposal cost and to illustrate the difference between an oversimplified approach and a more nuanced one enabled by FEV CycleBat.

2.1 Oversimplified approach

We find this approach to be used in many cases where the topic of battery recycling still is an afterthought overall. The less companies know about the topic the more likely they typically are to treat the issue of battery recycling with too little care. A typical approach could therefore look like this:

1. Analyzing the battery capacities sold each year
2. Applying current gate fees for battery recycling
3. Projecting ten years into the future when the batteries are presumed to return for recycling

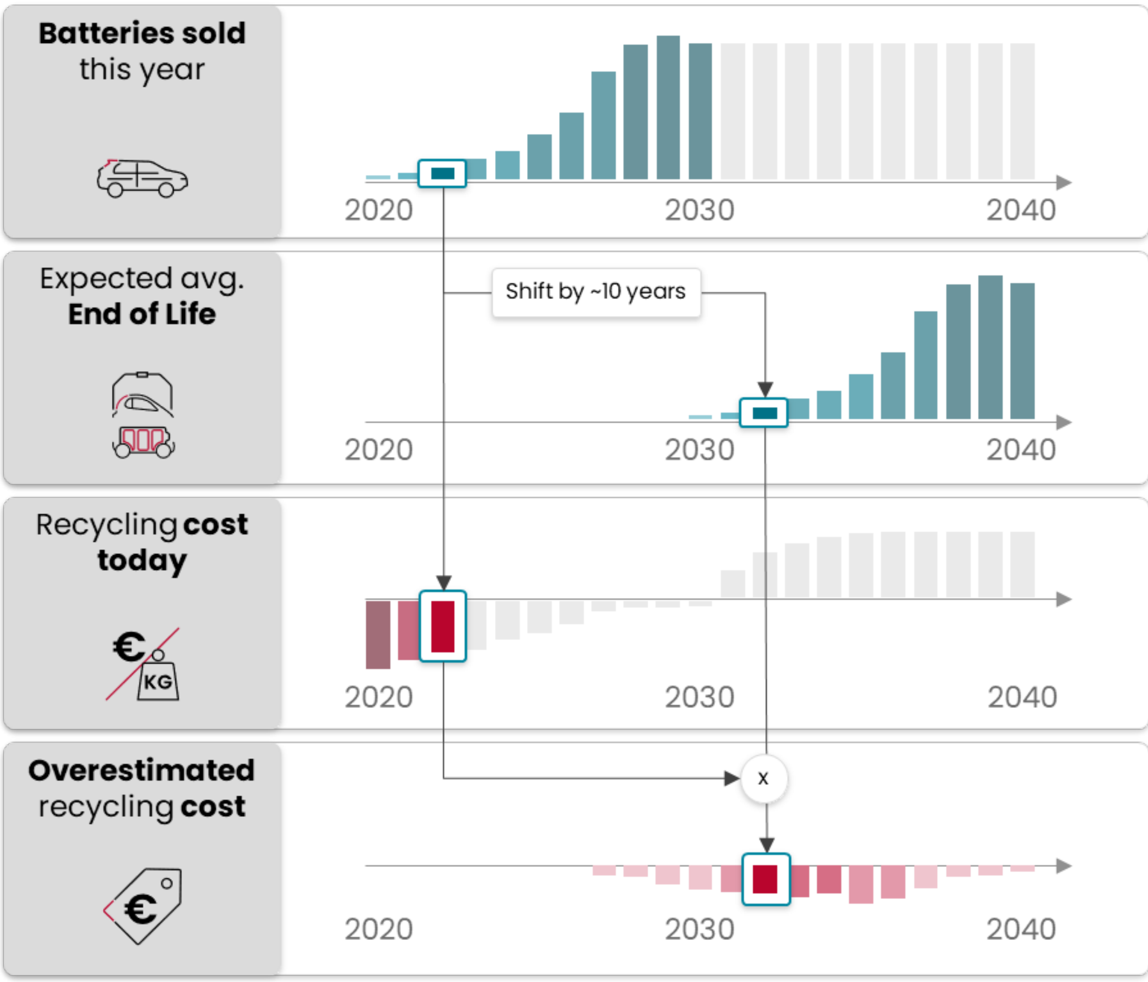

Fig. 1 Illustration: Oversimplified battery recycling cost estimation approach

While straightforward, this method can severely misrepresent the cost of recycling by failing to account for variations in battery longevity, fluctuations in recycling costs and recycled material values, and other dynamic variables.

