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# Inspection and Evaluation Method to Repurpose Used Batteries

Circular Economy and Battery Energy Storage Systems:  
Extending Battery Life for Sustainable Energy Utilization

Master's Thesis in Industrial and Materials Science - IMSX30

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MASTER'S THESIS 2024

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Cover: Visualization of Battery Energy Storage Systems constructed with industrial  
batteries to enable electricity and charging whenever needed.

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## Abstract

This Master's Thesis presents a comprehensive study on the inspection and evaluation method for repurposing used batteries. Focusing on the transition from serving its first life in an electric vehicle (EV) to becoming a part of a Battery Energy Storage System (BESS). The research addresses the need for a standardized and scalable evaluation method, in order to ensure safe and effective utilization of second-life batteries (SLB). By leveraging insights from the batteries first life, performance requirements for BESS applications, and existing industry practices, the thesis proposes a structured evaluation process.

Through a combination of background study, literature review, empirical studies, and interviews with industry stakeholders, the thesis identifies key factors in developing an efficient evaluation method for repurposing used batteries. The results highlight the challenges and opportunities in the current industry practices, emphasizing the importance of established policies and regulatory standards in enabling successful battery repurposing. The proposed evaluation method is presented using the IDEF0 modeling methodology, and consists of four major activities. The activities are referred to as visual inspection and safety evaluation, first screening, diagnostic packages, and finally classification and BESS matching.

The findings of the research study contribute to advancing the field of battery repurposing by providing a practical framework for stakeholders in the automotive industry, remanufacturers, and energy utility suppliers. The proposed evaluation method offers a systematic and comprehensive approach to repurposing used batteries, facilitating the transition towards a circular economy and sustainable energy solutions. The findings and recommendations presented in this thesis serve as a valuable guide for enhancing current practices in battery repurposing and promoting the generalization of the results. The findings of this study will serve as a guideline for the sorting, grading, and assessment of retired flat and cubic batteries from EVs, as well as demonstrate the technical feasibility of how to grade and repurpose retired batteries for two different types of BESS applications.

**Keywords:** Electrification, Sustainable Energy, Circular Economy, Battery Repurposing, second-life Applications, Battery Management System, Battery Energy Storage System, Sustainable Transition, Performance Evaluation.



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A sincere thank you also goes out to all interviewees who took the time for interviews and meetings, internally and externally. Your experiences and perspectives have been interesting and educational to learn from. We appreciate your openness and helpfulness, which have contributed to a broad insight into the industry in which you operate. Without your participation, the work would not have achieved such good results. A broader understanding has been achieved in an area where there has historically been quite a bit of uncertainty.

Daniel Svensson & Albert Särnevång, Gothenburg, June 2024



# List of Abbreviations and Acronyms

Below is the list of abbreviations and acronyms that have been used throughout this thesis listed in alphabetical order:

|      |  |
|------|--|
| BESS | Battery Energy Storage System          |
| BMS  | Battery Management System              |
| BP   | Battery Pack                           |
| BTM  | Behind-the-meter                       |
| C&I  | Commercial & Industrial                |
| DoD  | Depth of Discharge                     |
| EIS  | Electrochemical Impedance Spectroscopy |
| EoL  | End-of-Line                            |
| EV   | Electric Vehicle                       |
| FTM  | Front-of-the-meter                     |
| HPPC | Hybrid Pulse Power Characteristic      |
| IR   | Internal Resistance                    |
| LIB  | Lithium-ion Battery                    |
| OEM  | Original Equipment Manufacturer        |
| RM   | Repurposing Manufacturers              |
| RUL  | Remaining Useful Life                  |
| SDGs | Sustainable Development Goals          |
| SoC  | State of Charge                        |
| SoH  | State of Health                        |



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# 1

## Introduction

The introduction section sets the scene for the research study, starting with emphasizing the current electrification transition in the automotive industry. External drivers such as climate actions in accordance to sustainable regulations, EV market trends, and circular economy strategies are approached as part of the problematization. Furthermore, the case company Volvo Energy is presented. Lastly, the general purpose of the thesis will be examined, resulting in the stated research questions. Delimitations are listed to express the scope of the study.

### 1.1 Background

The transition of electrification is happening all across the globe and is in particular transforming the automotive industry to a large extent. This could briefly be explained by external drivers related to climate action, which are reducing the carbon footprint, fulfilling regulations & requirements, and developing businesses internally to meet consumer demands for decarbonization through cleaner transports [1]. By decarbonizing processes and most importantly exchanging energy sources providing high carbon emissions with renewable and electrified systems, the transition paves the way for a sustainable future. Mainly in the environmental aspect but also economically and socially in the long term perspective. With electrification, the usage of batteries and the battery technology itself will play a key role, which sheds light on the increase of used batteries. Due to the global expansion of the electric vehicle (EV) market the forecast points towards dramatic changes along the supply chain, e.g. energy infrastructure and closing the loop of battery handling. Specifically interesting for this case is the expected increase in the number of used batteries, that could be given a second-life in another application with lower energy and power requirements. Thus, utilizing the battery's remaining economic value and contributing to circularity [2], [3].

Volvo Energy AB, established in 2022, is a business area of Volvo Group focused on enhancing battery and charging solutions and working on developing repurposing and recycling activities. Volvo Group is a company that is undergoing a large-scale electrification transition, meaning that they have a higher demand for batteries now than ever. This has resulted in the establishment of a sole entity that focuses on accelerating the electrification transition in various areas. Volvo Energy can be seen as a start-up but is backed by experience and knowledge from the entire Volvo Group [4]. Being “the enablers behind the ongoing electric revolution”, Volvo Energy has been looking into how to develop the business model of batteries. Studies

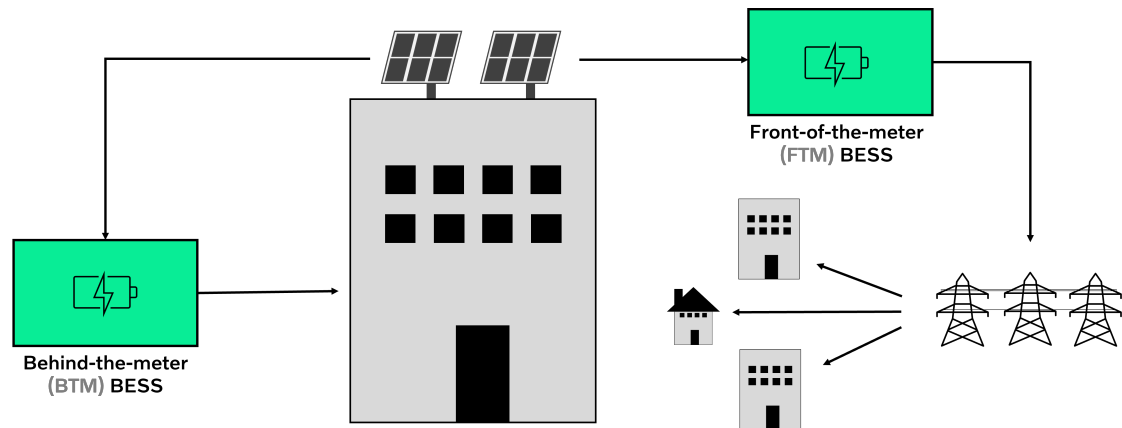
are made specifically in the field of repurposing to find safe and effective methods to evaluate and secure a battery's life, performance and safety after the first life, before possibly entering its second-life in a new application [5].

Repurposing is one of the strategies to achieve a more circular economy, and it can be defined as a process where an alternative use case is applied to the battery. The battery undergoes the phases: design, evaluation, sorting and grading, re-assembly, and installation of the Battery Management System (BMS) to add new value to the customer in a different application [6]. A repurposing challenge is the dismantling process due to the complexity of the current battery pack (BP) design that earlier has only strived to optimize the energy density of its modules and cells [3]. At the end of the battery's first life, each battery has a unique history and the aging processes can vary. Thus, a thorough evaluation method is needed to ensure safe and functional performance to enable clustering of similar batteries in new applications [7].

A part of Volvo Energy's vision is to repurpose batteries that have served approximately 8-10 years in an EV on the road, referred to as its first life [8]. The value of existing batteries can be retained without exploiting new resources, by using already produced materials and goods for a longer period of time. Extending the retired batteries' lifetime will also make the overall battery value chain more profitable than recycling them directly [7].

One way of extending the battery lifecycle from linear to circular is to utilize its remaining useful life (RUL) as a second-life battery in a BESS. However, used batteries may not be as reliable as new ones, because the performance declines over time and the lifecycle of an EV battery is known for its unpredictable nonlinear aging [9]. The wear of used batteries is influenced by their operating environment, operating conditions, and driving habits, impacting their performance in the second-life [10]. Therefore, it's important to thoroughly assess their safety and performance in evaluation before repurposing them [11]. BESS is a product that enables a greener grid with applications from a large to small scale, for example, by stabilizing fluctuations in the grid created from renewable energy sources, storing energy to reduce peak power demands, and improving overall power quality [12], [10]. Within the field of energy storage, there are three categories referred to as front-of-the-meter (FTM), behind-the-meter (BTM), and mobile applications. The BTM category focuses on distributed energy resources for temporary power as well as localized power generation and storage at commercial and industrial scale [3], [13]. The differences of FTM and BTM is visualized in Fig. 1.1.

In the situation of today, the supply of second life batteries is relatively low but the forecast for the near future shows that millions of EV batteries will reach the end of their first life and need to be taken care of [4]. There will be a large-scale retirement of lithium batteries globally, with an estimated annual generation of 200-500 million tons by 2030 [10]. One expected challenge that could arise with the growing inflow of used batteries is the lack of traceability throughout the supply chain.



**Figure 1.1:** Visualization of FTM and BTM Applications (adapted from [13])

Currently, the time required to diagnose each BP is too long to efficiently handle a larger inflow of batteries. Several activities must occur before a battery can be safely repurposed, but some current diagnostic steps are too time-consuming in relation to their added value. A safety evaluation (visual and mechanical) based on the battery's pre-conditions needs to take place, followed by a state of health (SoH) assessment to understand the current health of the battery. Lastly, the battery's level of performance should be classified to find suitable second-life applications. The evaluation method has to be streamlined, quality-assured and standardized, to function at a larger scale especially for BESS systems to compete with new first-life systems (Personal communication, January 17, 2024). Scrapping and directly recycling batteries that retire from the roads on a remaining capacity of approximately 80 percent is a waste of economical and environmental value [10].

In the situation of today, there is a gap in the field of regulations and standards in Europe, regarding the repurposing process of used batteries. However, drafts of new regulations and standards are currently being developed by the International Electrotechnical Commission, as well as by the EU Commission and will apply at later stages, from 2024 to 2028 (Personal communication, February 29, 2024). The American Standard UL 1974 will also be used to give a comprehensive clue of what a future European standard could include [14].

Electrification is happening all across the globe and Volvo Energy, among other stakeholders, has realized the economic and environmental value in the repurposing opportunities. Repurposed batteries have a considerable environmental value that will bring competitiveness to the battery market [3], [10]. By transforming the battery lifecycle from linear to circular, the battery value chain will become more profitable and standardized. The problem to be addressed relates to the explorative nature of the field and how batteries could be evaluated by leveraging the information from their first life together with a thorough diagnosis.

### 1.2 Aim and Research Questions

Considering that there is room for new ideas of ways to ease and accelerate the shift to electrification, this thesis aims to develop a standardized, scaleable evaluation method for repurposing batteries from EVs for use in BESS applications. Considering their unique histories and varied aging processes, the goal is to safely ensure these batteries are sorted and used effectively in a second-life [7]. Thus, to handle the increasing prevalence of batteries in EVs, the need to extend their life through the circular strategy of repurposing is crucial [15]. The focus is on establishing an efficient and standardized approach based on theoretical and empirical studies, where none currently exists.

Furthermore, current practices in the industry will be examined to identify influential challenges and map legal requirements regarding repurposing of used batteries. What is referred to as the industry includes stakeholders such as automotive original equipment manufacturers (OEM), battery health assessors and energy utility suppliers [16]. Thus, the current state analysis aims to reflect industry practices besides Volvo Energy's operations. Understanding the entirety of the battery supply chain is important from a circular economy perspective, but also to ensure generalizability and reach a broad relevance of the conclusions.

The proposed method aims to leverage knowledge from the battery's first life, standards, and regulations, and propose a grading scheme based on the performance requirements of a BESS. Based on the aim, the following research questions will be addressed:

- RQ1: What are the battery performance requirements for BTM BESS applications, along with legal requirements and challenges to repurpose used batteries?
- RQ2: What are the key factors in a standardized evaluation method used for battery diagnostics to enable repurposing of used batteries?

### 1.3 Delimitations

This subsection defines the delimitations of this Master thesis work, which include:

- This thesis work operates within a constrained time frame of approximately five months, emphasizing the need for swift decision-making. It prioritizes efficiency by opting for quick decisions and an applicable solution in production rather than extensive data processing and analysis.
- The report aims to address fundamental battery concepts without delving deeply into complex detailed technical, chemical or specialized aspects of battery technology.
- The testing will focus on two particular types of batteries used in the Volvo Group today, rather than attempting to cover all types. This limitation is

due to the varying characteristics and repurposing challenges associated with different battery types. Two types of BP are analyzed, flat and cubic.

- The thesis will address how grading and evaluation are to be made on BPs and not focus on diagnostic activities related to individual cells or modules.
- The testing equipment to collect primary data will be delimited to the one available in-house within Volvo Group.
- The scope of BESS applications will be delimited to BTM power unit solutions.
- The thesis work will delimit itself from delving into the economic aspects of repurposing batteries in BESS.
- The thesis will focus on the process of repurposing rather than other circular economy activities such as recycling, refurbishing, remanufacturing, etc.



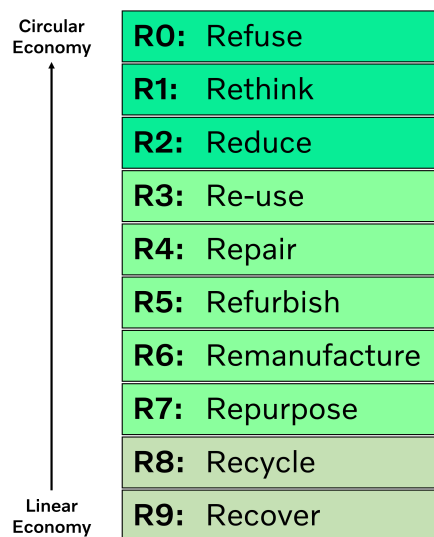
# 2

## Theory

This section aims to define and clarify the fundamental concepts of circular strategies and in particular battery repurposing. It covers enabling components of performance evaluation in the battery pack and crucial performance measures with aligned test methods suitable for battery diagnostics. The theoretical background also highlights and reviews relevant legal frameworks, including EU Battery Regulation and UL 1974 standards, providing a foundational understanding of battery repurposing.

### 2.1 Circular Economy

The term circular economy is an evolving concept that includes numerous perspectives that aim to minimize waste and maximize resource efficiency, which results in extending the life cycle of products [17], [18]. A list of ten commonly referred strategies is presented in Fig. 2.1, and the higher on the list, the more sustainable the strategy is [19], [20]. The first three (Refuse, Rethink and Reduce) are recognized for changing the usage of a product or the manufacturing of it. The strategies R3-R7 are ways to extend the lifespan of products and their parts. Lastly, recycling and recovering focus on the components of the product rather than the product itself, and involve specific principles of how to get as much raw material back into a new loop of utilization as possible without having to dispose of valuable resources as waste [19].



**Figure 2.1:** 10 Strategies for a Circular Economy (adapted from [20])

The strategies in focus for this project aim for an extended lifespan, and usually, it's an interplay between the different options. For example, a product traditionally needs to be evaluated to determine whether the most suitable action is to reuse, repair, refurbish, remanufacture or repurpose. If the remaining value of a product does not fulfill the criteria for any of them, it would be handed over into a recycling process [21]. In the scenario of a used car, its batteries must be tested first for refurbishment, remanufacturing, and second-life potential before recycling even becomes an option, [22]. However, if the product has a clear fault or damage it might be directly sent to recycling to avoid tiresome handling.

Re-use is when a product that is still in good condition can be used in the same application without any modifications [21]. A well-established use case of re-use is the second hand market, where a customer re-uses the same product with an understanding that the performance might not be as good as when new.

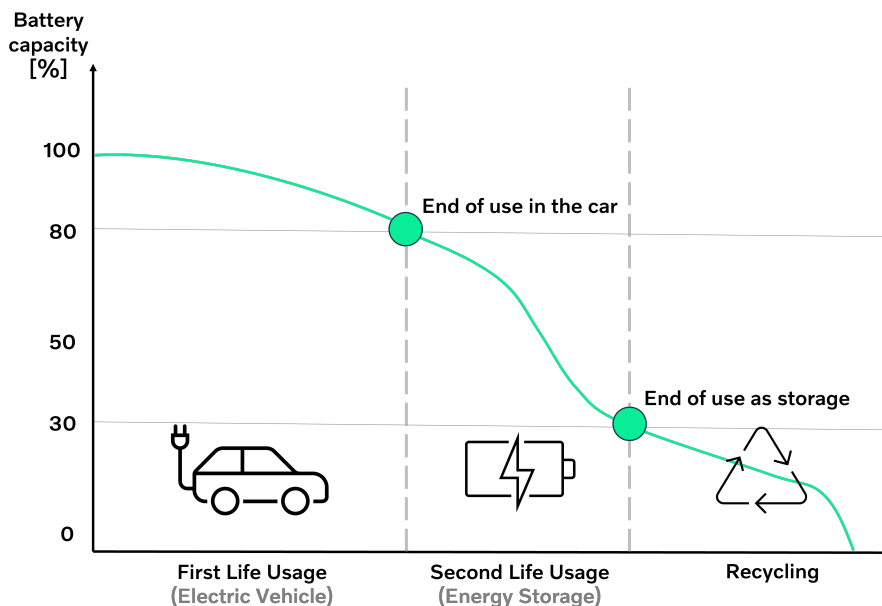
Refurbishing a used product is done by inserting new and updated components to turn the product into as good as new. This strategy is already in use, for example to refurbish an existing engine requires only about 15 percent of the emissions that it takes to make a new one [22]. Remanufacturing is similar to refurbishing but focuses on integrating used components that are still perfectly intact into new products, with the same function as the originally intended [19]. This strategy is widely used, for example in the automotive industry. Volvo Group has been offering the solution for 70 years, mainly operating with engines, filters, gearboxes and rear-axle transmissions, intending to cover more markets and more components in the future [23].

Repurposing on the other hand is a relatively unexplored strategy on an industrial scale within the automotive industry. It is a strategy that incorporates used products or components into a completely different product for a unique benefit or alternative purpose [19]. Recycling rates for key materials such as nickel, cobalt, manganese, and lithium are low, and the growth of EVs would create an urgent need to improve the recovery levels [22]. To slow down the need for drastic improvements in recycling, repurposing could add a new dimension to end-of-life usage and delay the need for recycling.

### 2.1.1 Repurposing EV batteries

Repurposing is defined as a process that utilizes the remains of a product as it is or with minor fixes and prolongs the lifetime in a new and different application from its intended use [21], [4]. This can be seen in Fig 2.2 and is usually referred to as its second-life [24]. By extending the retired batteries' lifetime the overall supply chain will also become more profitable than recycling them directly [7]. Requirements and guidelines from the OEMs of electric vehicle batteries state that replacement should be done when reaching a remaining estimated capacity of 70-80 percent [25], [26]. However, in practice can this limit vary due to differentiated cell chemistries, and aging patterns, etc, (Personal communication, May 13, 2024). From an environmen-

tally sustainable perspective, the interest in utilizing this capacity before recycling is aligned with global regulations and helps in the way of accomplishing climate targets. Used batteries also have a considerable economic value compared to new batteries in terms of lower price, which will introduce competitiveness to the battery market [3], [10]. The second-life scenarios can vary, so it is crucial to sort and grade the BPs in order to find a suitable application. Thus, the second-life scenario and its requirements have to be well understood and the condition of the battery has to be evaluated as part of the repurposing process [21]. The first life of the battery regarding performance/lifetime etc is generally well defined and understood. At the same time, most automotive OEMs lack a clear understanding of what can be expected in terms of lifetime/performance in the 2nd life, (Personal communication, May 13, 2024)



**Figure 2.2:** EV battery lifecycle first and second-life (adapted from [24])

## 2.2 Enablers of Performance Evaluation

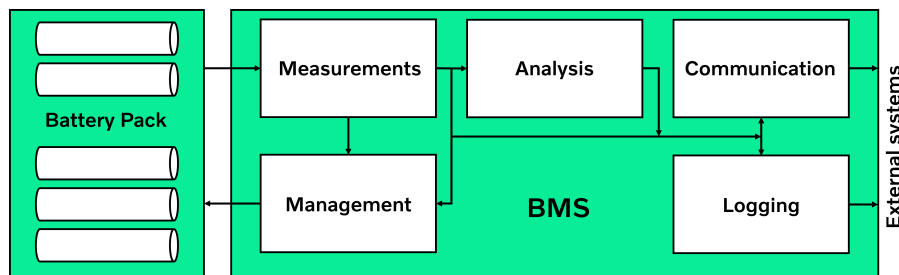
The following subsection will examine the core components that enable the performance evaluation of a BP. The functionality of the BMS is essential for determining the health and performance of the battery. Furthermore, the cell supervising circuit (CSC) will be introduced together with the overall battery disconnect unit (BDU), including the battery's control system.

### 2.2.1 BMS - Battery Management System

A BMS system, or BMU, is an integrated management scheme to control, monitor, and optimize overall battery functions in a BP [27], [28]. The BMS is the key component in regulating voltage flow from the battery into the application safely and

efficiently [29]. This component serves as the brain of the BP. It houses algorithms that assess and predict the pack’s status. Additionally, it’s designed to prevent electrical and thermal hazards and indicate violations in operating conditions [30].

As seen in Fig.2.3 the information flows both ways between the BMS and the BP. Battery feedback is given to estimate SOC and SOH and control mechanics to steer the charge-discharge with monitors and cell voltage sensors [31], [32]. These parameters are determined to improve performance and safety. The electrical characteristics of the battery are constantly monitored and controlled to keep the charge level within permitted levels and prevent unsatisfied events like fire and explosions. There are several ways to connect an external source to the BMS communication interface in order to read data from the battery, such as the wired connections of CAN, I2C, SPI, RS-485, and USB [30], [33]. The BMS talks to the vehicle using CAN language which is a secured and specific form that requires decryption for the operator to interpret it. To collect and transform the conditions of a battery into valuable output, the use of CAN-case and belonging software is required (Personal communication, January 17, 2024). An efficient and properly functioning BMS should ensure optimal battery performance through its essential components, including elements that regulate current flow and accurately oversee charge dynamics. The voltage and temperature of each cell are monitored to ensure that the battery operates in its safe operating area. This prevents risks such as overheating and ensures optimal battery health and longevity [32], [31].



**Figure 2.3:** BMS communication (adapted from [34])

The BMS is the brain of the BP and contains several key features, See Fig. 2.4. The battery structure usually consists of cells and modules in series and parallel to support sufficient current and voltage. In the general case the resulting capacity of the BP is thereby only as strong as the weakest cell in that particular pack, [35]. However, all these building blocks need to be matched in terms of e.g. capacity and voltage to function efficiently. In case of a mismatch, the *Cell Balancing* is carried out actively by the BMS [30]. To address these requirements, cells must be uniform in capacity and internal resistance (IR), while *Thermal Management* must be consistent across all cells. This necessitates stringent quality control in cell manufacturing and advanced pack engineering for comprehensive design and validation [35]. The BMS indicates when the system is outside its safe operating area and actively starts the cooling system of the pack, [29].

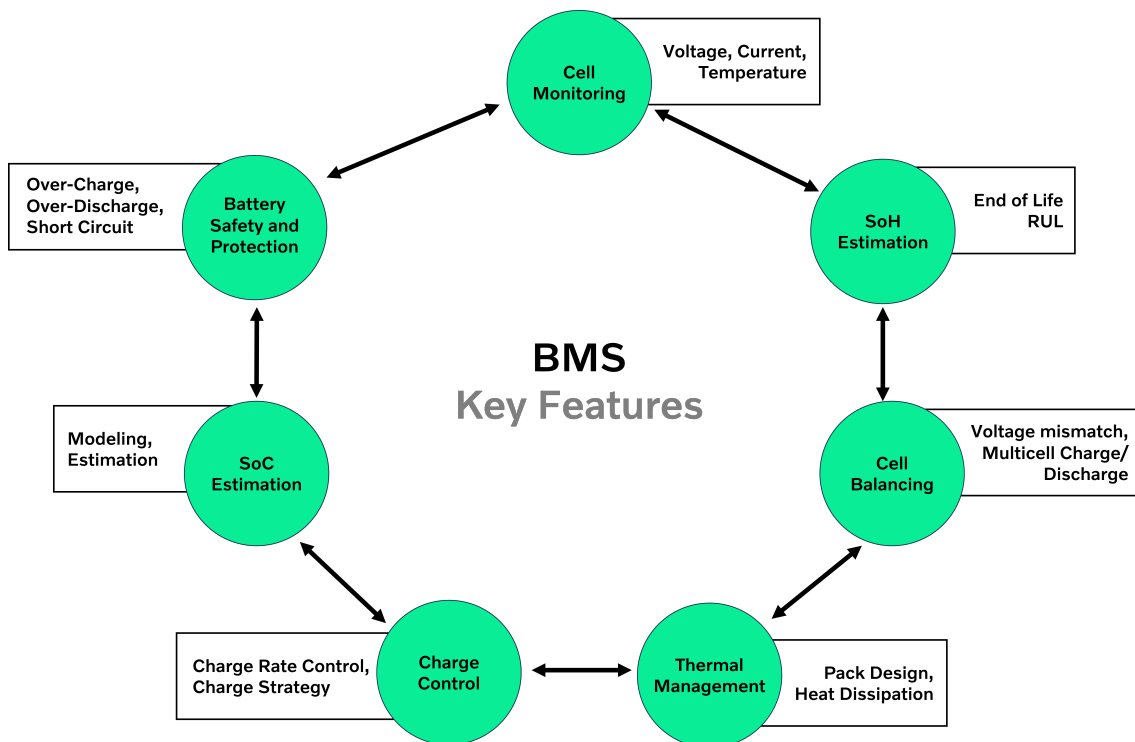


Figure 2.4: BMS Key Features (adapted from [29])

*Battery Safety and Protection* is a key feature of the BMS that protects the pack, user and environment from unpredictable events. The system alerts operators or external systems about safety issues like low SOC levels leading to deep discharge or excessive battery temperature risks via communication lines. Operators or systems can respond by taking necessary actions, such as reducing power consumption, activating cooling systems, or isolating the battery to prevent further damage [33], [31].

