D6.1 Disassembly of modules for 2nd life BS

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CONTENTS

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TABLE OF FIGURES

LIST OF TABLES

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Meaning
ACIR	Alternating Current Internal Resistance
BESS	Battery Energy Storage System
BMS	Battery Management System
BOM	Bill of Materials
BS	Battery System
CC	Constant Current
CV	Constant Voltage
DCA	Differential Capacity Analysis
DCIR	Direct Current Internal Resistance
EIS	Electrochemical Impedance Spectroscopy
ESS	Energy Storage System
EV	Electric Vehicle
GPS	Global Positioning System
IEC	International Electrotechnical Commission
KPI	Key Performance Indicator
OCV	Open-Circuit Voltage
PCB	Printed Circuit Boards
PPE	Personnel Protection Equipment
PPU	Power Processing Unit
UL	Underwriters Laboratories
SD	Secure Digital
SIM	Subscriber Identity Module
SoC	State of Charge
SoH	State of Health
SoS	State of Safety
SoS	State of Safety
SoW	State of Warranty
SoX	State of Battery
XPYS	X Sets of battery sells in Parallel, Y battery cells in Series

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EXECUTIVE SUMMARY

The document is divided in two parts: 1) Selection of modules from 1st life to 2nd life and 2) Disassembly steps of the 1st Battery System (BS).

In part 1, “Selection of modules from 1st life to 2nd life”, an introduction of the phases to make a module selection for the upcoming refurbishment is made. For both Pillars, the modules have been selected from the portfolios of SLG and MIBA, for the refurbishment to 2nd life and the design from 1st to 2nd life, respectively.

In part 2, “Disassembly steps of the 1st life Battery System”, the series of the disassembly steps of the 1st life BS is introduced, both for battery pack and module levels. Focus was given on the tests on mechanical, electrical and electrochemical aspects. Objective for Pillar 1 is to prepare a module for reassembly with the new BMS, thus the disassembly steps on both battery pack and module levels are described. Objective for Pillar 2 is to prepare a module, with BMS remaining the same from 1st life, so the disassembly steps described are referred on the battery pack level only.

The challenges and the risks for both parts are showcased also in this document, and they reflect on concerns regarding time consumption, increase on operational costs, personnel safety and the future upscale on mass production.

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1 INTRODUCTION

1.1 Project Introduction

BATTERY2LIFE is a project, funded by Horizon Europe program that will facilitate the smooth transition of batteries to 2nd life use and boost the innovation of the European Battery Industry by providing enablers to implement open adaptable smart Battery Management Systems (BMS) and improved system designs and proposing methods for the efficient and reliable reconfiguration of used batteries.

Battery2Life introduces two new battery system design frameworks serving the upcoming market needs: the first supports the business transition for the initial market by restructuring existing battery design patterns while the second one introduces completely new design principles for 1st and 2nd life of the battery. Furthermore, Battery2Life introduces innovative embedded sensing and more accurate SOX estimation algorithms, new SOX indicators appropriate for 2nd life use - i.e. SOS (safety) and SOW (warranty) - and a new EIS implementation approach by integrating it in the BMS, that will enable the detailed safety and reliability monitoring at both cell and module level during 1st and 2nd life usage. The project will specify an open BMS concept, data formats, considering and extending the battery passport concept, and interoperable communication via the cloud platform to third parties including the future passport exchange system, to facilitate monitoring and assessment.

Two demonstrations that represent two promising and sustainable business cases, serving the two most common stationary applications have been carefully selected: The domestic and industrial (grid-scale) storage, with respect to their operational specificities and requirements.

The project's duration extends from January 2024 to December 2026

1.2 Purpose of the deliverable

The purpose of the D6.1 is the introduction methodology on how to select or design a module for 2nd life applications and the definition of the steps needed to disassemble a 1st life battery pack, to be refurbished to a 2nd life battery system (BS).

We present:

1. The phases in the process of module selection and the challenges along with them.
2. Basic steps and tools that can be used in the disassembly of any battery pack in the market.
3. The evaluation methodology of the mechanical and electrical parts.
4. The electrical and electrochemical assessment of the cells.

All the steps were created to determine the safe and fast assessment of the health of the electrical, mechanical parts and the repurposed modules. Also, through this process, the sorting and grading of the modules will take place.

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D6.1 aims to contribute to the following outcomes and KPIs:

Topic Expected Outcome 3: BS design to enable disassembly and reconfiguration for 2nd life.

Topic Expected Outcome 4: Development of fast and efficient qualification strategies and assessment of electric vehicle batteries for 2nd life applications and quantify it with respect to state of the art in terms of time and efficiency.

Topic Expected Outcome 5: Reduction of 30% of repurposing/ refurbishment cost for adapting electric vehicle (EV) batteries to stationary applications in 2nd life.

KPI 1: 25% less time needed to manufacture the 2nd life batteries energy storage system (ESS) when using the project enablers compared to without the enablers.

KPI 5: EV battery assessment time is reduced by 25%.

KPI 6: 20% improvement in reliability of EV battery state assessment when using the innovative SoX algorithms and the diagnostic tool compared to conventional assessment methods.

KPI 7: Reduction of 30% of repurposing/ refurbishment cost for adapting EV batteries to stationary applications in 2nd life.

1.3 Intended audience.

Deliverable D6.1 is a public document aiming to inform the path of selecting a battery module for 2nd life applications and the sequence of the disassembly steps, to proceed with the refurbishment of the battery.

The document aims to inform technical experts interested in 2nd life applications about the planning of these two procedures, along with probable risks that might occur during the development period and the implementation phase.

1.4 Structure of the deliverable/ correlation with other WPs

The document consists of two parts: 1) Selection of modules from 1st life to 2nd life and 2) Disassembly steps of the 1st BS.

For the part 1 “Selection of modules from 1st life to 2nd life”, an introduction to the methodology regarding the selection of the batteries is provided for both Pillars, with an overview of the phases and the challenges that might occur. For part 2, “Disassembly steps of the 1st life Battery System”, an introduction to the disassembly steps of the 1st life BS is made, from the point at which the 1st life BS is received for refurbishment to the point at which the disassembled BS is ready for the reassembly.

2 SELECTION OF MODULES FROM 1ST LIFE TO 2ND LIFE

2.1 Selecting a Module for 2nd Life – Pillar 1

The main goal of Pillar 1 is to develop a prototype BS with 2nd life modules (Table 1). As a module consists of the scaled-up version of a battery after the cell level, with a specific type of battery cell, in capacity, size and other configurations (such as the position of the terminals), we get to have multiple types of modules in the market. Since SLG produces multiple sizes of lithium-ion battery packs, the research was focused on finding the module types that have been produced in multiple product codes. Then, using the SLG cloud database to finally decide the module type, and the probable batteries to bring back for the next step of the Pillar 1 tasks.

Terminology	Explanation
Cell	The smallest electrochemical unit in a battery, consisting of an anode, cathode, electrolyte and separator.
Macrocell	It is a mechanical unit consisting of n cylindrical cells in parallel connection (for Pillar 2 only).
Module	It is an intermediate unit in a battery pack, consisting of multiple cells connected.
Battery pack	It is a complete assembly that includes multiple modules, each containing several cells. Also, the BMS and the Power Protection Unit (PPU) are integrated in the battery pack.
Battery Management System	It is a crucial component of a battery pack, responsible for monitoring and managing the battery pack. It consists of Printed Circuit Boards (PCBs), cables, wires etc.
Power Protection Unit	Essential component for ensuring the safety and reliability of battery packs.