2.2 Advanced approach – enabled by CycleBat

FEV's CycleBat allows for a more nuanced methodology:

1. Analyzing the battery capacities sold each year
2. Employing "CycleBat Market" model to accurately predict the distribution of EoL batteries over time, recognizing that some batteries will reach EoL sooner, while many will last beyond 15 years
3. Using "CycleBat Value Chain" model to project the cost of recycling for each year's predicted EoL battery disposal demand

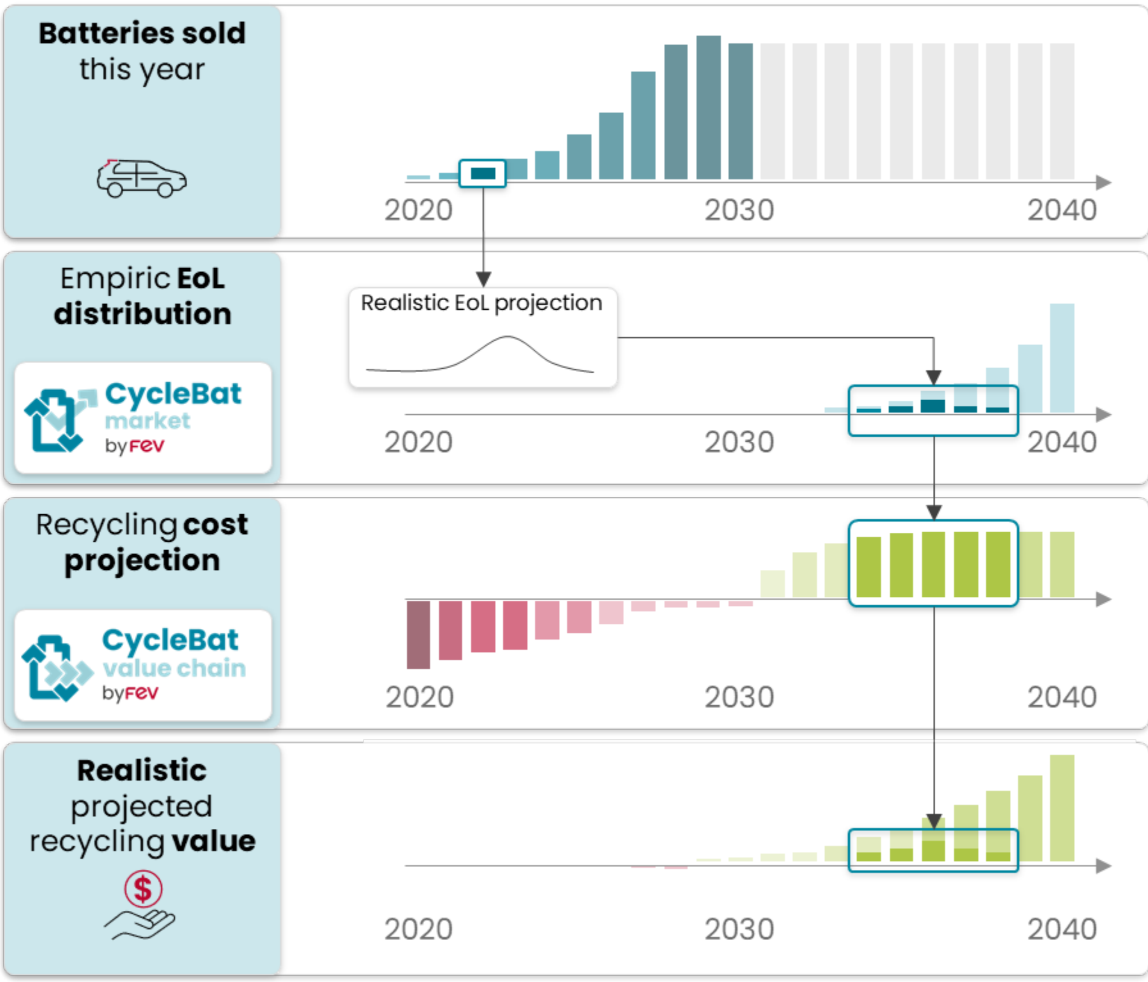

Fig. 2 Illustration: Advanced battery recycling cost estimation approach

By integrating predictive analytics into the equation, the CycleBat models provide a comprehensive and accurate assessment of future recycling costs. This approach leverages the temporal insights into EoL battery distribution and recycling costs to deliver a more accurate financial estimate.

