REINFORCE

BATTERY REQUIREMENTS FOR 2ND AND 3RD LIFE APPLICATION

29/09/2023

Funded by the European Union

Funded by the European Union Horizon Europe research and innovation programme under Grant Agreement No. 101104204 (REINFORCE). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

REINFORCE	
Project Name	Standardised, automated, safe and cost-efficient processing of end-of-life batteries for 2nd and 3rd life reuse and recycling
Funder	European Union
Programme	Horizon Europe
Call	HORIZON-CL5-2022-D2-01-10: Streamlined collection and reversed logistics, fully automated, safe and cost-efficient sorting, dismantling and second use before recycling
Duration	48 months
Start date	01/06/2023
End date	31/05/2027
Budget	4.999.993,75€
Website	https://reinforceproject.eu/

PROJECT PARTNERSHIP

Name	Role	Type	Country
INEGI	Coordinator	RTO	PT
CEA	Beneficiary	RTO	FR
ABEE – Avesta Battery & Energy Engineering	Beneficiary	Enterprise	BE
ITE – Instituto Tecnológico de la Energía	Beneficiary	RTO	ES
TECNALIA	Beneficiary	RTO	ES
NUTAI	Beneficiary	Enterprise	ES
COMAU	Beneficiary	Enterprise	IT
LUT University	Beneficiary	University	FI
THI - Technische Hochschule Ingolstadt	Beneficiary	University	DE
VDL Staalservice BV	Beneficiary	Enterprise	NL
VDL Parts BV	Affiliated Entity	Enterprise	NL
SIRO	Beneficiary	Enterprise	TK
Cobat Servizi	Beneficiary	Enterprise	IT
Everledger	Beneficiary	Enterprise	IE

Battery requirements for 2nd and 3rd life application	
Deliverable Code	D2.1
Due Date of Delivery	M4
Actual Date of Delivery	02/10/2023
Responsible Organisation	INEGI
Contributing Organisations	LUT, 3DS, ABEE, ITE, NUT, LUT, VDL, VDLP, SIRO, COB
Name of editor(s)	INEGI: Sara Pinto; Luís Oliveira; Mário Brox and Emanuel Lourenço LUT: Minttu Laukkanen and America Rocio Quinteros Condoretty
Nature	R – Document, Report
Dissemination Level	PU – Public
Version	3

QUALITY CONTROL			
Version	**Date of Review**	**Reviewer(s) name**	**Organisation**
Version 1	20/09/2023	Luís Oliveira Minttu Laukkanen and America Rocio Quinteros Condoretty	INEGI LUT
Version 2	25/09/2023	Mathilde Hemon and Rudy Pastuzak Luca Gentilini Luca de Bruyn Çağla Odabaşı Özer	3DS COBAT VDL SIRO
Version 3	29/09/2023	Luís Oliveira and Emanuel Lourenço Minttu Laukkanen and America Rocio Quinteros Condoretty	INEGI LUT

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1. Executive Summary

This document outlines the key activities carried out within the REINFORCE project. The primary objective is to establish the essential requirements for repurposing lithium-ion batteries for 2nd and 3rd life. The concept of extending the lifespan of applications has gained significance. This initiative focuses on the critical aspects that contribute to the longevity of lithium-ion batteries and the full extraction of their residual value after first life, either consolidated in a product, or in raw material form. By identifying and defining these requirements, this deliverable seeks to preliminarily identify the key aspects that enable the circularity of technology applications regarding EVs battery systems. Firstly, the REINFORCE concepts are explained, alongside with the main project ideas for enhanced circularity and second\third life valorisation. Applications are then identified, based on specific performance, legal and operational KPIs, per new use stages. A decision tree is presented according to the opportunities and different cost benefit analysis that need assessment, and a pathway is provided to better battery pack outcomes.

Overall, this document serves as a comprehensive overview of the REINFORCE project's activities and their implications for the sustainable future of technology applications during their 2nd and 3rd life for EV and stationary batteries.

2. Introduction

In the world of technological advancements, the battery field has experienced significant progress in recent years. Alongside the development of new batteries and chemistries, such as advanced lithium-ion batteries (LIBs) and solid-state batteries (SSBs), there has been a growing interest in batteries recycling and repurposing, also promoted by the new European Batteries Regulation (Regulation (EU) 2023/1542).

The growing demand for LIBs increases the importance of anticipating the occurrence of supply risks (Ballinger et al., 2019). LIBs are made of a combination of various metals and minerals: aluminium, copper, steel, iron, lithium, cobalt, nickel, graphite, and manganese, of which the latter five are considered critical raw materials (European Commission, 2022) that are not only of strategic or economic importance, but also at a higher risk of supply shortages or price volatility. Further, the increases in raw material price contribute to an unstable market of critical minerals (IEA, 2023a) have created the need to recapture and revalorize these materials through recycling processes and looping them back into the production of new batteries (Albertsen et al., 2021). Simultaneously, there exists potential for repurposing LIBs, which may have diminished capacity, for example, for energy storage systems, small-scale microgrids, renewable energy backup systems, and emergency power supply systems, depending on the health of the batteries (Ali et al., 2021). Repurposing LIBs and recycling valuable minerals is not just critical for securing supply and controlling the cost of raw materials but also mitigating the environmental impacts of LIB related material extraction and production. As electric vehicles (EVs) continue to become more common and when large volumes of LIBs start to come to the end of their life cycle (around 2030), the importance of sustainable repurpose and recycling solutions is expected to grow further.