Table 1: Basic terminology of the deliverable 6.1

A demonstration of the phases to select a battery module, is shown on the diagram below:

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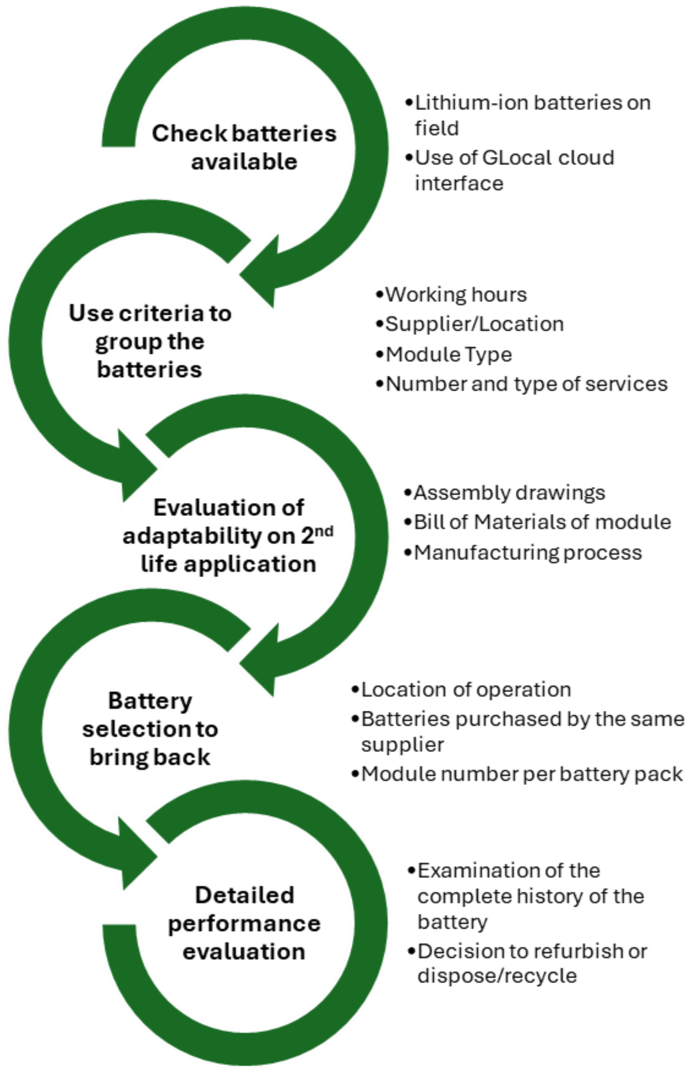

Figure 1: Battery Selection Methodology for Pillar 1

2.1.1.1 Check Batteries (and Modules) Available

There are numerous battery pack designs in the portfolio of SLG. The features they share are:

- multiple battery packs were designed and manufactured to use the same type of module and
- the battery technology, with all of them having lithium-ion cells.

Considering these common features, we focused on searching for the type of the module to use, not directly the battery pack. The size of the battery pack provides us the total number of modules inside. For the module type, we also have the flexibility to check the company portfolio. Differences between them in terms of performance and size are a result of different types of cells used and/or a different number of cells used in one module. As a result, there are modules with connectivity of 1P16S, 2P8S (same number, different connectivity), 1P8S, 1P13S (different number, different cell type), etc.

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2.1.1.2 Criteria of Selection to group the Batteries

To decide which module is better to have in our application, we are focusing on evaluating how many batteries and modules of the specific type are available and in use. So, by using the battery pack design data and by dividing them by the type of the module and by type of cell used, we grouped the available batteries. This helped us to have a better understanding of the most popular module types produced and used. That reflects on how easy it would be to bring the batteries back to SLG premises for 2nd life purposes. The quantitative results showed that more available types of batteries are the ones with modules of 1P16S and 2P8S. Interesting characteristic of both module types is that they both share the same type of cell, with 72Ah capacity, thus the total size of module is the same.

Following the above result, we also used our cloud database, GLocal, where all the statistics of the batteries are saved. Each battery pack has GPS, SD and SIM card. This means that a battery can be connected to the system and send data regarding its location, SoX and hours of operation. Other additional information is added on the GLocal database, such as number of services of the battery, customer information and charging times that did not follow the manufacturer guidelines.

Connecting all the information and sorting the criteria from most to least important:

1. Operating hours
2. Ownership/Location of operation
3. State of Health (SoH) of the battery pack
4. Number of available battery packs per module type
5. Number of modules inside a battery pack
6. Number of services on the battery pack

SLG evaluated all the criteria and decided that the module type 1P16S is preferable to move to 2nd life, as it has more battery packs with more operating hours, more battery packs available in total (thus modules available), multiple customers in Europe (easier transportation) and fewer services.

2.1.1.3 Evaluation of adaptability on 2nd life application

<u>Module assembly drawings:</u> We had a review of the drawings of modules to get all the information for the total dimensions, features of the complete assembly and the inner components.

<u>Bill of Materials (BOM) list:</u> We evaluated the list of components on the battery pack level and on module level:

- <u>On battery pack level</u>*:* We checked how many modules are in one pack, as a battery pack with more modules is preferable to reach the number of modules on the BS for 2nd life. We evaluated also which components can be used for 2nd life purposes, such us cables, stabilization bars, etc.

- On module level: We followed the same procedure as with the battery pack level, we also evaluated the components that are inside the module and how complex the disassembly is going to be.

Manufacturing process: SLG team received a module and pack assembly training from our Lithium-ion battery pack production manufacturing department. This helped us understand topics regarding reusability at the module level (results are shown in Battery2Life Deliverable 2.2) and at the pack level, as well as safety risks during disassembly and equipment required.

As a result of the above, the module type selected, with the cells having connection type of 1P16S, is validated to proceed for the 2nd life purposes of this project.

2.1.1.4 Next steps

The following steps exceed the purpose of this Deliverable, as they are more related to the Working Package 7. Bringing the batteries back to begin with the refurbishment process requires a series of actions: from the actual decision on which battery backs we should bring back, to the level of discussions than need to take place internally and externally. The fact that the former customer must now be considered as a supplier, adds more complexity to the process. Topics such as location of operation of the battery packs and the number of modules per battery pack, refer mostly to financial considerations.

Final step before the deciding to bring back the batteries is a further evaluation of the performance of the 1st life of the batteries. Areas of interest are mostly periods of unusual use and no-use. These insights will inform us about the performance issues the batteries might have and help determine whether to refurbish, dispose or recycle them.

2.1.1.5 Challenges

Challenges in the methodology were:

1. To evaluate if the required number of batteries is available in the supply chain of the battery industry.
2. Establishing communication to build the network for when the modules are needed, because the customers must be considered as suppliers.
3. Potential missing of information on the cloud database, that could help us decline a battery to come back for refurbishment.
4. Determining the sequence of the tests to avoid wasting valuable time.

