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Sustainable Battery Lifecycle: Non-Destructive Separation of Batteries and Potential Second Life Applications

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Abstract: Large quantities of battery systems will be discarded from electric vehicles in the future. Non-destructive separation of used electric vehicle (EV) traction batteries enables a second life of battery components, extraction of high value secondary materials, and reduces the environmental footprint of recycling and separation processes. In this study, the key performance indicators (KPIs) for the second life application of spent EV batteries are identified. Three battery packs are analyzed in terms of the joining techniques used—and possible separation techniques—considering only direct recycling methods. The components that can be recovered from these batteries are evaluated against the KPIs. This study shows that all the batteries analyzed allow a second life in stationary and semi-stationary electrical storage systems and marine applications when used at the pack and module levels. Two packs can be reused in electric vehicles such as forklifts. However, the feasibility of re-use in micro-mobility and consumer electronics is very limited. This study shows that technically feasible separation methods are dictated and constrained by the joining techniques used. As welding and adhesive bonding pose challenges to separation processes, future efforts should prioritize 'design for disassembly' to ensure sustainable battery life cycle management.

Keywords: second life; sustainable battery lifecycle; resource utilization; lithium-ion batteries; electrical storage components; key performance indicators; joining methods; non-destructive separation; artificial intelligence

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1. Introduction

The shift to battery electric vehicles is considered as a highly promising strategy for the energy transition in the mobility sector, which should help to achieve the global decarbonization targets in the automotive industry [1]. A critical aspect of the performance and acceptance of battery electric vehicles is the power and capacity of the battery system they use [2]. Actually, the most popular system architecture is based on lithium-ion batteries (LIB), accounting for 94.4% of the global electrochemical energy storage market in 2021 [3]. Despite its advantages, e.g., superior energy density, longevity, and electrical and chemical properties [4], the sustainability of the used battery material is under discussion. This is due to the circumstances surrounding the extraction of critical materials like lithium and cobalt and the potential environmental and health hazards their disposal poses [5]. In addition to technical requirements, the above-mentioned topics are additional challenges that the automotive industry has to face to transform the transport sector [1]. Battery electric vehicle (BEV) sales are expected to increase significantly, reaching over 33 million per year by 2030 [6]. Making the conservative assumption that these BEVs will reach their end-of-life (EoL) after 10 years [7], it can be predicted that at least 33 million EoL battery packs will be available for disassembly by 2040 annually. This highlights the importance of developing efficient recycling processes, which involve disassembling battery packs and recovering valuable materials such as lithium, nickel, cobalt, and graphite [7].

The general trend in EoL management of BEV battery packs is moving towards a circular economy (see Figure 1). When electric vehicle batteries reach the end of their initial life, they still have a state of health (SoH) of approximately 70–80% [8–10]. Hence, the emphasis is on reusing or repurposing the energy storage components (ESCs) directly for second life applications [11–13]. If this cycle is not possible due to defects at the pack, module, or cell levels, the second key objective is to recover high-quality secondary raw materials instead of just disposing of the batteries [7].

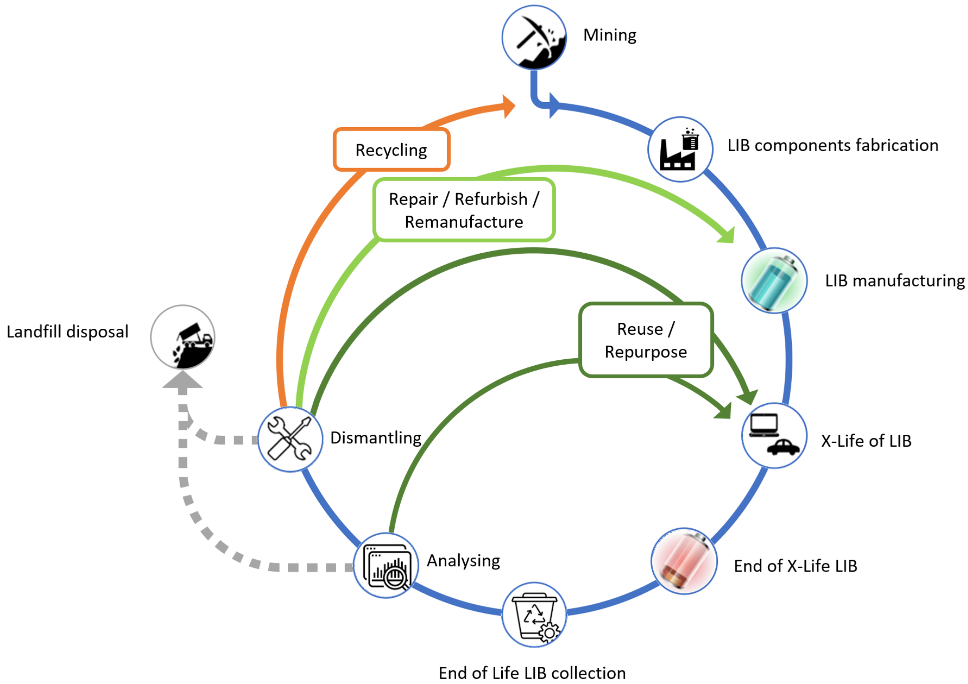

Figure 1. Different end-of-life paths of LIBs (adapted from [14]).

Therefore, the analysis (the penultimate station of the blue path in Figure 1) of the EoL of a LIB plays a crucial role in determining the necessary further steps for the optimal utilization of the collected batteries. On the one hand, this decision is influenced by assessing the possible further use of the battery by, for example, defining their state of usability (SOU). The SOU is a method for categorizing LIBs based on safety and performance indicators [15]. On the other hand, the decision is heavily influenced by regulatory requirements. There are several standards, like the IEC 63330 [16], IEC 63338 [17], UL 1974 [18] and EU Batteries Regulation, dealing with the safety of spent battery systems intended for applications different from their original use. IEC 63330 outlines the fundamental requirements for evaluating the safety of these LIBs, and UL 1974 focuses on their sorting and grading processes. IEC 63338 is under development and it will provide guidance on the safe and environmentally friendly reuse of LIBs [19].

Disassembly, in addition to analysis, also plays an important role not only in the process of reusing or repurposing a battery pack [20] (the last two steps of the blue path in Figure 1), but also in the processes of repairing, refurbishing, remanufacturing, or recycling. This is due to how electric vehicle (EV) traction battery packs are structured. They consist of numerous cells that are connected in a serial and/or parallel manner. These connected cells are then assembled into modules, which in turn are assembled into a pack. This is known as a cell-to-module (C2M) design and can be seen in Figure 2a. Figure 2b displays another approach where the cell stacks are directly integrated into the pack, which is known as a cell-to-pack (C2P) design [21–24]. The analysis of such a pack may show that it is no longer functional as a unit. However, individual ESCs may still be intact, either at the module or cell level. In this case, it would be necessary to disassemble the pack to separate the working ESCs from the defective ones. The first step is to separate good cells from defective ones. Dismantling and classifying may also be necessary to bring the ESCs into sizes and performance specifications that correspond to the boundary conditions of different second life applications.

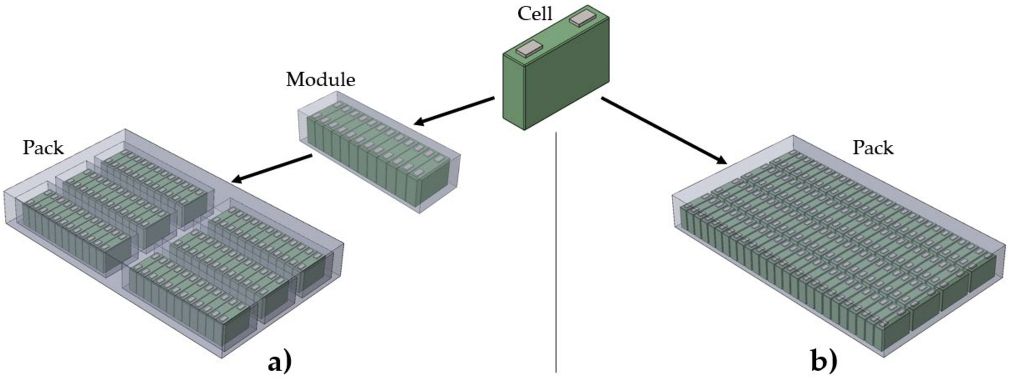

Figure 2. Schematic drawing of (**a**) cell-to-module design and (**b**) cell-to-pack design.

