Business critical: Understanding the material life cycle

ADVANCED PROPULSION CENTRE UK | Accelerating Progress

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The purpose of this report produced by the Advanced Propulsion Centre UK (APC) is to provide insight into how the sector needs to transition its product life cycle thinking if the industry is going to deliver on its net zero targets.

Contents

Executive Summary

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Globally the automotive sector has embarked on its transition to become net zero with many of the OEMs committing to dates for their entirety of business by 2050. However, this net zero ambition is not restricted to one sector or one region of the world, but it is something governments are internationally striving for. To deliver on this commitment internationally and regionally there needs to be stronger collaboration, agreements, and frameworks on how to deliver the right solutions for our future generations.

To develop these solutions, products need to become more sustainable which means that organisations need to become educated on the origination of the materials they are using. Better data on the impact on the extraction process through to the manufacturing of our products. The last few decades have given the automotive sector a reasonable start on understanding the emissions that come from our in-use functioning of vehicles, but now is the time to think more about recycling, repurposing, and re-use of components and materials within these vehicles.

It is not just about the recycling of the materials, it is also about understanding that value, for example, how much energy might be required to do this recycling, remanufacturing, or re-use to get the parts ready to add value back into the sectors – is this viable?

To be successful in this mission a holistic view is needed from the outset with all inputs and outputs being considered from across the system.

The purpose of this report produced by the Advanced Propulsion Centre UK (APC) is to provide insight into how the sector needs to transition its product life cycle thinking if the industry is going to deliver on its net zero targets. The first section of the report looks at what life cycle analysis means for the sector, highlighting some of the challenges that will need to be overcome. This will require businesses to apply common frameworks and tools which can help decisions to be made on material selection internationally.

The second section of the report then focusses on the challenge around batteries, the highest value system within an electric vehicle, and introduces the regulations that are being implemented and where the recycling opportunities are for the UK.

The final section of this report looks at this value chain to address how the sector can build a more circular and resilient supply chain for batteries. It is important to note that recycling, repurposing, and reuse is not just needed for the batteries but must be considered for all parts of the vehicle; further insight into these aspects will be released at a later date.

Batteries within electric vehicles are currently very costly in terms of manufacturing and transportation but at end-of-life more costs are incurred through collection and dismantling. In addition to this, safety risks make transport challenging, particularly for damaged batteries. Dismantling remains a manual and skilled task due to diversity of design. There is some great work in robotics, but to really gain advantage in using these technologies, improvements, and commonality to the standards on design and integration of batteries would greatly help reduce this cost. This report provides an overview about the battery recycling regulation coming into practice by the end of 2023. The introduction of this regulation is driving all parts of the supply chain to think about access to critical materials contained within the batteries.

The introduction of regulation is driving all parts of the supply chain to think about access to critical materials contained within the batteries.

Currently the UK is producing and exporting black mass, shredded battery material containing both anode and cathode components, this means the high-value materials contained therein leave the UK. This highlights the need to retain the value of these materials with the end-of-life batteries (including black mass) which are typically shipped overseas, often to Asia, which only adds to the life cycle embedded emissions impact of these products. The APC has developed this value chain to highlight the opportunity the UK has to retain that value. By developing work through the value chain, it will create a supply chain for battery manufacturing in the UK with a reduced life cycle impact.

Recycling stocks are hard to forecast with current collection rates of key materials being very low or non-existent. In addition to this, over the years the design of vehicles has improved and there remains uncertainty with consumers around which technology they should have in their vehicles. This has led to vehicle lifetime getting longer and therefore having a big impact on being able to access some of these critical materials. These are all factors that will be further explored within this report and are critical to planning the scale-up of capacity for recycling facilities building on existing expertise and capability that the UK already has.

Recommendations

The report highlights four key recommendations that need to be taken forward:

1. Supply chain collaboration to implement Life Cycle Analysis (LCA), prepare for future regulations, and agree standards and method.
2. Support smaller businesses with LCA skills
3. Recycling and Re-use regulation and permitting review
4. Education on emissions from raw materials versus recycled materials to aid decision-making on investment

The time has come to move to a circular economy. We now need to put in place the tools to help us understand the wider impact of this.

Life Cycle Analysis (LCA)

The circular economy

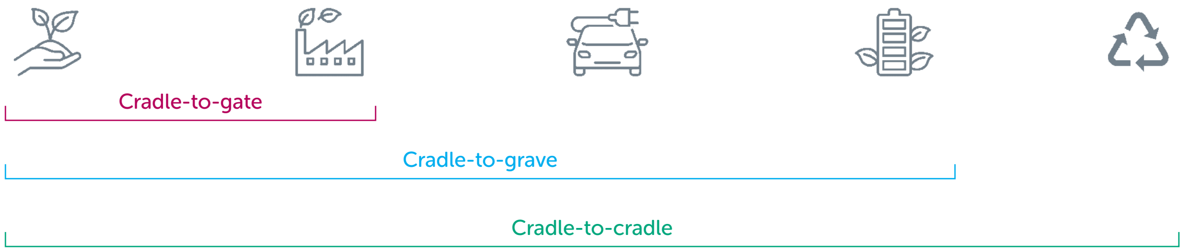
The current net zero strategy aims to reduce greenhouse gas emissions, primarily CO_2, and there has been some promising progress towards achieving this with carbon emission monitoring and recording now becoming commonplace in many industries. Now this is underway we must look more widely at our use of resources, such as water and land, as well as other emissions that could pose harm to health.

The time has come to move to a circular economy. We now need to put in place the tools to help us understand the wider impact of this.

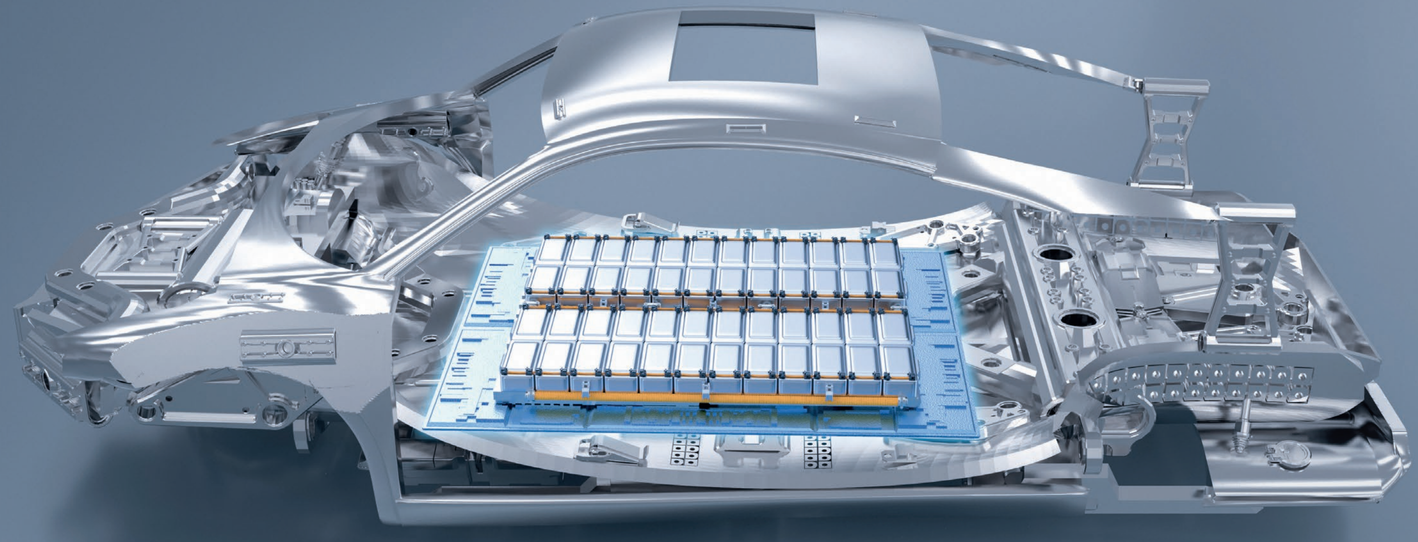
In the automotive industry, this means tracking all the way back to the start of the process which begins with the extraction of raw materials. There are three main stages that depict the life cycle spilt.

The current focus is on the cradle-to-grave stage but reporting and monitoring at all three stages would need to be in place to move to a fully circular economy.