2.2 Designing a Module for 2nd Life – Pillar 2

2.2.1.1 Module Requirements

The module requirements for the BS design, aimed at covering both the 1st life (EV application) and 2nd life (stationary application), include creating modules that endure dual life cycles with

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minimal modifications and developing a standardized disassembly methodology. The process should identify components incompatible with 2nd life applications, and selection criteria must consider capacity retention, safety, performance metrics, and material condition.

The design should ensure compatibility with specific application needs, maintain comprehensive documentation for traceability, and prioritize sustainability. Additionally, modules must be designed for ease of disassembly and reassembly to facilitate modification, assess specific parameters of incompatibility such as performance degradation and material fatigue, and comply with safety standards and regulations throughout both life cycles. The modular design should facilitate scalability, adaptability, and easy maintenance, ensuring efficient transitions between life stages.

2.2.1.2 Criteria of Design

Modular and scalable design

- Standardization: Design battery modules with standardized dimensions, connectors, and interfaces for easy integration and scalability.
- Flexibility: Ensure the modules can be easily reconfigured to meet the specific energy and power requirements for the 2nd applications.

Ease of Disassembly and Reassemble

- Non-Destructive Design: Develop modules that can be easily disassembled without damaging components, allowing for the facile replacement of cells and parts.
- Reusable Components: Design reusable and easily replaceable components to extend the module's overall lifespan.

Enhanced Safety Features

- Thermal Management System: Integrate advanced cooling systems to manage heat dissipation and prevent thermal runaway.
- Protection Circuits: Include robust overcharge, over-discharge, and short-circuit protection mechanisms.
- Fire Resistance: Use fire-resistant materials and incorporate design features that either contain or prevent potential fires.

As part of the process of defining suitable 2nd life batteries, a sorting of the available batteries is proposed depending on the target application. The classification will be based on EV 1st life data analysis, and laboratory tests which will enable the sorting according to the stationary 2nd life application characteristics.

First, data of the last month of operation in the 1st life EV application is analysed. The minimum data required is the voltage, current, temperature and SoC time series of the battery operation. Better evaluation can be done having access to cell level data, but if it is not available, module or

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even pack level data can also be used to assess the state of the system. In this case, pack level data is available which is analysed through the diagnosis tool that will be described further in Battery2Life Deliverable 4.1.

A previous step of data inspection, transformation and selection is also necessary. The delivered data by MIBA was in .mf4 format, which was transformed to MATLAB timetable format. The variables of interest were selected, including the time, the voltage at pack level, the current at pack level, the maximum-minimum temperature of the cells at module level and the SoC at pack level. Repetitions and incongruences were eliminated from the obtained data.

After the formatting, selection and cleaning of the data, the characteristics of the 1st life application is evaluated depending on the behaviour of the recorded variables in order to adjust the diagnosis algorithms, see Figure 2. In Figure 2, we observe the operation of a 1st life battery in the field, for three consecutive days. The diagrams show the current vs time, mean temperature vs time, voltage vs time and SoC % vs time for these three consecutive days. From that kind of graphs and for a greater sample of days or months, we can assess the conditions in which the battery was operated, including, temperatures, missing opportunities for charging, deep discharging etc. The use case under evaluation has deep charge and discharge events, where the charge process is controlled. Therefore, the estimators of the diagnosis are adjusted to these characteristics, more details can be found in Battery2Life Deliverable 4.1.

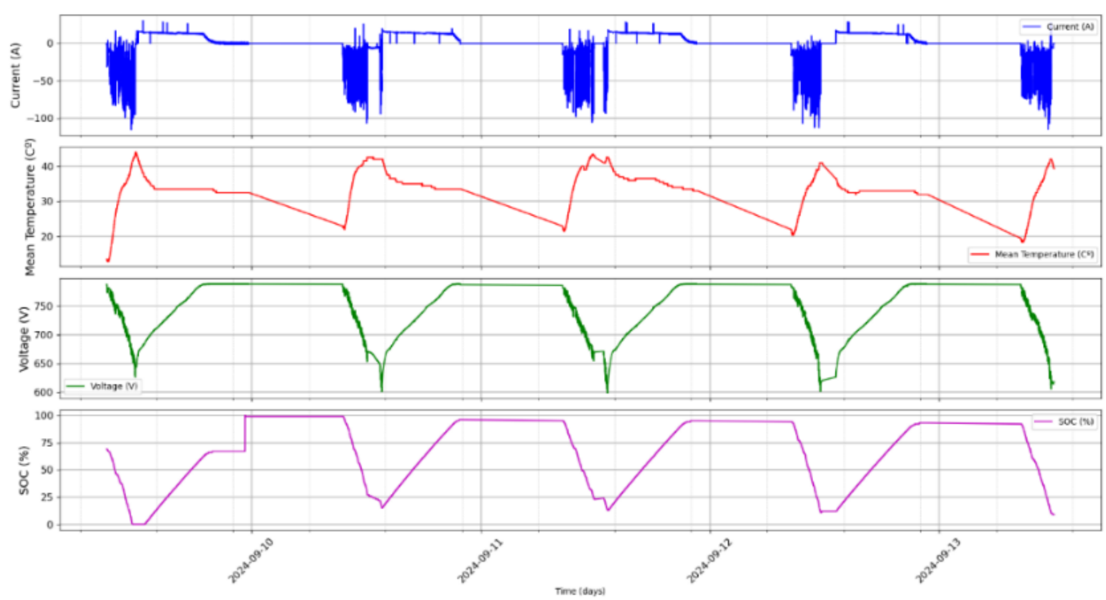

Figure 2: 1st life data after data pretreatment process, example

The data analysis gives as a result the values of the SoH and round-trip efficiency at pack level. These values assist in clustering and grouping the packs, but in addition they are used to predefine possible 2nd life use cases of interests. Hence, the diagnosed status of the batteries is contrasted with stationary 2nd life application characteristics. The fitness with each stationary application characteristics allows further clustering. These tests are applied to module level systems, which

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are the lowest disassembled unit of the repurposing battery packs. The data obtained from each test allows to go deeper on defining the status of the macrocells of each pack under evaluation.

The proposal methodology tries to demonstrate that the macrocells and packs that are grouped together have the same response under the tests designed. This procedure applied to all received end of 1st life modules is very time-consuming and increases the cost of the system. However, the 1st life data diagnosis allows to reduce the testing campaign by just testing one pack of each group, which in the future could have further reduction of tests by improving further the diagnosis tool, generating a disruptive impact in the 2nd life battery market by developing high-fidelity and low-cost systems.

2.2.1.3 Design Roadmap

The design roadmap is shown in the figure below.