*SoH Estimation* serves as a crucial metric for battery performance, employing an algorithm to indicate its current health state compared to its original state. However, there is no universal international standard related to SoH which makes comparison between models and suppliers difficult. The estimated parameter provides valuable insights, such as predicting the number of charge/discharge cycles before significant performance degradation occurs. It's crucial to distinguish between SoH, which evaluates the battery's current health regarding capacity fade and internal resistance increase, and RUL, which forecasts the trajectory of SOH in the future, [36]. RUL is used as a metric to indicate the replacement threshold and is dependent on manufacturing date, energy throughput and capacity throughput [37], (Internal Document 4, Personal Communication, March 22, 2024).

*Charge Control* is another key feature of the BMS that prevents dangerous situations from arising by avoiding deep discharging below a certain SoC. Furthermore, the battery can be controlled against overcharging it when fully charged, or using a charge rate (C-rate) higher than the safe level for the battery chemistry [30], [38].

Finally, the BMS also displays the *SoC Estimation*, which is another parameter that the BMS calculates based on multiple inputs, such as the current, active time, self-discharge and aging of the cell [30], [39]. SoC is a measure of the available charge in the battery compared to its fully nominal capacity. The metric can't be determined directly from the battery terminals, thus algorithms are used together with the measured data to indicate the real-time status. The SoC value is an enabler to optimize the depth of discharge for safe and energy-efficient operations [38].

### 2.2.2 BDU - Battery Disconnecting Unit

The Battery Disconnect Unit (BDU) plays a crucial role in the functionality of the high-voltage battery system. It serves as a safety mechanism and regulator tool by managing the activation and deactivation of the system during idle periods. Integrated into the pack enclosure or external to the BP, its role encompasses the flow of electrical energy, primarily through the utilization of contactors. Its main purpose is to ensure system safety by disconnecting the battery when necessary, a function controlled by its integrated system [40]. In the event of faults, such as abnormal electrical flow, the BDU engages additional protective measures like fuses. This unit, sometimes referred to as a service box, is designed for easy removal since its components wear over time and may need replacement during its lifetime, [29], [41], (Internal Document 4, Personal Communication, March 20, 2024).

### 2.2.3 CSC - Cell Supervising Circuit

As the BMS serves as the central coordinator, gathering crucial data from individual cells, sensors, and control mechanisms the supervision is executed by the CSC, also referred generally to the slave board. Thus enabling a structure characterized by modularity and flexibility in terms of size and power requirements. Within this architecture, the CSC is crucial for safety and reliability on a systematic level. Measurement is commonly done redundantly, ensuring the correct measurement values even if one system fails. Additionally, the CSC is responsible for the balancing of cells, by discharging the stronger cells and transfer voltage [42], [43]. Each CSC board can monitor temperature and voltage across multiple cells within a module. Other configurations with varying setups of core components are available on the market to control and measure the BMS functions, e.g. centralized BMS without excessive CSC boards [43].

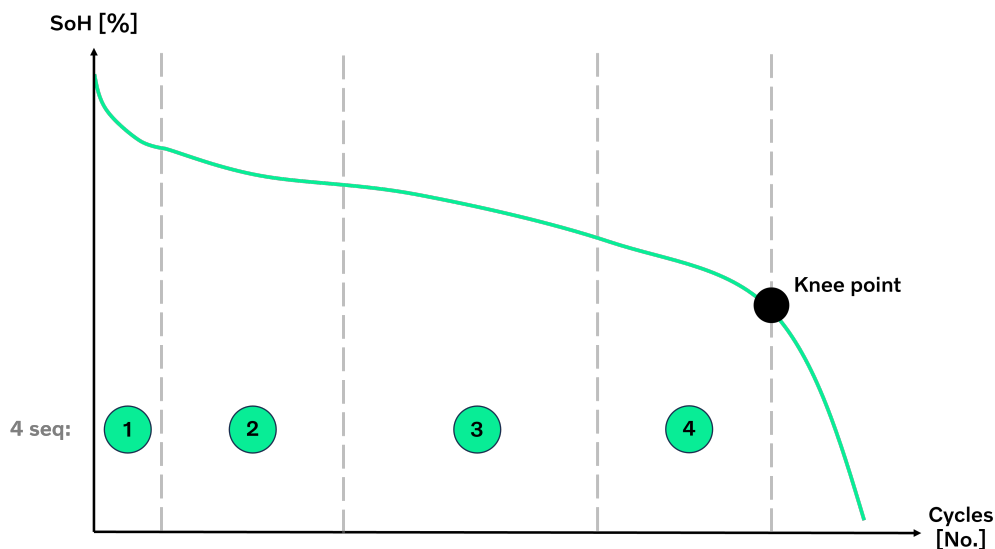
## 2.3 Performance Measures and Test Methods

In the upcoming section, various measures of battery performance and test methods will be defined, highlighting their significance in understanding batteries and their applicability in BESS. Firstly, it investigates the non-linearity in battery degradation, followed by SoH, IR and SOC to mention a few. These measures are defined to understand the importance of which will be key factors to include in a comprehensive inspection and evaluation method.

### 2.3.1 Aging and Battery Degradation

Battery aging can be structured into two causes: calendar aging and cyclic aging. Calendar aging is associated with the storage of batteries, meaning no charging or discharging is applied, [44]. Hence, it is also called passive aging and the constant slight decrease of performance is inevitable. Cyclic aging corresponds to the impact of battery usage on the SOH, i.e. aging due to charging and discharging [45]. High temperatures and a high state of charges are causing a fast battery calendar and cyclic aging. Other stressors accelerating battery aging are high C-rates as well as large depth-of-discharge (DoD) intervals. However, the battery stresses are interdependent and may cause varying impacts on the aging, [10].

The general battery aging process can be divided into four major sequences, visualized in Fig. 2.5. The first sequence indicates initial fast degradation. The second and third phase replicates typically linear aging at a relatively slow pace [9]. In phase four the BP discover accelerated aging. At a certain point, the degradation enters a non-linear region with a sudden SoH drop which is commonly referred to as the knee point [11], [9]. The cell cycling curve becomes steeper, which indicates that the battery capacity will rapidly decrease. It could result in arising safety issues and in what is called a "sudden death", if not detected and addressed properly [11], [46].



**Figure 2.5:** Knee point degradation (adapted from [46])

The concept of retirement points in battery lifecycle management encompasses two key elements: Determining when to retire second-life batteries and optimization between their value at first and second-life. The aspect influences both initial capacity and replacement frequency, playing a significant role in the economic sustainability of EVs and second-life applications, [47]. This point, dictates when a battery is retired from its primary use based on factors like capacity degradation and operational demands. Understanding degradation curves, particularly identifying the knee point where capacity sharply declines, inform decisions about the retirement point, which

is crucial for optimizing battery usage and overall system economics [48].

As batteries age, they become less reliable in terms of performance compared to new ones since their performance gradually decreases. This is particularly noticeable in EV batteries, which experience uncertain degradation behavior at a certain age. Thus, testing is needed to extend the useful lifespan, [9]. The wear of used batteries is influenced by their operating environment, operating conditions, and driving habits, impacting their performance in the second-life [10]. These discrepancies are further emphasized when comparing batteries from different models. Therefore, it is essential to avoid mixing batteries from diverse environments, and vehicle models when re-utilized, which poses a huge challenge [10].

DoD is a crucial metric in assessing the energy utilization of a battery, representing the proportion of its total capacity that has been extracted during a charging cycle. It's measured by comparing the initial SOC with the final SOC after discharging. For instance, if a battery starts fully charged at 85% SOC and is discharged to 15% SOC, the DoD would be 70% [38]. The different interval depends on usage patterns for the chosen application. The nominal energy of a BP stands for its maximum performance when newly produced. The useable energy can roughly be calculated by multiplying nominal energy with its DoD. In the case of a used BP, the calculation of useable energy must also consider SoH adding it as another multiplying factor. Understanding DoD is essential for optimizing battery usage and prolonging its lifespan, as exceeding certain DoD thresholds can accelerate degradation and affect performance [49], [50].

### 2.3.2 State of Health (SoH)

To understand the condition of a BP the consistency of SoH and SoC values is an essential performance measure. The concept of SoH is pivotal for assessing the extent of degradation experienced by a battery in comparison to its original nominal capacity. Generally, the performance measures a combination of internal resistance and capacity [51]. This value is calculated by an algorithm and determines the health of the pack by taking aspects such as aging, charging usage, energy throughput, etc into account [52]. SoH enables the determination of whether the battery remains capable of efficiently storing and supplying energy for its intended application. For instance, low SoH can be one of the reasons, among high IR, high C-rates etc, for lower capacity /energy throughput. Over time and usage, the battery's energy storage capacity decreases, with 100% SoH representing a new battery and 0% indicating complete degradation. However, a battery is typically seen as degraded when it falls between 80% and 70%, signifying that the battery has reached its end of life [49], [53]. The value can either be conducted by conventional testing based on other metrics or by relying on the BMS estimation which is easy to retrieve but has inaccuracies. [21].

Electrochemical Impedance Spectroscopy (EIS) is a method currently developed on cell and module level to test the overall performance of a battery regarding internal

resistance. In a couple of minutes a wide range of information regarding the SoH can be visualized in a standardized way [54], [55]. Impedance measurement involves applying a varied frequency sinusoidal signal to "disrupt" the battery. This broad frequency range ensures precision but requires considerable time. Additionally, the test cannot be conducted while the battery is in use. After the excitation, a thorough analysis, such as curve fitting, is performed to derive the resistance value [56], [57]. EIS testing can also identify and prevent failure in a cell. When the impedance reaches a certain level (obtained from OEM) the test equipment alarm action to avoid breakdown in the future. The history of the cells can be monitored and support accurate end-of-life prediction, although it's a time-demanding process. Furthermore is the technique immature for pack-level operations, which is expected to change in the upcoming years. If technological advancements are made the performance and control of the battery health can be improve in accuracy significantly [58].

### 2.3.3 Internal Resistance

The internal resistance of a battery is often used as a key indicator of its characteristics. Typically, as a battery degrades over time, its internal resistance increases, negatively affecting its performance due to energy loss as heat and faster voltage drop during discharge. Problems in the manufacturing process can also alter internal resistance, making it a critical evaluation factor in battery production [44]. Internal resistance also serves as a crucial parameter indicating a battery's capacity to carry current. When internal resistance is low, the battery can efficiently handle a significant current load. Vice verca, a battery with high internal resistance can only manage a limited current flow. This energy waste not only reduces efficiency but also accelerates battery degradation [59]. A performance measure related to internal resistance is the State of Resistance (SoR). This value is calculated by dividing the current internal resistance of a battery with its initial value, resulting in a percentage indicator of resistance growth (Personal communication, May 20, 2024).

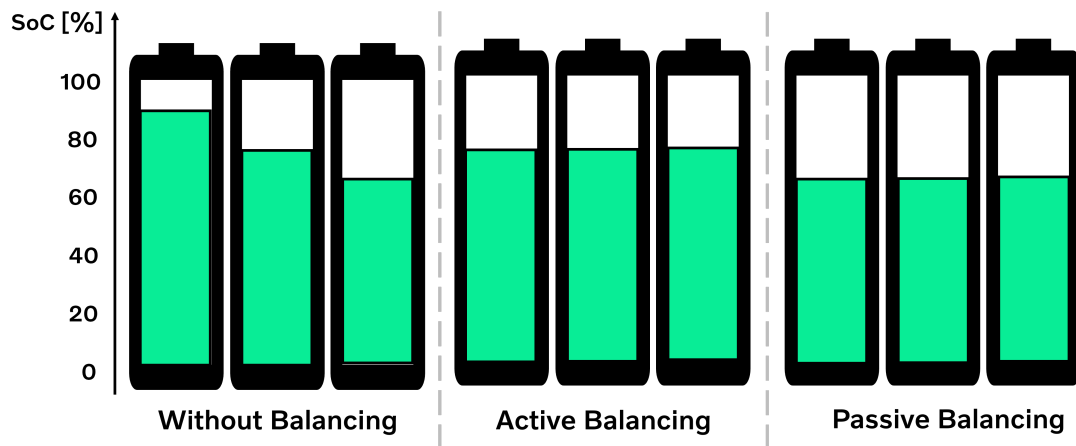
A High Power Pulse Characterization (HPPC) test is done to determine the final pack resistance and thus the performance capability. This method involves applying a specific pulse profile to the BP and analyzing the resulting current and voltage values. One key advantage of HPPC is its accuracy and potential for automation, making it efficient to execute. The test is completed within approximately one minute (Internal Document 25, Personal Communication, March 1, 2024), [53]. Moreover, it helps ensure proper electrical connections among all cells within the pack. To conduct HPPC, the initial steps involve preparing the battery SOC and ensuring the voltage levels are within acceptable limits. Then, a pulse profile is applied, and resistance is calculated based on the measured current and voltage [60]. A single triangular pulse wave should be as short as possible to not change the SOC of the battery. The pulses always occur in pairs due to a quick charge, followed by a quick discharge. The hardware needs to be powerful since the greater the current value, the the greater voltage change which makes the output resistance easier to record. However, it also makes the required tool expensive, [61].

### 2.3.4 State of Charge (SoC)

State of charge is a measure to indicate the remaining capacity and energy in a battery at a given time related to when fully charged. It can be compared to a fuel gauge sensor which indicates the distance to drive before stopping (Internal Document 4, Personal Communication, Feb 28, 2024). SoC is determined by constantly measuring the voltage, internal impedance, or counting Columbus regarding whether the battery is charged/ discharged. For instance, does a high voltage level indicate that the battery is under high pressure, thus it is full. However factors such as SoH, temperature and cell Chemistry can affect the voltage [62].

### 2.3.5 Balancing

BP balance is a state where all individual cells possess uniform capacity and voltage. Manufacturers ensure uniformity in voltage and chemistry when new. However, once installed and subjected to charging and discharging cycles, individual cell voltages may diverge, leading to cell imbalance over time [63], [64]. When cells are connected in series the resultant pack is only as strong as the weakest cell in the string. During cell imbalance, cells within the BP exhibit varying capacities and SOC levels, See Fig 2.6. Without proper balancing or redistribution, the pack might function ineffectively, either when the cell with the lowest capacity is out of charge or when the overall pack capacity matches that of the weakest cell [63].



**Figure 2.6:** Balancing function (adapted from [63])

Thus balancing tests are essential to ensure sufficient performance. With test control equipment internal measurement of cell voltages can be recorded. It's done by checking the cell sensors and alarm if the maximum cell voltage spread is indicated below the max required value. The tool can also check the inbuilt function of balancing in the BMS. Typically defects in welded joints and other parts of the slave can be detected for further handling. The test lasts for one minute and has high accuracy (Internal Document 25, Personal Communication, March 1, 2024), [65]

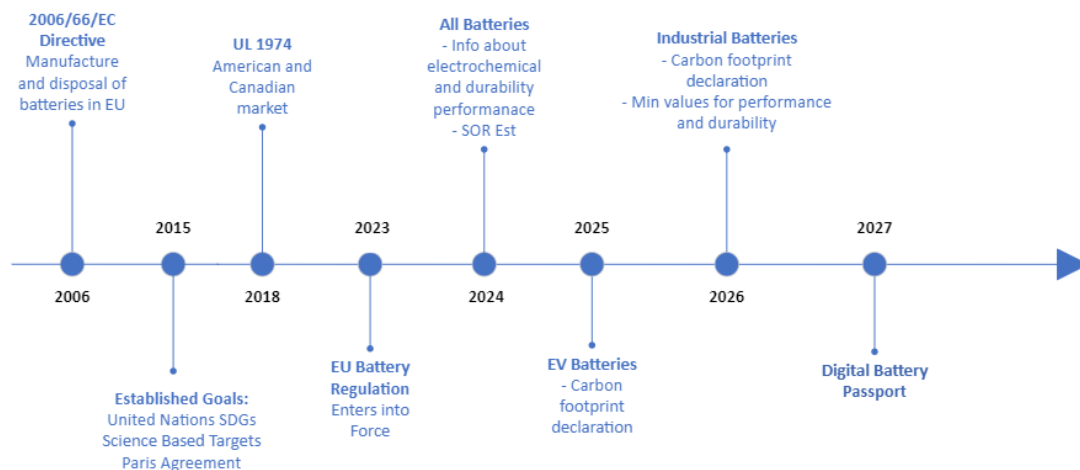
Cell voltages and State of Charge (SOC) can be balanced either passively or actively. In passive balancing, the BMS releases excess energy through resistors, which is a

straightforward and cost-effective method, although less energy efficient. Active balancing, on the other hand, involves transferring energy between cells using external tools. This method quickly equalizes the SOC levels without wasting excess energy. However, it is a more complex and expensive solution (Internal Document 4, Personal Communication, March 2, 2024), [63], [64].

## 2.4 Standards and Legal Framework

This section presents regulations, standards, and requirements for repurposing second-life batteries. The legal framework covers the existing regulations and responsibilities for repurposing manufacturers (RM) (Internal Document 33, Personal Communication, March 14, 2024). First is the standard for processing grading and sorting batteries to second-life uses examined (UL 1974), followed by the upcoming European regulation regarding batteries and waste batteries.

A holistic timeline of directives, regulations and goals that have influenced the battery, automotive and repurposing industry from 2006 to 2027, is presented in Fig.2.7. Current rules and regulations across markets are not consistent, because rulemaking is a political process and changes are happening slowly. The timeline highlights the rapidly increasing interest and concern of circular economy strategies related to battery life cycle management. As the market is quickly changing it constitutes challenges for the policymakers to keep pace [66].



**Figure 2.7:** Timeline of standards and regulations related to Industrial and EV batteries

### 2.4.1 UL 1974

UL 1974 is a manufacturing process standard designed to evaluate BPs, modules, and cells from used EV battery systems, ensuring compliance to safety and performance requirements during re-utilization activities. The standard ensures that assembled batteries meet end-product requirements when reassembled into second-

use batteries, similar to how UL 1973 is utilized for stationary batteries (Internal Document 16, Personal Communication, March 14, 2024).

The standard mandates that RMs implement a quality control program. Manufacturers must possess sufficient knowledge of the ongoing battery components and the BMS characteristics to perform sorting and grading for repurposing. Documented production process controls must be established, continuously monitoring and recording key elements of the repurposing manufacturing process that can affect safety (Internal Document 10, Personal Communication, March 12, 2024). These controls include:

- a) Control of incoming parts, including used batteries.
- b) Control of repurposing processes and data gathering.
- c) Control of outgoing production.
- d) Control of rejected parts.

Furthermore, UL 1974 regulates how the BMS and other protection controls should be evaluated to ensure their core functionality and safety. This includes analyzing BMS reliability and performance. Essential data retrieved from BMS, such as voltage, current, temperature, SoC, error messages, and contactor operation frequency, aids in determining battery health for repurposing. The standards also give a framework for the responsibility when used batteries are put into Energy Storage System (ESS) applications. According to NFPA 855 (Standard for the Installation of Stationary Energy Storage Systems) more requirements are set when designing, installing, and maintaining ESS systems. Thus a repurposed battery, defined as a BP previously used in a different field application, must undergo analysis and re-configuration for use in second-life ESS systems. Batteries previously used in for instance electric busses or trucks are not permitted for ESS use unless repurposed by a listed UL 1974-compliant. Additionally, a battery undergoing this process is not considered listed unless evaluated to safety standards like UL 1973 (Internal Document 10, Personal Communication, March 12, 2024).

Lastly, the standard for instance also explicitly regulates which batteries are to be rejected and disposed out of the process. The responsibility of detecting e.g. performance and exposure issues lies on the RM. Furthermore, this manufacturer has a responsibility to document and not introduce the products to the process anytime in the future. The UL 1973 standard states that specific tests for safety and performance, like electrical, mechanical, and environmental tests, must be done to pass, (Internal Document 16, Personal Communication, March 13, 2024).

### 2.4.2 EU Battery regulation

Within the European Union, the lifecycle and management of batteries have been subject to extensive regulation as part of the broader environmental and energy policy strategy. Initially, battery management was governed by directives such as the European Parliament and Council Directive 2006/66/EC, focusing on recycling, col-

lection of spent batteries, and requirements on battery composition [67]. However, since the directive allows member states to design their recycling programs, this led to a fragmented internal market for batteries. A new regulation covering the entire scope of batteries was needed (Internal Document 17 & 33, Personal Communication, March 5, 2024)

To address these challenges and better align legislation with rapid technological advancements and the shift toward electrified transportation, the European Commission proposed a new Battery Regulation towards the end of 2020. This new regulation aims to repeal and replace the older directive from 2006, introducing a more harmonized and unified legislation directly implemented across all member states [68]. The proposal aims to strengthen the internal market, reduce environmental and social impacts throughout the battery's lifecycle, and promote a circular economy (Internal Document 17, Personal Communication, Feb 29, 2024).

The new regulation expands existing battery categories to include batteries for electrified vehicles as a distinct group. EU has stated that performance parameters such as rated capacity (in Ah), capacity fade (in %), power capability (in W) and internal resistance (in Ohms) should meet the minimum requirements of the EV batteries. On the other hand, in the area of batteries for energy storage, existing measurement methods to test battery performance and durability are not considered to be sufficiently precise and representative to enable introducing minimum requirements [67] [69]. Additionally, an extended producer responsibility is established across the EU for all types of batteries, leading to uniform requirements for collection, reuse, and recycling. It is stated that "The manufacturer or importer placing the battery on the market or putting it into service is responsible for fulfilling the battery passport requirements" [69].

As part of the regulation proposal, battery passports are introduced for each battery released onto the market. The proposal describes an electronic exchange system, making data available of a battery's composition, manufacturing, and technical performance [21]. This digital passport will also contain essential information such as manufacturing date, content of hazardous substances, and sustainability parameters [67], [70]. The purpose of the battery passport is to increase transparency and enable more efficient management and end-of-life treatment of batteries. The responsibility for updating and registering information in the battery passport is transferred to the entity responsible for introducing the battery to the market in its first and/or second-life after any type of reconfiguration [67].

In the coming years it is expected that new requirements and standards will be added to update legislation and standards. The legislations emphasize the importance of evaluating the first life usage of a battery including its failure history to ensure that only safe and efficient batteries are re-utilized, [67]. For instance, a history of overcharging or insulation failures is expected not to pass certain safety requirements that are part of repurposing assessments. The regulation also requires thorough safety inspections, such as checking for electrolyte leaks and BP damage,

to ensure the batteries are fit for a new life e.g. in BESS applications. By setting these high standards, EU aims to ensure that repurposed batteries are used safely and effectively, aligning with environmental sustainability goals, (Internal Document 17, Personal Communication, February 29, 2024).

The IEC's proposed guidelines, for the reuse and repurposing of secondary cells and batteries by 2026, are expected to prioritize strict safety considerations. Previously mentioned is the importance of safety and in the UL 1974 for manufacturers to certify their operations. The upcoming IEC proposal will be valid in Europe and is expected to follow a similar path. Before any battery is reused or repurposed, it is expected to be comprehensively safety evaluated to ensure it fulfills the same criteria as for a new battery (Personal communication, January 30, 2014). Furthermore, traceability of the battery's historical data is highly probable to be included to ensure transparency of first-life usage, revealing crucial information before reutilization. Moreover, repurposed batteries will eventually need to comply with relevant functional safety standards and be properly labeled or marked (Internal Document 17, Personal Communication, February 29, 2024).

%subsectionState of Capacity (SoQ)

# 3

## Industrial Case

This chapter addresses the industrial-specific key principles for Volvo Energy to introduce BESS systems to the market. Thus, approaching circular economy utilizing used batteries in BESS applications. The chapter outlines the basic battery structure of interest for this Master thesis followed by relevant internal procedures and concepts already established at Volvo Energy and Volvo Group. Lastly repurposing is a concept discussed to cover the potential use cases and sustainability ambitions. The chapter addresses relevant industrial scenario which sets the framework and enables a standardized proposed evaluation method.

### 3.1 Sustainability Overview *at Volvo Energy*

The United Nations established a new agenda in September 2015, entitled as “Transforming our world: the 2030 Agenda for Sustainable Development” with a major focus on the two key features of economic security and environmental sustainability [5]. This is referred to as the Sustainable Development Goals (SDGs) and include 17 goals which consist of 169 targets in total [71].

One of the key targets for the project is SDG number 12, responsible consumption and production. Volvo Group’s ambition is to be net-zero in the value chain by 2040 where the management of natural resources needs to be sustainable and viable. A transition to the circular economy is crucial, focusing on overcoming barriers today e.g. product design, waste hierarchy and re-usability [72]. Since economic activity is expected to double by 2030 and triple by 2050, new ways of consuming and producing goods will be essential to meet the environmental goals. Thus, circular economy activities withheld huge potential to reduce the use of resources and decrease green house gas (GHG) emissions (Internal Document 34, Personal Communication, March 20, 2024).

Volvo Group is committed to reducing GHG emissions, recognizing them as a critical threat to the planet. With a clear vision, Volvo aims for a net-zero value chain by 2050, aligning with the targets of the Paris Agreement. To achieve this, Volvo have actively joined initiatives such as the GHG protocol and Science Based Targets to be innovative and at the same time competitive on the market, particularly during the use phase of their products [73]. It involves a gradual shift to electric propulsion while driving transformation in active business segments. Their strategy emphasizes electrification, aiming for 35 percent of vehicle sales to be fully electric by 2030 [73]. Collaboration is also a key factor in scaling up the road to a net-zero supply chain,

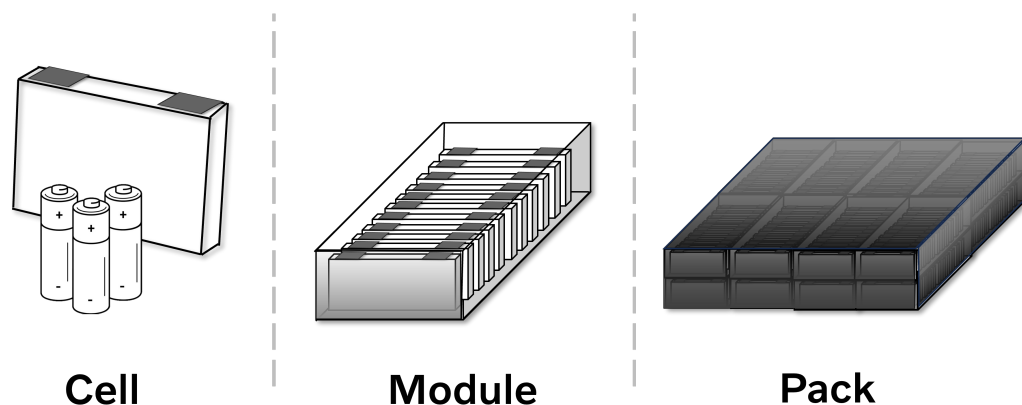
for instance regarding recycling and energy solutions [73], (Internal Document 34, Personal Communication, March 20, 2024). The importance of working together across different parts of a company is obvious, especially with the increasing pressure on supply chains. No single company can achieve circularity alone. [22].

