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6-031: EV Battery Next Lives

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Executive Summary

As the demand for lithium-ion (Li-ion) batteries grows, ensuring the availability of raw materials and addressing the environmental and social impacts of battery production and disposal have become vital concerns. Business models that give batteries a second life – through reuse, repurposing and recycling – can substantially reduce material needs and environmental effects. Over time, these practices may also unlock new domestic value streams, create job opportunities and reduce battery costs. This project is a comprehensive analysis of the end-of-life (EOL) electric vehicle (EV) battery landscape, focusing on circular economy principles and market valuation. It also examines the supply chain mechanisms for recovering and redistributing valuable materials from spent batteries and assesses the market dynamics that influence their economic value.

Current State: EOL battery availability is currently limited but projected to surge. According to the International Council on Clean Transportation, around 1.2 million batteries from battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) will reach end of life globally by 2030, increasing to 14 million by 2040 and 50 million by 2050. This anticipated growth demonstrates the critical need for a robust policy framework to support the reuse and recycling of these batteries.

EV Second-Life Management Strategies: The growth of the EV market has surged the demand for lithium-ion batteries. This demand brings forth the challenge of managing batteries at their end of life, which, if not addressed, could lead to significant environmental and health risks due to the hazardous materials they contain. This report outlines a possible circular economy for EOL EV batteries, the key stakeholders in the supply chain and the sustainable practices in the second-life battery supply chain. This report also outlines comprehensive lifecycle management strategies, including refurbishment, recycling and repurposing EOL batteries, such as in stationary energy storage applications.

Challenges and Opportunities: The emergence of EVs presents both challenges and opportunities across the entire automotive ecosystem. As the shift to EVs gains momentum, it is crucial to consider every aspect – from manufacturing vehicles and parts, to purchasing (dealers and financing), operations (charging infrastructure, repairs, servicing, roadside assistance and insurance), and end-of-life management (second-hand markets, battery recycling and Auction Houses). The value of EV batteries and their impact on repair economics and insurance claims necessitates proactive measures. The varied engagement and awareness levels of stakeholders makes it difficult to assess the effect of increasing EV adoption on insurance costs and repair dynamics. The absence of cost-effective repair options, limited post-accident diagnostic capabilities, low numbers of skilled technicians and constrained recycling solutions contribute to the escalating costs and challenges associated with EV battery second life, especially after minor accidents.

Manufacturers are currently not obliged to report on in-warranty collection rates, recovery rates and materials recycling efficiencies for EOL batteries. This absence of reporting standards hinders transparency and accountability in battery management practices, and limits stakeholders' ability to assess sustainability efforts and identify areas for improvement.

Addressing these challenges requires comprehensive training for technicians, improved diagnostic tools and robust recycling solutions. Australia lacks a comprehensive motor vehicle decommissioning and recycling framework. Infrastructure gaps and supply chain issues for recycling EOL EV batteries results in lost valuable materials. Closing this gap is essential for sustainable EV battery management. The Battery Stewardship Council, the FCAI and the MTAA are exploring stewardship options with the EV sector.

Circular Business Models (CBM): CBMs for EOL EV batteries are crucial for sustainability in the automotive industry. Circular business models focus on maximising value and extending the EV battery lifecycle through stakeholder collaboration. Case studies from 4R Energy Corporation, Nissan North America, BMW Group and others showcase diverse CBM approaches. Despite challenges like the declining cost of new batteries and lack of original equipment manufacturer (OEM) standardisation, efforts to reuse, repurpose and recycle EV batteries are vital for reducing waste, conserving resources and promoting a sustainable circular economy.

Reusing involves restoring EOL batteries to a like-new condition, making them suitable for reuse in EVs or other applications. This process includes:

- diagnostic testing: conducting thorough diagnostics to assess battery health and identify defective cells or modules
- repair and replacement: replacing damaged cells or components to restore the battery's performance
- reassembly and testing: reassembling the battery pack and performing extensive testing to ensure it meets safety and performance standards.

Reusing can significantly extend the lifespan of EV batteries, reducing the need for new batteries and minimising environmental impact.

Repurposing uses EOL batteries in new applications, extending their useful life. Common repurposing applications include:

- stationary energy storage systems (ESS): using EOL batteries for grid storage, backup power or renewable energy integration
- commercial and industrial applications: using EOL

batteries in commercial and industrial settings for load management and energy optimisation
- electric vehicle charging stations: repurposing EOL batteries to store energy for EV charging stations, enhancing their capacity and reliability.

Repurposing offers immediate revenue generation and environmental benefits, making it a viable option for managing EOL EV batteries.

Recycling focuses on extracting valuable materials from spent batteries, reducing the need for new raw materials and minimising environmental impact. The recycling process includes:

- collection and transportation: safely collecting and transporting EOL batteries to recycling facilities
- dismantling and material recovery: dismantling battery packs and recovering valuable materials such as lithium, cobalt, nickel and manganese through mechanical and chemical processes
- material processing: processing recovered materials to produce new battery components or other products.

Recycling can reduce environmental impact by conserving resources and reducing waste, but it requires significant investment in infrastructure and technology.

Supply Chain and Stakeholder Roles: A network of stakeholders, including manufacturers, recyclers, regulatory bodies, secondary market users, consumers and research entities, is essential. These diverse participants collaborate to recycle or repurpose batteries responsibly, fostering a circular economy in the EV sector. Effective supply chain management ensures that batteries are safely collected, transported and processed to maximise their residual value. In Australia, when repairing EV batteries isn't feasible, there is a notable gap in infrastructure and supply chain markets for recycling and repurposing these batteries. This gap leads to a significant loss of the valuable raw materials in EV batteries, which could otherwise be reintroduced into the supply chain. Closing this infrastructure and supply chain gap is essential for maximising the sustainability and resource efficiency of EV battery management in Australia.

Economic Considerations and Market Dynamics: This report analyses the economic viability of EOL EV batteries, and considers disassembly, testing and reintegration costs. Repurposing EV batteries offers immediate revenue and lower operational costs, making it a financially viable short-term option. The cost of acquiring second-life batteries is the largest component, followed by transportation and R&D for remanufacturing, which includes module disassembly, cell testing and selection, and battery reassembly. Partnerships with Australian repurposing companies can leverage existing infrastructure for maximum economic benefit. The economic analysis also considers the costs and benefits of refurbishment and recycling, highlighting the potential for significant cost savings and revenue generation.

Regulatory and Testing Standards: Ensuring safety and performance standards is crucial for successful second life applications. This report reviews existing testing protocols and highlights the need for international standard harmonisation to streamline EOL battery management across borders.

Auction Houses and Insurance Companies: Beyond in-warranty services, a considerable portion of battery failures stem from accidental damage or out-of-warranty issues. Consequently, the management of EOL EV batteries involves the participation of the insurance sector, aftermarket service providers and the auction industry. Auction houses and insurance companies play a crucial role in the EOL management of EV batteries.

Auction Houses can serve as repositories for EOL Electric vehicles, providing storage, dismantling and initial testing services. Insurance companies can facilitate the efficient collection and processing of EOL batteries through collaboration with auction houses and recycling or repurposing firms. This collaboration can streamline the management process, reduce costs and increase the value recovery from EOL batteries. These stakeholders will need to bolster their electrical safety expertise to effectively handle and manage retired EV batteries.

Key Observations of the Report:

1. Growing Demand and Supply Chain

- The popularity of EVs is driving demand for batteries and critical minerals.
- The EOL EV battery supply chain is emerging, with significant concentration in countries like China.
- Reducing reliance on critical minerals is crucial for a sustainable supply chain amid price fluctuations.

2. Retirement Practices

- Advancements in battery technology are reconsidering the practice of retiring batteries at 80% state of health (SOH).
- Different battery chemistries have a different optimal retirement point, suggesting that a more sophisticated decommissioning approach is needed.

3. Regulatory and Safety Standards

- Diverse regulations for handling crashed EVs highlight the need for a unified management approach that promotes international cooperation and standardisation.

4. Storage Protocols at Auction Sites

- Damaged EVs should be stored in quarantine zones at a safe distance from other structures or vehicles.

5. Economic Value of EOL Batteries

- EOL EV batteries are 'urban mines' – over 90% of their economic value is derived from seven main components.

- As of 2021, only 10% of spent Li-ion batteries are collected and recycled in Australia due to inefficient collection and lack of infrastructure.

6. Lack of Comprehensive Data

- A lack of data on the volume, condition and lifespan of retired batteries, along with unclear regulations, creates market uncertainties and discourages investment.

7. International Market Comparisons

- Markets with legislated product stewardship and higher government support for EV adoption have more advanced second-life battery industries.

8. Challenges for Insurers

- Insurers face challenges with increasing write-offs of low-mileage EVs due to minor damage, complicating risk assessment and increasing costs.

9. Auction Houses as Repositories

- Auction houses are expected to become major repositories for EOL EVs as older EV models are phased out.

10. Market Price Variation

- The market price for EOL batteries varies with quality – lower quality modules are priced between $65 and $76 per kWh, and higher quality modules at $152 to $174 per kWh.

1. Introduction

The automotive industry is undergoing a profound transformation towards sustainable transportation. The proliferation of electric vehicles (EVs) represents a promising leap forward and a complex challenge. Despite Australia's current lag in EV market share compared to other regions, the inevitable rise of EVs poses a significant upcoming challenge.

A critical challenge amidst the growing enthusiasm for electric mobility is the management of retired and written-off EV batteries. While the adoption of EVs in Australia remains modest, projections indicate a rapid acceleration in the coming years. This surge in EV ownership will inevitably increase the volume of retired EV batteries, presenting a pressing environmental and logistical dilemma. The sheer volume of written-off EV batteries will strain the automotive industry's supply chain.

Electric vehicle batteries possess unique characteristics that demand specialised handling at the end of their life. The degradation of batteries over time and usage necessitates replacement or retirement, raising concerns about proper disposal and recycling practices. The improper management of retired EV batteries poses environmental risks, such as soil and water contamination from toxic materials like lithium and cobalt.. Without efficient strategies for collection, recycling or repurposing, these batteries become a wasted resource, both economically and environmentally.

In navigating this challenge, the collaborative efforts of car insurance companies and auction houses emerge as pivotal. Car insurance companies provide coverage for vehicles and facilitate the claims process – they need to adapt to accommodate the unique needs of EV owners, including the proper management of retired EV batteries. Simultaneously, auction houses serve as essential hubs for reclaiming value in vehicles, salvage, and machinery and their components across multiple industries. They can be instrumental in the disposal and recycling of retired vehicles, including EVs and their batteries. As the industry evolves, auction houses have the opportunity to adapt to the unique challenges associated with EVs.

As Australia stands on the cusp of a potential EV revolution, it becomes imperative for stakeholders across the EV industry to come together and devise innovative solutions. The convergence of stakeholders – car insurance companies, auction houses, EV manufacturers, policymakers and consumers–underscores the urgency of addressing the management of retired EV batteries in Australia. By fostering collaboration, innovation and strategic partner- ships among these key players, we can pave the way for a sustainable and resilient future. Together, we can transform the EOL journey of EV batteries into an opportunity for en-vironmental stewardship and economic growth.

This report delves into the complex landscape of retired and written-off EV batteries in Australia, and examines EV second-life projects around the world and their associated supply chain mechanisms. Through dialogue and collaboration among stakeholders, we aspire to chart a course towards a future where car insurance companies and auction houses play integral roles in ensuring the responsible management of EV components, and drive forward the sustainability agenda in the Australian automobile.

2. Current State of EOL EV Batteries

2.1. Current State of EVs and Battery Demand

In 2023 global electric car sales approached 14 million, constituting 18% of total vehicle sales. Projections indicate 17 million sales in 2024, accounting for over 20% of all cars sold worldwide. This predicted surge is underscored by a 25% increase in EV sales in the first quarter of 2024 compared to the previous year. The International Energy Agency's forecast suggests that by 2035 every other car sold globally will be electric. In 2023 most electric car sales were concentrated in China (60%), Europe (25%) and the United States (10%).[1] EV sales in Australia reached a total of over 180,000 vehicles by the end of 2023, representing 8.45% of total vehicles sold in Australia in 2023.[2] Data from the China Automotive Technology & Research Centre projected that the volume of retired EV batteries from EVs in China would reach an alarming 1 million tons by 2025. A global analysis of EOL EV batteries forecasts that by 2030 second-life battery capacity will exceed 275 GWh annually, creating a transformative opportunity for energy storage. However, substantial technical, economic and regulatory challenges could prevent companies from fully realising this potential.[3, 4] The number of expired EV batteries is expected to grow significantly, reaching almost 30,000 tonnes per annum by 2030 and exceeding 360,000 tonnes per annum by 2040. By 2050, this figure is projected to soar to 1.6 million tonnes, highlighting the pressing need for effective waste management strategies.[5] EV salvage volumes are increasing month on month in Australia. In 2023 the highest salvage volume was sold to individual buyers in Queensland.

In 2023 the demand for EV batteries surged to over 750 GWh, marking a 40% increase compared to 2022. With the increased demand for batteries comes the challenge of sourcing and refining larger quantities of critical raw materials, notably lithium, cobalt and nickel. [1] The rapid increase in batteries could result in new resource challenges and supply-chain risks. [6] Anticipated strong growth in the EV sector is therefore driving significant investment across the supply chain.

Between 2022 and 2023, investment announcements in EV and battery manufacturing nearly reached USD 500 billion, with approximately 40% already committed. Over 20 major car manufacturers, representing over 90% of global car sales in 2023, have established electrification goals.[1] Cumulatively, the targets set by these automakers suggest that over 40 million electric cars could be sold by 2030, aligning with current policy projections. This shift is reshaping the automotive landscape, and expanding the second-hand EV market because significant price reductions make them competitive with combustion engine vehicles. Moreover, the expanding international trade in used EVs anticipates broader adoption in emerging and developing economies, further solidifying the position of the EV as the future of mobility.[1]

OBSERVATION 1

The growing popularity of EVs is fuelling the demand for batteries and essential minerals. The EOL EV battery supply chain is also emerging but projects and stakeholders are highly concentrated in certain areas, with China standing out as a major player in both battery production and the EV trade. It is crucial to minimise the reliance on critical minerals to ensure a sustainable, resilient and secure supply chain. This becomes even more significant in light of recent price fluctuations in battery materials.

2.2. Lifespan of EV Batteries

Li-ion batteries, which come in different forms, have been the preferred choice for automakers.[7] The longevity of EV batteries is contingent upon their chemistry and usage patterns. Batteries undergo changes over time and with age, and their capacity is influenced by various factors such as battery design, temperature, charging protocol and the current state of charge (SOC).

The normal lifespan of an EV battery begins upon its initial activation in a vehicle and continues until its capacity to provide adequate range and performance is compromised.

In some cases, factors beyond the owner's control can affect the usability of the vehicle. For instance, vehicle warranties often have clauses that are activated upon reaching specific age or mileage thresholds, which can lead to the end of warranty coverage or necessitate mandatory actions like inspections or replacements, particularly for battery packs in EVs. Moreover, legislative changes in different countries or regions may impose limitations on vehicle usage once they reach predetermined criteria, such as a specified age or mileage. This approach has been implemented in several European Union cities to reduce emissions. This encourages the turnover of vehicle fleets and the adoption of more efficient, less polluting vehicles.[8]

2.2.1. Retirement Criterion of EV Batteries

EVs pose significant challenges for batteries. They commonly undergo more than 1,000 incomplete charging and discharging cycles over a 5 to 10-year period and are subjected to wide temperature fluctuations ranging from -20 °C to 70 °C. Moreover, they withstand high depths of discharge, and rapid charging and discharging rates. Once an EV battery pack fails to meet the performance criteria for EVs, often marked by a considerable degradation in storage capacity, it is retired, marking the conclusion of its lifespan.[9]

The retirement criterion, established in 1996 by the United States Advanced Battery Consortium (USABC), advises battery replacement when it loses 20% of its initial capacity, indicating retirement at 80% SOH.[10, 11] However, the relevance of this threshold for current battery technologies is debated, as improvements in EV battery technology have significantly increased driving range, potentially shifting consumer expectations.[11] Various standards apply to EV battery retirement,[12, 13, 14, 15, 16, 17] categorising them into quantitative and qualitative approaches. Quantitative standards focus on capacity decline to 80%, while qualitative standards consider actual power tests. Research suggests that capacity degradation within a certain range may not significantly affect EV driving performance, thereby questioning the conservative 70%–80% retirement standard. However, safety concerns like internal short circuits and thermal runaway must also be considered when establishing retirement standards. Thus, defining EV battery retirement standards should incorporate both capacity degradation and safety performance evaluations.[18, 11]

To promote EV purchases and bolster consumer confidence, federal regulations in the USA mandate minimum warranties for EV high-voltage (HV) batteries, with California imposing a minimum warranty of 10 years or 150,000 miles, ensuring at least 80% battery capacity by 2030, an increase from 70% in 2026.[18] In Australia, warranties typically tolerate a 30% loss in capacity. Manufacturers have the freedom to exceed these standards, resulting in varying warranty periods across EV models.[18]

OBSERVATION 2

The current practice of retiring batteries at an 80% SOH is being questioned due to advancements in battery technology. The effect of different battery chemistries on the optimal retirement point suggests a more sophisticated approach is needed to determine when a battery should be decommissioned.

2.2.2. Written-Off Electric Vehicles

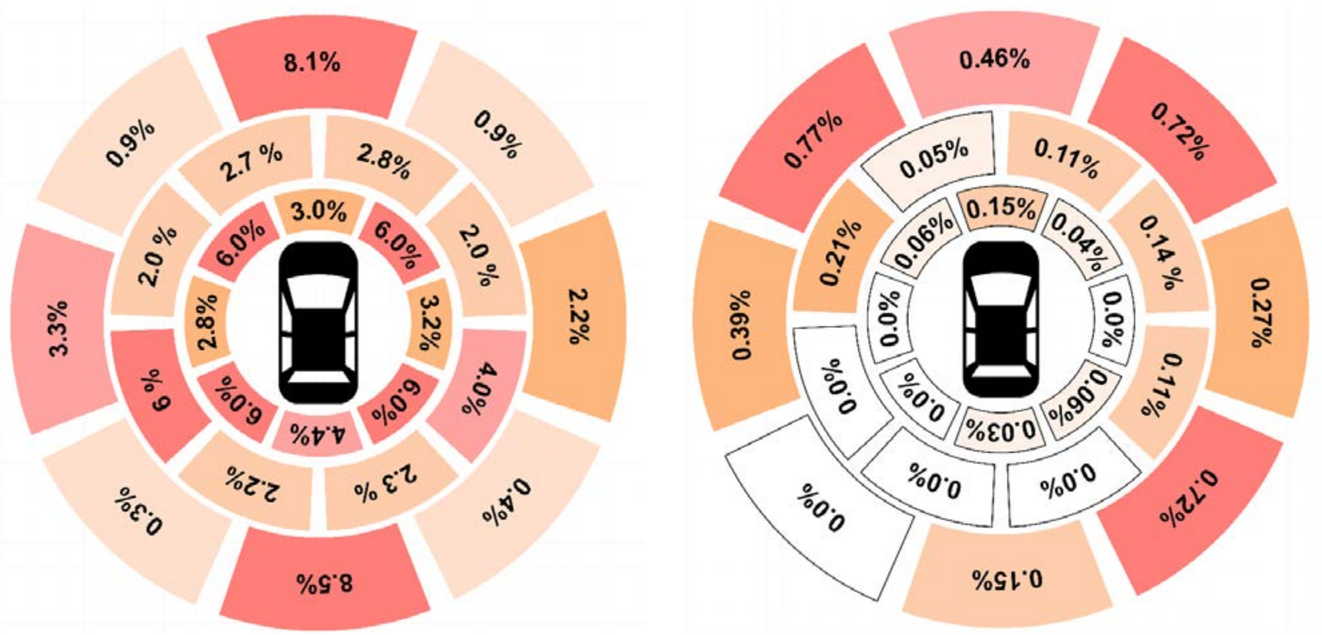
Written-off EVs are those deemed a total loss, typically due to severe damage that makes repairs uneconomical. They are usually scrapped or salvaged for parts, including batteries that can be repurposed or recycled. Several factors influence EV crash and write-off rates, including a shortage of skilled mechanics, insurance policies, advancements in road safety, adoption of autonomous driving technology, and vehicles equipped with advanced driver assistance systems (ADAS).[19]Electric cars tend to cause less damage than conventional vehicles. An Insurance Europe report shows that in motor liability insurance, EVs are involved in 5 to 10 percent fewer accidents on average than comparable internal combustion engine vehicles. The difference is even more pronounced in comprehensive insurance, where damages caused by EVs are up to 20 percent less frequent than those caused by conventional vehicles.

Research into vehicle accidents [19] conducted by Thatcham in the UK reveals that damage patterns observed in internal combustion engine vehicles and EVs are similar. This similarity allows us to use internal combustion engine vehicle claims data to help predict the likelihood of HV battery damage in specific accident scenarios. Estimates of battery damage scenarios are based on accidents that are likely to cause twisting, distortion or deformation of the battery casing. The probability of battery damage varies due to the diverse external and internal designs of batteries and their casings.

Damage Patterns of Crashed EVs and Batteries: Damage patterns can be classified into three main types: damage affecting adjacent body zones, damage involving nonadjacent body zones, and scenarios featuring at least one area of damage that does not involve the vehicle's body.[19] The frequency and prevalence of these damage patterns, as well as their impact on the likelihood of HV battery damage, are depicted in a concentric circle diagram presented in Figure 1. In this diagram, darker shades indicate a higher frequency of damage assessments for a particular pattern. The innermost circle represents damage confined to a single zone, the middle circle indicates damage spanning two adjacent zones (referred to as offset damage), and the outermost circle illustrates damage spread across three adjacent zones (referred to as distributed damage). This suggests that collisions involving the front and rear of the vehicle are among the most common, along with impacts on a single corner, often resulting from low-speed manoeuvres.

The findings indicated a 1.5% to 7.5% probability of battery damage for impacts confined to a single zone and a 25% to 35% probability for impacts spanning multiple zones. Notably, damage to the underside of a vehicle was identified as carrying an 85% likelihood of affecting the HV battery.[19]

Each battery recovered from a vehicle involved in a crash requires individual assessment by specialised EV mechanics. The presence of a high-voltage battery in EVs significantly increases safety risks, requiring repair facilities to have trained technicians, proper certifications and the right tools. EV manufacturers have added more parts near the vehicle's exterior to disperse crash energy efficiently, leading to more parts needing replacement, even with mild to moderate damage. Consequently, EVs require more replacement parts and additional repair cost compared to 2021 and newer internal combustion engine vehicles, primarily due to the extra steps needed to manage the high-voltage battery and restore safety systems to their pre-loss condition.[21]



(a) (b)

Figure 1: Simulation results of ALP for Case 1: (a) PEV damage patterns; b) Probability of HV battery damage [19]

OBSERVATION 3

The total loss frequency for EVs is comparable to that of gasoline vehicles from the 2021 model year and newer. Repair costs for EVs remain higher, with OEM parts used in most cases and labour making up nearly half of the total collision repair cost.

3. Circular Economy of EOL EV Batteries

The common belief that all second-life Li-ion batteries come from EOL EVs is inaccurate; in reality, three main channels exist [58], with the first two being most prevalent.

1. Warranty-related replacement of the battery pack.
2. Upgrading an existing battery pack.
3. Cases where an EV is declared a total loss by insurance.

Channel three is also seeing an increase in salvaged EVs. Synetiq, the UK's largest salvage company, processed approximately 20 written-off EVs every day in 2023.

Moving from a linear to a circular value chain can improve both the environmental and the economic footprint of batteries by getting more out of batteries while in use, and by harvesting EOL value from batteries. The principle of a circular economy for EOL EV batteries focuses on implementing sustainable management practices across their lifecycle to minimise waste and maximise resource efficiency. As the first wave of EV batteries approaches the end of their operational life, and as the global challenges of disposing of battery waste become more apparent, stakeholders in the EV sector face limited options for managing these materials. The potential management strategies for EOL EV batteries are reusing, recycling to reclaim valuable resources, repurposing into energy storage systems, and, as a last resort, disposal.

Currently, the development of a circular economy for EOL EV batteries is impeded by a combination of technical, economic and regulatory challenges. The commercial reuse of EV batteries at a large scale is still in its infancy and limited mostly to experimental projects. Regulatory hurdles and economic considerations often make recycling or reusing these batteries less attractive than cheaper, more conventional disposal methods.[22]

OBSERVATION 4

In the near future, auction houses are expected to become a significant repository for EOL EVs, as the initial fleets of EVs reach the end of their operational life or are phased out in favour of newer, more technologically advanced models. It is likely that this influx will be accelerated by government policies aimed at phasing out new petrol and diesel vehicles in favour of electric ones.

3.1. Possible Streams of Circular Economy for EOL EV Batteries

The growing volume of EOL batteries from EVs poses a considerable management challenge. Presently, four main approaches are being evaluated: disposal, recycling, reusing and repurposing. Each approach comes with its own set of environmental, economic, technical and political hurdles that affect decision-making processes.

Figure 2 shows the streams for EOL EV batteries.

3.1.1. Disposal of EOL EV Batteries

Disposal, often involving landfill, is the least environmentally friendly and energy-efficient option. It is, however, considered necessary in certain situations to prevent workers' exposure to hazardous electrolyte releases and the potential leaching of harmful chemicals. This method, while sometimes unavoidable, is not favoured due to the material wastage, heightened environmental and health risks, and the squandering of economic potential. Practices such as stockpiling or exporting EOL batteries for disposal as part of vehicle scrappage schemes are viewed unfavourably due to similar concerns.[23]

3.1.2. Recycling of EOL EV Batteries

Recycling of EOL EV batteries involves disassembling the batteries and extracting valuable metals for reuse, a process crucial for reducing resource consumption and advancing the sustainable development of EVs. This recycling effort is part of broader strategies aimed at enhancing the sustainability and security of supply chains by diminishing dependence on critical materials. Innovations in battery technology that require fewer minerals, the promotion of EVs with optimally sized batteries, and the development of effective recycling are pivotal in overcoming these challenges.[11]

The composition of Li-ion battery packs, with a blend of small and large formats and specific cathode chemistries, is estimated as follows (in weight percentage, i.e., kg material/kg lithium-ion battery pack): 4% nickel, 5% manganese, 7% cobalt, 7% Li_2CO_3 (lithium carbonate equivalent), 10% copper, 15% aluminium, 16% graphite and 33% other materials.[24]

The recycling of these batteries presents a promising opportunity, given the valuable materials they contain. While the full economic potential is still being explored, ongoing advancements in recycling technologies and demand suggest there is room for growth in this area.