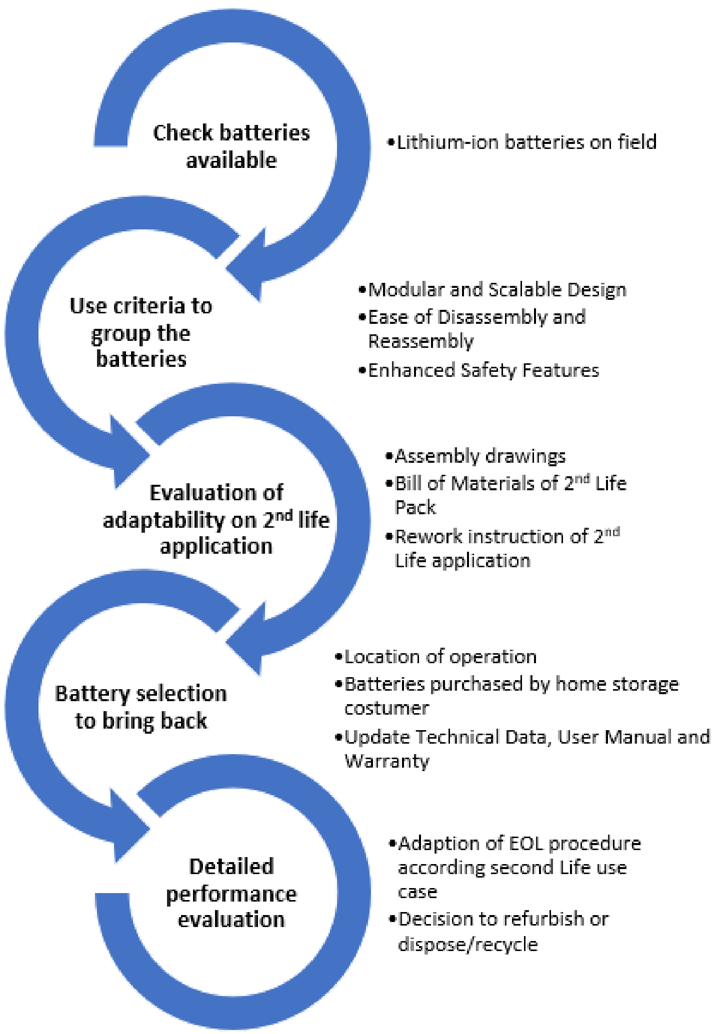

Figure 3: Battery Selection Methodology for Pillar 2

2.2.1.4 Challenges

Five key challenges have been identified. The first three are taken directly from the Grant Agreement of the project and are listed below:

Challenge 1 – Lack of flexible and standardized packaging.

The efficient transition of big numbers of BS to 2nd life applications necessitates an efficient disassembly, assessment, and reconfiguration method. Currently, disassembly is a purely manual process, which leads to high costs and poses safety risks to workers, because there is no standardized design or disassembling potentials. For example, current BS designs involve a lot of conductive connectors, provide limited accessibility to individual components and involve non-detachable (e.g. glued or welded) connections. Furthermore, the solid case of a battery module is often inseparable, thus, a defect of an individual cell leads to the disfunction of the whole battery module, so still working cells might be wasted. In this respect, new design principles for BS are needed to facilitate the battery disassembly, introducing means like wireless connectivity for the BMS. On the other hand, the diversity of the battery technologies to be recycled in the future implies that the system designs should be able to handle different technologies.

Challenge 2 – Lack of standardized, reliable and efficient means to monitor status, assess suitability and appropriately match used modules for 2nd life applications.

Batteries reach End-Of-Life at different states as they undergo different degradation conditions including temperature, C-rates, average State of Charge (SoC), and Depth of Discharge (DoD). Uncertainties as regards the quality, safety, and remaining lifetime of used modules do hamper the large-scale development of 2nd life battery repurposing. The lack of accurate and reliable knowledge about the modules state and prediction of their degradation obstructs the accurate estimation of their value. Knowing how the battery has been used would facilitate exploiting its full potential. To take informed decisions, the assessment of the suitability of retired EV batteries for 2nd life applications needs more accurate and reliable estimates of their remaining capacity and state, that cannot be done using existing estimators. Reliable diagnostic requires access to certain data on battery usage and history, which is normally stored in the BMS. But there is no standardized means so that third parties can access such data in harmonization with the recently introduced EU Battery Regulation Amendment, to assess the modules suitability for 2nd life applications.

Challenge 3 – Transferring a BMS design from 1st to 2nd life use is a challenging task, as system, functional and safety requirements are not the same.

Existing BMS systems are customized to serve the functional and safety constraints of a specific technology and a specific application, and this is a hindering factor for the wider promotion of the 2nd life applications of batteries. For example, BMS systems for automotive use are designed to serve the vehicle's mobility requirements and vehicle's auxiliary energy needs. For efficient use in 2nd life, the BMS must be adaptable to the requirements of the 2nd life operational application and

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ensure the safe and optimum performance of the new battery composed of its 2nd life modules. Furthermore, the power and energy requirements of 2nd life applications might require the combination of diverse battery technologies with different operational and technical specifications. This diversity may intensify as new technologies emerge in the future. There is a need for transitioning from a technology-driven rigid BMS to a data-driven, technology and application agnostic BMS.

The remaining two challenges have been identified during the project implementation:

Challenge 4 – Mass implementation

For mass implementation, current standards, such as UL 1974 [1], take a considerable amount of time and require sophisticated testing/production lines. These requirements are a hurdle, especially for large-scale application and integration. There is an urgent need for the development of shorter tests or a statistical approach that allows all the necessary data to be collected within the application. This data should then be accessible for final reuse to optimize the implementation process and reduce costs.

Challenge 5 – Prototype development and validation

During prototype development and subsequent validation, there is a risk that not all influencing factors of the process are fully covered. This is particularly since the sample size is often limited. This limitation entails the risk that batteries are operated under different conditions, which in turn can have different effects on all parameters. This can lead to unrecognized variations that could have a significant impact on the results. It is therefore essential to minimize such variations or develop appropriate strategies to understand and control their effects.

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3 DISSASEMBLY STEPS OF 1ST LIFE BATTERY SYSTEM

3.1 Methodology

A refurbishment methodology for the evaluation of 1st life used batteries, was adopted by Zhu et al. [2] that is based on already identified mandatory steps in the 2nd life battery market.