Life cycle view of a vehicle



Cradle-to-gate	Cradle-to-gate studies consider emissions generated from production of raw materials to point of sale
Cradle-to-grave	Cradle-to-grave studies includes the usage cycle and may include disposal
Cradle-to-cradle	Cradle-to-cradle studies include any disposal/recycling but also the re-use of material as a reduction of overall emissions



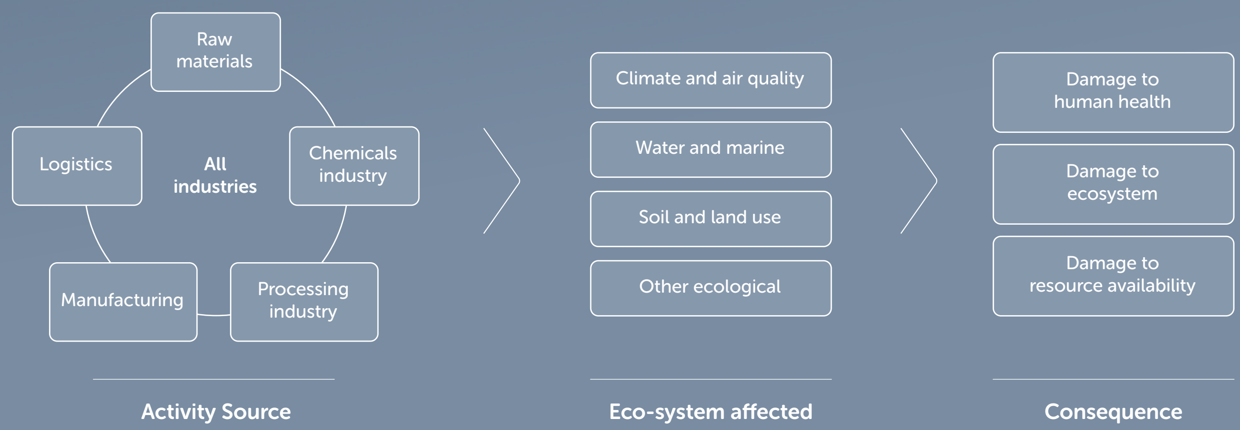
What is Life Cycle Analysis (LCA)

LCA is a tool to provide a measurable comparison, between different products, processes, or activities, of resource usage and emissions to air, water, and soil.

This simplified picture shows how LCA aims to record all activities taking place that may affect an ecosystem, for example, air-quality, and relate that activity to a consequence, such as damage to human health. By doing this we gain an understanding of the consequences on human health and the ecosystem as a whole in the production, disposal, and recycling of products.

From this understanding of impact scale, we can put targeted actions in place to best reduce this impact.

Life Cycle Impact Assessment (LCIA)



Up to 80% of emissions come from third party suppliers

The automotive industry is more complex than the simple linear image of a life cycle because of the many levels within it.

When running a life cycle assessment, the boundaries and measurement parameters are defined; this is challenging to do and to properly communicate for the automotive industry and makes it difficult to compare emissions from one manufacturer to the next.

The recording and communication of emissions can give a competitive edge, and yet up to 80% of an OEM's emissions may be in the supply chain.

Smaller suppliers in the supply chain could be unable to record the level of detail needed without support, so this is likely to be an area that automotive OEMs may need to focus on and offer direction.

For the UK automotive industry to be ready for new regulations and to compete on a level playing field, clarity, consensus, and cooperation will be needed from the sector to bring the knowledge and skills required to develop the whole supply chain.

This includes how to carry out LCA, tools to record and monitor emissions, consensus on boundaries and assumptions along with education on effective communication of results and strategies to reduce emissions.

Recommendation 1

Supply chain collaboration to implement Life Cycle Analysis (LCA), prepare for future regulations, and agree standards and method.

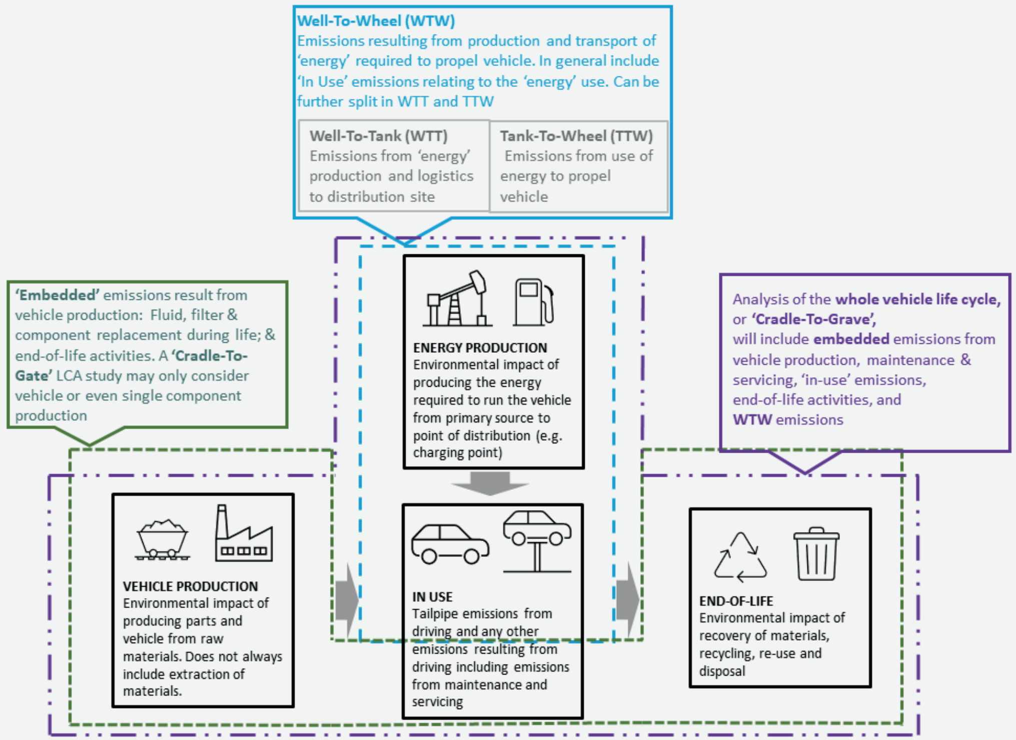
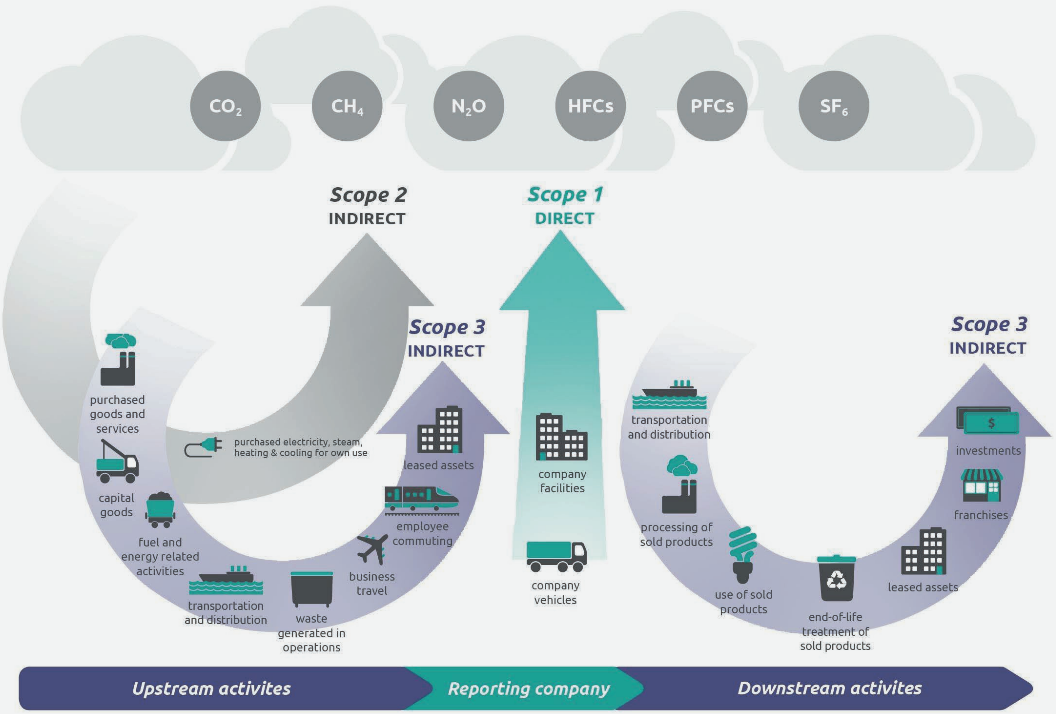


Image recreated from Ricardo Energy and Environment original

The Greenhouse Gas Protocol

The Greenhouse Gas Protocol, which provides the most widely recognised accounting standards for greenhouse gas emissions, categorises GHG emissions into three well-defined scopes:

- **Scope one emissions:**
  Covers emissions from sources that an organisation owns or controls directly.
- **Scope two emissions:**
  Relates to emissions that a company causes indirectly with the energy it purchases and uses.
- **Scope three emissions:**
  Encompasses emissions that are not produced by the company itself, and not the result of activities from assets owned or controlled by them, but by those that it is indirectly responsible for, up and down its value chain.



Carbon Emission Targets Explained (warwick.ac.uk)

The Regulatory Landscape

UK Battery Industrialisation Centre

The regulatory landscape – what will change?

As we build towards a net zero future, new regulations are coming in to force for the automotive sector. Battery production is leading this charge with an increased focus on life cycle and sustainability. This will have a significant impact on the automotive industry and its supply chain, changing the way it reports on the origins, recyclability, performance, and durability of the raw materials that make up the battery.