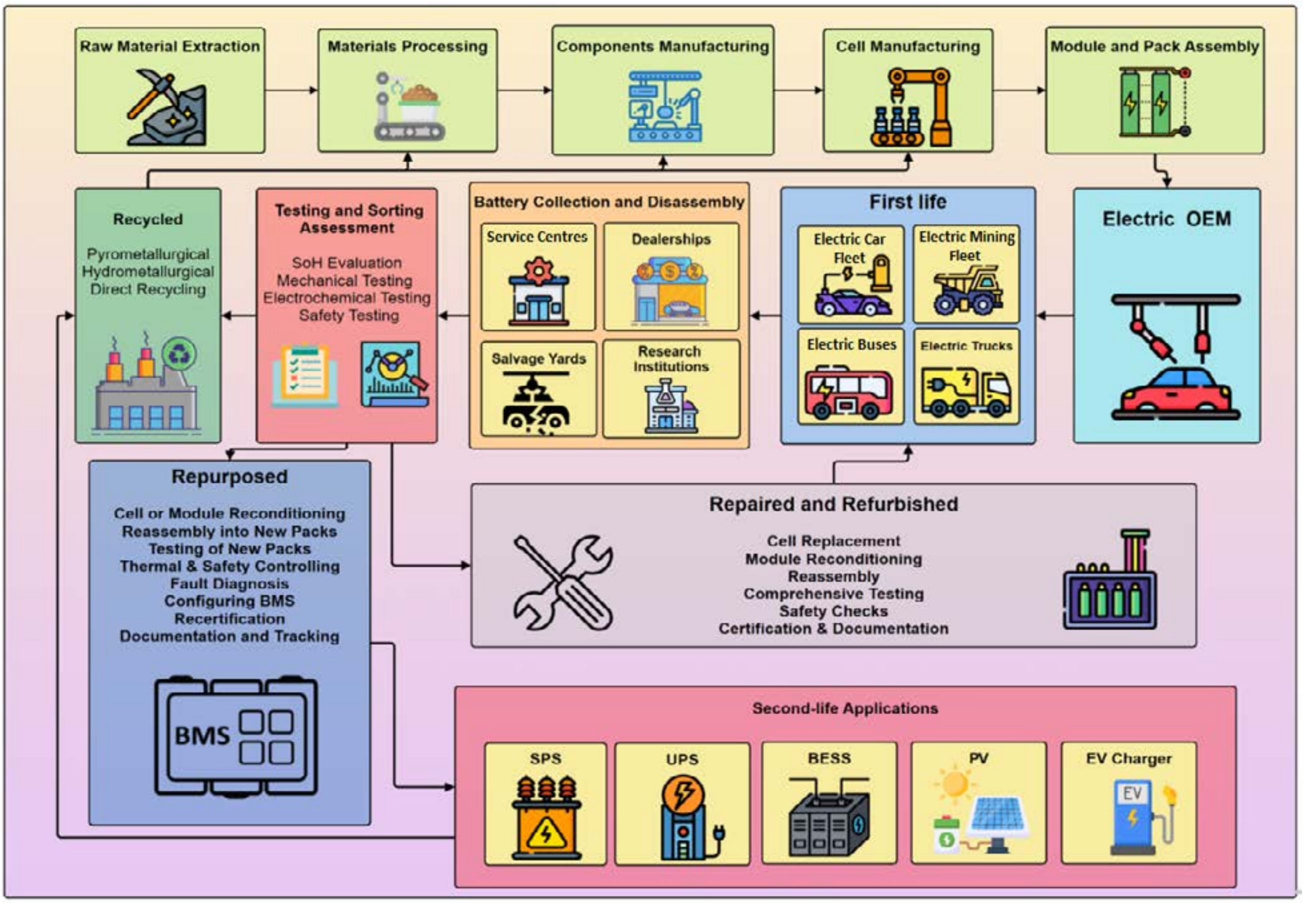


Figure 2: Lifecycle of EV batteries

While lithium recovery may become appealing in future, policy intervention such as improved collection systems, better traceability over battery lifetimes and standardisation in the design, transport, handling and recycling of EV batteries may be necessary to incentivise recycling due to the lack of current economic drivers. [25]

EV battery collection and recycling schemes have been established worldwide. For example, in North America, Tesla collaborates with Kinsbursky Brothers to recycle about 60% of its battery packs, while in Europe, partnerships with companies like Umicore facilitate recycling efforts. Other manufacturers, such as Nissan, encourage customers to return used batteries to licensed collection points; this highlights the critical role of recycling in addressing resource challenges, especially for lithium and cobalt. In a recent development in China, EV manufacturers are now held accountable for the recovery of batteries. This entails the establishment of recycling channels and service outlets dedicated to the collection, storage, and transfer of old batteries to recycling companies. One hundred-and-fifty-six recycling enterprises had joined China's traceability management platform as of 2023.[26] This platform aims to monitor the ownership information of discarded batteries.[27]

The recovery of raw materials from EOL EV batteries primarily employs metallurgical methods. The main recovery techniques are:[28]

1. Pyrometallurgical Recovery: a high-temperature furnace reduces metal oxides into base metals like cobalt, copper, iron and nickel, which can then be further refined through hydrometallurgical processes. The resulting slag, containing aluminium, manganese and lithium, finds use in industries such as cement making.[29]
2. Hydrometallurgical Metal Recovery: an aqueous solution, often a combination of H_2SO_4 and H_2O_2, leaches desired metals from the cathode material, effectively extracting various metals directly from the battery. [29]
3. Direct Recovery: cathode or anode material from the electrode is removed for reprocessing and reuse in remanufactured Li-ion batteries. [29]

Advancements in battery technology necessitate updates in to the recycling of EV batteries. While traditional recycling recovers cobalt, the industry's shift towards lithium, nickel and manganese, due to changing battery compositions and market preferences, emphasises the need for new, eco-friendly recycling methods that better align with current material demands and environmental considerations. Cutting-edge recycling processes for lithium-ion batteries present both economic and environmental prospects. To illustrate this point, the estimated 11 million tonnes of spent battery packs equates to roughly

US$65 billion in residual value from metals and other components.[24]

OBSERVATION 5

EOL EV batteries are "urban mines". More than 90% of the economic value of a spent lithium-ion battery is reported to be derived from seven main components: cobalt, lithium, copper, graphite, nickel, aluminium and manganese.

Presently, just 10% of spent Li-ion batteries are collected and recycled in Australia. The significantly low volume of recycling may be attributed to inefficient collection, lack of awareness and lack of infrastructure to deal with spent Li-ion batteries.

3.1.3. Refurbishing EOL EV Batteries

Refurbishment of EOL EV batteries is a crucial step in extending the life of these batteries beyond their initial automotive use. As EV batteries approach or reach their designed end of life, characterised by reduced capacity and performance, refurbishment processes aim to rejuvenate the batteries for further service. This may involve several key procedures:

1. Cell replacement: Faulty or degraded cells in the battery pack that significantly impair its performance are identified and replaced with functional ones.
2. Battery pack balancing: Over time, variations in cell performance can lead to imbalancesin the battery pack. Battery balancing maximises the useful capacity of the pack by guaranteeing that all cells in the pack have the same SOC.
3. Repairs and maintenance: Beyond cell replacement and balancing, refurbishment may also include repairing or replacing other components of the battery system, such as the battery management system (BMS), connectors and housing. Maintenance checks are performed to ensure all parts of the battery are functioning correctly and safely.
4. Health and safety checks: A comprehensive assessment of the battery's health and safety features is conducted to ensure it meets the required standards for its second-life application. This includes testing for electrical safety, thermal stability, and the integrity of safety circuits.
5. Capacity and performance testing: After refurbishment, batteries undergo rigorous testing to evaluate their restored capacity and performance levels. These tests help to determine the suitability of the refurbished batteries for various second-life applications, such as stationary energy storage, backup power systems, or even repurposing into other EV batteries.

3.1.4. Repurposing EOL EV Batteries

When EOL EV batteries are accurately diagnosed, sorted and repackaged, they can be repurposed for applications that demand lower performance levels than cars, extending their useful lifespan. This approach not only retains considerable economic and environmental value but also aligns with the "4R" concept of reuse, resell, refresh and recycle.

Figure 3 illustrates the relationship between battery capacity and life expectancy. Current standards indicate that EOL EV batteries retain 70%–80% of their initial capacity, making them suitable for secondary applications before material recovery is considered when their capacity drops to about 30%–40%. This strategy, which maximises the life of EV batteries, has gained significant attention and research interest, paving the way for the establishment of industrial chains in this field.[31, 28]

The United States has established UL1974, the Standard for Evaluation for Repurposing Batteries, which outlines a comprehensive process for assessing, testing and certifying repurposed batteries. It includes detailed requirements for the evaluation of battery packs' state of health, testing for safety and performance, and criteria for disassembly and reassembly into repurposed units.[32] Standards, such as BS EN IEC 63330 and BS EN 62933-5-2, are under development in Europe to provide guidelines for the state of health assessment and general requirements for second-life batteries. These standards emphasise the need for clear definitions between repair and modification, ensuring that repurposed batteries meet safety criteria and do not have significant alterations that could compromise their integrity.[32]

The primary challenge hindering the adoption of Li-ion batteries in energy storage has been their high cost. However, repurposing EV batteries as second-life batteries for energy storage presents a cost-effective solution. This not only reduces future EV costs and environmental impacts from battery disposal but also creates potential revenue through electricity system services and price arbitrage, thereby giving economic value to second-life batteries and promoting broader EV adoption.

Second-life Applications of EOL EV Batteries: Table 1 presents the principal second-life applications alongside their respective functions.

EOL EV batteries may no longer meet the performance standards required for powering electric vehicles, typically due to their capacity falling below 70% to 80% of their original state, but they often retain enough functional capacity to be repurposed for second-life applications.

In these secondary roles, EOL EV batteries have the potential to continue offering valuable service, often between 5 and 10 years. The duration of this extended service life is influenced by several critical factors. These include the condition of the battery at the time of repurposing, the specific demands and operational conditions of the secondary application, and the effectiveness of the

Table 1: Possible second-life applications of end-of-life EV batteries [33, 34, 35]

Application category	Requirement
User-side energy storage systems	Batteries have the largest market potential on the user side. They are installed by individuals, businesses and industrial parks. These systems reduce electricity costs by charging during off-peak rates and providing backup power for critical operations, such as data centres. User-side ESSs also support various applications including backup for communication base stations, powering EV charging stations, energy storage for low-speed electric vehicles and street lamps, as well as offering uninterrupted power supply (UPS) for continuous operations and residential energy management. They are versatile and have an essential role in energy optimisation and reliability.
Grid-side energy storage systems	They offer a range of services that enhance the flexibility and stability of power systems, including peak regulation, frequency modulation, emergency response to accidents and power quality improvement. For instance, in areas with a high-load power grid, a grid-side ESS can address short-term peak load demands and postpone the necessity for further infrastructure investments and construction. Additionally, it can alleviate congestion in transmission sections of regional power grids, particularly in regions where there is a lack of peak regulation capacity from thermal power units.
Renewable energy systems (RES)	EOL EV batteries can be integrated with wind, solar (photovoltaic, PV) and other renewable energy sources in various setups to create a RES with a steady and manageable output. It is anticipated that EOL EV batteries will play a significant role in the development of future RESs.

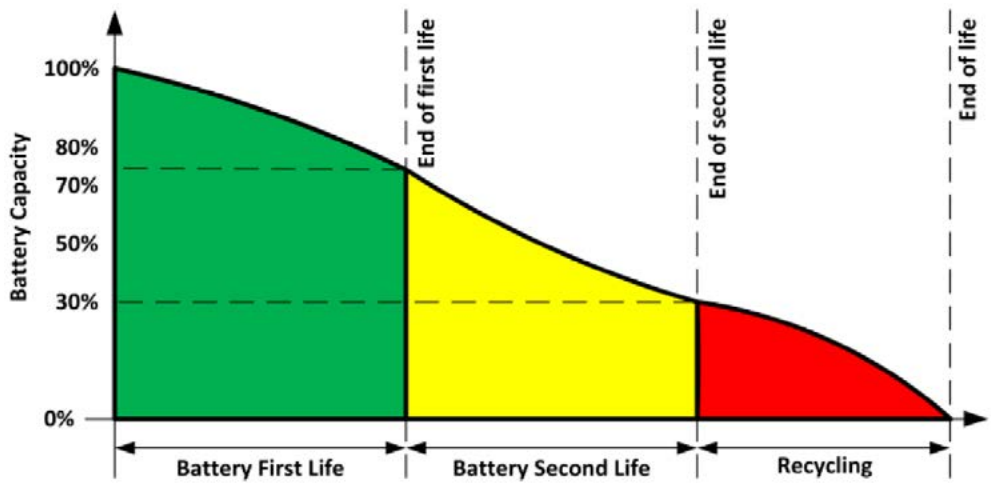


Figure 3: Plot of EV battery life range as a function of battery capacity [30]

BMS in optimising the battery's remaining performance and extending its lifespan.[36, 37]

Ongoing research and development endeavours are constantly exploring innovative methods to optimise the total lifespan and overall value of these batteries.

3.2. Drivers, Barriers, and Enablers to a Circular Economy for EOL EV Batteries

Transitioning to a circular economy for EOL EV batteries represents a shift towards a sustainable closed-loop system. This transformation faces various challenges, but is also propelled by significant drivers and supported by enabling mechanisms. Table 2 outlines the primary factors driving the circular economy for EOL EV batteries.

The advancement of a circular economy for EOL EV batteries encounters several barriers. The economic viability of re-purposing retired EV batteries for second-life applications remains uncertain, as it relies on understanding the impact of various critical factors often known only to battery and EV original equipment manufacturers (OEMs). Globally, authorised treatment facilities (ATFs) encounter difficulties in managing large volumes of Li-ion batteries. This is mainly due to the lack of a clearly defined commercial incentive, the early stage of technological development, and the diverse array of cell formats and pack configurations, each presenting unique challenges.

Current technologies for battery reuse and recovery are not optimised for cost effectiveness, and the diversity in battery chemistries and designs complicates standardisation and automation of disassembly and recycling. A lack of comprehensive data on the volume, condition, and lifespan of EOL batteries, along with unclear regulations, creates market uncertainties and discourages investment in

Table 2: Drivers for circular economy of end-of-life EV batteries [38, 3, 39]

Driver	Potential benefit
Cost savings and increased profits	Lower manufacturing costs leads to additional revenue streams and tax benefits, improving overall profitability
Better competitiveness	By fostering a green and environmentally responsible image, businesses can boost consumer trust and stand out in the market.
New and expanded market and employment opportunities	The shift creates opportunities for new market segments and job creation, stimulating economic growth.
Lower negative environmental impacts	This approach significantly cuts down on waste, greenhouse gas emissions, other environmental pollutants, and the total energy needed for mining, transporting, refining and manufacturing products.
Fewer resource constraints	Efficiently conserving high-value materials helps prevent resource constraints and decreases the demand for importing raw materials.

Table 3: Barriers for circular economy of end-of-life EV batteries [38, 3, 39]

Barrier	Description
Current technology, infrastructure, and processes	Presently, the technology, infrastructure and processes are inadequately optimised for the efficient and cost-effective circular economy for EOL EV batteries.
Lack of critical information and data	This includes essential information and data of the value and market potential for reused and recovered EOL EV batteries, their volume and composition, the condition and characteristics, and the quality, performance, reliability and safety.
Unclear, complex and varied laws and regulations	The laws and regulations governing the reuse and recovery of EOL EV batteries are often unclear, complex, and vary.
Lack of economic motivation	There is a limited economic incentive to support the collection, transport and reuse/recovery of EOL EV batteries. This extends to a lack of motivation to design EV batteries for durability, ease of reuse and recyclability.
Low market confidence in reused and repaired materials	Consumer confidence in reused and repaired EOL EV batteries is inadequate, which hampers the development of secondary markets for reuse and repair-for-reuse.

reuse and recovery processes. Moreover, the incentives for private investment in battery reuse or recovery are currently minimal, with reconditioning and recycling costs often outweighing the benefits.[38]

Presently, various countries, including Australia, have limited infrastructure for EV battery service, maintenance and repair. This is attributed to two main factors: firstly, the current minimal demand for battery repairs does not warrant the expense of training; and secondly, OEMs exercise extreme caution in providing access to BMS data for EV battery packs. Nevertheless, there is a reasonable expectation for this infrastructure to expand over time. The EV battery supply chain is keen on building a robust customer presence in the market in the coming months. Nevertheless, the significant hurdle lies in effectively managing the time delays inherent in crucial decision-making processes, commonly denoted as 'chicken and egg' situations, across the entire supply chain. To overcome this challenge, there is a need for mechanisms that can de-risk early investments and offer better clarity on demand, thus facilitating smoother market entry. Table 3 outlines the primary barriers of the circular economy for EOL EV batteries.

Advancements in battery design that focus on durability, reusability and recyclability are key to facilitating a circular economy. Government-funded research can reduce market uncertainty and spur private investment in the battery energy storage market. Standardisation and innovation in battery design can make reconditioning and refurbishing processes more economically viable. Economic incentives, such as subsidies and grants, along with clear regulatory policies, can promote sustainable management practices and investment in the sector. Collaborative initiatives and transparent information exchange among stakeholders can further aid the transition towards a circular economy for EOL EV batteries.[38] Table 4 outlines the primary enablers of the circular economy for EOL EV batteries. Key policy levers for EV battery reuse and recycling is provided in Table A in the Appendix.

Table 4: Enablers for circular economy of end-of-life EV batteries [38, 3, 39]

Enabler	Potential benefit
Research and development	Focused efforts are needed to analyse the value and market potential of reused and recovered battery materials, understand the volume, condition and composition of batteries, improve battery design, and improve refurbishment and recycling technologies. Techno-economic analyses and technical guidance can also play a vital role in reducing uncertainties and informing market opportunities.
Information exchange	Sharing information among various stakeholders in the EOL EV battery supply chain, including manufacturers, system owners and recyclers, is crucial. This can help reduce costs, clarify market and regulatory uncertainties, and build positive relationships within the industry.
Economic incentives	Incentives that promote the collection, transportation and reuse/recovery of EOL batteries, and encourage battery designs that are durable and suitable for reuse, can drive innovation and private investment, making early-stage ventures more economically appealing.
Regulation and policy	Clear policies mandating or incentivising EOL EV battery collection, reuse and recovery, and potentially restricting disposal, can significantly reduce associated risks. In the absence of stringent regulations, industry standards and goals aimed at durable, standardised battery designs can improve a company's competitiveness and foster consumer confidence in secondary markets.

3.3. Global Initiatives on EOL EV Battery Projects

Figure 4 illustrates various global industrial projects focused on repurposing EV batteries for a second life. Four notable trends are shaping the landscape. Firstly, there has been a remarkable increase in the number of projects over the past three years. Secondly, virtually all major automotive OEMs are actively engaged in or planning second-life application projects, collaborating either with their battery suppliers or third-party entities. Thirdly, there is a rising trend in the adoption of large-scale stationary ESS applications, especially for grids. Lastly, the spectrum of second-life applications is expanding, showcasing a diverse array of initiatives. Based on regional efforts, China, Europe, the USA and Australia have launched diverse initiatives aimed at tackling this challenge, with a focus on recycling, repurposing, and regulatory measures to guarantee a sustainable and effective management system for EOL batteries.

3.3.1. China

China, the world's largest market for electric vehicles, has implemented stringent regulations and policies to manage EOL EV batteries. The Chinese government has introduced policies mandating that manufacturers take responsibility for the recycling of EV batteries. These regulations encourage the development of a circular economy around EV batteries, focusing on the recovery of valuable metals and the promotion of second-life applications for used batteries. Companies like CATL and BYD, leading battery manufacturers in China, have established recycling programs and are exploring ways to repurpose batteries for ESSs.

Case Study 1 showcases an example of an EOL EV battery project in China.

3.3.2. Europe

Europe has been at the forefront of advocating for sustainable battery management through the introduction of the Battery Directive and the more recent European Battery Regulation proposal, aiming to establish a comprehensive framework for battery sustainability. The European Union's focus is not only on recycling but also on ensuring that batteries are designed with their EOL in mind, by promoting the use of sustainable materials and facilitating the reuse and repurposing of batteries. Initiatives like the European Battery Alliance also aim to secure a competitive and innovative battery industry in Europe, with an emphasis on sustainability and circular economy principles.

OBSERVATION 6

Most automakers claim their battery packs are repairable, but few appear willing to share battery data. A lack of comprehensive data on the volume of retired batteries volume and their condition, and the lifespan of EOL batteries, along with unclear regulations, creates market uncertainties and discourages investment in the second-life EV battery market.

OBSERVATION 7

International markets with legislated product stewardship, vehicle emissions regulations and higher government support for EV adoption consequently also have a more advanced second-life battery industry when compared to Australia. However, globally the industry is still in the introduction phase, with commercial viability in these countries driven by policy and legislation.

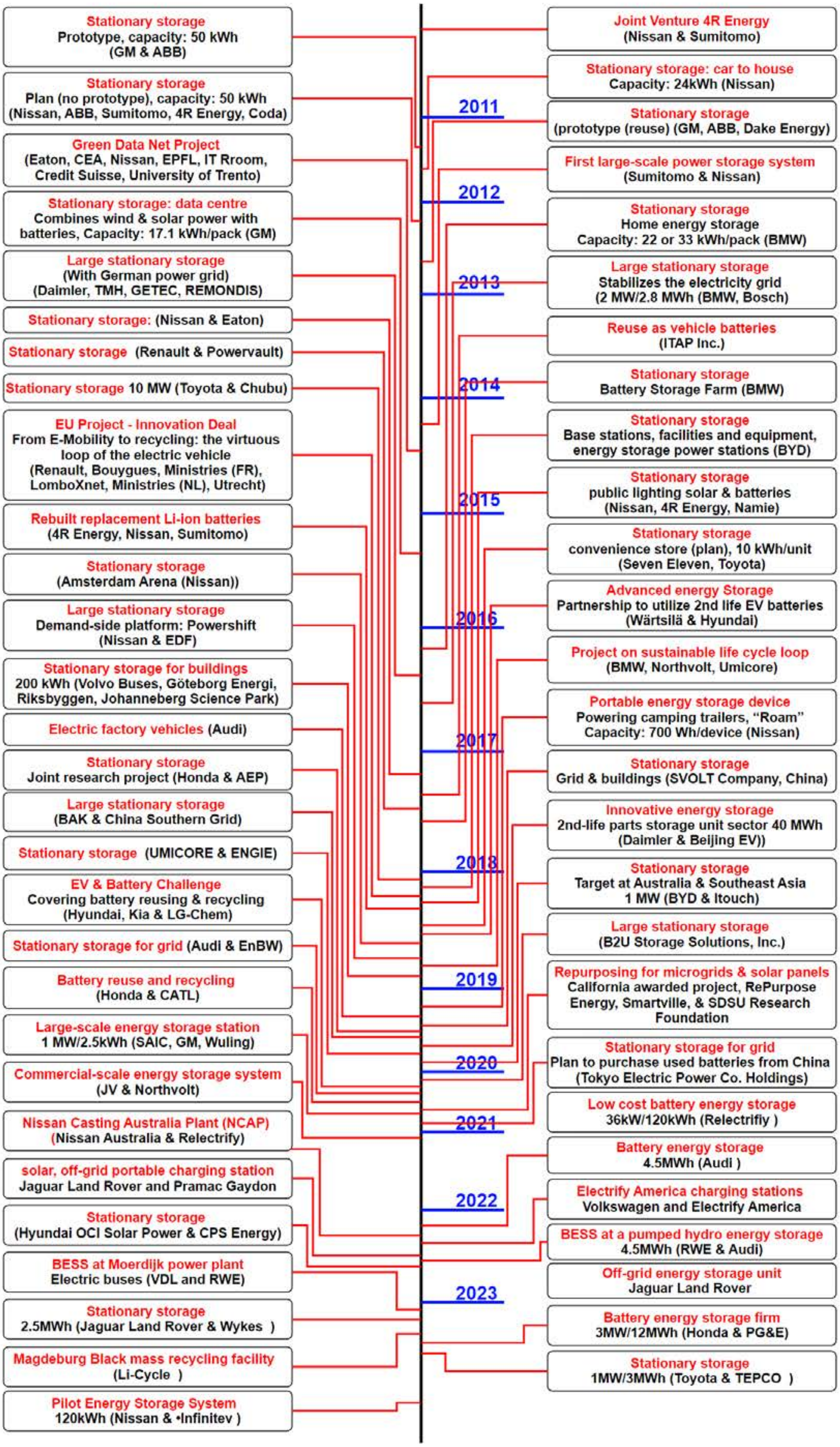


Figure 4: A historical overview of industrial projects on second-life battery applications [10]

CASE STUDY 1

BYD's strategic expansion into battery recycling and second-life use

BYD, a leading name in the EV and battery industry, has taken a significant step forward in its commitment to sustainability and innovation by establishing Taizhou Fudi Battery Co. Ltd in Taizhou. This new venture is a testament to BYD's strategic vision – while it makes and sells new batteries, it is also at the forefront of battery recycling and second-life applications. With a substantial investment of 50 million yuan, Taizhou Fudi Battery represents a key component of BYD's broader strategy to develop a comprehensive battery ecosystem, aiming to enhance the company's environmental credentials and leadership in the renewable energy sector [40].

Central to Taizhou Fudi Battery's mission is the implementation of a holistic approach to battery lifecycle management. This includes pioneering work in the recycling of new energy vehicle batteries and the utilisation of these batteries in subsequent applications, along with the development of new material technologies. Such efforts underscore BYD's commitment to the principles of a circular economy, as it seeks to extend the utility of batteries beyond their initial automotive use, thereby reducing waste and promoting sustainability [40].

Case Study 2 showcases an example of an EOL EV battery project in Europe.

3.3.3. USA

In the United States, the Department of Energy has launched several initiatives under its Energy Storage Grand Challenge, aiming to promote the reuse and recycling of EV batteries. The ReCell Centre, a collaborative research effort led by the department, focuses on advancing battery recycling technologies and developing a cost-effective recycling process. This initiative aims to reduce reliance on foreign materials, improve the environmental footprint of battery disposal, and support the domestic battery recycling industry. Additionally, several states have introduced legislation to encourage battery recycling.

Case Study 3 showcases an example of an EOL EV battery project in the USA.

3.3.4. Australia

Australia is relatively new to addressing EOL EV battery challenges but has made significant strides with the introduction of the Battery Stewardship Council and the National Battery Stewardship Scheme. These initiatives aim to increase the recycling rate of all types of batteries, including EV batteries, by creating a circular economy. The scheme encourages manufacturers, retailers and consumers to participate in responsible battery recycling programs. Australia's focus on research and development in the field of battery technology and recycling processes is growing, with institutions and companies exploring innovative solutions for battery reuse and materials recovery.

Case Study 4 showcases an example of an EOL EV battery project in Australia.

CASE STUDY 2

Nuremberg's EV charging stations powered by second-life batteries

In Nuremberg, Audi is pioneering a sustainable EV charging initiative by repurposing retired e-tron batteries to power charging stations, significantly cutting carbon emissions and aiming for zero emissions by 2050 [41].

The EOL e-tron batteries are fitted into 11kW power cubes with a 400V, 3-phase connection across three storage cubes that have a total capacity of 2.45 MWh. This setup can provide up to 70 quick charges daily through six ports, efficiently meeting EV charging demands [41].