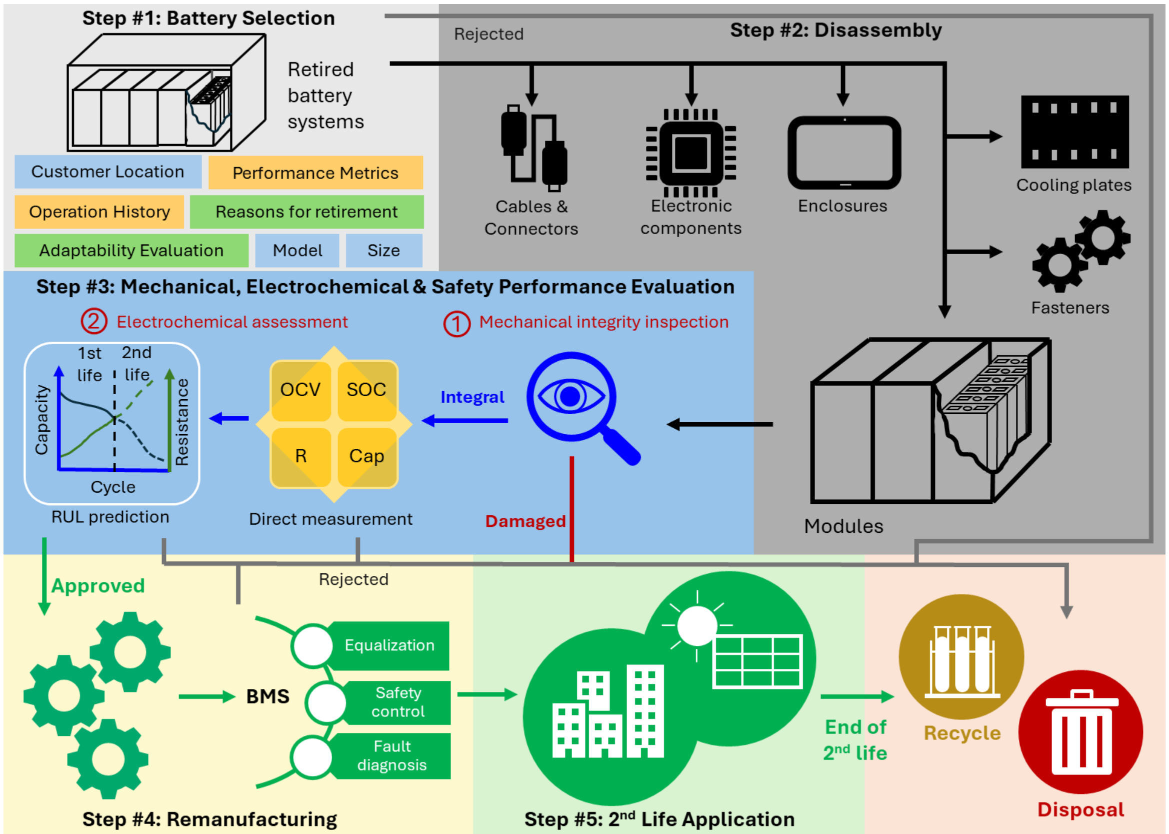

Figure 4: Summary of the Refurbishment Methodology introduced (redesigned from Zhu et al. [2])

As seen from the diagram above, the disassembly methodology can be distinguished in the following steps:

Step #1: Battery Selection. Refers to the procedure analysed in the 2nd section of this document, the selection of the battery type to refurbish.
Step #2: Disassembly. The procedure of removing all the components of the battery packs, until the module level.
Step #3: Mechanical, Electrochemical & Safety Performance Evaluation. Tests on mechanical, electrical and electrochemical level to ensure the safe use of the modules on 2nd life applications.
Step #4: Remanufacturing. Refers to the refurbishment procedure of preparing the module in 2nd life use.
Step #5: 2nd Life Application. The goal of this procedure.

In case of a battery pack or module gets rejected (at any step): Recycling and/or Disposal.

Steps of interest in this section are Steps #2 and #3. After this, we can proceed with the refurbishment, along with disassembly.

3.2 2nd life Performance and Safety Evaluation

After battery packs have been received, the modules must be evaluated regarding their performance on mechanical and electrical tests. By evaluating the performance of the modules, we ensure their safe operation during their 2nd life. According to this, a series of tests is introduced regarding this assessment. The sequence of the tests is selected to minimize the time consumed. Main risk on defining this sequence is that some procedures need to be made when the module is opened and disassembled on a specific level (for example for the terminals to become visible and accessible). So, first are the tests that can occur without disassembling the battery pack or the module, and step-by-step during the disassembly, the required test is going to be operated.

3.2.1 Mechanical tests

The list of mechanical tests that are going to occur on battery pack and on module level are the following:

1) Dimension measurement test
   Measurement of outer dimensions of the module, to evaluate potential changes (from swelling) after 1st life.
2) Visual inspection, checking for:
   a) Cracks, bents and damages on casing
   b) Swelling of cells or modules, vented cells
   c) Frayed, damaged wiring
   d) Traces of burning / Burn marks
   e) Isolation system damage
   f) Loose connections and parts
   g) Discoloration of insulation
   h) Notable odour, electrolyte leakage
   i) Corrosion on the terminals of the cells, the connections with the cables, etc.

3.2.2 Electrical Tests

The list of electrical tests followed on battery pack and on module level, regarding the battery grading and sorting, are following the standard UL 1974 [1]:

- Open Circuit Voltage (OCV)
- High-Voltage Isolation Check
- Capacity Check
- Internal Resistance Check
- Check of BMS controls and protection components

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- Activation – Change/discharge cycle (outside the UL 1974 – Proposal from CIDETEC)
  Objectives:
    - Activate the chemistry after possible long period of rest time
    - Monitor temperature, voltage and current at cell level
    - Prolonged testing observation for possible hidden faults

  Procedure:
    - 10 charge/discharge cycles are done at nominal current values at CC-CV charge and CC discharge at room temperature
- Discharge/Charge cycle test (temperature, voltage and current of cells and modules)
- Self-discharge test
- Lithium plating test (outside the UL 1974 – Proposal from CIDETEC)
  Objective:
    - To detect lithium plating

  Procedure:
    - Charge/discharge at C/10 CC at room temperature

The data obtained from each test allows to go deeper on defining the status of the modules under evaluation. The activation and lithium-plating tests are suggested since they will provide critical information that cannot be disclosed by the test described in UL 1974 [1].

3.2.3 Electrochemical Tests

Differential capacity analysis (DCA or incremental capacity analysis) is a method of characterizing SoH in secondary batteries through the identification of peaks that correspond to active material phase transformations [3,4]. The degradation of lithium-ion batteries is a complex non-measurable process caused by a variety of mechanisms.

Ageing mechanisms can be grouped into three degradation modes: **Conductivity loss, Loss of active material (LAM) and Loss of Lithium Inventory (LLI).** Many studies have analysed the effects of degradation modes using differential capacity analysis suggesting that they are suitable for the identification and quantification of the effects of the degradation mechanisms [4].

The main presentation of DCA curves used in the literature is dQ/dU vs V (Figure 5). Such curves give information about the structural transformations during the charge/ discharge process.

The advantage of the differential capacity analysis curves is that plateaus in the U vs Q charge curve can appear as clearly identifiable peaks in the dQ/dU vs. U curve. These peaks are associated with phase transitions of the electrode material. The shape of the discharge and the charge curves give information about the reversibility of the electrode reaction. Plotting the differential capacity dQ/dU vs cycle number allows the observation of any change (peak potentials, height, width) in the peaks, from one cycle to the next, and can help detect degradation over long test cycles [4].

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Degradation could be associated with side reactions involving electrolytes, active materials or non-active materials (current collectors, binders etc.). The evolution of the position and height of the peaks indicates the presence of different degradation mechanisms (Table 2).