## 3.2 Battery Structure

To enable a nuanced and comprehensive understanding of the research questions, the starting point is to dive deep into the basics and characteristics of the battery structure. In the present case study, the scope is delimited to focus on two types of BPs, flat and cubic. These consist of modules, which in turn consist of the smallest building bricks, the battery cells [74], (Internal Document 17, Personal Communication, March 25, 2014). A general overview is presented in Fig. 3.1.

### 3.2.1 Battery cells and modules

A high voltage BP consists of individual modules and cells organized in series and/or parallel. A cell is the smallest, packaged form a battery can take. Each cell is monitored by a CSC. Cells can be of several forms, whereas in this case, the cylindrical and prismatic cells are of interest. It is important to know which type a BP consists of, as that could lead to differences in aging patterns and a better understanding. A module consists of several cells generally connected in either series or parallel. A pack is then assembled by connecting modules together, again either in series or parallel [74]. A BP should hold any set of cells or modules connected and encapsulated within a casing to form a complete unit that the end customer does not intend to open or modify. Additionally, it should contain some sort of control system to ensure safety and functionality, e.g. a BMS (Internal Document 17, Personal Communication, March 25, 2014).



**Figure 3.1:** Battery structure - cell level to pack level (adapted from [75])

The thesis is delimited to address how grading and evaluation are to be made on pack level and not focus on diagnostic activities related to individual cells or mod-

ules. However, it is still of interest to understand how it is built up and what could vary in the structural battery characteristics. At present, the most frequently used battery type for the electric vehicle market is the lithium-ion battery (LIB), (Internal Document 7 & 9, Personal Communication, April 3, 2024). This is based on LIBs' longevity, power density and high energy, and the fact that their price has reduced considerably across the past 10 years [76]. It's particularly useful because it has a high energy-to-weight ratio. LIB cells also have a high power capability, both for charge and discharge. Thus, they can be optimized for energy storage [77].

There are battery test methods that require tests on a modular level, which in turn requires a dismantling of the BP. Some of these test methods are of interest as it is being investigated whether the same tests could be done on pack level in the future. One of these commonly occurring methods is the Electrochemical Impedance Spectroscopy (EIS) which gives a comprehensive condition status of a battery module [57].

### 3.2.2 Battery packs *at Volvo Energy*

The case study examines two types of BPs: the Flat BP, including two generations, and the Cubic BP. Both are of the LIB type. Comparative characteristics of these packs are outlined in Table 3.1 [78], [79]. To meet lifetime and power requirements, a conservative 70 percent usable state of charge window is enforced [78]. The flat BP consists of two layers of modules, which makes dismantling more challenging and complex. In the situation where a battery module is identified to be a weak link in the lower layer, all modules on the top layer needs to be taken out to identify its root cause (Personal Communication, February 8, 2024).

The cubic BP on the other hand consists of only six modules which are stacked vertically, which is an advantage in terms of dismantling. In case of a modular failure, each of the modules could simply be taken out and investigated (Personal Communication, February 8, 2024). When the cubic BP was introduced to the market in 2021 it had a 40 percent increase in energy density compared to what was previously available, allowing equipment to work for a longer time before a recharge is needed, [79]. This new battery offering was another step toward helping the transition to net-zero emissions.

**Table 3.1:** BP Characteristics of new-production

| Characteristics     | Flat Gen 1 (Gen 2) | Cubic      |
|---------------------|--------------------|------------|
| Application         | Medium Duty        | Heavy Duty |
| Number of Modules   | 30                 | 6          |
| Number of Cells     | 360                | 4500       |
| Cell Type           | Prismatic          | Cylindric  |
| Total Pack Capacity | 50 kWh (66 kWh)    | 90 kWh     |

The main trade-off in battery development is between power and capacity: batteries can be either high-power or high-capacity, but not optimized for both [74]. When a BP has been utilized on the roads for approximately 8-10 years it has typically reached the state referred to as its end of first life. [8]. It could be compared to a the smartphone degradation process as when the maximum capacity of the battery has decreased to 80 percent of the originally intended, the performance is no longer "good enough", based on personal experiences. Thus, the owner of the first life battery returns the BPs to the dealer because of warranties and operation insecurities.

The history of a BPs first life usage is of high interest, but the uncertainties and lack of traceability from the OEMs put a limit to the possibilities. Homogeneity within a BP decides the performance of a whole pack, meaning that if there is a weak link in terms of a cell that is performing worse than intended, this would affect its module and further on the whole BP (Internal Document 17, Personal Communication, April 15, 2024). When a BP reaches a return center it is in a majority of cases impossible to track where and how the battery has served its first life. It is neither possible to directly see what type of cells it consists of, what type of chemistries these cells are built upon, and how long ago the battery was put to the market (Personal communication, May 20, 2024). Some unknowns need to be investigated and briefly understood by inspection, testing, and evaluations.

The setup of cells into modules varies and the modular design into packs varies. Standardizing a process that has a starting point of approaching BPs case-by-case is a big challenge. In the rapidly evolving field of battery life cycle management, new regulations are immediately increasing pressure on stakeholders like OEMs to enhance traceability. Some regulations will directly impact OEMs, while others will affect stakeholders responsible for managing batteries after their initial use. These legal changes, detailed in the report, include the introduction of battery passports by 2027, streamlining information access and simplifying the repurposing process.

### **3.3 Established internal procedures**

To unlock the opportunities for electrification to enter the next stage of upscaling and repurposing, the evaluated method relies on various established internal procedures. In the following section safety guidelines, EoL test procedures, and the BMS will be evaluated further on. These are important aspects to consider for the proposed evaluation method to introduce standardization, not to reinvent the wheel.

#### **3.3.1 BMS**

The accuracy of estimating the SoH parameter is currently a topic of debate regarding its reliability. Various suppliers employ different algorithms to calculate this parameter. Additionally, the inaccuracy of approximately 5% in estimating SoH will be taken into account (Personal communication, April 8, 2024). Despite the significance of SoH in the BMS, OEMs maintain limited transparency regarding the calculation process and key factors influencing the outcome. To address this lack

of transparency, Volvo Group is conducting research in this area and developing its own algorithm. The aim is to significantly improve the level of accuracy (Personal communication, February 8, 2024).

### **3.3.2 Safety document**

An internal safety document from Volvo Group will be utilized to guide the visual inspection of incoming batteries. For instance all BPs are color-coded throughout the supply chain to detect if they are "New or used" (green), potentially could be damaged "Defective" (yellow), or need external handling due to safety and environmental issues "Severely damaged" (red). Within the safety document, there is a visual inspection checklist that provides operators and other actors of the supply chain a holistic overview of the initial state when considered for second-life usage (Internal Document 20, Personal Communication, May 10, 2024).

### **3.3.3 End-of-Line Test**

EoL test constitutes the last step of the existing quality approval method today in the production of new BPs. By understanding and learning from general requirements and structures can the design of the proposed evaluation method favor and be implemented at a scale by off-board test equipment. SoH is a crucial metric in the end-of-life and marks a baseline for further evaluation, together with complementary external testing. For a BP to be approved certain performance measures must be validated and quality approved. These are based on Internal OEM requirements from Volvo to satisfy, functionality test during manufacturing, but also external standards and requirements. E.g. voluntary documents from ISO and obligatory requirements forced by laws and governmental authorities (Internal Document 24, Personal Communication, April 26, 2024). The EoL test that is used at the case company lasts for approximately ten minutes and includes the valuable large scale test method often referred to as Pulse Power Test.

## **3.4 Repurposing at *Volvo Energy***

One key enabler for increased sustainability in the electromobility sector is to introduce circularity. Repurposing will drive the change towards extended battery usage and better utilization together with the other circular strategies defined in 2.1. In this section an ideal scenario for Volvo will be described together with the current state.

BPs are substituted from a truck for warranty and reliability reasons when reaching a remaining capacity of 80 percent, which indicates that it no longer fulfills the performance requirements from Volvo (Personal communication, Jan 18, 2024). A BP without errors that need no dismantling could directly go through an inspection and evaluation method. Reutilizing it as a second life battery with lower performance requirements in another application would enable a prolonged life by reducing the pace of battery degradation. The idea of introducing repurposing is meant to fill the

gap where a used BP can be re-used and function well in new applications (Personal communication, April 2, 2024).

The typically defined diagnostic process starts with extracting BPs from the vehicle body. That is followed by transporting the BPs to a returnal and collection facility. Furthermore, packs are dismantled into modules, and tests are performed on module and cell health where the replacement of defective or overaged modules/cells is done. Furthermore, modules of similar health metrics are matched to create a new pack consisting of homogeneous characteristics and aging. To overcome this time-consuming process, the BP can be kept intact and used for repurposing with limited handling. This concept is under investigation and intends to eliminate expensive and time consuming operations but still ensure a safe repurposing process. One of the proposed ideas from Volvo is to keep the pack intact, thus skipping the dismantling and modular matching. After collection, the idea is to perform a direct matching of similar EV BPs without disassembly and module-level grading, (Internal Document 32, Personal Communication, March 25, 2024).

#### 3.4.1 BESS Applications and Use-cases

BESS is an application area that recently has grown in popularity in line with a growing demand for renewable energy sources and the overall electrification trend. The customers generally looking for solutions to combine with in-house EVs. Temporary power solutions typically function as fast charging units to prolong working hours of machines. C&I systems is intended to provide value to the customers by enabling them to have backup power at working sites e.g. However, even if these are the most common applications today can the systems widen to more market segments and areas.

Power generated from renewable energy sources transforming energy via e.g. solar, wind and water is troublesome in the aspects of unpredictability and fluctuation in capacity [80]. A BESS can stabilize the grid, e.g. by storing energy when the sun is shining and utilizing it to support the grid during days when the grid is strained due to a higher demand. Within the field of energy storage, there are three categories referred to as FTM, BTM, and mobile applications [3]. The scope of BESS applications is delimited to BTM power unit solutions and there are several use cases of where, when and how a BESS can be used, whereas a few beneficial ones are listed below [12], [10].

- Peak shaving, to reduce peak power demand
- Capacity reserve for critical infrastructure and to stabilize fluctuations in the grid
- Frequency regulation, improving overall power quality

It is not uncommon to see a BESS that consists of newly produced BPs. Although, retired batteries can have significant power capabilities and sustainability advantages. However to outcompete new batteries, they need to be reliant and feasible in

terms of economy and performance [81]. While second life batteries have been used in all types of energy storage applications, some of them offer a better fit than others. Researchers from the University of Michigan and the University of Singapore looked into this issue and found out that the highest cost benefit can be achieved when the retired EV BPs are used for BTM applications. Consequently mainly because the refurbishment costs can be minimised [3].

The two investigated use cases of Volvo Energy can be separated into the fields of **Temporary Power** and **Commercial & Industrial (C&I)** systems. Looking at the statistics, the annual installation of temporary power systems grows rapidly (38 percent yearly increase rate) and forecasts shows 5.2 GWh installed globally by 2030 (Internal Document 32, personal communication, April 4, 2024).

A temporary power use case could take place in a scenario where connection to the grid is limited or non-existent. To reach the desired level of performance, a number of BPs are connected to build a system placed in a container with associated necessities, which enables mobile machinery fast charging and lower power costs (Internal Document 31, personal communication, April 4, 2024). The product is visualized in Fig.3.2. A potential use case could involve charging of a construction equipment machine during lunchtime of an operational working day. It's characterized as a power-intense application, and the focus lies on power output, which requires operating at higher C-rates and advanced software capabilities.



**Figure 3.2:** Temporary Power BESS Application [4]

The C&I use case takes place in a situation where the grid power is limited and the power is used for private EV charging (Internal Document 31, personal communication, April 4, 2024). The BESS consists of 24 BPs, with a main focus on providing capacity. Multiple trucks (models of FL and FM) use the BESS as a charging station and the main purpose of the product is to reinforce the grid capacity, enabling end-user peak shaving, maximizing self-production and self-consumption. During the day the BESS should be able to provide fast charging, but the important role is to provide slow overnight charging (Internal Document 31, Personal Communication, April 4, 2024). C&I applications are the number one use case for retired EV batteries [21]. Requirements for range which implies energy density, as well as power

capability during fast charging, are very high in temporary power applications [21]. During first life usage, a BP's capacity decreases and the internal resistance rises, which results in reaching a point when it can no longer fulfill its role in a temporary power application, (Internal Document 22, Personal Communication, May 6, 2024). The C&I application is identified as a less requiring use case for the further use of retired vehicle batteries, and the impact of selecting the most promising batteries out of the large pool of retired vehicle batteries is not as crucial [69].

# 4

## Methodology

This section presents the methodology that will guide the execution of the master thesis. The research process of this thesis took a case study approach, which follows six stages [82]. Each of them is reported in Fig. 4.1. The process started with planning and designing the thesis outline, followed by a preparatory literature review and background studies. The literature study involved a comprehensive review of existing research and publications. The case study research's collection stage was divided into a current practice analysis and an interview study. Lastly, the findings were analyzed, compared and modeled using the IDEF0 modeling methodology followed by communicating the result. In comparison to the original six stages, a necessary research-specific addition was the modeling part. This methodological approach ensured a thorough understanding of both theoretical and practical aspects of battery repurposing and aimed to mirror current industry practices.

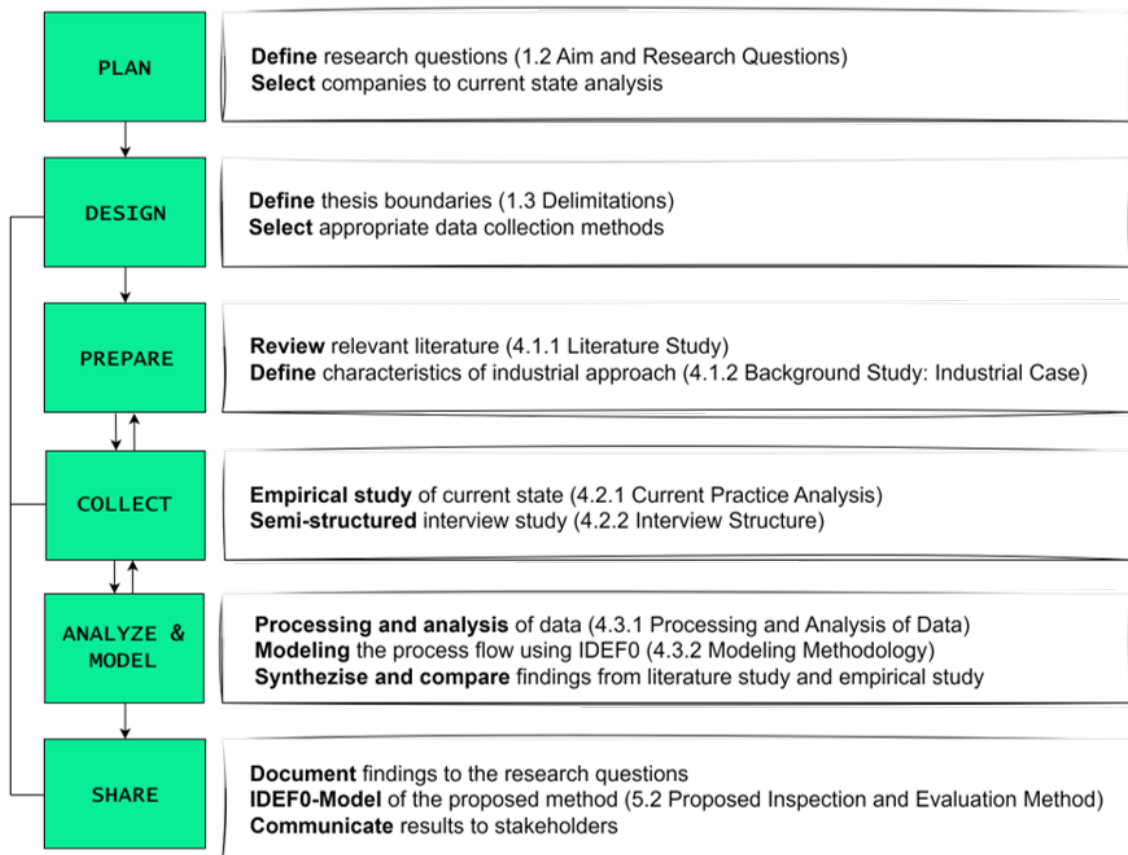


Figure 4.1: Methodological overview of the research structure

### 4.1 Plan, Design and Prepare

The plan and design stages of the case study research laid the foundation for the thesis, in terms of defining research questions and setting thesis boundaries. These were motivated and presented in the Introduction, Chapter 1. Furthermore, the literature study and background study were examined as a part of the overall preparation stage.

#### 4.1.1 Literature Study

To understand existing battery inspection and evaluation methods, a comprehensive literature study was conducted [83]. The aim was to gain insights into current practices among various stakeholders besides Volvo Energy for repurposing batteries in BESS and identify specific challenges in the process. Furthermore, the literature review focused on examining the components and structure of BPs in general, analyzing the important factors that contributed to the overall functionality. The study was explorative since the field currently has limited defined knowledge. An exploratory study aims to clarify the understanding of a problem about which there is not much prior knowledge [84].

To collect data, Scopus and Google Scholar were used in combination with provided academic journals by Volvo Energy and experts within the Volvo Group, due to their high relevance and credibility. This part of the study was described further in 4.1.2. The selection of relevant papers was based on their publication date, number of citations, and most importantly the presence of a methodological approach for scaling up processes, ensuring the most current and practical research is utilized [85]. In order not to investigate outdated material, a limit was set on the publication date to be a maximum of ten years old. Preferably papers including keywords such as “*case study*” or “*industrial implementation*” were used. Our search strategy was iterated multiple times, including the standard keyword of “*EV Batteries*” combined with search phrases as follows:

- BESS for a circular economy
- End-of-life management
- Diagnostics for repurposing
- Regulations and standards
- Challenges in repurposing activities
- State of health assessment
- Methods for inspection and evaluation

Thus, the key concepts for the master thesis were covered to complement the empirical study. The relevant regulations and standards were not included in the search string because more valuable material was found internally. Thus, this field was covered in the empirical study. The proposed search strategy led to the following

research string, which was used in Scopus advanced search.

- Research string 1 (40 matches): TITLE-ABS-KEY("batter\*" AND ("electric vehicle" OR "EV" OR "BEV") AND ("second-life" OR "repurpos\*" OR "reus\*" OR "re-us\*" OR "circular economy" OR "second\* use" OR "second\* utilization" OR "end-of-life" OR "EOL") AND ("BESS" OR "energy storage system" OR "ESS") AND ("evaluat\*" OR "inspect\*" OR "assess\*" OR "examin\*" OR "detect\*" OR "diagnos\*") AND ("state of" OR "case stud\*" OR "implementation") AND NOT ("LCA")) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND ( LIMIT-TO ( LANGUAGE,"English" ))

Articles were also found using the reference list of examined papers to find new relevant papers, without using the systematic literature search string. The used selection method is called the snowball sampling method which references referrals to new data sources [86]. The method was used complementary to the literature study to widen the study where citations were insufficient. However, the method has limitations in sampling bias if the conducted primary source only consults a small group of people. [87], [86].

### 4.1.2 Background Study: Industrial Case

The main outcome of the background study, presented as the Industrial Case in Chapter 3, enabled a further contextualization of the case. In addition to the provided theoretical concepts, it added a layer of product details and case company understanding. Adding surrounding context to the new and unexplored field of the research was seen as needed. Thus, the reader could be better prepared for how to read the findings shared in the result, discussion and conclusion sections.

Alongside the literature study, internal documents and academic journals were provided by Volvo Energy, guiding the exploration of additional scientific literature that contributed to the overall theoretical understanding of the research questions [Appendix F]. Internal expertise was also utilized to collect information, map challenges, discuss ideas, and get guidance on what could be implemented. Thus, the developed method was suitable for working cross-functionally within Volvo Group.

To get an understanding of how legislation could impact the developed method, several internally provided documents were investigated. Furthermore, details of interest were extracted and analyzed included in the following method. This laid the foundation for a composed map of requirements. For example, Volvo's method of managing used batteries by classifying them with red, yellow, or green labels. Instead of creating new safety guidelines, Volvo's existing standard documents were re-used. Furthermore, the background study focused on examining the components and structure of the case-specific flat BPs (three different models) and one cube model, analyzing the important factors that contribute to the overall functionality. To complement the literary findings, internal documents regarding test options were used (Internal Document 25, Personal Communication, May 13, 2024). Lastly, the

practical implications of the findings were investigated regarding scalability and relevance for Volvo Group. The insights from the background study enabled informed decision-making and developed standards, and new practices in the evaluation process.

### 4.2 Collect

The collection stage, previously presented in the methodological overview in Fig. 4.1, corresponds to the empirical study of the research. A current practice analysis was conducted using a benchmarking structure and observational study visits, to collect information and gain knowledge of repurposing batteries. Thus, relevant diagnostics parameters to complement literary findings was found. Furthermore, the research had a qualitative approach consisting of semi-structured interviews with relevant companies [88]. This primary data collection aimed to better understand customer needs, challenges and future application areas for BESS. Another primary data collection was in collaboration with experts at the internal testing lab regarding battery performance and characteristics.

#### 4.2.1 Current Practice Analysis

The definite stakeholders for the thesis is battery health assessors (service providing companies) and automotive OEMs addressing circular economy initiatives. The current practice analysis aimed to reflect the industry practices today and consists of stakeholders relevant to the repurposing of used batteries. Thus, strengths and weaknesses of today could be identified [89]. The methodological approach of benchmarking aimed to compare the performance and functionality of current practices on a systematic level. This gave a holistic understanding of how mature the evaluation process is today, taking inputs from various circular strategies in regards of battery life cycle management [90].

The benchmarking structure was utilized to facilitate comparison in current practice today between companies. It was also used to find already existing evaluation procedures to understand what a standardized method or ideal scenario could look like. This method complemented the interviews with direct insights from the industry practice of today, to contribute knowledge of e.g. test methods and ideas for future development. The interviews itself contributed to a more holistic view of each interviewee and their way of working. Another benefit of using benchmarking was to find process steps that could directly be applied to the proposed method, without the need for reinvention. Additionally, the method indicated if the proposed method headed in the right direction, and what competitors do. However, the method also has limitations in missing out on other innovative solutions. [91], [89].

#### 4.2.2 Interview Structure

The interviews utilized an interview protocol targeting key industry stakeholders to understand current practices and explore batteries' repurposing for a second-life

in BESS. This protocol included key areas to address the research questions structurally and in-depth. The interviews were conducted in a semi-structured approach, which enabled for asking questions in a specific but not fixed order [92]. Supplementary and open-ended questions were highly prioritized and valuable as the study was explorative. One downside of the interview type was the risk of introducing bias, which was thought of when designing the questions and was executed well. A guide for how to conduct a semi-structured interview was followed, which consisted of the following five steps [92]:

1. Set goals and objectives
2. Design questions
3. Assemble participants
4. Decide on medium
5. Conduct interviews

In the first step, the aim was addressed, which included gaining an understanding of current practices, challenges and influential performance metrics in the evaluation of used batteries. Further on, the questions were designed to address the key objectives of the thesis, resulting in an interview protocol for company representatives [Appendix A]. Thus, the set of questions could yield more detailed and targeted responses. To assemble the participants in the third step, relevant stakeholders were identified through internal recommendations. This study involved four companies operating in the EV battery sector. The companies were selected based on three main criteria: (1) Interest in repurposing of used batteries, (2) Expertise in diagnostics and testing (3) Willingness to invest time, cooperate and share information about their operations. In the fourth step, the medium was to be decided. Due to the wide spread of locations among the interviewees, three out of four meetings were conducted online using Microsoft Teams. In the last case, an interview could be conducted physically due to a study visit on the same occasion.

When possible and giving permission the interviews were transcribed to enable easier processing of how to cleanse and structure the data [92]. The interviewed companies are presented in Table 4.1, which were anonymized.

Using anonymous interviewees can prevent bias and maintain trust by ensuring that individuals feel secure, thus providing their experiences without fear of personal backlash. These ethical practices protect participants' and companies' privacy, allowing them to contribute more freely and honestly, which is crucial for the integrity of the research [93].