The project harnesses solar energy during the day to charge the batteries, ensuring the use of green energy for EV charging. Additionally, 200 kW of off-peak green energy is used overnight to further reduce environmental impact and prepare for the next day's charging requirements, exemplifying a model of sustainable infrastructure in the transition towards cleaner mobility [41].

CASE STUDY 3

Harnessing end-of-life EV batteries for solar energy storage in Southern California

In Southern California, a pioneering project is repurposing retired EV batteries from models such as the Nissan Leaf and Honda Clarity EV to revolutionise renewable energy storage. This initiative integrates retired batteries into solar farms as stationary energy storage systems, increasing the grid's ability to store and use solar power more efficiently. By doing so, it ensures a steady supply of clean energy, particularly during peak demand times when solar generation is low [42].

Supported by the US Department of Energy, , this project aligns with national efforts to promote a sustainable battery ecosystem and a circular economy. With the capability to power approximately 9,500 homes using 1,300 retired batteries, it showcases the practicality and impact of repurposing EV batteries for energy storage on a significant scale. [42]

CASE STUDY 4

Melbourne's pioneering EV battery repurposing initiative

The EV battery repurposing program in Melbourne, led by Kia Australia and Infinitev, is an innovative initiative aimed at managing EOL EV batteries sustainably [43].

The program employs Infinitev's HealthCheck diagnostic approach to assess EOL EV batteries and categorise them into three grades (A, B and C) based on their condition and capacity [43]:

- A grade modules are reused in new EVs
- B grade modules are repurposed for battery energy storage systems
- C grade modules are recycled to recover valuable materials.

This program significantly reduces environmental hazards and waste, promotes the recovery of precious materials, and supports the energy needs of charging networks and other power storage systems. By doing so, it not only mitigates the environmental impact associated with battery disposal but also fosters a circular economy, demonstrating a scalable model for global adoption in the EV sector.

4. Key Stakeholders in the EOL EV Batteries Supply Chain

The supply chain for EOL EV batteries encompasses a broad network of stakeholders. Each stakeholder fulfills crucial functions in the management of EOL batteries, tackling aspects related to environmental sustainability, economic implications or technical challenges.

This sections details the principal actors in the EOL EV battery supply chain and sheds light on their distinct roles and how they contribute to battery management.

4.1. EV and Battery Manufacturers

EV and battery manufacturers are integral to the supply chain, responsible not only for the initial design and production of EVs and their batteries but also for ensuring these batteries are handled responsibly at their EOL.

Proactive manufacturers engage in developing reverse logistics, recycling partnerships and research into battery design innovations that facilitate recycling or repurposing. The activities of some of the manufacturers involved in the supply chain of EOL EV batteries are summarised below.

Tesla [51] innovates in battery recycling and repurposing, aiming for lifespans beyond 500,000 miles and enabling applications like stationary energy storage.

Repurposing: Through its open-source platform, Tesla enables third-party development of second-life battery solutions. It partners with firms like Green Charge Networks and Smartville Inc for applications ranging from home energy storage with the Powerwall to grid-scale solutions with the Mega-Pack.

Recycling: Tesla collaborates with Redwood Materials and Talon Metals for ethical recycling of batteries, focusing on creating a closed-loop system to reuse recovered materials like lithium, cobalt and nickel. This initiative is supported by Tesla's recycling R&D facility near its Nevada Gigafactory, which explores efficient recycling technologies.

Logistic: Tesla leverages its logistics network to collect used batteries, prioritising those from service centres and warranty replacements. This collection network is potentially expanded through partnerships with companies like Redwood Materials or Li-Cycle.

Performance Testing: It is likely that Tesla conducts internal testing and sorting of used batteries for internal reuse and recycling decisions.

Nissan [44] repurposes Leaf batteries for stationary energy storage. 4R Energy, Nissan's joint venture with Sumitomo, is certified under the UL 1974 Standard to evaluate and reuse EV batteries. See Case Study 5.

Repurposing: Nissan collaborates with stakeholders like Sumitomo Corporation, Eaton and Enel to repurpose Leaf batteries for energy storage for residential, commercial and grid applications.

Recycling: Nissan is deeply engaged in EV battery recycling. 4R Energy refurbishes and recycles batteries in Japan. The company is expanding its recycling efforts with new factories in the US and Europe by 2025, aiming to reduce costs and reliance on critical metals.

Logistic: 4R Energy collects, tests and repurposes used EV batteries. Using its service and logistics networks, it efficiently manages battery collection, transportation and storage.

Performance Testing: Nissan has established testing facilities to assess the remaining capacity, health and safety of used batteries.

BMW [52] is pursuing second-life uses for EV batteries to extend their life beyond initial automotive use, and is establishing key partnerships with other companies to innovate and develop new applications.

Repurposing: BMW collaborates with stakeholders like PG&E, STILL and Off Grid Energy to repurpose EV batteries for uses including vehicle-to-grid services, energy storage and mobile power units, demonstrating innovative solutions for battery lifecycle extension and renewable energy integration.

Recycling: BMW collaborates with Duesenfeld, Northvolt, Umicore and others for Li-ion EV battery recycling, focusing on sustainable reuse of materials like nickel, lithium and cobalt. This effort aligns with BMW's sustainability principles and includes partnerships for responsible sourcing and recycling with companies like Glencore, enhancing the circular economy in BMW's EV production.

Logistic and enaluations: In partnership with Northvolt, Samsung SDI and CATL, BMW collects and evaluates used batteries at its dealerships and service centres. Suitable batteries are repurposed, such as for forklifts in BBA's China plants, with production aligned to vehicle manufacturing sites in Germany, China, and the US. This strategy emphasises responsible raw material sourcing from within BMW's supply chain.

4.2. Recycling Companies

Specialised firms that recycle and repurpose play a critical role in the EOL battery supply chain. These entities employ advanced technological processes to safely dismantle batteries, recover valuable materials for reuse in new batteries or other products, and repurpose batteries for second-life applications in ESSs.

There are several Li-ion battery recycling companies in China, including Taisen Recycling, Zhejiang Huayou Cobalt, Brunp, Jinqiao Group, Jiangxi Ganfeng Lithium and GEM. GEM operates 13 automated battery dismantling and

CASE STUDY 5

Nissan and 4R Energy Corporation

Nissan has partnered with Sumitomo Corp. to set up 4R Energy, to create a second life for EV batteries, as shown in Figure 5. Old EV batteries arriving at the 4R factory are graded for reuse or recycling. Grades A and B are repurposed for new EVs and energy storage, while C grade batteries serve as backup power. This process extends battery life by up to 15 years, minimising their environmental impact. Nissan's efforts include remanufacturing facilities and advanced BMSs to optimise second-life performance. EOL batteries are responsibly recycled or disposed of according to environmental regulations [44].

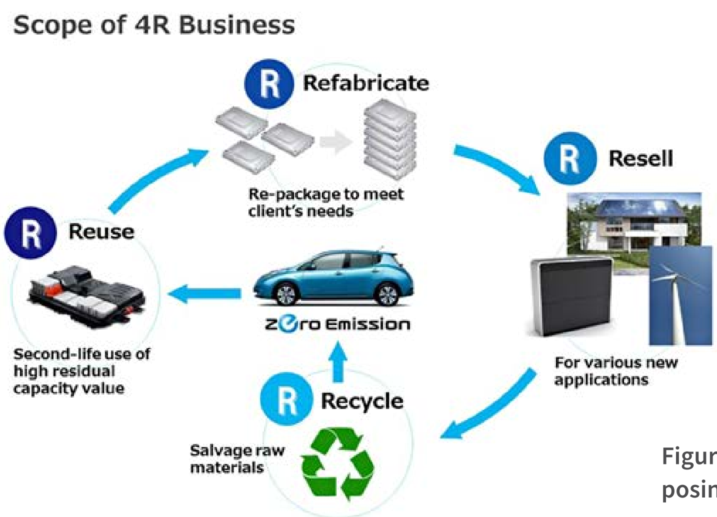


Figure 5: 4R Second life EV battery repurposing and recycling [44]

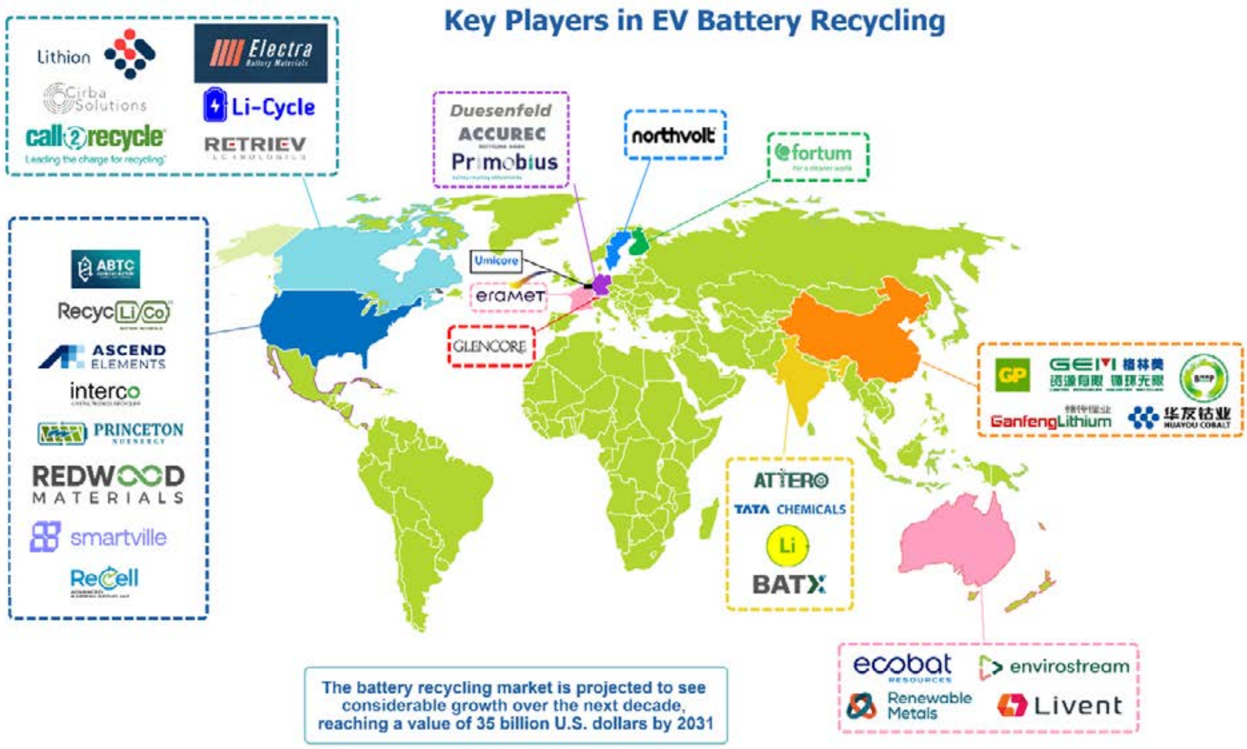


Figure 6: Key recyclers for EOL EV batteries

recycling facilities in China, where it produces cathode precursors. The company boasts an annual production capacity exceeding 50,000 tons for cobalt, nickel materials for Li-ion batteries and cathode material. While smaller in scale, companies from other parts of the world are also engaged in Li-ion battery recycling. These include TES-AMM in Singapore, that uses a hydrometallurgical process developed in France, SungEel in South Korea, Umicore in Belgium, Retriev Technologies in the US and Canada, Envirostream Australia in Australia, and Belmont Trading in Great Britain.

The challenges they face include handling hazardous materials, technological and economic barriers to recycling complex chemistries, and developing viable markets for EOL batteries. Figure 6 illustrates the worldwide distribution of leading recycling companies, and a detailed description of some key recyclers is provided in Table 5.

4.3. Repurposing Companies

As demand for sustainable energy solutions grows, companies specialising in energy storage become increasingly significant stakeholders. They use repurposed EV batteries in stationary ESSs, benefiting from the environmental and cost advantages of extending the useful life of EV batteries. This supports grid stability and renewable energy integration, and also offers a sustainable pathway for the valorisation of EOL batteries.Table 6 summarises some of worldwide EOL EV battery repurposers.

4.4. Logistics and Transportation Providers

The safe and efficient transportation of EOL batteries from collection points to recycling or repurposing facilities is managed by logistics and transportation providers. Given the hazardous nature of Li-ion batteries, the providers must navigate complex regulatory landscapes and adopt specialised handling and transportation protocols to prevent accidents and protect the environment. Table 7 summarises some of the worldwide EV battery logistics providers.

4.5. Performance Testers

Performance testers play a critical role in assessing EOL EV batteries for repurposing or recycling. They conduct capacity, efficiency and safety evaluations to determine the batteries' suitability for secondary use. Their work involves advanced testing techniques to measure power output, conduct safety checks and estimate the remaining lifespan. Table 8 summarises some of worldwide EV battery performance testers.

4.6. Insurance Providers

Insurance companies are responsible for the initial assessment of crashed EVs, and the safe transportation and storage of batteries at processing facilities. They also handle collection of retired EVs and EOL batteries from policyholders.

4.7. Auction Houses

Auction houses are responsible for ensuring safe storage of EOL electric vehicles. If equipped with triage stations, they can inspect, test and assess batteries to determine if they should be repurposed, reused or recycled. They can sell EOL batteries to designated repurposing or recycling companies, which are responsible for delivery to the end customer. Revenue is obtained from selling EOL batteries after considering transportation, storage and dismantling costs.

Table 5: Summary of global recyclers of end-of-life EV batteries

Recycler	Description
American Battery Technology Company [45]	ABTC in Nevada is a pioneer in Li-ion battery recycling with innovative, low emission technology that processes 20,000 tons annually. Its unique 'de-manufacturing' avoids traditional smelting for efficient material recovery, thereby boosting recycling benefits.
ACCUREC-Recycling GmbH [46]	ACCUREC-Recycling GmbH, based in Germany, processes over 3,000 tons of batteries annually under EU regulations. Its comprehensive recycling method includes collection, safe transport and advanced material recovery, and aims to lift lithium recovery rates significantly.
RecycLiCo [47]	RecycLiCo efficiently recycles EV batteries, recovering up to 99% of metals with minimal CO_2 emissions, using patented technology compatible with multiple cathode materials.
FORTUM CORPORATION [48]	Fortum in the Nordic region pilots second-life battery projects, using a comprehensive recycling process in Finland. It achieves an 80% recycling rate and recovers 95% of precious metals from EV batteries through advanced mechanical and hydrometallurgical processing.
Ascend Elements [49]	Ascend Elements, based in the US, innovates in EV battery recycling. Its patented Hydro-to-Cathode® direct precursor synthesis process transforms battery waste into high-value materials for future EV batteries.
Umicore Inc [50]	Umicore recycles EV batteries in Europe, using advanced methods to extract metals. It operates four North American drop-offs and a consolidation centre in North Carolina, with final processing in Belgium.

Table 6: Summary of global repurposers of end-of-life EV batteries

Repurposer	Description
Connected Energy [53]	Connected Energy pioneers circular economy solutions by transforming second-life EV batteries into scalable E-STOR ESSs for energy management flexibility.
Bee Planet Factory [54]	BeePlanet Factory repurposes spent EV batteries into energy storage solutions, offering a sustainable lifecycle from collection to recycling, supported by continuous monitoring for optimal performance.
Enel X SRL [55]	Enel X integrates second-life EV batteries for energy projects in Italy and Spain. It has installed sustainable, cost-effective storage solutions at Rome–Fiumicino Airport and Melilla, advancing CO_2 neutrality and power reliability.
Powervault [56]	Powervault repurposes second-life EV batteries for smart energy storage in the UK market. It partners with Renault and M&S Energy for home systems using Renault Zoe batteries.
Smartville Energy [57]	Smartville Energy in the US creates modular energy storage from repurposed EV batteries, focusing on safety and scalability. Its comprehensive sourcing and testing process ensures that batteries meet high standards for stationary use.
Cactos [58]	Cactos, a Finnish company, repurposes Tesla EV modules into Cactos One battery packs designed for stationary storage. They have a 100 kWh capacity and cloud control; Cactos One is a scalable energy solution.
Relectrify [59]	Relectrify, an Australian company founded in 2015, extends the life of EV batteries with innovative technology, reducing costs by up to 30% while increasing lifespan by the same margin.

Table 7: Summary of global EV battery logistics providers

Logistic provider	Description
DHL [60]	DHL provides comprehensive EV battery logistics, from sourcing materials to recycling. With experience from the FIA Formula E Championship, they use IoT for efficient, secure global battery transport.
Ceva Logistics [61]	Ceva specialises in EV battery logistics, providing global transport solutions with a focus on safety and efficiency. They are IATA-certified for lithium battery handling with trained staff and climate-controlled facilities.
UPS [62]	UPS provides specialised EV battery shipping in the US with temperature control and tracking. It handles damaged or recalled batteries under strict regulations, exclusively via ground within the contiguous 48 states.
CMA CGM [63]	Specialised EV shipping in container transport units and mandatory inspection for undamaged second-hand vehicles under 7 years.
Kuehne + Nagel [64]	Kuehne + Nagel's BatteryChain offers an end-to-end solution for lithium battery logistics, covering the entire battery lifecycle with compliance to international standards and real-time cargo tracking.
DSV [65]	DSV provides specialised EV battery transport solutions in Europe, focusing on the complexities of the electric vehicle market through its Electrification & Mobility Competence Centre.
Schenker AG [66]	Schenker, a German logistics firm, provides comprehensive EV battery logistics, covering transportation, recycling and disposal through a multi-modal network, ensuring regulatory compliance and safe handling of all battery types.

Table 8: Summary of global EV battery performance testers

Performance testers	Description
TÜV SÜD [67]	TÜV SÜD, a German-based global entity, conducts comprehensive EV battery evaluations in alignment with international norms such as SAE J2464 and UN 38.3, focusing on safety through extensive testing under extreme conditions.
JOT Automation [68]	JOT Automation in the US offers advanced automated testing for EV batteries, ensuring efficiency and precision from cell to pack analysis with high-quality standards.
Millbrook Proving Ground [69]	This UK firm offers advanced EV battery testing under UN ECE standards, ensuring safety and durability through rigorous procedures for cells and packs, including crash scenario simulations.
Mobile Power Solutions [70]	Mobile Power Solutions in Canada offers mobile battery testing labs that comply with international standards like ISO/IEC 17025:2017 for safety and performance evaluations.
ESPEC North America (EN) [71]	ESPEC North America tests EV batteries using conditions that mimic real-world environments, adhering to key standards like UL 1642, IEC 62133, and SAE J2464 for safety and performance evaluation.
Intertek Group plc [72]	This UK-based firm specialises in EV battery testing, focusing on performance, safety and chemical analysis to meet evolving industry standards.
SGS [73]	SGS provides extensive EV battery testing services, ensuring compliance with key standards like UN 38.3, IEC 62133, UL 2580 and IEC 62660 for global safety and performance requirements.
AVILOO [74]	Austrian firm AVILOO offers TÜV-certified EV battery testing; it provides a certificate with insights into the battery's SOH and a calculated range estimate.

4.8. Consumers and EV Owners

The role of consumers and EV owners is crucial. Their participation in EOL battery management programs, including returning batteries for recycling or repurposing, directly influences the efficiency of the EOL process. Consumer awareness and willingness to participate in such programs is essential for closing the loop in the battery lifecycle.[11]

4.9. Regulatory Bodies and Environmental Agencies

Regulatory bodies and environmental agencies establish and enforce the legal and environmental framework governing the disposal, recycling and repurposing of EOL EV batteries. Regulations ensure compliance with practices that minimise environmental impact, promote public health and safety, and encourage the development of a circular economy. They also play a role in incentivising innovation and investment in sustainable EOL battery management practices.[11]

4.10. Research Institutions and Technology Developers

Innovations in battery recycling technologies and second-life applications are often driven by research institutions and technology developers. They are at the forefront of developing new methods for material recovery, enhancing the efficiency of recycling processes, and exploring innovative uses for repurposed batteries. Collaborations between research entities and industry partners are vital for transferring these innovations from the laboratory to commercial-scale operations.[11]

CASE STUDY 6

Umicore supply chain for the recycling process

Umicore, a leader in the EV battery recycling industry in Europe, extracts valuable metals, including cobalt, nicket and copper, from spent EV batteries using advanced pyrometallurgical and hydrometallurgical methods. Figure 7 shows Umicore's recycling supply chain. [50]

Umicore has established four collection points in North America, including a consolidation centre in North Carolina for handling nickel-metal hydride and Li-ion batteries [50].

Initial dismantling occurs in Germany, where recyclable components like steel and copper are removed. The materials are then processed in Belgium, where sophisticated techniques recover valuable metals.

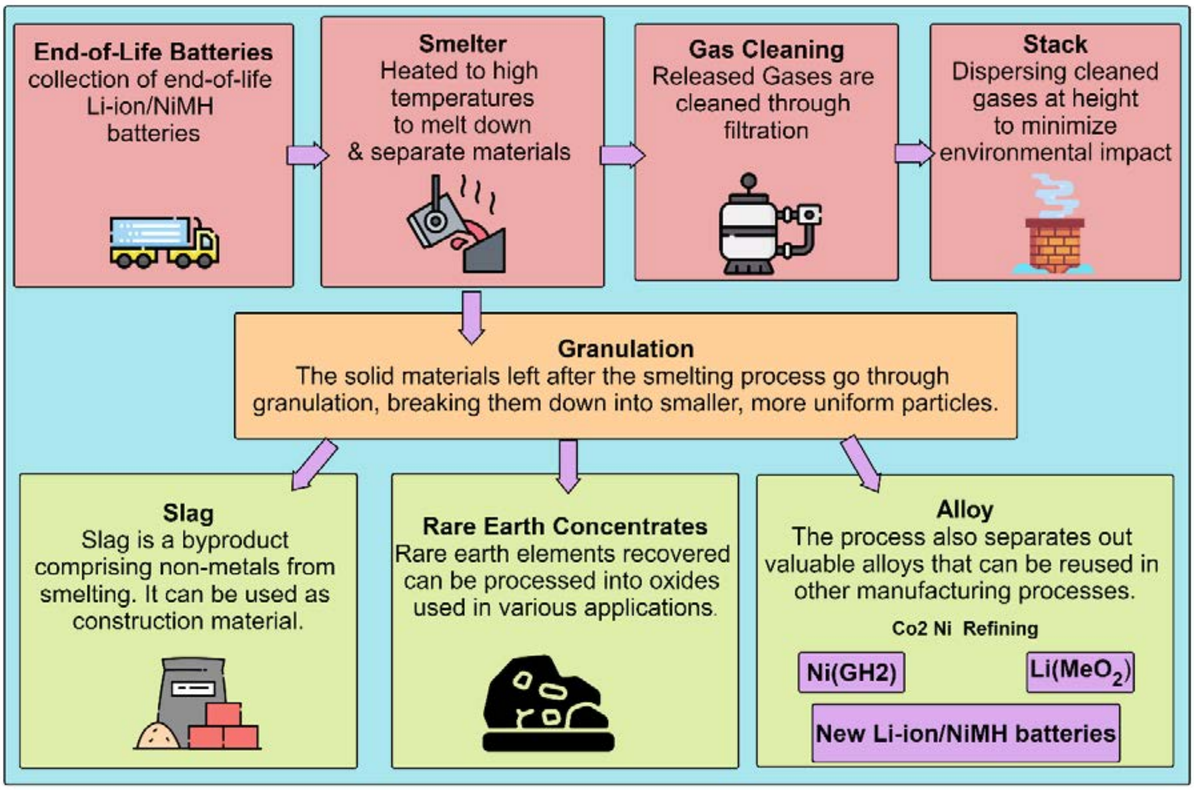


Figure 7: Umicore supply chain for recycling process

CASE STUDY 7

ReVolve Energy Storage System

The ReVolve ESS, shown in Figure 8, developed by Australian company Relectrify, repurposes Nissan Leaf batteries for grid-connected energy storage. Using CellSwitch technology, it optimises battery capacity and lifespan. Certified to International Electrotechnical Commission (IEC) safety standards, the modular design offers capacities ranging from 40kWh to 2MWh and powers from 20kW to 1MW. Applications include grid stability, peak shaving, microgrids and EV charging [59].

In 2019 Vector in New Zealand explored using EV batteries for home storage. In 2022 Counties Power deployed New Zealand's largest battery system with ReVolve, achieving 20% extra capacity and 88% efficiency. Colormaker in Australia integrated a 120kW ReVolve battery with solar, reducing grid imports by over 94% [59].

Figure 8: ReVolve ESS of Relectrify [59]

OBSERVATION 8

Insurance providers may face a challenge with an increase in writing off low-mileage, zero-emission cars due to minor damage. Accurately assessing risks, managing liability, and determining coverage and premiums are complicated by factors such as battery degradation, safety concerns, regulatory uncertainty and data scarcity. High repair costs, especially for batteries, strains insurers financially, as does the potential for expensive replacements and the scarcity of qualified technicians and specialised repair facilities, which further increases repair costs and claim turnaround times.

5. Current and Emerging Sustainable Supply Chain Practices for EOL EV Batteries

The supply chain for EOL EV batteries is a vital component of the expanding EV ecosystem. Its goals extend beyond minimising environmental impact and waste; it aims to reclaim valuable materials, lessen new raw material needs, and bolster secondary markets for these batteries.

The current and emerging sustainable supply chain practices for EOL EV batteries focus on several key areas, including collection points for EOL batteries, secure transportation networks, recycling centres for material recovery, and businesses dedicated to battery repurposing. Testing facilities critically assess batteries for safety and performance before reuse or recycling, while regulatory frameworks ensure environmentally safe and sustainable practices throughout the supply chain. Such a unified approach is instrumental in facilitating resource recovery and driving the shift towards a circular economy in the EV industry.

5.1. Collection and Logistics

It is essential to establish efficient collection systems for EOL EV batteries to ensure they are properly collected and transported to recycling or repurposing facilities. This involves setting up collection points at EV dealerships, service centres and recycling facilities, as well as developing reverse logistics networks to manage battery returns. Recycling facilities are equipped to safely store the batteries, mitigating risks of environmental contamination or safety incidents like leaks and fires.[75]

Li-ion batteries are potentially hazardous so collection points must enforce rigorous safety measures. Protocols include the use of protective containers to avert short circuits, maintaining controlled environments to regulate temperature and humidity, and implementing comprehensive emergency response strategies. Staff at these locations are thoroughly trained in hazardous material management.

Upon collection, batteries undergo an initial evaluation to determine their condition and feasibility for reuse or material recovery.[76] Adherence to local and international hazardous waste regulations is essential to reduce environmental impact and promote circular economy goals.[75, 76]

Efficient logistics and coordination among stakeholders, including battery manufacturers, vehicle owners, collection sites, and transport services, is key to enhancing the collection process. Emerging technologies such as tracking systems and blockchain are being explored to improve traceability and accountability, further streamlining the EOL EV battery supply chain.[76]

5.2. Storage of EOL EV Batteries

When replacing damaged, defective or recalled EV batteries, it is crucial to store the removed units safely until proper disposal. This helps mitigate fire risks associated with these batteries.

