Challenges in the Automated Disassembly Process of Electric Vehicle Battery Packs

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***Abstract*—The surge in the development and adoption of Electric Vehicles (EVs) globally is a trend many countries are paying close attention to. This inevitably means that a significant number of EV batteries will soon reach their End-of-Life (EoL). This looming issue reveals a notable challenge: there's currently a lack of sustainable strategies for managing Lithium-ion Batteries (LiBs) when they reach their EoL stage. The process of disassembling these battery packs is challenging due to their intricate design, involving several different materials and components integrated tightly for performance and safety. Consequently, effective disassembly and subsequent recycling procedures require highly specialized methods and equipment, and involve significant safety and health risks. Moreover, existing recycling technologies often fail to recover all valuable and potentially hazardous materials, leading to both economic and environmental loss. This paper provides an overview and analysis of possible challenges arising in the domain of automated battery disassembly and recycling of EV batteries that reached their EoL. We provide insight into the disassembly process as well as optimization of the disassembly sequence with the goal of minimizing the overall cost and environmental footprint.**

***Index Terms*—Electric Vehicles; Automated Battery Disassembly; Battery Recycling.**

I. Introduction

With a continuously increasing market share for Electric Vehicles (EVs), the volumes of used and recalled EV battery packs will increase exponentially (see Fig. 1). This poses a significant challenge from a cost and sustainability perspective. Recycling of battery metals is absolutely necessary to reduce pressure on virgin metal extraction [1]. A new industry committed to advancing green battery technology is currently being established, often together with premier manufacturers of Lithium-ion Batteries (LiBs), e.g., Northvolt AB. Recognizing the importance of electric vehicle battery recycling in its early stages, the industry is establishing pilot-scale recycling facilities, thereby paving the way for a closed-loop of the battery manufacturing process. The development of a proper recycling process is therefore of critical importance for both battery cell manufacturers and society [2]. As the volume of spent electric vehicle batteries grows, manual disassembly becomes less feasible due to its labor-intensive and time-consuming nature. Robotic disassembly can potentially offer a solution. Robots can be programmed to perform repetitive tasks more quickly and consistently than humans, potentially increasing the efficiency of the disassembly process. Additionally, robots can perform tasks in environments that may be hazardous to humans, reducing the risk of human exposure to the toxic materials contained in batteries.

However, robotic disassembly presents its own challenges. Programming robots to accurately and efficiently disassemble complex battery packs is a nontrivial task. The wide variety of battery designs and materials adds to this complexity. Furthermore, the initial investment for robotic equipment can be high. Research and development in this area are ongoing, focusing on developing cost-effective, flexible, and efficient robotic disassembly systems.

Our intention is to create a solid solution that would have the robustness needed for continuous industrialized disassembly, enabling the flexibility to add new types of battery packs with limited effort. Additionally, and benefiting the metal and EV battery mechanical recycling [3], the goal is to introduce and develop an extended technology portfolio to be used both in other battery recycling and battery manufacturing processes, in research, as well as in other manufacturing and waste industries [4].

II. Automated Battery Disassembly Challenges

EV batteries (Fig. 2) are sophisticated devices composed of numerous components, including the outer casing, module packaging, cells, and a variety of materials like lithium, cobalt, nickel, manganese, and graphite. This complexity poses significant challenges for automated disassembly. Battery models and internal architectures can also vary significantly between manufacturers, and even between different models from the same manufacturer. This variability makes it difficult to develop a single automated process that can handle all types of EV batteries. Meng *et al.* [5] provide an extensive overview of the intelligent disassembly of EV batteries.

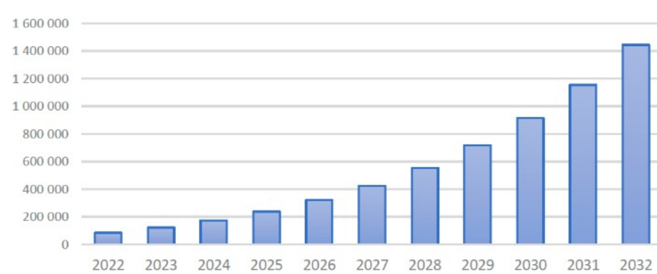

Fig. 1: Expected EoL EV Pack Volumes, Europe.