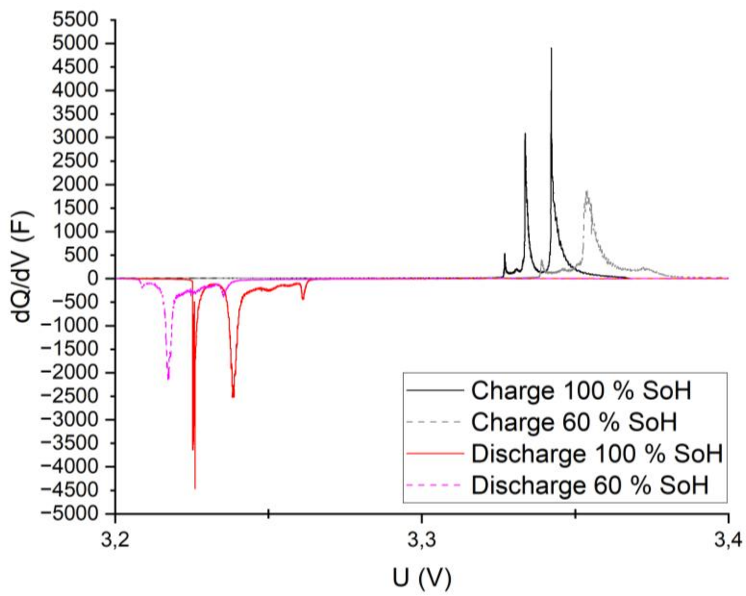

Figure 5: Differential capacity analysis curves of the cells of the Pillar 1. An inappropriate cell for use in 2nd life BS, with SoH 60%, experiences change transformations that appear as changes and shifts in the peaks of the differential capacity curves

Change in dQ/ dU vs U curves	Degradation modes	Potential ageing mechanisms
Shifting towards voltages	Conductivity loss	1) Current collector corrosion 2) Binder decomposition
Decrease of the heigh of the peaks and shift towards lower/higher voltages	Loss of lithium inventory	1) Electrolyte oxidation 2) Oxidation of the electrolyte 3) Lithium plating 4) Formation of Li grains 5) Solvent co-intercalation
Decrease of peak height at approximately constant voltage	Loss of active material	1) Decomposition of the electrode 2) Oxidation of the electrolyte 3) Intercalation gradient strains in the active particles 4) Formation of Li grains 5) Crystal structure disordering 6) Solvent co-intercalation

Table 2: Differential capacity analysis interpretations

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To obtain the differential capacity, dQ/dU, firstly a cycling procedure is performed at a slow rate (e.g. C/20) for both charge and discharge. The slower rate enables the collection of higher fidelity reaction information. The slow rate cycling procedure is performed at the cell level. Because, the testing procedure is time-consuming, it is required a sampling procedure to ensure better statistical representation of the data and of the battery "health". Also, the cells on the edges of the modules should always be tested and their differential capacity analysis curves to be produced because they tend to be the most aged cells.

The differential capacity, dQ/dU, is obtained by numerically differentiating the electric charge Q(t) with respect to the instantaneous voltage U(t), in the simplest case by applying the differential method.

$$\frac{dQ}{dU} = \frac{Q(t_{i+1}) - Q(t_{i-1})}{2h} + O(h^2) \approx \frac{Q(t_{i+1}) - Q(t_i)}{U(t_{i+1}) - U(t_i)} at\ \overline{U} = \frac{U_{i+1} + U_i}{2}$$

Where:

- $Q(t_i)$: Charge measured at time t_i
- $U(t_i)$: Voltage measured at time t_i
- h: Time step between measurements
- O: Truncation error

The unit of dQ/dU is Farad (F), where F = C/V = Ah V^{-1}.

3.3 Disassembly Steps on Battery Pack Level

3.3.1 Pillar 1

Battery pack disassembly steps include all the procedures up to the level where the modules can be fully removed from the pack [5].

Step 1: First series of Mechanical tests, visual inspection on the complete battery pack
- **Step 1.1:** Cracks, damages on casing, etc.
- **Step 1.2:** Corrosion on the ports and terminals of the pack

Step 2: First series of Electrical tests on the complete battery pack
- **Step 2.1:** Activation – Charge/Discharge Cycle
- **Step 2.2:** Check battery capacity by charging and discharging the battery according to IEC61960 (7.3.1) standard
- **Step 2.3:** Cycle the battery pack while monitoring the temperature, voltage and current

Step 3: Remove the side plate of the enclosure

Step 4: Series of Mechanical tests; Visual inspection for:
- **Step 4.1:** Burn marks, electrolyte leakage, frayed or damaged wiring
- **Step 4.2:** Loose connections and parts and corrosion on the connection with cables

Step 5: Remove the cables which connect the modules with the Master Board

Step 6: Remove cables connected with the modules and other subsystems

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Step 7: Second series of electrical tests:

Step 7.1: Measure Battery Pack OCV with multimeter

Step 7.2: Test Isolation Resistance of Battery Pack

Step 7.3: Measure AC Internal Resistance

Step 8: Remove the cables that connect the modules together and the control panel

Step 9: Remove the fixing components of the modules

Step 10: Remove the modules

Steps with Risks:

Step 2: First series of Electrical tests on the complete battery pack

These electrical tests consume much time to be completed, increasing the total time required in the refurbishment. The multiple charge/discharge cycles require chargers to be occupied, thus there will be a need to schedule for the availability of the chargers with the testing facilities.

Step 8: Remove the cables that connect the modules together

Depending on the battery size (also number of the modules and/or the ballast plates inside), the space to have access and remove the cables is limited.

Step 10: Remove the modules

Removing the modules from the enclosure, regarding their fixing and their weight, will require the battery assembly equipment. This remains as a risk, as a need to schedule the availability of the equipment with the production facilities is required.

At last, risks that find application in all the disassembly steps, are the possible hazards (electrical, chemical, etc.). During the steps of removing components and all the tests, all the required PPEs must be equipped, to avoid any possible hazard, along with the required room conditions.

3.3.2 Pillar 2

The methodology for Pillar 2 focuses on the systematic disassembly of the TERRA#05-Pack to ensure safety, efficiency, and the recovery of valuable components. This process is designed to minimize environmental impact and comply with all relevant health, safety, and environmental regulations [6].

Disassembly steps:

Step 1: Delivery of Packs

Step 2: Unpacking the Packs

Step 3: Incoming Goods Inspection

Step 4: Opening the Pack

Step 5: Cleaning the Housing

Step 6: Inspection of the Module

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Step 7: End of Line Tests
Step 8: Modules in Housing
Step 9: Sealing and Cleaning
Step 10: Leak and Function Test
Step 11: Packaging

Steps with Risks:

Step 1: Delivery of Packs

- Damage during transportation or unloading: Battery packs may get damaged due to inadequate packing or mishandling during transit.
- Delayed delivery: Delays in delivery can disrupt the workflow and scheduling of subsequent steps.

Step 2: Unpacking the Packs

Battery pack not securely fastened: If battery packs are not securely balanced while lifting, it could cause accidents or damage.

Step 3: Incoming Goods Inspection

Electrical hazards: Improper handling during inspections may lead to electrical shocks or electrocution.

Step 4: Opening the Pack

- Mechanical injury: Improper use of tools can cause physical injuries to the technicians.
- Short circuits: Accidental connections may cause short circuits, leading to sparks or fires.
- Voltage hazards: Incorrect handling of battery packs may result in exposure to dangerous voltages.

Step 7: End of Line Tests

Electrical hazards: Incorrect testing procedures can expose technicians to electrical risks.

Step 10: Leak and Function Test

Incorrect test setup: Improper setup of testing equipment can lead to erroneous results or safety hazards.

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3.4 Disassembly Steps on Module Level

3.4.1 Pillar 1

Module disassembly steps include all the ones occurring until the level where the top of the cells is completely exposed with the busbars connected on the terminals of the cells [5].

