Proposal for battery classification criteria and EoL strategy

22/12/2023

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CEA	Beneficiary	RTO	FR
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ITE – Instituto Tecnológico de la Energía	Beneficiary	RTO	ES
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NUTAI	Beneficiary	Enterprise	ES
COMAU	Beneficiary	Enterprise	IT
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VDL Staalservice BV	Beneficiary	Enterprise	NL
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1. Executive Summary

In response to intensifying sustainability imperatives, there is an urgent need to accelerate actions towards maximizing the potential of battery reuse in both second and third lives. This imperative arises from the increasing adoption of Electric Vehicles (EVs) and the associated surge in end-of-life batteries.

The concepts of reuse, remanufacture, refurbish, and recycle present avenues to extend the life cycle of EV batteries, mitigating environmental impact and optimizing resource utilization.

This executive summary outlines the critical steps in the battery lifecycle, from the conclusion of an EV's first life battery to the intricate processes of visual assessment, characterization, and the technical decisions regarding module or cell dismantling. It further explores the possibilities of repurposing for diverse applications, such as stationary energy storage or urban mobility, contributing to a more sustainable and circular battery economy.

A detailed decision tree is described in this document for the handling of Lithium Fer Phosphate (LFP) and Nickel Manganese Cobalt (NMC) EV batteries that are not suitable anymore for their first life purpose. It paves the way for 2nd and 3rd life scenarios for batteries in a variety of applications with the description of their associated key requirements. It specifically details the scenarios for module and cells repurpose.

2. Introduction

The management and classification of batteries at their end-of-life stage serve as pivotal cornerstones in the broader realm of sustainable circularity. This chapter aims to dissect the intricate web of principles and practices encompassing the sustainable lifecycle of batteries, primarily focusing on the fundamental concepts of 'Reduce, Redesign, Rethink, Repair, Reuse, Refurbish, Remanufacture, Repurpose, and Recycle.' These guiding principles form the backbone of a paradigm shift in resource management, underscoring the imperative need to re-evaluate our production, consumption, and disposal patterns, especially within the context of battery technologies.

In examining the diverse dimensions of battery life cycles, a comprehensive understanding of the 2nd and 3rd life concepts emerges as crucial. The notion of a battery's second and third life expands beyond mere initial use, emphasizing the possibilities of prolonging its utility through a series of strategies. These strategies, encapsulated within the principles of sustainable circularity, offer avenues for extending the functionality of batteries well beyond their primary applications.

The applications of sustainable circularity within the battery ecosystem find wide-ranging relevance across multiple sectors. Notably, within stationary energy storage, both on-grid and off-grid solutions benefit from the repurposing and reutilization of batteries, mitigating waste and contributing to a more efficient energy landscape. Similarly, telecom, mobile applications, back-up power systems, and urban micro-electro-mobility derive substantial advantages from implementing strategies aligned with the principles of sustainable circularity.

Focusing on specific battery chemistries, this document narrows its scope to Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP) technologies. These chemistries hold significant prominence within the battery landscape, and understanding their end-of-life strategies is imperative in shaping a more sustainable future for battery management and disposal.

To streamline the process, a proposed decision tree shall be introduced. This decision tree will guide the battery's journey from the moment it reaches the end of its initial life. It will detail the evaluation process, potentially leading to the dismantling of batteries at, at least, the module level, and ultimately culminating in the selection of the most suitable circular economy strategy.

In essence, this chapter delves into the intricate mechanisms and strategic pathways essential for the sustainable management of batteries at their end of life. By investigating the principles of sustainable circularity, exploring the diverse applications in various sectors, and proposing a structured decision tree, this document aims to lay the groundwork for a more cohesive and eco-conscious approach to the end-of-life management of NMC and LFP batteries, ensuring a more sustainable and circular battery economy.

3. Battery circular economy

In this section of the deliverable the concept of Battery Circular Economy is described.

3.1 Sustainable circularity of batteries

The sustainable circularity of batteries encapsulates a diverse array of foundational principles that resonate deeply with the ethos of a circular economy. At its core, this concept embodies a series of critical tenets—*'Reduce, Redesign, Rethink, Repair, Reuse, Refurbish, Remanufacture, Repurpose, and Recycle*.' These principles serve as the guiding pillars for a fundamental paradigm shift in our resource management strategies, urging a comprehensive re-evaluation of the ways we produce, consume, and discard materials.

'Reduce' stands as the initial and essential step, advocating for the diminished use of resources (Diehl, 2023), be it raw materials, energy, or water, during the manufacturing process of batteries. This principle emphasizes the optimization of production methods, aiming to curtail waste and energy consumption while fostering resource efficiency. Accompanying this is *'Redesign'*, a concept focusing on reconfiguring product design and manufacturing processes to minimize environmental impact. It involves integrating eco-friendly materials and ensuring products are more easily disassembled for future reuse or recycling.

'Rethink' mirrors a broader perspective—a call to reassess our consumerist culture and challenge conventional notions of ownership and disposability. This principle urges a shift in mindset toward durability and longevity, fostering a more responsible and sustainable relationship with products, including batteries. This implies a systemic re-design in principle, or even at the "system-of-system" level, broadening the concept to a more sociologic perspective. Furthermore, *'Repair'* encourages the practice of extending a product's lifespan through maintenance and repair services, reducing premature disposal and contributing to a circular economy.

'Reuse' and *'Refurbish'* align with the idea of extending a battery's lifespan. *'Reuse'* emphasizes utilizing complete or partial part of the batteries in their original form for the original purpose it was designed for, potentially after *'Repair'*, while *'Refurbish'* involves restoring batteries to a near-original state, increasing their usability and postponing their journey toward disposal.

Moreover, *'Remanufacture'* and *'Repurpose'* signify more intricate methods of restoring batteries. 'Remanufacture' involves disassembling, inspecting, and rebuilding batteries to a like-new condition for their original purpose, aligning with the principles of a circular economy. *'Repurpose'*, on the other hand, entails creatively reimagining old batteries for entirely different uses, preventing them from becoming waste and promoting resource efficiency.

Finally, *'Recycle'* signifies the end-of-life stage, advocating for the proper disposal and recycling of batteries to recover valuable materials, thereby closing the loop in the circular economy. These principles collectively serve as the guiding beacons, steering the discourse on sustainable circularity and underscoring their vital role in shaping the second and third lives of batteries. Through an exploration of each principle's significance, we aim to illuminate their pivotal role in achieving a sustainable and circular battery economy while mitigating environmental impact and optimizing resource utilization across multiple life stages.

Table 1 - Re-strategies for sustainable circularity of batteries (HSSMI, 2020)

Re-strategy	Definition
Reduce	Maximized material and energy efficiency, doing more with fewer resources
Redesign	Smarter manufacturing and product design
Rethink	Smarter mobility and energy storage
Repair	Restore of defects
Reuse	Complete or partial reuse of the battery for the original purpose the battery was designed for, potentially after repair
Refurbish	Restore an old product and bring it up to date for the original purpose
Remanufacture	Use parts of discarded products in a new product for the original purpose
Repurpose	Complete or partial use of the battery (battery packs and components) in a different application than its original purpose
Recycle	Turning batteries into raw materials (e.g., lithium, cobalt, graphite) which can be used again, usually for completely new products

Battery repurposing, often confused with reuse, means the complete or partial use of the battery in a different application than its original purpose. Batteries are rarely reused for their original purpose because their technical properties deteriorate during use (Hu et al., 2020). Instead, before recycling the lifetime of batteries can be extended through repurpose, i.e., a second-life application (Casals et al., 2019; Martinez-Laserna et al., 2018; Shahjalal et al., 2022) or even a third-life application (Ribeiro da Silva, 2023). Ideally, following the principles of a circular economy with the aim of extending the lifetime, batteries will go through multiple cycles before recycling as shown in Figure 1 (Quinteros-Condoretty et al., 2021).

2nd life batteries are those that have been removed from their original purpose (e.g., EVs) due to diminished capacity or performance due to some form of degradation, but still have enough capacity to be useful in less demanding applications. These batteries can be repurposed for applications that require lower power and energy (e.g., energy storage, ~60-80% capacity left), giving them a "second life".

Further, 3rd life batteries are those that have been removed from 2nd life applications (e.g., energy storage systems) due to diminished capacity or performance, but they still have enough capacity to be useful in less demanding applications (e.g., backup power, **~40-60% capacity left**), giving them a "third life".

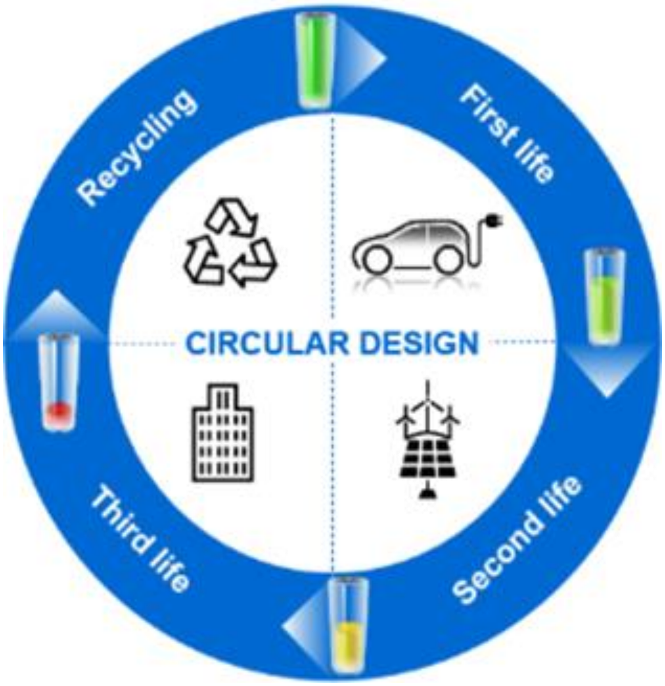

Figure 1 - Circular design of LIB with extended purposes (Quinteros-Condoretty et al., 2021)

It is worth mentioning that, depending on the state of health of batteries after 1st life, they could directly be allocated to 3rd life applications, due to their depletion, and inability to support 2nd life applications.

2nd and 3rd life applications of batteries offer a variety of benefits that go beyond their initial use, contributing to sustainable practices and resource optimization. Here is a breakdown of some advantages:

- **Reduced environmental impact and extended battery lifespan:** the 2nd and 3rd life applications of batteries significantly contribute to reducing environmental impact by extending the functional life of batteries. By repurposing and reusing batteries beyond their initial application, it lessens the frequency of raw material extraction and production processes. This approach effectively reduces the carbon footprint associated with the manufacturing of new batteries, thus conserving resources and energy. Additionally, it minimizes the environmental strain caused by the disposal of used batteries, as they are diverted from landfills or incineration, mitigating potential soil or air pollution that might arise from battery waste.

- **Optimized Energy Utilization:** utilizing batteries in the 2nd and 3rd lives significantly contributes to enhanced energy management. These batteries, which might have lower performance thresholds for certain applications after their initial use, find new life in secondary applications like stationary energy storage, grid support, of backup power systems. By repurposing these batteries, the energy storage infrastructure gains greater flexibility and reliability. This, in turn, leads to more efficient management of renewable energy sources and contributes to stabilizing the grid during peak demand periods. It allows for a more balanced and resilient energy network, reducing reliance on fossil fuels and promoting cleaner energy utilization.

- **Creation of new markets:** the 2nd and 3rd life applications of batteries pave the way for innovative market opportunities. As batteries are repurposed for secondary uses, such as energy storage solutions in various industries, it creates a new market niche. These applications foster the development of emerging industries centred around battery refurbishment, reconfiguration, and repurposing. This trend sparks entrepreneurial initiatives and stimulates a competitive market focused on the utilization of these batteries in novel, innovative ways. Such diversified market opportunities encourage economic growth and foster creativity in product development, driving forward a more sustainable and circular economy.

- **Reduced costs:** the use of batteries in their 2nd and 3rd life presents a cost-effective alternative to businesses and industries. Extending the lifespan of batteries minimizes the need for frequent replacements, thereby reducing the overall expenses associated with procuring new batteries. This approach not only lessens the financial burden on organizations but also contributes to a reduction in waste management and disposal costs. By employing batteries in secondary applications, the initial investment made in batteries pays off over an extended period, effectively optimizing resources and providing a more economically sustainable solution compared to frequent new purchases.

Nevertheless, potential drawbacks also need to be considered, such as:

- **Safety**: the risk of a fire or explosion is rising as the battery ages, as the probability of less careful handling compared to 1st life, is rising with time and usage, especially at 3rd life stages.
- **Reliability**: for similar reasons as mentioned in the above paragraph, the battery degradation might lead over time to them prematurely failing.
- **Cost**: the cost of refurbishing and repurposing lithium-ion batteries, especially at the 3rd life stage, may be high, and the economical equation might be not obvious compared to new batteries.

The viability of the third life of lithium-ion battery systems from electric vehicles (EVs) hinges on factors such as refurbishing costs, demand for third-life applications, and environmental benefits. Refurbishing costs are likely to decrease with technology advancements, and demand is expected to rise alongside the increasing number of EVs. Extending battery lifespan yields environmental benefits, reducing premature recycling needs and associated emissions. While third-life viability is promising under specific conditions, challenges like the need for open standards and automated methods persist. Improving safety, reliability, and reducing refurbishing costs can further enhance the potential of third-life batteries as EV adoption grows.

3.2 2nd and 3rd life applications

In this paragraph, we present succinctly the potential 2nd and 3rd life applications that will be detailed further on with a decision tree.

Multiple applications for EOL batteries could be found in the literature and in different projects across Europe. Some are based on application in stationary energy systems (SES) where batteries can be applied in different stages across the electricity chain, from huge storage systems supporting generation of electricity, to small devices for residential purposes and other uses for micro urban electromobility purposes. As a result, we classified and order the 2nd and further applications into 5 categories.

