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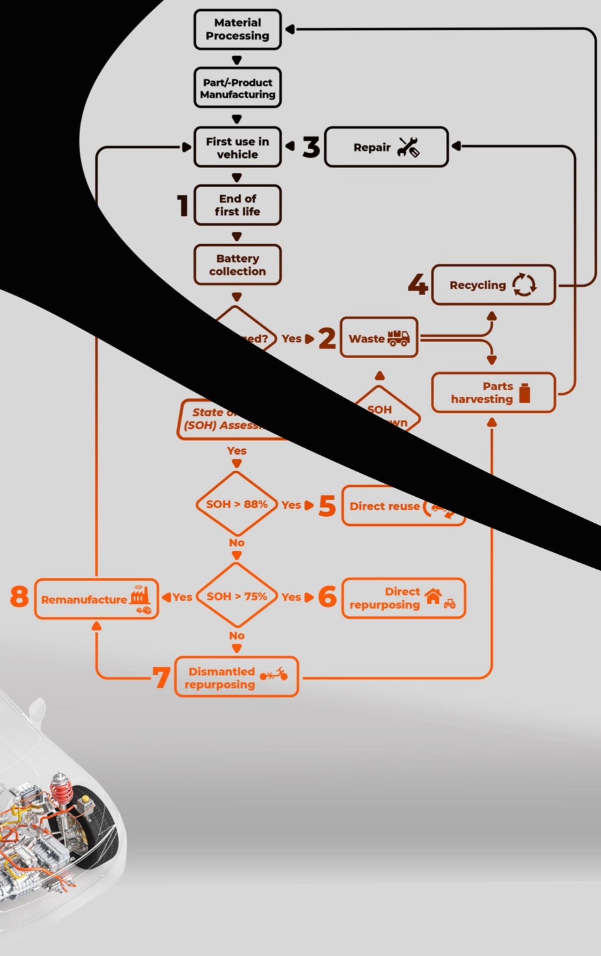


# End of Life Strategies for Electric Vehicle Lithium-Ion Batteries

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# Executive Summary

The increased pressure to move away from fossil fuels and internal combustion engines is driving the mass introduction of electric vehicles (EV) and their associated, predominantly lithium-ion, batteries (LIBs). Due to their hazardous nature, batteries pose a challenge when they reach their end of life (EoL). With around 6 million batteries expected to retire from EVs globally in 2030 (Figure 1), Original Equipment Manufacturers (OEMs) must act sooner rather than later in preparation for this wave of responsibility. Nevertheless, as EV LIBs will retire from transport applications when they reach 70-80% capacity, there is still a tremendous opportunity for OEMs to cascade this value into new functions and eventually recover the valuable materials these batteries are made from.

The circular economy concept presents itself as an interesting framework for approaching the EoL decision making process, with the aim of maximising the recovery of a product's inherent value. Unfortunately, today's EV LIB designs lead to destructive disassembly methods, thus making any attempt to rework the battery, and recover its value, a complicated process. Since modifications to a product and its process are difficult to implement once decided, OEMs are first encouraged to thoroughly evaluate EoL already in the design stage. Still, there are many opportunities to recover and maximise product value with the existing battery designs through reusing, refurbishing, remanufacturing, repurposing, and recycling. They all have their associated benefits and challenges related to, for example, cost and complexity, and need to be closely evaluated by the OEM in order to make a decision. There are also numerous considerations involved in the decision-making process that will likely impact which strategy or combination of strategies an OEM will prefer.

Aside from the level of circularity, the state of health is identified as one of the most important determinants in making a decision. Based on these two considerations, we can offer a strategic decision tree to guide the decision (Figure B). The overall recommendation, however,

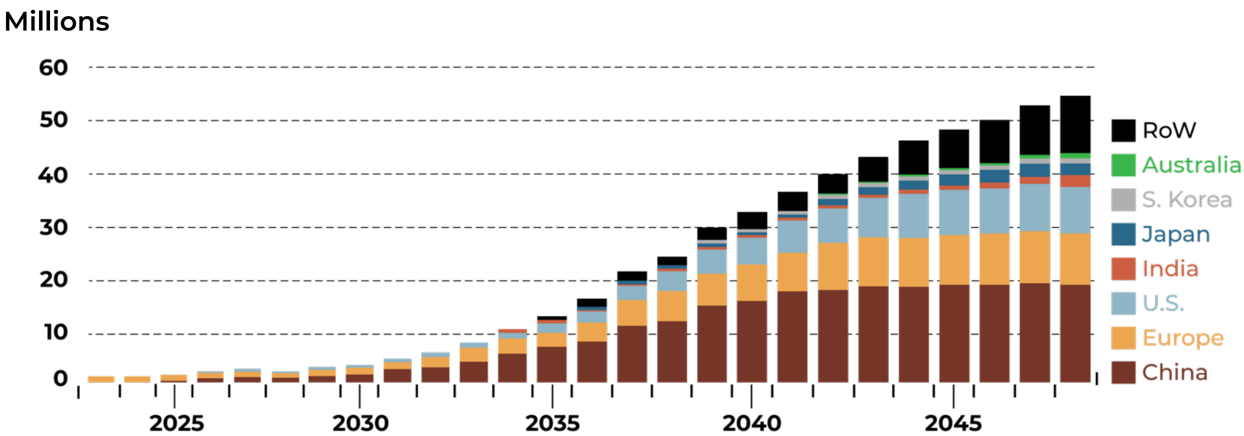


*Figure A: Forecast of EVs reaching end of life (Based on sales trends from BNEF, 2020)* is that the least technologically and financially risky option is repurposing EoL LIBs for secondary stationary storage applications. This recommendation is based on the reduction in complexity in dealing with the accessibility of the battery and the growing demand for energy storage units across the UK.

This work is based on HSSMI's experience gathered through multiple electrification projects and research work being undertaken by other companies and organisations. HSSMI actively promotes circular economy practices in the manufacturing industry and this white paper is aimed as a guide to enhance the life-cycle strategic decision-making of companies. It covers the EoL strategies, market and product considerations such as volume predictions, reliability, regulations and others, and concludes with the presentation of a strategic decision tree and recommendations to support the industry in its transition towards a circular approach to reduce cost and environmental impact.