In summary, the methodologies used in this study offer a holistic assessment of design for circularity approaches, weighing both environmental and financial factors. By employing our advanced modeling tools and leveraging our engineering expertise, we offer critical insights into the present and future state of EoL battery management.

3 Results

In this section, we will cover the transformative power of design for circularity in shaping the future of end-of-life (EoL) batteries. But before diving into the detailed results, it is crucial to understand the overarching financial implications. Inaccurate methods for projecting future EoL battery disposal costs can gravely mislead industry stakeholders. For instance, using a simplified approach, such as described previously considering only today's data, could erroneously estimate a burden of 14 billion euros in recycling costs for the EU automotive industry by 2040.

However, a more elaborate approach using predictive models tells a different story. Employing the FEV CycleBat framework, we find that by adopting measures to improve circularity, the industry could not only avoid this colossal expenditure but actually tap into a 25-billion-euro revenue pool by 2040. In addition to an industrialization of the whole EoL battery value chain, this remarkable swing from liability to asset hinges on the implementation of innovative approaches to battery design and end-of-life management, which we have analyzed in detail.

In the following segments, we will walk you through four pivotal measures that can have a significant impact on the cost of recycling overall: battery cell chemistry choice, battery pack design, utilization of Vehicle-On-Board (VOB) data, and logistics network design. Each measure holds the promise to substantially improve both the environmental footprint and the economic viability of EoL batteries.

3.1 Battery cell chemistry choice

The choice of battery cell chemistry is a critical aspect of design for circularity in the automotive industry. In our analysis, we focused on the two main chemistries currently being considered: NMC (Nickel Manganese Cobalt Oxide) and LFP (Lithium Iron Phosphate).

NMC offers higher performance compared to LFP, but it comes at a higher cost. On the other hand, LFP has lower power density but is more cost-effective. However, when considering the residual material value at end-of-life (EoL), NMC demonstrates a significant advantage. This is because NMC batteries not only contain lithium, but also valuable metals such as nickel, cobalt, and manganese. In contrast, LFP batteries primarily contain lithium as the precious material component. Other components of the cathode active material such as iron or phosphate have comparatively low value. This discrepancy in residual material value impacts the overall economics of recycling. Despite the reduced complexity of the metal extraction process for LFP, the majority of value chain steps, such as logistics and black mass treatment, remain the same. Consequently, the cost for recycling LFP batteries can be similarly expensive as that of NMC batteries. Moreover, when considering the cost of recycling per kilowatt-hour (€/kWh), LFP may even have a higher cost due to its lower energy density.