- **Stationary energy storage:** This includes applications such as backup power for homes and businesses, and grid-connected energy storage.
- **Telecoms:** Lithium-ion batteries can be used to power telecoms equipment, such as cell towers and base stations.

- **Mobile Applications**: various forms of transportation that rely on powerful mobile power sources (compared to smaller devices like e-bikes), including EV, etc. EV Charging stations are in this chapter, for 2nd life applications…
- **Uninterruptible power supplies (UPS):** UPSs are used to provide backup power for computers and other critical equipment.
- **Urban Electromobility:** applications for Light Means of Transport.

Table 2 – Classification of 2nd and 3rd life applications for EV batteries

Categories	Applications
Stationary Energy Storage (on-grid)	• Renewable farming • Area & Frequency Regulation • Load levelling • Generation-side Asset Management • Peak shovelling • Reactive Power Support
Stationary Energy Storage (off-grid)	• Microgrid • Smart Grid • Load Following • Power Quality & Reliability & Spinning Reserve
Telecoms	• Powering Telecom Towers • Powering Base Stations
Mobile Applications	• EV • Electric boats • Electric Aircraft and Drones • EV Charging Stations
Back-up Power Uninterruptible Power Supplies (UPS)	• For Home • For Businesses
Urban Electromobility	• E-Bikes • Scooters • Light Mobility Transportation

3.3 Battery key indicators definition

To facilitate informed decision-making regarding the repurposing of lithium-ion batteries (LIBs) for second and third life applications, the decision process should rely on precise technical parameters.

Here are defined the key technical indicators used throughout the document to assess battery state for decisions about their potential.

Table 3 – Definition of battery technical indicators

KPI	Unit	Definition
Capacity	Wh, kWh	Amount of energy a battery can store
Power Density	W/kg	Amount of power (e.g., energy per unit of time) that can be delivered from a battery per unit of mass. (Batteries with a higher power density allow EVs to accelerate faster)
Cycle lifetime	Cycles	Number of charge and discharge cycles that a battery can complete before losing performance.
Calendar Lifetime	Years	Number of years in which a battery loses its full capacity over time due to internal chemical processes.
C-rate (discharge/ charge rates)	C	It measures the speed at which a battery is charged or discharged. 1C means that a battery is charged from 0-100% in 1 hour.
Voltage	V	Amount of electrical potential a battery holds, measured in volts.
Operating Hours	Hours	Amount of time a battery is delivering energy
Ambient temperature /operating temperature range / Storage conditions for LIB	°C	LIBs should be stored in a dry, clean and well-ventilated warehouse with a temperature of 5 - 40 °C.
Energy Stored	Wh	It depends on voltage and on the charge entered by electrical current over certain time. The SI unit for energy is Joule. For batteries the unit Watthours [Wh] is used. (1 Wh = 3600 J)
Energy Density (gravimetric)	Wh/kg	Amount of energy that can be stored and released per unit mass of the battery. It is also called Specific Energy.

Energy Density (volumetric)	Wh/m³, Wh/l	Amount of energy that can be stored and released per unit volume of the battery
Charge Capacity	Ah	Amount of electric charge a battery can deliver or store. The more electrode material (charged particles) contained in the cell the greater is the capacity.
Charge Efficiency	%	The ratio of between the energy consumed by the charging process and the energy saved by the battery. Affected by battery type, temperature, rate of charge and state of charge.
Energy Efficiency	%	The ratio of electrical energy supplied by a battery over the amount of energy, required to return it into charged state.
Self-Discharge Rate	%	Rates how much capacity the battery loses over time if it is not recharged (batteries slowly discharge when left unused). Affected by battery type, temperature (higher temperatures increase self-discharge). determined by the electrode material, the manufacturing process, the storage conditions, and other factors. A typical Lithium-ion discharge rate is between 2-4% per month.
State of Charge (SoC) & Depth of Discharge (DoD)	%	The level of charge of an electric battery relative to its capacity. 0% = empty and 100 % = fully charged. Depth of discharge (DoD), is the inverse of the State of Charge, where 100 % DoD is equal to a fully discharged and 0 % is equal to a fully charged battery.
Capacity State of Health or State of Health (CSoH or SoH)	%	Ratio between of the energy capacity available at the time of the measure over the energy capacity when the measured battery was new (as specified). Battery's performance is affected by power, internal resistance, capacity, voltage, self-discharge.
Power State of Health (PSoH)	%	Power SoH is related to the increase in internal resistance of the battery module over time and is defined as the increase of the internal resistance relative to its original value, as stated by the manufacturer in its technical datasheet.
Coulombic Efficiency	%	Ratio of actual charge delivered during discharge to the charge supplied during charge. Effectiveness of the charge transfer process during cycling.
Cell Swelling, Constrained Swelling		Battery swelling, also known as lithium-ion battery swelling, is a phenomenon where a battery's physical dimensions increase beyond its normal size. Battery swelling is a cause for concern because it not only affects the performance of your device but also poses safety risks. Constrained Swelling is referring to battery swelling in constrained (not free) conditions, where many boundary factors affect the swelling force.
Open Circuit Voltage (OCV)	V	The OCV of a battery cell is the potential difference between the positive and negative terminals when no current flows and the cell is at rest. OCV needs to be established versus the State of Charge (SoC) of the cell from 0% to 100%

Internal Resistance	Ohm	Internal resistance defines the power loses the battery may experience under load and it is an indicator of power degradation with use, since it tends to increase as the battery is cycled. Generally, it may be calculated from as the ratio between its open circuit voltage and load voltage minus 1, multiplied by the load resistance.
Impedance	Ohm	While for some stationary batteries the internal resistance value is measured, for mobility and micro batteries, which deal more with fast current rates shifts, the impedance KPI is the standard reference to evaluate the characteristic of a cell in terms of opposition to the demanded flow of current. Battery impedance is a combination of internal resistance and reactance where internal resistance + reactance, or (L+ C), equals impedance when using an ac stimulus. The internal resistance of a battery is made up of two components: electrical, or ohmic, resistance and ionic resistance. Electrical resistance is a measure of the opposition to current flow in an electrical circuit whereas ionic resistance is a measure of opposition to current flow due to internal factors such as electrode surface area and electrolyte conductivity. Internal ohmic values (AC resistance) can be useful as a trending tool and can help to indicate the overall health of a battery being measured. This AC resistance can be measured using an "injection method" by where a small current, 1000Hz AC for example, is injected into the battery. Then, any variations are calculated using Ohm's law.
Energy Throughput	cycles	Energy throughput is the total amount of energy a battery can be expected to store and deliver over its lifetime. By extension, in 2nd or 3rd lives contexts, it is the total amount of energy left into a battery that it can be expected to store and deliver over its remaining lifetime. Although it should be expressed in Wh, we would express it as the expected full cycles of charge/discharge it can deliver in its remaining lifetime.
Cell Balancing		Cell balancing is the process of equalizing the voltages and States of Charge (SoC) among the cells when they are connected and at full charge in a battery module/pack.
Relative Voltage Spread	V	Battery relative voltage spread refers to the difference in voltage levels among individual cells within the battery system. It quantifies the extent of variation in voltage readings across the cells, providing insight into the uniformity of charge and discharge states. A low relative voltage spread indicates balanced cell performances, ensuing optimal energy distribution and enhancing the overall efficiency, longevity, and safety of the battery module or pack.
Voltage Balancing		It is a concept close to Cell balancing, specifically focusing on equalizing the voltage levels among individual cells within a battery module or pack.
Current Balancing		Current balancing addresses the distribution of current among cells during charging and discharging processes. It ensures that each cell within a battery module or pack receives a proportionate share of the total current during charging or discharging. It prevents certain cells from experiencing high currents than others, mitigating the risk of overcharging or over discharging specific cells. Imbalances in current distribution can

		lead to uneven wear and tear, affecting the overall performance and lifespan of the battery.
State of Function		The battery specific continuous or instantaneous power output capability in a period. In other words, the functional status (State of Function) of battery, namely refers under any given discharge and recharge condition, the charging and discharging currents limit of the battery that can dope, voltage limit and power threshold.
Cycling Efficiency		Cycling Efficiency is the ratio of energy output during discharge to the energy input during charging.
Rate Capability	C-rate	Rate capability refers to the ability of a battery to deliver or absorb electrical energy at different rates of charging or discharging. It is a measure of how well a battery can respond to changes in the demand for electrical power.

4. Preliminary decision tree

A decision tree is a specific type of flowchart to visually outline the decision-making process by mapping out different courses of action, the potential outcomes and consequences of a complex decision (Magee, 1964). Therefore, the REINFORCE strategic decision tree for 2nd and 3rd life applications provides a systematic framework to guide stakeholders in making informed choices regarding the repurposing of batteries.

The decision tree for EoL batteries incorporates various factors and considerations, starting with the assessment of the battery conditions and remaining capacity (HSSMI, 2020). Technical feasibility of batteries is evaluated based on their health, performance and safety (Zhu et al., 2021). Even though all EoL strategies are important for the circularity of LIBs, and they should be taken into account in decision-making, the focus in REINFORCE is on repurposing for 2nd and 3rd life and recycling.

4.1 Preliminary criteria for the decision tree

The following steps are considered in the decision-making for REINFORCE decision tree (Figure 2): (1) definition of the battery type; (2) identification of the battery chemistry; (3) definition of the battery unit; (4) availability of the battery management system (BMS); and (5) state of health (SoH) assessment of the battery.

- **Battery type**: REINFORCE is assessing two types of battery inputs:
    1) EoL batteries from EVs, which have gone through their 1st life.
    2) EoL batteries from stationary applications, which have gone through their 2nd life and previously have been used for EVs in their 1st life.

- **Battery chemistry**: REINFORCE is exploring two main LIB chemistries:
    1) Lithium nickel manganese cobalt oxide (NMC), which was dominant battery chemistry with 60% of the market share in 2022 (IEA, 2023b).
    2) Lithium iron phosphate (LFP), which has 30% of the market share in 2022 (IEA, 2023b).
- **Battery unit**: REINFORCE is assessing batteries at module and cell level. At a pack level, the assessment of the SoH is very difficult due to the ageing of the pack unevenly across the modules and cells (Harper, 2).
- **Battery Management System (BMS):** REINFORCE is studying both the batteries with BMS and the historical data available and the batteries without BMS and/or the historical data available.

- **State of Health (SoH) assessment**: REINFORCE is evaluating the SoH, e.g., the battery energy capacity, through a set of KPIs.

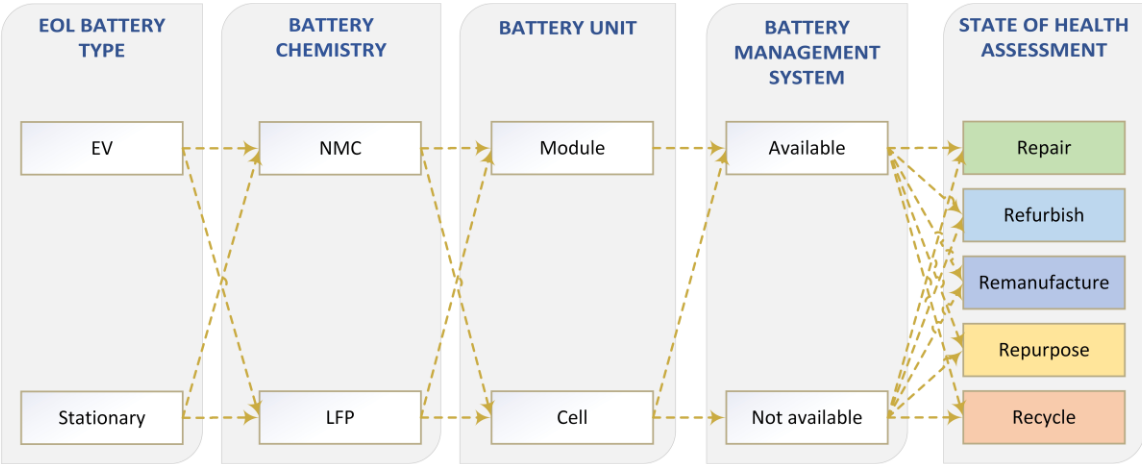

Figure 2 - Preliminary flow of variables

4.2 Preliminary decision tree for EoL batteries

In this section, we describe a 1st version of a decision tree for REINFORCE end-of-life battery assessment that will combine the key concepts, applications and KPIs disclosed in previous sections of the document to support the decision-making process of REINFORCE. Next section will detail the steps of the decision tree with precise KPIs.

Figure 3 presents the preliminary REINFORCE strategic decision tree for repurposing LIBs for 2nd and 3rd life. By following this strategic decision tree, stakeholders can make well-informed decisions that align with their objectives, maximize the value of batteries, and contribute to a more sustainable and efficient circular battery value chain.