To maximize the long-term efficient use of batteries before recycling, **REINFORCE studies repurposing for 2nd and 3rd life**. The concepts of 2nd life and 3rd life in the battery field introduce innovative approaches to prolonging the usefulness of batteries beyond their initial purpose. **2nd life applications have been studied more in recent years, but 3rd life has only mostly been mentioned.** However, REINFORCE studies both concepts and suggests that it is important to distinguish the 2nd and 3rd life. Different applications for 2nd life batteries have different technical requirements, for example, an end-of-life (EoL) EV battery (with the ~80% capacity left) may be "too good" as a backup power, as the number of cycles it would endure over its remaining life would be too diminished, as the overall provided energy by the system. Whereas 3rd life applications involve further extending the lifespan of batteries that have already undergone their 2nd life phase. These applications focus on maximizing the return on the remaining capacity of batteries that would otherwise be considered end-of-life. Consequently, a circular design of LIBs with extended purposes plays a crucial role to boost resource efficiency in the long term (Quinteros-Condoretty et al., 2021).

Several stakeholders play essential roles in driving the development, implementation, and utilization of 2nd and 3rd life applications in the battery field. Battery manufacturers are at the front, producing batteries for various applications, as they have a vested interest in exploring 2nd and 3rd life applications as it allows them to optimize the use of their products and extract additional residual value. EV manufacturers contribute to the 2nd life applications ecosystem by providing batteries that have reached the end of their useful first life, under automotive traction use. End users and consumers, such as homeowners, and businesses are beneficiaries of 2nd and 3rd life, and they can benefit from cost savings, improved energy reliability and reduced environmental impact (here diluted by a significant increased amount of kWh provided by the system) by utilizing repurposed batteries for energy storage, backup power, or charging solutions.

The collaboration and engagement of different stakeholders is crucial for the successful implementation and widespread adoption of 2nd and 3rd life applications. By repurposing batteries beyond their initial purpose, a more efficient circular economy approach can be achieved, leading to increased sustainability degree, energy efficiency and more resilient energy infrastructure. Exploring 2nd and 3rd life applications allows for optimizing battery usage, reducing waste, and enhancing sustainability in the battery field.

This document has, as an objective report, all relevant information regarding the requirements of the 2nd and 3rd life application to be met by the REINFORCE project and is aligned with a specific objective (SO) 1, that is described in REINFORCE proposal: "To identify and define the specific process design, technical specifications, standards, and users requirements that must be considered for EoL batteries reuse, repurpose, and recycling applications, optimized recycling of materials, and useful battery passports".

This document is structured in a logical progressive manner, where first, we define the key REINFORCE concepts. Following this initial stage, we present different 2nd life and 3rd life applications, as well as the application and battery regulations KPIs. Ultimately a preliminary decision tree is outlined. The main conclusions are presented in the last section of this deliverable.

3. Key REINFORCE concept definitions

In this particular section of the deliverable, the fundamental concepts that underpin the establishment of circularity within the context of LIBs are presented. The primary objective is to outline the key principles and strategies required to develop a sustainable circular value chain for LIBs and to consolidate the key REINFIRCE concepts, focused on batteries routing and repurposing for second and third life use.

3.1 Sustainable circularity of batteries

According to Geissdoerfer et al. (2020, p. 3), **circular economy is "An economic system in which resource input and waste, emission, and energy leakages are minimized by cycling, extending, intensifying, and dematerializing material and energy loops"**. This can be achieved through different circularity strategies, i.e., re-strategies: reduce, rethink, reuse, repair, repurpose, refurbish, remanufacture and recycling utilized in each supply chain phase (Figure 1). The conceptualization in Figure 1 provides a holistic view on circular economy, where looping products and wastes back into the supply chain helps minimize energy and material inputs, as well as to reduce the amount of waste and emissions leaked to the environment. In addition, different re-strategies are defined in Table 1.

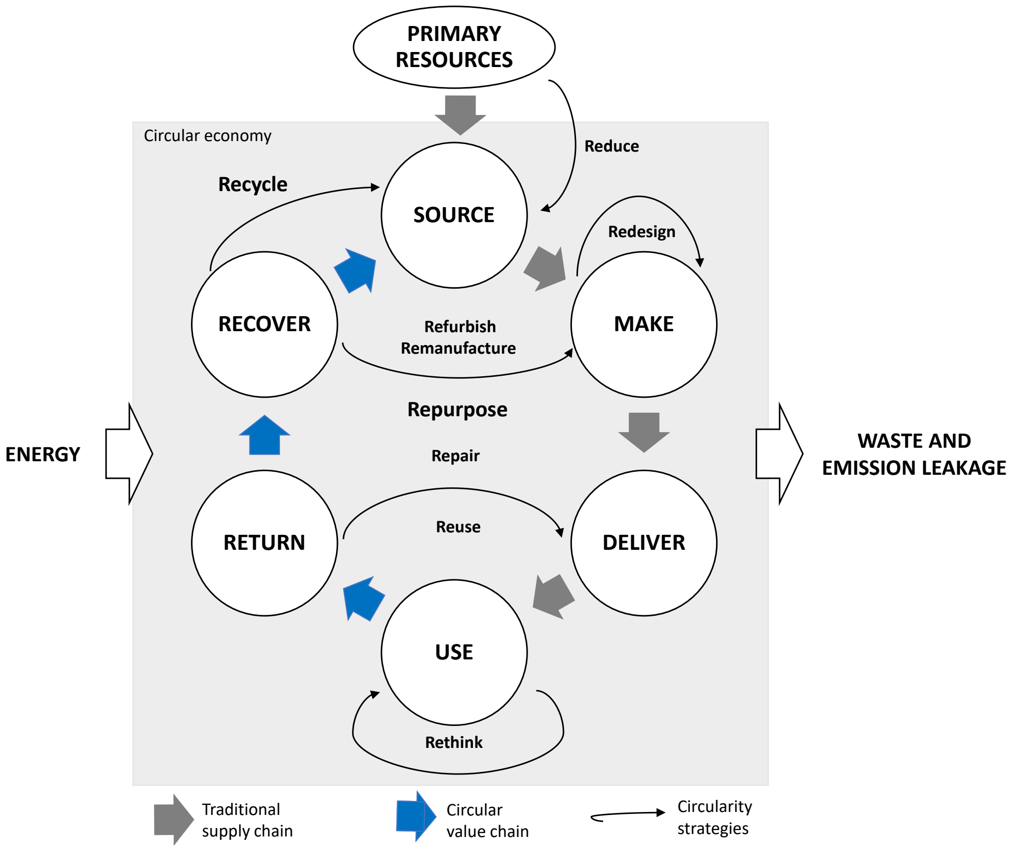

Figure 1 - Circularity strategies (adopted from Geissdoerfer et al., 2020; Laukkanen et al., 2023)