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Fig. 2: An example of an EV battery pack after the lid and the connection cables have been removed. It contains 8 modules.

A. Safety Concerns

Ensuring safety is a paramount concern in the disassembly of LiBs, which are the predominant type utilized in EVs. These batteries pose considerable risks due to their volatility. Mismanagement during the disassembly can instigate hazardous thermal reactions, trigger fires, or even cause devastating explosions. Therefore, maintaining safe handling procedures throughout the disassembly process is non-negotiable. Creating an automated process for the safe disassembly of LiBs is a task that is fraught with difficulties, but is nonetheless crucial. However, it also presents unique challenges. First, the design and programming of robots that can accurately and efficiently disassemble batteries without causing damage is a complex task. Second, the monitoring and control systems required to ensure safety during automated disassembly are complex. These systems need to be able to detect potential problems, such as rising temperatures or mechanical failures, and respond quickly to prevent incidents. Finally, the facilities for automated disassembly must be built to withstand potential incidents and to contain any fires or explosions that do occur. Additionally, these facilities must be equipped with appropriate ventilation and filtration systems to prevent the release of harmful substances into the environment.

B. Efficiency and Precision

Automated disassembly of EV batteries plays a crucial role in their recycling, requiring a careful balance between efficiency and precision. The rising volume of spent batteries necessitates quick processing to avoid storage issues and escalating costs. Efficient disassembly, therefore, should handle large quantities of spent batteries swiftly. On the other hand, the disassembly process must be precise in order to be able to disassemble battery packs without damaging the battery cells and to preserve valuable materials in these batteries. Precision ensures these materials are not lost or damaged, which would otherwise impact the recycling process's profitability and potentially lead to safety concerns. The challenge of achieving this balance involves utilizing advanced machinery and monitoring systems. These machines should adapt to various battery designs and sizes, accurately identifying and separating different components. Moreover, the monitoring systems should oversee the smooth running of the process, identifying potential issues that could cause material loss, damage, or safety incidents. Overall, achieving this balance is crucial for a sustainable and economically viable EV battery recycling process.

C. Economic Considerations

Implementing automated disassembly systems for EV battery recycling demands a large initial investment in advanced machinery, as well as the development and refinement of operational processes. This machinery, including robotics and computer systems, needs to be versatile and capable of handling various battery designs and sizes, as well as potential future technologies. Moreover, investing in software development for programming and monitoring systems is crucial. These systems are designed to oversee the process, identify potential issues, and maintain safety and efficiency. However, the economic viability of automated disassembly is challenging due to the relatively low value of the recovered materials, such as lithium, cobalt, nickel, and manganese, compared to the high costs of the recycling process. Additional considerations include operating costs, maintenance and upgrades for machinery, and expenses associated with waste management and environmental compliance.

D. Adaptability

As EV technology continues to evolve, the design and composition of batteries will change. For instance, solid-state batteries are on the horizon. This continual evolution means that automated disassembly processes must be adaptable to accommodate new battery designs and chemistries.

E. Environmental and Social Impacts

The development of the aforementioned technology is seen as a key enabler for a high-scale EV battery recycling process. The use of metal recycling methodologies for EV battery packs will help to reduce the carbon footprint in the metal obtention by approximately 70%, creating a circular supply chain for new battery production, and empowering the transition to fossil-free energy sources. Besides, the use of recycled materials will also have a direct impact on battery cell manufacturing, reducing the emissions ($KgCO_2e$/kWh cell capacity) by up to 75% combining the use of recycled material and carbon efficient manufacturing methods (reference value of $100-150$ $KgCO_2e$/kWh cell for an Asian cell manufacturer). Roy *et al.* [6] provide a comprehensive review on the recycling of LiBs. Moreover, the predicted industrialization and the increase of the exportation capacity will allow a distributed source of material, permitting a closer collection and recycling having a positive side effect also on the impact on transportation, manufacturing costs, and emissions to air and water. Besides the environmental benefits, battery recycling will induce a direct reduction of virgin materials extraction and mining activities, which often are met with very low social acceptance [7]. In addition to that, the ergonomics and safety of the dismantling process will be improved by reducing heavy lifting, and repetitive operations, and avoiding direct contact of the operators with hazardous materials.