REINFORCE decision tree follows the following steps:

- STEP 1. Evaluating the battery status and safety
- STEP 2. Evaluating the availability of BMS and battery historical data
- STEP 3. Dismantling the battery at a module level or at a cell level if necessary, depending on the assessment of the SoH of the battery unit.
- STEP 4. Determining the most adequate circular economy strategy
- STEP 5. Repurposing for 2nd and 3rd life

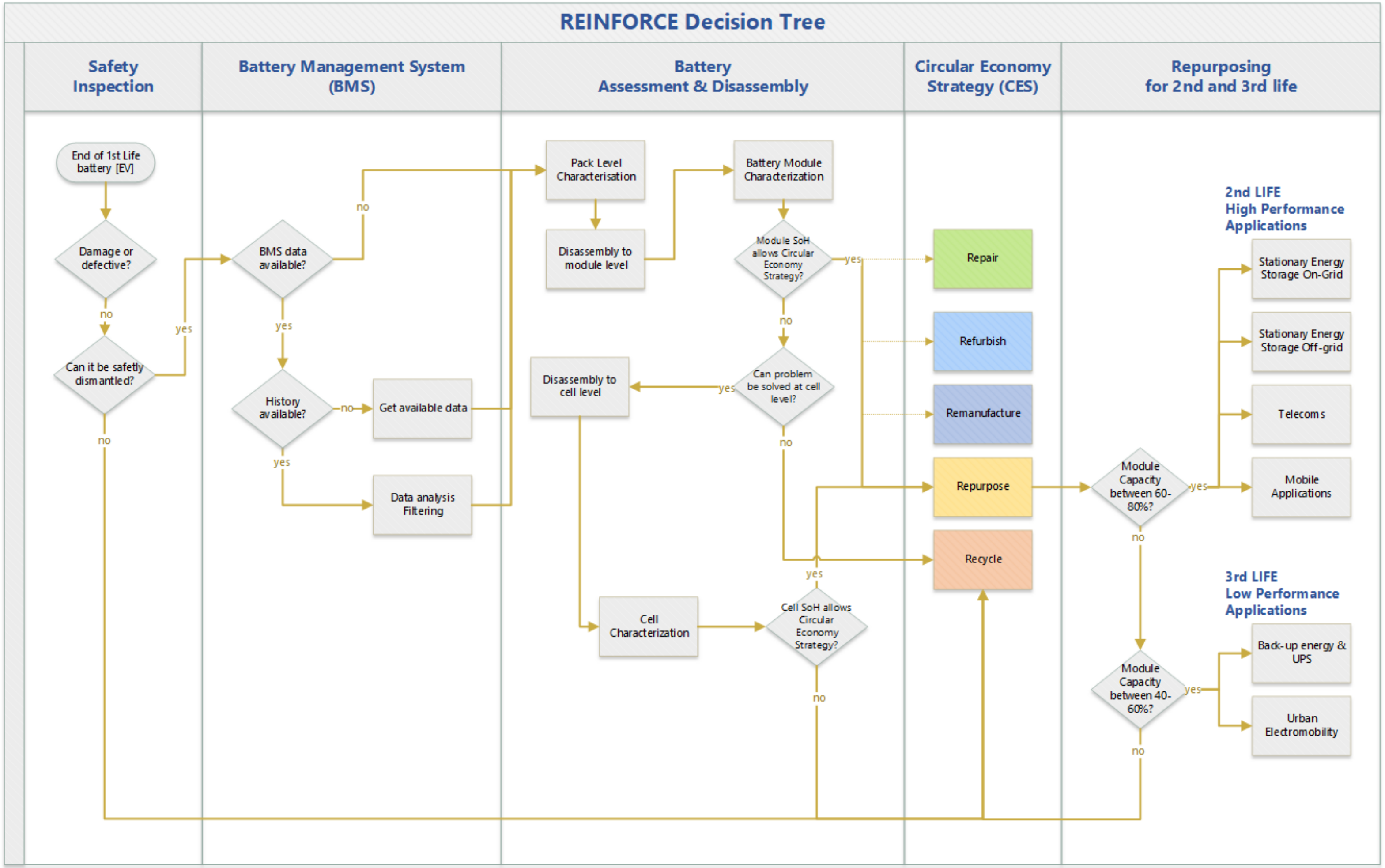

Figure 3 - Preliminary REINFORCE strategic decision tree for repurposing LIBs for 2nd and 3rd life

5. Detailed criteria for the decision tree

In this chapter, we detail the criteria that have been briefly described earlier in the document, to make more informed decisions at each step of the decision tree.

5.1 Safety Inspection

The first step of the decision tree consists in assessing if the battery unit is damaged and can be safely dismantled.

5.1.1 Damaged or defective battery

Recognizing the damage sustained by a battery is essential in screening incoming units and deciding whether to proceed with the second life procedure or to recycling. Modules and cells under abusive conditions may suffer serious damage that compromises their integrity. Abusive electrical conditions such as overcharge, over discharge and short circuit, as well as thermal abuse from external heating or overheat due to efficient dissipation of generated heat, can result in internal decomposition of the cell. Whilst external mechanical abuse, from impacts, vibrations, penetrations or overpressures can damage the electrodes and generate an internal short-circuit. These extreme conditions may result in thermal runaway, development of gases, safety vent cracking and, ultimately, fire and explosion (V. Rajaraman, 2021).

Visual recognition is required to evaluate the battery exterior state and discover any possible damage at pack level, and, if happens to be, at module level. If there is access, cells should also be checked for defects, both from an exterior source or from internal pressure, and for electrochemically induced constrained swelling (A. L. Govindaraj, 2022). Depth of defects in cell surfaces should be measured to evaluate penetration through the casing wall and into the active electrolytic material inside (Haoze Chen , 2022).

Moreover, the calendaric lifetime of the battery is a parameter defined as indicative of the level of potential defective state of the battery. It is generally established that a battery has reached its period of reliable operation after 10 standard calendaric years after the battery has been put in the market or into service. After this period, manufacturers are not required to keep standing technical documentation and importers are not required to keep a copy of the EU declaration of conformity at the disposal of national authorities, according to the last EU directive (The European Parliament and The Council, 2023).

Table 4 – Key indicators to identify damaged battery

KPIs		Defective
Depth of defect	> Casing width	Yes
	< Casing width	No
Constrained swelling	> 5%	Yes
	< 5%	No
Calendaric Lifetime	> 10 years	Yes
	< 10 years	No
Visual aspect	Cell swelling	Yes/No

5.1.2 Safe dismantling

Safety in dismantling is extremely relevant in the battery industry, but especially when treating with already used batteries destined to 2nd life reemployment, since they arrive at unknown states of hazard levels and degradation.

The first concern of the battery safety during its dismantling comes in knowing its chemistry, since each chemistry will have different hazard risks associated, relative to handling requirements and conditions, levels of toxicity of its components, levels of chemical reactivity and others. So, defining the chemistry of the battery with certainty is the first step in the handling and dismantling process.

Then, we must consider the electrical source of risk, which comes from the potential of uncontrolled discharges coming from the battery system, therefore the open circuit voltage of the battery at rest must be measured, both at pack and at module or cell level. Voltages within typical operating conditions can be considered safe for handling, but voltages out of operational boundaries pose a serious safety concern.

Table 5 – Key indicators for safe dismantling of batteries

KPIs		Safe
Cell chemistry	Defined chemistry	Yes
	Undefined chemistry	No
Open circuit Voltage (V)	$V_{max} > V > V_{min}$	Yes
	$V > V_{max}$; $V < V_{min}$	No

5.2 Battery Management System Data

BMS data recovery is a very important step in battery diagnosis for adequate Second Life routing. If the BMS is operational, the recorded data is trustworthy (presumably) and we have full access to it, we should utilize this data as reference in our analysis. A modern BMS can record data both at pack and at module level, allowing us to know the capacity fade spread among the modules and the module with the most degradation that conditions the whole pack. In fact, the main functions of a BMS are (Mahammad A. Hannan, 2018):

- Battery Cell Monitoring: Input and output current and voltage measurement, temperature control, over and undercharge protections, etc.
- Charge and discharge control
- State estimation: Observer-based estimation of SoC, SoH and SoF (State of Function)
- Battery protection
- Cell balancing and equalization
- Power management control
- Operating temperature and heat management
- Communication and networking
- Data acquisition and storage
- Fault diagnosis and assessment

The data that the BMS stores is the last record of voltage readings for each module/cell, charge/discharge conditions, last temperature sensor record, as well as the last state estimations, of SoC and of SoH, and other data such as values possibly required by the EMS (Energy Management System) or other host application.

Module/cell balancing is also a key functionality of a well performing BMS. There are different methods for module or cell balancing, divided in passive balancing, where charge differences between modules are passively dissipated with resistors, to active balancing, where charge is actively redistributed between them.

The main parameters that can be extracted from the BMS are:

- **OCV**: Open circuit Voltage is key in defining the current state of the battery on arrival, and is therefore interesting to read it for each module directly from BMS measurement, without need of further testing, allowing us to immediately recognize potentially unstable batteries (over or undercharged)

- **SoC**: State of charge is associated with voltage and reading it for each module directly from BMS estimations allows us to immediately characterize the battery.

- **SoH**: More specifically capacity SoH calculated by the BMS through observer-based algorithms online during use. Both at pack and at module level, to define the most degraded module [13].

- **Relative Voltage spread**: Describes the degree of cell balancing achieved by the BMS and gives us information on how well handled the pack has been. It is defined as the maximum difference in voltage between modules relative to the mean module voltage value (E. Brun, 2019): $s_{module}(\%) = \frac{V_{cell,max} - V_{cell,min}}{V_{cell,mean}}$

Table 6 – Parameters extracted from Battery Management System

KPIs	Units	Values
OCV Voltage	V	V> V_{max}; V< V_{min}
SoC (of pack and module)	%	0-100
SoH (of pack and module)	%	40-80
Relative Voltage Spread	%	2
Mileage	km	200.000

From early 2027 each LMT battery, each industrial battery with a capacity greater than 2 kWh and each electric vehicle battery placed on the market or put into service shall have an electronic record ('battery passport'). The battery passport shall contain information relating to the battery model and information specific to the individual battery, including resulting from the use of that battery (European Parliament, 2023).

The information in the battery passport shall comprise:

a) information accessible to the general public in accordance with point 1 of Annex XIII of the New European Batteries Regulation [Regulation (EU) 2023/1542];
b) information accessible only to notified bodies, market surveillance authorities and the Commission in accordance with points 2 and 3 of Annex XIII of the New European Batteries Regulation [Regulation (EU) 2023/1542]; and
c) information accessible only to any natural or legal person with a legitimate interest in accessing and processing that information for the purposes referred to in points (a) and (b) of the third subparagraph in accordance with points 2 and 4 of Annex XIII of the New European Batteries Regulation [Regulation (EU) 2023/1542].

According to of the New European Batteries Regulation - (EU) 2023/1542, the following information is to be included in the battery passport and made publicly accessible information relating to the battery model:

a) the information specified in Part A of Annex VI;
b) the material composition of the battery, including its chemistry, hazardous substances present in the battery, other than mercury, cadmium or lead, and critical raw materials present in the battery;
c) the carbon footprint information referred to in Article 7(1) and (2);
d) information on responsible sourcing as indicated in the report on battery due diligence policy referred to in Article 52(3);
e) recycled content information as contained in the documentation referred to in Article 8(1);
f) the share of renewable content;
g) rated capacity (in Ah);
h) minimal, nominal and maximum voltage, with temperature ranges when relevant;
i) original power capability (in Watts) and limits, with temperature range when relevant;
j) expected battery lifetime expressed in cycles, and reference test used;
k) capacity threshold for exhaustion (only for electric vehicle batteries);
l) temperature range the battery can withstand when not in use (reference test);
m) period for which the commercial warranty for the calendar life applies;
n) initial round trip energy efficiency and at 50 % of cycle-life;
o) internal battery cell and pack resistance;
p) c-rate of relevant cycle-life test.
q) the marking requirements laid down in Article 13(3) and (4);
r) the EU declaration of conformity referred to in Article 18;
s) the information regarding the prevention and management of waste batteries laid down in Article 74(1), points (a) to (f).

5.3 Battery Assessment

Characterization of the battery is essential to the correct establishment of Second Life procedures. Moreover, when data from BMS recordings is not fully or partially available or its trustworthiness may be compromised, maybe due to faulty BMS system or no incomplete recorded information, there must be a well-defined battery characterization process that allows us to obtain the missing data of the current state of the battery.

5.3.1 Battery Module Characterization

Characterization of the battery involves obtaining current values for key parameters that describe its current state, and its degree of degradation when compared to the original state of its parameters. It is from this point that we will decide the future destination of the battery modules, be it repair and reinstatement, refurbishing into new configurations, remanufacturing of the battery pack, repurposing, or, when no better option, recycling of the primary battery components.

The first KPI is the state of health of the modules (SoH), which, in short, defines the current degradation state of the energy storage system, that results in a decrease in performance with use, and has a limit value of 80% for first life use (Podias et al., 2018). Two different definitions of the SoH are (Topan et al., 2016): Firstly, we talk about capacity SoH when we refer to the battery capacity fade over time, and it is defined as the coefficient between the current capacity and the original capacity at beginning of use, normally taken from the manufacturers rated capacity in discharge, the defining equation is:

$$SoH_C = \frac{C_{current}}{C_{original}} * 100$$

Then, we talk about power SoH, which is related to the increase in internal resistance of the battery module over time, it is defined as the increase of the internal resistance relative to its original value, as stated by the manufacturer in its technical datasheet. The governing equation is:

$$SoH_R = \left(\frac{R_{int} - R_{int,0}}{R_{int}}\right) * 100$$

Therefore, as these coefficients are defined by the parameters of discharge capacity and internal resistance, we define those as key parameters of our system. Another KPI to consider is Coulombic efficiency (Shunli Wang, 2021), which describes the release capacity of the battery and is the ratio between the discharge capacity at full charge and the charge capacity of the same cycle. Due to electrolyte decomposition, material aging, ambient temperature, and different charge and discharge current rates, the discharge efficiency of the battery is affected, and it is therefore a value descriptive of the battery's charge delivery performance in its current state, making charge capacity key parameter of our analysis.

- **Capacity (charge and discharge)**: The charge capacity is a fundamental parameter to consider in essentially any second-life use, both in charge and discharge. It defines, as stated, the state of capacity degradation of the battery currently, and its recommended destination, as well as the future performance of the system in its second life application. It is subjected to regulations and customer requirements in order to optimize the sizing and economic planning of the second-life installation.

- **Internal resistance**: Internal resistance defines the power loss the battery may experience under load, and it is an indicator of power degradation with use, since it tends to increase as the battery is cycled.

Table 7 – Key indicators to identify battery modules to be repurposed

KPIs		Module to be repurposed
SOH_C	0 – 39 %	No
	40 – 80 %	Yes
SOH_R	0 – 39 %	No
	40 – 80 %	Yes
Coulombic efficiency	0 – 69 %	No
	70 – 100 %	Yes

The modules that cannot be repurposed for a 2nd or 3rd life applications will be dismantled at cell level if the joining technology allows it, as described in the following paragraph. Otherwise, the module will be recycled.