There are two fundamental approaches toward the cycling of resources: slowing resource loops and closing resource loops (Bocken et al., 2016; Hofmann, 2019). The slowing approach aims to extend the use period of products and their parts by designing and making them more durable, repairable, and reusable, and extending the product life e.g., through repair, reuse, and remanufacture (Lüdeke-Freund et al., 2019). The closing approach aims to create a circular flow of resources by recovering materials from products at the end of their life and reusing them to make new products, i.e, recycling.

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

REINFORCE is committed to the challenge of designing, developing, and deploying a novel sustainable, and highly efficient circular value chain serving as a reference for automated, safe and cost-efficient logistics and processing of EoL batteries from EV and stationary applications for repurposing and recycling.

Even though the focus in this project is on logistics, repurposing and recycling, the systemic view on multiple re-strategies and sustainable circularity of batteries is important. For example, repurpose may be worth considering, opposing to repair, and the project can give recommendations for redesign to further promote repurposing and recycling.

3.2 Batteries repurposing for second and third life

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 2 (Quinteros-Condoretty et al., 2021). EoL batteries are the batteries that have reached the end of their usefulness and/or lifespan and no longer operate at sufficient capacity its intended purpose (e.g., EV). **In this case, EoL EV batteries are no longer useful for EVs, as traction batteries, normally when delivered capacity is less than 80% of original (80% State of Health – SoH)**. Second 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".

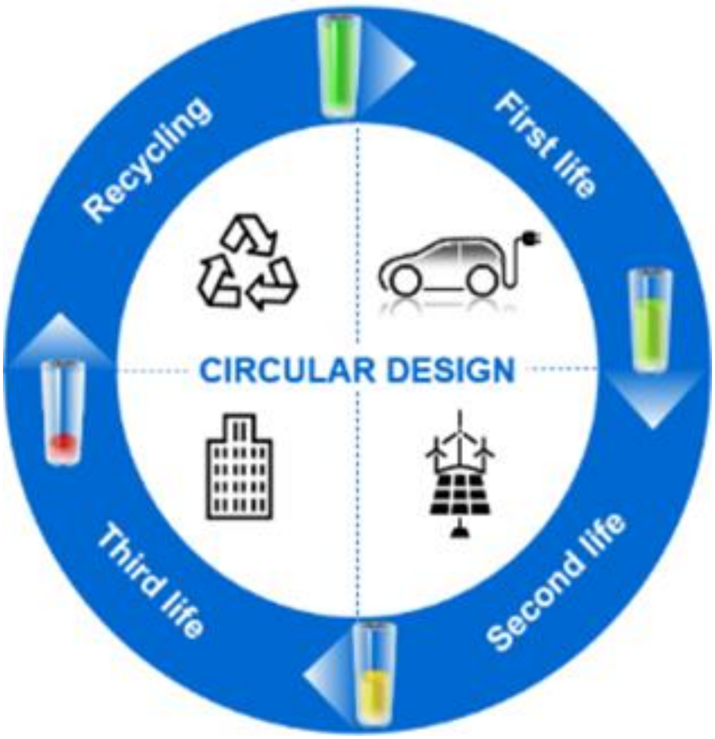

Figure 2 - Circular design of LIB with extended purposes (Quinteros-Condoretty et al., 2021)

Repurposing for 2nd and 3rd life has two significant system impacts (Global Battery Alliance, 2019): Firstly, it has the potential to **recover residual battery value** at the end of its life cycle, thereby enhancing the economic viability of batteries and expediting their market expansion. Secondly, repurposing can diminish the demand for new batteries within the power sector. Although there is a short-term trade-off when compared to battery recycling, analysis indicates that extending a battery's life would yield greater environmental benefits and is, therefore, the preferred approach over immediate recycling. Challenges in this endeavour encompass the possibility of high transaction costs, the absence of information regarding a battery's remaining health, and concerns about unwanted thermal incidents and performance relative to new batteries. Given the substantial uncertainty surrounding the evolution of these factors, targeted measures are necessary to create the essential conditions for repurposing batteries. REINFORCE meets these challenges.Table 2 summarizes the concepts that are associated with sustainable circular value chain of LIB batteries.

Table 2 - Key REINFORCE concepts

Concept	Definition
Lithium-ion (Li-ion) battery (LIB)	Lithium-ion batteries are a family of rechargeable battery types in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging.
NMC battery	Lithium-nickel-manganese-cobalt (NMC) batteries are the most common type of LIB used in electric vehicles (EVs) today. NMC batteries offer a good balance of energy density, power, and cost.
LFP battery	Lithium-iron-phosphate (LFP) batteries are known for their safety and cheaper price, but their energy density is lower.
End-of-life (EoL) battery	EoL Batteries are the batteries that have reached the end of their usefulness and/or lifespan and no longer operate at sufficient capacity its intended purpose.
Batteries reuse	Reuse is the complete or partial reuse of the battery for the original purpose the battery was designed for, potentially after repair
Batteries repurpose	Complete or partial use of the battery in a different application than its original purpose; repurpose (a 2nd life application or even a 3rd life application for used batteries) extends the lifetime of batteries, and potentially displaces some new batteries from e.g., stationary applications
2nd life batteries	2nd life batteries are those that have been removed from their original purpose (e.g., EVs) due to diminished capacity or performance, but they still have enough capacity to be useful in less demanding applications (e.g., energy storage), giving them a "second life"
3rd life batteries	3rd life batteries are those that have been removed from 2nd life applications (e.g., energy storage systems) due to diminished capacity