The separation of defective ESCs also has a significant influence on process efficiency in the recycling process flow (the orange path in Figure 1). Removing the pack and module components (a) provides an opportunity to reuse the components or to pass them into another recycling flow [1] and (b) increases the efficiency, particularly for the hydrometallurgical recycling process [25], as unwanted materials have already been removed in advance. The third method of current recycling trends, known as direct recycling, requires mechanical dismantling of cells and separation of electrodes to obtain the valuable materials [7,25].

Nowadays, the dismantling of battery packs in these two EoL processes is dominated by manual disassembly. Considering the expected volumes of EoL EV batteries in the future, this method is unsuitable for economical and sustainable EoL management of LIBs [26]. The process can be complex and non-linear. It often requires multiple tool changes and takes a long time, which can pose significant challenges. To improve the economic feasibility of recycling LIBs, it is essential to streamline these EOL processes and automate disassembly. Automation has been identified as the key to tackling these issues [27]. This will help improve the efficiency of separation procedures and reduce the time and costs associated with recycling EV batteries, according to studies by Lander et al. [7,28]. Furthermore, automating separation is mandatory for workers' safety, as manual disassembly of LIBs is not only inefficient and costly but also risky [29].

Wu et al.'s [1] literature review shows that research in the field of manual and automated battery pack disassembly has increased, particularly since 2018. Studies on automation have predominantly focused on conceptual disassembly down to different levels, but this has mostly been limited to abstract representations of layout concepts. There have been few investigations into implementing such concepts in an experimental or real-world environment. For example, Choux et al. [30] proposed an autonomous task planner to dismantle electric vehicle lithium-ion battery packs using a computer vision system. Li et al. [31] designed and prototyped an automatic disassembly system for lithium-ion pouch cells to dismantle and separate various components from the cells.

Several recent studies have focused on the development of robotic disassembly systems for LIB packs to improve efficiency and safety in the recycling process [29,30,32]. These studies underscore the significance of automation in disassembly processes, highlighting the potential for human–robot collaboration to achieve efficient cuts on the battery pack and quick sorting of components [29]. However, the literature shows a lack of information on pack disassembly processes and cost aspects, indicating the need for further research in this area [33]. Moreover, there is a growing emphasis on the need for smarter and more efficient disassembly processes through higher skills, driven by the rapid changes in EV battery innovations, and the design of modules and packs [28]. Artificial intelligence (AI)-based vision systems and decision making will contribute to economic disassembly processes in the near future.

The dismantling strategy and its derived processes, designed to separate the desired recyclable components and materials, have a significant influence on whether the recycling process is economical or not [25]. So far, a research gap is identified concerning the optimal separation process depending on cell type, cell dimension, achievable recycling rates, and costs [1].

The aim of this work is to find the factors that influence the optimum level of battery pack disassembly processes, depending on the cell type, the general pack architecture, and the required recycling rate. In the context of this work, the recycling rate is defined as being highest when the extraction of the ESCs in their different forms (pack, module, cell) is possible and they can be used in a second life application. When designing the study processes, the focus is therefore on achieving the highest possible resource utilization. Possible alternatives are reusing, repurposing, or direct mechanical recycling if a second life application is not possible. This general decision path for the process design is shown in Figure 3.

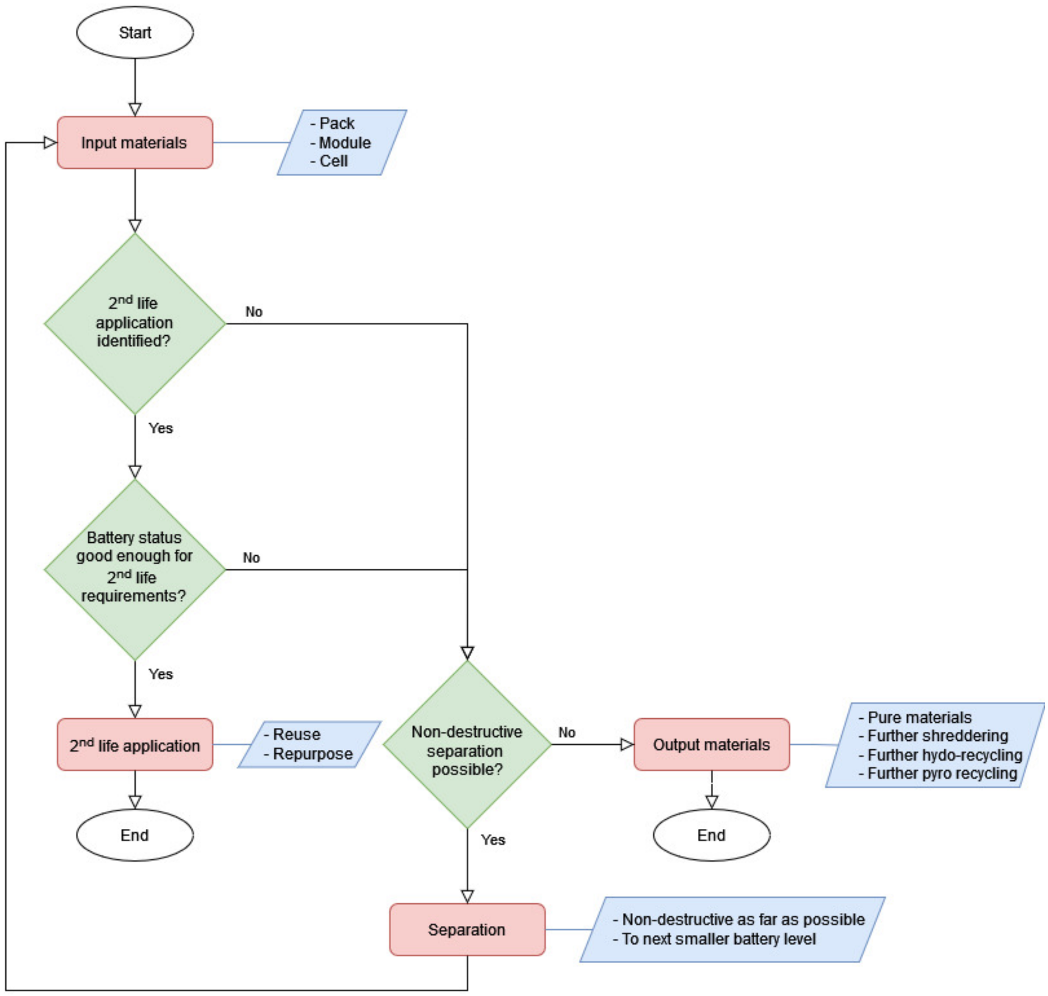

Figure 3. General decision path for separation of battery systems.

2. Materials and Methods

To investigate the optimum disassembly level in this work, the decision path shown in Figure 3 is used to derive a theoretical automated disassembly process for each of the three market-relevant battery packs with different architectures. The required steps to dismantle each system are derived from manual separation reports. For each of these three processes, the separation methods according to DIN 8580 [34] are systematically assigned to each separation step based on the joining technique used, with the assumption that non-destructive methods are required to ensure the reuse of the ESCs. To identify potential second life applications and associated key performance criteria, a literature review is conducted. The potential second life applications can then be used to define the required separation depth to which each system must be separated, and to compare it with the feasibility of non-destructive separation. This results in clear requirements regarding the degree to which highly automated, non-destructive separation processes are necessary and when strict separation of the individual materials is required.

The aim is to obtain a type of separation instruction for specific battery systems in which the influences of the system architecture and the performance data of the battery system are compared with the potential second life requirements. For this purpose, it is necessary to analyze the structure of the system in detail and to take a close look at the available separation processes. In addition, safety-relevant aspects as well as options for monitoring and controlling the separation processes and ESCs must also be included in the future. The inclusion of AI-based systems is a possible key to success, especially for these supporting activities (see Figure 4).