**Table 4.1:** List of Interviewees

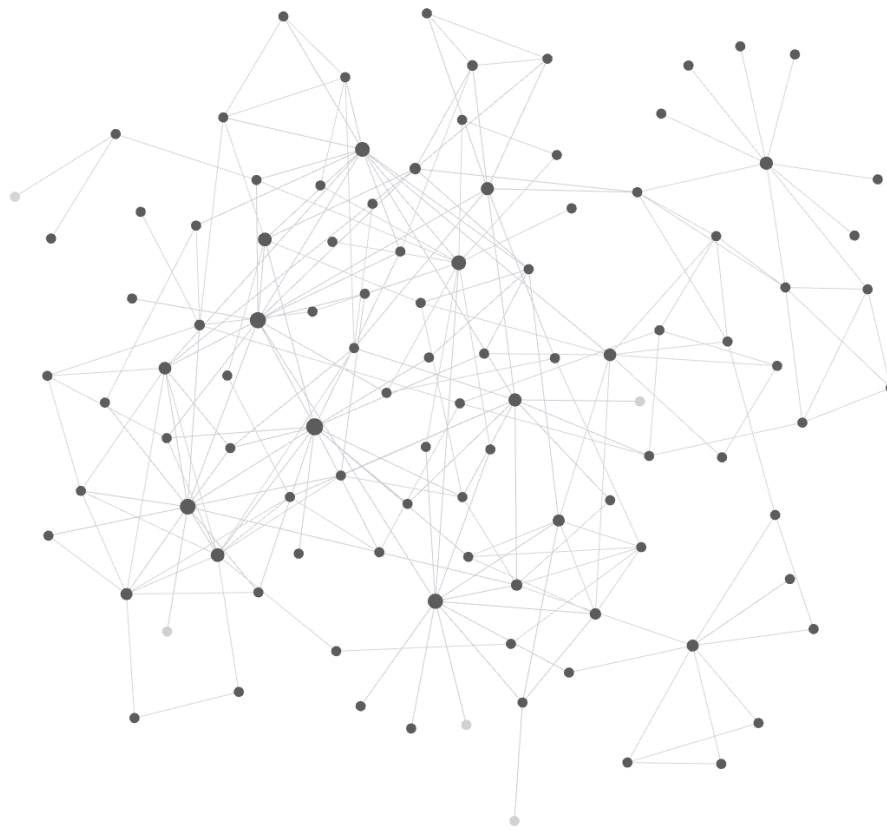
|                        | Company 1   | Company 2                                | Company 3   | Company 4   |
|------------------------|---|--|---|---|
| Sector                 | Renewable Resources                               | Automotive                               | Energy  | Energy  |
| Location               | Germany   | Sweden                                   | Norway  | USA   |
| Number of employees    | 51-100  | 51-100                                   | 11-50   | 11-50   |
| Role of representative | Head of Battery Health                            | Senior Project Manager                   | CEO/Co-Founder and Head of Battery Intelligence   | Business Development Analyst and Battery Testing Engineer |
| Business Operations    | Battery Health Assessor / Energy Utility Supplier | Automotive OEM / Battery Health Assessor | Battery Health Assessor / Energy Utility Supplier | Battery Health Assessor                                   |
| Date                   | 2024-02-01  | 2024-02-08                               | 2024-02-21  | 2024-02-21  |

### 4.3 Analyze & Model

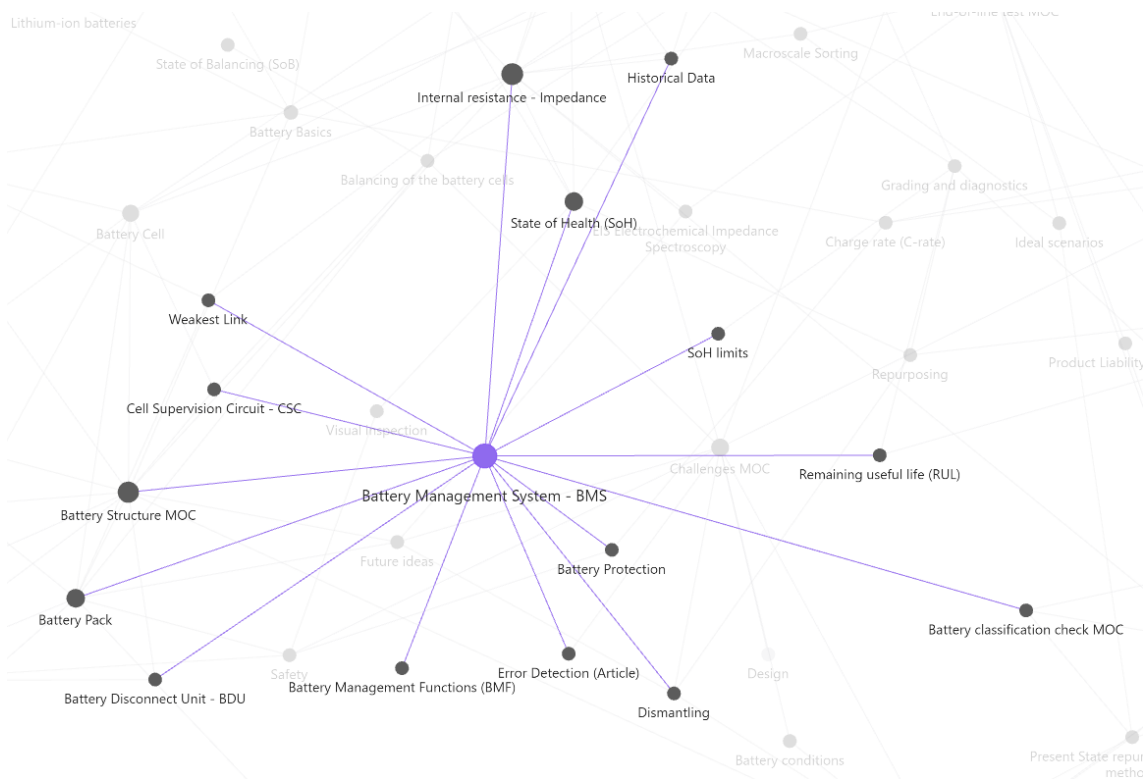
Following the collection phase, the different types of findings from the literature, background and empirical study were processed, analyzed, and synthesized, according to step five in Fig. 4.1. The analyses were executed with multiple back-and-forth iterations upstream of the research structure. This section also aims to illustrate how the findings were transformed into a process flow model using the IDEF0 methodology.

#### 4.3.1 Processing and Analysis of Data

To process and combine literary findings, from Scopus as well as from the background study of internal documents, a method called Zettelkasten was used. Zettelkasten actively replicates how the brain organizes concepts and ideas rather than classifying them in a typical filesystem like ordinary notes system does e.g. Google Drive, Windows etc. Ideas and thoughts were briefly annotated to notes which were connected creating a train of thoughts. Relationships were established between the notes, which retained information and grew knowledge exponentially. The process started by summarizing and rephrasing thoughts, and the reason behind each note was to solidify understanding and focus. Furthermore, the notes were structured by highlighting key elements and linking them for easy retrieval and connection, while regularly questioning and reviewing content to foster idea development and pattern recognition [94], [95]. The graph covering all of the project's notes and how these are connected is presented in Fig. 4.2, where each node corresponds to one note. A zoom-in on a specific topic is presented in Fig. 4.3, to show how ideas are connected.



**Figure 4.2:** Method to sort findings - Overview



**Figure 4.3:** Zoom-in on the "Battery Management System - BMS" node

Another source of data was connected to industrial visits with current practice analysis. This information was used to understand the information available in used batteries better today and develop a safe and standardized deployable evaluation method realistic to the preconditions.

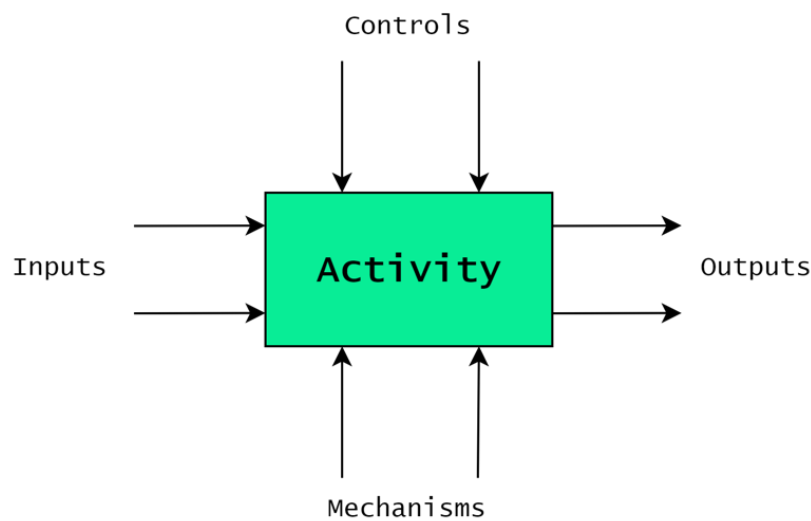
In the stages of testing, off-board equipment was used internally at Volvo Energy by experts from the departments of battery testing and data analytics. Thus, the tests were not conducted by the authors, but the test results were still of high interest for further analysis. The internal software was utilized to read data from the BMS into understandable output, along with provided test files and results from previous test sessions. Additionally, historical data from the vehicle's first life was also supplied internally. The data was used to support the decision-making of the newly proposed evaluation method to leverage historical usage. For instance, could the availability of data in tested batteries indicate what diagnostic packages were plausible in the evaluation method. Each department is responsible for validating the data and was not examined further by the authors.

To analyze the results of the interviews, transcripts were made and a thematic analysis was used, which was supported by identifying common patterns within the answers of different interviewees. These patterns were later turned into comparable data and analyzed using an inductive approach, which is open-ended and allowed the data to determine the themes [92].

### 4.3.2 Modeling methodology

In this section the method for sharing findings and finally the proposed evaluation process was examined according to the second last step of the research structure, see Fig. 4.1. To communicate the process flow an IDEF0 framework was used to give a holistic and at the same time thorough examination of each step of the proposed method. Thus, the findings from the study could be visually examined and shared to support the collected knowledge.

To create a scientific and understandable model of the process flow, the IDEF0 methodology was used. There are plenty of ways to diagram processes and this approach was found to be the most suitable because of its history of being used as a standard for process definition. IDEF0, originating from the well-established Structured Analysis and Design Technique (SADT), was created by the United States Air Force to offer a functional modeling method for analyzing and communicating a system's functional perspective [96]. The IDEF0 method is used to create function models, focusing on "what do I do" scenarios. These models outline major activities and their associated inputs, controls, outputs, and mechanisms (ICOMs), see Fig. 4.4. By portraying a process's key components, IDEF0 allows for deeper analysis [97].



**Figure 4.4:** Schematic overview of process in IDEF0 (adapted from [98])

What differentiates the method from traditional flowcharts is the use of arrows, especially control and mechanism arrows. Controls within the IDEF0 method serve to direct the activity of the process, acting as inputs but guiding the process rather than undergoing transformation [99]. Distinguishing between inputs and controls can be a challenge, but generally, inputs transform the input to generate outputs, while controls typically remain unchanged. Examples of controls include standards, requirements templates, and checklists. Mechanisms represent the resources and tools necessary for executing the process, such as skilled personnel, machinery, and equipment. This can often be seen as physical objects [98]. The modeling method was modified in the specific project by adding dashed arrows, as an indicator of a future input, output, control or mechanism. This modification was made to comply with the expanding and constantly evolving field. One example of a future input was the Battery Passport.



# 5

## Results

This chapter presents the results addressing research questions 1 and 2. Firstly, current practices are mapped in terms of existing evaluation methods and contribute to answering both of the research questions. Furthermore, the performance requirements for BTM BESS applications, legal requirements and challenges for repurposing are presented to answer RQ1. Next, it outlines the proposed evaluation method, consisting of four major activities, each thoroughly explored.

### 5.1 Map of current state

The first part of the result aims to give a holistic view of battery repurposing at the current state to define requirements forward and challenges to overcome. The automotive industry is rapidly changing towards electrification, enabling circular economy actors to find market segments for second-life batteries. Thus, addressing established policies and frameworks is important to enable new proposed evaluation methods.

#### 5.1.1 Existing inspection and evaluation methods

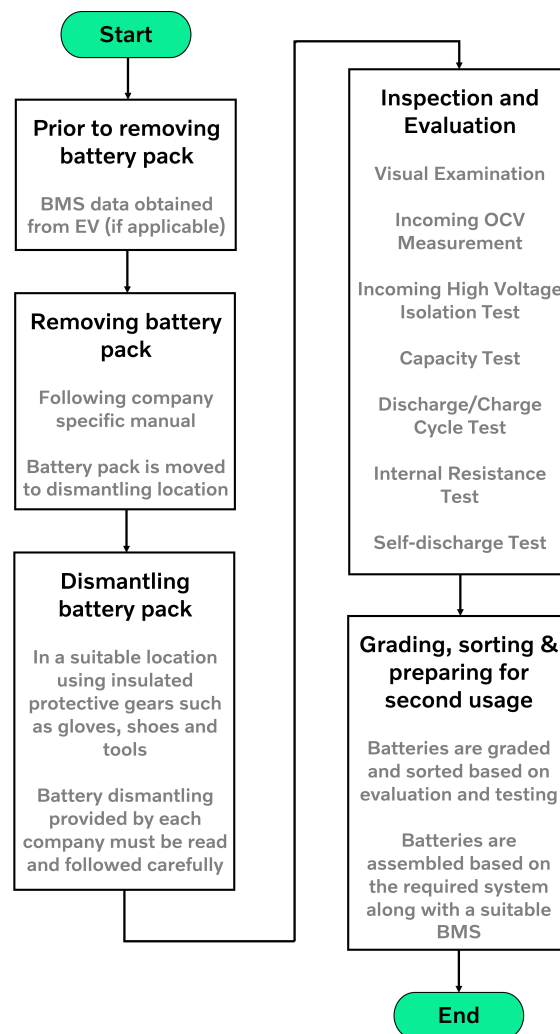
In this section, the results from the conducted interviews will be presented to examine existing inspection and evaluation methods. The number of contacted companies was 12, and the interviews were 4. Furthermore, the literature study will complement with findings, ideal scenarios, challenges and possibilities, etc. The resulting themes based on the thematic analyses of the interview transcripts became the five listed below:

- Challenges and Current Practices Today
- Preconditioning, First Screening
- State of Health Assessment and Evaluation
- Grading Scheme and BESS Applications
- Requirements, Standards, and Regulations

The existing inspection and evaluation method in this report was structured in five stages based on available literature regarding second-life battery evaluation, see Fig 5.1 [100]. The first two activities address the logistics of transferring the battery pack (BP) from first life to a battery return center, as well as collecting necessary BMS data. The next step is dismantling (if not kept as a whole pack) associated

with safety precautions. Further on is inspection and evaluation executed by conducting external testing procedures. Finally, the batteries can be evaluated based on these diagnostics and prepared for second-life application.

An ideal scenario could also involve the development of a practical aging model for accurate SoH estimation during online operation, tailored to specific applications. The models performance can be enhanced by integrating degradation data from initial use, if more data was stored in the cloud, [53]. To conduct evaluations effectively, standardized battery test procedures are essential, leveraging modeling tools and machine learning to assess battery health and predict aging, [36].



**Figure 5.1:** Second-life EV batteries assessment guide (adapted from [100])

Additionally, the research institute RISE has in a research project investigated how retired EV batteries can find purpose in new applications [101]. They proposed a method including three primary categories of how to ensure that a BP is suitable and safe for second-life usage. It included a visual, electrical, and mechanical inspection and a battery management system inspection [102]. These structures and designs laid the foundation for the proposed evaluation method seen in Section 5.2.

The interview objects all stated an evaluation method that had a similar structure to Fig. 5.1, but differed in some activities. Representatives from Company 1 for instance provided the service of battery testing and evaluation rather than delivering complete BPs. The method laid its foundation in fast EIS testing on a modular level. Current practice was defined by analysis of operating history from suppliers and a first screening checking for immediate safety risks and ensuring the batteries meet minimum performance criteria. Then followed a dismantling of BPs to modules and lastly a mechanical, electrochemical and safety evaluation. After EIS and external tests were performed could the modules be grouped and matched for similar second-life applications in BESS [Appx. B]. Also, Company 3 used EIS to evaluate batteries, with in-house-built hardware and algorithms to quickly evaluate the modules. However, they bought modules that already were safety-approved when delivered and didn't need any dismantling in their process. After the EIS a functional safety test performed to ensure quality, no further tests were needed. The only data that Company 3 utilized and registered were the available voltages, currents, and temperatures on the cell level [Appx. D].

According to Company 4, they designed their evaluation method to work on both module and pack level, which is unique among the interviews listed. Once safety is evaluated (manual process) they connect each battery to their hardware where they conduct multiple tests. Company 4 doesn't rely at all on BMS data since the inaccuracy of the BMS is too large. Hence no standardized method was established. After EIS they also used ML algorithms to cluster batteries based on internal resistance (IR) and capacity values [Appx. E]. Company 3 used a very similar approach to 5.1. The process starts with cleaning, electrical and visual safety evaluation and data transfer from the BMS. There was no standardized way of extracting first-life data nor troubleshooting error codes, which currently is being developed. A heavy focus lay on understanding why the BP malfunctioned in the first place. Then the BPs are dismantled into modules where performance testing is conducted, followed by repairs and a final EoL test [Appx. D].

One result from the interviews was that they share the commonality of not being able to fully standardize their processes. In-house hardware and software were mostly used to compensate for lacking data from the suppliers. Another similarity among the majority of the companies was that they conducted manual electrical safety tests to ensure no current flows unpredictably and the BP was undercharged. They mainly differed in how grading and BESS matching were executed, as their solutions aimed to address different market segments and customers.

### 5.1.2 Performance requirements for BESS and use cases

When evaluating performance requirements for BESS applications, it consistently boils down to the same fundamental question: What are the specific practical use cases? How much energy is required? How much power is needed? Does the solu-

tion comply with safety and legal requirements? The number of questions quickly increases and it is difficult to address a standardized approach, without having a diagram of system boundaries made for every specific use-case [103].

During the interview with Company 1, the importance of adapting to a specific use case and the understanding that all batteries and customer demands are different were seen as crucial aspects [Appx. B]. The representative of Company 2 had similar thoughts, emphasizing that where the BPs will end up depends on various factors which is difficult to generalize [Appx. C]. Company 3 took it further, with the representative saying "It is seen as a challenge and close to impossible to put a numerical limit of how to grade a battery for a specific BESS application. It's important to understand the usage profile for second-life..." [Appx. D]. Company 4 had a clear vision for its second-life applications, "The vision is to put repurposed batteries on the market that are available to run in a second-life application for 10 years" [Appx. E].

To investigate battery performance requirements for BESS applications, the approach of making it partly case-dependent was possible due to close industrial collaboration. Typically, when assessing BTM applications for BESS, it is possible to identify two distinct divisions, one that emphasizes on power and one on capacity. Based on internally known industrial use cases of temporary power and C&I BESS applications, the numbers representing the cubic BP type can be seen in Table 5.1. Some of the observed use cases imply that the BESS is being used more than once per day, which in turn requires an increase in capacity, change of typical user cycles, or can put restrictions for higher C-rates. Taking temperature into consideration is important as that can affect how well a battery can perform, but as it is not part of our research scope the average temperature within the range 10-38 degrees is assumed without further investigations (Internal Document 31, Personal Communication, April 4, 2024).

**Table 5.1:** Performance Requirements for BESS applications

| Application                   | Temporary Power system | C&I system    |
|-------------------------------|------------------------|---------------|
| Nominal Capacity (kWh)        | >500                   | >2000         |
| Daily energy throughput (kWh) | 300-600                | 240-600       |
| Discharging Power (kW)        | 0-320                  | 0-900 (0-320) |
| DoD (%)                       | 70 (15-85)             | 70 (15-85)    |
| C Rate (C)                    | 0.15-0.25              | 0.10-0.20     |

The most evident difference between the BESS types is the physical size of the system. The nominal capacity of the C&I system should be four times the temporary power system, which indicates that four times the amount of battery packs will be needed. During the day the C&I type should be able to provide fast charging, but the important role is to provide slow overnight charging (Internal Document 31,

Personal Communication, April 4, 2024). What characterizes the temporary power BESS is the higher power intensity, which requires operations at higher C-rates.

The nominal capacity for a cubic BP is 90 kWh and for a flat BP it lies between 50-66 kWh depending on generation, referring back to Fig. 3.1. The DoD of 70 percent will be enforced for BESS usage, to achieve a good trade-off between lifetime and power requirements [78]. The daily energy throughput per battery, derived from observed use cases, functions as an indicator for RUL and suitability for recommended second-life use.

For example, a retired cubic BP with a SoH value of 80 percent would hold a useable capacity of 50.4 kWh ( $90 \cdot 0.7 \cdot 0.8$ ), whereas a flat BP (second generation) with similar conditions would hold a useable capacity of 37.0 kWh ( $66 \cdot 0.7 \cdot 0.8$ ). The performance requirement of daily energy throughput is in the range of 300-600 kWh for the temporary power application and 240-600 kWh for the C&I. Hence, it indicates how many BPs the system would need to reach the requested level of performance. When a system needs more BPs than what the structure can handle it is no longer suited for second-life usage in the specific BTM application. Additionally, if a BP delivered a lot more energy than required, an alternative is to use less amount of BPs or reduce the SoC window to favor a longer lifetime.

### 5.1.3 Map of legal requirements and standards

In order to form the new landscape of electrification and prolonged life of EV batteries, a good understanding of the most relevant requirements and regulations is important. It is also essential to look further in the future at what will regulate the markets, hence designing the evaluation method to match the upcoming legal framework. In Table. 5.2 the most relevant standards and regulations presented followed by those under development.

Company 1 stated that they had put much effort into complying with the new EU regulation that was implemented at the beginning of 2024. According to the company representative will the new requirement of the suppliers be a key enabler to save time in diagnostics and better understand the unique history of the battery. For instance, they mentioned that the requirement of an estimated IR value is an important measure to utilize for second-life use [Appx. B]. Also representatives from Company 2 discussed IR and SOR to be essential in determining if a battery is suitable for second-life- use. They also elaborated on the rigorous current safety requirements that need to be fulfilled today, since they do dismantling on the BP [Appx. C]. According to Company 3 is there currently no standardized methodology for both ensuring the performance of the battery as well as meeting security criteria. However they claim to comply with the EU regulation with ease since they have a good structure of documenting health assessment, characterization etc for the future, [Appx. D].

**Table 5.2:** Map of legal Requirements, standards and policies relevant to repurposing

| Title  | No.          | Standard | Regulation | Under development |
|--|--------------|----------|------------|-------------------|
| Evaluation for Repurposing or Remanufacturing Batteries  | UL 1974      | ✓        |            |                   |
| Requirements for reuse of secondary batteries  | IEC PT 63330 | ✓        |            | ✓                 |
| Environmental requirements for battery-based energy storage systems (BESS) with reused batteries | EC 62933-4-4 | ✓        |            |                   |
| Standards for Battery secondary use  | SAE J2997    | ✓        |            | ✓                 |
| General guidance for reuse of secondary cells and batteries                                      | IEC PT 63338 | ✓        |            | ✓                 |
| EU Battery Regulations   |              |          | ✓          | ✓                 |

The upcoming battery passport is discussed by all of the interviewees. For instance, Company 3 stresses how transparency needs to be addressed both by suppliers and also for RMs. Also, representatives from Company 2 stated that they have already prepared documentation procedures and digital tools to track batteries for battery passport legislation. A common thread among the interviewees is that they see battery passports as a necessity and something that will enable the industry to scale up, be efficient, and prolong the life of the batteries.

The standard EC 62933-4-4 and especially UL 1974 still holds considerable influence over the industry of RMs. For instance, stakeholders must follow procedures to quality test, meet end product requirements and comply with numerous safety guidelines. For RMs, the policy explicitly controls which parts to be taken into the process, which BPs to be approved and which to be rejected. Lastly does current legal framework also states responsibilities in the value chain and throughout the second-life.

#### 5.1.4 Challenges for repurposing batteries in BESS

The current and most influential challenges explored by the literature study, background study, interviews and observational studies are listed below. The map of

challenges regarding repurposing of used batteries addresses RQ1. These findings also guide RQ2 into finding the proposed key factors, by overseeing what's feasible to implement at current state.

- Non-linear degradation (Predicting Remaining Useful Life)
- Lack of first-life usage data
- Unreliable and unprecise data from OEMs
- Immature technologies on BP level

#### **Non-linear degradation (Predicting Remaining Useful Life):**

A BP's degradation is challenging to predict due to its ability to change from a linear degradation path to a non-linear one, which can occur before the "knee point". At 60-70% remaining capacity the non-linear phase usually takes place [104], but can vary depending on usage. The main target related to this challenge is to take care of a BP before it hits this knee point, characterized by a sudden drop in SoH, [47]. Thus, it would be highly beneficial to improve knee point prediction when it's about to occur, which was emphasized in 2.3.1. Finding a new purpose for the BP could extend the lifetime of the battery following the expected trajectory due to typically lower energy and power performance requirements [9].

The lifetime of a battery can depend on several different factors. For instance, a BP that has been abused during its first life in terms of overcharging, discharging at high C-rates, frequent charging cycles, and/or high surrounding temperature, holds a higher risk of entering the region of fast degradation [8]. This would result in a shortened lifetime and an abrupt decrease in capacity. The interviewees emphasized the difficulties related to predicting when the knee point was about to occur, and the companies approach it in various ways. Company 1 introduced the idea of using a digital twin to create forecasts of degradation. Company 3 looks for specific degradation patterns, and Company 4 uses a case-by-case approach as each battery is seen to be unique due to the degradation complexities. The common denominator is the complexity of standardizing.

#### **Lack of first-life-usage data:**

The lack of data, and especially from the first life usage of EV BPs, is a challenge that every stakeholder involved in re-utilization operations has to adapt to [10]. Company 2 expressed that the data in the incoming BPs was insufficient and operators have little or no knowledge of first life use. For instance, does the BMS only give situational values and have no memory showing historical events captured during first-life usage, which could have been useful in the evaluation process. A future idea would be to introduce some kind of cloud-connected BMS, which keeps track of first-life data.

The introduction of the Battery Passport is seen as a valuable incoming aspect to help change this from being a challenge to becoming an asset, putting pressure to enhance transparency along supply and value chains for all stakeholders (Internal Document 17, Personal communication, March 10, 2024). Company 1 stated that

"It will be a future enabler to save time in the diagnostics phase", Company 2 followed on the same track: "The biggest hurdle we face today lies in navigating the relatively unexplored territory of battery data". Company 3 emphasized the battery passport as a driver for more transparent and standardized evaluation methods, while Company 4 didn't rely on historical information at all.

### **Unreliable and unprecise data from OEMs:**

Another challenge related to the lack of data and transparency is the BMS SoH estimation and its accuracy. In general battery packs have an inaccuracy of approximately  $\pm 5\%$  which has to be considered when evaluated. Additionally, the transparency is low on how the parameter is estimated and how the inaccuracy develops over time [105]. Some BPs offer better estimations with inaccuracies of  $\pm 2\%$  and according to Company 4, some have worse such as  $\pm 10\%$ . Thus it's case-by-case dependent on the supplier of the BMS. Therefore, Company 4 decided not to work with data provided by the OEMs and only rely on their in-house software and hardware outputs. The new EU Battery Regulation puts pressure on OEMs, e.g. in terms of adding a requirement to estimate what is referred to as a BP's SoR by the end of 2024. Although, these batteries will reach end of first life in approximately 10 years, it will not be included in the proposed evaluation method, but rather a future additional feature.

### **Immature technologies on BP level:**

The whole idea of repurposing used EV batteries into BESS applications is based on keeping the pack intact, utilizing it as it is, with as little processing time and investigations as possible. However, the amount of established test methods and diagnostics on pack level are limited. Several companies do battery testing, diagnostics, evaluation, etc., but on a modular or cell level. All of the four companies interviewed in the empirical study are working mainly on a modular level. The challenge is then to transfer the knowledge and testing procedures to the pack level, without losing accuracy or validity. Many technologies in the field of battery lifecycle management are under rapid development. Stakeholders that perform dismantling are not competitors to our result, but rather seen as a complementing operation to prolong the lifetime of EV batteries with other faults. Although, what has been found during the study is the need for add-on activities related to dismantling. For example, as soon as the BP is no longer intact, it has to be completely dismantled into every single component before being put back into a pack again. It also requires a leakage test to be performed as soon as the lid of the pack is taken off.

## **5.2 Proposed Inspection and Evaluation Method**

In this section, the resulting proposed inspection and evaluation method will be presented by describing and visualizing its consisting flow charts. This was constructed by following the IDEF0 modeling methodology, see Section 4.3.2. Based on the collection and analysis phases of the research, both literary and empirically, the method resulted to consist of five major activities (A1-A5) to ensure a comprehensive evaluation. The process was systematically built with inspiration from prior

work and research, which laid the foundation for the IDEF0 [100], [101]. This was also complemented with interview findings and internal expertise.