Concept	Definition
	or performance, but they still have enough capacity to be useful in less demanding applications (e.g., backup power), giving them a "third life"
Batteries recycling	Recycling means turning batteries into raw materials (e.g., lithium, cobalt, graphite) which can be used again, usually for completely new products
Supply chain	A supply chain is an entire process/system of producing and delivering a product or service, from sourcing raw materials to the final delivery of the product or service to end users
Value chain	A value chain (a broader concept than a supply chain as it covers the aspect of value creation) is a set of activities needed to deliver a valuable product or service to the end customer. The value chain consists of the primary (directly related to the process of creation and retention of value) and support (practices that support the execution of the primary) practices.
Circular value chain	A circular value chain includes activities beyond customer use and extending the life cycle of products. It involves sharing, reusing, repairing, and recycling existing materials and products as long as possible. New technologies and business models must be developed to ensure circularity and close the loop for materials in the battery value chain.
Business model	A business model describes the rationale of how an organization creates, delivers, and captures value (Osterwalder & Pigneur, 2010). It provides a link between an individual company and the larger production and consumption system of which it is part (Boons et al., 2013).
Circular business model	Circular business models aim to enhance the transition from a traditional linear and unsustainable “take-make-dispose” economy to a circular and sustainable “reduce-reuse-recycle” economy by slowing, closing, and narrowing resource loops (Bocken et al., 2016). The six major circular business model types are repair and maintenance; reuse and distribution; refurbishment and remanufacturing; recycling; cascading and repurposing; and organic feedstock (Lüdeke-Freund et al., 2019). (Note: It is not self-evident that all circular business models are sustainable.)
Sustainable business model	A sustainable business model creates significant positive and/or significantly reduced negative impacts on the environment and/or society through changes in how the company and its value network create and deliver value, and capture value or change their value propositions (Bocken et al., 2014).

4. Applications for 2nd and 3rd life

As the world shifts towards sustainable energy solutions, EVs have emerged as a pivotal component of the transportation landscape (Virmani et al., 2023). Central to the performance of these vehicles are the lithium-ion batteries that power them. However, what happens to these batteries when their driving days are over? This question has given rise to an exciting and transformative field: the second and third life of EV batteries.

4.1 Current technical criteria to route to second and third life

The successful implementation of 2nd and 3rd life applications in the battery fields requires careful consideration of various requirements. These factors help determine the suitability and viability of repurposing batteries for extended use (Montes et al., 2022). By evaluating these requirements and indicators, stakeholders can make informed decisions regarding the selection, integration, and optimization of batteries for 2nd and 3rd life applications, promoting resource efficiency and maximizing the value derived from battery technologies. The second life of lithium-ion batteries from EVs is still in its early stages as the number of EVs on the road increases, the demand for second-life battery applications is also expected to grow. This fosters the creation of a new market for used EV batteries and makes them more sustainable, since, by 2023, it is expected to reach almost 1000 GWh of total accumulative second-life battery capacity (Reid et al, 2016).

In the context of batteries, 2nd and 3rd life are often used to refer to the generations and stages of battery technologies. Second-life applications involve repurposing batteries that are no longer suitable for their primary use, for instance, in electric vehicles. While these batteries may no longer meet the demanding requirements of their original applications, they often retain a significant portion of their capacity and can still be utilized in less demanding scenarios (Haram et al., 2021). Third-life applications involve further extending the lifespan of batteries that have already undergone their second life phase. These applications focus on maximizing the remaining capacity of batteries that would otherwise be considered end-of-life.

According to Venkatapathy et al. (2015) the moment for transitioning a battery from its first to its secondary life depends various factors – namely: aging, environmental conditions, and costs, which collectively determine when this shift should occur. By analysing a battery as a holistic system across different automotive and stationary applications, a shift in perspective emerges. Rather than categorizing a battery solely as a storage medium based on its application area (automotive or stationary storage), it is important to consider a battery as a utility, considering the main drivers that will determine the most adequate shifting period.

The battery characteristics are intricately shaped by a combination of its structural attributes and behaviour, all interconnected and interrelated, as depicted in the Figure 3. These interconnections define the main factors that influence transitioning a battery from its first to its secondary or third life - namely:

- **Aging** serves as a critical determinant, reflecting the present state of health and aiding in the prediction of the battery's remaining useful life;
- **Environmental factors** impose essential thermal and mechanical constraints on the structural design of the battery, tailored to a specific application;
- **Market dynamics, encompassing the cost** of materials, new batteries, the availability of used ones from electric vehicles, and the expenses associated with refurbishing used batteries for second-life applications, significantly influence the feasibility of these applications.

These factors, indispensable for a meaningful shifting assessment, are both influenced by and influencers of the battery system's structure and behaviour.