Step 1: First series of Mechanical tests:

- **Step 1.1:** Visual inspection for cracks, damages on casing, traces of burning
- **Step 1.2:** Corrosion of the terminals of the module
- **Step 1.3:** Dimension measurement of module

Step 2: First series of Electrical tests:

- **Step 2.1:** Self-Discharge test
- **Step 2.2:** Check module capacity by charge and discharge the module
- **Step 2.3:** Cycle the module while monitoring the temperature, voltage and current

Step 3: Remove the Top plate

Step 4: Second series of Mechanical tests; Visual inspection for:

- **Step 4.1:** Burn marks on the BMS, frayed or damaged wiring and electrolyte leakage
- **Step 4.2:** Discoloration of insulation films

Step 5: Remove the BMS:

- **Step 5.1:** Deactivate the BMS and turn off the switches
- **Step 5.2:** Remove the cables and the screws connected on the BMS
- **Step 5.3:** Take out the BMS

Step 6: Third series of Mechanical tests; Visual inspection for:

- **Step 6.1:** Swelling of the cells and corrosion of the terminals of the cells
- **Step 6.2:** Traces of burning

Step 7: Second series of Electrical tests:

- **Step 7.1:** Measure module OCV with multimeter
- **Step 7.2:** Measure AC Internal Resistance

Step 8: Remove the bolts on the busbars and terminals of cells to remove the rest of the cables

Step 9: Second Series of Electrical tests: Lithium plating on cell level

Step 10: Put back the bolts on the busbars and terminals of cells

Steps with Risks:

Step 5: Remove the BMS

Need to be precise and follow the deactivation of the BMS accordingly (mostly while removing the screws on the BMS), to not create a short circuit.

Step 8: Remove the bolts on the busbars and terminals of cells to remove the rest of the cables

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Danger of not being able to reassemble the busbar because of the produced pressure to hold the terminals in the first place and/or rejected after further quality inspection. As of this, it is suggested from SLG to stop the disassembly process after Step 9.

As last, risks that find application in all the disassembly steps, are the possible hazards (electrical, chemical, etc.). During the steps of removing components and all the tests, all the required Personnel Protection Equipment (PPE) must be worn, to avoid any possible hazard, along with the required room conditions.

3.4.2 Pillar 2

At the module level, where the pack is without housing, nearly no changes are required, maintaining the integrity and simplicity of the original disassembly process, as described in chapter 3.3.2.

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4 RESULTS

4.1 Selection of Modules from 1st Life to 2nd Life

The battery disassembly procedure can be very complex, dangerous and with multiple phases. For that reason, we have introduced in the Annexes section of this deliverable general lists of procedures and check points for the easier disassembly and testing of any lithium-ion battery pack and module in the market.

4.1.1 Pillar 1

The battery selection for Pillar 1 is very complex and involves multiple phases. It requires a great overview of the company's battery packs and modules portfolio, as well as the ability to analyze among the manufactured battery packs, which are available in various configurations. The criteria to select the battery pack were dictated mostly from the module types operating, their number per battery pack, their location of operation, and performance metrics. The module selected, having profile of 1P16S, is verified on providing the required level of disassembly for 2nd life purposes and shows an easier access, as a plethora of batteries manufactured with this type of module, has been released to the market. Next steps will involve communicating with the future suppliers and all the relevant stakeholders to implement the refurbishment plan. During this phase, a detailed evaluation of the battery performance must be made.

4.1.2 Pillar 2

The methodology for Pillar 2 focuses on designing a BS that seamlessly transitions from 1st life (EV application) to 2nd life (stationary application). This involves creating modules that can endure dual life cycles with minimal modifications and developing a standardized disassembly methodology. The TERRA#05 Battery was selected for its superior modular design, safety features, and ease of disassembly and reassembly. The design criteria emphasize on modularity, scalability, ease of disassembly, enhanced safety features and sustainability. Challenges include the lack of standardized packaging and monitoring systems and the complexity of transferring BMS design from 1st to 2nd life. The results indicate that the TERRA#05 Battery meets the necessary requirements for 2nd life applications, ensuring high reliability and performance.

4.2 Disassembly Steps of 1st Life Battery Systems

4.2.1 Pillar 1

The process on defining the disassembly steps was straightforward for both battery pack and module levels. As of great help were the well-defined assembly steps that were followed in reverse. This great result was met also from the methodology of battery selection, where a criterion during the battery selection, "Evaluation of adaptability on 2nd life application", is to check the manufacturing process and the assembly drawings [5].

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The mechanical, electrical and electrochemical tests that have been added also in these steps, were a necessary addition to the sequence of the disassembly, because if a battery pack or a module does not pass a test, goes directly to recycling or disposal, as it is no longer of safe use for 2nd life purposes. The electrical tests tend to follow specific standards, as they are described in detail and are highly considered for 2nd life batteries. Additional tests have been added to improve the existing standards.

Multiple risks appear on both levels of the disassembly, and most of them deal with safety of operation or time consumption. The fact that several risks have been addressed from this crucial level of planning, helps on managing them even further with proper actions during the implementation phase.

4.2.2 Pillar 2

The disassembly steps of 1st life battery systems, particularly focusing on the TERRA#05-Pack [6] – MiBA's 1st life macrocell, that is going to be repurposed for the Pillar 2, are meticulously designed to ensure safety, efficiency, and the recovery of valuable components. The process begins with the delivery and unpacking of battery packs, followed by a thorough incoming goods inspection to ensure the packs are in good condition. Subsequent steps involve opening the packs, disassemble and remove electrical parts, and inspecting the modules for reuse. The final stages include placing the modules back into the housing, sealing, cleaning, and conducting leak and function tests to verify the integrity and functionality of the packs. This systematic approach not only minimizes environmental impact but also adheres to all relevant health, safety, and environmental regulations, ensuring that the modules are ready for their 2nd life applications.

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5 CONCLUSIONS

The disassembly process of battery packs up to the module removal stage, for both Pillar 1 and Pillar 2, involves a structured approach that prioritizes safety, efficiency, and thorough inspection. Beginning with mechanical and electrical tests, the initial steps ensure that any visible damage, corrosion, or performance degradation is identified before proceeding with further disassembly. The careful removal of side plates, cables, and fixing components allows for a systematic breakdown of the battery pack while maintaining the integrity of the modules. Additionally, the second series of electrical tests provide a crucial checkpoint to assess the condition of the pack before the modules are extracted, ensuring that only viable components proceed to the next stages.

Several risks are inherent in the disassembly process, with concerns surrounding the electrical testing phase, accessibility constraints, and the safe removal of heavy modules. The extensive time required for electrical evaluations and the need for specialized equipment highlight logistical challenges that must be carefully managed. Furthermore, the handling of high-voltage components and potential exposure to hazardous materials necessitates strict adherence to safety protocols, including the use of proper PPE and controlled work environments. The complexity of disconnecting modules and cables without causing damage or introducing safety hazards underscores the need for skilled personnel and well-planned procedures.

Overall, the disassembly process balances meticulous testing and controlled disassembly to ensure the safe retrieval of modules for further use or recycling. Addressing risks at each stage, from mechanical integrity checks to electrical evaluations, contributes to a systematic and reliable methodology.

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6 REFERENCES

[1] Underwriters Laboratories. (2023). UL 1974: Evaluation for repurposing of remanufactured batteries.