- A1: Visual Inspection and Safety Evaluation
- A2: First Screening
- A3: Diagnostic Packages
- A4: Classification and BESS Matching
- A5: External Handling

The IDEF0 process flow consists of 10 different layers, the entirety of which can be seen in Appx. H. A few chosen layers are also extracted and highlighted in the result section. The first layer (A-0) is referred to as the parent diagram of the research and presents the main inputs, controls, mechanisms and outputs. The second layer (A0) is presented in Fig. 5.2, which shows the holistic view of the proposed inspection and evaluation method. The flow starts top left and moves in chronological order to the bottom right, whereas each of the four activity boxes will be described in the following sections of the report. The fifth activity box, referred to as *External Handling*, is a visual clarification of what happens to the BPs leaving the system by following the 'Not OK' arrows.

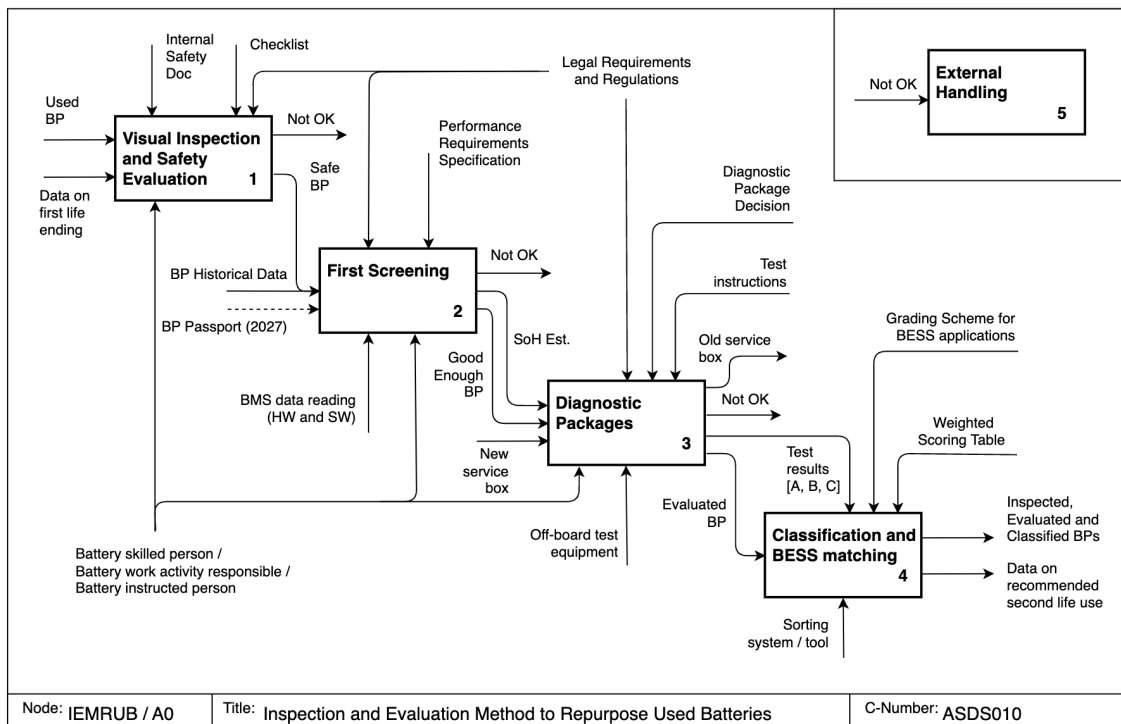


Figure 5.2: A0 - IDEF0 system perspective

### 5.2.1 Visual Inspection and Safety Evaluation

After the BPs have served a first life in an EV BPs are directed to a central return facility. The logistic center will allocate batteries to appropriate circular economy

activity e.g. refurbishment/ remanufacturing, repurposing as a BESS, recycling, etc. Maintaining comprehensive records of the battery's first life cycle and ensuring traceability throughout the entire process is crucial for appropriate use in the second-life. Therefore, the first step involves documenting and registering each BP.

To be further considered in the evaluation process do the batteries need to be visually inspected and safety evaluated. According to Volvo Group's established safety documents and guidelines only approved batteries be handled in second-life applications. Routines are established to handle hazardous or potentially damaged goods visually. Following a structured generalized checklist can mechanical or physical damages be addressed early on in the process. The safety document also gives guidance in responsibility and roles, precautions and visual indicators, etc.

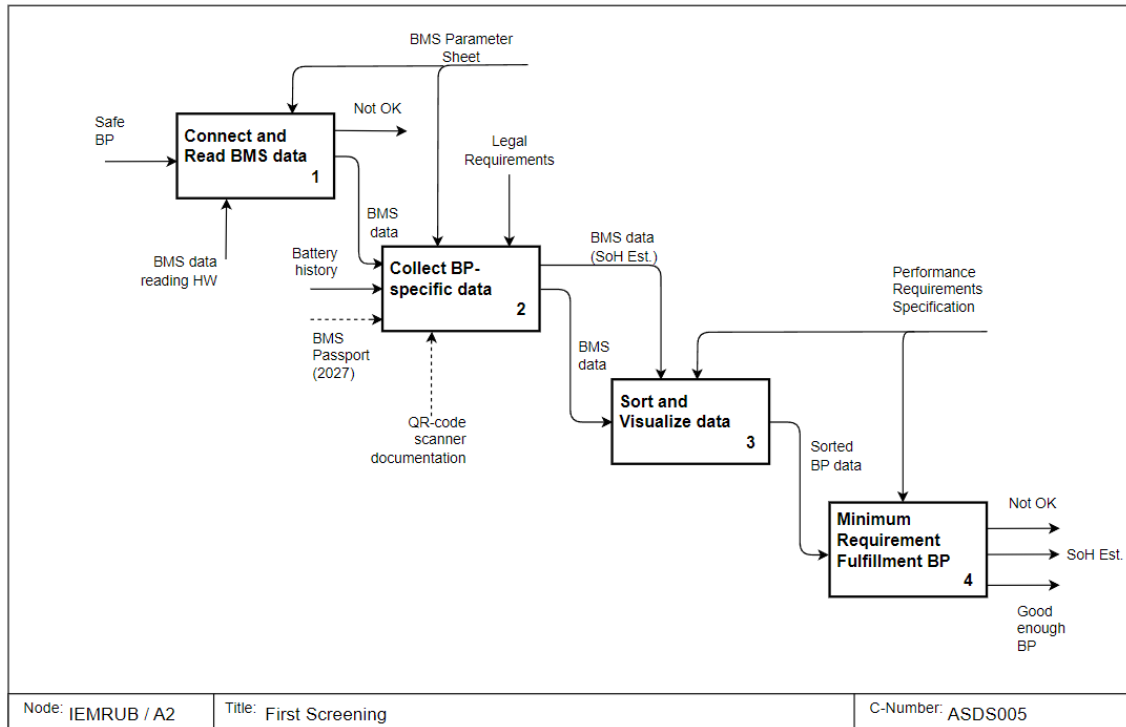
Furthermore, will the proposed method include a provided checklist with electrical safety to evaluate the BPs, according to UL 1974, see Section 5.2. Battery-skilled personnel with electrostatic discharge equipment will inspect each BP to verify proper functionality, thereby minimizing the risk of harm to individuals. Since the inflow of batteries can vary a lot in conditions and health, it will be essential to ensure no voltage flows in the pack or uncontrolled at the surrounding cover when the battery is in standby mode. With a voltmeter can the voltage be determined and ensure safe future handling quickly and easily.

### 5.2.2 First Screening

The second major activity in the proposed method is the first screening after the visual inspection and safety evaluation, see Fig. 5.2. The input to these processes is now safe batteries electrically and visually which are about to conduct a quick first evaluation. The procedure starts with the collection and handling of BMS data. The information is functional to use for analysis in the early stages of assessment and the data is collected via sensors and internal controls from the CSC. When connected to the reading hardware the data is instantaneously retrieved, easily accessible and gives a good holistic view of the battery. However, the limits are designed to comply with the inaccuracy that follows the estimated data. Furthermore, BMS has the potential to capture some of the essential battery history that would require time-consuming testing. The BMS parameters sheet controls which required performance parameters to collect, see Table. 5.3. The used metrics origins from the available data in the BMS for cubic and flat BPs and are designed to address the EoL test performed in later stages as well as legal minimum requirements (Internal Document 24, Personal Communication, April 20, 2024).

All of the described key features make the BMS a key enabler in ensuring further evaluation of BPs for second-life use. The information gathered in the brain of the battery can quickly be retrieved and used as a first indicator in the analysis of performance and health. Furthermore, BMS has the potential of capturing some of the essential battery history that would require time consuming testing. However, the large amount of unsorted data has to be dealt with. It requires further visualization

and sorting of data to reach the full potential of the BMS. It's also important to understand that estimated parameters are indicators with a certain degree of inaccuracy.



**Figure 5.3:** A2 - First Screening

The first screening activity also includes documentation to store data about the BPs first life to its second-life by scanning a battery-specific QR code. Thus, thorough tracking of essential data paves towards battery passport regulation in the future [21]. As seen in Fig. 5.3, data about first-life use e.g. charging rates, years in usage and total energy throughput are stored and saved for further evaluation. Note that the C-rates cannot directly be obtained without processing and algorithms to be calculated. Furthermore, the data is visualized and sorted for quality assurance purposes. Originally is the BMS data unstructured and hard for operators and engineers to analyze and sort which will be addressed in the third activity.

In the last step of the first screening the BP is evaluated regarding minimum requirement fulfillment controlled by a Performance Requirement Specification, see Fig. 5.4. SoH acts as a primary first indicator of overall health, while cell voltage imbalance indicates potential weak links or misuse in first life. Lastly, no error codes are solved in the proposed repurposing method. BPs with these faults are sent to external handling. Thus, BPs with lower SoH than 70% are also sent to external handling. The SoH estimate together with other BMS data is then transferred to the diagnostic phase of the method. The BPs are now both safe and good enough for further testing and analysis.

**Table 5.3:** BMS Parameter Sheet

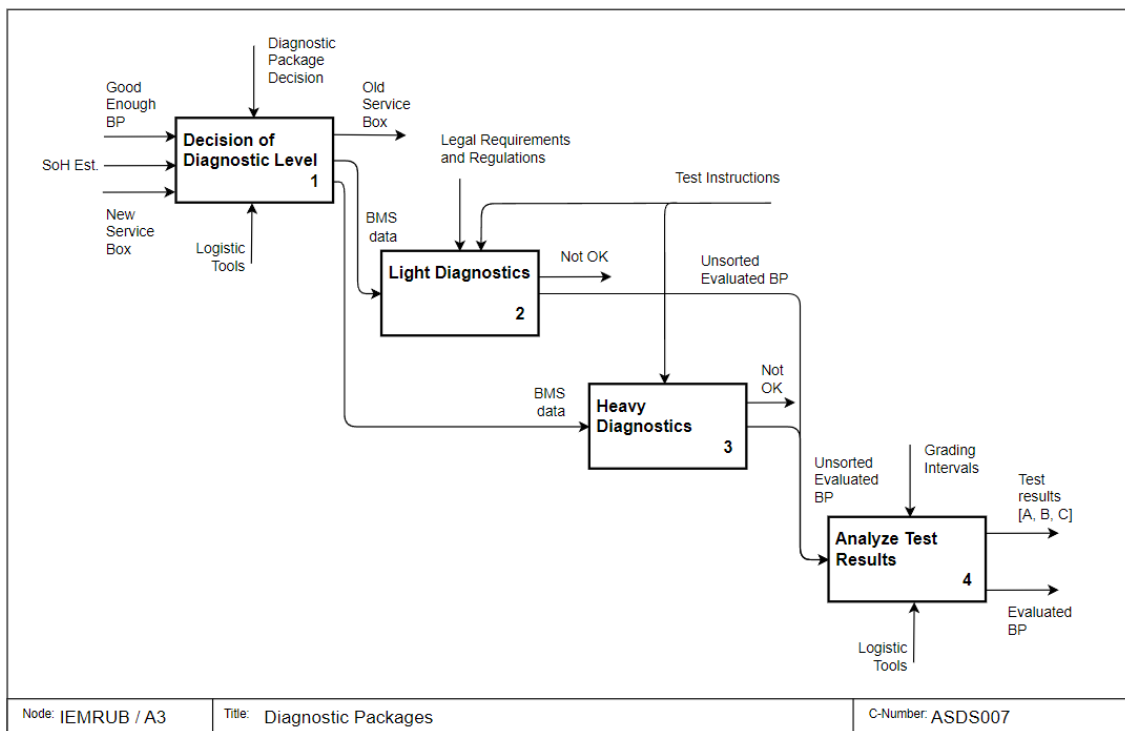
| Parameter (Prioritized parameters above the line)   | Unit              |
|---|-------------------|
| State Of Health Estimation                          | % [0-100]         |
| Pack Voltage Imbalance                              | % of ref value    |
| Total Charge Energy Throughput                      | kWh               |
| State of Resistance                                 | % [0-100]         |
| Current SoC   | % [0-100]         |
| Number of years completed by battery in usage       | years             |
| Number of years completed by battery in standby     | years             |
| Average SoC for battery idle condition              | % [0-100]         |
| Average discharge rate from drive cycle             | C-rate [0-10]     |
| Standard charging current                           | C-rate [0-10]     |
| Fast charging current rating                        | C-rate [0-10]     |
| Percentage of charging done with fast charger (>1C) | % [0-100]         |
| Relay Counter                                       | Amount [0-60 000] |

| <b>Performance Requirement Specifications</b>           |               |
|---|---------------|
| <b>Parameters</b>                                       | <b>Limits</b> |
| SoH [%]   | >70%          |
| Cell Voltage Imbalance<br>[% difference from ref value] | <15 %         |
| Error Codes [No.]                                       | 0             |

**Figure 5.4:** Performance Requirement Specification

### 5.2.3 Diagnostics Packages

From the first screening activity the battery can be classified as good enough for further evaluation and the step can be seen as a first quality control based on BMS data and safety guidelines. An important output from the previous step is the estimated SoH value, which acts as a deciding factor for further evaluation. Once a BP has passed the first screening it enters the second stage of the evaluation method for complementary performance testing, referred to as the *Diagnostic Packages* presented in Fig. 5.5. The main idea with this proposed evaluation stage is to introduce diagnostics on two levels: Light and Heavy, presented in Fig. 5.6.



**Figure 5.5:** A3 - Diagnostic Packages

The first activity is to decide the level of diagnostics, based on the Diagnostic Package Decision presented in Table 5.4. When to conduct light or heavy diagnostic is a complex decision that depends on numerous aspects such as economics, time management, and business strategy. Thereby are two alternatives presented as a result, see Table 5.4. These alternatives represent two out of many strategic decisions that can be taken regarding diagnostic package decisions. In alternative 1 heavy diagnostic is conducted on BPs with relatively high SoH: Time and investments in the testing and evaluation are spent on good batteries to maximize the best possible output. Alternative 2 can be argued from the opposite perspective. In this scenario, light diagnostics is conducted on BPs with high SOH due to their likability of already being "good enough". More testing is done with poorer performing BPs since they eventually might need tests to be quality-approved, safe, and well-functioning.

For repurposing of used BPs in BESS applications, only the SoH interval 90% - 70% will be considered. BPs that have higher SoH should be considered for circular activities such as remanufacturing or refurbishment due to their compatibility to serve in an EV again [Appx. C]. In the lower interval beneath 70% the battery will be discarded from repurposing activities since its conditions indicate that it's better suited for recycling or recovering. The RUL is likely to be too short and the risk of premature technical failure in second-life BESS applications will be higher if the lower limit is set to a value below 70 percent.

The general inaccuracies present in the estimated SoH value from the BMS are also considered in designing Fig. 5.4, which is approximately 5% for flat and cubic BPs, (Personal communication, April 10, 2024). Furthermore, several cases show that a

**Table 5.4:** Diagnostic Package Decision

| Alternative 1           | Alternative 2 | SOH Interval [95% - 70%] |
|-------------------------|---------------|--------------------------|
| Light                   | Light         | $\geq 95\%$              |
| Heavy                   | Light         | [95% - 90%]              |
| Heavy                   | Light         | (90% - 85%]              |
| Heavy                   | Heavy         | (85% - 75%]              |
| Light                   | Heavy         | (75% - 70%]              |
| Recycling, Recover etc. |               | $< 70\%$                 |

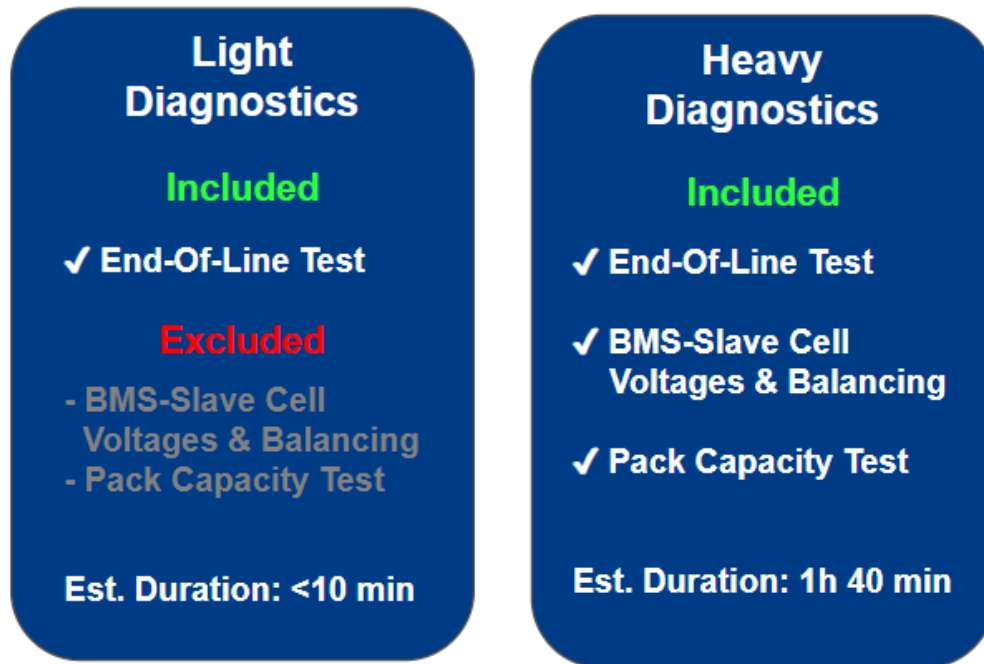
limit between 60 - 80% is appropriate to filter out malfunctioning and unsafe batteries [106], [107]. Additionally, three out of four interview objects state that the determined lower limit is suitable and appropriate for repurposing activities (Personal communication, March 2, 2024).

Before diagnostics are conducted the service box (BDU) of the BMS is switched as a part of the resulting method. The BDU is a crucial component in controlling and safeguarding the BP during its lifetime but is also exposed to wear and tear. A switch prolongs the lifetime and ensures steady operations in second-life applications, (Personal communication, February 8, 2024). The activity is planned before the diagnosis to test that communication and hardware functions work as intended. Lastly, the old service boxes are intended to be part of the circular economy with external actors managing the remanufacturing or recycling of the components.

The diagnostic packages include testing by established, efficient, and robust test methods. Light Diagnostic serves as extensive End-Of-Line testing to ensure functionality based on an internally established procedure defined in 3.3.3. These tests and checks will always be conducted, as a requirement from the OEM before putting a product on the market. By combining the results from the first screening with the Light Diagnostic package, it serves as an extensive basis for grading.

The heavy diagnostic package gives an ever more explicit overview of the state of health by conducting a balancing test and pack capacity test. The pack capacity test replaces SoH from BMS data. The test is relatively time-consuming (approx. 90 min) but is reliable, well established and accurate. Furthermore, the overall functionality of the inbuilt balancing of the BP is tested together with the cell voltage spread. This inbuilt function originates from the CSC, which is connected to each of the cells in the pack and constantly monitors the balancing of the pack. For the BP to function long-term in a second-life application it will be important to actively balance and keep track of the weak links internally. Additionally is IR an important measure that's included in the EoL diagnostic package, the HPPC test. The test is performed by applying a 10-second partial charge and discharge with 100A, and its result gives important information about IR growth compared to initial conditions. It indicates possible discharge rates of the battery performance and thereby

how well the BP could function e.g. in fast-charging BESS applications. The test is well-established, fast, and accurate, which enables the evaluation method to be scaled up with the potential of automation [53].



**Figure 5.6:** Diagnostic Packages Overview

In the last step will test result of the BPs be analyzed based on determined grading intervals. The grading intervals for the BP's IR relative growth, SoH, remaining capacity, imbalance and future RUL are presented in Fig. 5.7 and it corresponds to the evolution since the battery was new until the battery is not fulfilling the first screening requirements. The category of 'A+' is included to capture the holistic view, but is out of the case boundaries and rather useful in the circular strategies of reuse, repair, remanufacture and refurbishment. The limits are designed based on statistics from the cubic BP type and by comparing them to statistics of similar EV batteries at the end of first life. It is also validated internally and can be seen as generalized grading intervals. Given the exploratory nature of the field, there are no definitive answers, so it's important to be critical about varieties and inaccuracies. Earlier phases of literature and empirical research showed that different stakeholders prioritize various parameters, and setting limits involves business and economic considerations. Thus, a decision was made to use percentage-based grading intervals, which account for each battery's initial state, rather than uncertain numerical intervals. This enables for the grading concept to be generalized by changing the numerical limits. Although, in this study the method has been framed focusing on a technological and comprehensive viewpoint.

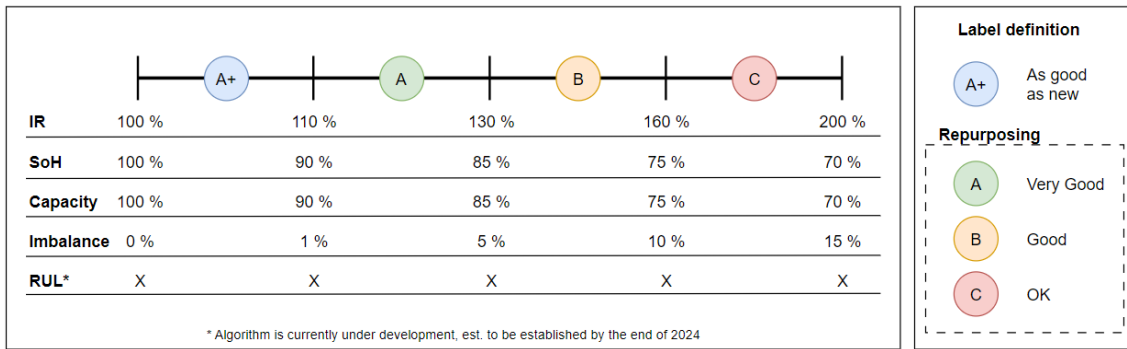


Figure 5.7: Grading Intervals - Evaluation Parameters

### 5.2.4 Classification and BESS Matching

The process flow of the fourth activity is presented in Fig. 5.8. Since all testing and diagnosis are completed the BP can be seen as evaluated based on Fig. 5.7. The first step is referred to as the decision of classification, whereas two grades are obtained to indicate compatibility with second-life application. Labeling and sorting is an expected aspect of importance to ensure traceability and comply with upcoming regulations, which was examined in the theoretical framework (Internal Document 17, Personal Communication, February 29, 2024). Furthermore, the second-life suitability is visualized using a grading scheme and a recommendation is provided regarding the two specific types of BTM BESS applications.

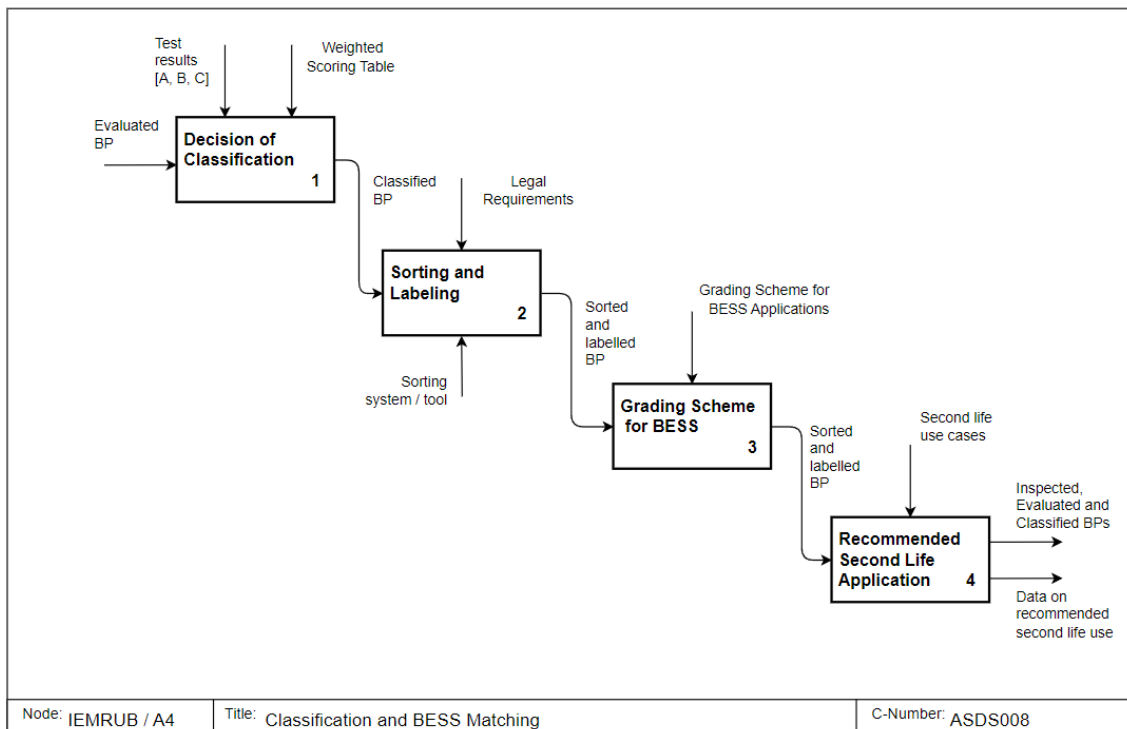


Figure 5.8: A4 - Classification and BESS Matching

After the BP has conducted light or heavy diagnostics, a decision of classification follows. To address performance requirements for the specific use cases described in 5.1.2, weighted scoring tables are created, see Fig. 5.5. The evaluation parameters have different impacts on the grade whether they should be used in applications optimized for capacity or power. Thus, the scoring tables address the most critical end-compatibility parameters: internal resistance, pack capacity and lastly pack imbalance. The last parameter is weighted less compared to IR and capacity but contributes with an extra dimension of grading in terms of BMS performance.