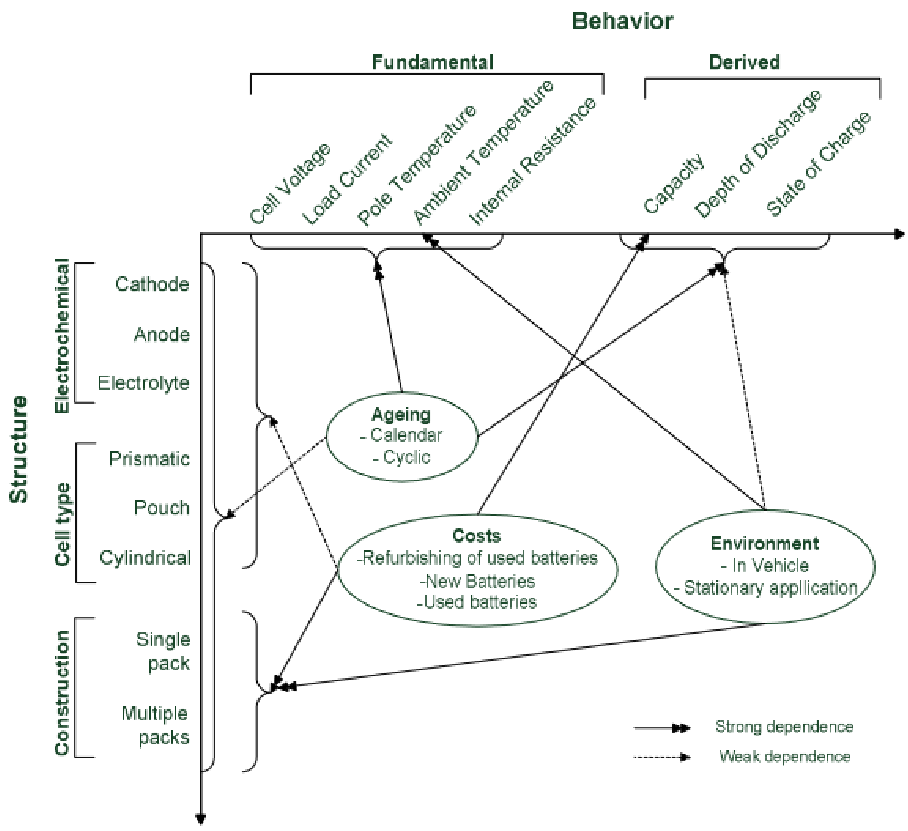

Figure 3 - Correlations between battery's structure and behaviour responsible for main transitioning factors (Venkatapathy et al., 2015)

4.2 Current 2nd and 3rd life uses for batteries

The second life of lithium-ion battery systems from EVs refers to the repurposing of these batteries after they have been retired from their original use in EVs. On average, a pre-owned electric vehicle lithium-ion battery retains about 70-80% of its original energy capacity (Barco et al., 2020; Martinez-Laserna et al., 2018). Former batteries can find valuable applications in areas like on-grid applications (renewable farming, area and frequency regulation, load levelling, generation-side asset management, peak reduction and voltage or reactive power support), off-grid applications (microgrid, smart grid, load following, power quality & reliability, and spinning reserve) and mobile applications (EV charging station, EV for short range trips, Vehicle to Grid[V2G] for fast charging and EV for long range trips) (Haram et al., 2021; Shahjalal et al., 2022).

Based on the data accessible, at each phase of the battery evaluation process, there is the opportunity to decide the appropriate course of action for the battery: recycle/disposal, repair/reuse, or assess a second-life (Montes et al., 2022). Occasionally, there may be no need for the full capacity of a new battery, making a second-life battery adequate to meet the necessary requirements (Shahjalal et al., 2022). Retired batteries may be effectively used in some sectors. According to Haram et al. (2021), the Table 3 shows the system requirements of EV battery to stationary applications.

Table 3 - Second-life typical application requirements (Haram et al., 2021).

Stationary Applications - KPIs	
Voltage Required	~ 800 – 1000 V
Operating Hours for 10A	Max. 87,800 h (on)
Ambient Temperature	10 to 35ºC
C Rates	If Continuous: <0.5 C
	If Peak 0.2 to 2 C
Thermal Management	Passive (only active in specific use cases with critical temperatures)
Vibration	None (Stationary)
SoH	From 90-70% (at beginning of 2nd life)

LIBs find diverse applications across various industries, from providing backup power to homes and businesses to supporting renewable energy solutions and telecom infrastructure, below is the description on each potential 2nd life application:

- **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.

- **Uninterruptible power supplies (UPS):** UPSs are used to provide backup power for computers and other critical equipment.

- **Solar and wind power:** Lithium-ion batteries can be used to store energy from solar and wind power plants, helping to stabilize the grid and make renewable energy more reliable.

In Europe, numerous automobile manufacturers, especially those who were early leaders in the electric car industry, have incorporated second-life batteries into various types of energy storage systems. These systems encompass a wide range, from small residential setups to more substantial containerized grid-scale solutions depicted in Figure 4 (Melin, 2018). The study by Melin (2018), supports the strategic routing of second-life EV batteries into a myriad of stationary energy storage systems.

Car maker	Second life initiative	Car maker	Second life initiative
BJEV	EV-charging, backup power	Mitsubishi	C&I energy storage
BMW	Grid-scale energy storage, EV-charging	PSA	C&I energy storage
BYD	Grid-scale energy storage, backup power	Renault	EV-charging, residential energy storage, grid-scale energy storage
Chengan	Backup power	Tesla	Remanufacturing
Daimler	Grid-scale energy storage, C&I energy storage	Toyota	C&I energy storage, grid-scale energy storage (NiMH)
General Motors	Remanufacturing,	SAIC	Backup power
Great Walll Motor	Backup power	Volkswagen (Audi)	C&I energy storage
Hyundai	Grid-scale energy storage, C&I energy storage	Volvo	Residential energy storage
Nissan	Remanufacturing, C&I energy storage, EV-charging	Volvo Cars	Residential energy storage
		Yin-Long	Backup power, C&I energy storage

Figure 4 - Second-life initiatives in Europe by several vehicle manufacturer (Melin et al.,2018)

The second life of lithium-ion batteries from EVs can help to reduce the environmental impact of these batteries. When batteries are recycled, the materials they contain can be reused, but this process can be energy-intensive and generate emissions (Kwade et al., 2018). Several studies (Aziz et al., 2014; Cready et al., 2003; Lih et al., 2012; Williams et al., 2011, Dong et al., 2023) state that second-life batteries are suitable for services that require lower energy storage performance, when compared the needs of and EVs. Using retired EV batteries may contribute to a reduced cost and environmental impacts of energy storage systems. By reusing batteries in second-life applications, we can extend their lifespan and reduce the need for recycling.