5.3.2 Battery Cell Characterization

This paragraph presents a decisional framework to assess the best circular economy strategies for single cells obtained by the disassembly of battery modules. Of course, this is possible only if cells can effectively be disassembled from modules.

Commercial battery modules sometimes exploit joining technologies which limit the possibilities to perform disassembly at cells level. The most common examples are:

- **Cell-to-cell ultrasonic welding of pouch cells**: pouch cells are joined without the use of an external busbar. The poles (metallic foils) are directly welded together. In this case, cells disassembly must be performed by poles cutting, and the same cells can't be reassembled.
- **Glue**: sometimes cells are glued together. If so, the cells extraction process becomes too aggressive to guarantee the non-damage of cells.

As a consequence, the decisional step of this paragraph is applied only to those batteries suitable for cells level disassembly.

Li-Ion cells constitute the fundamental brick of battery assemblies (modules, packs). They can't be repaired or refurbished to restore their electrochemical performance. Therefore, their circular economy approaches are limited to three options:

Cell to be remanufactured: namely a cell which can be reused in the same battery (or the same battery model) of its first life. It's the most added value scenario, to be prioritized when the cell has compliant KPIs. A clear definition of remanufacturing is provided by the new European Regulation of Batteries and Waste Batteries (Chapter 1, Article 3, Definition 32):

'remanufacturing' means any technical operation on a used battery that includes the disassembly and evaluation of all its battery cells and modules and the use of a certain number of battery cells and modules that are new, used or recovered from waste, or other battery components, to restore the battery capacity to at least 90 % of the original rated capacity, and where the state of health of all individual battery cells does not differ more than 3 % between cells, and results in the battery being used for the same purpose or application as the one for which the battery was originally designed;

Cell to be repurposed: when a cell is not suitable for remanufacturing, but its performance is still acceptable (according to the manufacturer's recommendation), it can be repurposed for a less demanding application.

Cell to be recycled: if the cell residual performance is not acceptable, the cell must be recycled.

The above-mentioned circular economy strategies for cells are unlocked by the combined compliance of specific parameters, measured on each cell.

- **Capacity SoH**: the capacity state of health is the most used parameter to assess the residual performance of a battery. It is calculated as a percentage of the residual capacity of the battery cell [mAh], compared with the nominal capacity.

- **Impedance**: each battery cell model has a maximum impedance threshold (verified at standard testing conditions, typically 1 kHz). Cells to be either remanufactured or reused must not exceed this threshold.

- **OCV**: each battery cell model has a maximum and minimum operating Open Circuit Voltage. If the diagnosis of the cell measures an OCV above maximum allowed value or below minimum allowed value, the cell must be considered defective and not reusable.

All the above-mentioned reference parameters, and the diagnosis guidelines, can be found in each battery cell model manufacturer datasheet. Here are two examples: (SAMSUNG SDI), (LG Chem).

The circular economy strategies identified for battery cells, and the parameters to drive the decision are combined according to the matchmaking table below. A circular economy strategy is unlocked only if all the parameters are satisfied.

Table 8 – Key indicators to define cell end-of-life strategy

	Cell to be remanufactured	Cell to be repurposed	Cell to be recycled
SoH	≥ 90% *from definition of remanufacturing	≥ 80% *standard threshold for reuse	<80%
I	≤ cell datasheet threshold	≤ cell datasheet threshold	>datasheet threshold
OCV	OCV_Min < OCV < OCV_Max	OCV_Min < OCV < OCV_Max	OCV <= OCV_Min OR OCV>= OCV_Max

6. Repurposing for 2nd and 3rd life

This paragraph defines the 2nd and 3rd life scenarios for batteries in a variety of applications with the description of their associated key requirements.

6.1 Stationary energy storage (on-grid)

6.1.1 What are stationary energy storage batteries (on-grid)?

On grid stationary storage will provide a solution to (temporary) store sustainable energy which can be used when there is a lack of energy provision or higher need of consumption, with access to the grid. In case of overcapacity of generated energy there is the possibility of delivering energy to the grid, so energy will be spilled and can be used elsewhere.

The usage of second life cells and modules forms an electrochemical energy storage system from 1 kW up to 50 MW depending on the application.

6.1.2 On-grid Energy Storage Technologies

The largest form of grid energy storage is done by balancing the grid and aligning the supply and demand of electricity. In the past it was mainly done by upscaling and down scaling power plants. Moreover, hydroelectric power stations where water reservoirs are a flexible source to provide energy to the grid.

With the introduction of renewable energy (solar and wind) there is no possibility to control the supply of electricity. The rise of energy storage by the use of batteries is becoming more interesting. To ensure a small- and large-scale solution nowadays LFP battery energy storage is predominant in 1st life, whereas we see a shift to NMC battery energy storage in 2nd life due to the fact that this is mainly used in electrical vehicles first life.

6.1.3 Requirement for Stationary Applications (on-grid)

The stationary applications on grid requirements don’t differ a lot from an off-grid application therefore, remaining capacity, high efficiency and low resistance are the first 3 KPI’s to decide if batteries are able to be used. Moreover, to add value as a 2nd life opportunity there has to be enough capacity available of the same generation and SoH of the different modules to balance into a system up to 50 MW, depending on the scale of the storage.

The main difference in comparison with other stationary applications is that this energy storage is not a stand-alone solution and always has to be connected to the grid. Therefore, additional inverters are needed as power conditioning equipment. Due to the variety of applications multiple inverters can be applicable based on the voltage output and ad/dc conversion.

6.1.4 KPIs for Stationary Applications

- **Mechanical Stress Tolerance:** Less requirements than automotive sector.
- **Chemical Stability:** Long-term stability against chemical reactions within the cell is important for maintaining performance over its operational life. The stability of the electrolyte and the cell's internal components is critical for durability.
- **Cycling Performance:** The ability of the cell to maintain its performance over multiple charge and discharge cycles. Good durability in cells ensures that their capacity, internal resistance, and overall performance degrade at a slower rate over time.
- **Thermal Stability:** The ability to handle varying temperatures without significant degradation in performance or damage.
- **Energy Throughput**: Energy throughput at the module or pack level will depend on the specific configuration, state of the cells, and operational conditions. In second life applications, this figure might vary but usually aligns with the cumulative cycles and overall health of the combined cells in the module or pack.
- **Cycling Efficiency**: The expected efficiency for batteries from second life NMC or LFP is above 80% in charge and discharge cycles.
- **Standard Charge Rate** (C-rate): For second life packs, a conservative charge rate of 0.2C to 0.3C is commonly recommended to preserve the remaining capacity and health of the cells in the pack. Generally speaking, lower C rates imply less degradation.

Table 9 – KPIs at Cell level for 2nd life Stationary Applications (on-grid)

KPI	Value
Energy density	100 – 300 Wh/KG
Capacity	25 Ah
Cycle life	550 cycles 80% SOH
Self-discharge	<8%
Resistance	< 1.2 m Ω
Operating temperature	Discharge: -20 to 55 °C Charge: 0 to 40 °C
Rate capabilities	Charge: 3C Discharge: 4C
Standard Charge rate	0.5C

Table 10 – KPIs at Pack Level Stationary Applications (on-grid)

Voltage and current balancing	3.7 V
Temperature management	<40°C
Charge strategy.	4.2V per cell maximum 2.8V per cell minimum
Energy density	Around 100 Wh/kg for NMC
State of Health	70-80%
State of SoC	10-90%

6.2 Stationary energy storage (off-grid)

6.2.1 What are stationary energy storage batteries (off-grid)?

Off-grid stationary energy storage batteries are referred as the battery systems used to supply or complement systems that are not connected to the conventional electricity distribution system, or “macrogrid” (see the first case in next section). This application is often associated with renewable energies such as Photovoltaic and Wind Power, because of its versatility when combined, but this is not the only case of application. Amongst the different case scenarios, off-grid energy storage makes isolated locations suitable for electricity consumption and help regulating the supply conditions in grid of a wide range of size. The most common off-grid stationary energy storage typologies will be described in the following paragraphs.

6.2.2 Stationary energy storage off-grid applications

- **"Microgrid":** this term refers to isolated systems from the conventional electricity distribution system (macrogrid). These leads to a wider range of applications, enabling remote locations to electricity consumption and allowing PV and Wind Power owners to "isolate" the installation from the macrogrid. The biggest issue in these renewables production systems is the dependence on external conditions, energy is not regularly produced, Photovoltaic depends on radiation and Wind Power on wind. The use of these stationary energy storages increases the range of operations using exclusively this kind of energy. In general, batteries would provide a better stability to microgrid systems.

- "**Smart grid":** once the size of the grid increases, without it being connected to the macrogrid, more and more energy sources intervene in the mix of energy. Even with a greater mix of sources, the fluctuance in energy production is lower, it is still necessary to implement certain methods, as stationary batteries, that serve as a tool for peak levelling.

- **Load Following**: a similar approach as described above is Load Following. Generators can change their output to match changes in electric demand. Mechanical systems have more stress if their operation conditions are not stable, for this reason, batteries can be used to adjust the output digitally, without the mechanical components being adjusted.

- **Power quality & reliability**: stationary systems can serve as a backup, that can complement certain supply deficiencies, such as fluctuations in current or short blackouts. Other uses are related to military and emergency uses, as these kinds of systems can prevent the cease of supply in hospitals and military facilities

- **Spinning reserve**: in case of a failure occurring in any of the generators of the grid, the use of a spinning reserve can cover this part of the power supply. This extra power, the spinning reserve, is often obtained increasing the operation conditions of the rest of generators, but it can also be covered by a stationary battery system that provides when the failure is detected.

6.2.3 KPIs for Stationary Applications (off-grid)

As mentioned in section 5.4.1.3, off-grid stationary battery requirements are similar to on-grid applications, as in most of its applications the battery system will serve as a backup (Table 1).

For second life applications, a significant remaining capacity and high efficiency are the most important, but also an optimal monitoring to ensure balance between cells, temperature and current stability to prevent degradation is also required.

For third life applications, high-capacity retention and low internal resistance ensure sustained power delivery during outages, crucial for maintaining uninterrupted communication services. Reliable cycle life and low self-discharge rates guarantee longevity and reliability, essential for backup power in case of prolonged power disruptions, this also can be referred as ability to sustain deep discharging. Wide operating temperature ranges and the ability to handle moderate to fast charging rates are necessary to accommodate various environmental conditions and rapid recharging needs in backup applications Safety features, including effective voltage, current and thermal management, are vital to prevent hazards and ensure stable operation.

Table 11 – Typical values expected for Off-grid stationary battery systems applications.

System	Parameters	Value	Life	
			Second	Third
Battery Overall System	Backup hours	hours	6-18	1
	Capacity required	kWh	5-500	1-100
	Current	A	20-50	16-200
	Power	kW	1-10	5-50
	Cycles per day	Cycles	1-2	<1
	Battery cycles	Cycles	3000	1000
	Battery lifetime	Years	5	2-3

The wide range of this parameters is related to the wide variety of systems that can be included in the potential use case scenarios, hence the difference between each of the potential uses described above is not so high, there are multiple systems that can require this type of backup systems.

6.2.4 KPIs for Off-grid stationary applications (Module/Pack Level)

- **Voltage and Current Balancing**: Ensuring uniform voltage and current across all cells in a module OR pack to optimize performance and lifespan. Ideally, cells in a module or pack should be balanced within a few millivolts of each other for voltage and within a few milliamps for current. Cells in a module or pack should ideally be balanced within a few mV for voltage and within a few mA for current, ensuring uniform performance.

- **Temperature Management**: Monitoring and controlling the temperature of the entire battery pack to prevent overheating and ensure optimal performance. Operating within a range of 0°C to 40°C or wider, with proper cooling or heating systems to maintain the batteries within safe temperature limits. Operating within a range of 0°C to 40°C for NMC and 0°C to 45°C for LFP, with active cooling or heating systems to maintain safe temperature limits.

- **Safety and Monitoring Systems**: Implementing safety measures, such as overcharge and over- discharge protection, short-circuit protection, and cell balancing circuits. Essential for preventing overcharging, over-discharging, and overheating. Set thresholds could be around 4.2V per cell for maximum voltage and 3.2V for minimum voltage. Similar to the general guidelines, ensuring thresholds for overcharge, over-discharge, and maximum and minimum voltage for both NMC and LFP chemistries.

- **Energy Density**: The amount of energy stored per unit volume or weight, which impacts the overall size and weight of the battery pack. Second life batteries may aim for energy densities of 100-200 watt- hours per kilogram (Wh/kg) or more, depending on the specific requirements for space and weight. Second life batteries might have slightly reduced energy density, aiming for around 80-160 Wh/kg for NMC and 90-180 Wh/kg for LFP.

- **Power Density**: At the module or pack level, the power density is usually slightly lower than that of individual cells, ranging from 200 W/kg to 600 W/kg. The power density at this level is affected by the arrangement, thermal management, and packaging of cells in the module or pack.

- **State of Health (SoH) and State of Charge (SoC) Monitoring**: Continuous monitoring of the health and charge level of the entire battery pack. Monitoring to maintain the SoH above 80% and to ensure accurate tracking of SoC for operational readiness. Continuous monitoring to maintain the SoH above 70-80% and accurate tracking of SoC for operational readiness in case of 2nd life applications. Power applications, meaning 3rd life applications, can work with a SoH of 50-70% as long as the frequency of use is restricted to fewer cycles and lower discharges. Once degradation is more than 50% of loss of capacity, the performance of the pack declines faster.

- **Cycling Efficiency**: The expected efficiency for batteries from second life NMC or LFP is above 85% in charge and discharge cycles.

- **Standard Charge Rate (C-rate):** For second life packs, a conservative charge rate of 0.2C to 0.3C is commonly recommended to preserve the remaining capacity and health of the cells in the pack. Generally speaking, lower C rates imply less degradation.

- **Fast-Charge Rate:** Fast-charging rates might be restricted to lower values, around 0.5C or below, to prevent accelerated degradation in the second life phase.