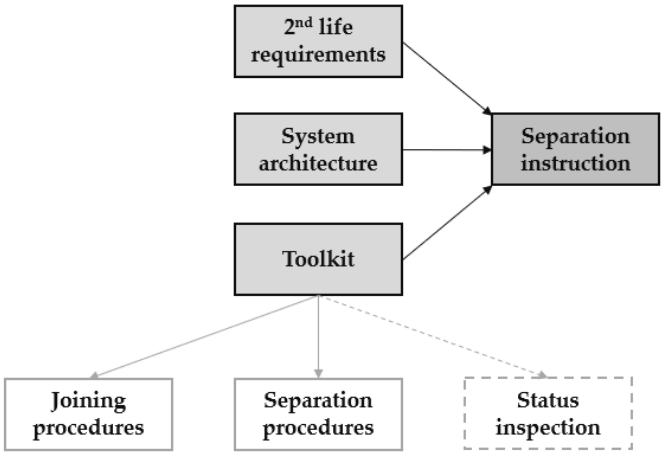

Figure 4. Approach for separation instruction.

To ensure a structured approach, the following objectives are pursued:

- Categorization of second life applications.
- Definition of requirements and key performance indicators (KPIs) of second life applications.
- Selection of the three commercially available battery systems to evaluate the applicability of non-destructive separation methods.
- Use case study: joining techniques used in these battery systems.
- Use case study: potential separation methods for non-destructive extraction of ESCs for further use.

2.1. Categorization of Second Life Applications

Based on the literature review, second life use cases are categorized based on four criteria, namely the degree of mobility, application type, load profile/duty, and hierarchical level, as shown in Figure 5. The categorization reveals that load profiles/duties can be assigned to different application types, which are categorized according to their status in stationary, semi-stationary, and mobile applications. The various application types and use cases are briefly outlined: an energy storage system (ESS) can be used in a private household (residential); in a commercial manner, like an electric vehicle charging station; or at an industrial site to assist energy generation and distribution. Additionally, in every application, several load profiles are applicable. First, 'Load following' refers to shifting loads throughout the day regarding the demand to optimize costs and usage. Second, 'Load profile peak shaving' serves for providing energy to the grid when the demand is highest [35]. Third, 'Load levelling' aims to reduce large fluctuations in customer demand by storing energy during periods of light loading and delivering it when it is required [36]. Fourth, 'Renewable firming' is the storage's capability to compensate renewable energy source (RES) production variation caused by a sudden change in the environmental conditions [37]. Fifth, 'Spinning reserves' are used as a type of intermediate back-up storage which starts operating within milliseconds to minutes when a system change is occurring to avoid any system disruptions [38]. Finally, the 'Transmission stabilization storages' support the grid by transferring power from remote generation sides to the distribution networks [39]. In addition to (semi-) stationary storages, mobile applications can have partly similar driving cycles and requirements to first life scenarios, but the requirements can also differ significantly depending on the actual use. Light EV applications are subsequently understood to mean reuse in vehicles designed for short distances, but also industrial tasks with similar requirements, such as forklifts. For further use in micro-mobility, e-bikes, e-scooters, and e-wheelchairs, for example, offer potential fields of application. To conclude, consumer electronics batteries provide energy to any kind of kitchen or working tool that is powered cordless.

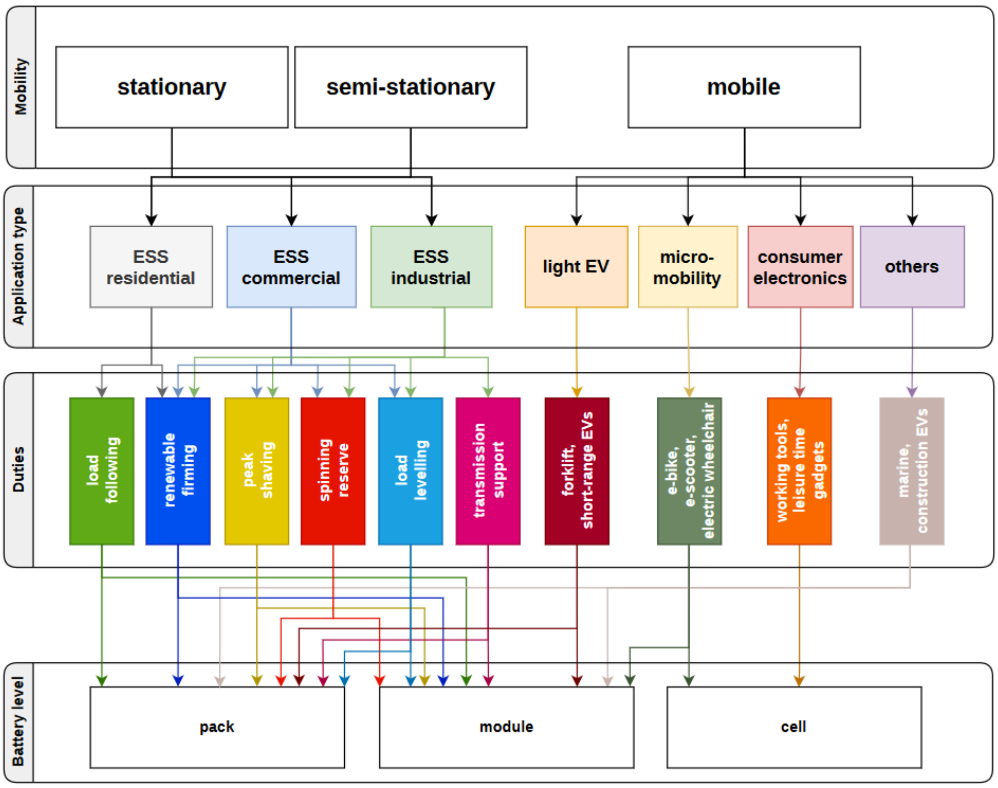

Figure 5. Categorization of typical second life use cases.

If one estimates the research and development interests based on the number of published papers and completed projects, the most widespread second life application is (semi-) stationary ESS. This is not surprising, as the requirements for a (semi-)stationary ESS show huge bandwidth in terms of load profiles compared to other applications. (Semi-) stationary ESSs are the most promising technologies to pursue Europe's green deal targets [40,41], as commercial and industrial ESSs can be installed on a large scale and can foster the usability of e-mobility through, e.g., the expansion of EV charging stations. Additionally, the ESS's compatibility with its connected systems (e.g., photovoltaic) has developed further in the past few years and has become feasible, which increases the demand for residential ESS installations. Spent battery packs can almost directly be used in an ESS without major disassembly efforts [42–44]. On the cell level, consumer electronics (working/kitchen tools) offer great potential for repurposing batteries as they are either used infrequently or can be easily replaced/exchanged. The technical potential of a second life application in a light EV, which is defined in this paper as a smaller, short-range EV, a micro-mobility, a marine product, or a construction EV, is for sure given; however, further research for serial development, like a plausible feasibility study which covers the second life usage in those scenarios, is not given yet.

2.1.1. Definition of KPIs for Second Life Applications

The requirements for second life batteries vary depending on the area of application. To quantify the suitability of used batteries for second life, they are evaluated using KPIs. The definition of KPIs for batteries depends on subjective assessment. The European technology and innovation platform 'Batteries Europe' has provided a comprehensive set of battery-related KPIs [45], but lacks specific requirements for second life applications. Nevertheless, the KPIs for second life applications of ESCs can be determined with the following bases:

- Lifetime (calendar lifetime of the entire system);
- Power (required to meet the specification of the surrounding systems);
- Capacity (of the entire system);
- C-Rate (to meet the required energy consumption);
- Volume (of the entire system);
- Mass (of the entire system);
- Serviceability (of the entire system in order to maintain or shut it down, taking into account the associated consequences).

2.1.2. KPIs of Different Second Life Applications

The data from the researched second life applications have been analyzed and classified according to the defined KPIs. The allocation has been deliberately defined at application level to ensure an appropriate overview. Table 1 shows the qualitative results of the literature research. This clearly indicates that the range of KPIs can vary widely depending on the specific task of the application. In particular, the overall electrical and geometrical boundaries of the second life application determine the requirements. On the one hand the potential reuse of battery packs can already be anticipated, especially for industrial and commercial ESSs and special applications such as in the marine sector. For residential ESSs or light EVs, on the other hand, the use of an entire pack only seems possible to a limited extent. In consumer electronics and micro-mobility, where installation space is limited, the use of single modules and cells seems plausible.