Crashed EVs introduce specific challenges not encountered with traditional internal combustion engine vehicles, largely due to their HV batteries. These batteries are capable of retaining a significant charge even when damaged, and pose risks such as chemical leaks, fires or thermal runaway, a dangerous condition where the battery temperature uncontrollably rises, potentially resulting in explosion or fire.

In the event of an accident, damaged EVs should be handled with caution, as there is a possibility of reignition [78,79]. As a precaution, it is advisable to move them to a designated quarantine area, ensuring separation from other vehicles and structures in line with safety guidelines.

Thatcham Research in the UK has conducted an in-depth analysis of EV quarantine practices and provided guidance on the necessary distances for safe isolation. This analysis allows for adjustments to quarantine distances with the use of fire-resistant barriers or by placing the vehicle in a specially protected area. The research considers various factors, including the layout of storage areas and the dimensions of UK cars, to determine the effective use of quarantine space.[19]

OBSERVATION 9

At vehicle auction sites, appropriate storage protocols are important to ensure the optimal preservation of damaged EVs. These vehicles should be stored in designated quarantine zones with adequate separation from other structures or vehicles to maintain safety. Implementing exclusion zones between each stored EV could further enhance safety and storage practices..

Figure 11a shows that an outdoor area intended to accommodate 100 cars could, due to safety requirements, only quarantine 2 EVs, indicating a 98% reduction in capacity based on an average quarantine radius of 11.67 metres. Without surrounding infrastructure and through strategic placement, Figure 11b shows that efficient space management in quarantine could lower the capacity reduction to to 92%.

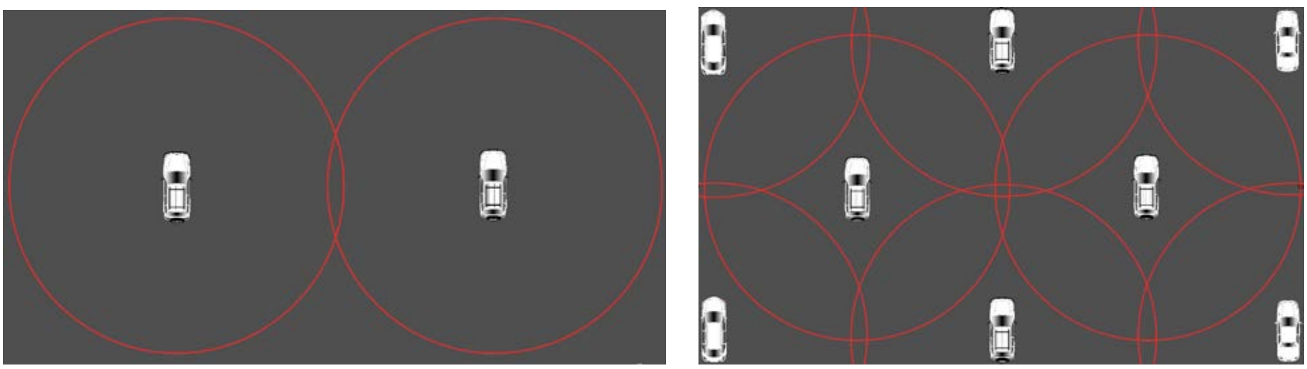
The storage of crashed EVs necessitates diligent practices as listed in Table 9.[19]

5.3. Transportation of EOL EV Batteries

The transportation of EOL EV batteries is a pivotal phase in their lifecycle management, and bridging the gap between their original use in vehicles and the next stages of recycling or repurposing.

5.3.1. Transportation of Retired EVs

At collection, the challenge shifts to transporting EVs and their batteries to appropriate facilities for recycling or further use. This stage is fraught with complexities, including safety risks associated with the potential for battery malfunctions and the economic implications of long-distance transportation. Ensuring compliance with stringent regulatory standards further complicates this phase.[81]



(a) (b)

Figure 11: (a) Quarantine Arrangement of a storage area with surrounding infrastructure [19].; b) Quarantine Arrangement of a storage area without surrounding infrastructure [19]

Table 9: Proper practices for storing crashed EVs

Practice	Description
Documentation and tracking	Maintaining detailed records of stored crashed EVs, including their condition, location within the storage area, and any actions taken (e.g., battery removal or decontamination)
Isolation and quarantine zones	Designated areas away from other vehicles and structures to minimise the risk of fire spreading. The National Highway Traffic Safety Administration (NHTSA) and the National Fire Protection Association (NFPA) (both in the US) recommend storing damaged EV batteries in a safe zone at least 15 metres away from buildings and other combustible material.
Safety measures	Use of fire-resistant barriers, adequate spacing between stored vehicles and the use of protective equipment by personnel.
Regulatory compliance	Adherence to local and national regulations governing the storage of crashed EVs, including environmental standards and safety protocols. This includes compliance with specific guidelines for battery handling and disposal.
Training and awareness	Ensuring that personnel involved in the storage of crashed EVs are trained on the specific hazards associated with these vehicles. Training programs focus on safe handling practices, emergency response procedures and environmental protection measures.
Fire suppression systems	Installation of advanced fire suppression systems suitable for handling EV fires, which may include dry powder or specialised foam extinguishers. These systems are essential for quickly suppressing fires in crashed EVs, particularly those involving HV batteries.
Emergency preparedness	Developing an emergency response plan specifically tailored to the risks associated with storing crashed EVs. Things to cover include answers to these questions: • What should employees do when an EV catches fire? • Do responders need to wear special personal protective equipment? • Where on your property is it safe to store a damaged EV? • How close can other cars be to an EV?
Environmental protection	Use of containment systems to prevent battery leaks from contaminating soil or water sources.
Conduct regular inspections	Regularly inspect EVs and their batteries. Inspection improves the chance of diagnosing a battery fault or failure before it leads to a more serious event, such as a fire.

The safe transport of damaged EVs demands specialised expertise and careful handling to mitigate risks and avoid damage to the vehicle's HV electrical systems. Damage from collisions or other events can compromise the electrical integrity and battery safety of an EV, presenting unique transportation challenges distinct from those associated with conventional vehicles.[19] It is imperative to exercise extreme caution when transporting damaged EVs, especially those equipped with HV systems. Minimising movement or vibration is essential during transport to prevent increasing the potential internal damage to the HV battery system, which might not be immediately observable through visual inspection.

Organisations such as the Suppliers Partnership for the Environment and Call2Recycle have offered crucial guidance related to the transportation, packaging and storage of EOL EV batteries.[82] This advice is vital for developing effective collection systems and storage solutions, ensuring batteries are efficiently consolidated for recycling, reuse or repurposing.

The UN Manual of Tests and Criteria sets global transport standards for dangerous goods, including lithium batteries, requiring third-party testing for manufacturer compliance. It requires that all batteries, with limited exceptions, meet specific safety tests before transport. SAE J2950 provides guidance on transporting damaged or defective lithium-ion batteries while SAE J2974 standardises language for transporting end-of-life EV lithium-ion batteries between recyclers, dismantlers, and other parties.[81] The IEEE and SAE develop safety standards for mobile devices and EV batteries, respectively, while UL standards offer additional safety tests and certification for international shipping.[83, 84]

5.3.2. Collection and Transportation Costs

The cost of collecting and transporting batteries for recycling depends on the condition of the batteries, distance to the recycling centre and the number transported. Damaged batteries require extra safety measures, including UN-standard packaging, which increases the costs. Moreover, costs rise with longer distances and smaller shipment sizes, par-

CASE STUDY 8

KN Batterychain Solution for EV Battery Logistic

Kuehne + Nagel excels in EV battery logistics, as shown in Figure 9, with its innovative KN BatteryChain solution that addresses the lifecycle needs of lithium batteries. This comprehensive service ensures compliance with IATF 16949 standards and dangerous goods regulations, offering strategies for CO_2 reduction and real-time shipment tracking. [64]

KN BatteryChain ensures transparency through real-time tracking. Clients receive continual updates from pickup to delivery. Kuehne + Nagel has developed both standardised and customised solutions to meet diverse needs, encompassing the supply chain from lithium cell manufacturing to battery assembly, and from distribution to EOL recycling.

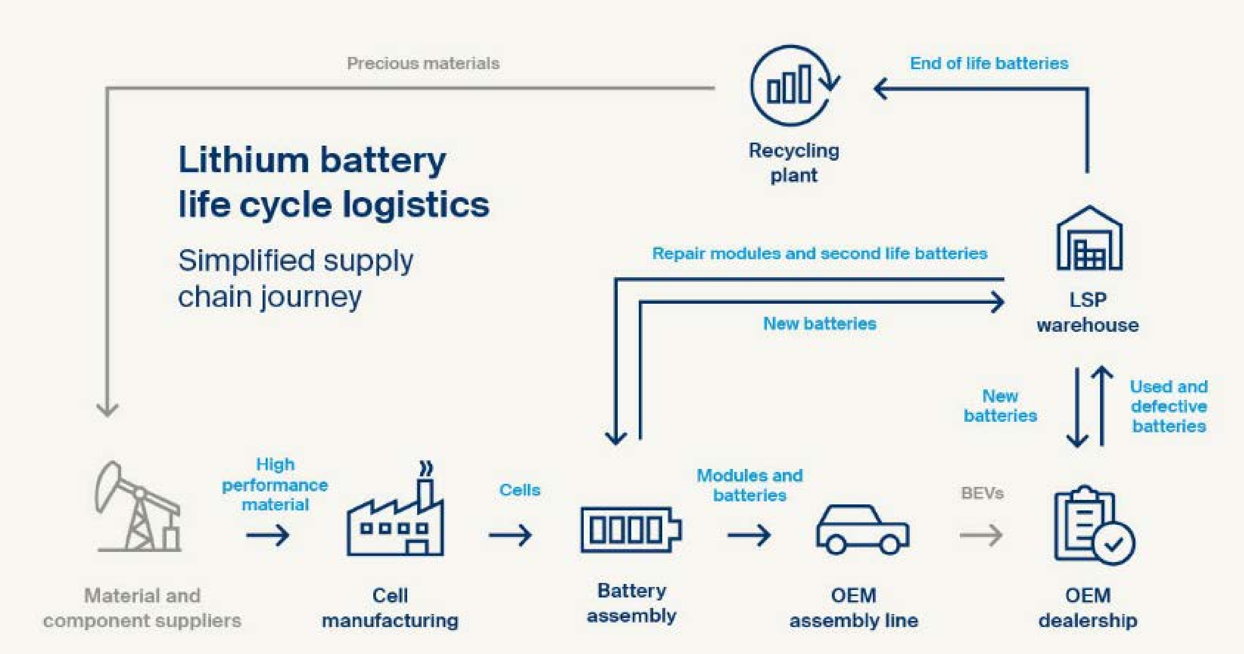


Figure 9: Kuehne + Nagel comprehensive solution called KN BatteryChain logistics [64]

CASE STUDY 9

AVILOO Performance Testing

AVILOO, an Austrian company, offers EV battery testing services with a focus on convenience and accessibility. Key features include on-site testing, quick results, a focus on state of health, and transparent, reliable data [74].

AVILOO provides two services: the FLASH Test for a quick battery assessment and estimated range, and the PREMIUM Test for a detailed analysis including cell voltages and internal resistance.

AVILOO is TÜV certified and offers certificates with transparent SOH and battery range information as shown in Figure 10. In this certificate, the battery capacity is represented with a 100% rating.

Figure 10: AVILOO's Performance Testing Certificate [74]

ticularly in remote areas where shipments may not fill a transport vehicle, necessitating special hazardous material permits and leading to inefficiencies.[30]

Creating an efficient collection network can mitigate these costs. This involves strategically locating collection points and making use of existing dismantler and dealership infrastructure. Manufacturers can lead this effort, ensuring effective recycling and benefiting from economies of scale. As the volume of EOL batteries increases, logistics costs are expected to decrease, making battery recycling more viable and making EVs more affordable and sustainable. Achieving economies of scale, especially by transporting full loads, will be key to reducing costs.

5.4. Performance Testing and Evaluation of EOL EV Batteries

Performance testing and evaluation of EOL EV batteries provides an opportunity to assess their remaining capacity, degradation levels, and potential for reuse or recycling.

This involves capacity testing, cycling tests, rate capability testing, temperature testing, safety testing, and data analysis to gain insights into the battery's condition and performance under various conditions. Based on the results, stakeholders can explore options and make informed decisions regarding repurposing for second-life applications, recycling to recover valuable materials, or ensuring environmentally responsible disposal.

5.4.1. Initial Evaluation for EOL EV Batteries

The initial assessment of EOL EV batteries evaluates the various factors that lead to their wear, including temperature changes, usage frequency, charge levels and discharge rates. This process starts with gathering essential details about the battery, such as the maker, model, batch, production date, and key specs like capacity and chemistry.

Understanding the battery's usage history and the reasons for its retirement is crucial for this evaluation.[20] The battery's past use significantly affects its current state. Key considerations include how it was charged and used, temperature management and user charging habits.

The depth of assessment for potential second-life applications of EOL EV batteries depends on the tester. Manufacturers with detailed usage data can make more accurate assessments, while third parties, like dealers, might struggle due to varied battery conditions and lack of detailed history. Here, data-driven approaches can help to estimate the battery's value for second-life applications, minimising the need for physical tests.[9, 20]

However, often the lack of complete information requires dismantling and detailed testing of battery packs to decide their fitness for second-life applications. This ensures that each battery is accurately evaluated for reuse, following safety standards and maximising recycling or repurposing benefits.

5.4.2. Disassembly of EOL EV Batteries

The disassembly of EOL EV batteries entails a structured breakdown of the batteries to recover valuable components and materials for recycling or repurposing. This retrieval of critical minerals and other valuable components reduces the demand for raw materials and fosters the growth of an environmentally sustainable economy.[85]

Levels of Disassembly: The disassembly level for EOL EV batteries varies based on their intended reuse and is characterised by a three-tiered structure: cell, module and pack. The choice of disassembly level affects the complexity, cost and viability of repurposing efforts.[86]

- **Cell-level:** Disassembling to the cell level is labour-intensive, costly and generates significant waste. Regrouping cells adds material costs and potential safety risks, making cell-level disassembly less favourable from an economic and safety perspective. The process involves intricate removal of components, often challenging due to non-modular design and welded joints, which necessitates forceful opening. Despite these challenges, cell-level disassembly is crucial for extracting recyclable materials effectively.

- **Module-level:** Opting for module-level disassembly offers an optimal balance of economic efficiency, ease of reassembly and market adaptability, making it a preferred choice for second-life applications. This approach avoids the complexities and costs associated with cell-level disassembly.

CASE STUDY 10

FirePro FPC technology for transporting crashed EVs

A fire-resistant box for transporting crashed EVs is illustrated in Figure 13. In the event of a fire, the Firebox transport system activates an alarm, which in turn triggers an automatic aerosol extinguishing system and a sprinkler system. These systems promptly suppress and cool the flames. Simultaneously, the Firebox system communicates the emergency to on-site and external fire- fighting teams, ensuring a synchronised and effective responseto the incident [77]

Figure 13: Firebox container with FirePro FPC technology [77]

CASE STUDY 11

Fire-Resistant Container Trucks for Transporting Crashed EVs

Specialised containers for safe EV transportation are offered by companies like SEDA-Umwelttechnik GmbH and Ecobatt. SEDA's Electric Vehicle Safety Container, a 20-foot roll-on roll-off unit as shown in Figure 14, is engineered for secure EV transport and storage. Similarly, Ecobatt provides a container system designed for the safe handling of damaged or EOL EVs, especially those with unstable batteries. These containers are critical because of the increasing number of incidents caused by unstable EV batteries. Key features include puncture-resistant construction, an integrated fire suppression system, ventilation, secure containment, and compatibility with lifting and transport mechanisms [80].

Figure 14: Fire-resistant container for transporting damaged EVs by SEDA-Umwelttechnik GmbH [80]

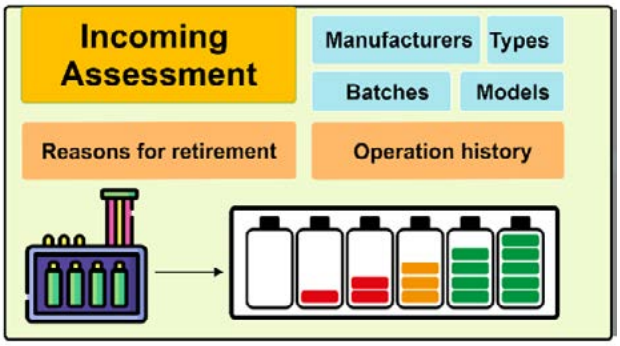


Figure 15: Initial assessment for EOL EV batteries

- **Pack-level:** Reusing entire battery packs is the most cost-effective repurposing strategy, and it preserves pre-existing safety standards. However, variations in pack design across different EVs poses challenges in regrouping, and internal cell inconsistencies can diminish the value of EOL packs. Despite these issues, pack-level reuse is highly feasible for applications like large-scale energy storage systems.

Key Challenges in the Disassembly of EV Batteries: The disassembly of EOL EV batteries is fraught with complexities and hazards. The significant challenges are as follows [9, 87]:

1. **Safety Risks:** Disassembling EV batteries poses significant safety hazards, including the risk of short circuits, hazardous leaks and potential explosions or fires due to improper handling. These dangers present real threats to worker safety and property, emphasising the need for strict safety protocols during disassembly.
2. **Chemical Hazards:** The process exposes workers to toxic substances found in battery electrolytes and electrodes, posing serious health risks. Protective measures are crucial to safeguard workers from these chemical hazards.

3. **Structural and Technological Variability:** The diversity in battery designs, connection methods and technologies across different manufacturers complicates disassembly. This variability challenges the automation of disassembly, requiring customised approaches for each battery type. These efforts are further complicated as the market introduces new EV models.
4. **Technical Challenges:** A lack of skilled personnel and the complexity of EV battery connections hinders disassembly, decreasing efficiency and increasing costs, especially in high labour cost regions. These technical obstacles affect the overall feasibility of battery recycling and repurposing.
5. **Economic Challenges:** The high cost of manual disassembly, particularly when compared to the rapidly decreasing prices of new batteries, poses a significant economic challenge. The expense of manual disassembly can render second-life applications economically unfeasible without advancements in disassembly technology.

Automation in EV Battery Dismantling: The industry widely acknowledges the necessity of automating the dismantling and inspection of EOL EV batteries, with robotic disassembly being a key innovation. Success in automation hinges on standardising battery components. This necessitates collaboration between battery makers, car manufacturers and automation tech firms. This standardisation aims to make disassembly more efficient and reduce costs at a large scale.[88]

Recent advancements in robotics and image recognition algorithms offer promising prospects for automating battery inspections, though challenges arise due to the complex nature of battery evaluations.[89]

A notable obstacle in implementing an automated disassembly line for batteries is the associated cost. The investment required is significant and needs to be carefully balanced against the expected benefits. Thus, developing efficient and cost-effective disassembly strategies is essential to justify the investment in automation and ensure its economic viability in the long term.

5.4.3. Testing Protocols for EOL EV Batteries

The establishment of testing standards for EOL EV batteries is critical to ensure their safety and operational performance for second-life applications. Current guidelines set forth protocols for assessing cells, modules and battery packs. However, these standards fall short of addressing the wide range of conditions that retired and and written-off EV batteries may present. The inherent variability in the quality and condition of EOL batteries poses a significant challenge when creating uniform testing criteria that can comprehensively guarantee their safe and effective functionality in new applications.[37]

The accurate assessment of retired EV batteries, taking into account their residual lifespan, chemical composition and performance characteristics, demands the establishment of more precise testing procedures. The creation of such standards is essential for the battery recycling and repurposing sector; it will offer a dependable method for evaluating the suitability of EOL EV batteries for second-life applications.

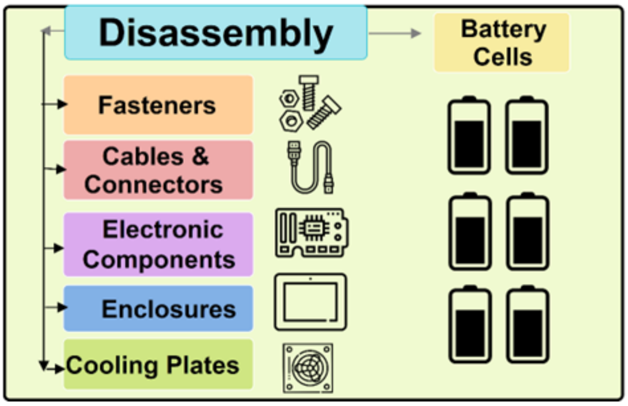


Figure 16: Disassembly procedures for EV batteries

In the United States, the National Electrical Code (NEC) [90] and Underwriters Laboratories (UL) [91] standards are the primary frameworks governing lithium battery installations and safety protocols. Europe relies on the European Committee for Standardisation (CEN) to standardise electrical energy storage. China adopts its own set of guidelines under the China National Standards (GB/T) for lithium battery testing and safety requirements. Japan's Japanese Industrial Standards (JIS) oversees lithium battery testing methods and safety. In Australia, Standards Australia sets the guidelines for electrical safety and battery technology, ensuring compliance with standards set by the IEC and UN. Table 10 provides a summary of key testing protocols relevant to EOL EV batteries.

5.4.4. Performance Testing for EOL EV Batteries

Assessing the health of EV batteries begins before they reach the end of their primary usage. Health indicators are monitored through direct vehicle data or cloud-based systems, and consider factors like mileage, age, ambient temperature and charging behaviour. This early monitoring, involving SOH calculations, ranges from simple to complex algorithms, and can enhance repurposing efforts.[92]

Upon reaching their end of life, batteries undergo a thorough evaluation, including physical, electrochemical and safety assessments:

- **Mechanical Integrity Evaluation:** This step identifies potential risks such as leaks or structural damage that could lead to safety incidents like short circuits or thermal runaway. Despite the inefficiency of discarding deformed cells, understanding the impact of deformations is vital. Non-contact techniques such as digital imaging or X-rays offer efficient alternatives to manual inspections.[93]

Table 10: Key testing protocols relevant to EOL EV batteries [37]

Testing Protocol	Description
UN Manual of Tests and Criteria	Establishes international safety testing for lithium batteries, including thermal stability and external short circuit tests under UN 38.3.
International Organization for Standardisation (ISO)	Sets worldwide standards for lithium batteries concerning environmental safety, performance and testing procedures
International Civil Aviation Organization (ICAO)	Provides guidelines for safely transporting lithium batteries by air.
International Electrotechnical Commission (IEC)	IEC 62660 Series: Specifies performance, reliability and safety testing for EV Li-ion cells. IEC 62281: Focuses on safety during lithium battery transport. IEC Standards for Safety and Performance: Includes various standards (IEC 62057, IEC 63056, IEC 62485-6) for safety requirements in different applications and transport regulations. IEC 62620: Outlines safety and performance requirements for industrial lithium batteries.

- **Electrochemical Performance Assessment:** Following mechanical checks, batteries are further examined for electrochemical integrity. Tests measure open circuit voltage, internal resistance, capacity and temperature to screen batteries for repurposing. This phase includes evaluating the BMS and conducting tests in accordance with standards like UL 1974.[93]
- **Safety Evaluation:** Safety remains a critical concern, particularly for stationary energy storage systems. Recent incidents [94] highlight the risks. Adhering to established safety envelopes and standards is essential, considering the increased risks posed by degraded retired batteries. Degradation characterisation, crucial for estimating the remaining useful life and SOH, involves understanding the chemical and structural changes that batteries undergo. Prognostic methods include post-mortem examination, charge–discharge curve analysis, and electrochemical impedance spectroscopy, with data-driven approaches providing time-efficient estimations. Accurate safety assessment of EOL EV batteries is challenging due to the complexity of degradation mechanisms. While conventional safety tests remain relevant, specialised tests and algorithms are needed to detect issues like internal short circuits.

5.4.5. Sorting and Regrouping of EOL EV Batteries

Repurposing EOL EV batteries into second-life applications faces significant challenges due to their diverse designs, sizes, electrode chemistries and states of health. This heterogeneity leads to variations in internal impedance, capacity and self-discharge rates among different cells, potentially causing imbalances in battery assemblies and diminishing the efficacy of traditional equalisation methods.[11]

In addition, as EV batteries age, they experience material losses and decreased reactivity, which can alter their safety profile. Research has shown that the threshold for thermal runaway increases with age, underscoring the need to factor in aging effects when assessing the safety of repurposed batteries.

Performance Parameters: The substantial performance variability among cells and modules in EOL EV batteries calls for a sophisticated sorting and regrouping process. This approach ensures that batteries with similar performance characteristics are paired together, thereby maintaining uniformity in second-life energy storage solutions. The precision and efficiency of the sorting and regrouping process is vital for safeguarding battery safety and extending their service life in new applications, though it can introduce significant costs and delays.[95]

To address these challenges, establishing accurate and relevant sorting indices is essential. These indices should consider [11]:

- accuracy and relevance: precisely mirror the current state of the batteries, taking into account key factors such as capacity, safety, estimated remaining life and past performance to ensure accurate classification
- economic and operational feasibility: be viable for large-scale application without excessive costs or complex assessment techniques
- use of historical data: employ a data-driven approach to improve the efficiency of critical parameter estimation, such as internal resistance and capacity, thereby streamlining the sorting process and minimising costs.