Table 12 – Module/Pack KPIs for Off-grid stationary battery systems applications

KPI	MicroGrid and Smart Grid		Load Following	
	2nd Life	3rd Life	2nd Life	3rd Life
V/A Balance	Depends on the module and application			
Temperature	0-40 ºC	0-35 ºC	0-40 ºC	0-40 ºC
Safety and Monitoring	YES, mandatory			
Energy Density	50-200 Wh/kg (Depends on the module and application)			
Power Density	100-300 W/kg (Depends on the module and application)			
SoH	80%	>70%	80%	>70%
Cycle Efficiency	90%	80%	90%	80%
C-rate	0.3-0.5	0.2-0.3	0.8-1	0.7-0.8
Fast charge-rate	1	0.5	1.5	1

KPI	Power Quality and Reliability		Spinning Reserve	
	2nd Life	3rd Life	2nd Life	3rd Life
V/A Balance	Depends on the module and application			
Temperature	0-45 ºC	0-45 ºC	0-45 ºC	0-45 ºC
Safety and Monitoring	YES, mandatory			
Energy Density	40-200 Wh/kg (Depends on the module and application)			
Power Density	200-600 W/kg (Depends on the module and application)			
SoH	70%	>50%	70-80%	>50%
Cycle Efficiency	80%	70%	85%	80%
C-rate	1-1.5	0.8-1	0.6-0.8	0.4-0.6
Fast charge-rate	2	1.5	1	0.8

6.2.5 KPIs for Off-grid stationary applications (Cell Level)

- **Power Density**: For NMC or LFP Li-ion cells, the power density often ranges from 300 W/kg to 800 W/kg. This measurement indicates the rate at which the cells can deliver power. High power density is vital for applications where high bursts of power are required, such as during grid failure in power grids.
- **Capacity**: It measures the total amount of charge a cell can store and deliver. It's typically measured in ampere-hours (Ah) or milliampere-hours (mAh). Household batteries often require a minimum capacity range of around 80% to 100% of the rated capacity to ensure they can meet the demand during power outages or other critical situations. Household batteries utilizing second life NMC or LFP Li-ion cells typically aim for a capacity retention of 70-90% of the original rated capacity to ensure practical usability in grid backup systems.

- **Internal Resistance**: This indicates the opposition to the flow of current within the cell. Lower internal resistance means better efficiency and power delivery. Lower values are generally better, but typically, a range between 1-50 milliohms could be acceptable, depending on the technology and specific application. For second life applications, internal resistance within the range of 5-40 milliohms could be acceptable for NMC cells, while LFP cells might typically have lower internal resistance in the range of 2-20 milliohms.

- **Cycle Life**: It refers to the number of charge/discharge cycles a cell can undergo while maintaining a certain level of capacity or performance. Second and third life batteries should typically support several hundred to several thousand charge/discharge cycles. For example, a minimum of 500 cycles might be considered necessary for second life applications. Second life applications often have different cycle life expectations due to previous usage. For NMC, a minimum of 800 cycles, while LFP might maintain over 2000 cycles could be expected.

- **Self-Discharge Rate**: The rate at which a cell loses its charge when not in use, which is crucial for standby or backup applications. Grid backup batteries should have a low self-discharge rate, often less than 3% per month for reliable standby power. Low self-discharge rates are crucial in standby power applications. For second life NMC or LFP cells, a self-discharge rate of less than 3% per month is typical.

- **Operating Temperature Range**: The range of temperatures within which the cell can safely and efficiently operate. The operational temperature range can vary based on the specific battery chemistry but typically spans from -20°C to 50°C or wider, to ensure functionality in various environments. Similar to the general Li-ion ranges but likely to be slightly more conservative due to the cells being in the second life phase, around -10°C to 45°C for NMC and -10°C to 50°C for LFP cells.

- **Rate Capability**: It indicates the ability of the cell to deliver or accept charge at different rates. The ability to deliver and accept charge at different rates is essential. Second life batteries might need to support C-rates (charge/discharge rates) from C/5 to C/1 (where C is the capacity of the battery in ampere-hours). NMC and LFP cells in second life applications should support C-rates from C/5 to C/1 with NMC being relatively more sensitive to high C-rates compared to LFP cells.
- **Standard Charge Rate (C-rate):** Similar to the first life, around 0.5C to 1C charge rate is generally acceptable for NMC or LFP cells in second life applications.

- **Fast Charge Rate**: Generally, it's advisable to limit fast-charging in second life cells to minimize further degradation, usually below 1C.

- **Mechanical Stress Tolerance**: Less requirements than automotive sector.

- **Chemical Stability**: Long-term stability against chemical reactions within the cell is important for maintaining performance over its operational life. The stability of the electrolyte and the cell's internal components is critical for durability.

- **Cycling Performance**: The ability of the cell to maintain its performance over multiple charge and discharge cycles. Good durability in cells ensures that their capacity, internal resistance, and overall performance degrade at a slower rate over time.

- **Thermal Stability**: The ability to handle varying temperatures without significant degradation in performance or damage.

Table 13 – Cell KPIs for Off-grid stationary battery systems applications.

KPI	MicroGrid and Smart Grid		Load Following	
	2nd Life	3rd Life	2nd Life	3rd Life
Power Density	100-300 W/kg (Depends on the module and application)			
Capacity	>80%	>70%	>80%	>70%
Internal Resistance*	1.2	1.5	1.2	1.5
Cycle Life	3000	2000	3000	2000
Self-Discharge Rate	5% per month	8% per month	5% per month	8% per month
Temperature	0-40 ºC	0-35 ºC	0-40 ºC	0-40 ºC
Rate capability	0.3 to 1	0.2 to 0.5	0.8 to 1	0.7 to 1
C-rate	0.3-0.5	0.2-0.3	0.8-1	0.7-0.8
Fast charge-rate	1	0.5	1.5	1
Mechanical Stress Tolerance	Moderate	Moderate	Moderate	Moderate
Chemical Stability	High	High	High	High
Cycling Performance	90%	80%	90%	80%
Thermal Stability	High	Moderate-High	High	Moderate-High

*Internal resistance compared with nominal values. In this table, increments of 20% to 50% are admitted.

KPI	Power Quality and Reliability		Spinning Reserve	
	2nd Life	3rd Life	2nd Life	3rd Life
Power Density	40-200 Wh/kg (Depends on the module and application)			
Capacity	70%	>50%	70-80%	>50%
Internal Resistance	1.5	1.7	1.2	1.5
Cycle Life	1500	700	3000	2000
Self-Discharge Rate	10% per month	20% per month	5% per month	8% per month
Temperature	0-45 ºC	0-45 ºC	0-45 ºC	0-45 ºC
Rate capability	1 to 2	0.8 to 1.5	0.6 to 1	0.4 to 0.8
C-rate	1-1.5	0.8-1	0.6-0.8	0.4-0.6
Fast charge-rate	2	1.5	1	0.8
Mechanical Stress Tolerance	Moderate	Moderate	Moderate	Moderate
Chemical Stability	High	High	High	High
Cycling Performance	80%	70%	85%	80%
Thermal Stability	Moderate	Moderate	Moderate	Moderate

6.3 Telecoms

6.3.1 What are Telecom Batteries?

Telecom batteries are cells, blocks and/or modules connected to provide a 48V direct current (DC) electrochemical energy storage system able to supply electricity to an ICT or Telecom site when the main power source is unavailable or insufficient.
In case of unavailability or insufficiency of the main power source, telecom batteries provide instant and continued DC voltage power to all redundant equipment to ensure the critical telecom applications are not disrupted.

In addition to this classical use case, there are more and more off-grid Telecom towers combined with renewable energy sources or other hybrid systems, especially in emerging countries with a lack of grids or in remote areas. In these cases, the batteries provide electrical current when the energy from renewable sources is not sufficient or available (to back the intermittent power outage up).

6.3.2 Telecom Battery Technologies

The dominant technologies for Telecom Batteries are still today the Valve Regulated Lead-Acid Batteries (VRLA) with Absorbent Glass Mat technology (AGM) for reliable grids, and VRLA with Gelled Electrolyte (GEL) in unstable or off-grid areas.
That said, there is a rise of Lithium technologies. Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC) cathodes with graphite anodes are the predominant Lithium technologies, with a rise of NMC graphite silicon composite anodes by 2030.

In general, lithium-ion[1] batteries weigh less, charge faster and last longer than valve regulated lead acid (VRLA) batteries - all without outgassing. While these advantages come with a higher initial acquisition cost, total cost of ownership savings are quickly seen with elimination of maintenance costs and longer cyclic battery life. In general, payback is realized after the first comparable VRLA replacement cycle.

6.3.3 Requirements for Telecom Batteries

Due to a variety of different and new applications, and some differences in geographical fluctuations of power outages, the battery performance has to meet these customer requirements. This means, for example, that for pure stand-by function, the

[1] For lower temperature locations, however, lead-acid batteries would still be the cheaper option

battery would require a significantly lower energy throughput in areas with very stable grids than in areas with very unstable grids.

Telecom batteries, whether in their initial or subsequent life phases, demand specific qualities to suit the rigorous demands of continuous power supply and backup in telecom applications. **High-capacity retention** and **low internal resistance** ensure sustained power delivery during outages, crucial for maintaining uninterrupted communication services. **Reliable cycle life** and **low self-discharge** rates guarantee longevity and reliability, essential for backup power in case of prolonged power disruptions, this can also refer to the **ability to sustain deep discharge**. **Wide operating temperature ranges** and the ability to **handle moderate to fast charging rates** are necessary to accommodate various environmental conditions and rapid recharging needs in telecom settings. Safety features, including effective voltage and thermal management, are vital to prevent hazards and ensure stable operation.

In their second life, retaining substantial capacity, maintaining good health and charge, and observing conservative charging rates are imperative for prolonged and dependable service within telecom environments, where reliability is paramount for continuous operations. Durability against stress, stability against wear, and efficient energy throughput are essential for the sustained performance of these batteries in demanding telecom scenarios.

A typical (Ghazali, Iziddin, 2020) parameters for an overall hybrid (VRLA Lead-Acid + Li-ion) configuration for Telecom Installation was the following, giving some insights about a typical battery system requirements configuration.

Table 14 – Battery KPIs for Telecom Applications

System	Parameters	Value	Battery Type	
			Lithium-ion	Lead Acid
Battery Overall System	**Backup Hours**	hours	**0.32 to 12**	2 to 16
	Capacity Required	Ah	**50 to 1,000**	167 to 1,333
	Current	A	**83 to 500**	16 to 133
	Charging Power	kW	**4.6 to 28**	0.8 to 6.4
	Cycles per Day	# of cycles	**1**	2
	Battery Cycles	#	**3,000**	1,000
	Battery lifetime	years	**2.7**	1.3 to 2.7

Here the high ranges are for different hybrid combinations from 4% Li / 96% VRLA to 75% Li / 25% VRLA.

If Batteries of Telecom Towers back-up in reality base stations, we compiled here some general figures about KPIs where we would potentially distinguish between:

- **Telecom Towers**: that might be located in remote locations with harsher weather conditions, still powering base stations
- **Base Stations**: that would be considered as more indoors in more urban areas.

6.3.4 KPIs at module/pack level for Telecom Applications

- **Voltage and Current Balancing**: Ensuring uniform voltage and current across all cells in a module or pack to optimize performance and lifespan. Ideally, cells in a module or pack should be balanced within a few millivolts of each other for voltage and within a few milliamps for current. Cells in a module or pack should ideally be balanced within a few millivolts for voltage and within a few milliamps for current, ensuring uniform performance.

- **Temperature Management**: Monitoring and controlling the temperature of the entire battery pack to prevent overheating and ensure optimal performance. Operating within a range of 0°C to 40°C or wider, with proper cooling or heating systems to maintain the batteries within safe temperature limits. Operating within a range of 0°C to 40°C for NMC and 0°C to 45°C for LFP, with active cooling or heating systems to maintain safe temperature limits.

- **Safety and Monitoring Systems**: Implementing safety measures, such as overcharge and over-discharge protection, short-circuit protection, and cell balancing circuits. Essential for preventing overcharging, over-discharging, and overheating. Set thresholds could be around 4.2V per cell for maximum voltage and 2.5-3V for minimum voltage. Similar to the general guidelines, ensuring thresholds for overcharge, over-discharge, and maximum and minimum voltage for both NMC and LFP chemistries.

- **Energy Density**: The amount of energy stored per unit volume or weight, which impacts the overall size and weight of the battery pack. Telecom batteries may aim for energy densities of 100-200 watt-hours per kilogram (Wh/kg) or more, depending on the specific requirements for space and weight. Second life batteries might have slightly reduced energy density, aiming for around 80-160 Wh/kg for NMC and 90-180 Wh/kg for LFP.

- **Power Density**: At the module or pack level, the power density is usually slightly lower than that of individual cells, ranging from 200 W/kg to 600 W/kg. The power density at this level is affected by the arrangement, thermal management, and packaging of cells in the module or pack.

- **Energy Throughput**: Energy throughput at the module or pack level will depend on the specific configuration, state of the cells, and operational conditions. In second life applications, this figure might vary but usually aligns with the cumulative cycles and overall health of the combined cells in the module or pack.

- **State of Health (SoH) and State of Charge (SoC) Monitoring**: Continuous monitoring of the health and charge level of the entire battery pack. Monitoring to maintain the SoH above 80% and to ensure accurate tracking of SoC for operational readiness. Continuous monitoring to maintain the SoH above 70-80% and accurate tracking of SoC for operational readiness in case of 2nd life applications.

- **Cycling Efficiency**: The efficiency of the charge and discharge cycle at the pack level. Telecom batteries often aim for efficiencies above 90% in charge and discharge cycles. Telecom batteries from second life NMC or LFP cells often aim for efficiencies above 85% in charge and discharge cycles.