Where manufacturers are currently only required to monitor powertrain in-use emissions, new regulations will see the whole of the battery supply chain impacted by the need to report on its carbon emissions. The result will be greater transparency of emissions information, setting standards for the industry which will benefit both the consumer and the automotive manufacturers.

Additionally, providing clear data of emissions from the point of material extraction to vehicle end-of-life will ensure accurate carbon figures are reported as we transition to fully electric vehicles. The process will be a big undertaking, with up to 80 percent of an automotive manufacturer's carbon footprint accounted for within its supply chain.

What is in place currently to gear up for change?

In readiness for the EU battery regulation – one of the key major regulation changes with an LCA focus- draft legislation is now underway. While in the UK, the DEFRA Waste Batteries and Accumulators Regulation is under consultation.

The impact

The new regulations will mean significant change and there is no option to operate in silos. With transparency at the heart of the change there will be no opportunities to 'hide' emissions or mis-manage waste. The impact is likely to be felt the most by smaller businesses lower down the supply chain. The task ahead to collate, monitor and report the data will be a daunting prospect for them.

Every part of the supply chain will be required to monitor and report its carbon emissions, and this will place a burden on those that lack the people and financial resource to implement change at this scale. The onus will be on the automotive manufacturers to support their supply chain partners to be ready for legislative change and to work together to share data and best practice.

> Future legislation is likely to cover wider life cycle environmental and sustainability impact measures.

Regulation – what is confirmed?

(Full details of regulations both current and upcoming are available in the annexe document)

There is already regulation in place, both confirmed and upcoming in the UK and in Europe, that has set targets for carbon emission reduction as part of the drive to reach net zero. These new regulations specifically affect the automotive industry and are wider reaching, impacting other sectors and industries. Current vehicle (cars and vans) emission regulations focus on tailpipe emissions with set reduction targets in place for 2030 and 2035, which will see a focus on 100 percent CO_2 emission reduction compared to 2021 levels. There is also the upcoming ban on the sale of new petrol and diesel cars and vans which will be introduced in 2030.

Regulation covering battery disposal is also underway with full implementation plans by 2023 prohibiting the disposal in landfills or by incineration of waste industrial and automotive batteries. The battery regulation provides a mechanism for tracking supply chain emissions, the expectation is that the same mechanism can be deployed across multiple vehicle parts. In addition, there are several directives set by governing bodies, such as HSE and DEFRA, setting out guidelines and actions for the environmentally safe disposal of hazardous chemicals and effluent.

Upcoming regulation under development is likely to be more comprehensive, supporting the introduction of wider LCA with a common methodology to be agreed by 2025, addressing CO_2 emissions of cars and vans placed on sale in the EU market. This will be joined by further regulation to encompass the publication/reporting of sustainability information across all ESG topics alongside financial information in company directors' reports.

Finally, regulation is also underway to support the full cradle-to-cradle concept, and this is where we will see a framework for achieving the EU's 2050 climate neutrality target and to halt biodiversity loss. Furthermore, there is the EU Zero Pollution Action Plan (ZPAP) which has a focus on air, sea, and soil pollutants.

From what we can see, future legislation is likely to cover wider life cycle environmental and sustainability impact measures.

Battery production is leading this charge with an increased focus on life cycle and sustainability establishing the mechanisms for full life cycle monitoring.

The table below shows the regulations, directives, and working groups looking at the life cycle of products, including vehicles, from cradle to cradle. Overall, each aspect of life cycle impact, not just CO_2, is covered. The battery directive, which provides the mechanism to track CO_2 across the lifetime of a battery pack, was generated by the Circular Economy Action Plan (CEAP) which is not automotive focussed.

While the first rollout of full life cycle tracking has started with batteries this establishes the mechanisms for full life cycle impact monitoring.

LCA category	Raw Materials	Manufacturing	Product In use	Disposal	Recycling / Recovery
Air quality	CSRD, ZPAP	CSRD, ZPAP	Emissions regulation	CSRD, ZPAP	CSRD, ZPAP
Water and marine	Effluent regulation ZPAP	Effluent regulation ZPAP	-	Effluent regulation ZPAP	Effluent regulation ZPAP
Soil and land use	CEAP, ZPAP, CSRP	CEAP, ZPAP, CSRP	-	CEAP, ZPAP, CSRP	CEAP, ZPAP, CSRP
Other ecological damage	ZPAP	ZPAP	ZPAP	ZPAP	ZPAP

LCIA (Life Cycle Impact Analysis); **CEAP** (Circular Economy Action Plan); **CSRD** (Corporate Sustainability Reporting Directive); **ZPAP** (Zero Pollution Action Plan)

Recommendation 2

Support smaller businesses with LCA skills

The next chapter

The UK automotive industry has an opportunity to learn and grow together as part of this process. All parts of the supply chain must be encouraged to share best practice and help them understand the requirements now.

We have time to get this right and if we do, it poses a real opportunity for UK automotive manufacturers to lead the way and have a competitive advantage with a full set of emissions reports available.

It will be important for OEMs and industry to engage across the supply chain to share learning and identify early opportunities.

Battery passports are coming, and look set to be introduced by 2027. While these create a mechanism for monitoring carbon emissions across the supply chain, there is a level of supporting detail that will be incredibly complex and a real challenge for the industry to collate. This is where support will be needed from automotive manufacturers, especially to smaller companies in the supply chain, who cannot hire a team of LCA experts. It is imperative that best practice and knowledge is shared by everyone involved.

These battery passports also create a framework for recording further life cycle impact requirements, enabling a gradual rollout of the recording, and limiting of a number of emissions. It is not difficult to see it replicated across other parts of a vehicle, such as the motors, until the whole vehicle is covered under the same process.

The current and upcoming regulations for automotive battery production have an increased focus on life cycle and sustainability and these prove great building blocks. There are four key next steps that help break down the task in hand and provide realistic timescales:

> We have time to get this right and if we do, it poses a real opportunity for UK automotive manufacturers to lead the way

Activity	Now to 2025 →	2025 to 2030 →	2030+ →
Measure and record	**Carbon footprint** Identify all sources of carbon emission resulting from your business activities and set-up recording systems for scope 1, 2 and 3 GHG emissions.	**Life cycle Impact Analysis (LCIA) wider footprint** Understand the wider environmental impact of your business activities and implement a LCIA monitoring system. See CSRP and CEAP.	**Total environmental footprint** Develop a deep understanding of all emissions and environmental impacts to the eco-system. See ZPAP and CEAP.
Apply digital tools	**Battery passport – prepare** Automate the recording of carbon footprint data via digital tools. Prepare online solutions and platforms for passport sharing.	**Battery passport – implement** Implement an easy-to-access common digital passport that works across multiple systems, the battery supply chain and related industries.	**Battery passport – extend** Expand the use of battery passports to wider LCIA for complete environmental impact assessment. Develop advanced data analytics.
Minimise and Optimise	**Carbon footprint reduction** Actions covering, but not limited to: • In-house processes • Impact from scope 2 and 3 • Supplier selection	**Net-zero carbon ambition** Aim to achieve a net-zero carbon footprint across your business activities by addressing the data harvested in earlier years.	**LCIA footprint reduction** Based on wider LCIA and other ecological impacts, take action to optimise business processes, materials and supply routes.
Increase circularity	**Develop circularity** Improve waste management and increase use of battery recycled materials. Develop partnerships / capability in battery recycling and end-of-life collections.	**Increase circularity** Meet or exceed the EU minimum recycled content for Co, Li and Ni in new batteries. Consolidate and anchor recycled material supply chains.	**Widen circularity** Develop a long-term strategy for your business activities and supply chains to address wider ecological damage through circularity, CSRP reporting and CEAP.