Figure 19 shows the common sorting indices in molecular scale, micro-nano scale, internal macro scale (internal characteristics) and external macro scale (external characteristics). While microscale indices provide a detailed assessment, practicality often dictates the use of macroscale characteristics for sorting due to their suitabil-

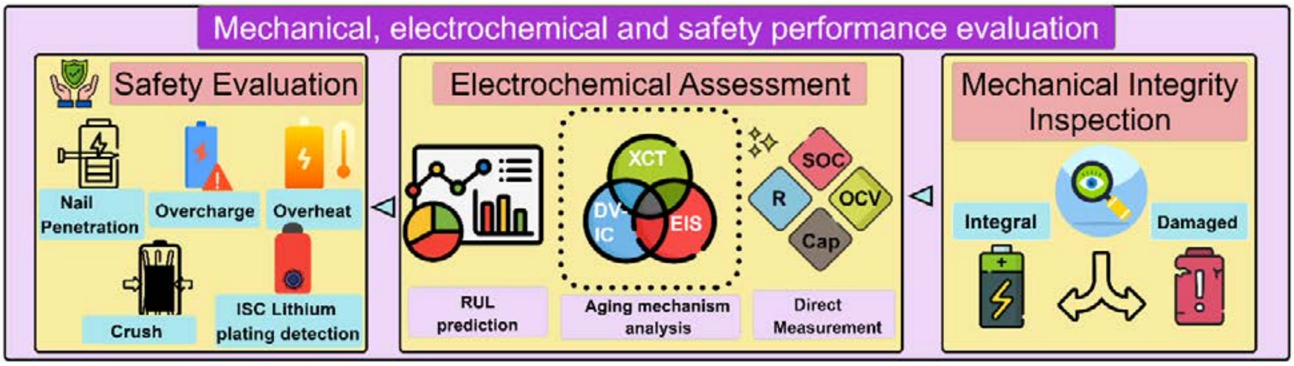


Figure 17: Mechanical, electrochemical and safety evaluation of EV batteries

ity for broad applications. This balance between detailed assessment and operational feasibility is crucial for the successful repurposing of EOL EV batteries.[11]

Regrouping Considerations: When regrouping EOL EV batteries, it is vital to align the process with the batteries' intended future uses. Batteries destined for energy-centric applications should have higher capacities, while those for power-intensive uses should exhibit lower internal resistance. The sorting process must prioritise both speed and accuracy to ensure batteries are repurposed effectively and safely. Challenges arise when batteries lack historical data and where traditional testing methods prove too time-consuming, necessitating the development of a rapid, precise and versatile sorting system. For batteries with accessible historical data, efficiently processing this information to facilitate sorting poses an additional challenge, but it is essential for their successful integration into second-life applications.[11]

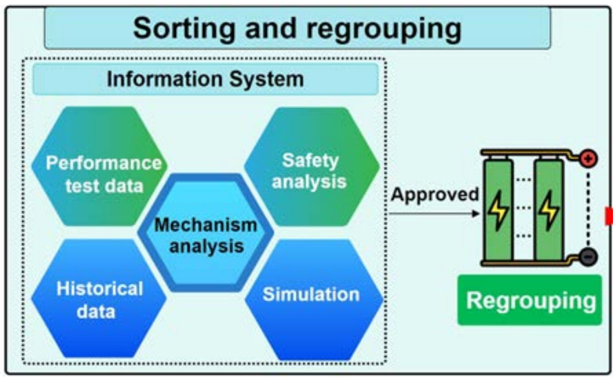


Figure 18: Sorting and regrouping process

Effective management of EOL EV batteries in ESSs involves ensuring proper sizing, using algorithms for uniformity and applying advanced diagnostics for safety. These strategies prevent overcharging, manage inconsistencies and detect potential failures, ensuring reliable and safe repurposing of batteries

6. Circular Business Model for EOL EV Batteries

A business model generally outlines how an organisation creates, delivers and captures value to generate revenue and sustain profitability. The core elements are: [96, 97]

- value proposition: defining unique products or services that meet customer needs
- value co-creation: collaborating with stakeholders to jointly create value
- value delivery: describing the channels and methods for delivering the value proposition
- value capture: detailing how the organisation retains revenue through various streams.

In the context of EOL EV batteries, a circular business model (CBM) should be adopted. This is a closed-loop system that employs reuse, refurbishment, recycling, repurposing, and, as a last resort, safe disposal. The aim is sustainable management practices to minimise waste and maximise resource efficiency.

6.1. Types of Circular Business Models for EOL EV Batteries

Three CBMs for the management of EOL EV batteries are presented. Each has unique roles for stakeholders in value creation and capture. These models emphasise lifecycle propositions, system-level design and service transitions for second-life batteries. Successful implementation depends on close collaboration among stakeholders to build trust and mitigate uncertainties within the EV ecosystem.

Extending CBM: The goal is to prolong the life of EV batteries, both in their first use and through refurbishment for secondary applications. This involves refurbishing, upgrading, repairing and maintaining the batteries to minimise waste and reduce the demand for new resources. [98, 99]

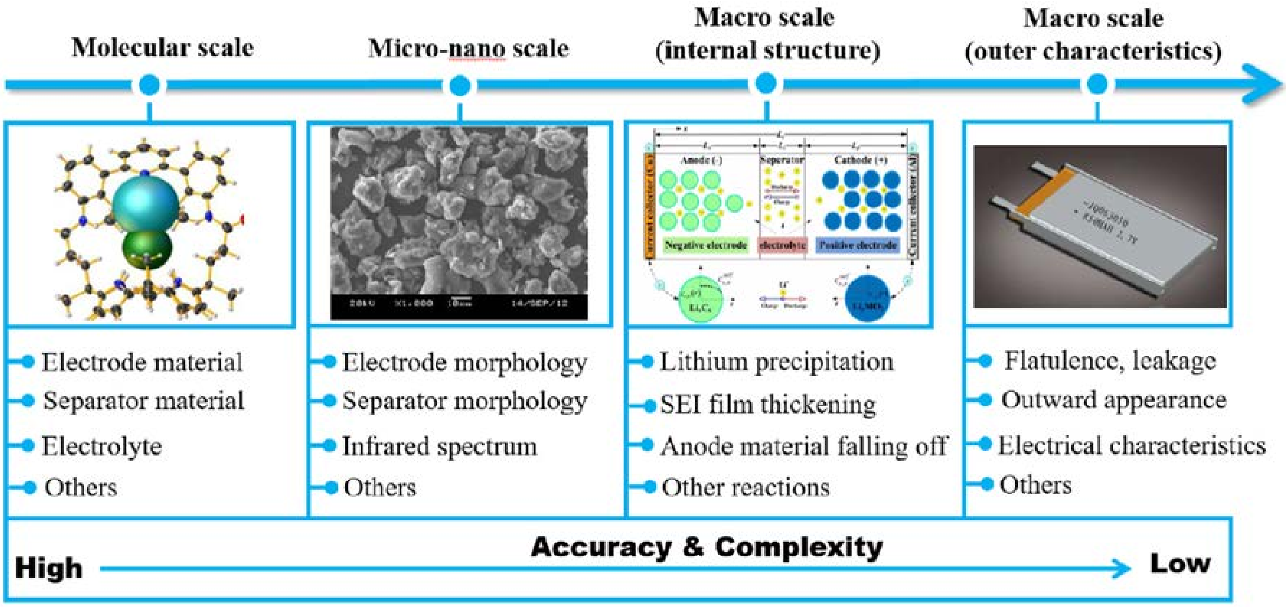


Figure 19: Performance parameters for sorting end-of-life EV batteries [11]

Sharing CBM: The goal is to maximise the use of EV batteries through systematic strategies such as battery-as-a-service, shared responsibilities, shared ownership and shared access to battery design and development technologies. This approach significantly reduces the demand for new EV batteries and optimally conserves resources.[98, 99]

Looping CBM: The goal is to keep EV batteries, their components and their materials in looping systems to retain maximum value. This involves preserving resources, sustainable recycling, provision of virgin materials, energy management, and estimating the total lifecycle of batteries. [98, 99]

These CBMs aim to maximise value and extend the life of EV batteries through different levels of stakeholder collaboration and engagement. They vary in ownership, data management and technology sharing. There are three primary market-based models that describe these variations: [100, 101]

- **Closed-Market Model:** OEMs retain full ownership and limit technology and data sharing to protect their competitive advantage and critical data. In this model OEMs handle all aspects of battery collection, testing, repurposing and recycling.
- **Intermediate-Market Model:** Ownership is transferred from OEMs to EOL EV battery service providers, with partial or full sharing of technology and data to facilitate battery refurbishment and repurposing. While improving collaboration, this approach poses risks to OEMs' control over technology and data integrity.
- **Open-Market Model:** This model features open ownership and service provision, in which stakeholders use online platforms for trading and repurposing batteries. Although this model allows for flexible trading and broader data sharing, it faces challenges in standardisation and consistent quality, limiting its effectiveness.

6.2. Examples of Circular Business Models for EOL EV Batteries

At the early stage of global development in the battery second-use industry, commercial-scale business models are still limited. This section outlines the business models of stakeholders who have progressed beyond technical trials or demonstrations, and are developing or beginning commercial operation phases of second-life battery projects.

6.2.1. 4R Energy Corporation: An Intelligent Mobile Charging System

4R Energy Corporation, a joint venture established by Nissan and Sumitomo Corporation in 2010, focuses on the research, development and commercialisation of second-life applications for EOL EV batteries. This collaboration aims to repurpose used EV batteries for new energy storage solutions, thus contributing to a sustainable lifecycle for these batteries. This CBM is shown in Figure 20.

4R Energy collaborates with Freewire, a California-based company that offers mobile EV charging systems powered by repurposed EV batteries. This partnership seeks to provide cost-effective and flexible charging solutions in a sustainable manner. Ownership of EOL EV batteries is transferred from Nissan to Freewire, but Nissan retains its data and technology within 4R Energy Corporation.

Stakeholder Motivations:

Nissan:

- Generate additional revenue streams from reused batteries.

- Align with sustainable EV practices.

4R Energy:

- Extend the profitable life of battery packs.
- Maximise revenue through integrated battery management services.

Freewire:

- Reduce system costs for competitive energy storage solutions.
- Gain market entry and growth benefits through association with Nissan.

Operational Models:

Nissan's Model:

- Operates on a B2B model, selling used EV batteries at reduced prices through 4R Energy.
- Collects batteries via dealerships for repurposing.
- Generates additional revenue and saves on potential recycling costs.
- Delays recycling, thereby reducing pollution, waste and energy usage.
- Provides second-life batteries at lower costs to support the energy storage industry.

4R Energy's Model:

- Acts as the distributor, battery repurposer and lifecycle service provider.
- Extends the lifespan of retired batteries sourced from Nissan.
- Disassembles, tests and grades batteries, then sells modules to Freewire.
- Provides logistical support to Nissan for collection, transportation and storage.

Freewire's Model:

- Develops scalable and flexible mobile charging systems using EOL EV batteries.
- Targets corporations with multiple EV-driving employees.
- Uses hardware and software innovations to extend battery lifespan.
- Profits from monthly service fees paid by corporate clients.
- Recycles batteries at the end of their second life.

Challenges for the Model:

- **Declining Cost of New Batteries:** Increasing affordability of new batteries erodes the cost advantage of second-life batteries, making competition in the energy storage market harder for Nissan and Freewire.
- **Lack of OEM Standardisation:** Freewire faces challenges with inconsistent supply due to the lack of standardisation from OEMs. Issues include inconsistent battery supply, non-transparent pricing, lack of standardised contracts and absence of suitable warranties.
- **Policy Imbalance:** Government subsidies often favour new batteries, reducing the cost-competitiveness of second-life options and creating a challenging market environment for second-life battery applications.

6.2.2. Nissan North America's Circular Business Model: Energy Management Services for Industrial and Commercial Buildings

This example explores Nissan North America's CBM, which repurposes EOL EV batteries for energy management in commercial and industrial settings. In partnership with Green Charge, Nissan offers energy-saving solutions without upfront costs, and uses predictive software and financed battery hardware to reduce demand charges. This CBM is shown in Figure 21.

Ownership of the EOL batteries is transferred to Green Charge, with data and knowledge shared between stakeholders to ensure battery suitability for storage systems.

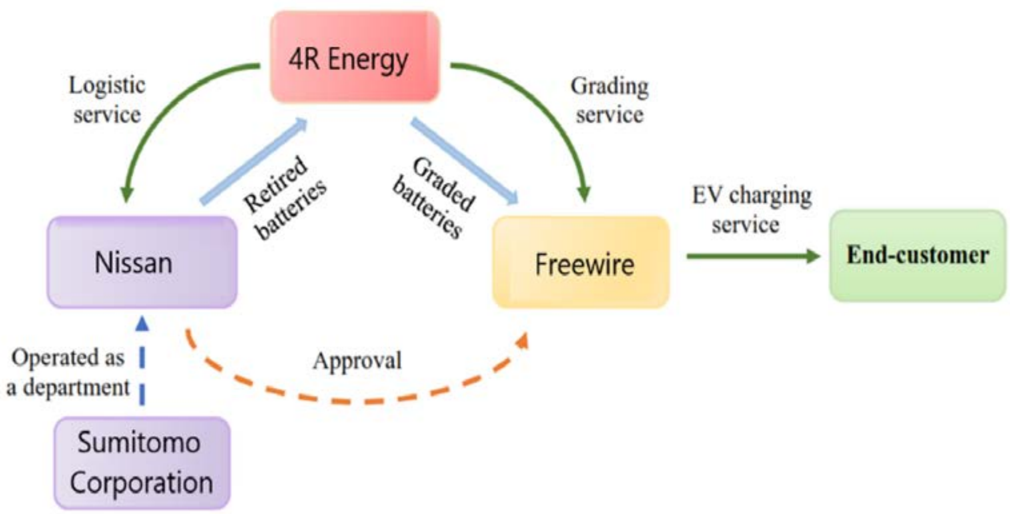


Figure 20: 4R Energy CBM for EOL EV Batteries

The system provides cost-effective and flexible solutions for businesses, effectively managing energy demands and reducing operational costs.

Stakeholder Motivations:

Nissan:

- Supplies EOL EV batteries and promotes a circular economy by extending the life of its battery products.

Green Charge:

- Develops and manages energy storage solutions, integrating second-life batteries to reduce energy costs for clients. They operate these systems and share energy savings with customers, demonstrating sustainable practices in energy storage.

Operational Models:

Nissan's Model:

- Offers cost-effective, capable second-life batteries that integrate seamlessly into Green Charge's systems. This includes optimising used batteries to meet new performance standards.
- Handles the collection, repurposing, testing and grading of used battery packs.
- Collaborates with Green Charge to ensure the batteries fulfill specific system requirements, using detailed battery data from their global data centre.
- Provides a 10-year performance guarantee for the batteries, and offers replacements if they fail to meet agreed performance standards.

Green Charge's Model:

- Reduces electricity bills for commercial and industrial clients by managing demand peaks with energy storage systems using second-life batteries.
- Installs these systems at no upfront charge to the customer and profits by sharing the savings on energy bills.
- Handles system design and integration, working with various partners and contractors.
- Owns and operates the systems, and provides energy services like load levelling, energy arbitrage and renewable integration to reduce power costs and support environmental sustainability.
- Provides a 10-year service contract to customers. After this period, Green Charge returns the batteries to Nissan for recycling.

Challenges for Stakeholders:

- **Declining Cost of New Batteries:** The increasing affordability of new batteries erodes the cost advantage of second-life batteries, making it harder for Nissan and Green Charge to compete in the energy storage market.
- **Lack of Market Establishment:** The market for second-life batteries is still developing, presenting challenges in market adoption and customer acquisition.

6.2.3. Circular Business Model by Nissan Europe and Eaton Corporation

In this CBM Nissan Europe is the OEM, while Eaton, a multinational power management company headquartered in Dublin, Ireland, acts as the primary partner. The partnership integrates resources and expertise to develop second-life battery solutions for energy storage systems. The CBM is shown in Figure 22.

Stakeholder Motivations:

Nissan:

- Aims to extend the life of second-life batteries to meet energy storage demands, convert recycling costs into revenue, and offer a sustainable alternative to traditional battery disposal.

Eaton:

- Uses cost-effective second-life batteries to meet specific market needs, enhancing its product offerings and extending its market reach through its partnership with Nissan.

Operational Models:

Nissan's Model:

- Provides economical, capable second-life batteries that integrate seamlessly into Eaton's systems, including optimising used batteries to meet new performance standards.
- Collects, repurposes, tests, and grades used battery packs, and collaborates with Eaton to ensure the batteries fulfill specific system requirements. Nissan uses detailed battery data from its global data centre to assess battery health and optimise for second-life applications.
- Directly distributes to end customers by offering leasing options through its finance division.
- Garners profits from module sales and through broader engagement in product distribution and leasing initiatives.

Eaton's Model:

- Reduces electricity bills for commercial and industrial customers by managing demand peaks through energy storage systems using second-life batteries. Installs systems at no upfront cost to the customer and profits by sharing savings on energy bills.
- Handles system design and integration by working with various partners and contractors. Owns and operate the systems and provides energy services like load levelling, energy arbitrage, and renewable integration to reduce power costs and support environmental sustainability.
- Integrates and develops the final product, offering it through its channels and Nissan's dealerships.
- Generates revenue from product sales and associated services. Eaton earns a share of returns from connecting customers with electricity aggregators.

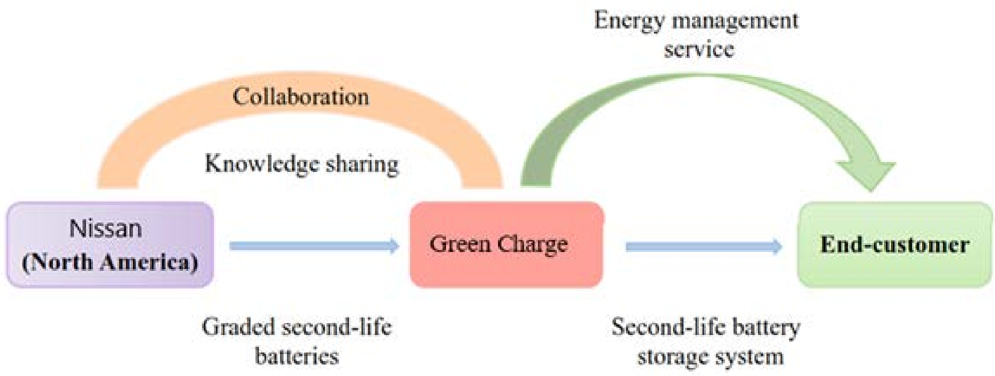


Figure 21: North America Nissan CBM for EOL EV batteries

- Provides a 10-year warranty and ensures responsible end-of-life management by returning depleted battery modules to Nissan for recycling.

Challenges for the Model:

- **Declining Cost of New Batteries:** Increasing affordability of new batteries erodes the cost advantage of second-life batteries, making market competition challenging.
- **Return Flow of Batteries:** Longer battery life spans in EVs may result in fewer batteries available for second-life use.
- **Performance Uncertainty:** Despite Nissan's warranty, there is uncertainty about the performance of second-life batteries in new applications, creating potential information asymmetry.
- **Customer Bias:** Overcoming the perception of second-life batteries as 'used products' and managing expectations regarding price and value.
- **Regulation:** Lack of transparent regulation in the grid ancillary services market complicates the conditions for buying and selling power to the grid.

6.2.4. BMW Group's Circular Business Model for Second-Life EV Batteries

BMW, a leader in the European EV market, develops customised second-life battery systems tailored to customer needs and sells the batteries primarily to electricity utilities. Depending on the contracts, BMW may take back battery packs for recycling at their end of life. BMW does not retain ownership of EV batteries after the sale, nor does it share data and knowledge.

BMW Motivations:

- Guarantees EV customers a residual battery capacity of at least 70% with an 8-year warranty.
- Aims to maximise resource efficiency and battery usage and receive revenue from selling second-life batteries and consultancy services.
- Focuses on sustainability and reducing carbon emissions over pure economic gains.

Operational Model:

- Provides tailored second-life battery systems to clients, using its expertise to match aged batteries with suitable applications, and offering technical solutions and consulting services.
- Uses advanced software, analytical tools and battery data to design custom systems.
- Uses its knowledge of cell chemistry to improve performance prediction and analysis, and assists clients with system integrators and energy management services.
- BMW is the second-life battery supplier and the developer of the tailor-made battery systems, as well as the business to user (B2U) service provider. It oversees construction, procurement and integration for client installations, and collaborates with partners to create home storage products and backup solutions for decentralised services.
- BMW's design strategy allows battery packs to be reused without adding additional cost to disassemble the battery pack , preserving components and reducing costs. This approach maximises battery value throughout its lifecycle.

Challenges for the Model:

- **Competitive Market:** New batteries are becoming cheaper, posing a competitive challenge.
- **Battery Capacity:** Lower capacity of second-life batteries affects price competitiveness.
- **Customer Hesitation:** Absence of warranties on second-life batteries may increase customer hesitation.
- **System Design:** Systems must accommodate both new and second-life batteries due to unpredictable return volumes.
- BMW does not retain the ownership of EV batteries after the sale, missing out the potential profits from the energy services these batteries later provide.

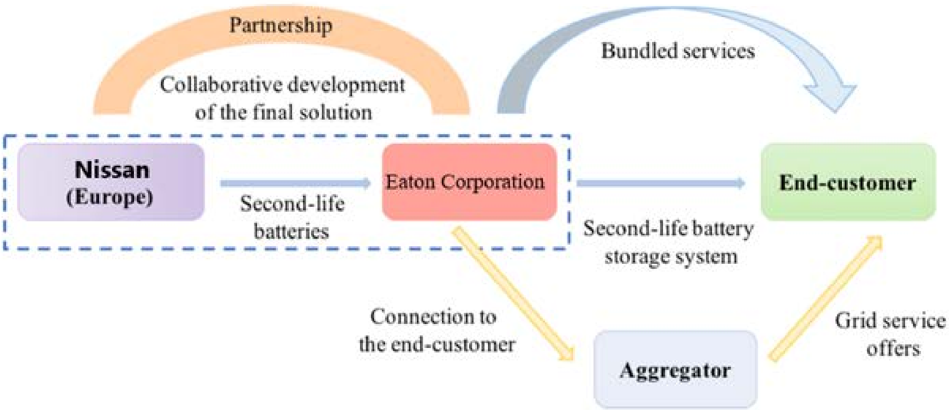


Figure 22: Europe Nissan CBM for EOL EV batteries

6.2.5. Grid-Scale Energy Services – Mercedes-Benz and the Mobility House Collaboration

A consortium comprising Mercedes-Benz (OEM), the Mobility House (energy storage company), GETEC (energy trader) and Remondis (battery recycling company) complete the battery value creation and recycling chain by working together to repurpose EV batteries into energy storage units . Mercedes-Benz retains ownership of the batteries and sharing data and knowledge with the Mobility House to develop solutions collaboratively. REMONDIS is responsible for recycling battery systems at the end of their lifecycle and returning valuable raw materials to the production cycle. This CBM is shown in Figure 23.

Stakeholder Motivations:

Mercedes-Benz:

- Uses EOL EV batteries in stationary storage to extend their use.
- Aims to employ the second-life batteries for 10 years.

The Mobility House:

- Supports the German energy transition using second-life batteries.
- Provides cost-effective storage solutions due to the variability of renewable energy sources.

Operational Model:

Mercedes-Benz:

- Collects used battery packs and outsources their testing and grading.
- Acts as a provider of second-life batteries, a system integrator and a knowledge resource in the business model system.

The Mobility House:

- Integrates the batteries to provide storage capacity suitable for various grid-related energy services.
- Refines battery storage systems in collaboration with Mercedes-Benz, using their combined expertise in automotive and energy storage solutions.
- Uses its deep knowledge of the energy market to strategise cost-effective battery storage monetising, trading and marketing.
- Generates profit by selling the electricity generated by energy storage systems to energy markets

Challenges for the Model:

- **Standard battery design:** OEMs are designing batteries primarily for vehicle use, not second-life applications.
- **Cost effectiveness:** The B2U cost structure needs optimisation in terms of battery design and maintenance. Outsourced battery testing and grading add extra costs.
- **Standard BMS:** Existing BMS are unsuitable for stationary storage, requiring a new BMS.
- **Open energy market:** Need for a more open and economically oriented energy market to fully exploit B2U potential.

6.2.6. Renault's Second-Life Battery Solutions

To address the influx of EOL batteries from its EVs, Renault collaborates with various partners in the energy sector to test and commercialise second-life batteries. This CBM is shown in Figure 24 and uses Renault's partnership with Connected Energy as an example.

Stakeholder Motivations:

Renault:

- Aims to reduce the total cost of ownership for EV customers.
- Uses revenue from second-life batteries to lower EV prices.

Connected Energy:

- Functions both as a customer and partner.
- Integrates second-life batteries into ESSs, providing

cost-effective solutions for managing grid demand and supporting renewable energy sources.

Operational Model:

Renault:

- Sells second-life battery packs at competitive prices, including essential components such as the BMS and wiring.
- Leverages extensive knowledge of battery technology, covering behaviour, functionality, and safety features.
- Monitors the SOH of the batteries using simulations to assess quality and predict degradation.
- Provides detailed performance information to partners to optimise battery use in second-life applications.
- Profits from selling battery packs but does not gain ongoing value in the energy market, limiting potential revenues.

Connected Energy:

- Acts as both the system integrator and provider of second-life battery solutions.
- Specialises in power electronics and network systems. It constructs comprehensive BMS and integrates advanced control software. It installs, operates and maintains the systems.
- Ensures that end-users maximise the commercial value and efficiency of their investments.
- Leases batteries to EV customers, allowing Renault to maintain ownership and control over the battery's lifecycle, facilitating effective management of second-life battery quality and supply.

Challenges for the Model:

- **Transportation Costs:** Expenses are higher because batteries are classified as dangerous goods.
- **Regulatory Clarity:** Unclear regulations on the status of second-life batteries complicate operations.
- **Battery Condition Variability:** Predicting performance is challenging due to variability in battery conditions.
- **Inconsistent Supply:** The unpredictable availability of EOL EV batteries complicates business planning and sustainability.

6.2.7. SYNETIQ's Collaborative Approach to Sustainability and Economic Value

EVs present unique challenges and opportunities for insurance companies and auction houses. EVs have distinct risk profiles and higher repair costs compared to traditional cars – this affects the pricing and management of insurance policies. Auction houses need to adapt to handle EV-specific components like batteries and electric drivetrains, marking a significant shift from their usual operations. This evolving landscape reflects the broader transformations within the automotive ecosystem.

The collaboration between LV-General Insurance (LVGIG), SYNETIQ (UK's vehicle salvage, dismantling and recycling specialist) and Allye Energy has established a pioneering model that gives EV batteries a second life through repurposing. Allye tests and purchases EV packs from SYNETIQ for use in its 300kWh battery storage systems, each of which contains four salvaged EV battery packs. Allye leases the battery packs to customers such as industrial clients and renewable energy companies, including notable clients like AeroVolt, which uses the Allye Max battery energy storage system for electric aircraft power solutions.

Operational Models:

SYNETIQ's Model:

- Acquires batteries from EVs deemed irreparable after accidents under agreements with GI. These vehicles are generally less than five years old, and have batteries that are often in good condition and have substantial remaining life.
- Holds ownership of the batteries upon acquisition.
- Removes the batteries and conducts rigorous testing to ensure they are safe and functional for secondary use.

Allye Energy's Model:

- Uses advanced diagnostic technology to assess the health of batteries provided by SYNETIQ to determine

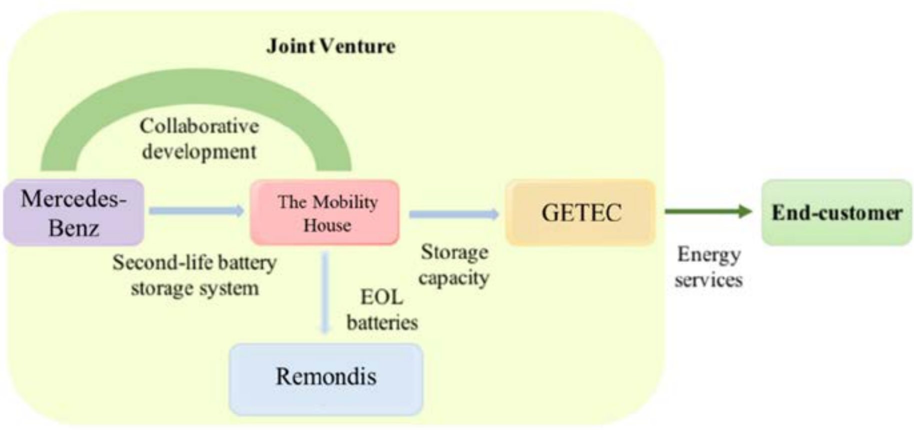


Figure 23: Mercedes-Benz CBM for EOL EV batteries

which batteries are suitable for repurposing.