- **Charge Rates**
  - **Standard Charge Rate** (C-rate): For second life packs, a conservative charge rate of 0.2C to 0.3C might be recommended to preserve the remaining capacity and health of the cells in the pack.
  - **Fast Charge Rate**: Fast-charging rates might be restricted to lower values, around 0.5C or below, to prevent accelerated degradation in the second life phase.

6.3.5 KPIs at the Cell Level for Telecom Applications

- **Power Density**: For NMC or LFP Li-ion cells in telecom applications, the power density often ranges from 300 W/kg to 800 W/kg. This measurement indicates the rate at which the cells can deliver power. High power density is vital for applications where high bursts of power are required, such as during grid failure in telecom systems.

- **Capacity**: It measures the total amount of charge a cell can store and deliver. It's typically measured in ampere-hours (Ah) or milliampere-hours (mAh). Telecom batteries often require a minimum capacity range of around 80% to 100% of the rated capacity to ensure they can meet the demand during power outages or other critical situations. Telecom batteries utilizing second life NMC or LFP Li-ion cells typically aim for a capacity retention of 70-90% of the original rated capacity to ensure practical usability in telecom backup systems.

- **Internal Resistance**: This indicates the opposition to the flow of current within the cell. Lower internal resistance means better efficiency and power delivery. Lower values are generally better for telecom batteries, but typically, a range between 1-50 milliohms could be acceptable, depending on the technology and specific application. According to P. Trinuruk et Al., lower internal resistance is found in LFP compared to NMC batteries, and higher internal resistances are found for cylindrical batteries compared to prismatic and pouch form factors. ETSI TS 151 043 standard specifies that the maximum internal resistance allowed is 1.5 Ohm at 25°C and 1C discharge current. That being said, typical internal resistances of batteries cells in first life are less than 1 mOhm (Samsung SDI94). In addition, Mohammed Hussein Saleh Mohammed Haram and Al. suggested that a typical LFP battery internal resistance was in the 25-50 mOhms.

- **Cycle Life**: It refers to the number of charge/discharge cycles a cell can undergo while maintaining a certain level of capacity or performance. Telecom batteries should typically support several hundred to several thousand charge/discharge cycles. For example, a minimum of 500 cycles might be considered necessary for telecom applications. Second life applications often have different cycle life expectations due to previous usage. Mohammed Hussein Saleh Mohammed Haram and Al. Suggested that the typical cycle life at 80% discharge for a LFP battery was 1000-2000 cycles range.

- **Self-Discharge Rate**: The rate at which a cell loses its charge when not in use, which is crucial for standby or backup applications. Telecom backup batteries should have a low self-discharge rate, often less than 3% per month for reliable standby power. Low self-discharge rates are crucial in standby power applications. For second life NMC or LFP cells, a self-discharge rate of less than 3% per month is typical.

- **Operating Temperature Range**: The range of temperatures within which the cell can safely and efficiently operate. The operational temperature range can vary based on the specific battery chemistry but typically spans from -20°C to 50°C or wider, to ensure functionality in various environments. Similar to the general Li-ion ranges but likely to be slightly more conservative due to the cells being in the second life phase, around -10°C to 45°C for NMC and -10°C to 50-55°C for LFP cells.

- **C-rate capability's:** It indicates the ability of the cell to deliver or accept charge at different rates. The ability to deliver and accept charge at different rates is essential. Telecom batteries might need to support C-rates (charge/discharge rates) from 0.2C to 1C (where C is the capacity of the battery in ampere-hours). NMC and LFP cells in second life applications should support C-rates from 0.2C to 1C with NMC being relatively more sensitive to high C-rates compared to LFP cells.

- **Energy Throughput**: For second life NMC or LFP Li-ion cells in telecom, the energy throughput typically ranges from 500 cycles to 2000 cycles. This parameter measures the total amount of energy a cell can deliver over its lifetime. In the context of second life applications, especially for repurposed batteries, the energy throughput might have already been used to some extent in the first life of the cells, so it's important to consider the remaining cycles.

- **Charge Rates**
    - **Standard Charge Rate** (C-rate): Similar to the first life, around 0.5C to 1C charge rate is generally acceptable for NMC or LFP cells in second life applications.
    - **Fast Charge Rate**: Generally, it's advisable to limit fast-charging in second life cells to minimize further degradation, usually below 1C.

- **Durability**
    - **Mechanical Stress Tolerance**: Cells should be able to withstand mechanical stresses and vibrations, especially in telecom applications where they might be subject to movement or transportation. Proper design and construction of the cells, including robust packaging and internal structure, are crucial for durability.
    - **Chemical Stability**: Long-term stability against chemical reactions within the cell is important for maintaining performance over its operational life. The stability of the electrolyte and the cell's internal components is critical for durability.

- **Cycling Performance**: The ability of the cell to maintain its performance over multiple charge and discharge cycles. Good durability in cells ensures that their capacity, internal resistance, and overall performance degrade at a slower rate over time.
- **Thermal Stability**: The ability to handle varying temperatures without significant degradation in performance or damage. This is crucial for telecom applications where environmental conditions can fluctuate.

6.3.6 Base station and Telecom Tower Battery requirements differences

There are slight differences between the end applications for Telecom Batteries whether they would be used in Base Stations or in Telecom Towers.

First, let's dwell on the **similarities**:
Batteries need to be reliable to ensure uninterrupted communication services. In both cases, batteries with a long cycle life are required to allow frequent charge and discharge cycles. High capacity is also important for extended backup durations, providing sufficient time for continuous operation during power outages. Finally, safety features such as voltage and thermal management are mandatory for both applications to prevent hazards and ensure stable battery operations.

For the **differences**, we could mention the following:

- Base stations often demand higher power density and may require fast-charging capabilities, as they may need to handle high power demands during periods of heavy communication traffic. As such, the acceptable charging rates and power delivery capabilities might differ
- Telecom towers, especially those in remote locations, may prioritize energy efficiency and the ability to sustain power over longer durations without frequent recharging.
- Environmental conditions can vary significantly between Telecom towers and base stations, where Telecom towers may be exposed to harsher climates in remote locations, impacting the batteries' temperature management requirements (and of course the mechanical protections).

Therefore, the following differences have been summarized in the table below. It is to be noted that those KPIs might vary much depending on the demanding status of the installation. Some installations might, for cost mitigations and space availability, be fine with lower requirements on the specifications, whilst other, which would be in tougher weather conditions or with stringent space constraints, would push the limits towards very high-quality 2nd life modules.

Table 15 – Battery cell KPIs for Telecom Applications

KPI	Cell	
	Telecom Tower	Base Station
Power Density	NMC: 250-600 W/kg (typical 150- kW/kg) LFP: 200-500 W/kg (typical 150+ kW/kgNMC]) Lower power density requirements to accommodate longer discharge periods	NMC: 300-700 W/kg LFP: 250-600 W/kg Potential for higher bursts of power during peak demand
Energy Density	NMC/LFP: 80-150 Wh/kg (average NMC cells around 215 Wh/kg (was 150-220 before)) (average LFP 160 Wh/kg (was 90-120 before)) Energy efficiency and sustained power are priorities, with slightly lower energy density requirements	NMC/LFP: 90-180 Wh/kg
Capacity	70-90% of original rated capacity Typical Module 48V 50 Ah: 2.4 kWh (source)	Higher capacity retention compared to Telecom Towers
Internal Resistance	Depending on applications. In general LFP have lower internal resistance than NMC. Those values are only indicative for longer performances. Some standards are specifying limits to 1 or 1.5 Ohm NMC: <40 mΩ (1st life typically < 1mΩ) LFP: <20-25 mΩ	Depending on applications. In general LFP have lower internal resistance than NMC. Those values are only indicative for longer performances. Some standards are specifying limits to 1 or 1.5 Ohm NMC: <50 mΩ (1st life typically < 1mΩ) LFP: <20-25 mΩ
Cycle life	NMC: 800 cycles LFP: 2,000 cycles Telecom towers may prioritize and longer cycle life to maintain back-up capability	Even though base station may require a substantial cycle life, the emphasis would be more on power delivery during peak demands
State of Health / State of Charge	Ideally >=80% - >60% might play in some less stringent applications	
Self-discharge rate	<3% per month	<4% per month
Operating Temperature Range	NMC: -20°C to 45°C LFP: -30°C to 55°C (45°C acceptable too)	NMC: -15°C to 50°C LFP: -25°C to 60°C Battery design for base stations may incorporate components better suited to operate at slightly higher temperatures compared to telecom towers. Still Telecom Towers need to tolerate harsh conditions in coldness or hotness
Rate Capability	0.2C to 1C - conservative charging rates, with variations based on specific applications	

Table 16 – Battery module and pack KPIs for Telecom Applications

KPI	Module/Pack	
	Telecom Tower	Base Stations
Power Density	NMC: 100-300 W/kg LFP: 80-200 W/kg	NMC: 120-350 W/kg LFP: 100-250 W/kg
Energy Density	NMC/LFP: 60-120 Wh/kg Efficiency and sustained power for longer periods	NMC: 70-140 Wh/kg Balancing need for efficiency with potential higher power demands
Energy Throughput	Cumulative cycles and overall health of the combined cells	
Capacity		
Internal Resistance	NMC: <40 mΩ LFP: <20 (30-50 found as well) mΩ	NMC: <50 mΩ LFP: <25 (30-50 found as well) mΩ
Cycling Efficiency	>85% in charge and discharge cycles	
State of Health / State of Charge	>70% + accurate tracking of SoC	
Self-discharge rate	NMC: <4% per month LFP: <2% per month	NMC: <7% per month LFP: <3% per month
Operating Temperature Range	NMC: -20 to 40°C LFP: -30 to 50-55°C Charge: 0-55°C Discharge: -20-50-55°C (source)	NMC: -15°C to 45°C LFP: -25°C to 55°C
Rate Capability	0.2C - 0.3C max 0.5C	
Voltage and Current Balancing	few mV and few mA	
Safety and monitoring systems	Max: 4.2V per cell Min: 2.5-3V per cell	
Geometrical Space	Telecom tower might have more constraint on limited space	

6.4 Mobility Applications

6.4.1 What are mobility applications?

Mobility applications of batteries refer to their use in various forms of transportation that rely on mobile power sources. Some key mobility applications of batteries are provided below for 2nd life use of batteries:

- **Electric Vehicles (EVs)**: Batteries power electric cars, contributing to the shift towards sustainable and zero-emission transportation.

- **Electric Boats**: Batteries are used to power electric propulsion systems in boats, contributing to cleaner and quieter water transportation. Electric boats represent a promising frontier in green maritime transport. Second-life batteries, originally designed for electric vehicles, can be repurposed to power electric boats. This approach not only mitigates environmental impact but also provides a cost-effective solution for the marine industry. By integrating retired EV batteries into electric boats, there is an opportunity to extend the life of these energy storage systems, reduce costs, and contribute to a more sustainable future for waterborne transportation.

- **Electric Aircraft and Drones**: Batteries play a crucial role in the development of electric aircraft and drones, offering possibilities for short-range and eco-friendly flight. The aviation industry is exploring electric propulsion for a cleaner and sustainable future. Second-life batteries, retired from electric vehicles, present an intriguing option for electric aircraft. Repurposing these batteries for airborne applications can contribute to the development of more environmentally friendly air travel. By integrating second-life batteries, the aviation sector can explore cost-effective solutions that align with the growing demand for sustainable transportation options. Drones are integral to various industries, and their energy source is a critical consideration. Second-life batteries, originally designed for EVs, offer a viable solution for powering drones. Repurposing these batteries for drone applications not only ensures efficient resource utilization but also provides a sustainable power source for aerial technologies. By integrating second-life batteries into drone systems, industries can benefit from reduced costs and a more environmentally friendly approach to aerial operations.

- **EV Charging Stations**: As the global shift toward electric vehicles (EVs) gains momentum for a cleaner transportation future, the need for efficient and widespread EV charging infrastructure becomes increasingly crucial. One innovative solution emerging in this landscape involves the repurposing of second-life batteries—those retired from electric vehicles but still functional—for integration into charging stations. This strategy not only addresses the challenge of sustainable disposal but also proves to be a cost-effective means of enhancing charging infrastructure. By incorporating second-life batteries, EV charging stations can reduce costs, promote environmental sustainability, bolster grid stability, and offer greater charging flexibility. Moreover, as the demand for fast charging grows, especially in fleet depots, local energy storage becomes integral. It not only supports fast chargers during peak demand but also facilitates the incorporation of renewable energy sources like solar panels, aligning with companies' decarbonization objectives. This combination of repurposed batteries and local energy solutions holds significant promise in shaping the future of efficient and sustainable EV charging.

6.4.2 What are the battery technologies in key mobility applications?

Table 17 – Battery technologies in mobility applications

Application	Battery Type	Chemistry	Shape
Electric vehicles (EVs)	- Lithium-ion (Li-ion) batteries are the predominant technology due to their high energy density, long cycle life, and suitability for automotive applications. - Solid-state batteries are an emerging technology showing promise for EVs, offering potential advantages in terms of safety, energy density, and longevity.	Lithium-ion batteries dominate, with cathodes often containing a combination of lithium nickel manganese cobalt oxide (NMC) or lithium iron phosphate (LiFePO4).	Pouch, cylindrical, or prismatic cells are commonly used in EVs, with the choice influenced by factors like packaging efficiency and thermal management.
Electric boats	- Lithium-ion batteries are commonly used in electric boats, providing a balance between energy density and weight for marine applications.	Lithium-ion, typically NMC or lithium cobalt oxide (LCO) chemistries.	Pouch or cylindrical cells, taking into account factors like weight distribution and space efficiency.
Electric aircraft and drones	- Lithium-polymer and lithium-ion batteries are prevalent in drones due to their high energy density and lightweight characteristics.	Lithium-polymer or lithium-ion batteries with variations such as lithium-sulfur (Li-S) for their lightweight characteristics.	Compact pouch or cylindrical cells, emphasizing energy density and weight considerations for aerial applications.
EV charging stations	Electric vehicle (EV) charging stations typically use lithium-ion batteries for energy storage. These batteries help manage peak demand, balance the grid, and provide backup power. Advanced technologies, such as solid-state batteries, are also being explored for future applications in EV charging infrastructure.	The chemistry of batteries used in EV charging stations is predominantly lithium-ion. Within lithium-ion batteries, various chemistries exist, such as lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP), and lithium nickel cobalt aluminum oxide (NCA). Each chemistry offers a balance between energy density, lifespan, and cost.	The batteries are typically in the form of prismatic or cylindrical cells. - Prismatic cells have a flat, rectangular shape, while cylindrical cells are, as the name suggests, cylindrical. The choice of cell shape depends on factors like packaging efficiency, cooling requirements, and the overall design of the battery system.