Table 1. KPIs of different second life applications.

KPI	ESS Industrial	ESS Commercial	ESS Residential	Light EV	Micro Mobility	Consumer Electronics	Marine
Lifetime/years	20	20	15	8–10	2	3	10–15
Capacity/kWh	700–120,000	5–4000	2.5–20	12–90	0.18–1.5	0.02–0.5	35–5000
Power/kW	500–10,000	100–300	5–7	1.5–8	0.2–1	0.05–2	8–500
Volume/m^3	5–50	2–5	0.5–2	0.4–1.5	$3 \cdot 10^{-3}$	10^{-4}	100
Mass/kg	5–40,000	800–5000	100–250	350–1000	1–7	0.1–2	1000–150,000
Serviceability	very high	high	medium	high	low	very low	very high
C-Rate	0.5–8	0.5–8	1	2–3	0.5–2	2–5; >10	0.7–3
Sources	[46–49]	[11,50–54]	[43,51,55–58]	[58–61]	[58,62–67]	[58,68–70]	[71–73]

In order to be able to qualitatively classify the KPIs of the various applications and present them visually, the respective values have been standardized according to Table 2.

Table 2. Standardization of KPIs.

Lifetime /years	Capacity /kWh	Power /kW	Volume /m^3	Mass /kg	Serviceability	C-Rate	Standardized Value
0–2	0–0.5	0–5	0–0.05	0–2	very low	0–1 C	1
2–3	0.5–2	5–20	0.05–2	2–5	low	1–2 C	2
3–5	2–20	20–100	2–5	5–100	medium	2–3 C	3
5–15	20–100	100–500	5–50	100–1000	high	3–5 C	4
>15	>100	>500	>50	>1000	very high	>5 C	5

By combining the quantitative values of the researched KPIs in Table 1 and comparing them with Table 2, a standardized categorization for different second life applications can be derived as shown in Figure 6.

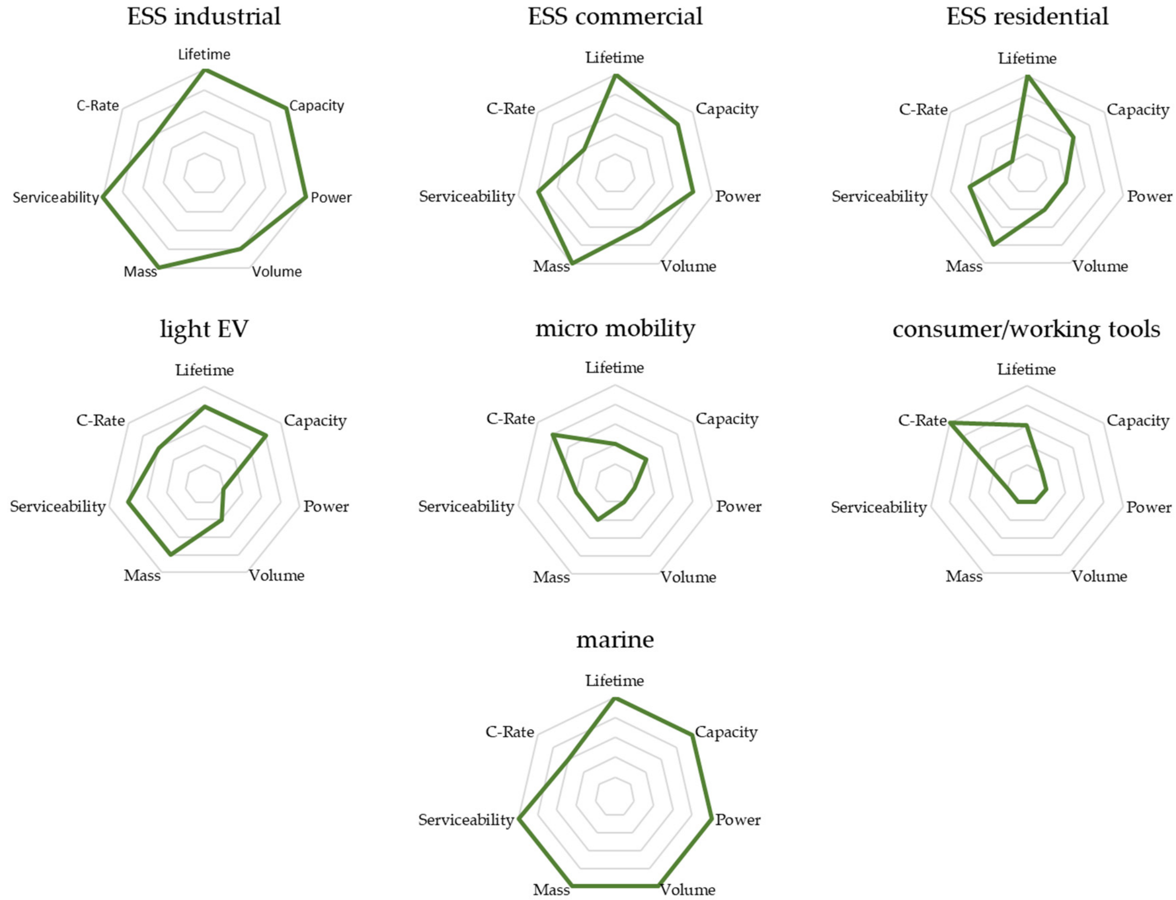

Figure 6. Standardized KPIs from different second life applications according to Tables 1 and 2.

Looking at the individual KPIs, three main conclusions can be drawn:

- (Semi-) stationary ESSs offer a wide range of possibilities for product development;
- Geometric and mass-specific requirements are associated with high disassembly effort;
- From a technical perspective, all the use cases considered are feasible, but may be severely constrained by the highly individual load profiles within the application type.

2.2. Selection of Suitable Battery Systems for Investigation

As there are many EVs with different battery system architectures in use worldwide, the selection of representative systems is crucial for the analysis, to demonstrate the diversity of the world market: Three BEVs from three different original equipment manufacturers (OEMs) with different cell types were selected. Two are C2M designs and one system is based on the C2P approach (see Table 3). These systems are anonymized and referred to as type A, B, and C. Type A is based on the modular design in which pouch cells are installed, while type B uses cylindrical cells. The main difference between A and B is the number of installed cells. In type C, prismatic cells are installed and assembled directly into a complete pack.

Table 3. Overview of investigated battery systems.

	Type A (C2M_I)	Type B (C2M_II)	Type C (C2P)
System architecture	Cell–Module–Pack	Cell–Module–Pack	Cell–Pack
Cell type	Pouch	Cylindric	Prismatic
Capacity (nominal)	~60 kWh	~80 kWh	~75 kWh
Power (continuous)	~70 kW	~120 kW	~125 kW
Voltage (nominal)	400 V	400 V	400 V
Number of cells	216	4416	118
Overall weight	385 kg	479 kg	535 kg
Origin of OEM	Europe	North America	Asia
Source	[74,75]	[76,77]	[78,79]

The following analysis of the joining and separating techniques used relates to these three battery systems.

2.3. Joining and Separation Procedures of Investigated Battery Systems

The case studies have been analyzed according to DIN 8580, which divides the manufacturing processes into six main groups (Figures 7 and 8). The groups 'separation' and 'joining' are relevant for this work. For example, 'separation' includes many different specific manufacturing technologies such as 'cutting' and 'milling', but also 'disassembly'. In order to ensure a consistent and unambiguous definition of the specific processes, the terms 'separation' and 'joining' are always used in the following as a superordinate classification and all other terms refer to the specific processes according to DIN 8580.