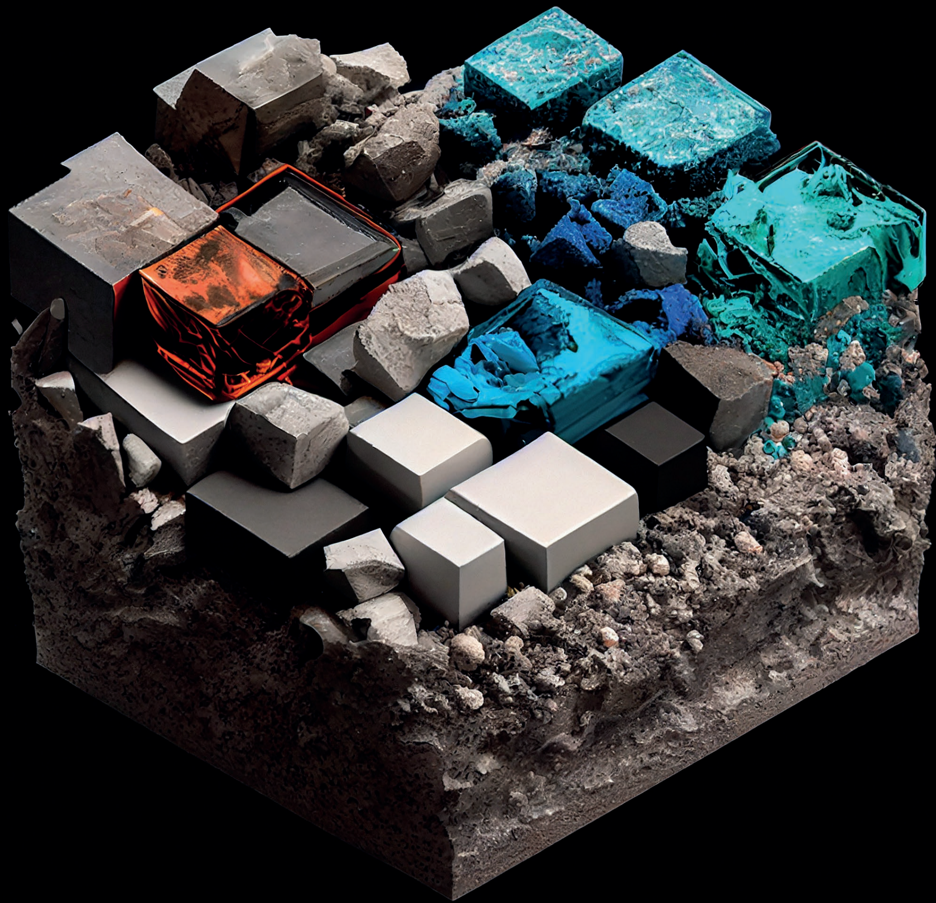
Value Chain Overview

Battery end-of-life value chain

With the growing adoption of electric vehicles (EVs) comes a new demand for the critical minerals needed to build new batteries, alongside a potential second-use market. The European battery directive provides targets for collection and recycling of EV batteries with minimum targets for recycled content in new EV batteries.

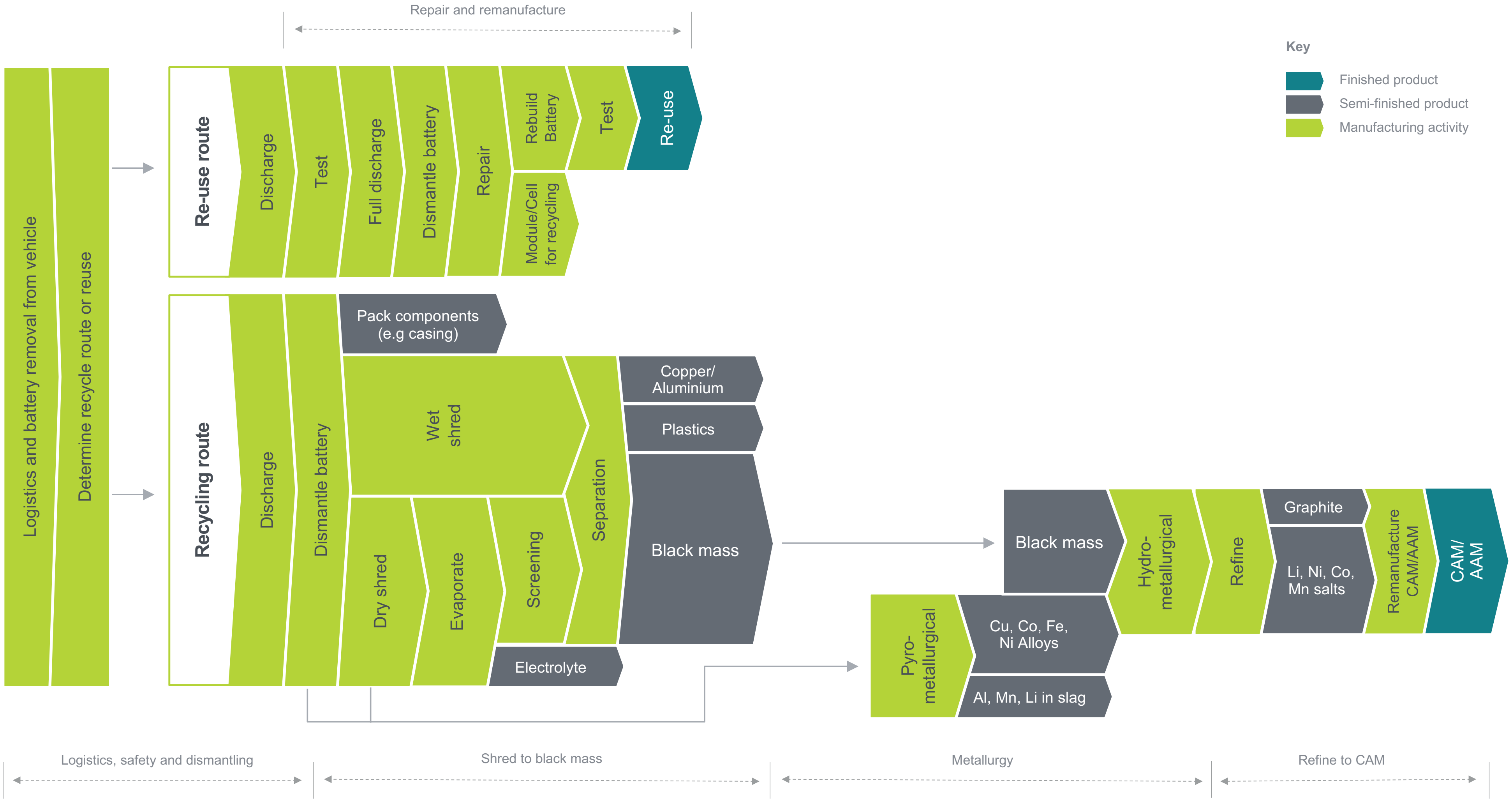
This automotive battery end-of-life value chain map shows the path of the UK's growing re-use and recycling industry.

Developed by the Advanced Propulsion Centre UK (APC), in conjunction with experts from industry and academia, this new value chain details the journey of an automotive battery from the end of vehicle use to second life and recycling to become cathode active material (CAM) and anode active material (AAM).



Lithium Ion Battery Mineral Components - Generative Ai

Automotive battery end-of-life value chain

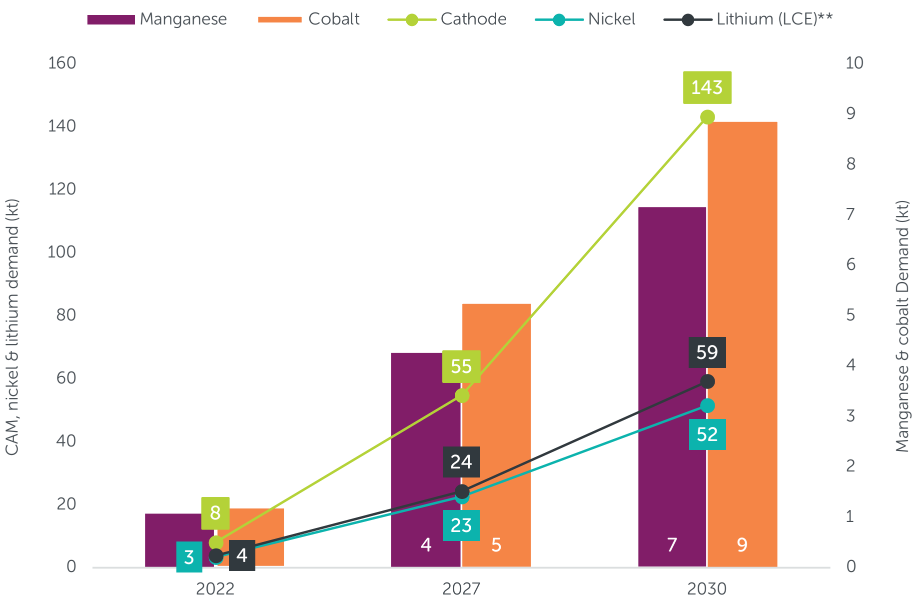


UK recycling forecast

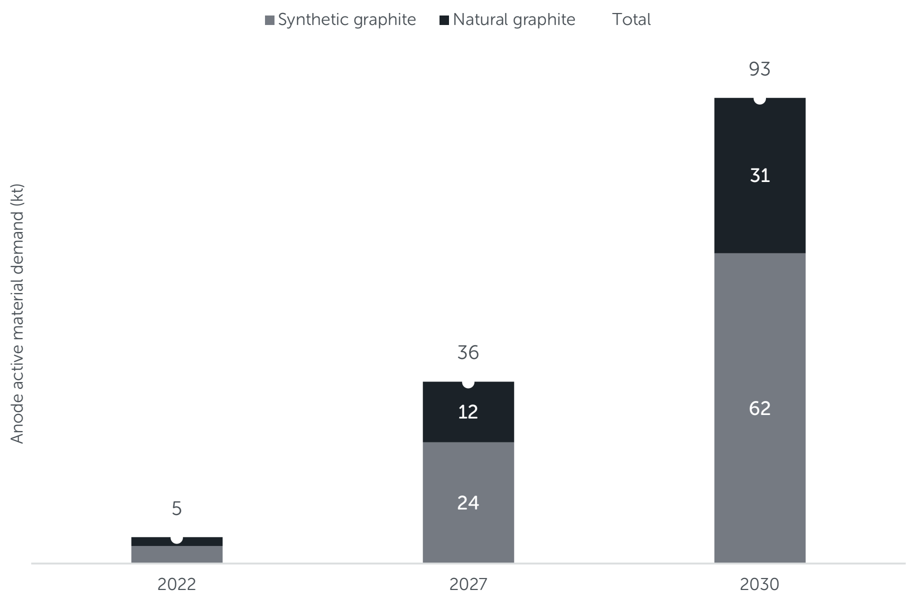
Recycling lithium-ion batteries has the potential to provide a source of critical materials for further lithium-ion battery production in the UK. Looking ahead, EV (including all electric vehicles: battery, hybrid, and fuel cell) retirements (xEV) are likely to become a dominant source of recycling feedstock. However, the near term is more difficult to forecast as we are still assessing the lifespan of EV batteries, both on the road and in secondary applications.