Funded by the European Union

6.4.3 What are the key requirements for Mobility Applications?

General key requirements for batteries used in various mobility applications are given below. These requirements collectively determine the suitability and effectiveness of batteries in various mobility applications.

- **Energy Density**: Higher energy density allows for longer range or extended operation between charges.

- **Power Density**: Higher power density supports acceleration, climbing, and other dynamic performance aspects.

- **Cycle Life**: Longer cycle life enhances the durability and lifespan of the battery.

- **Fast Charging Capability**: Ability to recharge a battery quickly. Enables convenient and time-efficient charging for users.

- **Thermal Management**: Effective control of battery temperature during operation. Ensures safety, optimal performance, and longevity.

- **Weight and Size**: Overall weight and dimensions of the battery. Compact and lightweight batteries contribute to overall vehicle efficiency and design.
- **Cost Efficiency**: Economic feasibility of the battery technology. Lowering the cost of batteries makes electric mobility more accessible.

- **Safety**: Protection against thermal runaway, short circuits, and other safety risks. Ensures user safety and prevents accidents.

- **Charge Time**: Duration required to recharge the battery to a usable level. Shorter charge times enhance user convenience.

Table 18 – Battery KPIs for mobility applications

Application	Energy Density (Wh/kg)	Power Output (W/kg)	Cycle Life (cycles)	Charge Time
Electric vehicles (Evs)	150-300	150-300	800-1200	80% charge in 30 minutes
Electric boats	100-200	100-500	500-1000	4-8
Electric aircraft and drones	150-300	150-500	300-800	1-3 hours
EV charging stations	150-250	50-350	500-1500	20 minutes-8 hours

6.4.4 KPIs for Key Mobility 2nd life Applications

Each mobility application area requires different KPIs. A generalized range of key battery pack requirements for various mobility applications can be found below.

Providing specific numerical values or ranges for cell-level requirements can be challenging due to the diversity of battery technologies and chemistries. However, general ranges based on common characteristics can be found in contemporary battery technologies:

Table 19 – Battery cell KPIs for mobility applications

KPI	Range	Comment
Energy Density	100-300 Wh/kg	
Power Density	100-500 W/kg	
Cycle Life	500-1,500 cycles	Varies with technology and application
Fast Charging Capability	Cells able of charging to 80% capacity in 15-60 mns	
Operating Temperatures	-20°C to 60°C	Varies among technologies
Weight & Size	Few hundred grams to few kg per cell	Varies among technologies
Cost Efficiency	\$100-\$300/ kWh	Varies based on chemistry and production scale
Safety at cell Level	Advanced safety features, including thermal protection and circuitry to prevent overcharging and short circuits	
Charge Time	1C to 5C or more	Varies among technology and application

6.5 Back-up UPS Applications

6.5.1 What are Uninterruptible Power Suppliers (UPS)?

Electric vehicle (EV) makers advise replacing EV batteries when their State of Health (SoH) drops to approximately 70-80% or after about 8 years or 160,000 kilometers. Nevertheless, even after experiencing this reduction in capacity, these batteries retain sufficient energy for alternative, less demanding applications in their second life. Examples include their use in stationary energy storage systems, such as Uninterruptible Power Supply (UPS) systems (Rallo et al., 2020).

An Uninterruptible Power Supply (UPS) is a device that provides emergency power to a load when the main power source fails (Dhal, 2015). Although the battery life of most uninterruptible power supplies is relatively short, a standby power source is typically adequate for a secure device's proper startup or shutdown (Paul, 2022).

In general, UPS systems can be categorized as Static UPS and Rotary UPS. The Static UPS system employs power electronics converters and inverters to manage, store, and distribute power during grid failures, while the Rotary UPS utilizes motors and generators to perform the same function (Aamir, 2016). It is designed to ensure electronic equipment and systems have a stable and uninterrupted power supply, even during power outages or fluctuations (Emadi, 2017).

The primary purpose of a UPS is to prevent data loss and protect sensitive electronic equipment from damage that can occur when the power supply is suddenly interrupted (Paul, 2022).

6.5.2 Typical Applications for UPS technologies?

UPS systems find extensive use across diverse industries, serving various purposes. Their widespread applications span from low power ratings, suitable for **personal computer systems**, to medium power ratings, essential for **medical facilities, life-support systems, data storage**, and **emergency equipment**. Additionally, UPS systems with high power ratings play a crucial role in supporting telecommunications, industrial processing, and inline management systems (Nasiri, 2010). Different considerations come into play for these applications. For instance, in **emergency systems, the UPS should sustain the system for at least 90 minutes**, while for other **sensitive loads, it's typically designed for 15-20 minutes**, after which a graceful shutdown occurs if power isn't restored. Longer backup periods necessitate larger, costlier batteries and more space. Some UPS systems for high-power applications allow enough time for secondary power sources, like diesel generators, to start up. However, integrating UPS systems into industrial setups adds complexity and installation/maintenance costs, potentially impacting system efficiency and the power factor correction mechanism (Nasiri, 2011). Careful UPS selection based on load characteristics is crucial. For instance, motor loads demand consideration of high inrush currents, requiring UPS units with higher transient overloads. Non-linear loads, such as switching power supplies, have higher instantaneous current compared to RMS current, necessitating tailored UPS selection. **Selecting the appropriate UPS approach depends on the specific industry, its critical load requirements, and the trade-offs between flexibility, redundancy, maintenance ease, and upfront costs.**

6.5.3 What are UPS technologies?

Based on Aamir et al. (2016), the UPS system is classified as **Offline UPS, Line interactive UPS, Online UPS, Universal UPS, Rotary UPS, Hybrid Static/Rotary UPS** system, depending on the topological configuration.

The **offline UPS** is composed of a battery charger, a static switch, and an inverter. In the event of a power outage, the static switch links the load to the inverter, and the battery supplies power through the inverter. This system provides advantages such as **affordability, straightforward design**, and **compact size**. Nonetheless, its key drawbacks include a **lack of genuine isolation** from the load and **insufficient voltage regulation**.

The **line interactive UPS** is comprised of a static switch, a bidirectional converter/inverter, and a battery bank. When the grid fails, the static switch separates the load from the primary supply, and the bidirectional converter/inverter furnishes power to the load. This system offers benefits like **cost-effectiveness, compact size**, and **high efficiency**. However, its main limitation is the **lack of voltage regulation** during normal operation.

The **online UPS** is composed of a rectifier, an inverter, and a static switch. When there's a power failure, a magnetic contactor disconnects the AC line, but the inverter continues to provide uninterrupted power to the load from the battery bank. The merits of the online UPS include **load isolation** from the main line and an almost **negligible switch time**. However, its significant drawbacks encompass **low efficiency, a low power factor**, and **high total harmonic distortion**.

Universal UPS, also referred to as the "Series-Parallel" or "Delta Conversion" UPS, draws its design from the unified power quality conditioner (UPQC) topology. It effectively amalgamates the strengths of both online and line-interactive UPS systems.

This configuration enables the attainment of unity power factor, precise output voltage regulation, and high efficiency concurrently.

Rotary UPS systems - in simpler terms, Rotary UPS systems utilize the stored energy in electrical machines to supply power to devices during power outages. These systems come in various configurations, with the most basic setup involving an AC motor and an AC generator connected together mechanically. A flywheel is also part of the setup, attached to the machines' shafts to store additional kinetic energy in the system. During normal operation, the input AC line supplies power to the AC motor, which in turn drives the AC generator.

Hybrid static/rotary UPS systems - merge the key characteristics of both static and rotary UPS systems. These systems offer a blend of advantages including low output impedance, high reliability, excellent frequency stability, and minimal maintenance needs.

In the table below is depicted the main performance comparison of different configurations of UPS systems according to Adel Nasiri

Table 20 – Comparison of different configurations of UPS systems

Parameter	On-line	Line interactive	Off-line	Universal	Rotary	Hybrid
Surge protection	Excellent	Good	Good	Good	Excellent	Excellent
Transition time	Excellent	Good	Poor	Good	Excellent	Excellent
Line conditioning	Poor	Good	Poor	Excellent	Good	Good
Backup duration	Depends on battery	Depends on battery	Depends on battery	Depends on battery	Typically 0.1–0.5 s	Depends on battery
Efficiency	Low around 80%	High up to 95%	High	High up to 95%	High typically above 85%	High typically around 95%
Input/Output isolation	Poor	Poor	Poor	Poor	Perfect	Perfect
Cost	High	Medium-high	Low	High	Very high	Very high

6.5.4 Energy Storage for UPS

Three primary energy storage devices dominate both current and future UPS systems: **batteries, flywheels**, and **fuel cells**. Here, the focus will be on batteries as the primary energy storage component in contemporary static UPS systems.
The battery determines the UPS's capacity and runtime. In smaller units, the UPS size is determined by the battery's size. **Various types of batteries find use in UPS systems, with lead-acid, nickel-cadmium, and lithium-ion being the most commonly utilized.**

Lead-acid batteries in cars operate through the reaction of sulfuric acid on lead plates submerged in liquid. However, these are unsuitable for UPS applications due to potential acid spillage and the release of explosive hydrogen during charging. UPS-specific lead-acid batteries, termed **sealed or valve-regulated**, address these safety concerns.

Nickel-cadmium batteries represent another popular UPS battery type, typically offering **higher energy and power density compared to lead-acid batteries**. Their nominal voltage of 1.2 V is lower than the 1.5 V of lead-acid batteries, yet they exhibit less voltage variation across different charge levels and possess lower series resistance, allowing for higher surge currents.

In contrast, **lithium-ion batteries boast significantly higher energy density** and can be shaped to fit various configurations. With a nominal voltage of 4.2 V, they offer unique advantages. However, one notable disadvantage is that regardless of use and charge conditions, they tend to lose capacity gradually from the time of manufacturing.

The table below shows a comparison between different kinds of batteries for UPS application, taking into account Battery type, Energy density, Power density and respective theological maturity for each battery type.

Table 21 – Comparison between different kinds of batteries for UPS application

Battery type	Energy density (WH/kg)	Power density (W/kg)	Commercial availability
Lead-acid	35	300	Very mature and readily available
Nickel–cadmium	40	200	Mature and available
Lithium-ion	120	180	Available
Nickel hydride	70	200	Available
Zinc-air	350	60–225	Research stage
Aluminum-air	400	10	Research stage
Sodium chloride	110	150	Available
Sodium sulfur	170	260	Available
Zinc bromine	70	100	Available

6.5.5 What are the typical requirements for UPS Batteries?

UPS systems commonly use one of three types of batteries: lead-acid batteries, lithium-ion batteries, or nickel-cadmium batteries (Balog, 2012), (Šimić, 2021).

- **Lead-acid batteries** – have a high discharge rate and low energy. They are commonly installed in UPS systems.

- **Lithium-ion batteries** – have a higher energy density, longer lifespan, and lighter weight than lead-acid batteries. They are often used in modern, compact, and high-performance UPS systems.
- **Nickel-cadmium batteries** – have a high durability and ability to withstand high temperatures, however, they are being replaced by newer technologies like lithium-ion.

6.5.6 Performance Parameters of UPS

The technical parameters of the UPS power supply are important indicators of the quality of the UPS and the main basis for selection. Aiming at whether the UPS power supply can provide clean and uninterrupted power supply to the load equipment normally and safely, a detailed understanding of its performance parameters is required.

- **Capacity**: Measured in volt-amperes (VA) or watts (W), indicating the maximum load a UPS can support.
- **Battery Backup Time**: Determines how long the UPS can provide power to connected devices during an outage. This depends on the load and battery capacity.
- **Surge Protection**: Protects connected devices from sudden voltage spikes or surges.
- **Frequency Regulation**: Controls the output frequency within a specified range to ensure compatibility with sensitive equipment.
- **Monitoring and Management**: Some UPS units offer remote monitoring, management software, and additional features like automatic shutdown to preserve battery life during extended outages.

6.6 Urban Electromobility and micro batteries

6.6.1 What are urban electromobility applications?

Urban electromobility batteries are those batteries providing power for traction of full electric or hybrid human-electric small mobility devices as scooters, e-bikes, etc.

It is possible to provide a more detailed definition of urban electromobility (micro) batteries by exploiting the definition of Light Means of Transport (LMT) battery given in the new European Regulation on Batteries and Waste Batteries Chapter I, Article 3, Definition 11:

‘Light means of transport battery’ or ‘LMT battery’ means a battery that is sealed, weighs 25 kg or less and is specifically designed to provide electric power for the traction of wheeled vehicles that can be powered by an electric motor alone or by a combination of motor and human power, including type-approved vehicles of category L within the meaning of Regulation (EU) No 168/2013 of the European Parliament and of the Council (43), and that is not an electric vehicle battery.

This definition better identifies the specifications, in terms of weight of the battery and vehicle type, to distinguish between urban electromobility (micro) batteries and electric vehicles batteries.

Despite the very specific application, the fast-growing exploitation of light mobility in Europe is bringing on city roads many of these components.

This chapter analyses **micro batteries** together with urban electromobility batteries. The category of micro batteries refers to those small batteries providing energy to home appliances and portable units such as laptops and mobile devices. Referring again to the new EU Regulation, micro batteries fall under the portable batteries definition (Chapter I, Article 3, Definition 10):

‘Portable battery’ means a battery that is sealed, weighs 5 kg or less, is not designed specifically for industrial use and is neither an electric vehicle battery, an LMT battery, nor an SLI battery.