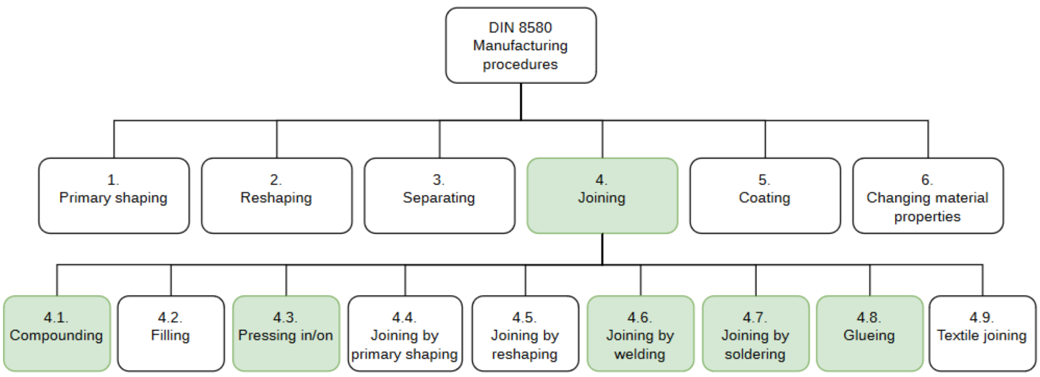

Figure 7. Classification of used joining procedures for the investigated systems [34].

Non-destructive separation is generally the first choice for the recycling techniques at the pack and module levels. For the benchmark, each pack has been manually separated and the process of separation has been documented according to a pre-defined instruction to ensure a consistent and equivalent examination of components, materials, joining techniques, and potential separation methods.

The first step was to analyze the joining processes of each battery in order to derive appropriate separation procedures in a second step. Force-fit, form-fit, and material-fit connections can be distinguished, further specifying them according to joining methods, used materials, and component properties.

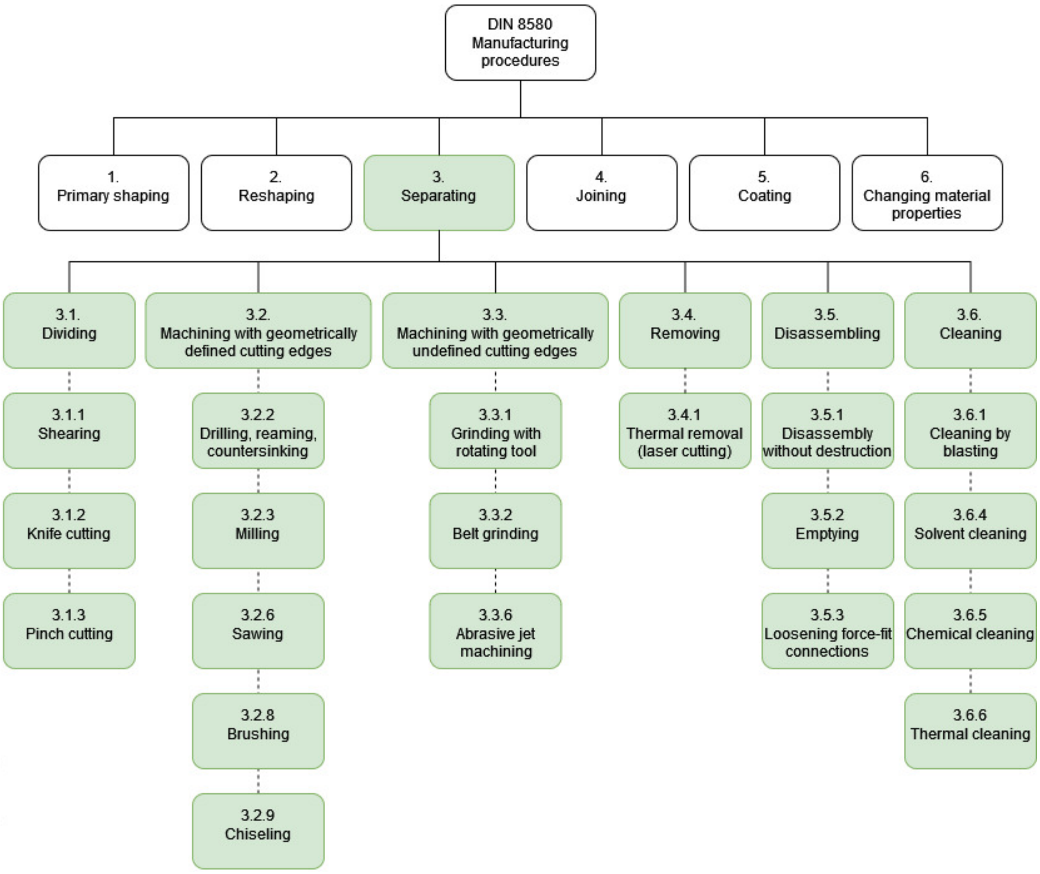

Figure 8. Classification of used separating procedures for the investigated systems [34].

The joining processes considered (see Figure 7) are limited to only five subclasses according to DIN 8580:

- 4.1.1 Assembling;
- 4.3.1 Screwing;
- 4.3.2 Clamping;
- 4.6 Welding (Arc, Laser, Ultrasonic and Fusion welding);
- 4.7 Soldering and;
- 4.8 Gluing.

For direct mechanical recycling, non-destructive methods are preferred to ensure the reuse of ESCs at all levels. Combined with the requirements of second life applications, the required separation depth can be determined and compared with the actual feasibility of non-destructive separation. In the pursuit of separating diverse battery systems, several crucial boundary conditions are considered to ensure a methodical and comprehensive separation process:

- The separation processes are limited to the pack and module levels. Cell disassembly into anode, cathode, and other components is not considered in this study.
- The pack separation process focuses on separating the ESCs so that modules and cells are separated from the peripheral components as quickly as possible.
- The further separation of various components and materials is only taken into account if this is necessary for a hypothetical automated process or can be carried out easily and cost-effectively. This can include the removal of adhesives from the housing, as well as the removal of cooling plates, sensors, and valves.

Potential non-destructive separation processes for different battery systems are identified in compliance with these defined boundary conditions, which contributes to a comprehensive understanding of the separation processes and at the same time preserves the integrity of the product for further actions.

As with the joining processes, the separating processes are also analyzed on the basis of DIN 8580. Separating processes can be further subdivided into six subgroups: dividing, machining with geometrically defined cutting edges, machining with geometrically undefined cutting edges, removing, disassembling, and cleaning. The materials and components applied in the three systems under consideration, and the joining processes used for them, can be separated by the methods highlighted in Figure 8.

3. Results

As part of the benchmark, the three representative battery systems have been investigated. The components installed and the joining procedures used have been analyzed first. The theoretical usability of ESCs has been evaluated based on the KPIs and compared with non-destructive separation methods. This resulted in different separation strategies for the sustainable further use of the three systems.

3.1. Joining Procedures of Different Battery Systems

For the three different battery systems defined in Section 2.2, the joining processes used at the pack and module levels have been determined. This elaboration examines the number of joining elements and not, for example, the surface area, volume, or mass of the joints.

3.1.1. Type A

The main components of type A are the housing, the top cover, the HV (high voltage) busbar, the BMU (battery management unit), the MCU (module control unit) and the EEU (electric/electronic unit) as well as the modules with integrated cells (Figure 9).

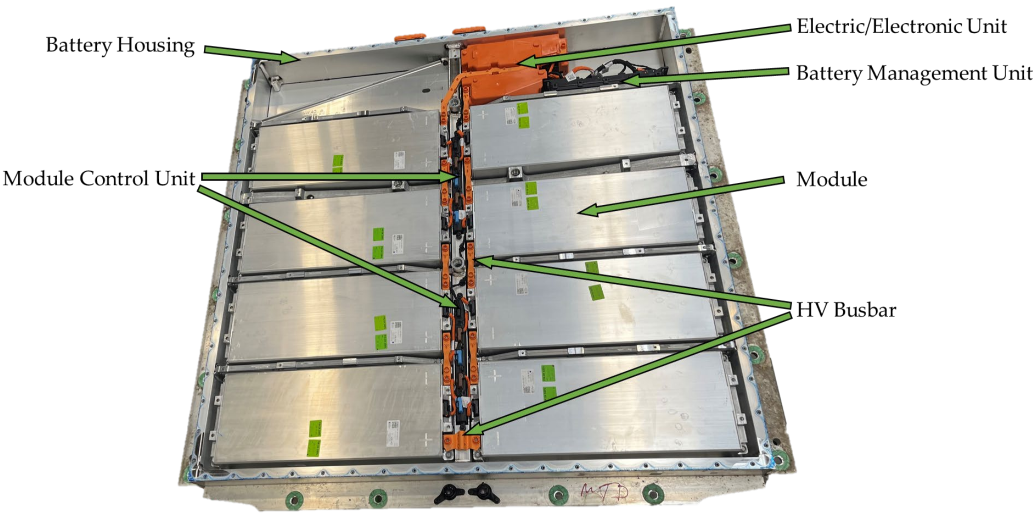

Figure 9. Main components of the battery pack of type A with removed top cover.