- Integrates the selected batteries into the Allye Max mobile battery energy storage system, transforming them into versatile energy storage solutions.
- Combines various lithium-ion chemistries, such as NMC (nickel manganese cobalt) and LFP (lithium iron phosphate) to ensure that the final product meets diverse energy needs.

LVGIG's Model:

- Damaged or 'total loss' vehicles insured by LVare used for recovery and recycling of EV batteries.
- An increase in the use of green parts within the insurer's bodyshop network for vehicle repairs.
- LVGIG achieve its sustainability goals of reducing the environmental impact of its operations.

Challenges for the Model:

- **Market for Aftermarket Parts:** The market for HV components lags behind as EV adoption soars.
- **Repair Costs:** The complexity of EV electrical systems makes repairs expensive; insurers often write off vehicles as total losses even when batteries are still functional.

6.2.8. Closed-Loop System for EV Battery Recycling in the UK

LVGIG, SYNETIQ, the UK's leading vehicle salvage yard, and Altilium, a clean technology group, have announced a partnership to recycle the growing number of batteries from written-off EVs. SYNETIQ will supply feedstock for Altilium's fully circular battery recycling ecosystem, which will include the UK's largest battery recycling and refining plant. The plant will recycle EOL batteries from 150,000 EVs annually, producing 30,000 MT of cathode active materials – enough to meet 20% of the expected UK demand by 2030. This collaboration will help close the loop on the UK battery supply chain and conserve natural resources.

Business Model Description:

Identification and Recovery:

- LVGIG identifies written-off EVs with batteries suitable for recovery.
- SYNETIQ removes the batteries and conducts safety checks to ensure suitability for the next stage.
- Batteries will be securely stored by SYNETIQ, according to to stringent safety standards to prevent risks such as fires or environmental hazards.

Transportation and Processing:

- Batteries will be carefully transported from SYNETIQ's facilities to Altilium's processing centre, ensuring safety and efficiency.
- At Altilium the batteries will undergo a sophisticated recycling process where valuable materials like lithium, nickel and cobalt are extracted. Altilium's advanced hydrometallurgical processes enable them to recover these materials at impressive rates, over 95% in many cases.

Material Resale:

- Recovered materials are sold to battery manufacturers or other relevant industries.
- This process injects valuable raw materials back into the supply chain in a circular economy.

6.2.9. Integrated Lifecycle Management of EV Batteries in Norway

Norway, a leader in EV adoption, has established an integrated system for managing the lifecycle of EV batteries, from salvage to recycling. This system is a collaborative effort by various Norwegian insurance companies, Grønvolds Bil-Demontering (GBD), Batteriretur Høyenergi AS, Stena Recycling AS Batteri, Hydrovolt, Autoretur and the Norwegian Car Importers' Association.

Business Model Description:

Insurance Companies:

- Provide a steady influx of written-off EVs for recycling and repurposing.

Grønvolds Bil-Demontering (GBD):

- **Assessment and Removal:** Handles the initial assessment and removal of batteries.
- **Safety and Diagnosis:** Ensures safe removal and accurate condition diagnosis to maintain traceability and quality.

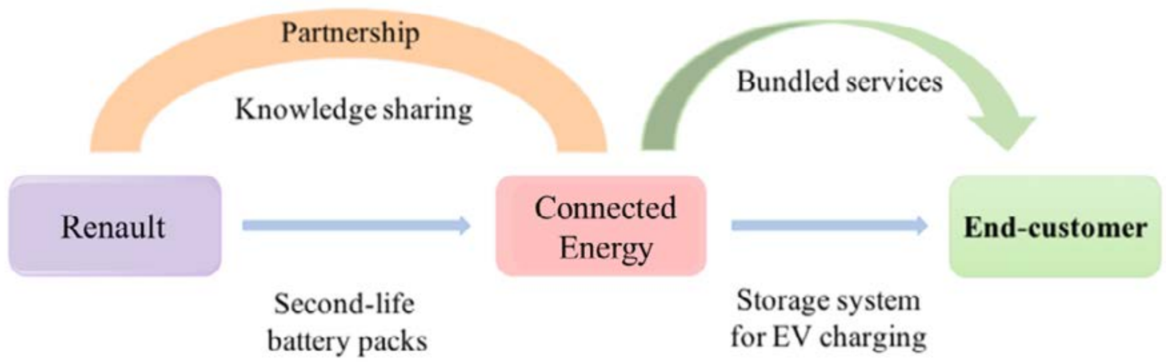


Figure 24: Renault CBM for EOL EV batteries

- **Repurposing:** Refurbishes suitable batteries for energy storage and vehicle conversions.

Recycling Facilities and Processing (Batteriretur Høyenergi AS, Stena Recycling AS Batteri):

- Thoroughly discharge and dismantle batteries and send the cells to fragmentation plants.

Hydrovolt Cell Fragmentation and Metal Recovery:

- Uses advanced technology to recover valuable metals, enabling the production of 3–5 new batteries from each discarded one.

Autoretur and Norwegian Car Importers' Association National Collection System:

- Provides a comprehensive system for collecting EOL EVs for efficient nationwide processing.

Challenges for stakeholders:

- **Technical Expertise:** Ongoing training is required to handle evolving battery technologies.
- **Logistical Coordination:** Efficient transportation and processing of hazardous materials pose a significant challenge.
- **Regulatory Compliance:** Adherence to stringent environmental and safety regulations is essential to navigating complex legal frameworks and ensuring compliance.
- **Market Dynamics:** Adapting to fluctuations in the supply and demand for recycled materials requires continual adjustment to market shifts.

6.2.10. Relectrify's Global Leadership in Battery Control Technology

Relectrify, a Australian pioneer in battery control technology, operates on a global scale. Relectrify deploys repurposed second-life EV batteries for residential, commercial, industrial and grid-supported applications. The company collaborates with various financial and technical partners to expand its business across the USA, EU, Japan, South Korea and New Zealand. Relectrify partners with OEMs like Nissan and Toyota to use EOL batteries, and enhance technology sharing and repurposing efforts. This CBM is shown in Figure 25.

Financial Collaborators:

Clean Energy Finance Corporation (CEFC):

- An Australian government green bank that funds clean energy projects.
- Invested A$6.2 million in Relectrify for energy storage solutions.

Energy & Environment Investment, Inc.:

- A Japanese financial sector entity that supports green energy innovations.
- Invests in Relectrify to promote sustainable energy solutions globally.

Creative Victoria:

- A state-owned body that supports innovative projects in Victoria, Australia.
- Funds Relectrify's advanced control solutions for battery storage, which extend the life of EV batteries.

Energy Innovation Capital (USA):

- Invests in companies transforming energy solutions through sustainability and digital technologies.
- Supports Relectrify's initiatives to repurpose EV EOL batteries.

GS Futures (South Korea):

- An early-stage funding body that focuses on future energy technologies.
- Invests in Relectrify for innovative storage solutions development.

ARENA (Australia):

- Provides $3.3 million to Relectrify for developing commercial and industrial storage applications using repurposed EV batteries.

Energias de Portugal (EDP, Portugal):

- Supports businesses and early-stage technologies in green energy.
- Invests in Relectrify's innovative energy storage applications.

Toyota Venture (USA):

- A venture firm that supports early-stage climate-resilient technologies.
- Funds Relectrify's sustainable energy storage solutions that use repurposed EV batteries.

Technology Collaborators:

4R Energy Corporation:

- A partnership between Nissan and Sumitomo that is focused on EV second-life battery applications.
- Collaborates with Relectrify to repurpose Nissan Leaf EV batteries for energy storage.

Creative Venture (USA):

- A global tech firm that supports deep tech applications.
- Provides technical support to Relectrify for advancing energy storage systems using EV second-life batteries.

Commercial and Industrial:

Dynamic Manufacturing (USA):

- Developed a commercial storage solution with an estimated capacity of 60kWh for three-phase 380-480V systems.

Nissan NCAP (Australia):

- Launched the Nissan Node project using second-life Nissan Leaf EV batteries for staff EV charging facilities.

Chubu Electric Power (Japan):

- Installed large-scale CellSwitch technology by Relectrify.

Energy Providers:

American Electric Power (USA):

- Developed a utility-scale 25MWh throughput energy storage system in collaboration with Nissan North America.

Counties Power (New Zealand):

- Installed a grid storage system for peak shaving applications; this is Relectrify's second largest international project.

6.2.11. Infinitev's Comprehensive Business Models for Battery Management

Infinitev, part of the IM Group, is dedicated to the reuse, repurposing and recycling of EOL batteries from hybrid and EVs. It has three primary business models: refurbishing batteries for reuse in EVs; repurposing batteries for stationary energy storage applications; and recycling batteries through partnerships with third-party firms. This circular approach ensures the maximal utilisation of battery materials, contributing to both environmental sustainability and economic efficiency.

Infinitev collaborates with automotive OEMs, including Mazda, Toyota, Kia, Lexus and Honda, to promote sustainable practices and extend battery life through various reuse and repurposing initiatives.

Reusing Business Model:

Infinitev refurbishes hybrid and EV batteries to extend their life for reuse in vehicles. This process involves stripping, disassembly, charging, cycling, isolating healthy cells, reassembling and shipping refurbished batteries. Infinitev also handles the collection and transport of batteries unsuitable for reuse in mobility applications.

- **Clients:** Charging Infrastructure Companies for EV (Australia): Ritium, EVSE, EV Up, JET Charge, CHARGEFOX, Tesla Charging Network, Evie Network, JOLT

Repurposing Business Model:

Infinitev repurposes batteries unsuitable for mobility applications into stationary energy storage solutions. The process is similar to that of the reusing model and is tailored for ESSs.

- **Clients:** Energy generation and distribution utility companies, such as AGL Energy, and standalone energy storage and renewable energy solutions companies.

Recycling Business Model:

Infinitev collaborates with Resource Innovative Recycling to recycle faulty battery cells that are unsuitable for reuse or repurposing. This includes isolating faulty cells, providing reverse logistics, recycling, recovering critical materials, grading and disposing of hazardous materials..

- **Clients:** Cell, battery and electronics manufacturers that use recycled materials for new products.

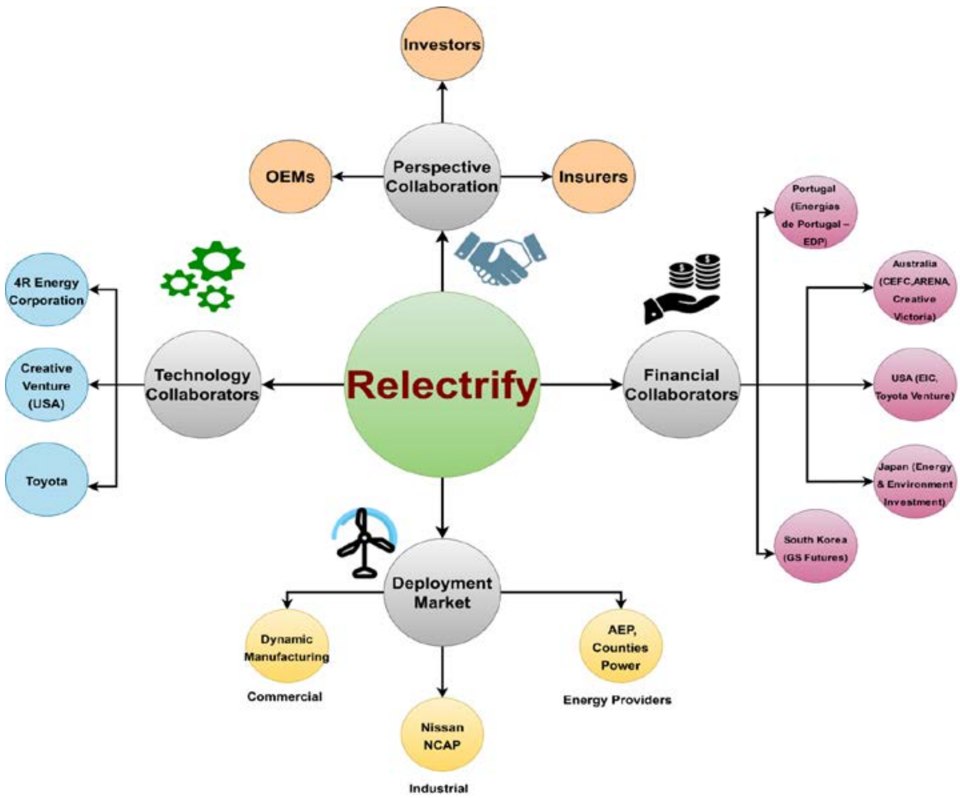


Figure 25: Relectrify CBM for EOL EV batteries

7. Proposed Circular Business Models for Insurance and Auction Houses

Concerns about the management of EOL EV batteries are rising. This section outlines two CBMs specifically for insurance companies and auction houses. By adopting CBMs and fostering collaborative partnerships, stakeholders can maximise the value obtained from EOL EV batteries while minimising environmental impact. The model focuses on integrating specialised infrastructure and protocols, and cultivating partnerships with key stakeholders to steer the industry towards a more sustainable and efficient future.

7.1. Circular Business Models for Insurance and Auction Houses for Managing EOL Electric Vehicles

To capitalise on EV batteries from crashed EVs, a CBM should include insurers and auction houses. The model should define stakeholder integration for battery repurposing or recycling. In Australia, insurers can reduce the costs of written-off EVs by partnering with auction houses, and employing advanced battery assessment, repurposing and recycling techniques, as illustrated in Figure 26.

7.1.1. Full-Service Business Model

This full-service business model, as shown in Figure 26, entails a partnership between the insurance sector and auction houses. Auction houses have the opportunity to expand their role by recovering parts and exploring processes for testing, sorting, grading, and safely storing EV batteries. A potential partnership could involve investment in specialized equipment and employee training, enabling auction houses to develop capabilities in assessing battery health and other EV-specific components. As the market for EVs evolves, this approach could help identify pathways for maximizing the value of high-value batteries and other reusable parts, positioning auction houses as valuable partners to the insurance industry.

Establish Robust Infrastructure and Protocols for Sustainable EV Battery Salvage:

1. A potential solution is to equip auction houses with specialized workspaces, including restricted access areas, quarantine zones, depollution ramps, HV safety gear, and lifting tools for EV components. This could support safe and efficient battery handling while ensuring compliance.
2. Invest in diagnostic tools and sorting and testing equipment for battery grading based on the battery's health and capacity. (ReJoule Energy offers diagnostic tools that test any EV battery in under 10 minutes and are usable inside or outside the vehicle. Teams can be trained in one day.)
3. Tested battery modules that are less than 3 to 5 years old or have a high SOH (>90%) can be refurbished and regrouped as an EV battery pack and sold to auto repair shops. Batteries that are around 5 to 10 years old or have an SOH >70%, should be sold to repurposing companies. Lastly, batteries with a lower SOH, or that are damaged, should be sold to the recyclers.
4. One possible approach is to develop storage facilities with designated concrete areas that are dry, temperature-controlled, and equipped with fire suppression systems. Incorporating large-scale racking, purpose-built depollution facilities, and upgraded dismantling setups could enhance the safe and efficient handling of EV components.
5. Staff need comprehensive training on EV procedures, battery handling, transport, storage, diagnostics and fire protocols, along with industry certifications to boost credibility and safety.

Harness the Power of an Online Auction Marketplace: Introducing an online auction marketplace will facilitate the sale of assessed EV batteries and vehicle parts, and expand the customer base beyond traditional boundaries.

1. The online marketplace will integrate with the auction house's inventory system for real-time, accurate listings. This platform could present an opportunity to unlock new revenue streams, improve margins, and provide valuable market analytics to inform strategic decisions. While the full potential is still being explored, it holds promise for future growth and insights.
2. A comprehensive, safe and standardised logistics and shipping framework will be required to ensure the efficient delivery of parts.

Implement a Leasing Program for Rigorously Tested EV Batteries at the Auction House:

1. Offer flexible agreements tailored to diverse customer needs, ensuring continual maintenance for optimal performance with end-of-lease options to renew, upgrade or purchase batteries.
2. Forge strategic partnerships with dealerships and repair shops to broaden customer base.
3. Emphasise cost effectiveness and environmental benefits in marketing efforts.
4. Address reliability and regulatory concerns through advanced diagnostics and adherence to guidelines.
5. This forward-looking approach will promote accessible EV ownership, sustainability and open new business opportunities. This model would provide steady revenue through leasing fees and position the yard as a leader in sustainability by extending battery lifecycles and reducing waste.

Diverse Customers:

1. Supply repurposed batteries to energy storage providers for mining, industrial and residential use.
2. Provide EOL batteries for EV charging infrastructure, including mobile units and grid stabilisation.
3. Offer refurbished batteries with warranties to auto repair shops, creating affordable repair options for EV owners.

4. Supply salvaged batteries to recyclers for black mass production, reducing the need for new material mining.
5. Engage with EV battery partners to establish closed-loop systems to promote sustainability and generate additional revenue

7.1.2. Hybrid Partnership Model for Effective EV Battery Lifecycle Management

Figure 27 shows a hybrid partnership model for insurers and auction houses. This model integrates specialised partners, ensuring streamlined operations and strategic collaborations, and optimising processes from assessment to the sale of repurposed or recycled materials. The collaborative model, though potentially yielding lower revenue compared to full-service approaches, offers substantial benefits. It minimises capital investment in specialised equipment, leverages partner strengths, promotes sustainability by reusing/recycling batteries, and exemplifies the effectiveness of strategic alliances to increase operational efficiency and market presence.

Collaboration Process & Technical Requirements:

1. Investigate the potential to establish a specialised dismantling centre within the auction house for safe disassembly of EV batteries. The centre will be equipped with necessary tools and safety protocols to handle HV components efficiently.
2. Implement strict protocols and safety standards for transportation of EOL batteries to repurposing or recycling partners, that adhere to Australian Code for Transport of Dangerous Goods.
3. Redirect resources from in-house processing to leverage the expertise and equipment of strategic partners to reduce capital investment and operational costs.
4. Explore collaboration with repurposing companies for battery testing to mitigate additional costs associated with logistics and transportation.
5. Foster partnerships with repurposing and recycling companies for detailed assessment and processing of batteries to improve marketability and create new revenue streams.
6. Beyond logistics and sales, actively collaborate with recycling partners. This unlocks value, with each ton of recycled batteries potentially worth A$6000 in black mass bags, and avoids five tons of CO_2 emissions.
7. Actively engage in knowledge sharing and collaborative product development with partners to strengthen market position and unlock additional revenue opportunities.

Strategic Technical Procedures:

1. Establish an EV battery testing centre:

- Diagnostic Equipment: Invest in advanced tools.
- Certification Standards: Develop rigorous testing protocols.
- Data Analytics: Implement a predictive data management system.
- Warranty Formulation: Offer warranties based on testing results.
- Value Addition: Certify batteries to increase market value.
- Market Outreach: Promote the testing centre's capabilities to potential clients.

2. Early Collaboration:

- Form undisclosed partnerships aligning goals and resources.
- Establish joint testing facilities for rigorous battery assessment.
- Share resources for testing facilities to reduce costs and risks.
- Prototype solutions to refine technical specifications before scaling.

3. EV Sales Monitoring:

- Gather and analyse EV sales data regularly.

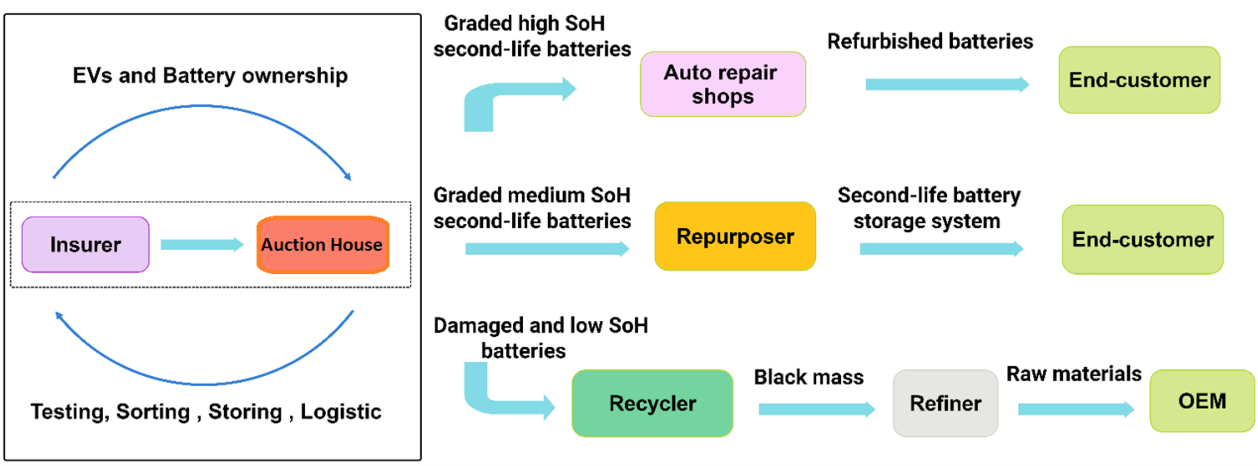


Figure 26: EV full-service business models

- Predict the battery types that will enter auction houses for better preparation.
- Train technicians on handling specific battery technologies.
- Invest in tools for efficient processing of common battery types.
- Strengthen partnerships with manufacturers for repair insights.
- Collaborate with academia and tech firms on battery innovations.
- Innovate salvage processes to adapt to diverse battery designs.

4. Incentivise EV Battery Repurposing and Recycling ventures.

- Conduct annual market research to identify active repurposers, recyclers and their specialisations.
- Organise technical integration sessions for collaboration.
- Negotiate contracts with clear terms on battery supply, pricing and performance.
- Form supply agreements detailing battery quality, quantity and delivery schedules.
- Target diverse market segments like residential energy storage, industrial backup power, and EV charging infrastructure to broaden the customer base and reduce reliance on any single market.
- Initiate joint development projects to refine battery diagnostics and refurbishment processes.
- Provide salvaged batteries for their R&D efforts.
- Develop shared testing facilities for battery evaluation.
- Implement technical exchange programs for knowledge sharing
- Support innovation and R&D activities by providing operational insights.
- Create a performance certification process for modified batteries.
- Establish a feedback loop for continuous improvement.
- Formalise partnership agreements with clear roles and revenue-sharing models.

5. Pursue Global OEM Collaborations

- Collaborate with OEMs with expertise in EV battery second-life projects.
- Leverage OEM knowledge and resources to improve operations and market positioning.
- Use OEM diagnostic tools for accurate battery assessment.
- Benefit from brand association to enhance reputation and trust.
- Explore new market segments through OEM partnerships.
- Reduce costs through shared technology and infrastructure.
- Prioritise OEMs with active second-life battery programs and local presence.
- Clearly communicate joint venture value proposition to OEMs.
- Initiate pilot projects to demonstrate capabilities and build trust.

6. Access Government Funding

- Seek federal and local incentives to support EV battery projects in Australia.
- Monitor and identify relevant grants and incentives from government programs.
- Align projects with government goals to increase funding approval chances.
- Collaborate with research institutions to lift project credibility and access additional grants.
- Explore public-private partnerships with local governments for funding and support.

7.2. Collaborative Stakeholders in Australia

There are numerous repurposing and recycling companies with which insurance companies and auction houses can collaborate to manage EOL EV batteries. Examples are listed below.

1. Infinitev & IM Group
   - Specialisation: Refurbishing, repurposing and recycling EV and HEV batteries.
   - Advanced Grading System: Identifies battery failure causes and determines the best use – reuse, repurposing or recycling.
   - Partnerships: Collaborates with Mazda Australia and Kia Australia to create a circular economy for EV batteries.
2. Relectrify
   - Specialisation: Repurposing second-life EV batteries into battery energy storage systems (BESS) with integrated battery management and bi-directional inverting.
   - Projects: Engaged in projects with Counties Power (New Zealand) and Chubu Electric Power (Japan).
   - Funding: Secured a grant from the Australian Renewable Energy Agency (ARENA) to develop and deploy big battery technology using recycled EV batteries.
3. Envirostream
   - Recycling Expertise: Recycling home energy storage batteries and EOL batteries from various EV OEMs.
   - High Recovery Rate: Capable of recovering over 90% of the resources from EOL batteries.
   - Strategic Role: Plays a pivotal role in battery recycling initiatives following safety recalls and other large-scale recycling needs.

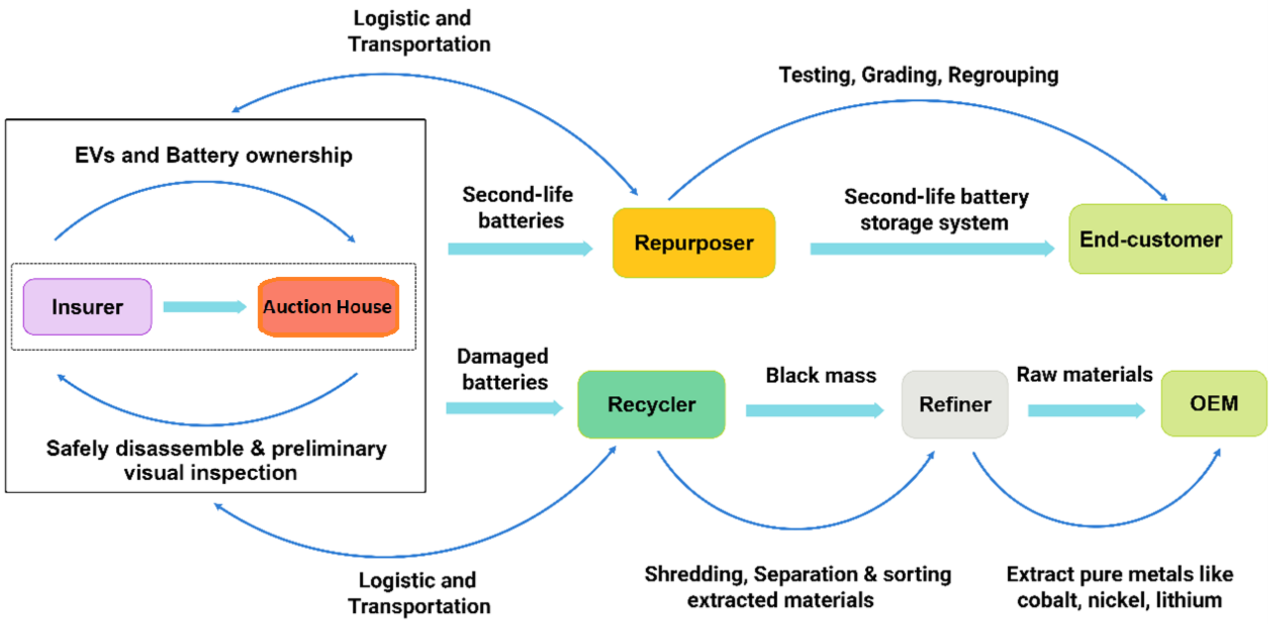


Figure 27: Hybrid partnership business model

4. Ecobatt
   - Comprehensive Services: Safe collection, transportation, processing and recycling of battery products.
   - Investment in Infrastructure: $30 million investment in a Li-ion battery recycling plant.
   - Specialised Containers: Provides safe collection, transportation and transport containers for damaged vehicles and batteries.
   - Partnerships: Works with Hyundai and other EV OEMs to recycle batteries from recalled vehicles.