[2] Zhu, J., Mathews, I., Ren, D., Li, W., Cogswell, D., Xing, B., ... & Bazant, M. Z. (2021). End-of-life or second-life options for retired electric vehicle batteries. Cell Reports Physical Science, 2(8). https://doi.org/10.1016/j.xcrp.2021.100537

[3] Kurzweil, P., Scheuerpflug, W., Frenzel, B., Schell, C., & Schottenbauer, J. (2022). Differential capacity as a tool for SOC and SOH estimation of lithium-ion batteries using charge/discharge curves, cyclic voltammetry, impedance spectroscopy, and heat events: A tutorial. Energies, 15(13), 4520. https://doi.org/10.3390/en15134520

[4] Hamed, H., Yusuf, M., Suliga, M., Choobar, B. G., Kostos, R., & Safari, M. (2023). An incremental capacity analysis-based state-of-health estimation model for lithium-ion batteries in high-power applications. Batteries & Supercaps, 6, e202300140. https://doi.org/10.1002/batt.202300140

[5] SLG. (2024, July). Module assembly training manual. SLG Battery Assembly Production Facilities

[6] MIBA. (2024, October). Disassembly testing report on TERRA#05 battery pack. MIBA Facilities.

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7 ANNEX A: INITIAL SORTING PROCEDURES

Disclaimer: The following sections are a recommendation on how to monitor all the information regarding the system and subsystems of a battery pack and a module for quality control purposes.

7.1 Annex A1: Information Gathering

Battery Information	Input
Battery markings	
Date of manufacturing	
Battery schematics	
Battery chemistry	
Charging/ Discharging history	
Storage	
Service/ handling/ procedure manual	
Battery configuration	
Battery weight	
Battery dimensions	
Contents of Battery	
Cooling system	
Isolation monitoring system	
High voltage bus	
Reason for retirement	
Date of removal from service	
Information and handling on storage before repurposing	
BMS specifications	
BMS algorithms for charging and discharging	
BMS manufacturer	
BMS part number	
BMS date of manufacturing	
Records of the battery faults	

Table 3: Battery Pack Information Gathering

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Module Information	Input
Module markings	
Date of manufacturing	
Module specifications	
Module configuration	
Contents of module	
Module weight	
Module dimensions	

Table 4: Module Information Gathering

Cells Information	Input
Date of manufacturing	
Cell chemistry	
Cell weight	
Cell dimensions	
Cell design	
Manufacturer	
Part number	
Cell markings	
Cell specification sheet	
Safety test data	
Calendar expiration date	

Table 5: Cells Information Gathering

BMS Information	Input
Date of manufacture	
Part number	
Manufacturer	
Specifications regarding current	
Voltage protection	
Temperature protection	
Communication protocols	
CANBUS message schemes	
Software version update	
Schematics	

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Algorithms	
Manual about installation use operation programming and maintenance	

Table 6: BMS Information Gathering

7.2 Annex A2: Visual Inspection

Criterion	True	False
Cracks	☐	☐
Swelling	☐	☐
Notable odour	☐	☐
Discoloration	☐	☐
Burn marks	☐	☐
Corrosion of modules	☐	☐
Corrosion of cells	☐	☐

Table 7: Visual Inspection Checklist

7.3 Annex A3: BMS data gathering

BMS Data	Inputs	Total times
Average values of voltage		
Extreme values of voltage		
Average values of current		
Extreme values of current		
Average values of temperature		
Extreme values of Temperature		
Average values of SOC		
Extreme values of SOC		
Out of specification values for voltage		
Out of specification values for current		
Out of specification values for temperature		
Total charge and discharge throughput over the lifetime		
Under charge times		
Under discharge times		
Number of error messages		
Type of error messages		

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Number of times contactor operated		

Table 8: BMS Date Gathering

Cooling System Information	Input
Manufacturer	
Part number	
Specifications regarding temperature and controls	
System flow rate	
Incoming & outgoing temperatures	
Coolant material	
Parts list	
Information on installation, trouble shooting, operating, maintenance	

Table 9: Cooling System Information

Information for other systems	Input
Manufacturer	
Part number	
Datasheets	
Information on installation, trouble shooting, operating, maintenance	

Table 10: Information for Other Systems

In some cases, BMS data may not be available for analysis. In such situation, a process for conducting an in-depth analysis of the incoming samples is required. This include a procedure for determining the health of the cells and other parts of the system without the aid of BMS data, using testing of samples and documentation provided on the cells, and comparing with data from fresh samples or specifications for the cells.

7.4 Annex A4: Testing for Sorting and Grading Process

Cells and modules that have been disassembled from a battery pack and battery packs that have been found suitable for repurposing through evaluation and testing shall be graded in a manner to ensure they are assembled with cells, modules and battery pack that are equivalent regarding remaining usable energy and state of health. The main measurements, according to the UL 1974 for evaluation of 2nd life batteries are:

- Open Circuit Voltage
- High Voltage Isolation
- Capacity
- Internal Resistance
- BMS controls and protection components

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- Discharge/ Charge cycle test
- Self-discharge

If only a module or a cell is going to be repurposed the only testing required on the battery pack is the incoming OCV and the incoming high voltage isolation check tests.

7.5 Annex A5: Corrosion and Cracking Inspection

Corrosion inspection

The main factors that cause corrosion of materials are the moisture, chemicals, temperature changes, or environmental conditions. The inspection aims to identify areas affected by corrosion, gauge the severity of the damage, and develop effective strategies to prevent and mitigate corrosion.

Through techniques like:

- Visual inspections
- Non-destructive testing
- Laboratory analysis

The extent of corrosion to structures, equipment and materials is evaluated.

The techniques that may be used to evaluate the corrosion of a material are:

Visual Inspection

With this method, the surface of a material is examined for visible signs of corrosion, such as rust, discoloration, pits, or irregularities.

Crack inspection

Crack inspection is a non-destructive technique (NDT) method used to detect and assess the presence and severity of cracks on the surface of a material without causing damage to it.

7.6 Annex A6: Rejection Criteria

Rejection Criterion	True	False
Vehicle crash	☐	☐
Vehicle flooding	☐	☐
Damaged modules	☐	☐
Damaged cells	☐	☐
Operation temperature < 10ºC	☐	☐
State of Health < 60 %	☐	☐

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Capacity < Specified limits	☐	☐

Table 11: Rejection criteria of battery pack, modules, cells

Criterion	Component	True	False
Damage of thermal management systems	Thermal Management System	☐	☐
Damaged HV bus	HV Bus	☐	☐
Damaged wiring	Wiring	☐	☐
Discoloured insulation	Wiring	☐	☐
Damaged casings	Enclosure	☐	☐

Table 12: Rejection criteria of battery electrical and electronic components

7.7 Annex A7: Disposal of damaged and rejected cells

Proper disposal of lithium-ion batteries is essential for safety and environmental protection. Below the reader can find some guidelines:

- Cells must be sorted based on their chemistry and condition.
- Cells must be discharged to their low voltage limit.
- Cells must be stored in a battery disposal box that is filled with vermiculite.
- The transport of used batteries (Europe) is regulated by several frameworks to ensure safety and environmental protection. The European regulations that must be taken into consideration are:
    a. The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR).
    b. The EU battery regulation (2023/ 1542).

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