Benefits of the second life of lithium-ion battery systems from EVs, include (Dong et al., 2023, Song et al., 2022, Engel et al., 2019):

- **Reduced environmental impact**: Reusing batteries in second-life applications can help to reduce the environmental impact of EV batteries, as it reduces the need for recycling and the associated emissions when capacity retention is still viable for a certain application.
- **Extended battery lifespan**: Second-life applications can extend the lifespan of EV batteries, which can save money and resources, thus diluting impacts.
- **Creating new markets**: The second life of EV batteries can create new markets for used batteries, which can boost the economy and create jobs. Alongside with novel business model (i.e., remanufacturing of packs).
- **Reduced costs**: Second-life batteries are foreseen to cost between 30% and 70% of new batteries in 2025.

The third-life of lithium-ion battery systems (from earlier EVs and stationary applications) is a concept that is still in its early stages, but it has the potential to extend the lifespan of these batteries even further. In a third-life batteries would be used for less demanding applications, such as:

- **Portable power**: This could include applications such as power tools, laptops, and mobile devices;
- **E-bikes and scooters**: Lithium-ion batteries can be used to power e-bikes and scooters, which are becoming increasingly popular;
- **Home appliances**: Lithium-ion batteries can be used to power home appliances, such as refrigerators and washing machines.

The third life of lithium-ion battery systems from EVs and stationary applications could help to reduce the environmental impact of these batteries even further (Fan et al, 2023). By reusing batteries in third-life applications, we can extend their lifespan even longer and, once again, reduce the need for recycling. Nevertheless, the cost-benefit analysis should be performed in an application-based approach, as the benefits of introducing the materials in the production of new systems, with consequential higher efficiency, is still to be evaluated (Shen et al, 2023). For this, other considerations and potential drawbacks also need to be considered:

- **Safety**: Lithium-ion batteries can be dangerous if they are not handled properly. In a third-life application, where the batteries are used for less demanding applications, there is a risk that they may not be handled as carefully as they would be in a first- or second-life application. This could increase the risk of a fire or explosion.
- **Reliability**: The performance of lithium-ion batteries can degrade over time. In a third-life application, where the batteries are used for less demanding applications, they may not be able to provide the same level of performance as they would in a first- or second-life application. This could lead to premature failure of the batteries.
- **Cost**: The cost of refurbishing and repurposing lithium-ion batteries for third-life applications can be high. This could make it difficult to find a market for these batteries, as the cost of third-life batteries may be higher than the cost of new batteries.

Whether the third life of lithium-ion battery systems from EVs makes sense from a cost-benefit perspective depends on several factors, including the **cost of refurbishing** and **repurposing batteries**, the **demand** for third-life battery applications, and the **environmental benefits** of extending the lifespan of these batteries.

In general, the cost of refurbishing and repurposing batteries is likely to **decrease** as technology matures and more efficient methods are developed. The demand for third-life battery applications is also expected to grow as the number of EVs on the road increases. Alongside, the environmental benefits of extending the lifespan of these batteries are significant, as they can reduce the need for earlier-than-needed recycling and the associated emissions – the full residual value of the system, being it either economic, environmental or social.

Based on these factors, it is likely that the third life of lithium-ion battery systems from EVs will make sense from a cost-benefit perspective in the future, under specific circumstances. However, it is important to note that the technology is still in its early stages, and there are still some challenges that need to be addressed, being a key one, open standards that allow faster and accurate characterization of the modules, faulty cells, and matched systems. Studies show that there are clear needs for automated and cost-effective methods acting as enablers (Román-Ramírez et al, 2022; Kritzinger, w et al. 2018; Woo, Y. et al. 2013).

Overall, the third life of lithium-ion battery systems from EVs has some potential drawbacks, but the potential benefits are also significant. As the number of EVs on the road increases, the demand for third-life battery **applications** is also expected to grow. This could help to address the safety and reliability concerns and make third-life batteries a more viable option. Some ways to mitigate the relevant shortcomings and potentiate their usage are:

- **Improve battery safety**: This can be done by developing new battery chemistries that are less flammable, or by improving the design of battery packs to make them more resistant to fire hazards.
- **Increase battery reliability**: This can be done by developing new battery management systems that can monitor the health of batteries and prevent them from failing prematurely.
- **Reduce the cost of refurbishing and repurposing batteries**: This can be done by developing more efficient and cost-effective methods for refurbishing batteries, and applying the Sustainable and Safe by Design (SSbD) Framework from the early stages of battery system development.

5. Application driven and battery regulations derived KPIs

Due to incomplete or inadequate environmental regulations related to discarded batteries, many of these batteries currently find their way to landfills, while only a minuscule portion of used batteries is directed to established recycling centres (Mayyas et al., 2019), however, the European Union (EU) has been actively working on updating and strengthening regulations related to batteries to address environmental and safety concerns. A new regulation (Regulation (EU) 2023/1542), concerning battery management systems and battery passports, aims to guarantee the collection, reuse, and recycling of batteries in Europe. The newly implemented batteries regulation is designed to maximize the environmental impact of batteries, reduce the use of harmful substances and decrease the reliance on raw materials from non-EU nations.

This regulation represents a comprehensive approach that encompasses the entire lifecycle of lithium batteries, spanning from raw material extraction, through production, design, labelling, traceability, collection, recycling, and reuse.

According to this regulation, batteries with a capacity exceeding 2 kWh that are introduced into the Union market will need to undergo electronic registration. The Battery Passport serves as a digital record facilitating enhanced communication among manufacturers, end-users, and recycling operators. It offers details about the carbon emissions associated with battery manufacturing and guarantees the ability to track the journey of batteries (Saari et al., 2022). **More specifically, the battery passport will be required to store the following information:**

- Information identifying the manufacturer;
- Type of battery and information identifying the battery (batch or serial number);
- Technical information of the battery (e.g., rated capacity, voltage. Original power capability, expected lifetime in cycles, temperature range);
- Geographical location of manufacturing;
- Date of manufacture (month and year);
- Weight;
- Capacity;
- Chemistry composition;
- Carbon footprint information;
- Potentially hazardous substances contained in the battery;
- Usable extinguishing agent;
- Critical raw materials present in the battery;
- Dismantling information;

- Treatment, recycling and recovery methods the battery can undergo at the end of its life.