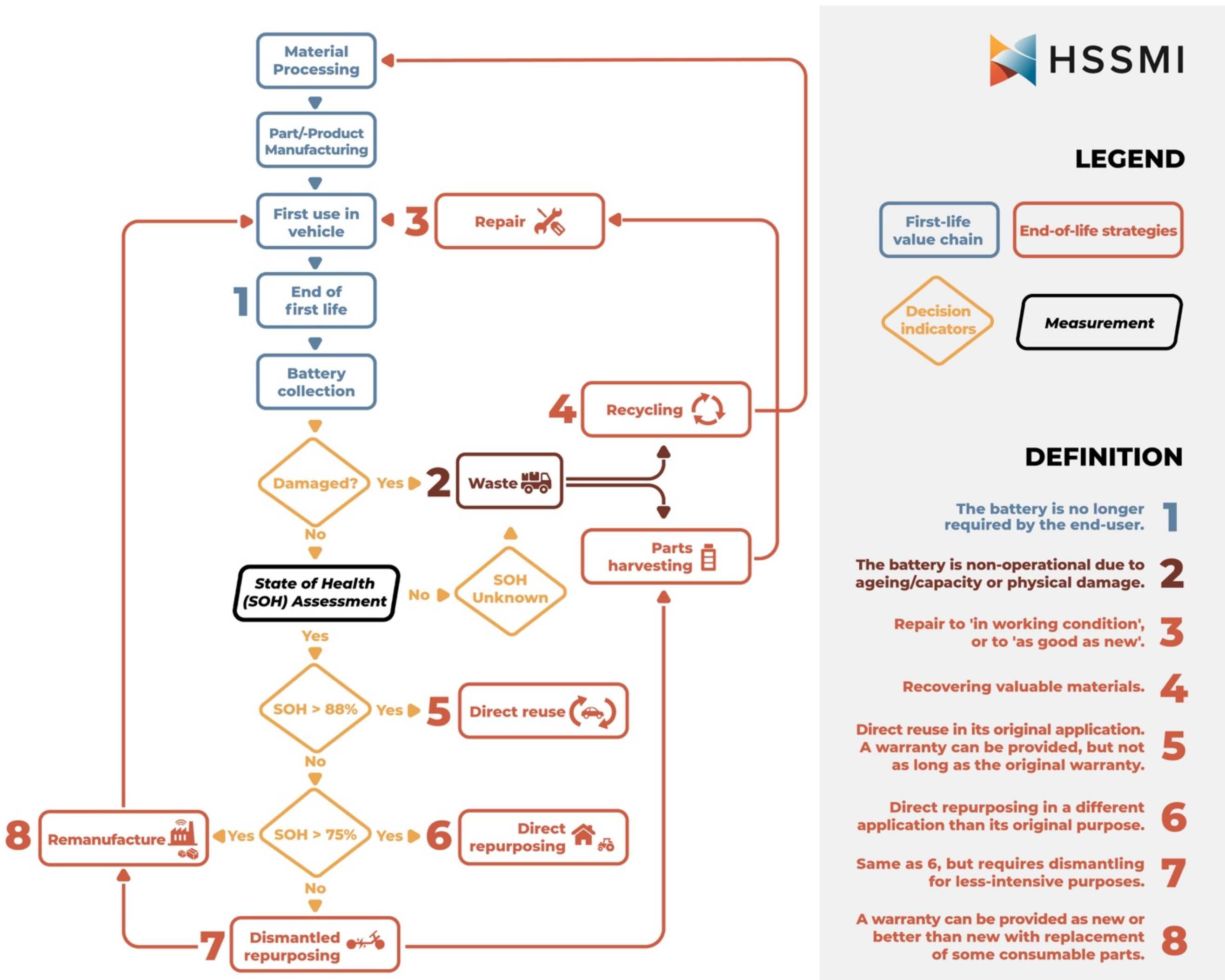


*Figure B: EV battery end of life decision tree*

# Table of Contents

# List of Figures

# Abbreviations

| | | |
|---|---|---|
| 1 | APC | Advanced Propulsion Centre |
| 2 | BEV | Battery Electric Vehicle |
| 3 | BESS | Battery Energy Storage System |
| 4 | BMS | Battery Management System |
| 5 | CRM | Critical Raw Material |
| 6 | EBA | European Battery Alliance |
| 7 | EoL | End of Life |
| 8 | EV | Electric Vehicle |
| 9 | FTE | Full-time Equivalent |
| 10 | ICE | Internal Combustion Engine |
| 11 | LIB | Lithium-ion Battery |
| 12 | NPL | National Physical Laboratory |
| 13 | MWh | MegaWatt Hours |
| 14 | OEM | Original Equipment Manufacturer |
| 15 | R2LiB | Reclamation, Remanufacture of Li-ion Batteries |
| 16 | PBL | Planbureau voor de Leefomgeving |
| 17 | SNT | Spiers New Technologies |
| 18 | SOH | State of Health |
| 19 | UCL | University College London |

# Introduction

Global electric vehicle (EV) deployment has grown rapidly in the last ten years, with a total of 2.1 million EVs sold globally in 2019. Although sales are expected to drop in 2020 to 1.7 million due to COVID-19, they will continue to rise with an expected forecast of 8.5 million EVs sold in 2025 (BNEF, 2020). This growth is driven nowadays mainly by developments in policy and regulation and increasingly by customer demand, although actual sales of EVs do not currently reflect this. Nevertheless, it is the advancements in battery technology, charging infrastructure, and falling battery prices that are enabling and accelerating the adoption of EVs (McKinsey & Company, 2019a).

Lithium-ion batteries (LIBs) have a higher energy density than other major commercialised battery types and are therefore the most widely used battery type today for EVs (Iclodean et al., 2017). The advancements in this technology over the last decade have contributed to significant improvements in the range and performance of EVs. However, the widespread use of LIBs has been criticised due to the environmental and ethical impact of sourcing critical raw materials (CRMs) such as lithium and cobalt, and their associated geopolitical risks as illustrated in Figure 1 (Harper et al., 2019). LIBs are also difficult to recycle at the end of their life due to non-reversible bonding methods, mix of materials, and lack of standardisation (Harper et al., 2019).

Since batteries are classed as hazardous waste, there is a European Parliament directive (2006/66/EC) enforced in the UK by the Waste Batteries and Accumulators 2009 Regulation and the End of Life Vehicles (ELVs) Regulation, which state that battery retailers (those that put batteries on the market) are responsible for the management and disposal of the batteries they sell, and additionally that it is illegal for batteries to be sent to landfill

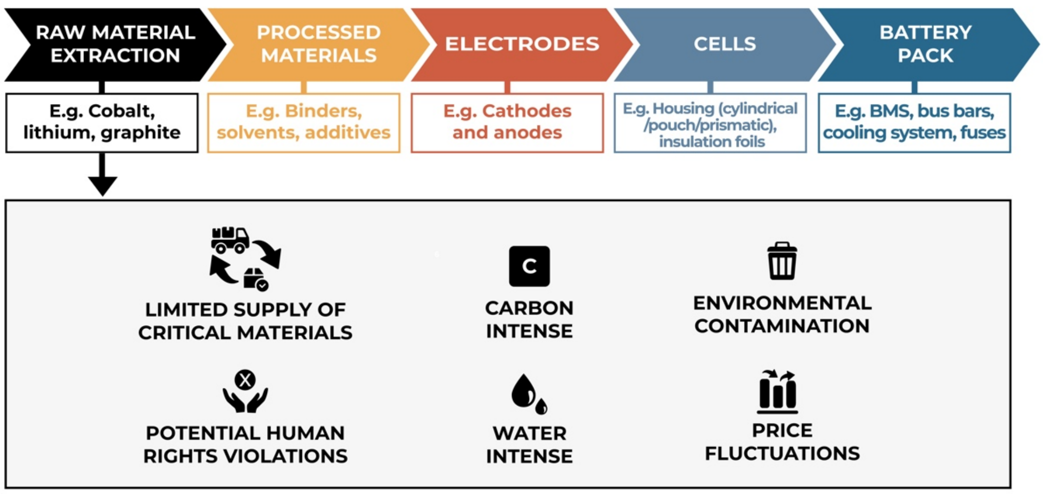


*Figure 1: Ethical and environmental issues with raw material extraction for LIBs (Harper et al, 2019)*

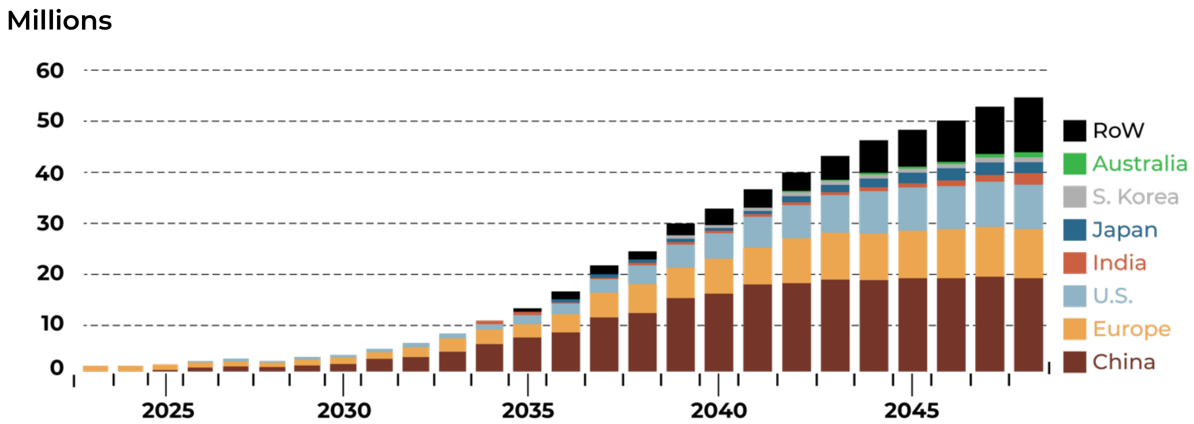


*Figure 2: Forecast of EVs reaching end of life (Based on sales trends from BNEF, 2020)*

or incineration, as they pose a safety hazard (European Parliament, 2018; HM UK Government, 2019, 2017). The regulation leaves few options for OEMs, as current recycling technology is also expensive, difficult, and unavailable (Harper et al., 2019). Although the EU Directive will no longer apply to the UK after December 2020, it is assumed that the UK Regulations enforcing the Directive will remain in force. This acts as one of the premises for our recommendations in this paper.

With an expected first-life period for **non-commercial** EVs lasting **8-10 years**, we can use current EV sales trends to determine when these battery packs will reach their end of life (Figure 2). It is likely that post-consumer batteries will become increasingly significant from around 2030 with around 6 million battery packs retiring from EVs globally (BNEF, 2020; Jiao, 2019). However, in HSSMI's experience with **commercial** EV fleets, the first-life period can end **as early as 5 years** after purchase. Therefore, OEMs who operate in both commercial and non-commercial markets should be vigilant in expecting battery returns earlier than 2030.

Additionally, there will be an influx of LIBs from manufacturing rejects and accidents that will reach their EoL much earlier than planned.