APC has created a UK forecast of potential recycling from xEV retirements, cell manufacturing scrap, and portable electronics. Here is a reminder of UK critical material demand for battery manufacturing.

UK cathode material demand



UK anode material demand



The UK needs more than 93kt graphite, 59kt of lithium carbonate equivalent, 50kt of nickel, 9kt of cobalt, and 7kt of manganese if all batteries used in xEV production in the UK are to be made here by 2030.

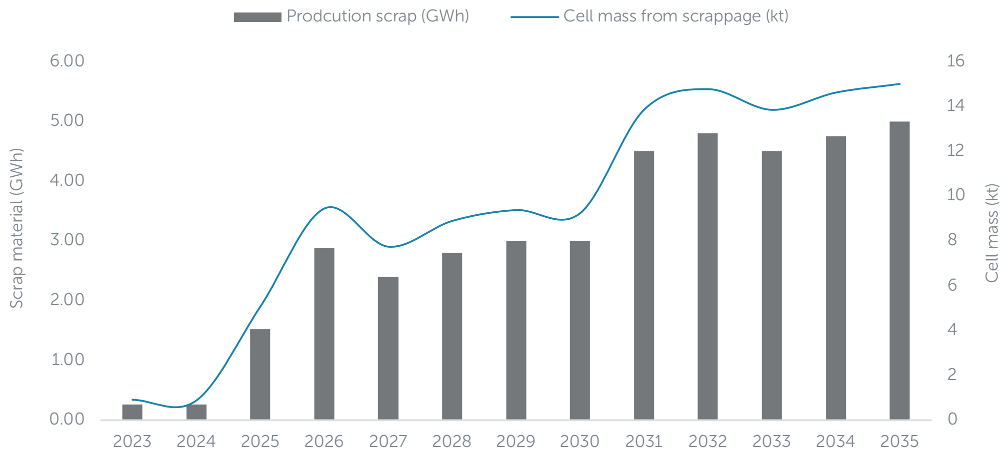
UK battery cell manufacturing scrap forecast

Scrappage from cell manufacturing or gigafactories occurs when the final cells are tested, but the majority comes from the process of making the cell itself. Cells are made by layering sheets of cathode, anode, and separator materials, and in the case of cylindrical cells, rolling the material. Cutting these sheets to shape produces offcuts, which can then be recycled.

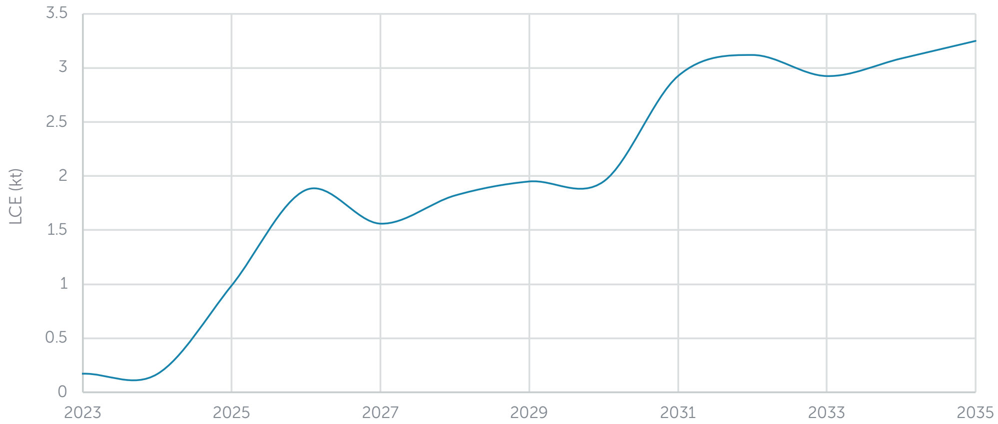
This chart is a dynamic model of UK gigafactory scrappage, estimating a 2030 production capacity of 60GWh and 100GWh in 2035. We assume new gigafactories will have a high scrappage rate of 20 percent in year one while production scales up, reducing to 5 percent when operating at full capacity.

The graphs pictured on this page demonstrate the expectation that large new facilities will initially have higher than average scrappage rates. If we assume a 95 percent recycling efficiency for Lithium Carbonate Equivalent (LCE) from cell manufacturing scrap, the more than 3kt per year of LCE from 2030 onwards is achievable. There is significant potential for variability in this forecast as new manufacturing facilities may be announced and facilities coming online could be more efficient than our assumptions.

UK cell manufacturing scrap



LCE from UK manufacturing scrappage



UK portable electronics scrappage forecast

The target for collection of portable battery waste in the UK is currently 45 percent, overall, including Pb-acid and Ni-Cd. The latest data for 2022 and 2021 shows a recycling rate of 10 percent for lithium-ion batteries. Looking back to 2018 it was as high as 20 percent.

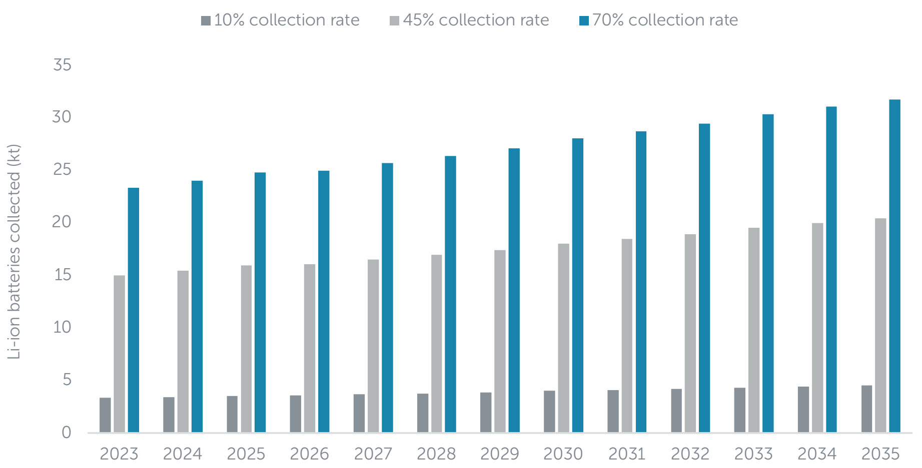
The EU battery directive targets 73 percent for the collection rate of portable electronics by 2031. DEFRA is currently consulting on updating its battery regulations.

In the chart below, we have modelled collection rates at 10 percent, 45 percent, and 70 percent to align with current achieved collection rates, the UK target, and the EU target. We assume a 70 percent LCE recovery efficiency, in line with EU targets.

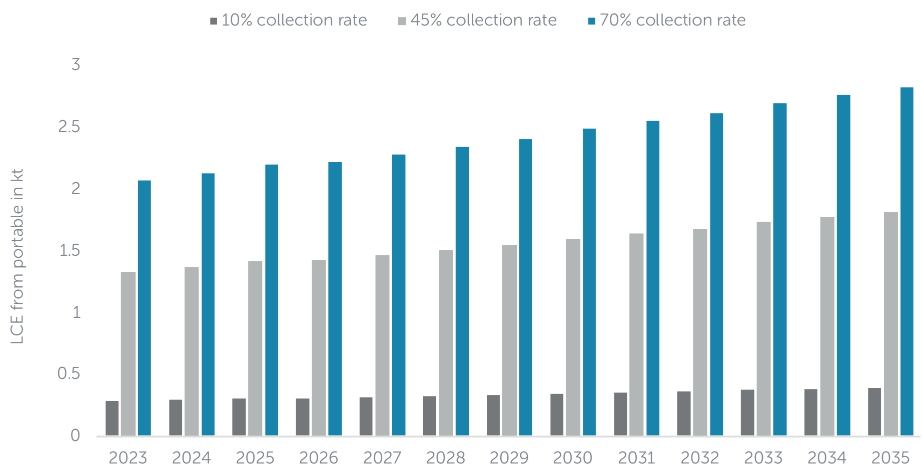
At current collection rates, portable electronics would not significantly impact lithium supply compared to contribution from cell manufacturing scrap. However, if this could be increased to meet the 73 percent target, portable electronics contribution would be comparable to that from cell manufacturing scrap.