Figure 10 shows an overview of the joining processes implemented for type A. It can be seen that removable connections in the form of screws, which are subordinate to joining process 4.3 (pressing in/on), are predominant at the pack level. This can be attributed to the large number of screw and bolt connections, used in the cover and housing as well as other components such as module or busbar connections. The other joining techniques applied include assembling, laser welding, arc welding, soldering, and gluing. At the module level, laser welding, and gluing are mainly used to weld the cell terminals to the busbar, to connect the cells to each other and to the module housing.

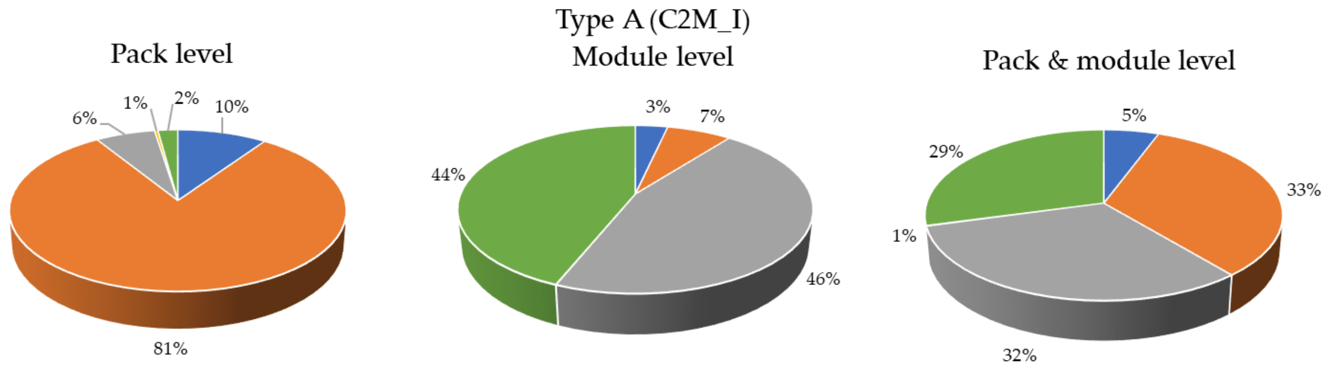

Figure 10. Share of joining procedures used on pack and module level for investigated type A.

3.1.2. Type B

Figure 11 shows the share of the joining processes used in type B. The same as with A, housing, top cover, HV busbar, BMU, MCU, and EEU account for the main components to be separated at the pack level. Again, screwing is the dominant joining procedure for pack components. For module and cell stack joining, type B features more welding and gluing processes as compared to type A. The number of connections at the module level is very high due to the use of a large number of cylindrical cells compared to the smaller number of pouch cells in type A.

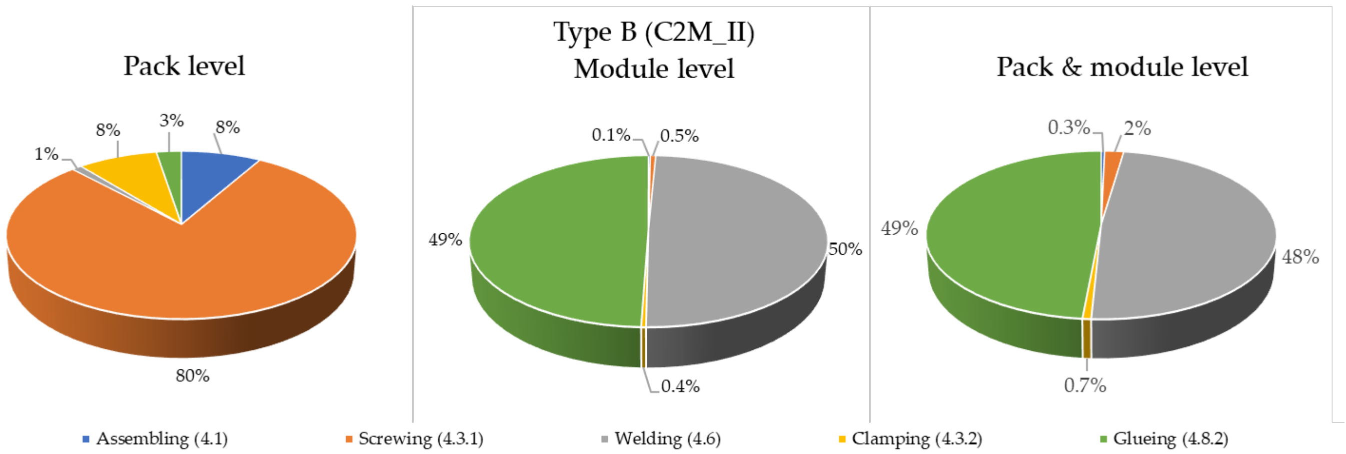

Figure 11. Share of joining procedures used on pack and module level for investigated type B.

This high number of connections in a module also significantly influences the number of joining operations. It has to be mentioned that the gluing process to fill the gap between the cells is one joining step, but the individual cells are connected to the adjacent ones and can therefore be seen as a single connection. For this system a non-destructive disassembly of the pack is feasible, but separation of the cells can only be achieved in a destructive manner. Single cells could be damaged in this process, and the removal of adhesive residue from the cells still remains very challenging.

3.1.3. Type C

Type C features a cell-to-pack design, where prismatic cells are integrated directly into the battery pack. This means that the ESC hierarchy is shorter, containing only pack level and cell level. The share of joining processes implemented for type C can therefore be summarized in Figure 12 on the pack level. As with the previous systems, screwing is extensively used for components like the top cover and HV connectors, as well as for the BMU, MCU, and EEU joined with the housing. The fixation of the cells in the housing is achieved by gluing and screwing. The single cells are connected by laser welding to a FPC (flexible printed circuit) as a busbar.

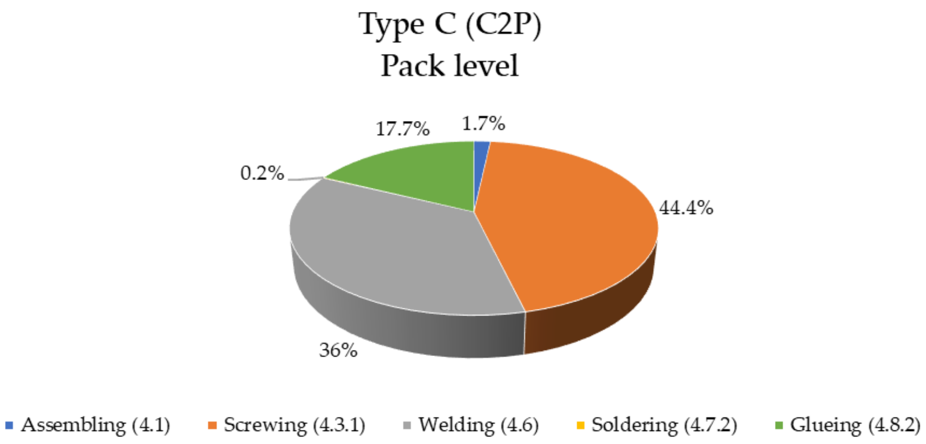

Figure 12. Share of joining procedures used on pack level for type C.

3.2. Separation Procedures

As shown in Section 2.1.2, second life applications for LIBs can be divided into a wide variety of categories and have specific basic requirements. Some of these can be derived into KPIs that enable a subsequent quantitative assessment. These KPIs provide important constraints on the extent to which non-destructive separation of specific battery packs makes sense. If there is no potential second life application, the requirements for the separation process change accordingly. The defined KPIs serve as boundaries for evaluating the usability of the benchmarked systems.