In order to allow the Battery Passport to access current data on battery health and the anticipated lifespan of each linked energy storage system, **the newly approved European Battery Regulation mandates that every battery must be furnished with a Battery Management System (BMS)**. Aside from its role in cell balancing, which extends the battery's longevity, **a BMS can estimate the battery's State of Charge (SoC) and State of Health (SoH) based on the battery's voltage and current measurements**. There are a few parameters that determine the SoH of electric vehicle packs, stationary battery storage systems and light means of transport (LMT) batteries:

- **For electric vehicles**:
  - State of Certified Energy (SOCE)

- **For stationary battery energy storage systems and LMT batteries**:
  - The remaining capacity;
  - The remaining power capacity (if possible);
  - The remaining round trip efficiency (if possible);
  - The evolution of self-discharging rates;
  - The ohmic resistance (if possible).

These key points underscore that the battery industry's participants will encounter extensive and novel responsibilities due to the recently introduced Battery Regulation. Companies in this sector must, therefore, thoroughly assess their current procedures, production methods, and supply chain practices to ensure they are well-prepared for compliance with the upcoming European battery legislation, and in line with the European vision for energy transition and integration.

Regarding transportation regulations, there is the ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road), which is a comprehensive regulatory framework that governs the safe transportation of hazardous materials via road networks across Europe. Since **LIBs are classified as hazardous materials under the ADR regulation, this implies following a set of rigorous requirements for transportation of the LIBs** (ADR, 2023).

The ADR requirements for the **transport of LIBs vary depending on the type of battery, its size, and its quantity**. In general, **LIBs must be packed and labelled**

correctly, and they must be transported in a vehicle that is equipped with the appropriate safety features (ADR, 2023).

Below, is a summary of the key ADR requirements for the transport of lithium-ion batteries (ADR, 2023):

- **Packing**: Lithium-ion batteries **must be packed in strong, outer packaging that is able to protect the batteries from physical damage and prevent them from leaking**. The packaging must also be able to withstand the heat and cold that the batteries may be exposed to during transport.

- **Labelling**: Lithium-ion batteries must be **labelled with the appropriate UN number** (UN 3480 or UN 3090), **the battery type, and the state of charge**. The labels must be visible and durable, and they must be placed on the outer packaging of the batteries.

- **Transport**: Lithium-ion batteries **must be transported in a vehicle that is equipped with the appropriate safety features**, such as fire extinguishers and emergency disconnect switches. The vehicle must also be driven by a driver who is trained in the safe transport of dangerous goods.

In addition to the general ADR requirements, there are a number of special provisions that apply to the transport of lithium-ion batteries:

- LIBs with a capacity of more than 100 Wh must be transported as dangerous good;
- LIBs that are damaged or defective must be transported as dangerous goods.

6. Preliminary decision tree for EoL batteries

In this section, we describe a 1st VERSION of a decision tree for REINFORCE EoL battery assessment that will combine the key concepts, applications and KPIs disclosed in previous sections to support the decision-making process of REINFORCE. Deliverable 2.2 will provide an improved version of the decision tree with more detailed KPIs and the economic and environmental dimensions (Lozano & Lozano, 2023).

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.

6.1 Preliminary criteria for the decision tree

The following steps are considered in the decision-making for REINFORCE decision tree (Figure 5): (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, 2023).
- **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.

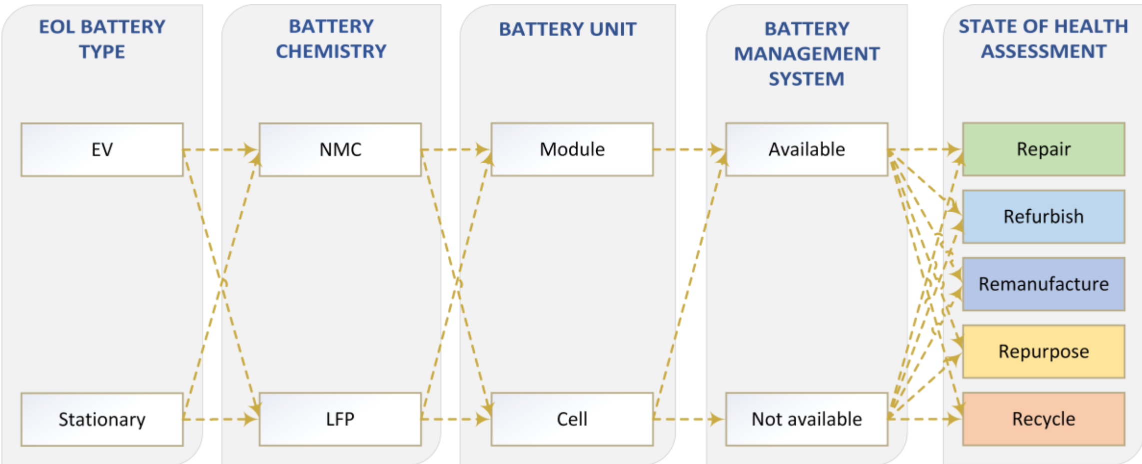

Figure 5 - Preliminary flow of variables

6.2 Strategic decision tree for 2nd and 3rd life of EoL batteries

Figure 6 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
- STEP 4. Assessing the SoH of a battery
- STEP 5. Determining the best circular economy strategy
- STEP 6. Repurposing for 2nd and 3rd life