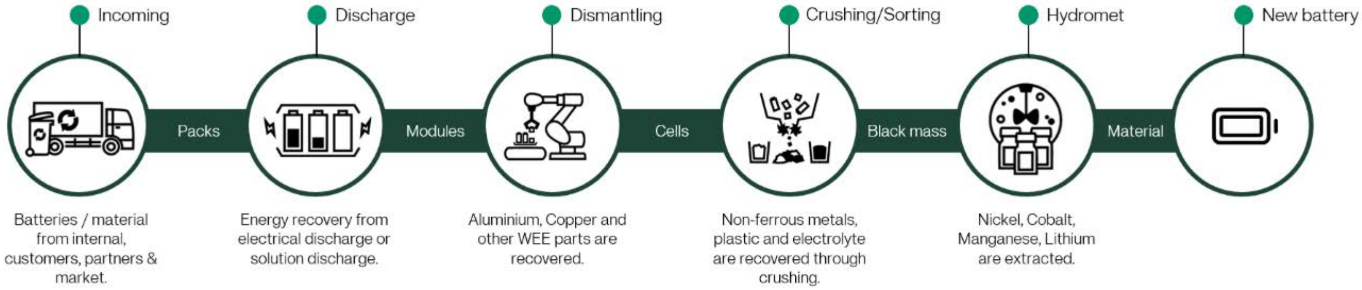

Fig. 3: The overview of the recycling process.

F. Solving the Challenges

To overcome these challenges, a combination of efforts is required. Technological innovation can lead to more efficient and adaptable disassembly processes. Improved battery design standardization across the industry could simplify the disassembly process. Policy interventions, like financial incentives for recycling companies, could help offset the costs of developing and implementing automated disassembly systems.

III. Disassembly Process

Before initiating the process of disassembly, it's crucial to thoroughly comprehend the particular configuration of the assembly and the mutual relations among the internal parts. This includes understanding the count of parts to be taken apart, the connective relations among these parts, as well as the spatial limitations between components. Typically, this data can be obtained from a CAD model if such a model is available, or from recording the manual process of disassembly. The information gained plays a crucial part in optimizing the disassembly process (Sect. IV).

In general, the disassembly of EV batteries involves several complex steps, as shown in Fig. 3, and the specific approach can vary depending on the design of the battery, the types of materials it contains, and the equipment available at the recycling facility. However, a generalized process typically involves the following stages:

a) Battery Collection and Preparation.: Before the disassembly process begins, spent batteries must be collected and prepared. This includes safe transportation to the recycling facility, discharge of remaining electricity, and external cleaning of the batteries to remove any dirt or dust.

b) Battery Sorting.: In this phase, batteries are sorted by chemistry and manufacturer. This is a crucial step because each type of battery requires a different process for safe and effective disassembly and recycling.

c) Mechanical Disassembly.: The first stage of disassembly involves removing the battery lid. This is very challenging since different manufacturers have different ways of attaching the lid to the casing, many of which were not designed with the intention of being disassembled. The two most common ways are to glue the lid or use fasteners such as screws. So far, the process of lid removal has been performed manually. Our goal is not only to automate it but to make it flexible, i.e., to be able to handle different battery packs with the same robotic disassembly unit. Keeping in mind the multiformity of EV batteries, the robot must utilize various tools in order to be able to handle as many different EV battery packs as possible. This means that the robot must have access to different tools related to gripping, cutting, drilling, and milling [8]. After the removal, the lid and the casing are typically sent to the local recycling facility, as we are primarily focused on the recycling of the battery cells.

d) Module and Pack Disassembly.: Once the lid is removed, the battery modules and packs need to be disassembled. This involves removing any wiring, circuitry, battery management system, and other components that connect the individual cells. These are often recyclable as well, but they must be separated from the cells themselves. The main goal here is to free the modules consisting of battery cells, so they can be extracted using a robot with appropriate gripper.