Currently, recycling and reuse of LIBs is considered low due to:

- Very small battery volumes reaching EoL; battery EVs (BEVs) have only been sold over the past 5 to 10 years, thus very few vehicles have reached the end-of-life stage;
- Design has not yet been optimised for disassembly;
- A lack of standard pack and cell marking, leading to ambiguity regarding specific cell chemistry.

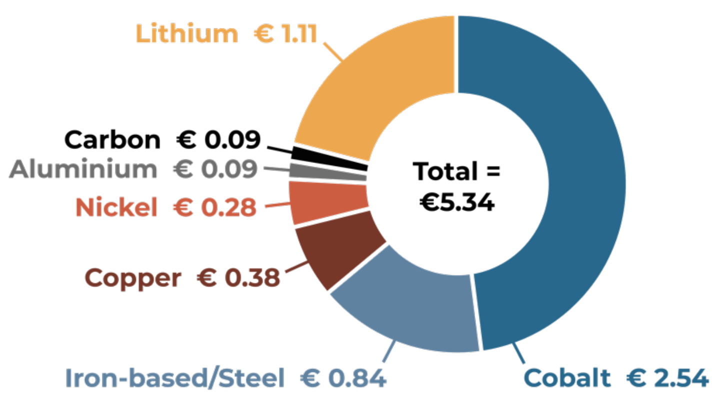


*Figure 3: Recycled material value in average LIB per kg (adapted from European Commission, 2019a)*

By 2025, there will be up to 250 new EV models featuring LIBs from more than 15 manufacturers (McKinsey & Company, 2019b). As each battery is designed for specific EV models, lack of standardisation will lead to more complex recovery methods. This is somewhat manageable at present as there are a limited number of post-consumer EV batteries available. However, with the expected increase in the volumes of EVs and their respective batteries reaching the end of their first life in the coming decade, OEMs will have to find an effective longer-term solution.

Disposal of end of life batteries can be leveraged as a financial and resource opportunity, rather than being perceived as only being done to meet the regulation. There are many valuable materials in a LIB that can be salvaged at the EoL. Their value per kilo is displayed in Figure 3 (European Commission, 2019a). Due to this residual value and the expected volumes of LIBs, the CEPS (2018) estimates that €408-€555 million can be recovered from cobalt, nickel, aluminium and lithium in 2030 in the EU. McKinsey & Company (2019b) also estimate that the global market value of EoL batteries will reach $30 billion by 2030 (McKinsey & Company, 2019b). That means EoL batteries present a large revenue opportunity as the salvaged materials can be sold forward in the value chain or used to manufacture new batteries.

There are also shortages of the critical raw materials (CRMs) used in batteries, such as lithium and cobalt which causes an increase in cost. This, coupled with the lack of accessible mineral deposits or reserves within Europe, makes it crucial that manufacturers find strategies to make access to these high-value materials easier and, ideally, cheaper.

The current difficulty of treating batteries at their end of life coupled with the increasing volumes will pose a challenge

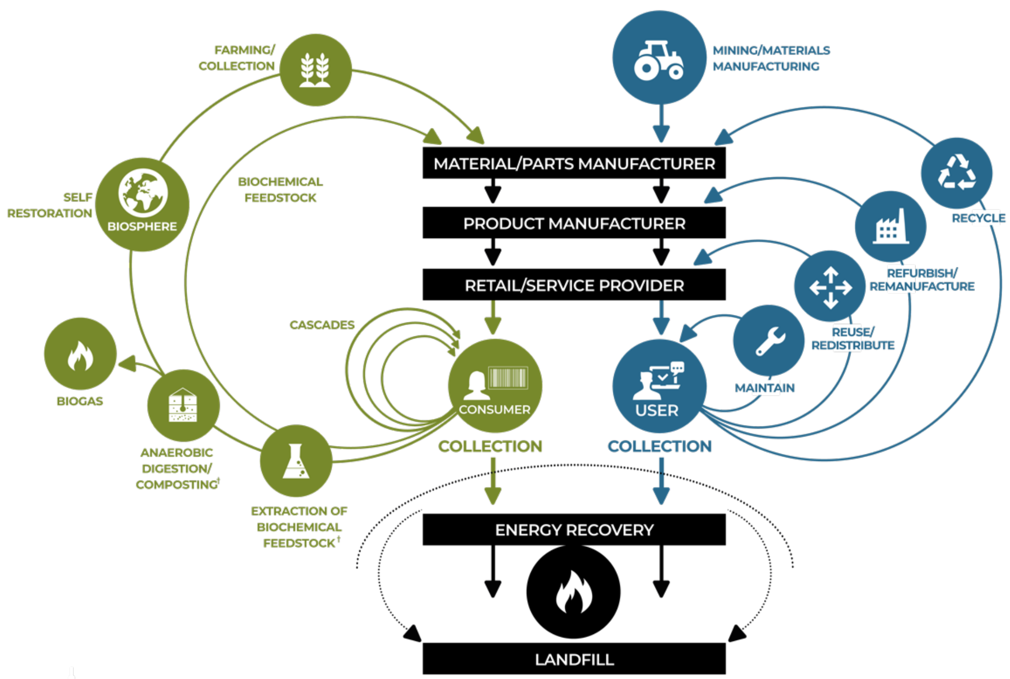


*Figure 4: Butterfly diagram (Ellen MacArthur Foundation, 2019)*

that OEMs need to prepare for. Equally, it also presents a chance to strategically transform their obligation into a business opportunity. There is an emerging approach that can guide how OEMs manage EV batteries at the end of their life, encapsulated by the concept of a 'circular economy' illustrated by Figure 4 (Ellen MacArthur Foundation, 2019). This model aims to move supply chains away from the traditional linear model of 'take, make, consume and dispose', and towards circular models where products and materials are brought back into the supply chain, their life in service extended, and their value recovered.

To assist the decision-making process, the next chapters will present arguments for and against each circular strategy, outline the relevant considerations needed to make a decision, and will conclude with a decision tree that will help guide the strategic direction. Although the sections in this white paper can be used in any order, Figure 5 aims to illustrate how they can fit together:

1. Consider the business context to inform which EoL strategies are relevant;
2. Assess the relevant EoL strategies;
3. Use the decision tree to determine at which SOH levels each strategy is most valuable.

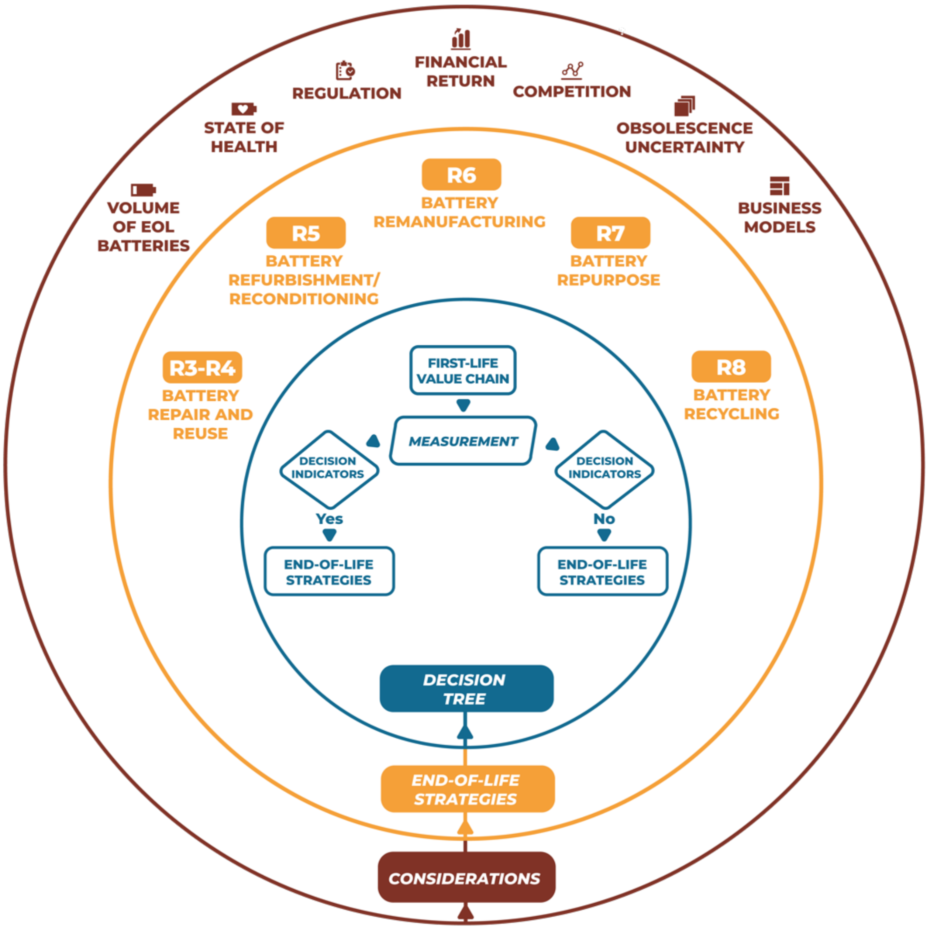


*Figure 5: Overview of decision tree, EOL strategies and considerations*

# Circular Economy as a Way Forward

Several frameworks can be used to assess "circular" strategies:

1. The waste hierarchy ranks waste management options according to what is best for the environment (DEFRA, n.d.).

2. The Butterfly Diagram (Figure 4) visualises the circular loops that products, components and materials can take at the end of their life as opposed to disposal. The model distinguishes between biological and technical materials, and although batteries are mostly related to the technical hemisphere, a recycling method called bio-hydrometallurgy involving bacteria to extract valuable metals relates it to the bio-hemisphere as well.