**Table 5.5:** Weighted Scoring Table - Heavy Diagnostic

| Evaluation Parameters                                       | Unit                   | Weighting Power | Weighting Capacity |
|---|------------------------|-----------------|--------------------|
| SoH (BMS data)  | [%]                    | 0               | 0                  |
| IR Growth (HPPC Test)                                       | [%]                    | 0.65            | 0.25               |
| Capacity (Pack Capacity Test)                               | [kWh]                  | 0.25            | 0.65               |
| Pack Imbalance (BMS-Slave Cell Voltages and Balancing Test) | [% of reference value] | 0.1             | 0.1                |
| <b>Tot:</b>   |                        | 1.0             | 1.0                |

The final classification of each BP depends on whether it has undergone light or heavy diagnostics. For light-diagnosed batteries the SoH and IR growth values directly transferred to capacity respectively power, see Fig. 5.7. Thus, input SoH values that range between 90% - 70% get directly a grade regarding **Capacity**. Similarly, input values of IR growth ranging between 100% - 200% serves as grading basis for **Power**.

When BPs undergo heavy diagnostics, an algorithm to calculate the weighted results is used. The grades (A, B, C) are assigned numerical representations (3, 2, 1) and then multiplied by their corresponding weighted parameters. This enables a calculated total value for capacity and power respectively in the range from 1-3. Fig. 5.9, extracted from G, demonstrates an example of a grading where the total value regarding Power equals 2.25 (Grade B) respectively for capacity 2.65 (Grade A).

| Inputs  |     | Point |   |  |
|---------|-----|-------|---|--|
| Cap [%] | 85  | 3     |   |  |
| IR [%]  | 130 |       | 2 |  |
| lmb [%] | 8   |       | 2 |  |

| Classification |          |
|----------------|----------|
| Power          | Capacity |
| B              | A        |

**Figure 5.9:** Final Grading Case: Heavy Diagnosed BP

The final grading procedure and algorithms for each possible scenario are presented in [Appx G]. The calculation logic is transparently designed to allow for easy generalization or modification, as grading limits may change in response to new require-

ments, regulations, and standards, among other factors. Classifying the used BPs and sorting them is important to reach homogeneous battery strings in the system. As earlier mentioned, the impact of selecting the most promising batteries out of the large pool of retired vehicle batteries is not as crucial for the C&I applications as for the temporary power, due to the lower performance requirements [21].

From a technological perspective, a grading scheme for two types of BESS applications (Capacity and Power) was created to give guidance on which classification outcome results in which type, presented in Fig. 5.10. Each BP thereby gets two grades with an indication of recommended second-life application. For each BESS type, there are several use cases, so the fourth step is to bring data on alternatives for recommended second-life use. The suitability of each string of BPs could be highly dependent on the end-customer demand, which by adding alternative recommendations in different use cases enables for a standardized approach. A commonly known concept is the *First In, First Out* (FIFO) approach. However for the inspected, evaluated, and classified BPs the approach will rather be *Highest In, First Out* (HIFO). The underlying cause is that battery degradation is occurring at all times, so the potential of the highest performing batteries should be used first, the sooner the better (Personal communication, 22 January 2024).

| Classifications |   |   |   |
|-----------------|---|---|---|
| Capacity        | A | B | C |
| Power           | A | B | C |

| Grading Scheme for BESS |             |             |             |
|-------------------------|-------------|-------------|-------------|
|                         | $A_{power}$ | $B_{power}$ | $C_{power}$ |
| $A_{capacity}$          | BOTH        | CAPACITY    | CAPACITY    |
| $B_{capacity}$          | POWER       | BOTH        | CAPACITY    |
| $C_{capacity}$          | POWER       | POWER       | BOTH        |

**Figure 5.10:** An excerpt from A4G1 [Appx. H]

# 6

## Discussion

In the following section were the presented results generalized, motivated, challenged and discussed. The aim was to examine both sides of the result addressing RQ1 and RQ2 and to review the findings and implications. Common themes and interesting topics were discussed regarding the methodology chosen, contribution, the generalizability of the result and finally future research possibilities.

### 6.1 Methodology

The research was decided to be approached by following a case study design proposed by Yin, motivated by choosing a grounded theory to turn research findings trustworthy and of high credibility [82], [108]. The approach included a literature study and background study to explore existing battery evaluation methods for repurposing in BESS applications, supplemented by interviews with industry stakeholders and observational studies to develop a structured evaluation process for used batteries [83]. Due to the nature of the research question and the unexplored field the method was suited for its purpose [84]. The interviews gave great insights as many of them were in the initial phase of battery diagnostics and initiatives such as repurposing, and had a lot of newly gained insights to share. Furthermore, it could be seen as a strength to back it up with a structured literature study where many efforts are put today. An alternative approach could have included even more proof of concept and tests, or alternatively a more general overview of the current state and way forward. The disadvantage of the chosen approach is that the result can be a bit too tangible, technical and specific. Thereby, a lot of efforts have been made to generalize and contribute to further research rather than delivering solely a case-specific report for Volvo Group.

The third step of the semi-structured interview procedure, to assemble interview participants, was a challenge. Out of the 12 companies contacted, only 4 interviews were successfully conducted. It possessed a challenge mainly due to the low amount of industrialized companies in the newborn industry, the confidentiality of sensitive information, and the lack of available timeslots in the schedules of company representatives. All of the interviews were conducted with companies striving to succeed in re-utilizing the potential of retired EV batteries, which could introduce a risk of turning realistic sharings into optimistic sharings. The interview structure worked out well, thematic analysis of the answers enabled to find patterns in the answers and turn it into comparable data to consent or contradict the thesis results [92].

The delimitation of focusing on repurposing as a circular strategy instead of covering all of the R's in Fig. 2.1, investigating BTM solutions solely, as well as not delving into economic aspects of BESS applications, were seen as successful decisions in relation to the timeframe and scope of the research project. Another delimitation of high importance was to focus on keeping the pack intact and not to investigate battery diagnostics for modular or cell level, which shaped the findings and enabled transferability of the results [108]. The delimitations steered the research into a specific direction, maybe missing out on possible scenarios higher valuable in terms of how to turn the battery value chain more sustainable, but according to the background study and the nature of the project the assumptions and delimitations were seen as necessary.

The IDEF0 method was originally used to create function models, focusing on "what do I do" scenarios [97]. In our research, it was used as a framework for sharing the proposed method, due to its high credibility and history of being a standard for process flow charts. The systematic way of working with layers enabled a beneficial iterative processing and several drafts were made to arrive at the final version. To cover all aspects of the proposed method the layers were needed, not to make it challenging to read and understand, as an important part of the aim was to add guidance to an unexplored field and not to add new uncertainties. One drawback of using IDEF0 as a modeling tool was that the requirements of the tool forced the layers to consist of a set minimum number of activity boxes. At some points of time that resulted in being too caught up in the technique and formalities rather than making progress.

In the data processing and analysis the methodology of Zettelkasten was used to effectively create notes and link information together, [94]. The main contribution to our project was to efficiently structure data into easily retrievable notes, which improved overall understanding and memorization. One drawback of the method was that we did not fully utilize the potential of all notes written and the connections in between. The scope of the project changed dynamically throughout the process which resulted in a lot of cards never being used. However, another method would be to directly state the findings retrieved during the research, which might have been a faster solution. On the other hand the tool of Zettelkasten enabled collaboration, shared findings and a more efficient structure of theoretical framework.

## 6.2 Results

The following section will discuss the results of RQ1 and RQ2, and how these contribute to theoretical research gaps and practical insights. The research questions were overlapped during the research to get a comprehensive understanding of a field with an explorative and unknown nature. The generalizability of the results is important, as the aim is to propose an inspection and evaluation method suited for any stakeholder interested in the circular strategy of repurposing used EV batteries.

### 6.2.1 Research Question 1

Regarding the first research question, "What are the battery performance requirements for BTM BESS applications, along with legal requirements and challenges to repurpose used batteries?" the objective was to establish the performance criteria for repurposed BPs, ensuring their suitability for a second-life in the BESS applications Temporary Power and C&I. The idea was to better understand what could be requirements, thereby laying a foundation of what needed to be further investigated in the following research question using reverse engineering. To narrow the scope and avoid coming to a vague conclusion the research was delimited to only looking into BTM BESS applications. The presented requirements were in terms of battery performance requirements and a map of legal obligations affecting second life utilization, specifically repurposing activities. In the future the amount of available and precise data can be seen as a key enabler. Regulators can thereby influence the industry by introducing regulations and policies that emphasizes on transparency of data. This could facilitate the implementation of evaluation processes throughout the industry as it solves one of the four most influential challenges in battery repurposing.

The research investigated the field from several perspectives, with the help of literary and empirical studies. Established use cases from Volvo Energy were observed and utilized to cover varying scenarios in the second-life use, (Internal Document 31, Personal Communication, April 15, 2024). Furthermore, the identified challenges regarding repurposing of batteries clarified the current state analysis in RQ1. By mapping barriers of today a further understanding of repurposing could be conducted.

By synthesizing and analyzing literary findings with interviews, the study showed that the field is way too case-by-case dependent to establish general battery performance requirements, (Personal communication, May 3, 2024). The long-term goal was clear and agreed upon by all interview respondents, to put a repurposed product to the market which should be available to run in a second-life application for many years. The vision of Company 4 (a service-providing company working with EIS) was set for the BPs to reach a prolonged lifetime of 10 years. This timespan could be used in the proposed evaluation method to indicate what battery conditions to allow through the proposed method, which was found insightful. The way to get there includes several challenges and uncertainties, resulting in a somewhat open conclusion to the part of RQ1 regarding the battery performance requirements.

It became evident that the most effective approach to conclude was to connect RQ1 to a case. When investigating case-specific industrial use cases, the result showed that BESS applications are either emphasizing power or capacity, (Personal communication, May 13, 2024). Thus, batteries must fulfill performance requirements in the parameters of capacity and power and the requirement of daily energy throughput. The lack of first-life usage data and the unprecise data from OEMs were unexpected insights, [11]. The map of influential challenges highlighted what needed to be considered in a proposed evaluation method in RQ2. Even if the results of RQ1 didn't

bring a completely clear path for what would be parameters to focus on in RQ2, it brought a framework that was beneficially used in the structuring of the empirical interview protocol. It also enabled the idea of grading batteries in two separate categories, emphasizing capacity or power abilities.

### 6.2.2 Research Question 2

The result of this study showed that an inspection and evaluation method for repurposing used batteries is realistic, deployable, and generalizable in the near future. It's interesting to see that already existing data, safety procedures, and off-the-shelf equipment can be used in a standardized way to quality-assured batteries (Internal Document 25, Personal Communication, May 1, 2024). However, the market is immature and there are several challenges to overcome. The study has not shown actual Proof of Concept nor deployment in a real industry case, where many other aspects than the technical influences. For instance, lack of data regarding grading limits and the fact that several key metrics are under current development [11].

The result of having a visual inspection and safety evaluation followed by a first screening was expected from early on in the project. Merely the only established and standardized activity was the two activities, (Internal Document 20, Personal Communication, April 30, 2024). The result of the first screening also shared a lot of similarities with other industry practices, interviews and literature findings, [53], [11]. However, the differences in current practice and the proposed method in the last two steps turned out to be surprising. The idea of having light and heavy diagnostics was seen to be rarely unique. Also, the business decision on which BPs should have either less or more testing was left as an open question for adopters. A clear pattern in the result can be seen: It's not effective to let all BPs undergo the same amount of testing and diagnostics. Another thing that wasn't obvious in the beginning was that BPs could explicitly be matched to either power or capacity BESS applications and get grades based on either of them, (Personal communication, April 2, 2024).

In order to state that the results ended up as a Proof of Concept, the procedure would have needed to be validated and practiced step by step in a reality-based scenario. The proposed method was constructed based on technical aspects delimiting from economical considerations, for example whether or not parts of the process could be motivated to be implemented at a large scale. The two first occurring major activities in the process, visual inspection and first screening, could be seen as validated due to the fact that these are proven methodologies in current practices. During an observational study we had the possibility to get hands-on experience of real BMS data collection. The proposed method included usage of the same software and hardware, which enabled us to state that the first screening activity was seen to be deployable in a real scenario of battery repurposing assessment. The diagnostic packages were not tested during the research, however the included test methods one by one are proven to be accurate and deployable. Setting the values of grading limits was one of the most challenging tasks during the project. The unexplored field of research on BP-intact evaluation made us rely on statistics and

simulated degradation patterns provided from internal experts and literary findings. The investigated types of BPs have not yet been deployed for enough time to have reached the retirement point at a large scale. This was an obstacle which made us unable to test the complete evaluation method on a BP that had spent 8-10 years in its first life. The collected values were made on fewer usage cycles. Stressing and speeding up battery degradation with non-realistic conditions was seen as a non-value-adding activity, giving unrealistic insights. The real data that we got our hands on were of batteries that had evaluation parameter values close to being as good as new.

### 6.2.3 Contribution to Theory

This thesis contributes to theory by providing industrial evidence into a field of literature that is at a very early stage. The interviews performed with experts represent a valuable source of knowledge for further research. In the mentioned interviews several statements, which include that there is a lack of guidelines and methods for battery repurposing provide evidence of the immature industry, [58]. By mapping categories of battery performance requirements (Research question 1) common approaches to second-life reutilization can be addressed. To answer the second research question, a proposed comprehensive method was constructed, which is a conceptual method but yet contributes to gaps in previous research. Theoretically, can further research be developed on methods where the BP is kept intact (pack level) and where different diagnostic is used for various types of BPs.

For sure there are also benefits with circular strategies that implement a dismantling activity of the BP into modules. It can be seen as a complementing operation to prolong the lifetime to a wider extent of retired EV batteries. The dismantling activity enables battery test methods that are solely mature on a modular level. Additionally can also error codes be taken care of. Although, what was found during the study is the need for add-on activities related to dismantling. The time-consuming effect of the dismantling activity favors the concept of keeping the BP intact and avoiding further handling. As the result from the interviews showed, many technologies in the field of battery lifecycle management are under development, so what is immature today will of high probability become mature before the end of the decade and solve parts of the challenge that has to do with pack-intact evaluation, (Personal communication, May 3, 2024).

One important part of the result from this study claims that retired EV batteries must fulfill the minimum requirement of 70 percent remaining capacity, referred to as the SoH estimation or result from the HPPCv test. Otherwise, the BP is not good enough for repurposing activities, motivated by the risk of entering the degradation phase after the knee-point, which could result in abrupt and non-linear aging. This result confirms current practice and previous research in the field, which have shown limits of remaining capacity suitable for repurposing activities in the range from 65-70% [Appx. B], 80% [Appx. D], 70% [Appx. E], 60-80% [107], and 70% [48]. One research paper in the literature review was found to contradict this,

stating that "the results obtained contradict the suitability of the 70-80% remaining capacity threshold as a standard criterion" [109]. Although, as that research was conducted on cells instead of modules or packs and subjected to laboratory aging tests during their first life, it was not seen as contradicting enough for our results to adapt.

Any considerations regarding the economic feasibility of utilizing second-life batteries for BESS were intentionally excluded from the scope of this research. However, what can be seen as a contribution to theory is the valuable asset that used batteries will be in the upcoming decades. The insightful interviews and upscaling of these types of techniques and markets have shown the potential of BESS. Together with the forecasts of the rapid increase in the retired EV battery market, it can be seen as obvious to utilize second life batteries in the field of energy storage, which is not yet recognized nor compensated in current markets. That is partly due to the slow political processes in need of change. The results show that current rules and regulations across markets are not consistent and are lagging in time, which if it takes too long can decide if the future of BESS is bright even more than technology itself [66].

### 6.2.4 Contribution to Practice

This study contributes to practice by providing a thorough analysis of a rather unknown field to an industrial sector that urgently needs to scale up and be more efficient, [3]. The major consequence of the results is that a proposed classification and BESS matching can be made based on BP. More studies and practical examples from the interviewees can be seen on cell and modular level advancement, but less on pack level. The proposed grading scheme based on the performance requirements of BESS applications provides a structured approach for evaluating and repurposing used batteries. By outlining these requirements, suggesting both internal and external diagnostics, and finally proposing a chronological method, it sheds light on improvements in current industry practices. Ensuring battery quality through just four major activities can be tested on a large scale.

One notable practice among companies is to limit their operations to their products. In our case, Volvo focuses solely on managing BPs that have been utilized in Volvo Trucks, Buses, Penta, and similar vehicles. Conversely, start-ups and other stakeholders lacking their first-life usage products must contend with a diverse range of incoming BPs, complicating the entire process. As a result, the transition from vehicle to second-life application becomes challenging to standardize, prompting these companies to prioritize efficiency in battery performance assessments instead, [11].

In discussing SoH upper and lower limits for repurposing, it's relevant to consider the consistency of setting the thresholds at 90% and 70% with various sources of information, including interviews, literature reviews, and internal expert validation [48]. This underscores the importance of basing SoH limits on empirical evidence and industry expertise rather than fixed thresholds. For instance, Company 2 highlights

that the BMS data value for SoH cannot be modified, even if tested values indicate otherwise. This raises questions about the rationale behind conducting capacity tests if the BMS data remains unchanged. Such practical insights from industry players shed light on the complexities of implementing SoH limits and underscore the need for a nuanced approach. However, during discussions with internal Volvo Group experts it came to our understanding that the new EU battery regulation is expected to require OEMs to implement a BMS software reset function, which could prevent the previously mentioned obstacle. By incorporating feedback from cross-functional stakeholders and validating key aspects, this approach ensures that the established parameters are representative of the broader battery lifecycle management industry.

### 6.2.5 Generalizability of results

Creating generalizations between phenomena, whether explored theoretically or practically, is not simple. However, the thesis attempts to gather insights from both research and practice to potentially create generalizations within the field. From an industrial perspective, the data from the case study proved to be rather complex to handle, particularly because the involved companies are often concerned with confidentiality. The access to confidential Volvo Energy information was an asset during the process of the thesis work. Despite the challenge of sharing results and writing the report due to confidentiality, the process of generalizing was easier since we couldn't mention specific values or forecasts, from internal documents.

It was made clear that capacity and power were the two most important battery performance parameters that guided the scope in RQ2. The need for answers to questions regarding the specific use-case made it close to impossible to come up with specific values of performance requirements that could be widely representative. The answer to RQ2 involved more aspects that needed generalization. Decisions on how to design the proposed evaluation method were motivated mainly by insights from the interviews and internal documents. To validate the decisions made, internal expertise and literary findings were seen as tools to either contradict or consent, (Personal communication, May 14, 2024).

The unit of analysis in this case study comprises two different types of BPs. However, it is anticipated that the results will be transferable across each product type. As the types are supplied by different OEMs, it comes with differences e.g. in inaccuracies of the BMS estimated values. Mean values between the two types were used, and it was also emphasized that other battery types could be worse or better performing in any aspect. Therefore the idea of having all of the grading limits in percentage units turned the classification part of the result generalized. The splits of the interval from 'A+' to 'C' can be moved around and lead to differences in the handling of the used BPs, that is just a proposed framework in a field where guidance and guidelines are close to non-existent. So even if the result shows a clear roadmap including numerical limits and boxes that require values within a given range, the idea is still to show a comprehensive method of how to standardize the inspection and evaluation. For instance, it could be seen that there is a relationship between

SoH decline and IR growth, but it is complex to quantify the process. The grading intervals, previously presented in 5.7, showed a correlation between each of the four parameters. Stating that "130% IR growth could be the case at a SoH value of 85%", can be reasonable in the long run but it is not possible to generalize it to say that it depends linearly e.g. 10% increase in IR growth is equal to 5% SOH decrease. This is because it happens non-linearly for both of the evaluation parameters (Personal communication, May 2, 2024). Regulations that will be valid in the coming five years will be changing the scene, which is also being prepared for in our model, see Section 5.1.3. These future introductions are shown using dashed arrows in the IDEF0.

### 6.3 Future Research Possibilities

The field of reutilizing used batteries and the exploration of circular strategies will require a much more extensive period of investigation. For instance, significant advancements in evaluating used batteries, such as SOR, EIS and RUL algorithms are being established. However, it's recommended to execute additional studies to examine the impact on diagnostics in general. Quickly and accurately obtaining the capacity and internal resistance of used BPs is the key to large-scale sorting. Currently, there is no good solution to this [10]. More research on this topic is necessary before the relationship between the performance parameters and the state of health can be better understood/clarified. For instance, it is complex to predict RUL even though a lot of BMS data is available. If a robust algorithm could accurately estimate first-life data, second-life applications like BESS could benefit. The increased knowledge would most likely improve the proposed method even further and decrease the throughput time. It's also interesting to see how RMs in the industry adapt to Battery passports and the vast amount of data available. By then might stakeholders also have time to implement ML algorithms in repurposing and other circular economy strategies, which several interviews and literature findings proposed as huge potential. For example using it to enable pattern recognition, forecast aging, and simulate first-life and second-life scenarios. Thus optimize the way to prolong the lifetime and energy throughput of a BP.

As a way of streamlining the process even further the proposed method includes batch testing in early stages. Due to the large variety in the inflow of batteries, inaccuracies in SOH, low traceability, etc could these methodologies not be implemented in their current state. However is it interesting to elaborate with better traceability to enable the grouping of batteries in the early stages. If BP with verified similar backgrounds e.g. operating conditions and age, ambient climate, application, etc, could be sorted together might it not be necessary to test them all for lower performance requirements like BESS. Therefore this can enable upscaling and better economics at repurposing activities.

It's also interesting to elaborate further in future research on what the most efficient way to prolong battery life is: Keep the batteries at pack level or dismantle them to cells. The interviews and literature were rather fragmented regarding whether

dismantling was too complex and resource-insensitive or on the contrary, a necessary part of the process. It can therefore be discussed that a design for dismantling could be a potential in the future, enabling more stakeholders to implement circular economy activities. For instance to set requirements on suppliers to enable a quick and easy change of modules, without the need of dismantling the whole pack.



# 7

## Conclusion

The field of batteries and the exploration of circular economy strategies will require a much more extensive period of investigation. However, this master's thesis on inspection and evaluation methods for repurposing used batteries represents a significant contribution to the field of sustainable energy solutions and circular economy practices. By addressing the four most influential challenges and opportunities in repurposing batteries from electric vehicles for BESS applications, the study offers a structured and standardized approach to ensure safe and effective utilization of second life batteries.

Through a thorough analysis of industry practices, performance requirements for BESS applications, and existing evaluation methods, the thesis proposes a grading scheme and evaluation process that leverages knowledge from the batteries' first life. The findings underscore the importance of having safety procedures, first screening, adherence to regulatory standards, and the implementation of efficient evaluation procedures to streamline the repurposing process.

The practical insights and recommendations provided in this thesis serve as a roadmap for industry practitioners, policymakers, and researchers seeking to enhance current practices in battery repurposing and promote sustainability in the energy sector. By bridging the gap between theory and application, the research contributes to advancing the circular economy for batteries and accelerating the transition toward a more electrified and resource-efficient future.

Overall, the insights and recommendations presented in this thesis lay the foundation for future research and innovation in the field of battery repurposing, offering a holistic and systematic approach to address the increasing demand for energy storage solutions. The findings of this research have the potential to be generalized and adapted to various application areas. A proposed evaluation method can be conducted including performance requirements for batteries to function longer and be resource efficient in a second-life application as BTM BESS.



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# A

## Interview Protocol

### **A.1 Challenges and current practices today:**

- What are the current practices of battery evaluation and testing methods today?
- What are the main barriers to repurposing used batteries today?
- How to optimize the testing procedure, are all batteries going through the same evaluation or are there different diagnostic packages?
  - Are batch testing being made or evaluated as a method for the future?
- Which battery types is your solution suitable for? How flexible is the solution?

### **A.2 Preconditioning, first screening:**

- How can first-life vehicle data be used in the diagnostic phase? What methods are relevant to use?
- How should the first screening be designed to consider the unique history of the battery?

### **A.3 State of health assessment and evaluation:**

- What are the most crucial parameters in determining health and further screening?
- How can the battery pack's performance be safely evaluated to function in a BESS?
- In diagnostics, what are the challenges and key enablers for the process to reach its full potential?

### **A.4 Grading Scheme and BESS Applications:**

- How can the compatibility of the end product to various types of BESS application be verified?
- What are the needs of the market? What BESS application has the greatest potential in the future?

### **A.5 Requirements, standards and regulations:**

- Which regulations and standards are primarily influential in the battery evaluation process today? Do you see any large changes in this field in the near future?
- What performance requirements of the battery are most crucial to ensure repurposing in second life?

# B

## Interview 1

The interview was conducted on the 1st of February 2024, online, with a representative from Company 1. The interviewee is engaged in sophisticated testing and monitoring solutions for second-life batteries. The company in focus specializes in the electromobility sector, dedicating its efforts to requalifying used electric vehicle batteries for BESS applications. Its business model emphasizes the focus of circularity. The company is recognized as a comprehensive service provider, offering testing and diagnosis of batteries alongside putting new products to the market.

### B.1 Challenges and Current Practices Today

The conversation began with exploring the inherent challenges in managing EV batteries, particularly focusing on dismantling, safety and performance metrics. The risks associated with overcharging and overheating were compared to nail penetration hazards, underlining the importance of identifying and mitigating potential safety issues. "Understanding the chemistry used in EV batteries and assessing safety margins are critical steps in evaluating the feasibility of repurposing these batteries", the interviewee noted, highlighting the need for comprehensive diagnostics to detect circuit failures and high self-discharge rates. It's of high importance to identify bad performing modules, often referred to as the weak links since they influence the performance of the whole battery pack.

From a system-level viewpoint, the logistics are described as complex due to the simultaneous inflow of various types of batteries. Additionally, the interviewer highlighted the challenge of dealing with insufficient data provided by suppliers, which complicates the prognosis of the Remaining Useful Life (RUL) for batteries. Current evaluation practice today involves analysis of operation history, the dismantling of the pack and mechanical, electrochemical, and safety evaluation. Lastly, the packs are grouped and matched for second life applications in the BESS.

### B.2 Preconditioning, First Screening

The preconditioning and first screening processes were identified as crucial initial steps in preparing batteries for a second life. "This preliminary assessment involves checking for immediate safety risks and ensuring the batteries meet minimum performance criteria. It's a vital phase for identifying batteries that are suitable for

further evaluation and repurposing", the interviewee explained. The remaining capacity is the most important criteria, holding a lower bar of 65-70%. For power demanding use-cases the internal resistance is of higher importance.

This approach sets the stage for a more detailed examination of the batteries' state of health, facilitating the selection process for repurposing. Grouping is made to optimize the lifetime and performance of the end application. Digital twin was mentioned as an idea to create forecasts of degradation in second life applications based on parameters from testing and initial screening data.