e) Battery Cell Disassembly: Battery cells are finally extracted from the modules. There are three commonly used types: cylindrical, prismatic, and pouch. Battery cell disassembly is the most intricate step. Each cell contains a variety of different materials, including the cathode, anode, and separator, each of which needs to be separated for recycling. Automated shredding and crushing equipment is often used to break down the cells into smaller pieces. These pieces are then separated based on their properties, such as magnetism or density, in order to segregate different material fractions.

f) Material Recovery.: After the cells have been disassembled and sorted, the different materials can be sent for further processing to recover valuable elements like lithium, cobalt, nickel, and others. This typically involves thermal and/or hydrometallurgical treatment processes, and the specifics vary depending on the materials being recovered.

The automation of the above process is a complex task and comes with a range of challenges, as previously discussed. It requires a deep understanding of battery design and chemistry, sophisticated machinery, and robust safety procedures. However, the development of effective and efficient automated battery disassembly systems is crucial to managing the growing number of spent EV batteries and supporting the transition toward a more sustainable and circular economy.

IV. Battery Pack Disassembly Sequence Optimization

The process of automated battery pack disassembly poses a great challenge, as the battery pack disassembly planning sequence must consider factors like the specific battery design, safety, and cost-effectiveness of the process [9]. Different battery types and designs will require different disassembly processes. For these reasons, it is important to have a robust planner that can create an optimized disassembly sequence for each battery pack.

In order to articulate the relationships between components more distinctly, a disassembly relationship graph needs to be built based on the constraints and relations between the components. This graph simultaneously expresses the connection and disassembly precedence relationships among components. The disassembly precedence relationship indicates that there are restrictions on the disassembly sequence of two parts—one has to be disassembled prior to the other. On the other hand, the connection relationship relates to the mechanical bond between two parts. In practical disassembly, the complexity of disconnecting varies based on the nature of the connection. For instance, in Disassembly Sequence Planning (DSP) the aim is to maximize revenue and the cost of disconnecting different connections differs. hence, the connection relationship among different components is an indispensable parameter in such optimization processes. The disassembly relationship graph used for DSP consists of nodes and edges. For an assembly with n components, the nodes denote these n components, while the edges between nodes signify the disassembly precedence and connection relationships among the components.

It is also a common practice to use Disassembly Relationship Matrix (DRM) to express the relations between different components. The way this works is to have a defined matrix A of size $n \times n$. If for component i all the elements in i-th row are 0 it means that component i is independent, i.e., it has no relationship with other components. However, if element j in i-th row has value 1, it means that there is a precedence constraint between components i and j, i.e., component i has to be disassembled before component j. By using integer identifiers, we can also model other connection relationships.

Optimizing the sequence of disassembly can significantly improve the efficiency of the battery recycling process. The idea is to identify the optimal order of steps to minimize the time, cost, and energy required for disassembly while maximizing the recovery of valuable materials. Various optimization algorithms can be employed, including the Genetic Algorithm (GA) [10], other heuristic algorithms [11], or exact solvers [12]. These methods typically involve creating a mathematical model of the disassembly process and then using the optimization algorithm to find the best sequence of steps. As an example, Ke*et al.* [13] proposed a genetic algorithm-based approach to optimize the disassembly sequence. Bazzouzi *et al.* [14] also used a disassembly sequence planner based on GA.

V. Conclusion

The outcome of this work will genuinely contribute to the industrialization of the dismantling and recycling processes. Apart from upgraded working conditions, the technologies proposed in this work will aim to reduce the current dismantling cycle time by 50% and increase the automation level up to 60%. The new possibilities in process distribution and exportation, and the increase in process performance and safety, will introduce major improvements in the battery recycling industry and especially in the collection network, facilitating logistics and operations. Moreover, technological contributions will open new possibilities in the field of automation of EoL battery recycling. Another benefit of the proposed approach is the reduction of the personnel requirements, allowing personnel with less experience, knowledge, and expertise to work on the dismantling of battery packs. This will be of extreme importance when the volumes of EoL batteries increase in the coming years.

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