3. Figure 6 by PBL further defines the looping strategies and additionally ranks them according to circularity. PBL's framework has an additional three strategies – refuse, rethink and reduce – that are ranked even more circular and are important to evaluate. The choice of product recovery strategy will usually depend on the product type and its quality. These frameworks are not battery specific, but they can act as guidelines.

The circular economy methods are not entirely new and have overlapping values with other methodologies and schools of thought. Therefore, several companies who adopt, for example, lean manufacturing principles may also be implementing circular economy methods and principles without realising it.

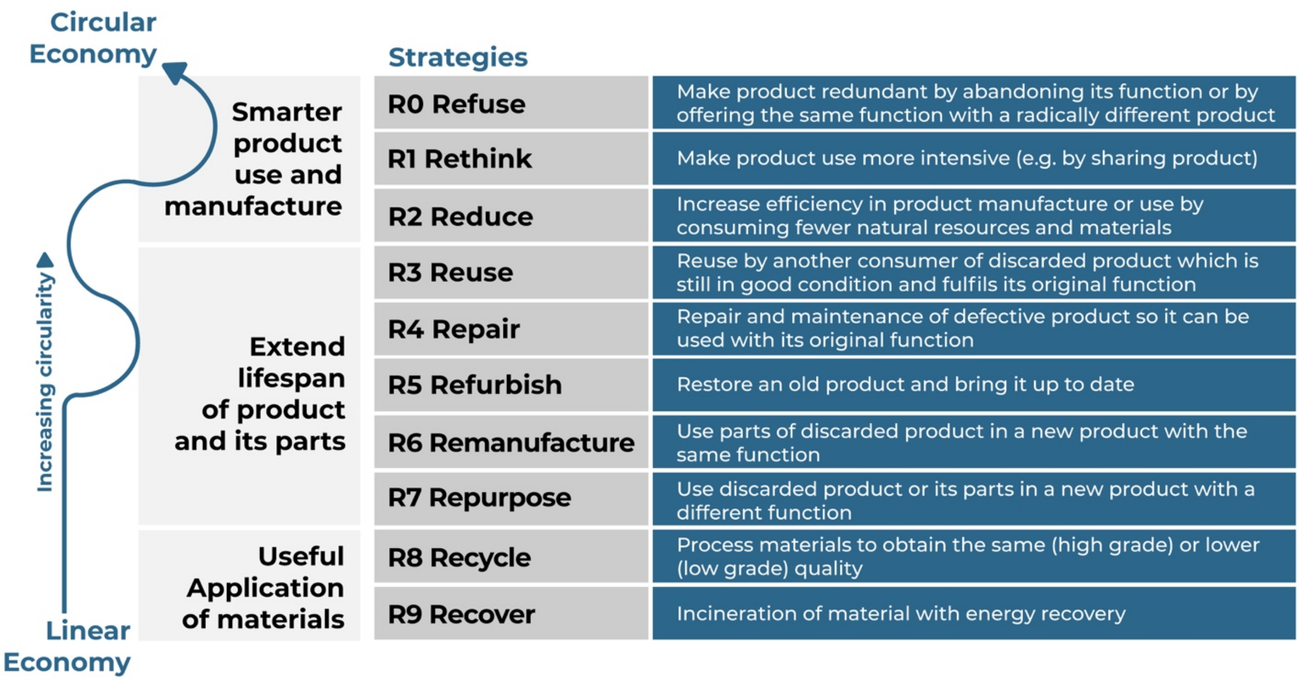


*Figure 6: The 9R framework (adapted from PBL, 2017)*

The circular economy is aimed at maximising the recovery of a product's inherent value, in terms of raw materials (such as platinum, gold, copper, steels, plastic, lithium etc.), embedded energy, and economic value while incurring the least amount of cost and waste. The principles encompass the design stage, product use or business model, and the end of life treatment. Although EVs have zero tailpipe emissions, the extraction of raw materials and the battery production is incredibly carbon-intensive, especially in some countries. It is therefore particularly important to maximise the recovery and lifetime of the raw materials to offset these initial emissions. For comparison, producing an EV currently contributes on average 1.3-2 times as much emissions as producing an internal combustion engine (ICE) car (European Environment Agency, 2018).

As modifications to a product and its process are very difficult to implement once decided, it is important to thoroughly evaluate circularity at the design stage. Below are some principles of circular product design:

- Long lasting and slow degradation
- Standardised and compatible products and components
- Ease of maintenance and repair
- Upgradeability, modularity, and adaptability
- Design for disassembly
- Design for test
- Easily recycled materials

Evidence suggests that manufacturers that take a proactive approach in applying circular strategies early in the design stage will achieve both large operational and


*Figure 7: UK Battery Supply Chain (Faraday Institution, 2019)*

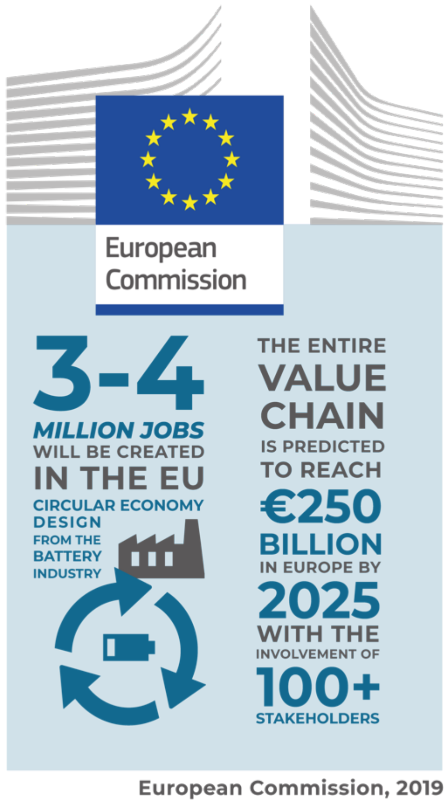


*Figure 8: European Circular Economy Battery Industry (European Commission, 2019b)*

economic benefits for the user, as well as greater alignment with consumer needs and environmental benefits. These are all key elements that businesses aim to capitalise on to stay competitive and will be discussed in greater detail in the next section.

In the UK alone, The Faraday Institution (2019) estimates that employment in the automotive industry and its battery supply chain could increase by 60,000, from 186,000 to 246,000, full-time equivalent (FTE) jobs by 2040 (Figure 7). Combined with a decline in manufacturing traditional ICE vehicles there will be a total of 83,000 FTE jobs in the EV and battery manufacturing industry. These jobs will be within EV manufacturing, battery manufacturing, battery supply chain and battery R&D (The Faraday Institution, 2019). Furthermore, the European Commission (2019b) predicts the entire value chain, driven by circular economy design, will reach €250 billion in Europe by 2025 (Figure 8; European Commission, 2019b). This growth demonstrates that there is a rapidly emerging opportunity for OEMs to gain competitive advantage by utilising the circular economy strategies. The next section will present the specific EoL strategies for LIBs.

# End of Life Strategies

The processes for recovering EV batteries include the steps in Figure 9, where each of the steps have their own associated costs and challenges.

This section covers the benefits and challenges of the circular EoL strategies for EV batteries and the application opportunities for OEMs. They will be covered in the same order as the 9R framework by PBL (Figure 6).