Despite urban mobility and micro batteries are used for different applications, they share many peculiarities and have comparable KPIs:

- Type of technology: currently only Li-Ion.
- Dimension: smaller than other types of batteries.
- Packaging: both of them must be sealed.
- Cell geometry: cylindrical or pouch.
- Performance: autonomy and durability are the most relevant for both.

For these reasons, this document analyses together these two categories.

6.6.2 What are Urban Electromobility (micro) battery technologies?

Urban electromobility vehicles are a relatively new category of products. The integration of energy storage in lightweight affordable vehicles is enabled by the availability of reliable, durable, high energy density batteries.

In fact, urban electromobility vehicles production is basically Li-Ion batteries dependent, as no other common battery technology (lead acid, nickel cadmium, etc.) is adequate for the scope in terms of energy density, self-discharge rate, depth of discharge, lifecycle, charging time.

On the other side, even if home appliances and portable units have existed for many decades, the Li-Ion technology has been disruptive for this segment, and nowadays, it basically monopolizes this market.

Within the Li-Ion batteries world, all the most common cathodic chemistries (NMC, NMC 622, NMC 811, NCA, LFP) are used for this scope. Geometry wise, cylindrical cells are the most used, because they can be assembled in three dimensional shaped packs and because they are the easiest to manage in the context of small lot production. Micro applications (for example mobile phones) exploit pouch cells instead of cylindrical ones.

6.6.3 What are typical requirements for Urban Electromobility (micro) batteries?

Urban electromobility and micro batteries are products which must satisfy two main complementary challenges: to be a safe, ergonomic, non-bulky component; to be an effective energy storage system for the traction of the vehicle or powering of the micro device.
These needs are reflected in the two main requirements categories which rule urban electromobility and micro batteries: structural and performance.

Concerning structural requirements, here a brief list of the main aspects:

- **Sealing**: urban electromobility and micro batteries work in stressful environments. Their proper sealing must be guaranteed to avoid the penetration of humidity and oxidation agents in the electric circuits of the battery. Moreover, according to the new European Regulation on Batteries and Waste Batteries, LMT and portable batteries must be sealed (Chapter I, Article 3, Definition 10-11).

- **Removability and replaceability** are important concepts for urban electromobility and micro batteries, both in the context of battery substitution for repair and of battery swapping for recharge. Moreover, according to the new European Regulation on Batteries and Waste Batteries, LMT and portable batteries must be easily removeable and replaceable (Chapter II, Article 11).

- **Safety**: it's quite common to read news about Li-Ion battery units which catch fire and/or detonate. These phenomena might cause serious consequences for human health, if not properly prevented and managed (Hsieh et al., 2021). New generation batteries for urban electromobility must have redundant safety solutions to lower the risk of battery thermal runaway and minimize the risk derived by battery fault.

- **Lightweight and ergonomics**: the concept of urban mobility small vehicles works only if batteries are light and shaped to not alter the design of the main vehicle. In general, batteries for urban electromobility account for less than 15% of the vehicle weight. In an example (Schünemann et al. 2023).

Concerning performance requirements, technical details about electrochemical specs of urban electromobility and micro batteries are discussed in the next paragraphs of this document. But, the top-level requirements, which are here defined, are related to autonomy, speed, and durability:

The **autonomy** of electric scooters / mopeds is typically in the 15-60 km range. Of course, the autonomy is direct consequence of the capacity of cells of the battery pack and the number of series parallel replications. Details in the next paragraphs. Autonomy is a key requirement also for micro applications, which are expected to provide hours of functionality without recharging.

To ensure a **speed** of typically 30 km/h (scooters), 45 km/h (mopeds), batteries for urban electromobility must provide adequate power, which is typically reached selecting cells with the correct power/capacity ratio and assembling them rising voltage exploiting series connections. Details in the next paragraphs.

Market standards require batteries for urban electromobility and micro to last between 2 to 4 years and between 5000 to 8000 km (in case of mobility). Their **durability** in different environmental conditions is managed by selecting reliable cells (some chemistries have shown in the years better performance than others) and maintained by a smart battery management system. Details in the next paragraphs.

6.6.4 KPIs at Cell Level for Urban Electromobility and micro batteries

Cells are the fundamental brick of every Li-Ion battery unit, and batteries for urban electromobility and micro applications are not an exception. The above-mentioned battery performance requirements are managed by battery assemblers by the selection of performing cells. In case of small battery units, this concept is even magnified, because the small battery dimension obliges to avoid parallel cells connections, and therefore the capacity, power and reliability of the whole battery system must be provided by the single cell.

Before presenting quantitative KPIs, here an introduction of general criteria which are used for the selection of Li-Ion cells for urban electromobility and micro appliances:

- **Chemistry**: as in all other mobility applications, in urban electromobility batteries as well, the NMC cathode is the most exploited chemistry. Concerning micro batteries instead, the chemistry most used is LFP.

- **Geometry**: it has already been introduced how cylindrical cells are preferred for this specific scope. Specifically, the most exploited type of cells is 18650 (meaning 18mm diameter, 650mm height), while a fast-rising alternative are the bigger 21700. The pouch alternative is also used, mostly for micro batteries.

After this quantitative introduction, to highlight the qualitative KPIs representing the benchmark for Li-Ion cells used for urban electromobility and micro battery units, two largely used battery cells models are taken as a reference, both NMC, one 18650 and one 21700:

- LG Chem INR18650 MH1 3200mAh.
- Samsung SDI INR21700-50E.

For each identified KPI, the reference values highlighted in the two above mentioned datasheets are then confirmed by broader literature research. Moreover, it is specified for each KPI if it refers to urban electromobility batteries, micro batteries, or both.
Here the main KPIs for urban electromobility and micro Li-Ion batteries at cell level:

- **Power density**: depends on the chemistry of the battery and its internal design (mainly the thickness of the cathodic and anodic powder layers). This KPIs is naturally in tradeoff with the energy density parameter.

- **Capacity**: **i**s the KPI which mostly influences the *autonomy* battery requirement. Typical capacity for cylindrical NMC batteries used in urban electromobility and micro applications is:

Table 22 – Battery capacity for urban electromobility

	18650 NMC	21700 NMC
Benchmark capacity KPI	≥ 3’000 mAh	≥ 4’800 mAh

- **Impedance**: while for some stationary batteries the internal resistance value is measured, for mobility and micro batteries, which deal more with fast current rates shifts, the impedance KPI is the standard reference to evaluate the characteristic of a cell in terms of opposition to the demanded flow of current. Typically measured at the standard and fixed frequency of 1 kHz at full charge. Typical impedance for cylindrical NMC batteries used in urban electromobility and micro applications is:

Table 23 – Battery impedance for urban electromobility

	18650 NMC	21700 NMC
Benchmark impedance KPI	≤ 42 mΩ	≤ 42 mΩ

- **Cycle life**: fundamental KPI for electromobility, as it is directly related to the *durability* requirement of this type of batteries. It refers to the number of charge/discharge cycles a cell can undergo while maintaining a certain level of capacity (typical market standards: 70%, 80%). Typical cycle life for cylindrical NMC batteries used in urban electromobility and micro applications is:

Table 24 – Battery cycle life for urban electromobility

	Minimum guaranteed	Reference KPI
Cycle life	500 cycles, 70% C_SoH	500 cycles, 80% C_SoH

- **Self-discharge rate**: not a crucial KPI for electromobility and micro, because the usage profile of these products is characterized by almost daily battery recharging. This KPI is aligned with general NMC self-discharge rates of 3% per month.

- **Operating temperature range**: crucial KPI for micro batteries, because they can operate in either very hot or cold environments.

Table 25 – Battery operating range temperature for urban electromobility

	Charge	Discharge
Operating temperature range	0 to 45°C	-20 to 60°C

- **Rate capability (charge and discharge rates)**: fundamental KPI for electromobility, as it is directly related to the *speed* requirement of this type of batteries. It indicates the ability of the cell to deliver or accept charge at different rates. Typical rate capability for cylindrical NMC batteries used in urban electromobility is:

Table 26 – Battery rate capability for urban electromobility

	Charge	Discharge
Rate capability, benchmark KPI	Optimal: 0.5C Max: 1C	Max, continuous discharge: 2C Max, peak: 4C

6.7 KPIs of Electromobility and micro batteries at Pack level

Batteries for micro applications are quite often composed of one or two cells only. For micro batteries, KPIs for cells and pack are therefore superimposable.

Therefore, this paragraph is structured for the analysis of **KPIs at pack level only referring to batteries for urban electromobility**.

Batteries for urban electromobility are assembled with a cell-to-pack approach, because their dimensions don't require the intermediate modules assembly.

The cell related characteristics are multiplied into packs, and completed by an operative electronic and structural over-structure, to achieve the full functional requirements of the unit. This paragraph summarizes the pack-level KPIs into two main families: the cell-related KPIs, and the external components related KPIs. When relevant, KPIs are differentiated for e-scooters and e-mopeds.

6.7.1 KPIs of Electromobility (micro) batteries at Cell level

- **Voltage**: regardless of their power and capacity, NMC cells have a nominal open circuit voltage (OCV) of 3.6/3.7 V. The voltage, and therefore power, of battery packs is reached by the series connection of multiple cells or cell groups.

Table 27 – Battery cell voltage for urban electromobility

Voltage	Typically, e-scooter or e-moped batteries fall into one of these six buckets: 36V, 48V, 52V, 60V, 72V, or 84V

- **Capacity**: the single cells capacity is multiplied by series and (sometimes, mostly for e-mopeds) parallel connections, to ensure that the final capacity of the pack is adequate to guarantee the *autonomy* of the vehicle.

Table 28 – Battery cell capacity for urban electromobility

	e-scooter	e-moped
Benchmark capacity KPI	Min: ≥ 100 Wh Reference KPI: ≥ 250 Wh (approx. 20 km)	Min: ≥ 250 Wh Reference KPI: ≥ 600 Wh (approx. 50 km)

- **Power**: the above-mentioned *speed* requirements for urban electromobility are managed by the right power capabilities of the battery packs, direct consequence of the single cells power supply capabilities and their series multiplication.

Table 29 – Battery cell power for urban electromobility

	e-scooter	e-moped
Benchmark power KPI	Min: ≥ 250 W Reference KPI: ≥ 500 W	Min: ≥ 1 kW Reference KPI: ≥ 2 kW

6.7.2 External Components KPIs for Electromobility

KPIs managed by the BMS. The battery management system is the electronic unit which manages the battery pack, and has several functions:

- **Voltage and Current Balancing**: Li-Ion cells suffer current and voltage unbalancing for many reasons: manufacturing inhomogeneity, different current and temperature stresses during their operative cycles, defective soldering, etc. Specifically in the context of second life batteries, one of the main goals of the BMS is the active balancing of cells in the pack, within a few millivolts for voltage and within a few milliamps for current, ensuring uniform performance.

- **Temperature management**: as above described, NMC cells have precise temperature ranges for safe operation. The BMs must monitor the battery temperature and block it if temperature boundaries are exceeded. This is crucial to ensure the *safety* battery requirement.
- **General monitoring**: the simple but extremely important management of cells to be maintained in the min-max voltage ranges and never overstressed in terms of charge/ discharge C_rates.
- **State of Health (SoH) and State of Charge (SoC) Monitoring**: the BMS also provides raw data to the vehicle CPU (e.g. Coulomb counting mechanism) for the estimation of SoH and SoC of the battery.

KPIs managed by the battery assembly. The battery requirements in terms of ergonomics, structural robustness and removability are achieved by different assembly design features:

- **Cells soldering**: the robust and homogeneous busbars connection to single cells guarantee a correct current balancing in parallel and series connection and that the battery assembly doesn’t suffer vibrations and other mechanical stimuli. For small cylindrical cells units, the typical assembly technology used is the so-called resistance projection welding (Das et al., 2018).
- **Junction block**: namely the connection interface between the battery pack and the electric circuit of the vehicle, which must be robust and ergonomic for easy swapping.
- **External housing**: which must guarantee sealing and robustness while maintaining its lightweight. Fiber reinforced polymers are widely exploited materials for this purpose for their combined strength and lightness.

6.8 Probability of occurrence of applications for 2nd life

It is worth here as well referring to a study (Haram, 2021) that classifies the probability of occurrences of specific applications for first and second life battery, stating the following:

Table 30 – Probability of occurrence of specific applications for first and second life battery

	Applications	Frequent	Occasional	Rare
On Grid	Renewable farming	x		
	Area & Frequency Regulation	x		
	Load levelling		x	
	Generation-side asset management		x	
	Peak Shovelling			x
	Voltage or reactive power support			x
Off Grid	Microgrid	x		
	Smart grid	x		
	Load following		x	
	Power quality & reliability			x
	Spinning reserve			x
Mobile	EV charging station		x	
	EV for short range trips		x	

7. Conclusions

This study has delineated strategies to systematically promote the repurposing of electric vehicle (EV) batteries within second and third life contexts. The primary objective is to enhance circularity, diminish carbon footprint, and reduce reliance on raw materials amid the ongoing electrification transformation.

The document intricately outlined a decision tree framework for the handling of batteries, elucidating specific steps and key criteria essential at each stage of the proposed process.

Notably, this discussion refrains from delving into economic considerations, recognizing their increasing significance as batteries age. The emphasis remains sharply on repurposing steps, with acknowledgment that reuse and remanufacture are not exhaustively detailed.

Furthermore, while the document provided a comprehensive exploration of modules and cells dismantling, assessment and decisions regarding recycling or refurbishing, it omits a specific mention of the reuse of packs in a stacked configuration – a possibility expounded upon in existing literature.

This document underscored the importance of specific Key Performance Indicators (KPIs) and technical feasibility as catalysts for the proliferation of such practices. Although ample literature exists on the economic modelling for various reuse scenarios, such depth is intentionally excluded from this document, leaving it to the reader's discretion to delve into further investigation.

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