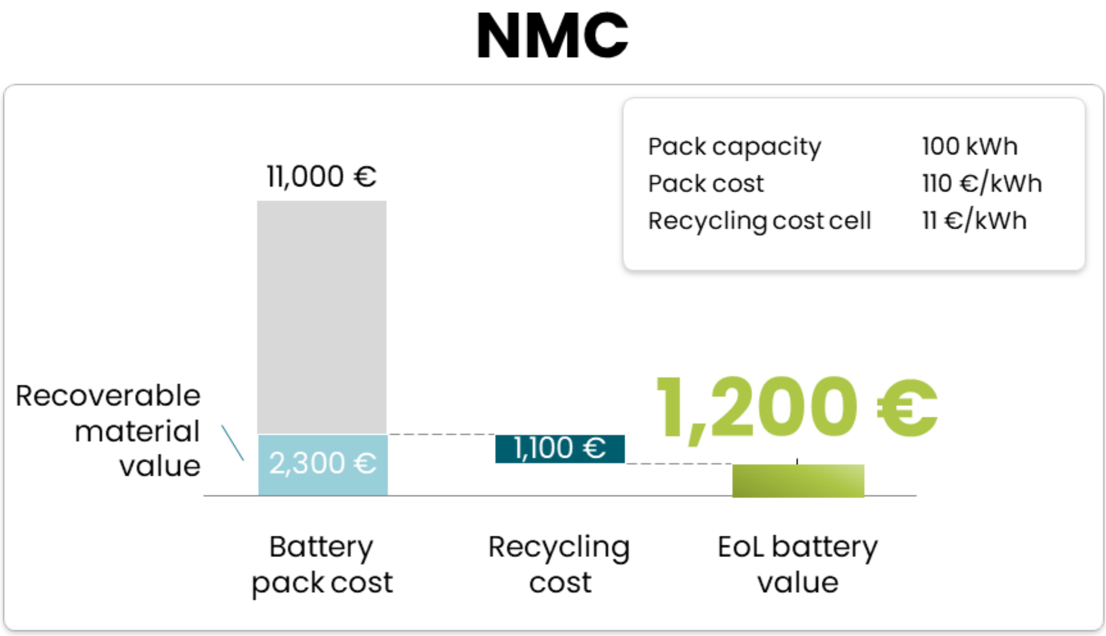

Fig. 3 NMC end-of-life battery value for typical passenger car in 2040

Looking ahead to 2040, our analysis indicates that the recycling of NMC batteries is expected to yield a positive value of about 1,200€ (see Figure 3), taking into account the residual material value of 2,300€. In contrast, LFP batteries are projected to still incur a negative value of -900€ due to the lower precious metal content (see Figure 4).

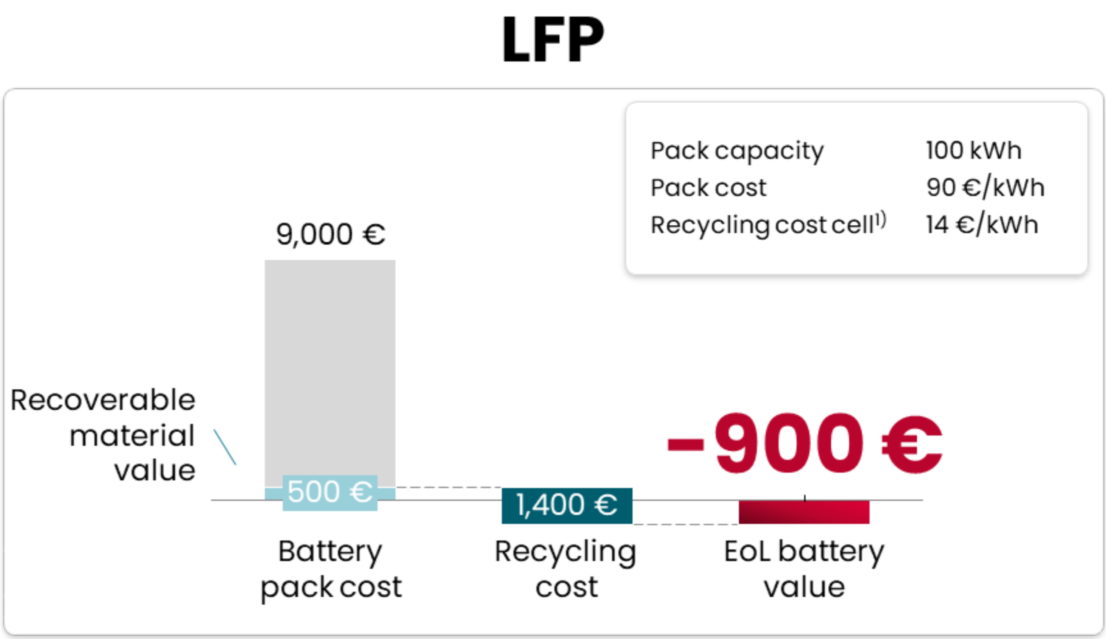

Fig. 4 LFP end-of-life battery value for typical passenger car in 2040

This results in an EoL battery value gap of roughly 2,100€ for a typical battery electric vehicle, underscoring the importance of considering battery cell chemistry choice as a design approach for circularity.

3.2 Battery Pack Design

Battery pack design plays a crucial role in facilitating circularity and the sustainable management of end-of-life (EoL) batteries. This topic can be further explored through three key aspects: "cell to pack" vs. modular pack design, material mix considerations, and joining methods.

In "cell to pack" designs, battery cells are directly linked to the pack, often using glue or other irreversible joining methods. This makes disassembly challenging, and in cases of malfunctioning cells, the entire battery pack may need to be replaced. In contrast, modular pack designs allow for individual modules to be exchanged, simplifying repair processes. Additionally, modular designs offer the possibility of recombining healthy modules for remanufacturing or repurposing applications. This flexibility not only enhances repairability but also maximizes resource utilization.

Fig. 5 “Cell to pack” example (BYD Blade); Pictures from FEV Benchmarking

Fig. 6 “Cell to module” example (VW ID.3); Pictures from FEV Benchmarking

When considering material choices in battery pack design, it is crucial to understand the eventual recycling process the battery will undergo. Some material combinations, such as aluminum (Al) and lithium (Li), pose challenges for separation even when using hydrometallurgical processes. To address this, it is important to ensure the possibility of material separation during dismantling. By enabling easier separation, the value of resulting black mass increases, subsequently improving the yield of the metal extraction process and ultimately enhancing the value of the EoL battery. Moreover, pre-processing steps that enhance recycling efficiency, such as early separation of high-value components like HV (High Voltage) components and electronics, can enable their reuse or specialized recycling routes.