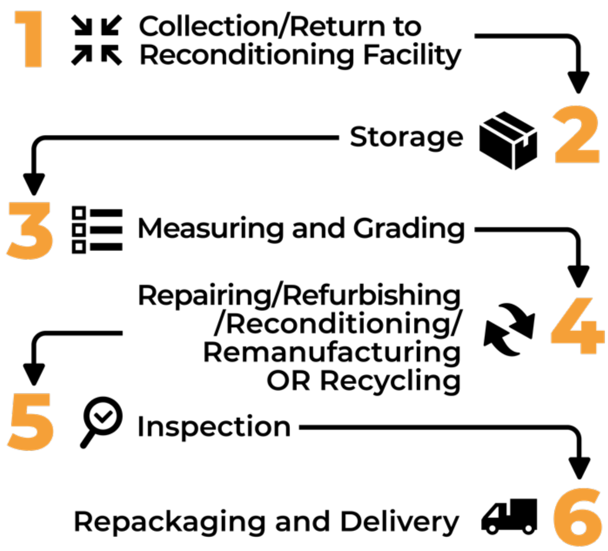


*Figure 9: Common steps in second life application*

## *R3 - R4: Battery Repair & Reuse*

Reuse, not to be confused with repurposing (R7), is the complete or partial reuse of the battery for the **original** purpose the battery was designed for, potentially after repair. Repurposing is for applications **different** than the original intention. Reusing would provide a warranty for the battery, but not as long as the original warranty (European Commission, 2019a).

***Benefits*** ***R3-R4***

- The least energy and resource intensive
- The most economically and environmentally effective option for the life-cycle extension / end-of-life treatment of batteries
- Costs are well below 25% of the cost of producing a new battery

Challenges

- For battery reuse, the costs are mainly related to the battery collection and sorting/grading steps
- Limited cases, as not many EV batteries have been through their first life cycles yet

## R5: Battery Refurbishment/ Reconditioning

Refurbishment and reconditioning are terms that are used interchangeably. It is possible to refurbish LIBs, however available knowledge of these practices is sparse. Refurbishment involves returning a used battery to a satisfactory working condition by replacing or repairing cells or modules that are visibly older or used, even where there are no reported or apparent faults in those components.

Refurbishing EV batteries starts with partial disassembly of the battery pack. The next step involves identification of cells that are no longer working, replacing them with other cells capable of holding a sufficient charge, and reassembly of the battery pack, either in its original format or in a newer format suitable for the application. This process involves diagnostic and screening tests to correctly identify the EV battery chemistries and designs.

A few studies in literature have explored the ideas of reconfigurable battery packs specifically designed for modular disassembly or cell change out, but very few have explored these ideas on an industrial scale.

Warranty for the reconditioned battery will be less than for a new or a remanufactured product but the warranty will cover the whole product. The performance of the product will be less that of a new product.

### Benefits

**R5**

- Preserves most of the battery as a whole and only individual cells or modules are switched out

### Challenges

- Limited information on the practical implications around refurbishment
- Current battery designs make this very difficult to achieve
- Costs may outweigh the value

### Examples

- Nissan refurbishes LIBs from the Leaf model in Japan (Kelleher Environmental, 2019).
- Spiers New Technologies specialises in among other things refurbishment (Spiers New Technologies, n.d.)
- Informal businesses refurbish batteries (Kelleher Environmental, 2019).

## *R6: Battery Remanufacturing*

Remanufacturing involves returning a used product back to at least its original performance with a warranty that is equivalent to or better than the newly manufactured product.

The remanufacturing process involves testing, dismantling, restoring, and replacing components and testing the final product to ensure that it is within the original design specification. Performance after remanufacturing is expected to be at least to the original performance specification, if not even better due to newer components.

R6

### *Benefits*

- Can be returned to "new" or "better than new" standard/warranty (European Commission, 2019a)
- Cost is 10% less than the cost of a new pack (European Commission, 2019a)

### *Challenges*

- Non-standard remanufacturing processes make remanufacturing complex
- Legislation and warranty are unclear. E.g.: Lack of distinction between "new" and "better than new" battery packs if older battery cells degrade faster
- If third parties are remanufacturing the battery, at what stages do OEMs and third parties take responsibility? Who will take the liability if a remanufactured battery causes a serious risk to users?

### *Examples*

- Nissan remanufacture LIBs from the Leaf model (Reuters, 2018)
- Spiers New Technologies specialises in among other things, remanufacturing (Spiers New Technologies, n.d.)
- Research project: Reclamation, Remanufacture of Lithium-ion Batteries (R2LiB) (UKRI, 2020)

## *R7: Battery Repurpose*

Battery repurposing, often confused with reuse, means the complete or partial use of the battery in a **different** application than its original purpose. Existing second life applications have focused on repurposing the battery when its capacity no longer meets the needs of the operating cycles and performance requirements of automotive use (80%) but is still perfectly acceptable for other applications such as stationary energy storage. In energy storage, second life batteries can expect to last a further 12 years, but depending on the application, the lifespan of a second-life battery can reach up to 30 years (Casals et al., 2019).

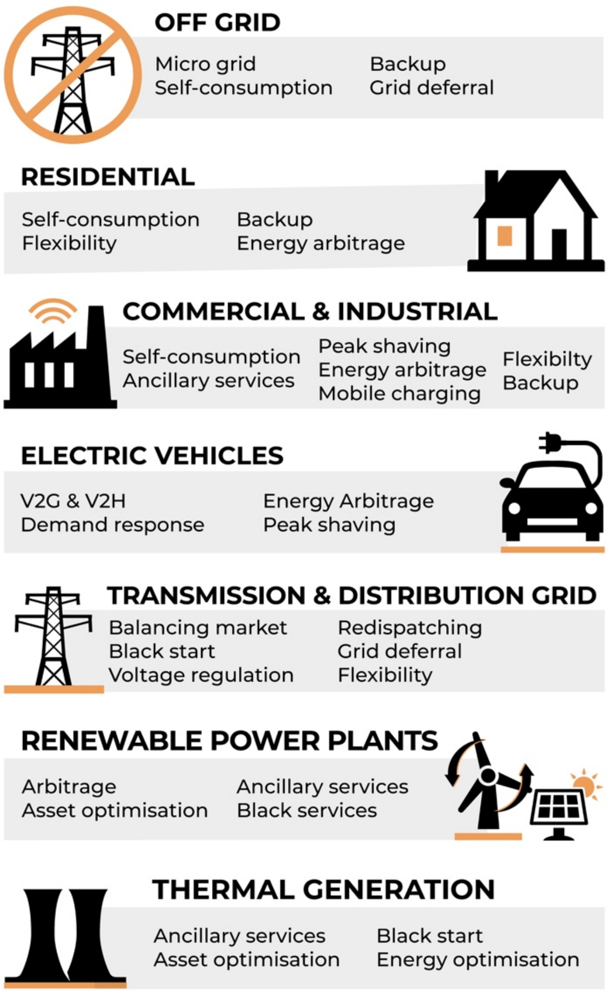


*Figure 10: Overview of potential battery repurpose use cases (adapted from Reid & Julve, 2016)*

### *Benefits* — *R7*

- Bringing down the cost of energy storage can help integrate more renewable energy to the grid (European Commission, 2019a)
- 25% of the cost of a new battery (European Commission, 2019a)

### *Challenges*

- The state of health of the returned battery is uncertain and will dictate which repurposing applications are suitable (Jiao, 2019).
- Some repurposing applications for lower capacity functions require further disassembly, adding complexity (Harper et al., 2019).

### *Examples*

- Audi uses in factory vehicles (Audi, 2019a)
- Audi uses for factory energy storage (Audi, 2019b)
- Nissan and Volvo use for home energy storage (EATON, 2019; Volvo Buses, 2018)
- Volvo uses for mobile charging unit (Volvo Cars, 2018)
- Further examples in Figure 10

## *R8: Battery Recycling*

As all EV batteries are banned from landfill or incineration, they will eventually be treated for metal/materials recycling. When the LIB is no longer usable or repairable it must be sent to a recycling facility to recover its basic materials. Metals recovered include lithium, nickel, cobalt, manganese, copper, aluminium, and iron. Processes to recover these elements consist of both pyrometallurgy and multistage hydrometallurgical methods, with further research being conducted on bio-hydrometallurgical methods (Velázquez-Martínez et al., 2019). The specific steps of the above processes can be found in Figure 11 (Swain, 2017).