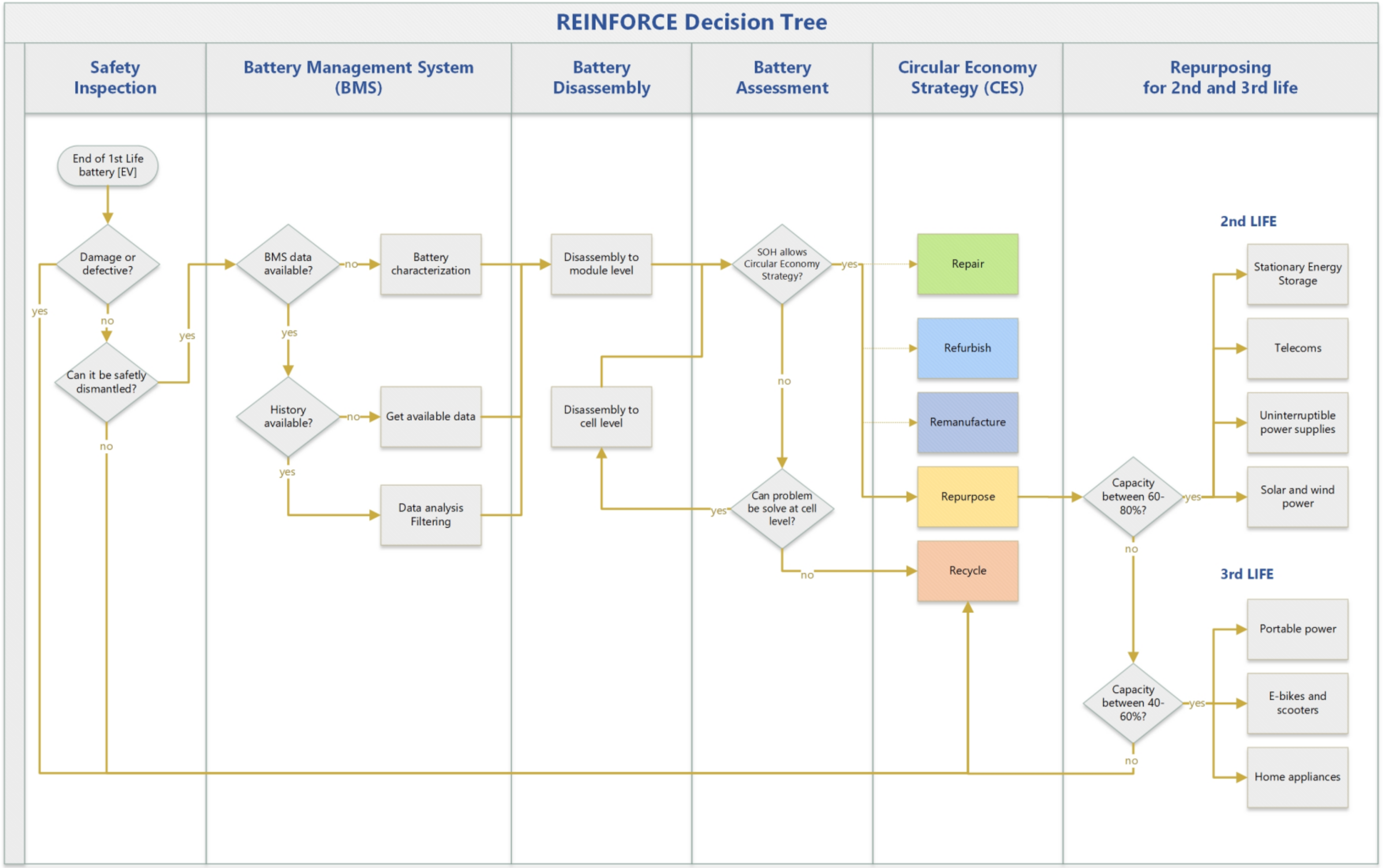

Figure 6 - Preliminary REINFORCE strategic decision tree for repurposing LIBs for 2nd and 3rd life

7. Conclusions

- In the context of batteries, 2nd and 3rd life are often used to refer to the generations and stages of battery technologies.
- Second life of lithium-ion battery systems from EVs refers to the repurposing of these batteries after they have been retired from their original use in EVs. On average, a pre-owned electric vehicle lithium-ion battery retains about 70-80% of its original energy capacity.

- The third-life of lithium-ion battery systems from stationary applications is a concept that is still in its early stages, but it has the potential to extend the lifespan of these batteries even further. In a third-life application, stationary batteries would be used for less demanding applications, such as: Portable power; E-bikes and scooters; Home appliances.

- The second and third life of lithium-ion batteries from EVs can help to reduce the environmental impacts and of battery systems.

- As battery technology advances, the concepts of 2nd and 3rd life batteries continues to evolve, and new applications may emerge over time.

- The successful implementation of 2nd and 3rd life applications in the battery fields requires careful consideration of various requirements.

- The moment for transitioning a battery from its first to its secondary life depends various factors namely: aging, environmental conditions, and costs, which collectively determine when this shift should occur.

- The value and performance of 2nd life batteries will vary based on their original chemistry, usage history, remaining capacity, etc. Careful monitoring and management are essential to ensure their safe and effective use in new applications.

- Different battery chemistries come with their own set of technical considerations and requirements. Additionally, advances in battery technology are continually evolving, leading to improvements in energy density, cycle life, and other factors.

- New regulation (Regulation (EU) 2023/1542), concerning battery management systems and battery passports, aims to guarantee the collection, reuse, and recycling of batteries in Europe.

- The new regulation foresees that, batteries with a capacity exceeding 2 kWh that are introduced into the Union market will need to undergo electronic registration -

Battery Passport, which serves as a digital record facilitating enhanced communication among manufacturers, end-users, and recycling operators.

- LIBs are classified as hazardous materials under the ADR regulation, this implies following a set of rigorous requirements for transportation of the LIBs.
- The 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. 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.

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Funded by
the European Union

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