Joining methods employed in battery pack design should consider accessibility for and simplicity of non-destructive dismantling and repairing. For instance, the VW ID.3 incorporates plastic screws during assembly and disassembly, resulting in automatic insulation. This approach facilitates disassembly without damaging the components. In contrast, the BYD blade battery pack is heavily glued and welded, making dismantling challenging and requiring excessive force. Additionally, the possibility for automated disassembly needs to be considered already when designing the pack. For instance, critical joining points can often no longer be reached by robots when disassembling the pack, making a high share of manual labor necessary. By utilizing more accessible and non-destructive joining methods, battery packs can be disassembled more efficiently, promoting repairability and enabling valuable components to be salvaged.

Considerations in battery pack design, such as adopting modular designs, mindful material choices, and suitable joining methods, play a vital role in enhancing circularity and the value of EoL batteries. These design approaches enable easier repair, improve recycling efficiency, and facilitate the reuse or specialized recycling of valuable components.

3.3 Utilization of Vehicle-On-Board (VOB) data

To ensure the effective remanufacturing and repurposing of end-of-life (EoL) batteries, understanding their true state of health (SoH) is of utmost importance. However, traditional methods such as extensive cycling of the battery to measure its SoH are time-consuming and costly.

Fortunately, by leveraging large datasets, sufficiently accurate predictions about the future health of a battery can be made by only measuring its internal resistance. To further improve the accuracy of these predictions, additional data points about the battery's history can be incorporated. Factors such as the number of cycles, the age of the cell, and the average temperature the battery has experienced can provide valuable insights into its condition. Original Equipment Manufacturers (OEMs) have a unique advantage in enriching the data through their access to driving data and logging events such as mechanical shocks to the battery pack.

Making accurate predictions regarding the residual health of EoL batteries allows for informed decision-making regarding the appropriate pathway for each battery pack — whether it should undergo remanufacturing, repurposing, or be sent straight to recycling. This approach minimizes waste along the value stream by avoiding the unnecessary transportation of unsuitable battery packs to remanufacturing or repurposing facilities. Moreover, accurate health predictions contribute to effective risk management, enabling better pricing of the risk involved and maximizing profitability.

By leveraging advanced data analytics techniques and incorporating historical battery data, the automotive industry can significantly enhance the circularity and value extraction from EoL batteries. These predictive capabilities not only enable optimized decision-making but also reduce waste and improve risk management throughout the battery lifecycle.