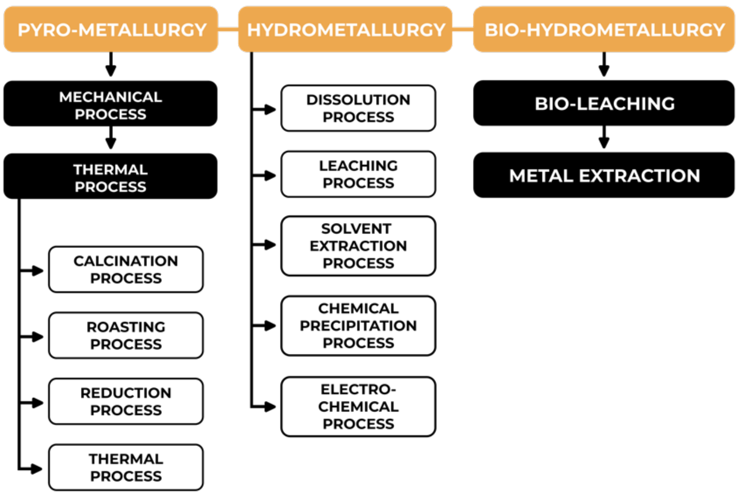


*Figure 11: Steps of pyro-metallurgy hydrometallurgy, and bio-hydrometallurgy (adapted from Swain, 2017)*

### *Benefits* R8

- Generally, recycling methods can recover up to 70-90% of metals (Velázquez-Martínez et al., 2019).
- Lab tested methods combining mechanical, hydrometallurgical and pyrometallurgical processes can recover up to 99% of metals (Velázquez-Martínez et al., 2019).
- From a material recovery point of view, cobalt, lithium, copper and nickel are the most valuable materials embedded in the LIB and can offer a financial opportunity (Lebedeva et al., 2016; European Commission, 2019a).

### *Challenges*

- Due to the complexity of materials contained within batteries, their multiple chemistries and very low concentrations, many important metals (e.g. lithium, cadmium, manganese, rare-earth elements) are not recovered during mainstream recycling processes (Velázquez-Martínez et al., 2019).
- The processes to recover valuable materials can be expensive to operate and highly polluting (Velázquez-Martínez et al., 2019).

### *Examples*

- Umicore and SNAM are two of the larger recycling companies in Europe, receiving the majority of batteries from across the 28 member states.

## *Strategy Summary*

We can state that the level of circularity options for batteries at their end of life would follow the 9R Framework presented in the introduction, where directly reusing the battery (R3) would be the most circular and recycling (R8) would be the least favoured end of life option. However, as part of a strategy assessment, any business looking to implement circular strategies should evaluate potential strategy combinations.

The circular strategies have their individual benefits and challenges and can, therefore, suit different needs that the OEM may have. This also includes the first 3R's of the PBL framework: Refuse, Rethink and Reduce. Particularly Rethink presents a large opportunity for OEMs.

Currently, car manufacturers design batteries only for automotive purposes. This means that the battery repurposing cost is significantly affected by how the batteries were initially designed.

Although the design priority is for EV use, a systemic design thinking that incorporates second-life repurposing into the initial battery design would greatly smooth the whole repurposing process and reduce/avoid relevant costs. It is a matter of consideration, not cost, for approaching EoL strategies.  Some OEMs are aware of the importance of design for repurposing and have taken measures either in the form of battery architecture redesign or the improvement of battery control and data tracking systems.

Redesign of batteries in combination with remanufacturing could be profitable for one particular OEM, whilst reusing batteries for factory vehicles and repurposing for energy storage may be the most suitable combination for a different OEM.

However, this is not nuanced enough for OEMs when making a decision on which of these strategies to utilise. To maximise value for the OEM there are several important factors to consider on a case by case basis that we will be presenting in the following section:

- Volume of batteries
- Quality
- Regulation
- Financial return
- Competition
- Business models
- Obsolescence uncertainty
- State of Health (SOH) testing

# Considerations

## *Volume of EoL Batteries*

The expected volume of batteries returning to the OEM at end of life can influence the preferred circular economy strategies that the OEM chooses.

Currently, there is a lack of EoL batteries in supply due to the relatively recent uptake in EV ownership. The rate of batteries returning to the OEM at the end of life can be uncertain as it depends on customer behaviour. An initial owner may, for example, use their battery well below the 70-80% capacity, which is the widely recommended replacement time (Jiao, 2019).

Higher volumes of EoL batteries can be important when assessing certain circular strategies as they require larger capital investment, such as for a remanufacturing facility. High volumes contribute to economies of scale which will make such an investment more economically viable, and therefore the strategy more favourable.

## *Reliability on Quality of EoL Batteries*

This requires ensuring that the quality of a battery that has been reused / repurposed / remanufactured is consistent and reliable – i.e. not heavily affected by ageing/degradation in the first-life usage.

Uncertain second-life battery performances such as remaining battery lifetime and performance degradation in various energy storage applications. This uncertainty is said to be caused by (a) the lack of systemic and sophisticated data collection onboard; (b) the lack of effective data analysis; and (c) the lack of sharing with downstream stakeholders on the battery health over its first life in vehicles.

The variation in capacity may affect battery volumes available for a certain EoL strategy, where there might be a higher number of returned batteries no longer suitable for high capacity repurposing.

## *Regulation*

There is currently no EV battery specific regulation outlining whether recycling or reuse is the appropriate path for an EV battery, contributing to uncertainty for OEMs (McKinsey & Company, 2019c). OEMs need to identify themselves what will be most value maximising and can employ multiple strategies.

There are three major regulatory challenges.

The first is the immature regulation specific to EV batteries and their classification, which impacts their carriage and transportation. Currently, in the UK and Europe EV batteries are classified under Dangerous Goods Class 9 Miscellaneous, making navigating the regulations complicated and expensive (UNECE, 2017). In addition, the second-life battery is currently not well defined and can sometimes be regarded as waste, which can further complicate transportation and other factors (Pistoia and Liaw, 2018).

The second regulatory challenge is concerned with the second-life battery being regarded as waste in the energy market specifically. If second-life batteries are not more clearly defined by legislation, the business models for using these batteries in storage solutions would be difficult to implement (McKinsey & Company, 2019c).

The third challenge is that in some countries, such as the UK, there is a lack of incentive programmes for second-life batteries, which makes it unfavourable for second-life batteries to compete in the energy market when new batteries become price competitive.

The European Commission is planning to propose a new regulatory framework in 2020 for batteries as part of their Circular Economy Action Plan. This will address batteries reaching their end of life and provide guidance on their method of treatment and hopefully improve clarity and incentives for OEMs. This could potentially increase the competitiveness of second-life batteries.

## *Financial Return*

Financial viability may be the deciding factor for many OEMs when assessing second life strategies. This is a very important consideration as it can determine the overall viability of the strategy. In theory, when evaluating circular strategies, the most circular are also the least costly. However, the technical complexity of battery disassembly, broader supply chain issues, and regulatory ambiguity affect the financial return.

Some of the circular strategies, such as remanufacturing and recycling, require more investment into facilities and technical labour. Dependent on volumes it could be more viable for an OEM to choose a less circular option, such as repurposing over remanufacturing, if they do not have the volumes to justify the investment.

## *Competition*

Second-life batteries face competition from increasingly cheap new batteries, which also promise better quality and performance. There are also specific areas, such as energy storage, where other battery chemistries are better suited and would therefore compete with LIBs.

OEMs are currently trying to reduce the cost of battery repurposing by using the whole battery pack to avoid costs of disassembly (e.g. reusing a battery as a mobile storage solution, rather than disassembling it with the purpose of refurbishing).

## *Business Models*

Several business models, on their own or in combination, are used to promote battery second-life opportunities.

- Product as a Service where the manufacturer offers power performance rather than the battery itself.

- Part harvesting for remanufacturing, reconditioning, repairing, reusing, and repurposing batteries. This allows manufacturers to store high value parts that correspond to the most frequent fault codes. OEMs can repair or recondition batteries in-house without having to send batteries for smaller modifications that would incur large transportation costs and longer lead times.

- Battery servicing where manufacturers can offer maintenance services for the remanufactured batteries for a fixed term. This generates additional revenue for manufacturers and peace of mind for customers.

- Battery hiring or leasing services where customers can use batteries for a fixed term for a specific fee. This allows the use of remanufactured batteries, while also allowing customers to exchange batteries during the term free of charge, should the batteries perform below the expected threshold. This benefits manufacturers as they retain full control of the battery. For the customer, this model means a cheaper battery with no maintenance costs.

- Incentivised return and reuse where customers pay an additional surcharge at the point of purchase. In return, manufacturers buy back the battery at an appropriate price dependent on the condition. This allows manufacturers to retain control of the battery, while selling a new battery to the customer. Customers will also be able to change the battery for a reduced cost.

- Warranty based services where extended warranties are offered for the whole battery or only for major components. Customers will have additional security over the battery performance whilst manufacturers can replace parts cheaply from part harvesting.