5. Magellan Power
   - Operations: Significant experience in battery energy storage systems, industrial AC and DC uninterruptible power supplies (UPS) and EV chargers.
   - Research & Development: Focuses on repurposing and recycling EV batteries.
   - Collaboration Potential: Could partner with auction houses to create energy storage solutions, EV chargers and UPS systems using EOL EV batteries.

6. Zenobe
   - Operations: Provides clean power and transport solutions via extensive battery storage and EV operations.
   - Research & Development: Focuses on repurposing EV batteries from electric bus fleets into second-life battery products for on-grid and off-grid applications.

7. CSIRO (Commonwealth Scientific and Industrial Research Organisation)
   - Research: Conducts extensive research on battery recycling technologies and the development of efficient recycling methods for Li-ion batteries.
   - Projects: Engages in projects aimed at advancing battery recycling processes and creating new materials for batteries.

8. Association for the Battery Recycling Industry (ABRI)
   - Role: Advocates for sustainable battery recycling practices and policies in Australia.
   - Membership: Includes stakeholders from various stages of the battery lifecycle, including manufacturers, recyclers and research institutions.

9. Battery Stewardship Council (BSC)
   - Mission: Promotes the development of a strategic approach to battery recycling and recovery in Australia.
   - Initiatives: Works towards creating a national plan for recycling and remanufacturing battery materials.

10. Battery Pollution Technologies
    - Company Goal: Lead battery recycling in the Asia Pacific region through partnerships and expertise.
    - Investment in Technologies:
      - Gen 2 recycling machinery for efficient material recovery.
      - Innovative packaging and engineering solutions for battery lifespan extension and safety improvement.
      - Robotics and manufacturing solutions for clean disassembly and recycling.
    - Ongoing Initiatives:
      - Container research for safe battery transportation.
      - Chemical solvents for optimised metal recovery.
      - Ties with Australian institutions for research on battery recycling.

11. TES-AMM Australia Pty Ltd
    - Extends asset lifecycles through repair and refurbishment for redeployment and resale.
    - Enables closed-loop and open-loop materials use with recycling services to promote environmental regeneration.

- Collaborates with clients to find high-end applications for all resources to minimise pressure on natural resources.
- TES-AMM Australia received $1,913,517 funding to establish NSW's local capability in circular Li-ion battery reuse and recycling. Its facility in Fairfield, Western Sydney, will be the first of its kind in NSW and Australia, processing up to 800 tonnes of Li-ion batteries per annum.

12. Second Life Battery Cells
    - Refurbishes batteries from E-bikes, E-scooters, power tools and EVs.
    - Rigorous testing and proprietary processes ensure quality.
    - Only undamaged and intact batteries are accepted for reuse.
    - Repairs are provided for faulty batteries.

8. Economic Analysis of EOL EV Batteries

Managing EOL EV batteries requires a comprehensive approach that includes logistics, testing, repurposing and recycling. The costs associated with these processes are significantly influenced by various factors, which are discussed in this section.

In this section, all costs are expressed in USD.

8.1. New EV Battery and Second-hand EV Battery Price

Technological advancements and reductions in material costs have led to a significant drop in lithium battery prices. According to the Boston Consulting Group, assuming a 6%–8% annual decrease in the costs of producing EV batteries, the manufacturing cost of battery packs is projected to fall to $97–$130/kWh by 2030 [107]. According to Bloomberg NEF's Battery Price Survey, Li-ion pack prices dropped 79% in real terms to $139/kWh in 2023, from more than $732/kWh in 2013.[102].The survey expects that by 2026, average prices will fall below $100/kWh. Studies using technological learning, literature and expert opinions have forecast that Li-ion pack costs are expected to be $132/kWh in 2030, $92/kWh in 2040, and $71/kWh in 2050. According to technology-specific and bottom-up modelling, advanced Li-ion batteries like the NMC811 will cost around $84/kWh in 2050.

Table 11 provides the historical and estimated prices for new and used EV batteries.

- In 2023 lithium iron phosphate (LFP) cells cost 32% less than cells using lithium nickel manganese cobalt oxide (NMC) chemistry.
- On a geographical comparison, China led with the lowest average prices for battery packs at $126/kWh. In contrast, pack prices in the United States and Europe were higher by 11% and 20%, respectively.
- Miners and metal traders anticipate further reductions in the prices of key battery metals like lithium, nickel and cobalt. Technological innovation and manufacturing improvement should drive further declines in battery pack prices in the coming years, to $113/kWh in 2025 and $80/kWh in 2030.

- Estimated second-life battery cost varies from $40–$160/kWh depending on repurposing cost, with prices for lower quality battery modules mostly ranging from $65 to $76/kWh, and higher quality modules mostly between $152 and $174/kWh.

8.2. Collection and Transportation Costs

The cost of collecting and transporting batteries is influenced by factors such as battery condition, distance to the recycling facility and shipment quantity. Safety measures, including custom-made UN-standard packaging, add to the costs. Expenses are higher for transporting small quantities, where trucks often operate below capacity and require a special Class 9 hazardous permit. Table 12 illustrates the costs of battery collection and transportation based on whether the materials are classified as hazardous or non-hazardous.[108] There is confidence that as the volume of second-hand battery packs increases over time, the cost associated with their logistics will decrease substantially.

An efficient collection network can help reduce these costs by strategically placing collection points and using existing dismantler and dealership infrastructures. OEMs play a leading role in this effort.

8.3. Dismantling and Testing Costs

Currently, disassembling battery packs to the module and cell levels is heavily reliant on manual labour, which significantly increases costs. For repurposing EOL EV batteries, retired batteries must be partially or entirely disassembled and checked for safety risks. Modules and cells may need replacement, regrouping and reconfiguring. The absence of standardisation among EV OEMs, such as variations in cell form factors and the use of adhesive, further hinders automation and necessitates manual disassembly. Minimising technician labour is crucial in repurposing operations. Replacing faulty cells is economically impractical, so avoiding modules with faulty cells is key. Using vehicle diagnostic data for used battery purchases is valuable for repurposers, as it potentially reduces repurposing costs to as low as $20/kWh. Recent advances in AI and ML offer new solutions for the automated disassembly of EV Li-ion batteries.[109]

Table 13 presents the disassembly costs per pack and per kWh for commercial EV batteries via manual and fully automated disassembly processes and the corresponding time. Based on publicly available information and battery

Table 11: EV Lithium-ion battery prices from 2013 to 2023, and estimation

Year	Type	Mean Price ($/kWh)	Ref.
2013	New EV battery	$732	[102]
2014	New EV battery	$692	[102]
2015	New EV battery	$448	[103]
2016	New EV battery	$345	[102]
2017	New EV battery	$232	[104]
2018	New EV battery	$211	[102]
2019	New EV battery	$183	[102]
2020	New EV battery	$170	[105]
2021	New EV battery	$150	[102]
2022	New EV battery	$161	[102]
2023	New EV battery	$139	[102]
2023	Second-hand EV battery	$80	[102]
2025	New EV battery (Forecast)	$113	[102]
2025	Second-hand EV battery (Forecast)	$70	[102]
2025	Second-hand EV battery	$72	[104]
2030	New EV battery (Forecast)	$70–100	[105]
2030	New EV battery (Forecast)	$150–250	[106]
2030	New EV battery (Forecast)	$97–130	[107]
2030	New EV battery (Forecast)	$80	[102]
2030	Repurposed battery selling price (Forecast)	$40	[102]
2030	Repurposed battery selling price (Forecast)	$40	[106]
2030	Repurposed battery selling price	$44–180	[106]
2050	New EV battery (Forecast)	$71	[105]
2050	Repurposed battery selling price	$40–50	[105]

teardowns analysis, the Nissan Leaf has the highest disassembly cost at US$0.78/kWh. The Tesla Model 3 pack at module level is the least cost-intensive, due to its lower number of parts, at US$0.30/kWh.[110] Tesla is followed by BYD (US$0.32/kWh) in terms of cost effectiveness. There is not much information available for Tesla disassembly at the cell level.

8.4. Repurposing Costs

Recycling Li-ion batteries involves costs and potential waste; this highlights the importance of repurposing them for a second or third life to maximise their economic and environmental value before recycling. However, in order for repurposed batteries to have a plausible business model, it must be economically feasible to purchase and refurbish batteries for less than it would cost to purchase a brand-new battery. Most batteries suitable for second-life applications would be repurposed by third-party workshops or OEMs/battery manufacturers. This process involves battery testing, partial pack disassembly, module separation and connecting different packs based on market requirements. Table C in the Appendix outlines the repurposing costs for EV battery projects, ranging from $90/kWh to $150/kWh. This total includes expenses for purchasing second-life batteries, disposal, remanufacturing and transportation. A sample of repurposing cost contribution [111] to EOL battery selling price is shown in Figure 28. The cost of acquiring the second-life battery is generally the largest component, followed by transport and R&D for remanufacturing, which covers module disassembly, cell testing and selection, and battery reassembly. Element Energy's 2019 EU study [112] on battery reuse economics estimates that repurposed batteries will cost $40/kWh in 2030, compared to $70/kWh for new batteries, offering end-users a 42% price reduction. Car OEMs benefit from repurposing by saving $4.5/residual kWh in avoided recycling fees and earning $0.3/residual kWh from additional margins on sold batteries, totalling $67 per battery unit – this positions repurposed batteries favourably in the market. A saving of $4.5/residual kWh equates to avoiding the cost of recycling approximately 18,220 tonnes (1.94 GWh) of batteries, which would otherwise incur a recycling fee of $480/tonne.

A real-world B2U project, EnBW's Second Life Battery Storage project in Karlsruhe, Germany, which has been monitored for over two years since 2020, found that new NMC batteries cost around $165/kWh.[30] Repurposing these batteries cost $40/kWh, including transport, equipment and labour. With a selling price of $110/kWh, manufacturers earned $70/kWh in profit. By 2030, recycling these batteries could generate an additional $27/kWh in revenue; avoiding disposal costs saved a further $13/kWh. Altogether, the total lifecycle cost benefit of B2U repurposing is observed as $120/kWh as shown in Figure 29.

In June 2015, the US Department of Energy's Vehicle Technologies Office and the National Renewable Energy Laboratory (NREL) [113] released the B2U Repurposing Cost Calculator, an Excel tool designed to help businesses assess the financial viability of refurbishing plug-in hybrid electric vehicle (PHEV) batteries. The model estimates key costs, such as capital and labour, and evaluates potential profitability.

NREL's research indicated that PHEV batteries could be repurposed for as little as $20/kWh, or about $500 per battery. The model breaks down costs to $24/kWh for the refurbishing process and $20/kWh for battery acquisition, totalling $44/kWh. This is significantly lower than the $350/kWh cost of new batteries at the time.

Though the NREL study is now 9 years old, it still provides useful cost estimates for EV battery reuse, and the model can be updated with current data. However, liability and insurance concerns related to reconditioned batteries in energy storage applications could influence these predictions.

Repurposing costs can be as low as $20/kWh, meaning a 40kWh battery pack [114] from current long-range Renault or Nissan models could cost around $800 to repurpose for stationary use. The University of California, Davis found costs for repurposing Chevy Volt and Nissan Leaf packs to be $1,150 and $1,780, respectively [34], significantly lower than their original prices. A 2024 study funded by the European Regional Development Fund for Finland shows that the initial investment in the second-life battery business can be recovered within 5 years, when batteries are processed at the pack or module level.[115] However, repurposing costs increase significantly at the cell level. The business remains feasible in scenarios where only modules with faulty cells are disassembled at the cell level, due to the limited number of faulty cells. Disassembling all battery packs at the cell level proves economically unfeasible due to the significant increase in labour and space requirements. With labour costs being the second largest expense after acquiring used batteries, this scenario becomes impractical, as the required resources far outweigh the potential benefits. Finland's Cactos and California's Smartville Inc. are using Tesla EV battery packs by repurposing them at the module level, rather than disassembling them down to individual cells, to create 100kWh behind-the-meter energy storage systems.[116] Both companies source their Tesla batteries from third-party salvage firms and plan to start shipping these innovative products in 2024.

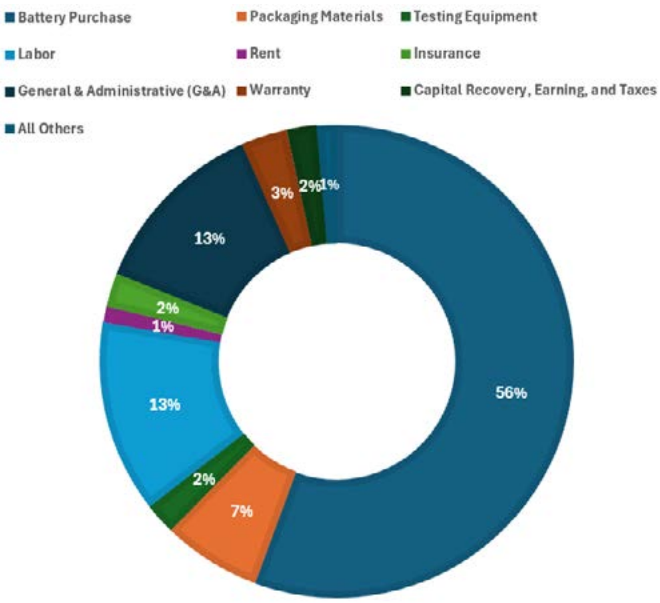


Figure 28: Repurposing cost contribution to EOL battery selling price [111]

8.5. Recycling Costs

The financial implications of recycling Li-ion batteries are multifaceted and encompass several stages, each with its own set of costs. The costs associated with recycling include the collection and transportation of the battery, the dismantling and disassembly for recycling, and then the recycling process [119, 120]. The biggest costs for an automotive battery recycling plant are hourly labour, purchase costs and transport costs as shown in Figure 30. [121] Currently, pack transport costs are covered by the vehicle manufacturers, but they must come down significantly to make recycling economically viable. Net recycling profit in $/kWh for different commercial battery designs for China, the US and the UK, with the collection point in the UK is presented in Figure 31.

See Table E in the Appendix for data. Figure 31 shows that Tesla's Model S has higher recycling profits (depending on the country) compared to other battery packs.[118] Comparing a uniform battery pack, LFP (lithium iron phosphate) and LMO (lithium-ion manganese oxide) chemistries provide lower recycling revenue in comparison to NCA (lithium nickel cobalt aluminium).[118] However, for direct recycling, the theoretical Tesla LFP pack is comparable to the Tesla NCA.[118] LFP remains more cost-intensive compared to the other battery chemistries. Recyclers are typically paid to process LFP-type

Table 12: Battery collection and transportation costs [$/ton-mile]

Transportation Mode	US	China	Korea
Hazardous Materials Transportation			
Rail	$0.97	$0.10	$0.20
Medium-duty Truck	$9.40	$1.00	$2.00
Heavy-duty Truck	$6.28	$0.60	$1.20
Barge	$0.50	$0.10	$0.10
Ocean Tanker	$0.50	$0.10	$0.10
Non-hazardous Materials Transportation			
Rail	$0.05	$0.01	$0.02
Medium-duty Truck	$0.15	$0.03	$0.05
Heavy-duty Truck	$0.14	$0.03	$0.05
Barge	$0.02	$0.01	$0.01
Ocean Tanker	$0.02	$0.01	$0.01

Table 13: Disassembly costs for commercial EV batteries

	Vehicle (Year)				
Item	Renault ZOE (2019)	Nissan Leaf (2018)	Peugeot 208 (2020)	BYD Han (2020)	Tesla Model 3 (2020)
Energy (kWh)	52	40	50	77	52
Energy (Wh/kg)	262	219	239	168	244
No. of Module	12	24	18	Pack to Cell	4
No. of Cell	192	192	216	178	2976
Weight (kg)	327.9	304.3	344.2	573.9	327.4
Pack to Module Cost (US$/kWh)	0.39	0.78	0.39	0.32	0.3
1 Module to Cell Cost (US$/kWh)	0.18	0.17	0.19	0.62	Not available
All Module to Cell Cost (US$/kWh)	2.16	4,08	3.42	0.62	Not available
Total Disassembly Cost (US$/kWh)	2.58	4.85	3.73	0.94	Not available
Manual Disassembly Cost (US$/Pack)	134.3	194.1	186.3	72	Not available
Automated Disassembly Cost (US$/Pack)	3.9	5.7	5.5	2.1	Not available
Manual Disassembly Time (min)	323.8	468.1	449.4	173.6	37.6 (Pack to Module)
Automated Disassembly Time (min)	47.3	68.4	65.7	25.4	Not available
Time Saving in Automation (%)	85.4	85.4	85.4	85.4	Not available

batteries due to their lower material value. In contrast, NMC-type batteries are highly valued for their rich content of nickel, manganese and cobalt, making them profitable to purchase for recycling, as they generate higher returns. Li-ion batteries are likely to dominate the market this decade, but by 2030 it is expected that alternatives will be available.

Battery recycling facilities charge a recycling or gate fee due to the complex and costly processes involved. Revenue comes from selling recovered metals, but this is insufficient to cover expenses. The fee's value depends on facility size, economies of scale, the value of recovered metals, battery chemistry, policy recovery targets, recycling efficiency and fluctuating metal commodity prices.

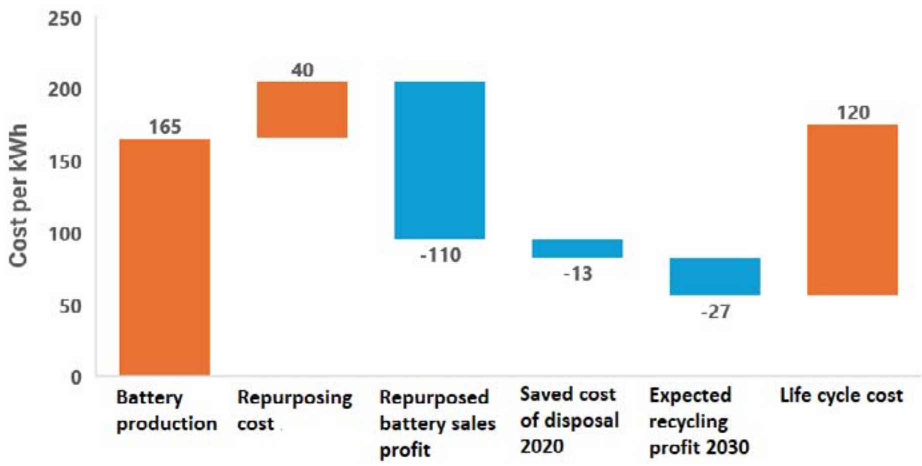


Figure 29: Total life cycle cost benefit of B2U repurposing

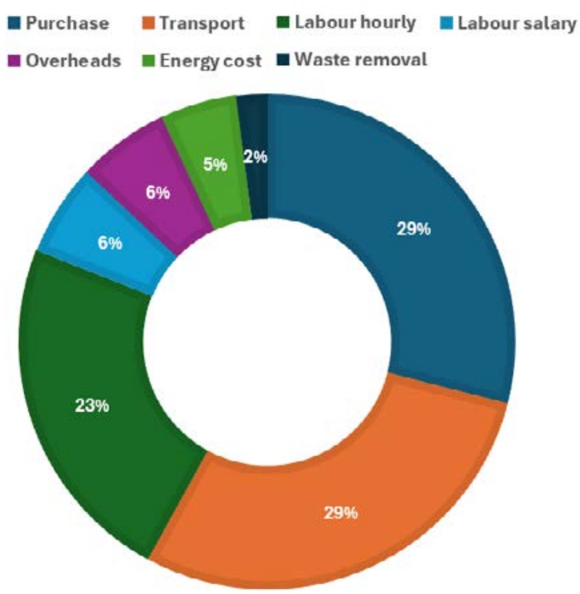


Figure 30: Cost breakdown for recycling plant [117]

Tesla pays approximately $4.50 per pound to recycle its battery packs, for a total price tag of around $6,750 per unit.[123] The total cost of recycling Li-ion batteries at their end of life is highly affected by economies of scale. The estimated recycling cost decreases significantly with volumes between 1,000 and 15,000 tonnes per year.[118] As throughput increases, processing costs decrease due to more efficient use of plant capacity. The break-even point for a 1.5 t/hr automotive Li-ion battery recycling plant in the UK, especially when the battery chemistry includes cobalt and nickel, is between 2,500 and 3,000 tonnes per year.[117] The break-even points for the three recycling processes for the US, UK and China as the collection point is shown in Figure 32. However, since little industry data for direct recycling is currently available, these cost and profitability thresholds should be interpreted with care.

8.6. Cost Benefit Analysis

The economics of remanufacturing are yet to be established but there are some clues when it comes to repurposing and recycling. The economics are affected by battery cell chemistry, geographic region and the specific application. US Department of Transport funded project analyzing the cost-benefit of remanufacturing, repurposing, and recycling a Chevrolet Volt 16 kWh battery (2014–2024) found that repurposed batteries could generate revenue between $50/kWh and $150/kWh, resulting in sales revenue of $800 to $2,400 per 16-kWh battery.[109] The analysis indicates that repurposing is profitable if the development costs are kept below $83/kWh to $114/kWh. See Table F in the Appendix for data. On the other hand, recycling is not currently profitable unless the price of lithium increases substantially, or operational costs are reduced by over 58.1%.

Remanufacturing may be the most profitable option but requires the full support of the OEM. The only evidence of a remanufacturing circular business model for an EU OEM was found at Daimler. [125]

In the battery reuse business model, the system is reinstalled in the same application, often after a vehicle accident that hasn't damaged the battery itself. This process generally requires collaboration with the OEM and demands that the processor can directly read the BMS. Germany's Model2Life project (2021–23) conducted a cost benefit analysis comparing remanufacturing/reuse, repurposing and recycling scenarios for the Audi e-tron 50 Quattro 71kWh battery.[122] See Table G in the Appendix for data. The reuse business case involves purchasing and reselling battery packs, factoring in a value loss of approximately 50% compared to the initial selling price. The hypothetical reuse scenario shows a positive economic outcome with moderate revenue relative to the incurred costs. The repurposing scenario incurs higher costs as shown in Figure 33 but generates significantly higher revenue, resulting in a net revenue higher than the remanufactur-

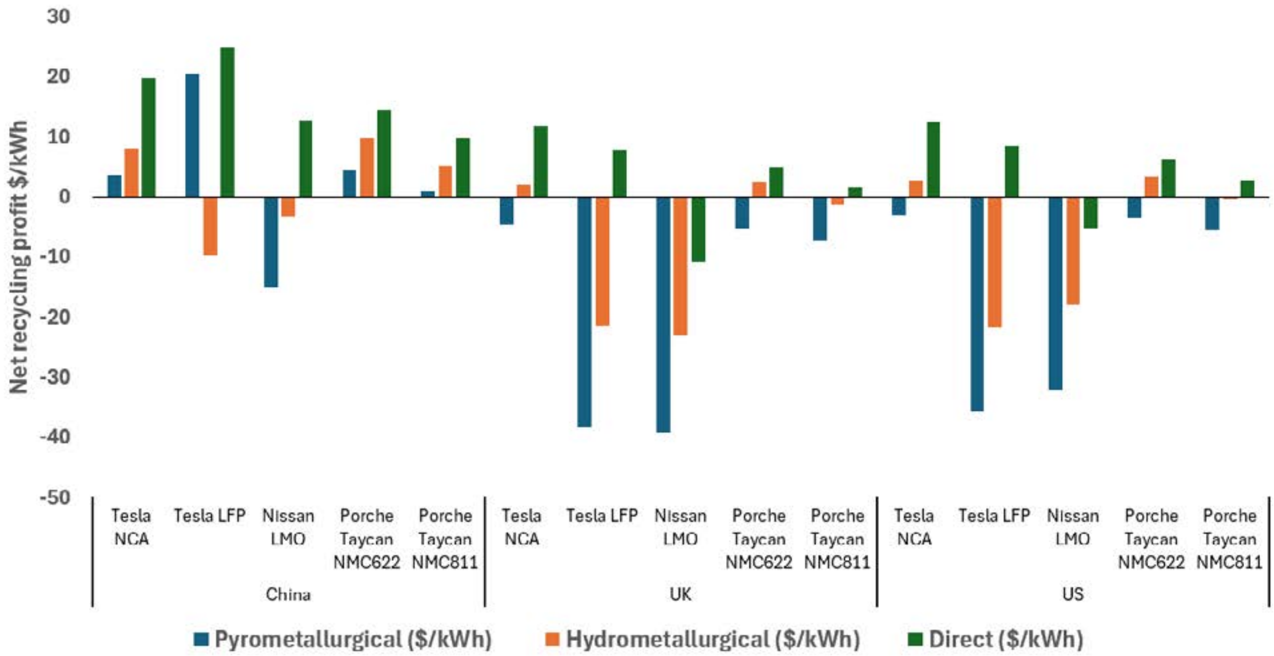


Figure 31: Net recycling profit in $/kWh for different commercial battery designs using pyrometallurgical, hydrometallurgical or direct recycling processes for China, the US, and the UK [118]

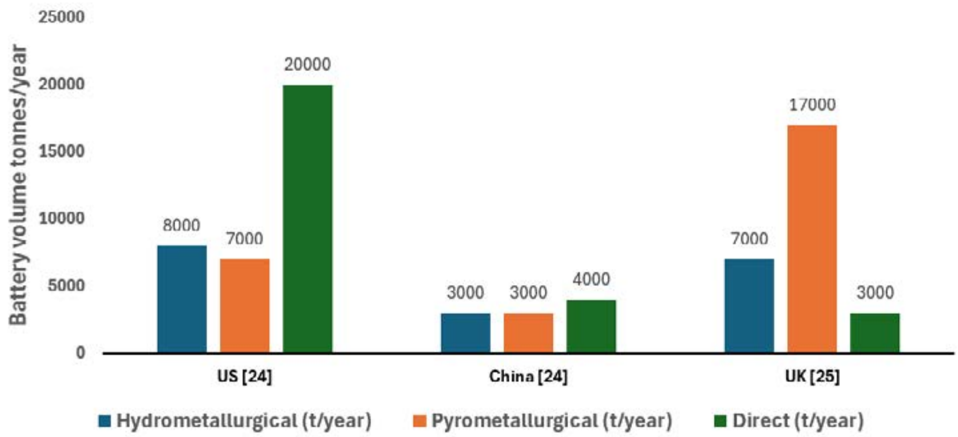


Figure 32: The break-even points when the recycling processes becomes profitable

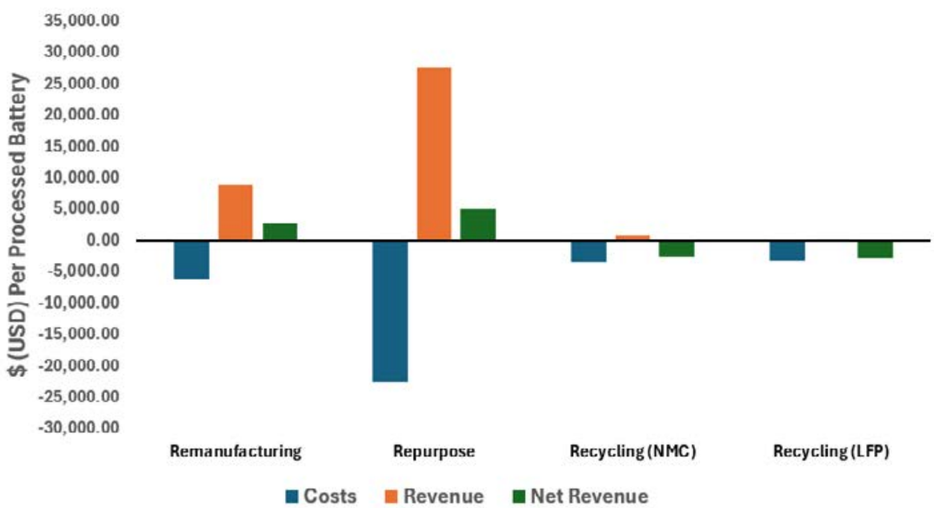


Figure 33: Cost Benefit Analysis for Audi e-tron 50 Quattro 71 kWh. Nearly all costs are attributed to the purchase of retired battery systems [122]

ing scenario. The recycling scenarios for NMC-811 (nickel, manganese, cobalt) and LFP (lithium, iron, phosphate) cathode batteries present two different situations. For NMC batteries, higher costs result in a negative net revenue. Recycling LFP batteries incurs even higher costs with lower revenue, also leading to a negative net revenue. Both recycling scenarios show a negative balance, indicating that costs exceed revenue, making these options economically unfavourable under current conditions.