There is a caveat to this, cell manufacturing scrap comes from just a few gigafactories. A recycler can be set up near a gigafactory and have a single dependable source, making recycling simpler compared to the variety produced from portable electronics.

UK collection of portable Li-ion batteries



LCE from portable lithium ion batteries



UK xEV retirements forecast

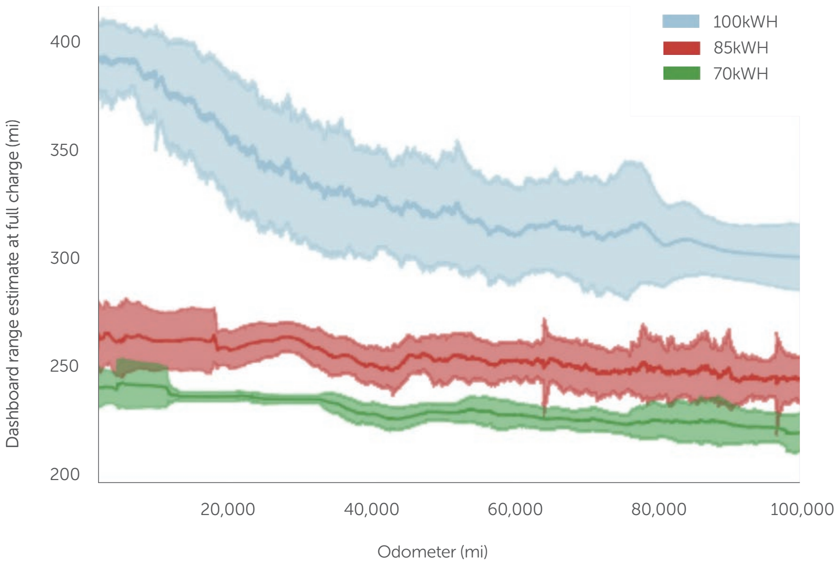
Currently, we do not yet know how long xEV batteries will last. The Nissan LEAF has been on the market for over 12 years now and Nic Thomas, Nissan's Marketing Director for the UK, told Forbes: *'Almost all of the batteries we've ever made are still in cars, and we've been selling electric cars for 12 years. We haven't got a great big stock of batteries that we can convert into something else.'*

In 2019 the managing director of Renault-Nissan Energy Services, Francisco Carranza, estimated that the batteries may last 22 years. The Tesla Model S has been on sale for over a decade and total EV battery replacements are less than 5 percent, which includes some recall events.

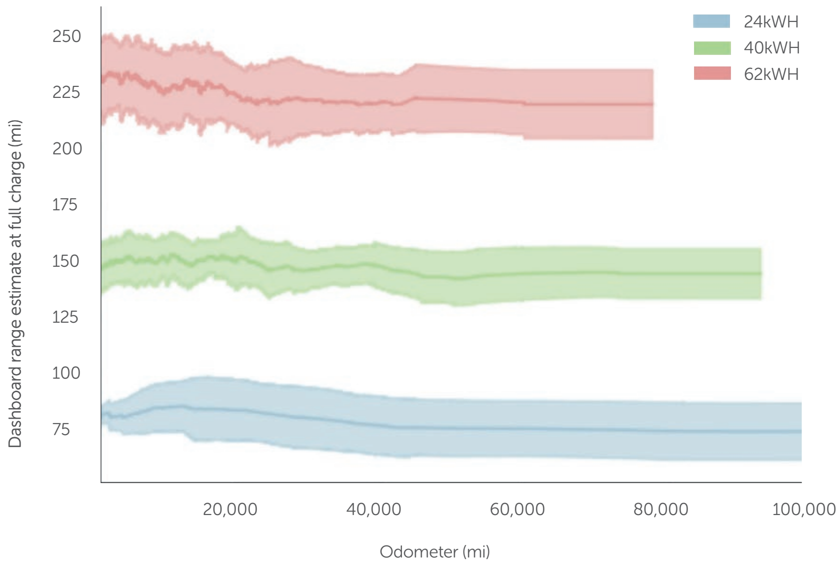
Even after the 8-year/100,000-mile warranty period ends, neither Tesla nor Nissan have seen an influx of batteries for replacement.

A study by Recurrent looking at the remaining range for Tesla Model S and Nissan LEAF vehicles after 100,000 miles shows very little change in range. Certainly not at a level that would be noticeable to the average xEV user. Interestingly, the larger 100 kWh Model S battery shows a significant degradation over the first 40,000 miles but then levels off.

Tesla Model S Range over time



Nissan Leaf range over time



Data supplied by Recurrent

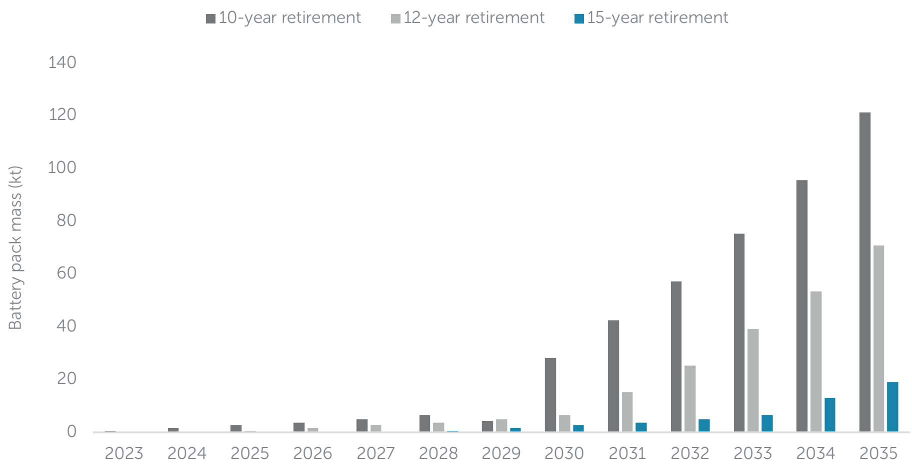
Newer models of xEV are likely to take lessons forward from earlier designs and make further improvements to battery life, however the impact of more rapid charging is not yet known. Here we have modelled 10, 12 and 15-year life for xEVs.

In this model we have assumed 20 percent of stationary energy storage demand is serviced by xEV retirements, with those batteries returning 10 years later into this recycling feedstock.

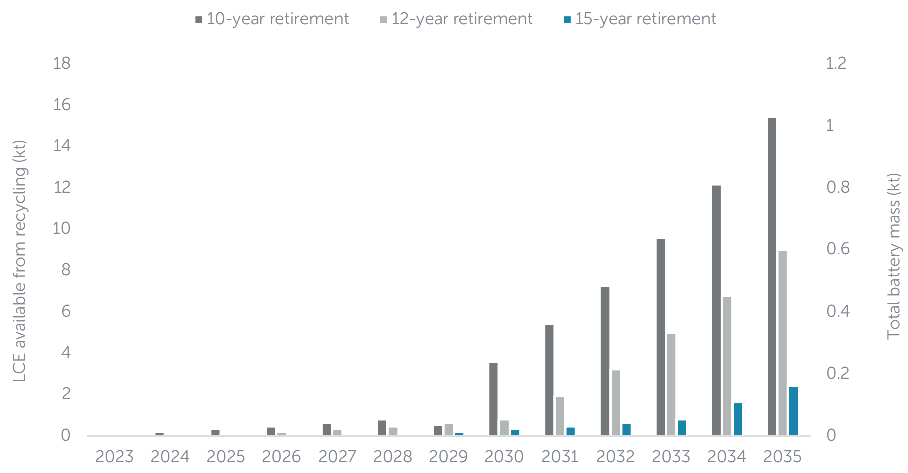
A 90 percent recycling efficiency has been assumed based on current research and development and is likely to be achievable by 2030.

A 10-year scenario is a common assumption, so based on this we see xEV retirements become the dominant source of LCE from 2030. However, this situation could quickly change if retirement is delayed by just a few years.