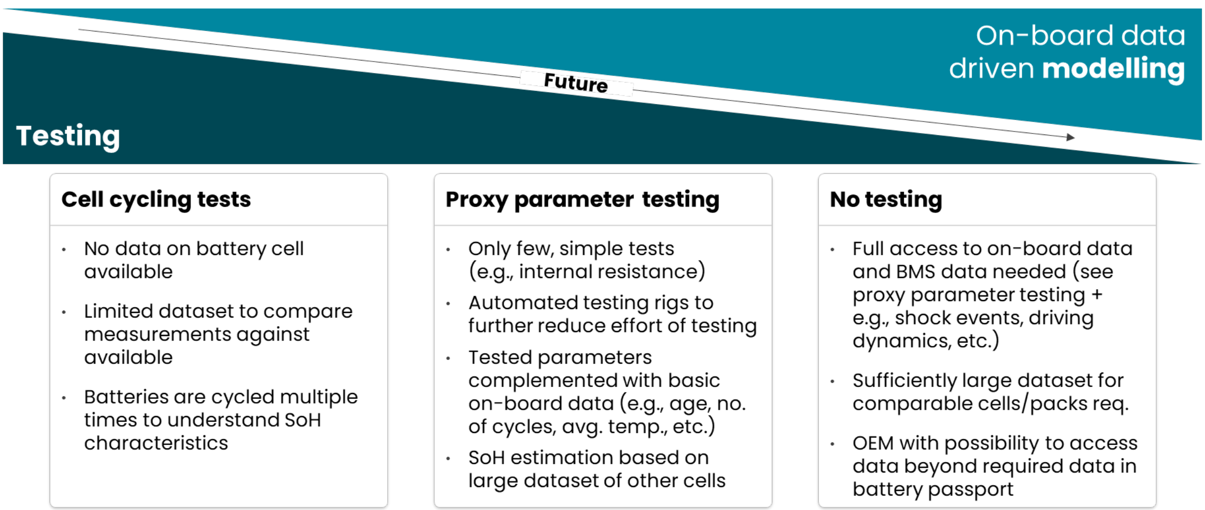

Fig. 7 Battery state of health prediction models

In addition, being able to monitor and predict the SoH of a vehicle battery accurately allows OEMs to actively prompt vehicle operators to replace the battery if sensible – increasing the likelihood of that battery remaining within their control and the vehicle owner within the reach of the OEM. For instance, the operator could be served a message through the infotainment system with an offer to replace the battery or the whole vehicle to be bought back including an automatically generated and priced purchase offer by the OEM.

3.4 Logistics network design

The design of the logistics network plays a crucial role in the overall cost of each end-of-life (EoL) battery pathway, including remanufacturing, repurposing, and recycling. Currently, the transportation of used batteries is expensive due to their classification as dangerous goods. In fact, logistics costs constitute a significant percentage of the overall recycling cost today, which is projected to decrease in the future.

One approach to reduce logistics costs is the implementation of a hub and spoke logistics concept, where batteries travel long distances in the form of black mass rather than as full battery packs. This can result in a substantial reduction in transportation costs per kilogram of cell equivalent per kilometer traveled. Depending on the scenario modelled, this can lead to a transportation cost reduction by more than 60%, according to our own CycleBat Value Chain model.

Transporting intact batteries requires compliance with the ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road) regulations, necessitating packaging according to P909 standards. This includes shockproof housing to protect batteries from damage and unintentional movement. Transporting damaged batteries requires packaging according to P908 for non-critically and P911 for critically damaged battery, which additionally increases transportation costs, as special metal containers are required, adding to the packaging cost, weight, and volume.

In contrast, once the batteries have been shredded and transformed into black mass, transportation becomes relatively straightforward. The black mass, which primarily consists of the cathode active material, can be transported in “big bags”, significantly reducing weight and volume compared to transporting full battery packs. The reduction in weight alone leads to a drastic decrease in transportation costs.

Furthermore, the overall distance traveled can be significantly reduced by establishing a hub and spoke network. This network consists of a wide array of medium-scale black mass production facilities spread across Europe, with a smaller number of large-scale metal extraction hubs. This way, the cost-effective black mass can serve as input to the metal extraction hubs. This emerging ecosystem is already taking shape, with industry players such as Glencore and Li-Cycle planning to establish their metal extraction hub in Sardinia, along with three black mass spokes planned in France, Norway, and Germany.

By optimizing the logistics network design and adopting a hub and spoke approach, the automotive industry can effectively reduce transportation costs for EoL batteries, particularly during the recycling process. This strategy not only contributes to the economic viability of battery circularity but also promotes the establishment of a sustainable and efficient battery recycling infrastructure throughout Europe.

4 Limitations

While this study sheds light on significant economic and environmental implications of design-for-circularity in electric vehicle batteries, it is not without limitations. Foremost, the analysis is concentrated on the European market, and hence, the findings may not be universally applicable. Different regions have varying regulatory landscapes, consumer behaviors, and industry dynamics that could alter the cost-benefit equation considerably.

The study also leans more towards economic analysis, with environmental impacts being secondary. Although the paper does touch upon the environmental benefits of a circular battery lifecycle, a more comprehensive life cycle assessment could offer a fuller picture.

Further, the figures presented are based on industry averages and scenario-based assumptions. While these provide a macro-level understanding, each Original Equipment Manufacturer (OEM) and recycler will have unique factors that affect their cost structures, processes, and environmental footprint. Consequently, the broad findings might not hold for every player in the ecosystem. For more precise, player-specific assessments, the CycleBat models can be tailored to account for these individual characteristics. For instance, this study assumes a generic hydrometallurgical process for the cost of metal extraction; however, each recycler may have a specific process route that should be modeled in the CycleBat tool to predict processing costs, energy consumption, and carbon footprint accurately.

5 Conclusion

In conclusion, the study highlights the critical importance of integrating design-for-circularity principles into the development of EV batteries as well as the set-up of the overall European battery ecosystem. OEMs need to overcome short-term cost pressures and align their design decisions with long-term sustainability goals. By doing so, they can improve the financials of batteries already today, unlock new business opportunities in the future, mitigate risks, and contribute to a more sustainable and circular future for the electric mobility industry.

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7 Acknowledgement

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