The comparison demonstrates that repurposing retired Li-ion EV batteries is the most economically viable option, with the highest net revenue despite higher initial costs. In stark contrast, both recycling scenarios (NMC and LFP) show negative net revenues, highlighting the economic challenges associated with recycling under the current assumptions.

9. Conclusion

The challenges posed by the evolving landscape of battery EVs and their second-life opportunities are multifaceted and require strategic interventions. The substantial value represented by EV batteries, coupled with their significant impact on repair economics and insurance claims, necessitates proactive measures to address the complexities at play.

For IAG, with its access to auction houses and written-off EV batteries in Australia and New Zealand, the decision between repurposing and recycling EV batteries should be made with a strong financial and economic perspective. Considering the current trends and future projections, repurposing EV batteries appears to be the more economically viable option in the short term, while recycling may become more viable in the long term. A successful storage system built from the EOL repurposed batteries could be sold within the range of 50/kWh to 150/kWh, which remains competitive compared to new battery costs. This includes costs for battery collection, transport, testing and reassembly. Furthermore, as Australia's transition to net-zero power systems progresses, there will be a sub- stantial demand for stationary ESSs, which will make re- purposing batteries a financially attractive option.

There is a lack of industry practice in reusing EV batteries in vehicles. Reuse involves reinstalling the battery system in its original application, such as after a vehicle accident that does not impact the battery and requires no component replacements. This process typically requires direct cooperation with an OEM and the ability to perform a direct BMS readout. Suitable packs for this scenario may come from EV service inspections, car resellers or insurance write-offs. As a business model, reusing the battery in the same or similar EV model could be pursued after a warranty extension or renewed operating certification. This approach remains underexplored, with few industry examples to reference. Daimler, Renault and VDL have ventured into this domain. Renault's battery swap system with Better Place failed due to high costs, leading Renault to use built-in batteries instead.[126] Kia [127] has recently announced a partnership in Korea to launch a pilot EV battery subscription service. Honda and Mitsubishi Corporation will also launch a 50/50 joint venture, ALTNA Co. Ltd, in July 2024, to explore EV battery repurposing and develop a battery leasing model in Japan.[128] However, there is no instance of such a partnership in Australia.

Recycling, on the other hand, involves higher initial costs. Recycling costs for a 400kg EV battery with 50% remaining capacity range from $500 to $1,500 per battery. These high costs are driven by the collection, transportation, dismantling and the energy-intensive recycling process. Australia is a supplier of raw materials for EV batteries, which potentially reduces the incentive for recycling due to the availability of these materials at lower prices. Additionally, the immediate costs and the need for significant infrastructure investment make recycling less attractive in the short term. However, as the volume of EOL EV batteries increases, economies of scale and technological advancements in recycling could make it more viable. The strategic recovery of materials like cobalt and lithium will also become increasingly important. Recycling remains uneconomical and profitability is achieved only under a very narrow set of conditions of chemistry, location, quantities and process. If the price of cobalt, nickel and lithium were to increase dramatically with the increase in demand, then a recycling plant could become profitable much sooner. The current trend to move away from high cobalt contents toward Nickel-rich and LFP battery chemistries will have an important impact on recycling profitability, as cobalt is the most valuable material in current battery chemistries. The high cost barrier to establish a recycling facility, due to high recycling process costs, combined with the uncertainty in domestic EV adoption rates and recycling demand, introduces challenges for firms looking to invest in this sector.

Short-term Strategy: In the short term, repurposing viable EV batteries for second-life application of battery stationary storage systems seems to be the more financially viable option, based on the limited financial information available. IAG should initiate conversations with companies such as Magellan Power, Relectrify and Infinitev for repurposing opportunities. These partnerships can help make use of existing infrastructure and market presence to maximise economic benefits.

Long-term Strategy: As the volume of EV batteries increases and recycling technologies improve, recycling will become more financially viable. IAG should prepare for this transition by establishing collaborations with companies like EcoBatt and Envirostream. These partnerships will be crucial for managing the future influx of EOL EV batteries and maximising material recovery. In addition, given that most companies are increasingly adopting lithium iron phosphate (LFP) batteries due to their lower cost and the affordability they bring to EVs, IAG must carefully consider the implications for recycling. LFP batteries, while cheaper and more stable, contain fewer valuable materials, such as iron and phosphate, compared to other chemistries like nickel manganese cobalt (NMC) batteries. Therefore, it is imperative for IAG to closely monitor industry trends and market developments over the next few years. By doing so, IAG can make informed decisions about the viability and timing of investing in recycling infrastructure, to ensure alignment with future economic realities and maximise the return on investment

Recommendations

10.Recommendations

To address EOL EV battery management, this section recommends sustainable practices through CBMs and collaborative partnerships. In Australia, vehicle insurers can reduce costs associated with written-off EVs by partnering with auction houses. This collaboration should leverage the second-life market for repurposing and recycling batteries to maximise value. Establishing a joint venture between insurers and auction houses can facilitate the integration of specialised partners who are focused on these areas. This approach will minimise capital investment, improve operational efficiency and promote sustainability by managing the lifecycle of EV batteries more effectively.

10.1. Recommendations for IAG and Auction Houses

Recommendations for IAG and its partner auction houses are:

- Develop a hybrid partnership CBM for managing batteries from crashed EVs that integrates insurers and auction houses with second-life businesses to enhance stakeholder collaboration for an effective second-life EV battery market.
- Foster partnerships with repurposing firms in near term and support the collaboration with recycling facilities in the long term. This collaborative approach will aid in building necessary infrastructure and ensuring sustainability as battery volumes grow.
- Nissan Leaf has the highest disassembly cost, and the Tesla Model 3 pack is the least cost-intensive followed by the BYD. Resale of Tesla and BYD for repurposing will earn more revenues.
- LFP (lithium iron phosphate) and LMO (lithium-ion manganese oxide) chemistries provide lower recycling revenue in comparison to NCA (lithium nickel-cobalt-aluminium)
- A lack of data on how to clearly identify the defective part in a battery pack is hindering the ability of EV technicians to repair battery packs after minor collisions. IAG's auction partners should invest in establishing designated triage stations, equipped with diagnostic tools like Autel's MaxiSys Ultra EV and SNT's ALFRED EV condition system, safety equipment, and workers training like ICAR Australia, to accurately assess batteries damage.
- IAG can collaborate with OEMs and independent training organisations like ICAR Australia to develop certified training programs for repair technicians and auction house worker. This would ensure that professionals have the necessary skills and knowledge to follow procedures to repair, sort and direct viable written-off batteries to reuse or repurposing.
- The cost of acquiring the second-life battery is the largest component, followed by transportation. With access to viable batteries from written-off EVs, IAG can save cost and improve economics with partnering with local transport companies for battery delivery.
- Continue tracking OEM initiatives and practices to inform future financial and feasibility analysis.

Possible partners in Australia and New Zealand are:

1. Infinitev & IM Group: Specialises in refurbishing, repurposing and recycling EV and HEV batteries, with advanced grading systems and partnerships with Mazda and Kia.
2. Relectrify: Converts second-life EV batteries into ESSs; it has projects in New Zealand and Japan, and is funded by ARENA.
3. Envirostream: Recycles home energy storage and EOL EV batteries, and achieves high recovery rates.
4. Ecobatt: Handles collection, transportation and recycling of battery products, with a $30 million investment in a recycling plant, in partnership with Hyundai.
5. Magellan Power: Develops energy storage solutions, EV chargers and UPS systems, with potential for collaboration on EOL EV batteries.
6. Zenobe: Provides battery storage and transport solutions; it focuses on repurposing EV batteries from bus fleets.
7. EVs Enhanced: Offers battery replacement and upgrade services in New Zealand for Nissan Leaf vehicles. Based in Christchurch, its offerings include upgrading a 30kWh battery to 40kWh, typically costing around $15,000. It also provides a trade-in program for old batteries.
8. Battery Pollution Technologies: Leads battery recycling in the Asia Pacific with advanced machinery and innovative solutions.
9. TES-AMM Australia Pty Ltd: Extends asset life through repair and refurbishment, with a new facility in Western Sydney that processes Li-ion batteries.
10. Second Life Battery Cells: Refurbishes batteries from various electric devices, with rigorous testing and proprietary processes.

10.2. Recommendations for Steering the EOL EV Battery Industry

- **Access to battery information:** Policies must be developed on the following: a) a physical labelling requirement to facilitate sorting and easy identification of battery and vehicle OEM; b) digital identifiers to identify Li-ion battery chemistry to improve safety during disassembly; and c) a universal diagnostic system to reduce the cost of testing and enable performance guarantees for reused and repurposed batteries.

- **Develop EOL Protocols:** Establish standardised protocols for the safe removal, transportation and recycling of EOL batteries. These protocols should address environmental and safety concerns and ensure compliance with local and international regulations.
- **Develop Industry Standards:** Collaborate with industry stakeholders to establish clear standards and best practices for battery recycling and dismantling processes. These standards should address safety protocols, environmental protections and operational procedures.
- **Implement Certification Programs:** Create certification programs for recycling and dismantling facilities to ensure they meet industry standards. Certification can serve as a mark of quality and reliability, and encourage best practice.
- **Enhance Data Sharing:** Promote the use of digital platforms for data sharing among stakeholders. Transparent tracking systems for batteries throughout their lifecycle can improve accountability and traceability, ensuring that all parties are informed about the status and condition of batteries.
- **Regulatory Alignment:** Work with regulatory bodies to align local, state and federal regulations to ensure consistent enforcement and reduce confusion among industry participants. A unified regulatory framework can simplify compliance and enhance transparency.
- **Training and Education:** Invest in training programs for workers in the recycling and dismantling sectors to ensure they are knowledgeable about industry standards and best practices. Continual education can help maintain high standards and help workers to adapt to new technologies and regulations.
- **Create a Centralised Battery Registry:** Implement a centralised registry to track EV batteries throughout their lifecycle. This registry would record key information such as battery ownership, performance data and EOL status to ensure transparency and accountability.
- **Encourage Dealer and OEM Participation:** Require dealerships and manufacturers to participate in battery take-back programs. They should be responsible for collecting used batteries and ensuring they are directed to authorised recycling facilities. OEMs should provide battery passporting data to vehicle and battery recyclers to enable accurate triaging and effective management of battery recycling processes.
- **Incentivise Second-Life and Recycling Ventures:** Incentivise the creation of second-life, recycling and passive energy storage businesses through investment credits and targeted grants. State investments should also support battery R&D activities and promote tech start-ups, while ensuring these ventures achieve a net positive value proposition with a reasonable profit margin.
- **Establish Battery Recycling Facilities:** Establish a systematic battery recycling process at these facilities. This involves collecting EV batteries, disassembling them, shredding to remove non-metallic components, heating for metal recovery, purification, and subsequent reuse in new batteries.
- **Standardise Contracts and Agreements:** Implement standardised contracts between manufacturers, owners, dismantlers and recyclers to clearly outline responsibilities and liabilities related to battery ownership and environmental impact.
- **Environmental Liability Clauses:** Include explicit environmental liability clauses in all agreements, specifying the party responsible for potential environmental damage during storage, transport and recycling. Greater clarity is needed about the transfer of liability at end of life.
- **Certification and Tracking Systems:** Develop a certification and tracking system for EV batteries, ensuring that ownership and responsibility are transparent and traceable throughout the battery's lifecycle.
- **Insurance and Risk Management:** Encourage the development of specialised insurance products to cover environmental liabilities associated with battery ownership and handling to provide an additional layer of financial protection.

10.2.1. Sustainable Practices for Insurance Companies in the Circular Economy of EOL EV Batteries

Crashed EVs

1. Develop Comprehensive Protocols for Evaluating Battery Condition
   - Claims Processing Integration
     - Workflow Integration: Incorporate battery health assessments into the claims processing workflow to streamline decision-making. Train claims adjusters and inspectors to evaluate battery condition as part of their routine assessments.
     - Real-time Decisions: Use real-time data and analytics to make prompt decisions about the battery's future, whether for refurbishment, repurposing or recycling.
     - Claims Documentation: Document assessment results and decisions in the claims management system for regulatory compliance and future reference.
   - Instructions for Policyholders During an Accident
     - Secure the Scene: Ensure the accident scene is safe from potential hazards associated with damaged batteries, such as fires or chemical leaks.
     - First Responder Training: Train first responders on handling EV accidents, focusing on identifying and mitigating risks related to EOL batteries.

  - Battery Isolation: Isolate the battery from the vehicle's electrical system to prevent further damage and reduce the risk of electrical hazards.
- On-Site Assessment and Containment
  - Preliminary Battery Assessment: Conduct an initial assessment of the battery's condition on-site to determine if it is safe for transport or requires immediate containment.
  - Containment Measures: If the battery is compromised, implement containment measures to prevent leakage or combustion during transport to a auction house or processing facility.

2. Safe Transportation of Compromised Batteries
   - Hazardous Material Handling Protocols: Follow strict protocols for transporting compromised batteries, including using fireproof and leak-proof containers.
   - Safety Equipment: Ensure transport vehicles are equipped with appropriate safety equipment, such as fire extinguishers and protective gear.
   - Priority Transport: Prioritise the transport of damaged batteries to minimise the time they spend in an unstable condition to reduce the risk of accidents.

3. Specialised Storage Facilities
   - Designated Storage Facilities: Establish storage facilities specifically designed for EOL batteries from crashed EVs, including:
     - Fire suppression systems to handle potential battery fires.
     - Temperature control systems to maintain a stable environment for stored batteries.
     - Secure containment areas to prevent leaks or fires.
   - Regular Monitoring: Implement regular monitoring of stored batteries to detect signs of deterioration or instability using advanced monitoring devices such as:
     - Temperature sensors to prevent overheating.
     - Smoke detectors to indicate a fire hazard.
     - Other necessary monitoring devices to ensure the safety of the storage area.

Retired EVs

1. Incentives for Proper Management of EOL EV Batteries
   - Educational Campaigns: Conduct educational campaigns to raise awareness about the importance of sustainable battery management, highlighting benefits and available incentives.
   - Premium Discounts: Offer premium discounts or rebates to policyholders who follow sustainable disposal practices for EOL batteries.
   - Reward Programs: Implement reward programs that provide policyholders with points or benefits for adhering to proper disposal protocols, redeemable for discounts on future insurance policies or other services.

2. Communication and Coordination with Policyholders
   - Communication Channels: Establish clear communication channels with policyholders to arrange for the collection and transportation of EOL batteries. Provide contact information for collection services and detailed, step-by-step instructions for transport.
   - Support Services: Offer comprehensive support services to policyholders, including assistance with scheduling pick-ups, answering questions about battery handling and providing guidance on safety protocols.

3. Detailed Instructions for Safe Battery Preparation
   - Clear Instructions: Provide policyholders with detailed instructions on how to safely prepare batteries for collection, including:
   - Steps for safely disconnecting the battery from the vehicle.
   - Guidelines on proper packaging to prevent damage during transport.
   - Instructions for labelling the battery to ensure it is handled correctly.

10.2.2. Sustainable Practices for auction Houses and Salvage Companies in the Circular Economy of EOL EV Batteries

1. Collection and Transportation
   - Efficient Logistics Systems
     - Specialised Containers: Use specialised containers designed for the safe transport of EOL batteries from retired and crashed vehicles. These containers should be fire-resistant, impact-resistant and capable of containing any potential leaks or spills.
     - Dedicated Vehicles: Employ dedicated vehicles equipped with safety features for transporting batteries, including temperature control, secure storage compartments, and monitoring systems to track the condition of the batteries during transport.
     - Reverse Logistics Processes: Develop a robust reverse logistics infrastructure to facilitate the delivery of used batteries to recycling or repurposing centres. This includes establishing collection points, managing logistics partners and coordinating transportation.
   - Standardised Dismantling Procedures
     - Comprehensive Training: Develop and implement comprehensive training programs for staff, covering the safe dismantling of EVs and the handling of EOL batteries from retired and crashed vehicles.
     - Safety Protocols: Include detailed safety protocols to prevent electrical hazards, fires and chemical exposure during dismantling.

  - Creation and Enforcement: Create and enforce standardised operating procedures (SOPs) for dismantling EVs, focusing on the safe removal, handling and storage of EOL batteries.
  - Regular Updates: Ensure that SOPs are regularly updated to reflect industry best practices and technological advancements.
- Safety Equipment: Equip staff with appropriate safety gear, including insulated tools, protective clothing, and fire suppression systems so they can handle batteries safely and efficiently.

2. Initial triage

- Triage Stations: Set up designated triage stations at auction houses and salvage yards for the initial assessment and cate- gorisation of batteries from retired and crashed EVs. Ensure these stations are equipped with diagnostic tools and the necessary safety equipment to perform accurate assessments.
- Categorisation Criteria: Use established criteria to categorise batteries based on their potential for reuse, repurposing or recycling. Consider factors such as physical condition, state of charge, internal resistance and historical performance data.
- Documentation: Maintain detailed records of the triage, documenting the condition of each battery, the assessment results, and the categorisation decision to ensure transparency and traceability.

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Appendices

Table A: Key policies for EV battery reuse and recycling [129]

Area of intervention	Policy	Examples of existing policy developments
Battery traceability and collection	Battery removability and battery traceability mechanisms: regulations that clearly define who is responsible for the battery when it reaches end of life	**China:** The government released a set of policies that place the responsibility of collecting EOL EV batteries on manufacturers or importers. In 2018 a platform was created to trace batteries throughout their life.[130]
Building domestic capacity for reuse and recycling	Incentives and grants for the development of domestic capacity for reuse and recycling	**United States:** The Battery Materials Processing Grants makes more than $3 billion available to state and local governments, for-profit and non-profit entities, and national laboratories to support domestic capacity for the reuse and recycling of batteries through project demonstration and other uses.[131]
Battery information	Regulations for the disclosure of battery information to optimise the battery reuse and recycling process	**European Union:** The European Commission proposed a labelling requirement for manufacturers to disclose information on batteries, such as the date of manufacture, chemistry and hazardous substances. The Commission has developed language for the creation of a battery passport, which links to a digital platform where manufacturers would disclose battery data to facilitate third-party reuse or recycling.[132]
Battery standards	Standards on battery durability Standards on accuracy and reporting of the state of health metric Standards on safety when handling EOL batteries	**California:** The Advanced Clean Cars II regulations set battery durability standards and require that batteries in EVs of model year 2026 and later maintain at least 80% of their range for 10 years or 150,000 miles [133]. Furthermore, California proposes an accuracy standard for reporting battery SOH [134] United States and Canada: the UL 1974 Standard for Evaluation for Repurposing Batteries sets general safety standards for sorting and grading used EV batteries and estimating their SOH.[135]
Recycling mandates	Element-specific mandates on the proportion of material that must be recovered Element-specific mandates on recycled material to be used in new manufactured batteries	**European Union:** the upcoming Battery Regulation will mandate element-specific recovery rates for battery recycling and element-specific shares of recycled material to be used in the production of new batteries.[136]

Table B: Labour cost for removing the battery from a car [137]

Item	Human Power	Time (minutes)	Cost ($)
Removing the battery from car			
Vehicle preparation	1	5	$4.28
Disconnection of service disconnect or LV battery	1	5	$4.28
Opening of trunk base	2	10	$18.19
Opening of underside vehicle covers	3	30	$80.25
Lowering of HV battery	2	10	8.19
Total		**60**	**$125.19**
Post-auto battery assessment			
Inspection & handling	2	60	$107.00
Connection of the electrical test equipment	2	10	$18.19
Initial voltage set & balance	1	100	$88.81
Battery characterisation	1	250	$222.56
Disconnection from electrical test equipment	2	10	$18.19
Final inspection	2	10	$18.19
Total		**440**	**$472.94**
Disassembly battery to modules			
Removal of package top	2	30	$53.50
Extraction of BJB	2	45	$80.25
Disconnection and extraction of CMCs	2	45	$80.25
Disconnection and extraction of BMS	2	30	$53.50
Dismantling of pre-charge circuit	2	30	$53.50
Extraction of modules	2	60	$107.00
Separation of HV battery base from HV battery support frame	2	20	$35.31
Removal of humidity buffer	2	20	$35.31
Removal of cooling plates	2	20	$35.31
Total		**300**	**$535.00**

Table C: Distribution of the cost price of a second-life battery

Item	Total cost $/kWh	Percentage of total cost
Brazil: Second-Life battery for a 45-kWh battery [138]		
Battery purchase	$58.50	65%
Transport to the reconditioning centre	$2.70	3%
Disposal of unusable cells	$2.70	3%
Remanufacturing cost	$26.10	29%
Total	**$90.00**	**100%**
Sandia National Lab in USA: Reconfigured EV Battery Pack Cost Breakdown [139]		
Battery purchase	$81.75	56%
Packaging materials	$9.92	7%
Testing equipment	$3.14	2%
Labour	$19.34	13%
Rent	$1.58	1%
Insurance	$3.42	2%
General & administrative (G&A)	$18.28	13%
Warranty	$4.57	3%
Capital recovery, earning, and taxes	$3.01	2%
All others	$2.00	1%
Total	**$146.01**	**100%**
Japan: Repurposing costs of a 260 kWh EV battery project [140]		
Battery purchase	$26.78	85.47%
Battery assembly cost	$1.39	4.42%
Battery other Costs	$2.14	6.80%
Total	**$30.42**	**100%**
JEU: Individual cost components for a repurposed EV battery [112]		
Battery purchase	$70.0	63%
Battery collection	$3.00	3%
Battery transport	$3.00	3%
OEM margin	$0.30	0%
Repurposing costs	$20.00	18%
Workshop overhead	$9.30	8%
End of 2nd Life Extended Producer Responsibility (EPR) costs	$0.80	1%
Workshop margin	$3.90	4%
Total	**$110.30**	**100%**
Repurposing costs		$40

Table D: Commercial EV battery designs

Battery Design	Tesla Model S (NCA: Lithium Nickel-Cobalt-Aluminium)	Tesla Model S (LFP: Lithium-Iron-Phosphate)	Nissan Leaf (LMO: Lithium-ion Manganese Oxide)	Porsche Taycan (NMC622: Lithium Manganese Nickel Cobalt Oxide)	Porsche Taycan (NMC811: Lithium Manganese Nickel Cobalt Oxide)
Total pack weight (kg)	540	1009	295	630	553
Weight cells only (kg)	319	788	151	382	305
Number of modules	16	16	48	33	33
Number of cells	7104	10368	192	396	396
Cell weight (kg)	0.045	0.0767	0.785	0.965	0.772
Energy (kWh)	85	85	24	93	93
Energy density (Wh/kg)	266	108	159	243	304

Table E: Net recycling profit in $/kWh for different commercial battery design [118]

Country	Car/Battery Chemistry	Pyrometallurgical ($/kWh)	Hydrometallurgical ($/kWh)	Direct ($/kWh)
China	Tesla NCA	3.56	7.95	19.74
	Tesla LFP	20.42	-9.85	24.72
	Nissan LMO	-15.18	-3.29	12.63
	Porsche Taycan NMC622	4.39	9.61	14.42
	Porsche Taycan NMC811	1.06	5.04	9.74
UK	Tesla NCA	-4.65	2.10	11.75
	Tesla LFP	-38.23	-21.55	7.74
	Nissan LMO	-39.26	-23.15	-10.82
	Porsche Taycan NMC622	-5.4	2.40	4.87
	Porsche Taycan NMC811	-7.36	-1.31	1.52
US	Tesla NCA	-3.14	2.56	12.55
	Tesla LFP	-35.71	-21.72	8.41
	Nissan LMO	-32.27	-18.05	-5.15
	Porsche Taycan NMC622	-3.41	3.29	6.12
	Porsche Taycan NMC811	-5.6	-0.40	2.72

Table F: Cost benefit analysis for Chevrolet Volt battery (16 kWh, 197 kg) (227 kg weight including packaging), $10000-new battery price, % increase in cost from 2014–24

Aspect (over ten years)	Remanufacturing (per battery)	Repurposing (per battery)	Recycling (per battery)
Operational costs	$4,178 to $5,785	$2,430 to $3364	$2,757 to $3,818
Revenues/cenefits	$8,105 to $7,377	$3,005 to $4159	$1,155 to $1,599
Total savings/loss	$3,927 to $1,592 Saving	$575 to $796 Saving	$1,602 to $2,219 Loss

Table G: Cost benefit analysis for Audi e-tron 50 Quattro 71 kWh

Scenario	Costs (USD)	Revenue (USD)	Net Revenue (USD)
Reuse	-6,030.97	8,893.64	2,862.67
Repurpose	-22,579.29	27,603.68	5,024.38
Recycling (NMC)	-3,400.11	863.70	-2,536.41
Recycling (LFP)	-3,165.57	295.53	-2,870.04