UK xEV battery mass from xEV retirements



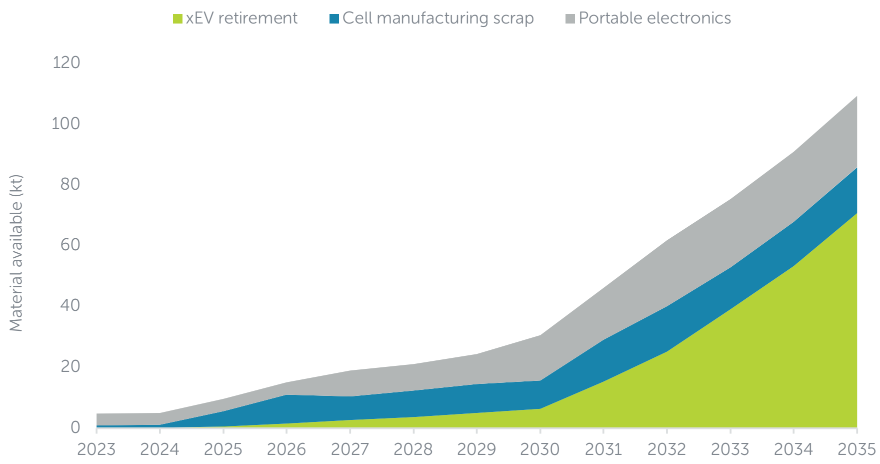
xEV retirements in UK



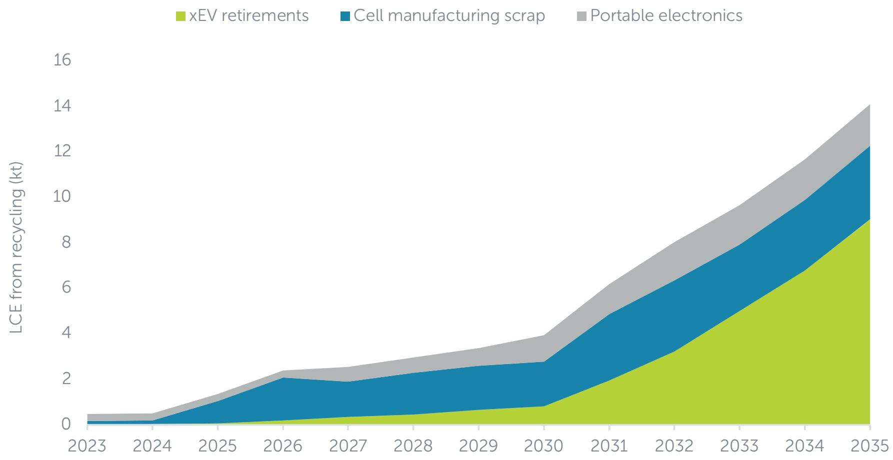
UK total material from recycling

This model of total available material and LCE from recycling takes the 12-year xEV retirement assumption. The model assumes that collection rates for portable electronics will improve from 10 percent in 2023 to 45 percent by 2035. Both assumptions have significant uncertainties, as pointed out in this overview.

UK Li-ion material for recycling

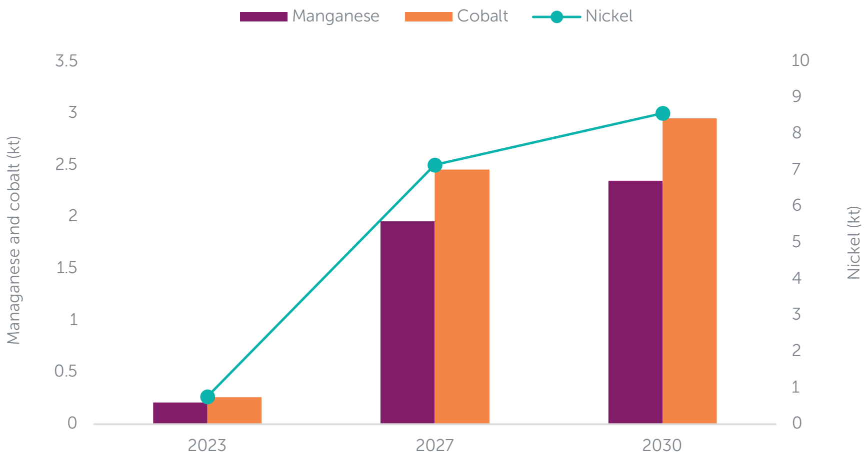


UK LCE from recycling

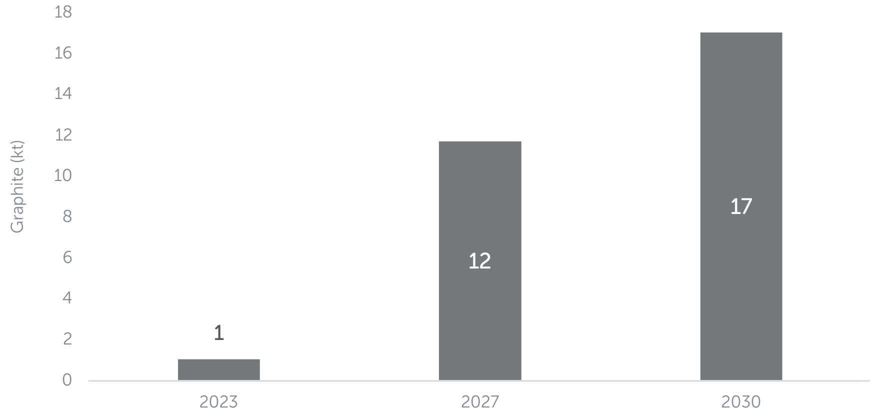


As a reminder, the UK would need 59kt of LCE to manufacture all batteries required for xEV production in the UK in 2030. By 2030 we estimate around 4kt of LCE would be sufficient to meet the 6 percent recycled content target from the EU battery directive. The same model has been used to generate forecasts for nickel, cobalt, manganese, and graphite. For nickel, cobalt, and manganese there is a 90 percent recovery efficiency and for graphite, a 70 percent recovery efficiency. Such a supply of manganese, cobalt and nickel would allow the UK to meet EU battery directive recycled content targets.

Cathode materials available from recycling



Anode material available from recycling



Focus on re-use

As already highlighted, the useful life of a battery could extend beyond the typical life of a car. Stationary energy storage provides an opportunity to reuse automotive batteries that might be deemed no longer suited to automotive needs.

This provides an opportunity for ongoing revenue for automotive batteries. An OEM is responsible for the end-of-life management of the battery, including battery repairs, refurbishment, and grading for secondary use. This enables OEMs to have a continuous revenue from batteries before they are finally recycled.

Companies such as Autocraft Solutions Group offer such a service where they take an automotive battery, check its health, and make necessary repairs. Consider a battery that has been in a crash. These are typically written off but may be in perfect condition. These batteries can be checked and reused for stationary energy storage. Other batteries which may have reduced capacity, could need some cells or modules replacing, but most of the battery can be reused. The replaced cells or modules can be recycled.

Refurbished batteries can be sold for ~£70/kWh into secondary use cases such as stationary storage. This creates a revenue opportunity for OEMs that maintain battery ownership and is in keeping with the spirit of the three Rs – Reduce, Reuse, and Recycle.

Extending battery life

The life of automotive batteries can be extended beyond the first vehicle, becoming a replacement battery for another vehicle, or applied as stationary energy storage.

Autocraft has received over 800 EV batteries. The majority of which can be reused, with some requiring repairs before being characterised for re-use in another EV or stationary storage. Typical repairs are just one battery module and some connectors again.

With the majority of each battery pack being re-used just 1.4% of battery mass received has gone on to a potential recycling route

Battery design is key to enabling simple repair. The majority of designs only allow for the changing of a whole module which will contain multiple battery cells. If only a single cell needs replacing it would be more efficient and low-cost where the design of the battery enables this.

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A conservative estimate of stationary storage demand would see demand outstripping potential supply from retired xEVs.

This has the potential to delay the onset of material availability from EV retirements. While that sounds like a negative, secondary and further use of batteries provides a potential extra revenue stream for OEMs, reducing the life cycle impact of battery manufacturing by continuing to use batteries for longer rather than producing new ones.

Image: battery dismantling provided by Autocraft

Value in battery materials

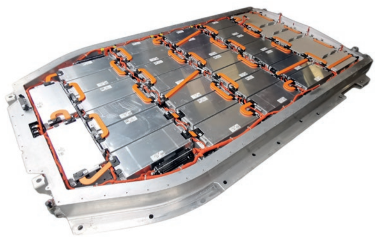
56 percent of the value of a battery pack is made up of its chemical components.

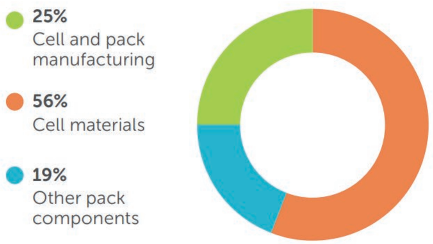
A battery cell value stack (NMC 811), based on a cost study conducted by APC in 2022, demonstrates that 45 percent of the value of a cell is in the cathode materials.

Given the value of materials within battery manufacturing, it would appear to be obvious to recycle those materials and while most battery materials can be recycled, it is not always practical and economical to do so. For example, currently graphite is not typically recycled. There is no process to refine the graphite from recycling into battery grade graphite and it is seen as abundant and low-cost so the financial incentive to recycle is low. Until recently, lithium has not typically been recycled but both the cost of lithium and the introduction of the EU battery directive for lithium recycling are starting to change this. The electrolyte accounts for 9 percent of the value of a cell and recovered electrolyte has a much lower value. In the absence of standardisation of electrolyte, it is difficult to sell on. Whilst it is possible to recover, it is typically incinerated to avoid onward contamination.