The specific KPIs of capacity, power, volume, mass, and C-rate of the various types are generally system-dependent and allow a very good estimation of theoretical usability for second life applications. The serviceability is generally independent of the first life system, as it is the design and implementation of the realized second life application that determine the serviceability. The lifetime, in turn, must be considered and evaluated for each individual vehicle. In addition, the combination of several ESCs is an obvious way of achieving the required performance data for second life in terms of capacity and power. However, the limitations in terms of permissible size and total weight are a decisive boundary condition here.

By analyzing the three battery systems, it can be systematically assessed that not every level of the ESC is applicable everywhere. Table 4 shows the theoretical second life usability of each individual ESC if it were undamaged and had at least 70–80% SoH to meet the requirements of the remaining lifetime. It can be seen that every type can be used at the pack level for EES or various special purposes such as marine applications. At the module and cell levels, there are usually volume- and weight-related application limits. The size and design of the respective cells also play an important role in their usability. In particular, it is obvious that the cylindrical cells assembled in type B can theoretically be implemented for all potential second life applications.

These findings are fundamental for the design of economically viable concepts for recycling processes/machines. The need for non-destructive separation for various system architectures and specifications is summarized in the following. Whenever an ESC can be reused or repurposed a non-destructive separation is required. Figures 13–15 show the recycling strategies for the use-case battery systems, including the possibility to recover undamaged cells.

Table 4. Theoretical second life usability of ESCs of all three investigated types, based on the defined KPIs.

Investigated Types	ESC Level	2nd Life Application										
		Stationary	Semi-Stationary		Mobile							
		EES			Electric Vehicle		Micro-Mobility			Consumer Electronic		Others
		EES Industrial	EES Commercial	ESS Residential	Short-Range EV	Forklift	E-Bike	E-Scooter	E-Wheelchair	Working Tools	Leisure Gadgets	Marine
A	Pack	✔	✔	✔	✖	✖	✖	✖	✖	✖	✖	✔
	Module	✔	✔	✔	✔	✔	✖	✖	✖	✖	✖	✔
	Cell	✔	✔	✔	✔	✔	✖	✖	✖	✖	✖	✔
B	Pack	✔	✔	✔	✖	✖	✖	✖	✖	✖	✖	✔
	Module	✔	✔	✔	✖	✖	✖	✖	✖	✖	✖	✔
	Cell	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
C	Pack	✔	✔	✔	✖	✖	✖	✖	✖	✖	✖	✔
	Cell	✔	✔	✔	✔	✔	✖	✖	✔	✖	✖	✔

✔ usable ✖ not usable

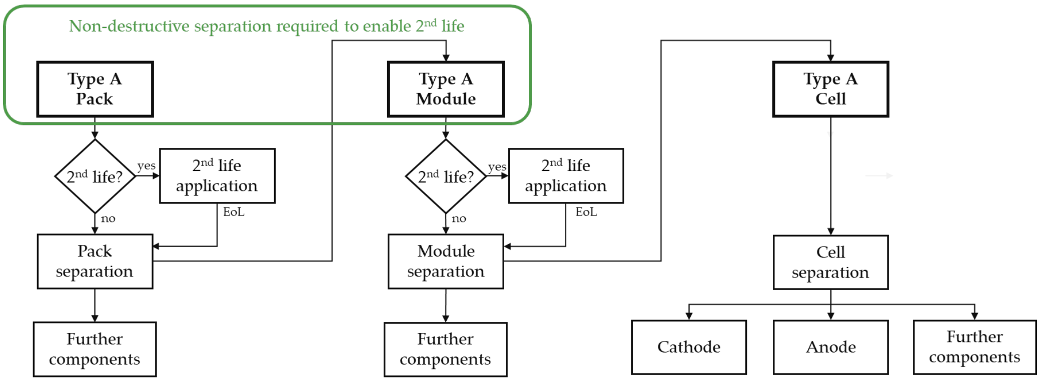

Figure 13. Separation strategy of type A.

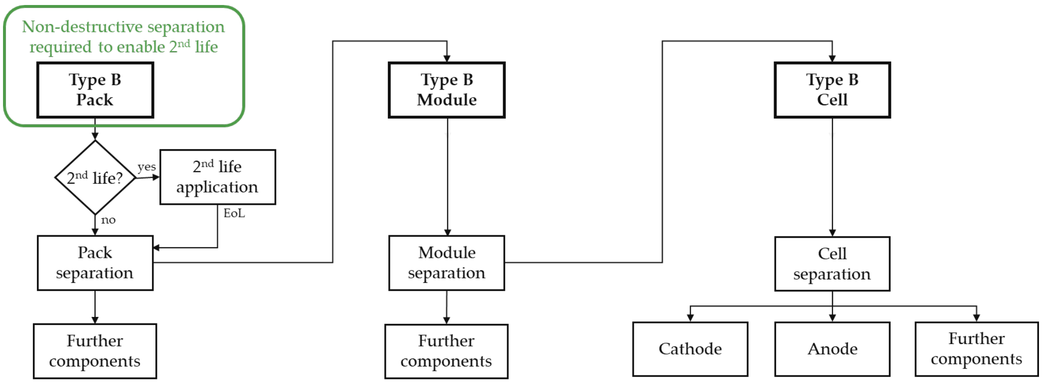

Figure 14. Separation strategy of type B.

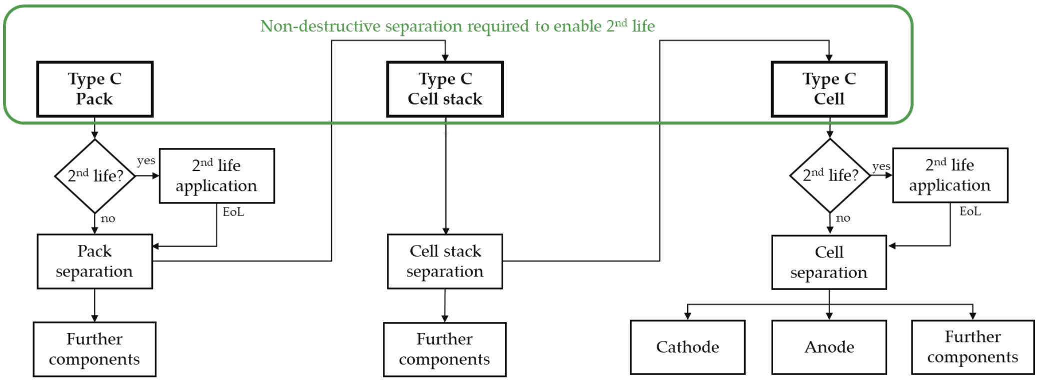

Figure 15. Separation strategy of type C.

The battery pack and modules of type A are suitable for stationary and certain mobile second life applications. Due to the fact that the pouch cells cannot be separated from each other without destroying them, the required integrity cannot be guaranteed (see Figure 13).

Separation of type B is difficult, and a non-destructive method is hardly realizable. As shown in Table 4, the cylindrical cells are basically useable for all further applications by reconnecting them to fit the respective specification. Since type B is not suitable for non-destructive separation, other separation processes can be used in principle, especially in comparison to type A, where non-destructive separation appears to be possible (Figure 14).

The different system architecture of type C offers an alternative to the modular design. While whole packs are useable for ESS in general, cells allow for more flexibility when it comes to possible second life applications. As the prismatic cells can also be used here, non-destructive separation down to the cell level is required. The only possible applications that cannot be realized are those with limited space and weight requirements and the associated discrepancies in achieving the required electrical specifications, like for consumer electronics (Figure 15). In addition, the following general problem arises with battery packs: The more individual elements there are with the same probability of failure, the more likely the entire system is to fail. This means that the probability that an entire pack is still usable decreases in comparison to its individual elements, i.e., the modules and cells.

The joining processes applied to the investigated types ultimately determine whether a second life application can actually be realized or not. Material-fit connections such as laser-welded joints are a challenge in this respect. In addition, the use of adhesives and thermally conductive pastes in all the systems investigated poses major challenges for automated separation, which must be overcome in the future. In contrast to the previously shown Table 4 on the theoretical applicability of the respective ESCs, non-destructive separability is also taken into account in Table 5.