## Obsolescence Uncertainty

New battery chemistries are being developed which may well overtake lithium-ion as the primary choice of battery for electric vehicles in the future, particularly if they prove to be less hazardous and with greater capacity. This could result in the current generation of LIBs being unfit for reuse, simply because technology has moved on. However, it may take a long time for new advanced chemistries to fully enter the market; this typically takes at least 10 years for a new chemistry (European Commission, 2019a). What will be important is to develop flexible BMSs that can handle different cell chemistries (European Commission, 2019a).

## State of Health Testing

*(Provided by the National Physical Laboratory and University College London)*

Battery State of Health (SOH) has a considerable impact on the reusability of LIBs. The SOH is influenced by a great number of factors, such as extreme temperature changes in the external environment, but is primarily influenced by user behaviour. Rapid, reliable, and reproducible measurement of SOH of LIBs is a significant challenge that requires a robust metrological framework.

As part of the Faraday Battery Challenge, scientists at the National Physical Laboratory (NPL) and University College London (UCL) are developing an automated triage-based approach to EoL testing of battery cells, modules, and packs. The approach is based on four primary test methods deployed sequentially in descending order of their speed of response:

1. Optical scanning (milliseconds to seconds)
2. Acoustic mapping (seconds)
3. X-ray imaging (seconds to minutes) (Figure 13)
4. Electrochemical measurement (minutes to hours)

This process facilitates rapid sorting of batteries at scale, allowing informed decisions to be made on the appropriate route for subsequent deployment, e.g. reuse, remanufacture, recycling, as shown schematically in Figure 12. The ultimate aim is to establish commercially viable EoL test capability in a production line environment in order to support the development of a complete EoL supply chain network within the UK.

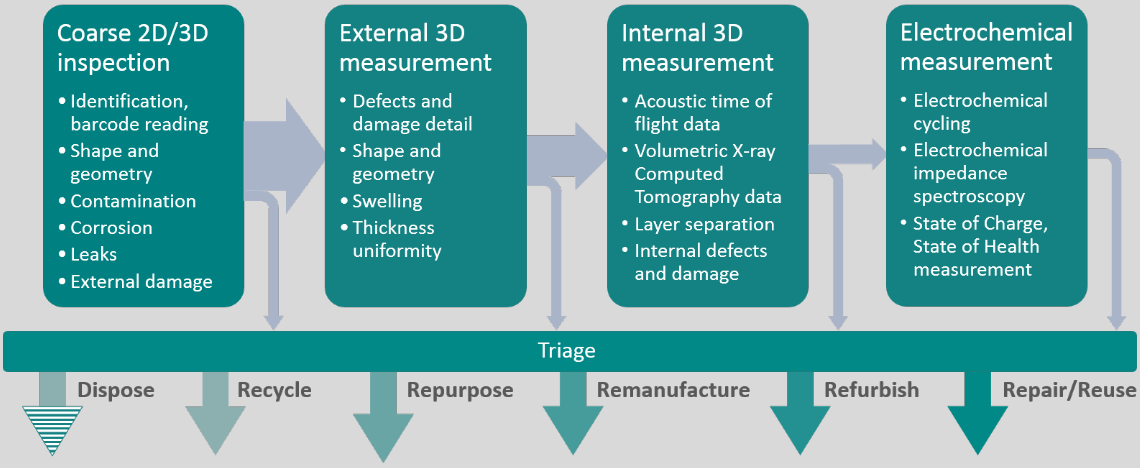


*Figure 12: Triage approach to EoL testing of EV batteries (NPL & UCL)*

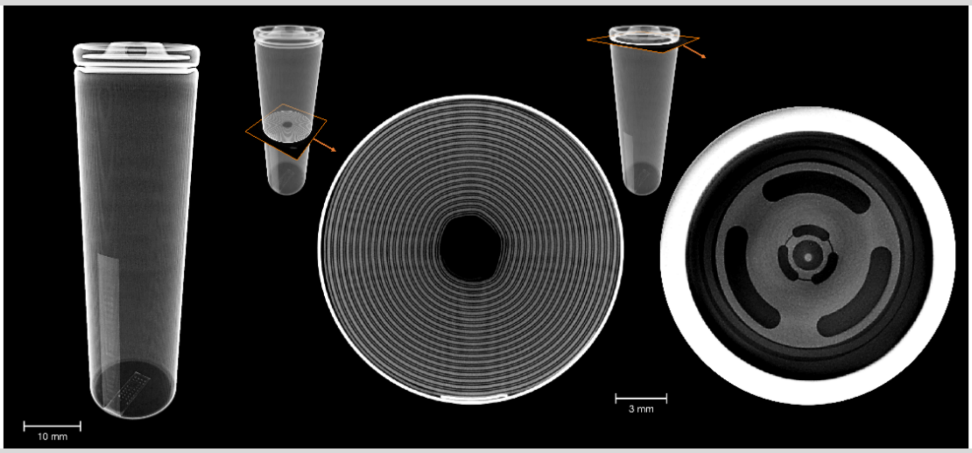


*Figure 13: X-ray image of cylindrical cell (UCL)*

# Strategy Recommendation

## *Recommended Approach*

As factors such as end of life battery design, business environment, and test capabilities will influence the success of an EoL strategy there can be no one-size-fits-all recommendation. However, there are various case studies and investments from OEMs indicating that a preferred strategy with low technology and financial risk is repurposing EoL batteries for stationary storage applications. This is based on the reduction in complexity in dealing with the accessibility of the battery coupled with the growing demand for energy storage units across the UK.

Remanufacturing is a potential second option as it minimises the dependence on imported key raw materials for LIBs. This is only if there is a reliable flow in volume intake of EoL batteries and if manufacturers improve the design of their batteries now.

HSSMI recommends a strategic approach to end of life treatment of EV lithium-ion batteries based on four key stages:

1) Design for end of life,
2) Assess end of life opportunities strategically using business considerations,
3) Develop an appropriate test strategy,
4) Implement the decision tree

### *1 - Design for end of life (disassembly and testing)*

*Be aware of the design of the end of life battery, and its ease of disassembly and accessibility for testing.*

The battery design in regard to its accessibility is an important factor when considering EoL strategies. A battery that requires several steps of dismantling and testing at end of life will incur additional time and cost. In comparison, a battery pack that could be easily dismantled would deliver a more economically viable EoL strategy. OEMs should, therefore, be mindful of the post-consumer battery design when assessing which strategy to utilise.

When designing future generation batteries, OEMs aiming to maximise life cycle value, should consider the principles of circular product design including, Design for Disassembly, Design for Test and Life Cycle Costing.

### *2 – Strategic end of life assessment using business considerations*

*Assess the end of life strategies but do so using the considerations relevant to the business and supply chain.*

As the success of a strategy will greatly vary depending on the business context, it is advised that the considerations mentioned in the previous chapter are taken into account when strategically assessing the end of life strategies.

### *3 – Develop an appropriate test strategy*

*Develop a strategy on how the business will accurately test the batteries for State of Health.*

The SOH of the battery is a key indicator. Typical failure modes during manufacturing, transport, operations / usage need to be taken into account to develop a test strategy and capabilities. This should include tests for regular degradation and accidental damage. The test strategy should also include the appropriate management of the life cycle data.

### *4 – Implement the decision tree*

*Once the preferred strategies have been identified in step 2, and a testing strategy has been determined in Step 3, the decision tree can be implemented.*

The decision tree will guide which preferred strategies will be suitable for different SOH levels.

## Decision Tree

A typical EV battery is considered to be at its EoL when the battery capacity fades to 80% of its initial capacity. This is mainly caused by the battery ageing, which is affected by the mileage and charging/discharging cycles of an EV.

A recurrent theme in HSSMI's involvement in battery EoL projects is the importance of monitoring and tracking the ageing level of LIBs to determine the appropriate EoL strategy. State of Health (SOH) is a key indicator to evaluate the ageing of batteries.

Using SOH as an indicator, it is possible to use a strategic decision tree to determine the most valuable EoL pathway, depending on the individual business case as shown in Figure 13.

The aim of the decision tree is to provide guidance for a direction, but for the OEM to properly assess the strategy and considerations with the help of the previous chapters.

### *Step 1*

The first check for suitable candidates of EoL batteries is to determine if the battery is physically damaged, and if so the extent of the damage. This damage could be swelling, heat damage, puncture or wiring faults and is assessed visually. If the battery is deemed unusable, it will then be considered for two potential outcomes:

- Recycling which aims to extract materials that can be used as raw materials.
- Parts harvesting which aims to extract components for production or to repair batteries still in their first life.

If the battery is still in a working condition, the SOH assessment will then determine the remaining pathways. There may also be further SOH values which are unknown or cannot be determined, which may also render the battery unusable.