### **B.3 State of Health Assessment and Evaluation**

Delving deeper into diagnostics, the conversation highlighted the methodologies for assessing a battery's state of health. "Employing a range of tests, from direct measurements to advanced techniques, allows us to gain insights into a battery's remaining capacity and internal resistance. This information is pivotal for determining a battery's suitability for second-life applications," stated the speaker.

The speaker elaborated on the direct measurement techniques utilized, including Open Circuit Voltage (OCV), Capacity test for State of Health (SoH), and Pulse test for internal resistance (SoHC and SoHR). Further, the dialogue ventured into aging assessment techniques such as Electrical Impedance Spectroscopy (EIS), which, despite taking only about a minute per module, requires careful attention to temperature sensitivity and is not developed in maturity to be done on pack level. Differential Voltage Analysis (ICA/DVA) was also discussed as a more sophisticated, although costly, method for analyzing battery behavior. This analysis is crucial for employing machine learning algorithms to discern patterns and correlations with the Remaining Useful Life (RUL) of the battery. Balancing is crucial, particularly because second-life batteries may be exposed to a broader range of cell degradation characteristics compared to their first life ones.

Imaging techniques form another critical component of the diagnostic toolkit. Visual checks using cameras and sensors, potentially augmented by machine learning to build a 3D model of the battery, help identify physical defects. Thermal imaging is employed to locate hotspots indicative of potential failures. The use of X-ray Computed Tomography (XCT) to peer inside the cell and assess mechanical characteristics was mentioned, though its practicality at the module level and high cost were noted as significant drawbacks.

### **B.4 Grading Scheme and BESS Applications**

At last, the dialogue covered the grading scheme for evaluating batteries and their potential applications within Battery Energy Storage Systems (BESS). Batteries are graded based on their health and performance metrics, which helps in determining their suitability for various BESS applications. This grading process is crucial in optimizing the utility and economic value of repurposed batteries, according to the representative. For instance, the company has set requirements for maximal internal

resistance and minimal capacity in order for the battery pack to be used in BESS applications. The importance of adapting to a specific use case, understanding that all batteries and customer demands are different, is seen as crucial for successful operations.

The interviewee mentioned the BESS applications of peak shaving, energy trading and UPS as use cases, whereas the first two have high potential but the energy trading involves risks due to fluctuations. Self-consumption optimization was seen as less profitable and an application for enthusiasts, with a probable breakeven return of investment.

## **B.5 Requirements, Standards, and Regulations**

As the discussion progressed, the focus shifted to the regulatory landscape and the standards guiding battery repurposing. "Complying to established safety standards and performance benchmarks is crucial, ensuring that batteries repurposed for second-life applications meet the requisite criteria for safety and efficiency," the speaker elaborated. This segment underscored the importance of regulatory compliance and the role of best practices in navigating the complexities of battery repurposing. By 2024 the suppliers will be required to include an estimated value of the internal resistance in the BMS, compared to today's state of health estimation, presented by upcoming EU regulation. The upcoming regulation regarding battery passport by 2027 was discussed as a future enabler to save time in the diagnostics phase and to provide a better understanding of the unique battery history.



# C

## Interview 2

The interview was conducted in person on the 8th of February 2024, with a representative from Company 2. The interviewee is engaged in developing a remanufacturing and refurbishment unit handling used batteries at an industry scale. Thus, the evaluation method is under development. Still, the business model of Company 2 is designed to add value to incoming batteries, enabling them to be sold under the premise of being "as good as new". This initiative is part of the company's broader circular economy efforts aimed at extending the lifecycle of used EV batteries.

### C.1 Challenges and Current Practices Today

"The biggest hurdle we face today lies in navigating the relatively unexplored territory of battery data," the interviewee stated. They emphasized that most efforts currently center on new battery production, with a notable gap in practices for remanufacturing. A significant challenge mentioned was the limited data from service centers and battery suppliers, which complicates the evaluation process. The interviewee also highlighted a unique challenge: even when test results show a battery's State of Health (SoH) differs from the Battery Management System (BMS) estimates, the BMS value remains unchangeable, posing a dilemma for accurately representing battery condition.

Today's production process begins with cleaning battery packs, followed by electrical diagnostics and data transfer of BMS data. The first screening aims to solve error codes and investigate further why the battery pack disfunctioned in the first life, which today is not a standardized operation. The packs are then disassembled for module inspection and repair, followed by physical performance tests. After reassembly, a final end-of-line functionality test ensures the packs meet the desired standards.

### C.2 Preconditioning, First Screening

Discussing the initial diagnostic phase, the interviewee explained, "First-life vehicle data, such as error codes and SoH, must be taken into consideration." However, the necessity of visual and electrical inspections remains crucial to ensure each battery's safety and functionality before further testing.

The electrical inspection and first screening process is executed as follows: A voltmeter (multimeter) is used to ensure zero voltage between the + and - terminals in standby mode, and between each terminal and the top cap, confirming safe handling. The CAN/LIN setup standardized data transfer from the BMS to software, to analyze parameters as SOH. SOC, relay counter, balancing, etc. A 24V input activates batteries, using versatile yet costly equipment suitable for all battery types handled in Company 2. Each battery needs to be individually inspected to maintain safety and quality reputation of Company 2. Performance metrics are documented in the cloud, focusing on visualization, analysis, and troubleshooting error codes to enable the battery mode. Unresolved issues are escalated.

### C.3 State of Health Assessment and Evaluation

The interviewee addresses that the health assessment and evaluation will take time to optimize, due to the low knowledge in this new field. It will be important to build up a knowledge base, for instance on how to find the root cause of each fault code. Thus, the large variety in the inflow of batteries will require the evaluation to take time.

They also highlighted the critical role of safety equipment and comprehensive operator training in evaluating a battery pack's performance safely and effectively. The state of health will at the beginning of this project focus a lot on SOH data from the BMS, together with complementary tests like Pulse power to determine SOR and mechanical tests. It's important that this diagnosis uses fast-paced methods in order to reach the target of 1500 handled batteries per year and create a streamlined plant. Standardization will be important once the final layout of the production site is in place.

### C.4 Grading Scheme and BESS Applications

On grading batteries for BESS applications, the interviewee noted, "The battery packs that need little or almost no handling should be considered for remanufacturing/ refurbishment while lower-performing BP should be considered for repurposing based on the SOH." They also discussed the grading process based on performance metrics and the stringent validation required for refurbished or remanufactured batteries. The evolving BESS market needs and the crucial role of end-of-line testing in validating battery packs before repurposing was also highlighted. However will the remanufacturing unit handle as many packs they can get in the beginning, and can thereby either send them out directly to the market or into BESS applications. Where the battery packs will end up depends on various factors, such as market demand and the final grading results.

## C.5 Requirements, Standards, and Regulations

"The stringent safety standards and regulatory compliance are non-negotiable in our process," remarked the interviewee. They detailed how the department ensures all activities align with these rigorous requirements. Essential performance criterias for repurposing were mentioned to involve SOH, SOR, and relay counter metrics. These factors are pivotal in determining whether a battery is suitable for a second life. Furthermore, Company 2 must follow rigorous safety standards and regulations due to the potential hazard of working inside an opened battery pack, which includes clean areas and safety equipment for operators. The construction and design department also marked processes as either Critical Characteristics (C.C.) or special Characteristics (S.C.) which had to be taken into consideration at each stage.



# D

## Interview 3

The interview, conducted online on the 21st of February 2024, featured two representatives from Company 3, the CEO & Co-Founder as well as the Head of Battery Intelligence. The company specializes in the diagnostics and characterization of battery modules within the energy sector. Company 3 innovates through its custom software testing solutions which are developed in-house, offers testing-as-a-service, and deploys Battery Energy Storage Systems (BESS) to the market. This venture is a key component of the company's commitment to the circular economy, focusing on enhancing the lifespan of electric vehicle (EV) battery modules by putting emphasis on reuse, repurposing, and recycling, thereby supporting sustainable energy solutions.

### D.1 Challenges and Current Practices Today

Representative 1 emphasized the complexity of accurately assessing batteries' health for second-life applications. He highlighted the absence of standardized practices that complicate the repurposing process, underlining the necessity for innovative diagnostic techniques and reliable data. 1. To improve the efficiency and accuracy of SoH, OEMs should make as much data as possible available to repurposed and testers. Representative 2 added that there are technical difficulties in extracting meaningful data from the BMS system, pointing out the variance in data quality and its impact on the assessment process.

Company 3 has an interesting approach to handling incoming batteries, conducting assessments before purchasing the battery modules. If first life data can be retrieved initially, there is no need for the time-consuming dismantling of the battery pack. 2. If first-life data is not made available at a sufficient granularity, Company 3 has developed a novel approach to test battery modules in 5 minutes using Electrochemical Impedance Spectroscopy (EIS). They use the in-house developed hardware and algorithms to characterize each battery module in less than 5 minutes. The company relies on the technology of EIS for their operations and they have ongoing collaborations with entities in the field of research as well as the technology sector. A part of their business is called "Testing-as-a-service", a way of testing on demand at the facility that bought their service. The company performs development of their testing and battery characterization applications in the lab. After the repurposing but before putting a BESS to the market they perform a functional safety test, which takes less than 30 minutes. It was said to surely be less than 30 minutes with a possible

speed up down to a few minutes if needed. So far this was not seen as a bottleneck in their system so it was not in focus to develop or streamline or efficient it at the time.

## **D.2 Preconditioning, First Screening**

The first step in the process is to perform some data assessment. There is a challenge in sharing data, as companies usually have a lot of data and you don't want to be overwhelmed with tons of data and the company doesn't want to give you all the details either unless it is financially purposeful for them. Thus, they are trying to limit the requested amount of data to what is strictly needed to make their assessment. Company 3 only let the "good enough" batteries through the first screening. Representative 1 said: "In simplified terms, we want battery modules with a remaining capacity of 80 percent, that would be good".

In order to end up with an efficient and reasonable value chain in the long-term perspective of battery handling after first life usage, they proposed that the first testing should be done at the supplier's location through the use of first life data analysis. That would enable it to send and assign the battery module or pack directly to the right business area for repurposing, reuse, and recycling. This approach is seen as more sustainable instead of every business area having an incoming flow of batteries of all kinds that need to be assessed one by one and re-directed if it's not a fit for the respective scenario.

## **D.3 State of Health Assessment and Evaluation**

Representative 1 outlined that the use of advanced diagnostic tools, such as EIS, is needed to provide a comprehensive view of a battery's health. Representative 2 added that EIS and other techniques have been applied in their research to identify specific degradation patterns, enhancing the accuracy of their health assessments.

In order to get an understanding of first-life vehicle usage, the idea and shortcut were explained in terms of registering a few snapshots of recent data rather than collecting data from the whole first life. Just looking at a few snapshots from weeks back in time could tell a lot about the battery's conditions and first life use.

The two most important parameters for battery characterization are State of Health and Internal Resistance, but these are conducted via testing and not taken from the BMS estimations as those estimations were seen as unreliable. From the BMS the only data that Company 3 utilized and registered were the available voltages, currents and temperatures on cell level.

## D.4 Grading Scheme and BESS Applications

Representative 1 argued that a grading scheme that categorizes batteries based on their suitability for various Battery Energy Storage System (BESS) applications would be appropriate to avoid the risks of weak links and low utilization of second life batteries. Although, it is seen as a challenge and close to impossible to put a numerical limit of how to grade a battery for a specific BESS application. There is more to it than just using a percentage number and finding the second life purpose that fits. It's important to understand the usage profile for second life, how many strings the application will need and how many modules will be connected in series. The aspects of heating and cooling systems were also mentioned as needing to be taken into account. These aspects influence a lot and both representatives emphasized the system-level approach to understand the full picture.

At the moment Company 3 does not classify the modules with A, B, or C. That is explained as what might be the case in the future with larger amounts of input or differentiating inputs. At the moment they rather put "good enough" battery modules in the same strings to reach homogeneity in performance and avoid weak links. They utilize similar battery modules in the same applications, but as long as fulfilling their prerequisites of being "good enough" that was not seen as a problem.

## D.5 Requirements, Standards, and Regulations

Representative 1 discussed upcoming regulations, including the battery passport initiative, stressing the importance of compliance and how it will drive the need for more transparent and standardized evaluation methods. Representative 2 explained the role of safety standards in the evaluation process, emphasizing the need for methodologies that not only assess performance but also ensure the batteries meet strict safety criteria.

Company 3 is regulated by the 2023 Battery regulation, which requires battery suppliers to make more data available in the BMS, e.g. a State of Resistance (SoR) estimation. The regulations are not seen as difficult to comply with as they have developed their way of working to fit with regulations since the start. One of the things they need to do is to show that they have done a health assessment of each battery with proof of that. The characterization of each module brings metrics and a recommendation of further usage to the client who wants their battery modules to be tested. This is given with a confidence level that is not 100 percent but within a reasonable range. Company 3 takes on the liability of battery modules it purchases to put into their own BESS product, but does not assume liability for battery modules tested but not purchased by themselves.



# E

## Interview 4

The interview, conducted online on the 21st of February 2024, featured two representatives from Company 4, the business development analyst & the battery testing engineer. The company specializes in SoH diagnostics to maximize the value of batteries within the energy sector. Company 4 uses its in-house developed software and hardware solutions for batteries on the cell, module and pack level. Thus they are recognized as a comprehensive service provider, offering testing and diagnosis of batteries with innovative new technology to grade batteries in a user-friendly, fast, and accurate way.

### E.1 Challenges and Current Practices Today

The current practice at Company 4 is explained as a fast, accurate and easy way to diagnose a battery's State of Health. They provide their in-house developed software and hardware solutions, "with the hardware we can test on pack level as well, with our new prototype", said representative 2.

It's done by connecting the hardware to the battery, and then running the test via their cloud software platform. Representative 1 mentioned that the interface is user-friendly, it comprehensively visualizes data insights that are easy to read and understand. The software platform is explained as "very easy to use", and the tests are run in the following three steps. Select the battery type, the device, and the type of model. The tests are based on Electrochemical Impedance Spectroscopy (EIS). It takes 5-10 minutes to test a battery module and currently, there is an ongoing development in running EIS tests on pack level. For the current prototype the tests are carried out on packs of 400V, but planning to work on 800V packs when commercialized. One advantage of their current method is that there is no relying on historical battery information. The solution can be used for any battery type, as long as there is a machine learning model built first. Then you can run the tests and estimate SoH. It's the same testing method for every battery, mostly focused on the Lithium-ion types, as that is where the most value lies.

### E.2 Preconditioning, First Screening

Before putting batteries to tests with their hardware and software a safety evaluation and first screening are performed. Company 4 has experience of denying batteries due to mechanical or liquid damages, as well as cracked or burnt terminals. All of

that is screened before putting it up for testing, which eliminates a "chunk" of batteries. The screening process has steps to follow but is still very manual, it consists of checking some safety requirements boxes. Once the physical inspection is done, there is a voltage check to investigate whether the battery is undercharged, and if too undercharged it's not a good sign as the materials of the battery will degrade.

Understanding the history of each battery is difficult as there is not much available data. To make use of the historical use, the operator has to read the BMS data, which sometimes need to be reverse engineered. This method neither is standardized nor easy, which explains why Company 4 doesn't always rely on historical information. It is sometimes needed to communicate with the BMS to close a battery's contactors to get access to the battery terminals.

### **E.3 State of Health Assessment and Evaluation**

The important battery performance parameters are internal resistance and capacity. Company 4 uses ML to cluster the modules and group them based on their capacity values. Internally they have a project to install some used batteries in an energy storage system. Normally the company uses 30-50 battery samples to train the ML models, sampling and EIS, building a ML model to estimate the SoH only. The grade is created once the SoH percentage is known.

Representative 2 mentioned that there is some interesting information in the BMS, for example, the SoH estimation. But in fact that it's inaccurate with an approximate 10 percent fault in precision, makes it unreliable. What the BMS does best is said to be the State of Charge (SOC) estimation.

### **E.4 Grading Scheme and BESS Applications**

A case by case approach is used to grade the batteries, as each battery is seen to be unique due to the degradation complexities. For the renewance application of Company 4 there is a lower limit of 70 percent for the SoH value. Batteries that are showing results of lower values were rejected and sent to recycling instead of being repurposed. A majority of the batteries are showing results closer to 80 percent and the grades of the grading scheme could be customized by the customer. The vision is to put repurposed batteries on the market that are available to run in a second life application for 10 years. It is argued that a battery failure is more at risk with a SoH value below 70 percent.

### **E.5 Requirements, Standards, and Regulations**

Company 4 is regulated by the American safety standard known as UL 1974. They have worked to speed up the test time stated in the UL1974. In a case study Company 4 was benchmarking its solution against the UL1974 6-hour cycling test, making sure its solution fulfilled the requirements. Two representatives from the

company are part of the UL 1974 committee and are working towards making their own testing process certified as an equivalent.



# F

## Internal documents

**Table F.1:** List of Internal Documents

| <b>Document Name</b> | <b>Document Type</b> | <b>Subject Area</b>                        | <b>Date</b> |
|----------------------|----------------------|--|-------------|
| Internal Document 1  | Presentation         | Battery Characteristics                    | Sep 2018    |
| Internal Document 2  | Presentation         | Business and Market                        | Sep 2019    |
| Internal Document 3  | Presentation         | Energy Storage Intro                       | Dec 2019    |
| Internal Document 4  | Presentation         | Energy Storage and Battery Characteristics | Sep 2018    |
| Internal Document 5  | Presentation         | Energy Storage                             | March 2021  |
| Internal Document 6  | Presentation         | Battery cells                              | Mar 2021    |
| Internal Document 7  | Presentation         | Cubic Battery Overview                     | Mar 2022    |
| Internal Document 8  | Excel Sheet          | Battery Performance                        | May 2022    |

Continued on next page

Table F.1 – Continued from previous page

| <b>Document Name</b> | <b>Document Type</b> | <b>Subject Area</b>                  | <b>Date</b> |
|----------------------|----------------------|--------------------------------------|-------------|
| Internal Document 9  | Presentation         | Flat Batteries Spec                  | May 2022    |
| Internal Document 10 | Presentation         | Regulation                           | Jun 2022    |
| Internal Document 11 | Excel sheet          | Technical Spec Batteries             | Jun 2022    |
| Internal Document 12 | Excel Sheet          | Battery State of Health Parameters   | Oct 2022    |
| Internal Document 13 | Manual               | Battery Technical Spec               | Nov 2022    |
| Internal Document 14 | Presentation         | Cubic Battery Spec                   | Nov 2022    |
| Internal Document 15 | Technical document   | Cubic Battery Spec                   | Sep 2023    |
| Internal Document 16 | Presentation         | Regulations                          | Oct 2023    |
| Internal Document 17 | Presentation         | Regulations                          | Oct 2023    |
| Internal Document 18 | Presentation         | Regulations and Markets Developments | Dec 2022    |
| Internal Document 19 | Manual               | Safety                               | Oct 2023    |
| Internal Document 20 | Presentation         | Battery State of Health              | Jan 2024    |

Continued on next page

Table F.1 – Continued from previous page

| <b>Document Name</b> | <b>Document Type</b> | <b>Subject Area</b>                  | <b>Date</b> |
|----------------------|----------------------|--------------------------------------|-------------|
| Internal Document 21 | Presentation         | Flat Batteries Overview              | Jan 2024    |
| Internal Document 22 | Presentation         | Energy Storage                       | Jun 2022    |
| Internal Document 23 | Technical Report     | Flat Batteries                       | Jun 2022    |
| Internal Document 24 | Word Document        | EOL Overview                         | Sep 2022    |
| Internal Document 25 | Presentation         | EOL Tests Overview                   | Sep 2019    |
| Internal Document 26 | Presentation         | Remanufacturing                      | Feb 2024    |
| Internal Document 27 | Excel Sheet          | Battery State of Health data         | Mar 2024    |
| Internal Document 28 | Presentation         | Energy Storage System Technical Spec | Mar 2024    |
| Internal Document 29 | Presentation         | Basic Battery characteristics        | Mar 2024    |
| Internal Document 30 | Presentation         | BESS Intro                           | Mar 2024    |
| Internal Document 31 | Presentation         | BESS Use Cases                       | Jan 2024    |
| Internal Document 32 | Presentation         | BESS Market Study                    | Jun 2022    |

Continued on next page

Table F.1 – Continued from previous page

| <b>Document Name</b> | <b>Document Type</b> | <b>Subject Area</b> | <b>Date</b> |
|----------------------|----------------------|---------------------|-------------|
| Internal Document 33 | Legal dokument       | Regulations         | Jun 2023    |
| Internal Document 34 | Report               | Sustainability      | Dec 2021    |

# G

## Final Grading

### G.1 Complete list of the possible grading scenarios

|          | W_Cap | W_IR | W_Imb | Cap | IR | Imb | Grade |   | A, B, C |
|----------|-------|------|-------|-----|----|-----|-------|---|---------|
| Power    | 0.25  | 0.65 | 0.1   | 1   | 1  | 1   | 1     |   | C       |
|          | 0.25  | 0.65 | 0.1   | 1   | 1  | 2   | 1.1   |   | C       |
|          | 0.25  | 0.65 | 0.1   | 1   | 1  | 3   | 1.2   |   | C       |
|          | 0.25  | 0.65 | 0.1   | 1   | 2  | 1   | 1.65  |   | C       |
|          | 0.25  | 0.65 | 0.1   | 1   | 2  | 2   | 1.75  |   | B       |
|          | 0.25  | 0.65 | 0.1   | 1   | 2  | 3   | 1.85  |   | B       |
|          | 0.25  | 0.65 | 0.1   | 1   | 3  | 1   | 2.3   |   | B       |
|          | 0.25  | 0.65 | 0.1   | 1   | 3  | 2   | 2.4   | A |         |
|          | 0.25  | 0.65 | 0.1   | 1   | 3  | 3   | 2.5   | A |         |
|          | 0.25  | 0.65 | 0.1   | 2   | 1  | 1   | 1.25  |   | C       |
|          | 0.25  | 0.65 | 0.1   | 2   | 1  | 2   | 1.35  |   | C       |
|          | 0.25  | 0.65 | 0.1   | 2   | 1  | 3   | 1.45  |   | C       |
|          | 0.25  | 0.65 | 0.1   | 2   | 2  | 1   | 1.9   |   | B       |
|          | 0.25  | 0.65 | 0.1   | 2   | 2  | 2   | 2     |   | B       |
|          | 0.25  | 0.65 | 0.1   | 2   | 2  | 3   | 2.1   |   | B       |
|          | 0.25  | 0.65 | 0.1   | 2   | 3  | 1   | 2.55  | A |         |
|          | 0.25  | 0.65 | 0.1   | 2   | 3  | 2   | 2.65  | A |         |
|          | 0.25  | 0.65 | 0.1   | 2   | 3  | 3   | 2.75  | A |         |
|          | 0.25  | 0.65 | 0.1   | 3   | 1  | 1   | 1.5   |   | C       |
|          | 0.25  | 0.65 | 0.1   | 3   | 1  | 2   | 1.6   |   | C       |
|          | 0.25  | 0.65 | 0.1   | 3   | 1  | 3   | 1.7   |   | B       |
|          | 0.25  | 0.65 | 0.1   | 3   | 2  | 1   | 2.15  |   | B       |
|          | 0.25  | 0.65 | 0.1   | 3   | 2  | 2   | 2.25  |   | B       |
|          | 0.25  | 0.65 | 0.1   | 3   | 2  | 3   | 2.35  | A |         |
|          | 0.25  | 0.65 | 0.1   | 3   | 3  | 1   | 2.8   | A |         |
|          | 0.25  | 0.65 | 0.1   | 3   | 3  | 2   | 2.9   | A |         |
|          | 0.25  | 0.65 | 0.1   | 3   | 3  | 3   | 3     | A |         |
|          | W_Cap | W_IR | W_Imb | Cap | IR | Imb | Grade |   | A, B, C |
| Capacity | 0.65  | 0.25 | 0.1   | 1   | 1  | 1   | 1     |   | C       |
|          | 0.65  | 0.25 | 0.1   | 1   | 1  | 2   | 1.1   |   | C       |
|          | 0.65  | 0.25 | 0.1   | 1   | 1  | 3   | 1.2   |   | C       |
|          | 0.65  | 0.25 | 0.1   | 1   | 2  | 1   | 1.25  |   | C       |
|          | 0.65  | 0.25 | 0.1   | 1   | 2  | 2   | 1.35  |   | C       |
|          | 0.65  | 0.25 | 0.1   | 1   | 2  | 3   | 1.45  |   | C       |
|          | 0.65  | 0.25 | 0.1   | 1   | 3  | 1   | 1.5   |   | C       |
|          | 0.65  | 0.25 | 0.1   | 1   | 3  | 2   | 1.6   |   | C       |
|          | 0.65  | 0.25 | 0.1   | 1   | 3  | 3   | 1.7   |   | B       |
|          | 0.65  | 0.25 | 0.1   | 2   | 1  | 1   | 1.65  |   | C       |
|          | 0.65  | 0.25 | 0.1   | 2   | 1  | 2   | 1.75  |   | B       |
|          | 0.65  | 0.25 | 0.1   | 2   | 1  | 3   | 1.85  |   | B       |
|          | 0.65  | 0.25 | 0.1   | 2   | 2  | 1   | 1.9   |   | B       |
|          | 0.65  | 0.25 | 0.1   | 2   | 2  | 2   | 2     |   | B       |
|          | 0.65  | 0.25 | 0.1   | 2   | 2  | 3   | 2.1   |   | B       |
|          | 0.65  | 0.25 | 0.1   | 2   | 3  | 1   | 2.15  |   | B       |
|          | 0.65  | 0.25 | 0.1   | 2   | 3  | 2   | 2.25  |   | B       |
|          | 0.65  | 0.25 | 0.1   | 2   | 3  | 3   | 2.35  | A |         |
|          | 0.65  | 0.25 | 0.1   | 3   | 1  | 1   | 2.3   |   | B       |
|          | 0.65  | 0.25 | 0.1   | 3   | 1  | 2   | 2.4   | A |         |
|          | 0.65  | 0.25 | 0.1   | 3   | 1  | 3   | 2.5   | A |         |
|          | 0.65  | 0.25 | 0.1   | 3   | 2  | 1   | 2.55  | A |         |
|          | 0.65  | 0.25 | 0.1   | 3   | 2  | 2   | 2.65  | A |         |
|          | 0.65  | 0.25 | 0.1   | 3   | 2  | 3   | 2.75  | A |         |
|          | 0.65  | 0.25 | 0.1   | 3   | 3  | 1   | 2.8   | A |         |
|          | 0.65  | 0.25 | 0.1   | 3   | 3  | 2   | 2.9   | A |         |
|          | 0.65  | 0.25 | 0.1   | 3   | 3  | 3   | 3     | A |         |