Compared to Table 4, this summary of possible areas of application highlights in particular the cells marked with an exclamation mark, where non-destructive separation is not possible due to the joining processes used. To sum that up, Table 4 provides the basic usability based on the defined KPIs and Table 5 expands on this to show the limitations of the joining processes and the associated separation processes. This can also be interpreted as highlighting the necessary ‘design for disassembly’ approaches for future versions of the types in a very clear and focused manner. It is particularly interesting to note that type C, which follows the C2P approach, makes non-destructive separation possible in principle, whereas the C2M-based types rule out non-destructive separation at cell level even at this superficial level. However, reference must also be made to the influence of the properties of the different cell types, as the pouch cells used in type A can be damaged much more easily during the separation process. To ensure that an accurate assessment can be made in accordance with the decision graph (see Figure 3), the separation processes must be precisely defined and any possible damage to an ESC must be considered.

Table 5. Practical second life usability of ESCs of all three investigated types, based on the defined KPIs and the possibility of non-destructive separation.

Investigated Types	ESC Level	2nd life Application										
		Stationary	Semi-Stationary		Mobile							
		EES			Electric Vehicle		Micro-Mobility			Consumer Electronic		Others
		EES Industrial	EES Commercial	ESS Residential	Short-Range EV	Forklift	E-Bike	E-Scooter	E-Wheelchair	Working Tools	Leisure Gadgets	Marine
A	Pack	✔	✔	✔	✖	✖	✖	✖	✖	✖	✖	✔
	Module	✔	✔	✔	✔	✔	✖	✖	✖	✖	✖	✔
	Cell	!	!	!	!	!	✖	✖	✖	✖	✖	!
B	Pack	✔	✔	✔	✖	✖	✖	✖	✖	✖	✖	✔
	Module	✔	✔	✔	✖	✖	✖	✖	✖	✖	✖	✔
	Cell	!	!	!	!	!	!	!	!	!	!	!
C	Pack	✔	✔	✔	✖	✖	✖	✖	✖	✖	✖	✔
	Cell	✔	✔	✔	✔	✔	✖	✖	✔	✖	✖	✔
✔	usable/non-destructive separation				✖	not usable		!	destructive separation necessary			

4. Discussion and Conclusions

This study highlights that, in addition to the loads on a LIB during its initial application, the choice of joining techniques in battery pack design has a significant impact on the efficient resource utilization in the battery lifecycle of LIBs. This is because these joining techniques determine the possible process performance of an automated battery pack separation, which is crucial in determining whether or not the ESC requirements (cells, modules, or packs) demanded by the market for second life applications can be met after the battery pack has been dismantled.

The market analysis underscores the diversity and broad scope of potential second life applications. The establishment and categorization of KPIs facilitate a comprehensive delineation of requirements for various application domains. Hereby, the performance data of the battery systems such as capacity and power must be emphasized, but limitations such as installation space and weight limits are also decisive. Moreover, battery-specific data encompassing general usage patterns and anticipated lifetime ultimately dictate the feasibility and suitability of reuse or repurpose. Despite the wealth of conceivable second life applications, there are ultimately only a few that can actually be implemented in practice. These are not to be found in micro-mobility and consumer electronics, but in applications with ESCs at the pack or module level. It is evident that the best option is to use the whole battery pack for stationary or semi-stationary ESSs. A further reduction will take place as soon as the costs and safety aspects are taken into account. Then, the reusability of battery systems for residential ESS will probably be further restricted.

If the demand in the market is not met, a direct mechanical recycling of the battery components as far as possible is recommended. For further use of ESCs of the respective levels, non-destructive separation is necessary. Individual analysis of various market-relevant battery systems from different OEMs demonstrates that traction batteries are assembled using a variety of joining methods. Primarily, screwing, welding, and gluing are the dominant joining techniques employed. When separating battery modules from the pack, screw connections are primarily to be detached. These constitute 81% of all connections in the analyzed type A and 80% in type B. Various welding technologies and gluing are predominantly used during the integration of cells into the modules. The distribution of these two joining techniques at this ESC level is mainly assignable to the fact that the electrical interconnection of individual battery cells is primarily implemented via welding, while mechanical cohesion largely relied on adhesive methods. Thus, at least one welding and one gluing process can be assigned to each cell. Additionally, the integration of other components and housing parts is considered. Examining the entire system, i.e., the joining processes at both the pack and module levels, type A exhibits a very balanced distribution of screwing (33%), welding (32%), and gluing (29%). In contrast, type B presents a different picture in the overall view, with 49% of welding and 48% of gluing processes. This is due to the high number of cylindrical cells installed. Compared to this, the C2P approach of type C is generally similar to type A since screwing (44%), welding (36%), and gluing (18%) are dominant here as well.

The employed joining techniques determine the applicable separation methods. Non-destructive separation is necessary to utilize ESCs at the module and cell levels. It is evident that this is not consistently possible, significantly limiting the usability of various separation methods. Furthermore, non-destructive direct recycling is not necessary everywhere, as where no second life applications are envisioned, special attention need not be paid to the integrity of the energy carrier.

Non-destructive separation processes, such as the loosening of force-fit connections, can generally be automated very well. However, destructive methods are often even more productive and the process is less sensitive to irregularities. For example, removing the top cover from the pack requires the loosening of between 76 and 90 screw connections in all three systems when using non-destructive methods. On the one hand, problems can occur here if the screws are damaged or corroded, which cannot be ruled out in the case of used cars, especially those that have been involved in accidents. On the other hand, this large number of screw connections can limit productivity in systems where short cycle times are required. Here, destructive separation processes such as laser cutting can offer better results [80,81], which can only be achieved with non-destructive loosening of the screws by means of tool change systems and parallelization of the work flow process. In addition, the process reliability with regard to irregularities and the applicability to different changing products is a major advantage of laser cutting in this case.

Non-destructive separation allows to maintain the purity of the output materials, which alternatively can only be achieved by complex downstream dismantling and sorting processes after destructive separation methods. The impairment of the product from a safety perspective is one of the biggest and most relevant differences between the various methods. The mechanical and thermal energy input from destructive processes in battery systems must be considered very critical, especially as the process approaches to the battery cell. Furthermore, the associated generation of waste materials such as metal chips and impurities can lead to external short circuits. However, the biggest advantage of non-destructive methods is the significantly increased reusability of individual components.

The right balance must be found when selecting suitable processes, depending on what is being targeted after the end of the first life. This decision is influenced by the number of battery systems, the product variance with regard to the required process and system flexibility, but also the lifetime of the products, as more and more different systems will reach the EoL in the coming years and will need to be recycled. Cell chemistries, cell types, and system architectures may change or disappear from the market in the future, but new ones may also be added. This could push direct recycling in particular to its limits and make highly specialized recycling plants obsolete. For this reason, forward-looking plant planning and the selection of suitable and flexible separation processes are of long-term importance for the sustainable and profitable operation of such plants. A hybrid plant layout with automated, semi-automated, and manual work steps also appears to be a reasonable solution to tackle the complexity of non-destructive separation. However, for all potential reuse and repurpose applications, non-destructive separation forms the basis for a sustainable battery lifecycle.

As already mentioned in the introduction, the safety requirements for batteries intended for second life applications play the most important role in legislation. They are the knock-out criterion for any further use of the LIBs if they are not to be recycled. For this reason, when selecting from this pool of possible methods, explicit and precise consideration must be given to which procedures are sensible from a safety point of view. In any case, it must be avoided that any mechanical, thermal, chemical, or environmental stress on the ESCs caused by the process results in them no longer meeting the legal requirements for further use. This major influence of safety shows that there is still a great need for future research to define its role in the separation processes and its effect on the best possible disassembly depth.

As welding, and especially gluing connections, hinder or sometimes make it impossible to separate ESCs without putting excessive strain on them, emphasis must be placed on 'design for disassembly' in the future.

In addition, the continuous monitoring and control of the separation processes and ESCs must be included. AI-supported systems are an obvious solution for this.

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