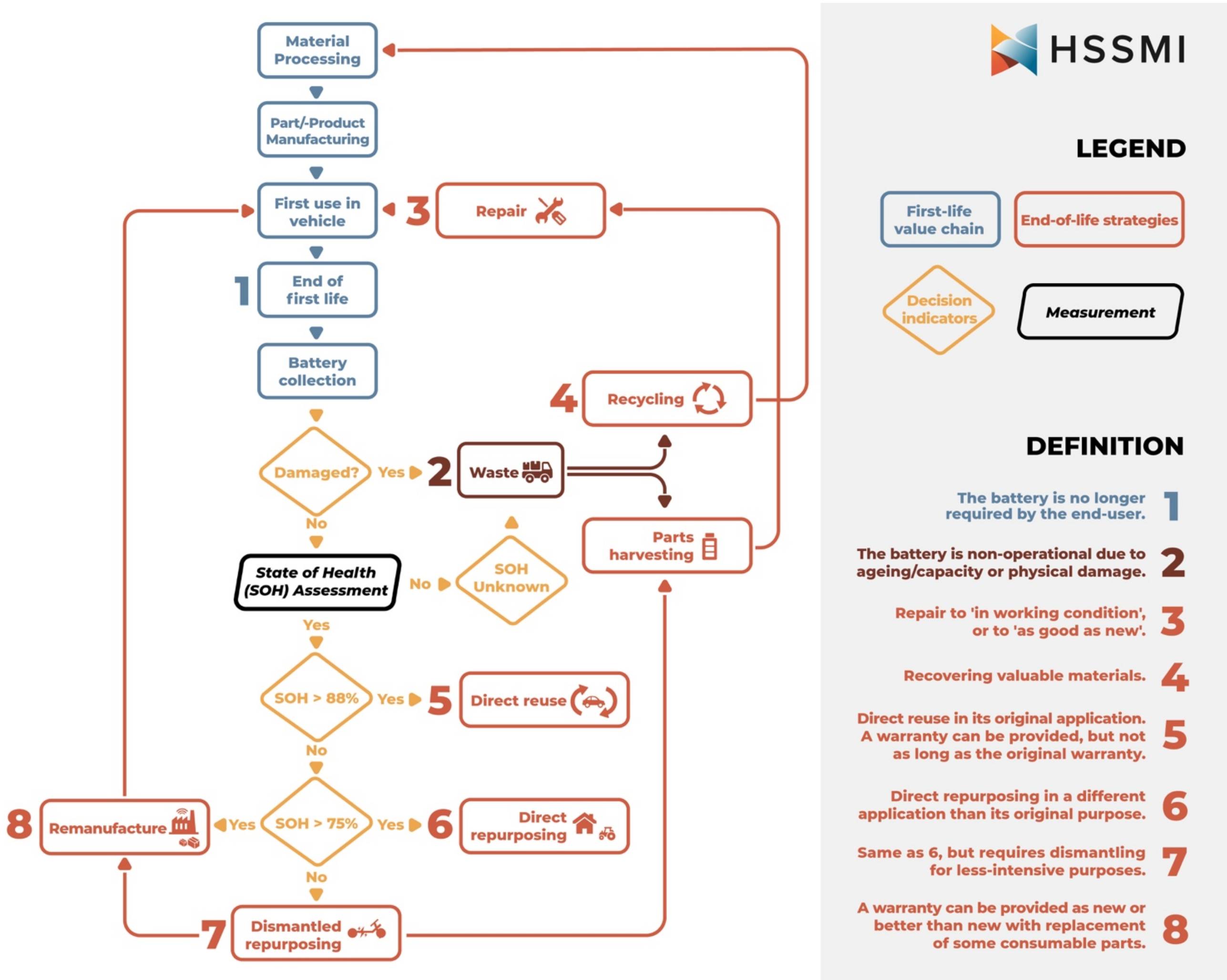


*Figure 14: EV battery end of life decision tree*

## *Step 2*

This SOH assessment can be conducted using techniques such as optical scanning, acoustic mapping, x-ray imaging and electrochemical measurement. The outcome of this assessment is split into several categories below. These categories are based on HSSMI's experience in electrification projects.

- >88% SOH

  R3-R4: Batteries above 88% SOH can generally be directly reused again (as first life) or as spare parts to replace damaged or older batteries (Canals Casals et al., 2017).

- >75% SOH

  R6: Batteries between 75 – 88% SOH are suitable to be remanufactured and reintroduced to the first life value chain.

  R7: LIBs can also be repurposed for stationary applications as these functions are less demanding on the battery's performance. Examples can range from home energy storage, mobile charging, factory energy storage and vehicle charging solutions. A more recent development is to also use these EoL batteries for other transportation services with lower power requirements such as urban trucks, hybrid vehicles or in boats/ferries to manoeuvre in and out of ports which also reduces noise and pollution.

- <75% SOH

  R7: For batteries of lower SOH, it is suggested that they be dismantled into modules or cells for repurposing in less intensive applications such as E-bikes, electronics, golf carts or mobile robots. The dismantled modules or cells can also be used for parts harvesting or remanufacturing.

In summary, SOH is an important determinant of the EoL strategy. However, the EoL strategy is highly affected by the considerations detailed in the previous chapter.

## *Opportunities*

It is important to consider EoL strategies now, as the current infrastructure to recycle or remanufacture LIBs will not meet the predicted future demand. OEMs (e.g. Nissan, Toyota, Fiat, Chevrolet) and other commercial organisations (e.g. Aceleron, LiCycle, Powervault, Box of Energy) are already beginning to develop business models and solutions that can repurpose, remanufacture or recycle EV car batteries.

With the increasing market demands for energy storage and raw materials found in batteries, business opportunities will emerge for OEMs to capitalise on and profit from. The increasing amount of cumulative business investment in infrastructure will, in turn, also reduce overall business cost (Mahmood and Gutteridge, 2019). Furthermore, implementing circular strategies and business models can have a positive effect on customer satisfaction as cost savings will cascade to them, in turn, contributing to higher brand loyalty. Overall, it is of strategic importance to evaluate a circular strategy to gain competitive advantage.

# Conclusion

Managing batteries at the end of their first life is a challenge that OEMs and the broader automotive industry need to proactively solve in preparation for the surge in EV sales. However, it also presents an opportunity for new revenues and risk mitigation.

Some pioneering OEMs are currently testing EoL strategies and this paper has aimed to present these strategies and highlight associated considerations to inform and aid the decision-making process.

A strategic approach based on four stages is recommended combined with a strategic decision tree to aid the direction based on the circularity of the strategy and the State of Health (SOH).

Currently, there are limited post-consumer EV batteries available, and thus it is difficult to recommend a particular route. However, the expected number of post-consumer batteries will become increasingly significant from 2020 onwards as the trend in uptake of EV ownership increases. The general recommendation is that the less dismantling a battery requires the easier it is for the OEM. Nevertheless, the optimum strategy for one OEM may not work for another, depending on variables such as regulation, battery design, etc.

This white paper aims to provide OEMs and industry with guidance on how to proceed with assessing available options. It is important that an OEM takes these elements (decision tree, EoL strategies and considerations) and evaluates them in the context of their business, product design and supply chain. Nevertheless, implementing a strategy in a new field can be challenging and HSSMI has extensive experience in battery end of life projects. From these experiences we have developed tools and services that can help companies to develop and implement a successful EoL strategy. This includes examples such as:

- End of Life For CE (EoL ForCE)
- Circular Economy Maturity Assessment (CEMA)
- Life Cycle Assessments (LCAs)

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# Get in Touch

HSSMI is a sustainable manufacturing innovation consultancy, committed to helping manufacturing companies achieve their ambitions. HSSMI works across manufacturing industries to help companies respond to market challenges by increasing productivity, transitioning towards a circular economy, and upscaling their products and processes.

Since being founded in 2012, HSSMI has worked with government bodies, established manufacturers, and aspiring start-ups. HSSMI connects industry experts with people who want to make their products in a cost effective, innovative, and sustainable way.

HSSMI's areas of expertise include manufacturing strategy, digital manufacturing tools, circular economy, lean manufacturing and automation, hydrogen propulsion, advanced manufacturing simulation, E-drives, battery technology, and project management.

HSSMI has experience in projects that consider EoL strategies in EV batteries and have worked with several UK automotive companies and are also part of the Sustainable Batteries Steering Group. One of these projects is VALUABLE, which aims to create a new and complete end of life supply chain network within the UK by developing significant reuse, remanufacturing, and recycling routes for second life automotive Li-ion batteries. Other projects HSSMI are part of include UK Range Extender EV (UK REEV), EV-LIFT and EVE.

Our products and services related to battery EoL are:

- End of Life for Circular Economy (EoL ForCE)
- Circular Economy Maturity Assessment (CEMA)
- Life Cycle Assessments (LCAs)

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