Figure G.1: Complete Grading Sheet

## G.2 Grading Case

| Inputs  |     | Point |   |  |
|---------|-----|-------|---|--|
| Cap [%] | 85  | 3     |   |  |
| IR [%]  | 130 |       | 2 |  |
| Imb [%] | 8   |       | 2 |  |

| Classification |          |
|----------------|----------|
| Power          | Capacity |
| B              | A        |

Figure G.2: Grading Sheet Case

# H

## IDEF0 Flow chart: Proposed Inspection and Evaluation Method

### H.1 IDEF0 Flow chart

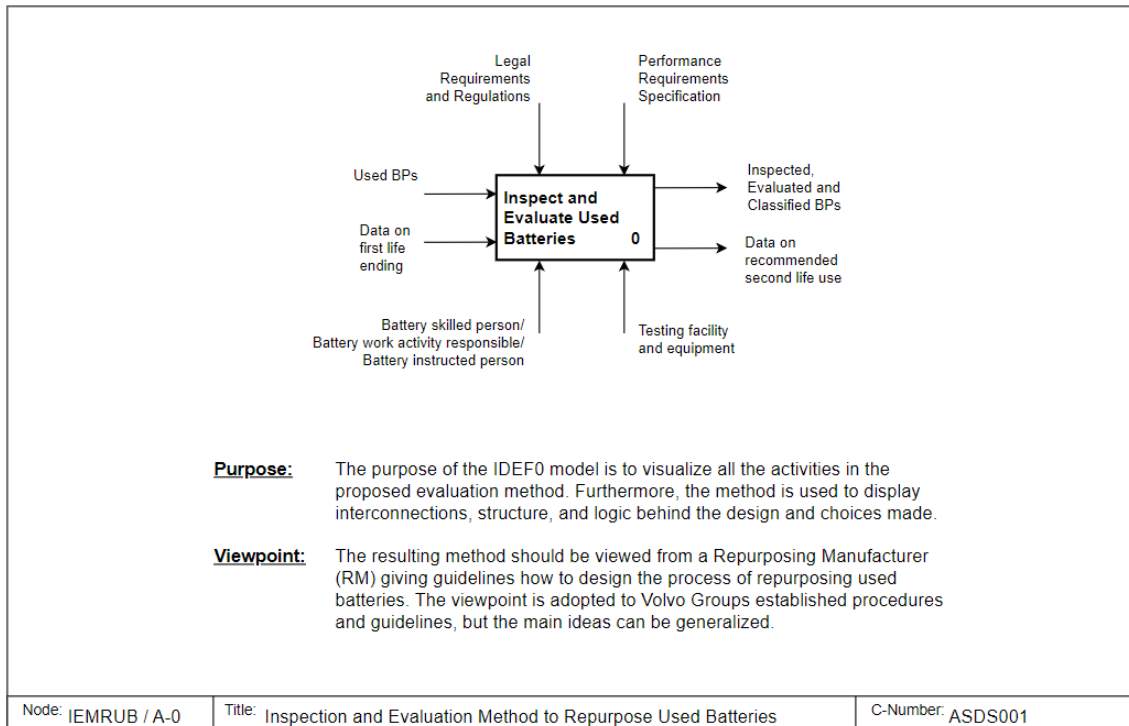
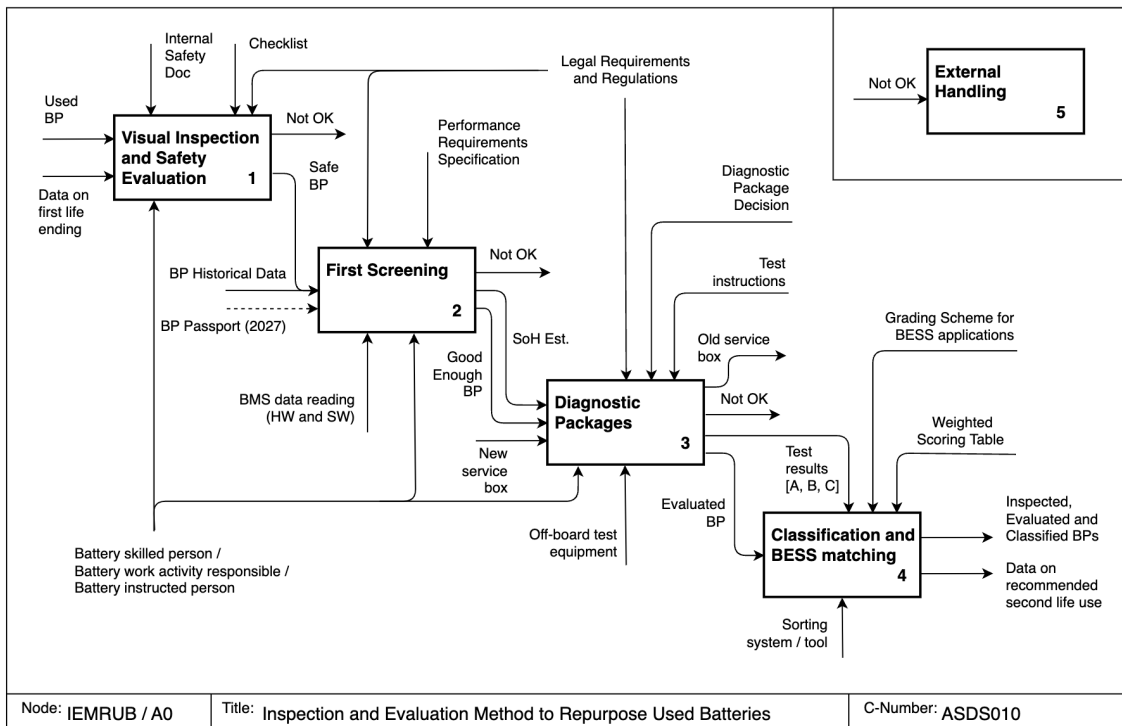
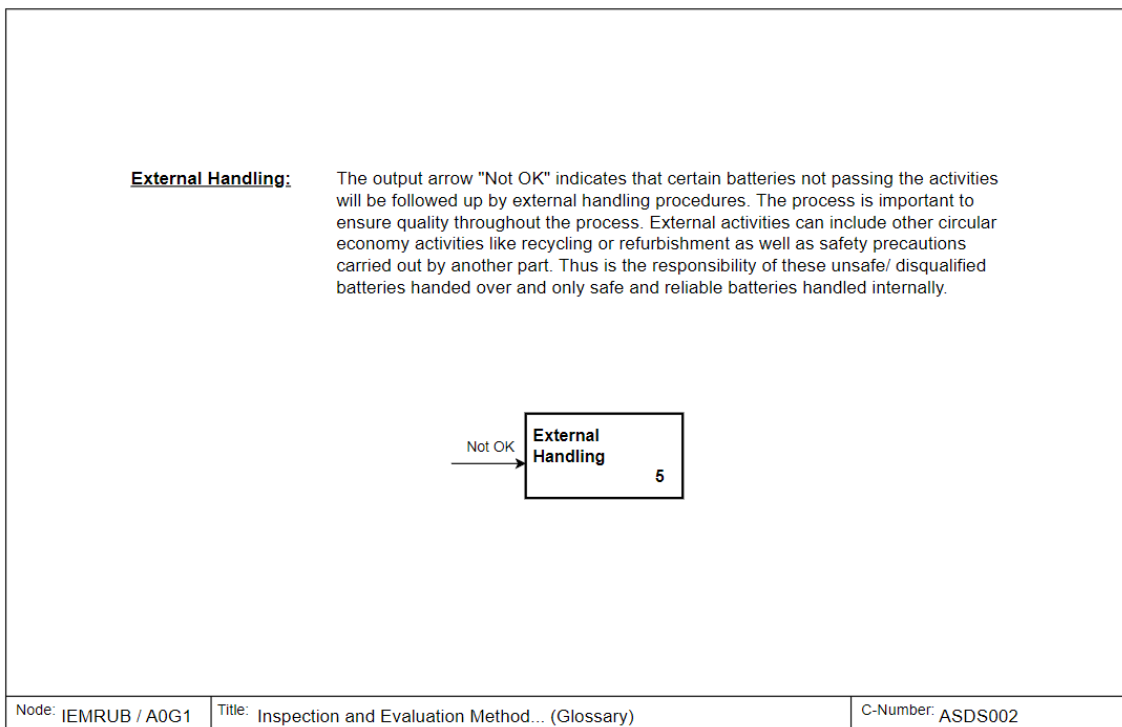


Figure H.1: Inspection and Evaluation Method to Repurpose Used Batteries

## H. IDEF0 Flow chart: Proposed Inspection and Evaluation Method

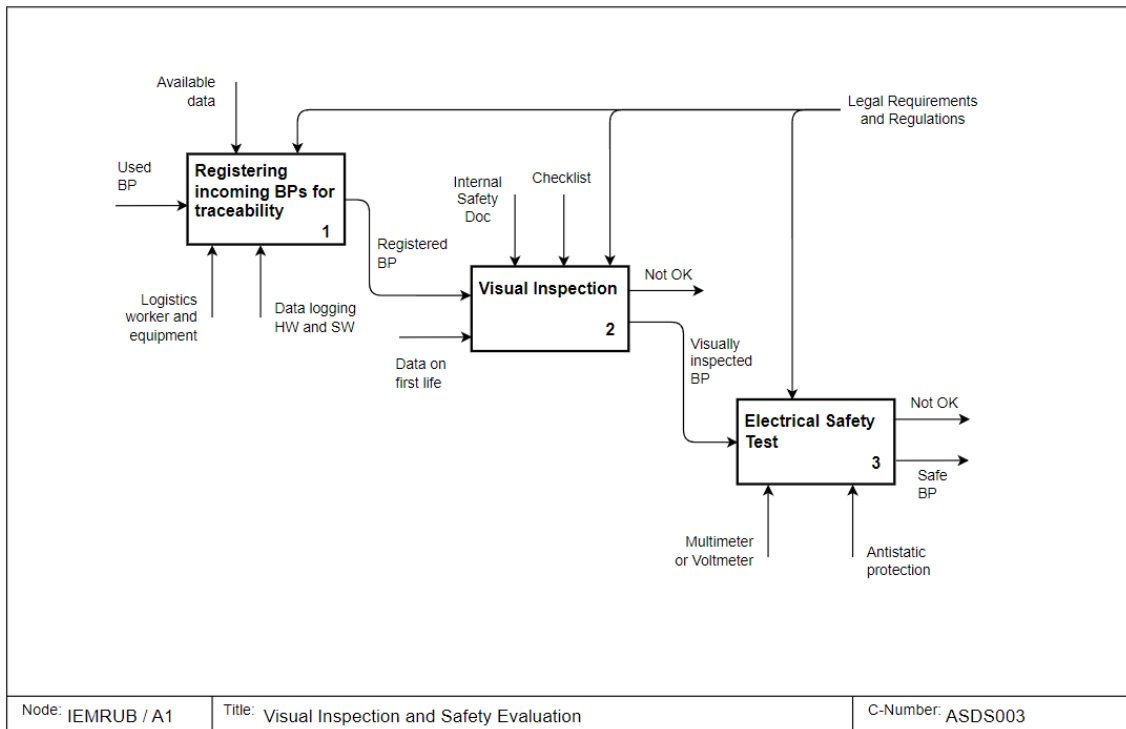


**Figure H.2:** Inspection and Evaluation Method to Repurpose Used Batteries



**Figure H.3:** Inspection and Evaluation Method... (Glossary)

## H. IDEF0 Flow chart: Proposed Inspection and Evaluation Method



**Figure H.4:** Visual Inspection and Safety Evaluation

|  |  |
|--|--|
| <b><u>Internal Safety Doc:</u></b>           | A safety document that is used internally at Volvo Group to reach an understanding of how to classify Li-Ion batteries (LIB). Classification of LIB has to follow standardized internal guidelines, e.g. by color coding batteries as green, yellow or red based on present conditions.  |
| <b><u>Checklist (Visual Inspection):</u></b> | Before any operation is carried out on a battery, the visual inspection has to be made following a checklist in the <b>Internal Safety Doc</b> including aspects of physical or mechanical damage e.g. fumes, smell, temperature, internal damage. This could be generalized to any other OEM in the industry substituting to their respective safety guidelines.                            |
| <b><u>Electrical Safety Test:</u></b>        | Conducting a voltmeter (multimeter) measurement at the outlet to verify that the voltage between the positive and negative terminals is 0 in standby mode. Additionally, measurements between the positive terminal and the top cover, as well as between the negative terminal and the top cover, are performed to ensure safe continued handling. The test takes approximately 15 seconds. |
| <b><u>Data on First Life:</u></b>            | In order to understand why the battery pack has been sent to the "Battery Return Center", data supporting the end of first life decision could be crucial for further evaluation and second life suitability.  |

|                     |   |                   |
|---------------------|---|-------------------|
| Node: IEMRUB / A1G1 | Title: Visual Inspection and Safety Evaluation (Glossary) | C-Number: ASDS004 |
|---------------------|---|-------------------|

**Figure H.5:** Visual Inspection and Safety Evaluation (Glossary)

## H. IDEF0 Flow chart: Proposed Inspection and Evaluation Method

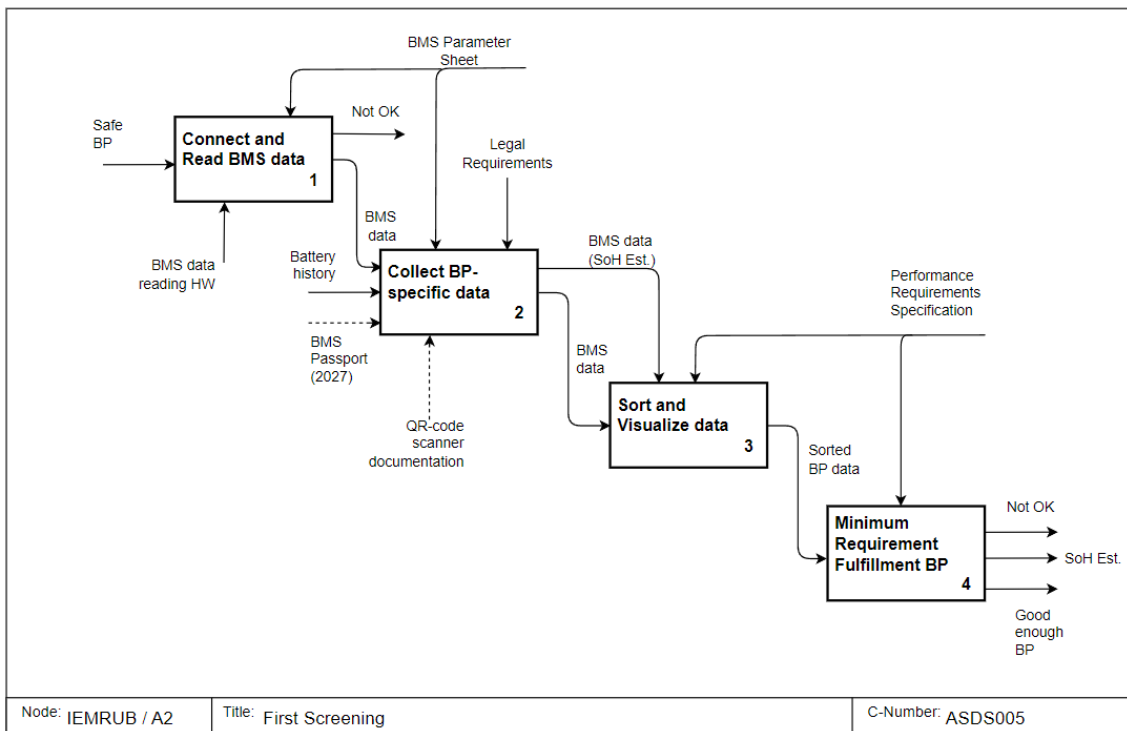


Figure H.6: First Screening

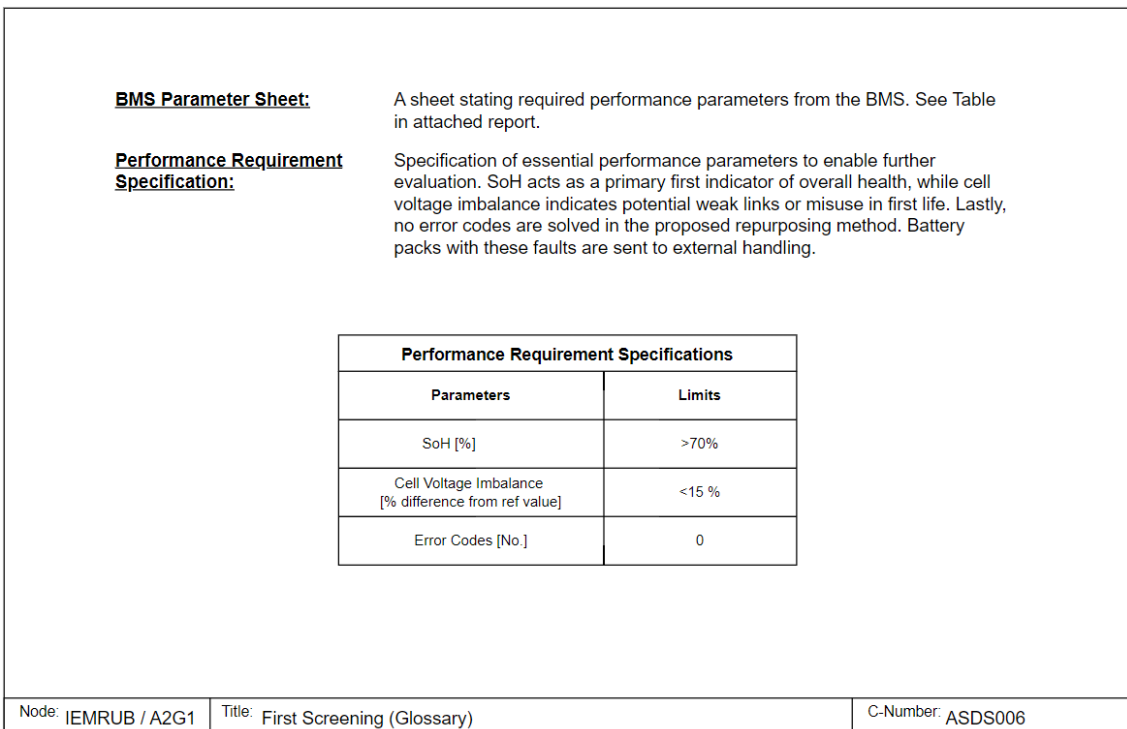


Figure H.7: First Screening (Glossary)

## H. IDEF0 Flow chart: Proposed Inspection and Evaluation Method

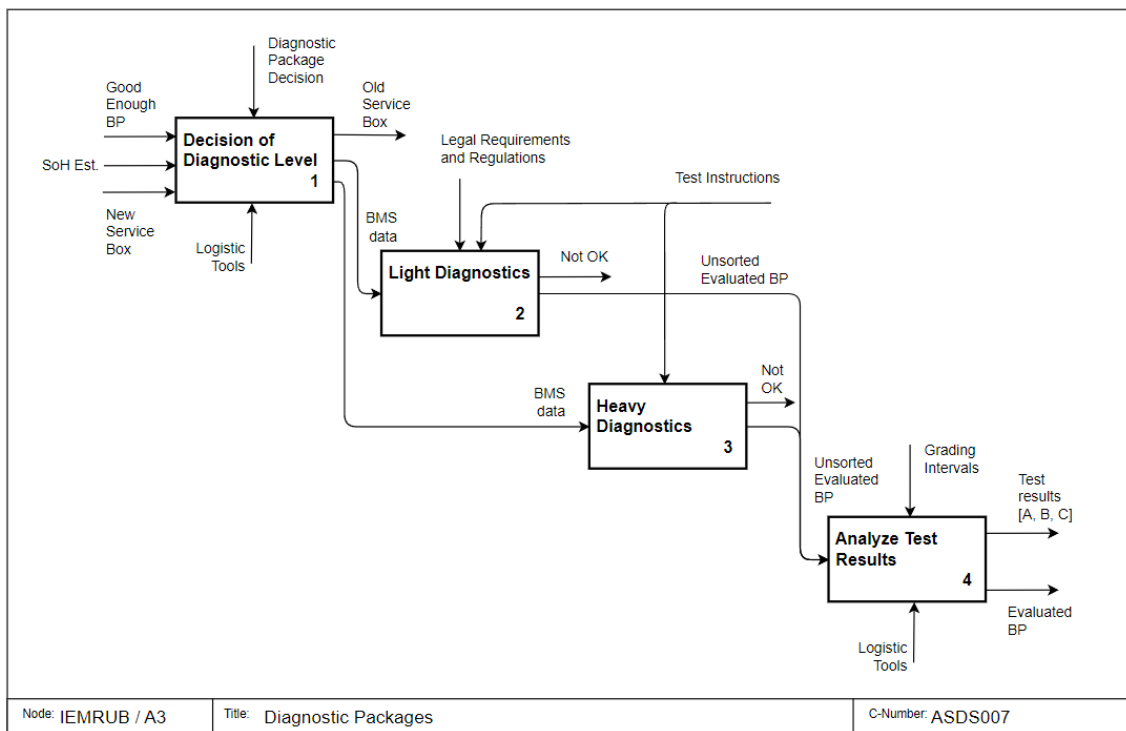


Figure H.8: Diagnostic Packages

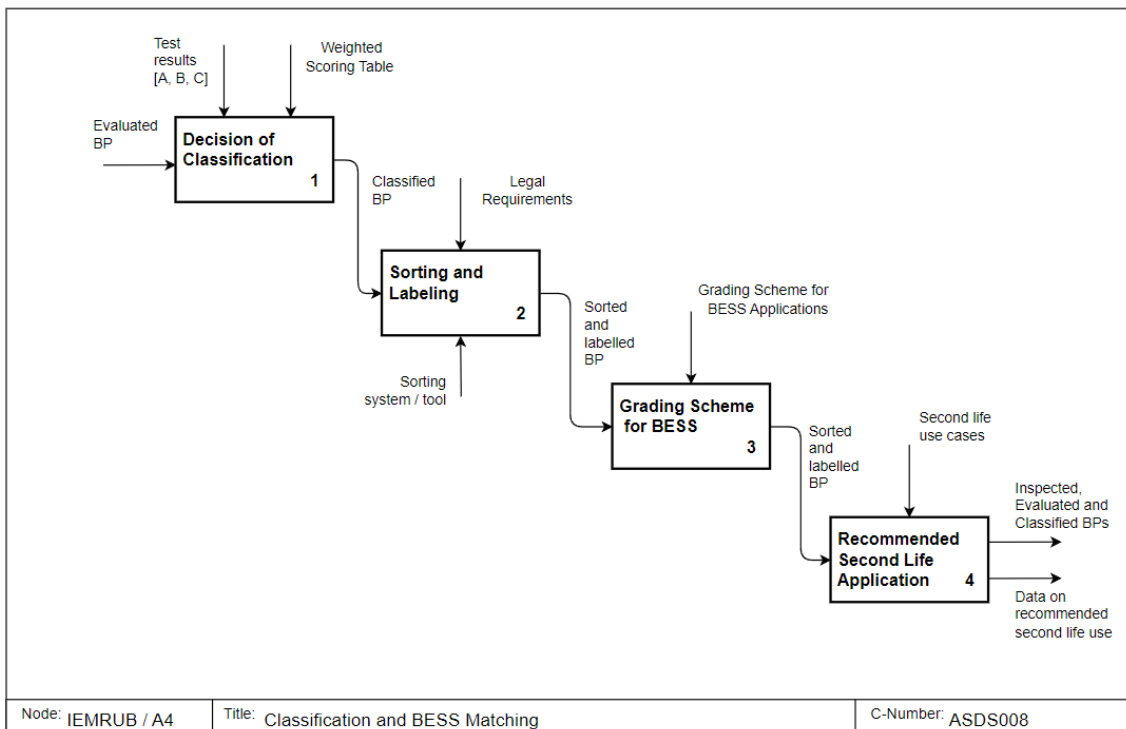


Figure H.9: Classification and BESS Matching

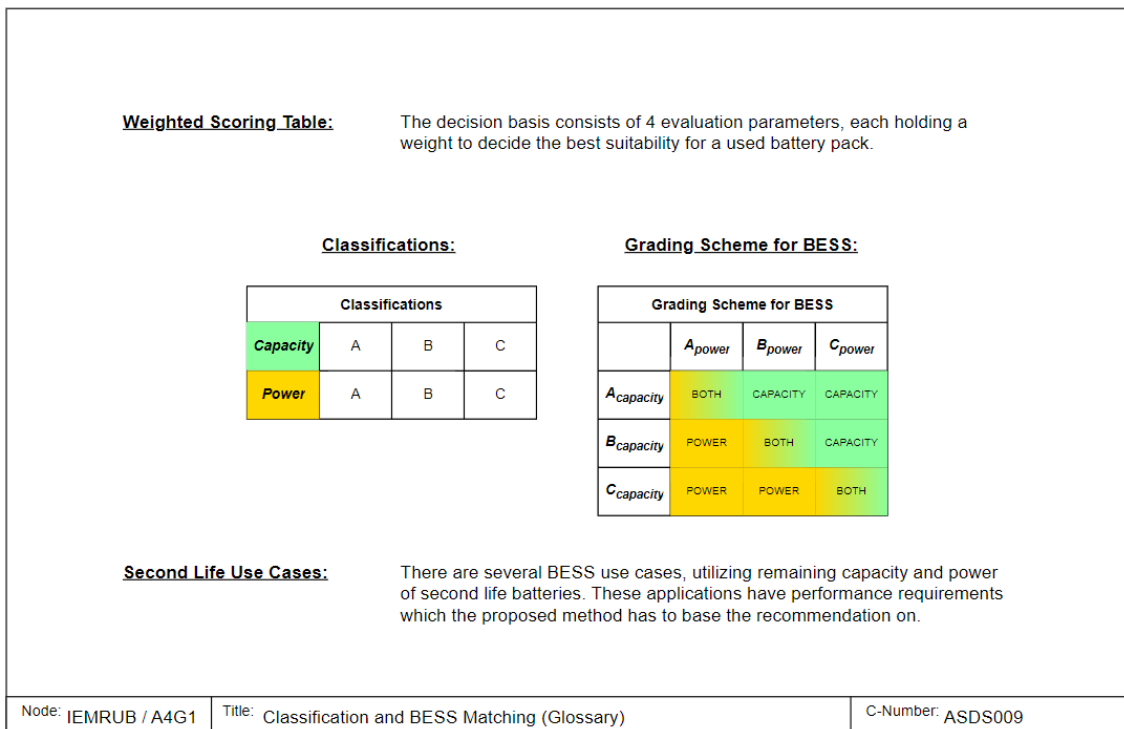


Figure H.10: Classification and BESS Matching (Glossary)

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