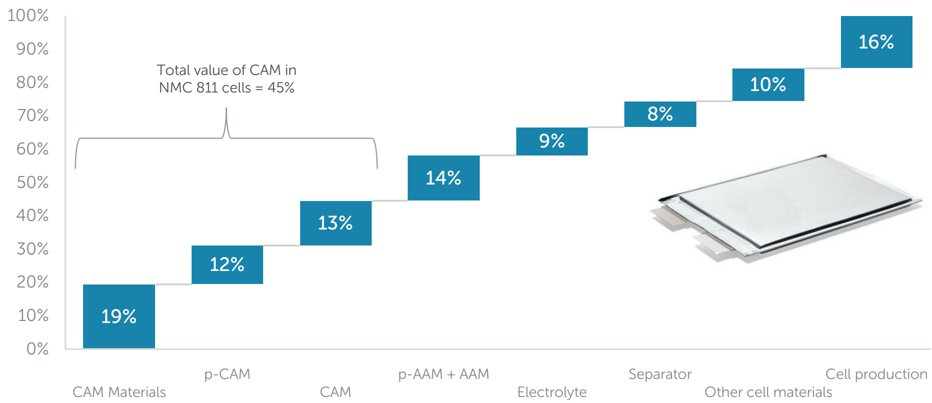
Currently LFP is not recycled, although there are processes being developed in UK universities to enable this. The APC forecast does not include LFP recycling. However, if we assume that available material from xEV batteries, cell manufacturing, scrap, and portable electronics is recycled and the value of materials from recycling can match that of virgin material, then the value that can be extracted is significant. **Based on APC's recycling forecast, the value of critical materials for cathode and anode production, along with steel, aluminium and copper could be worth more than £0.7 billion by 2030.**

Based on these assumptions, revenue per kWh from a battery would be roughly £150/kWh.

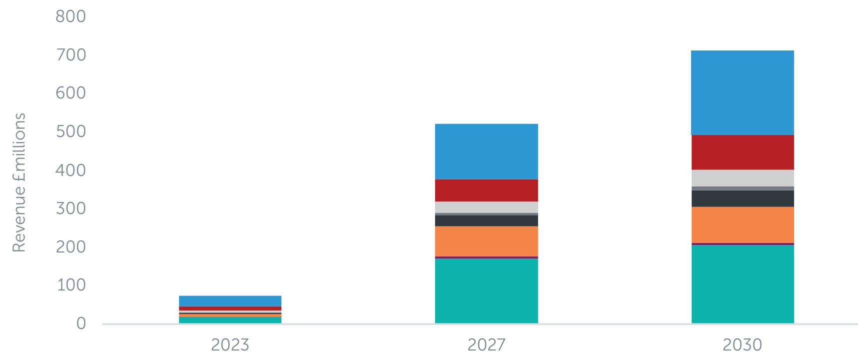




Battery cell value chain



Potential revenue from recycled battery materials



Current UK capacity

The UK currently has some capacity to produce black mass and this capacity is growing with projects like RECOVAS underway. However, this is predominately exported to undergo pyrometallurgical recovery. As it stands, the best prices for black mass are found in Asia, so UK-produced black mass can undertake a considerable journey before being recycled.

The UK has no hydrometallurgical capacity and no CAM production. Ideally, the refinement processes would be aligned from hydrometallurgy process to the CAM process.

Going from black mass to CAM multiplies the value of the material. Investing in hydrometallurgy and CAM facilities in the UK would enable this revenue to stay here, keeping critical materials for UK battery manufacturing. Our nation has an opportunity to create a low carbon circular battery economy over the coming decades if the building blocks are put in place now.

The next few years will be challenging as only a small number of facilities would be commercially viable with some significant risk in the supply of material to recycle, but this will ramp up over the next 20 years. This is an opportunity that government, OEMs and private investors can take advantage of through supporting R&D and initial plant deployments. Great work is already being done by UK universities and as part of projects like RECOVAS and RELIB.

Our nation has an opportunity to create a low carbon circular battery economy over the coming decades if the building blocks are put in place now.

Costed value chain

Most of the value in a battery pack is in the cells and its chemical components – the majority of the value lies in the chemicals used for anodes, cathodes, and electrolyte.

	Logistics, safety, and dismantling	Shred to black mass	Metallurgy	Refine to CAM
CAPEX (per kt capacity)		£1-2 million	£15-20 million	>£20 million
OPEX (per kt processed)	£1-3 million	£0.5-1 million	£2-3 million	£5-20 million*

*Depending on input and output materials and target chemistry.

By going from black mass to salts ready for CAM manufacturer the value of the material is increased four fold. Based on percentage of each material in black mass generated from an average battery.

Black mass value

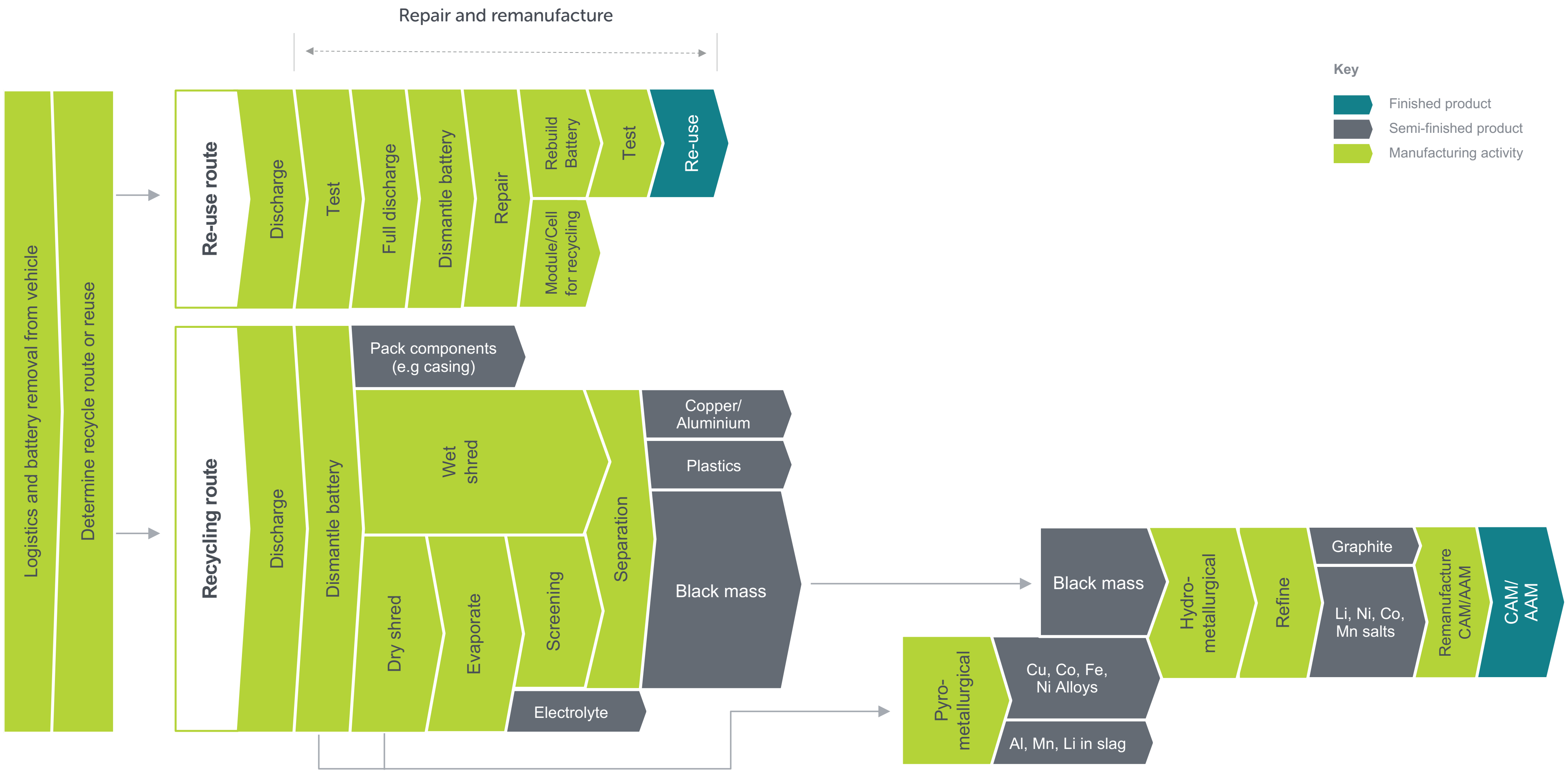
£4 millon per kiloton

Processed value

£16 millon per kiloton

Value is increased four fold when material is processed

Researchers shred cells in the safety chamber at the University of Birmingham



	Logistics, safety, and dismantling	Shred to black mass	Metallurgy	Refine to CAM
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Regulation and Permitting

The initial challenge for setting up new recycling facilities for EV batteries is obtaining the required permits. First, the environmental permits must be in place for a facility. The next step is to apply for Approved Battery Treatment Operator (ABTO) and Approved Battery Exporter (ABE). While the costs are relatively low, the time required to get permits in place can be considerable (in the region of 18-24 months), therefore potentially adding to costs owing to land being unused during this period.

Logistics

The initial cost of transporting a used battery can be high due to health and safety concerns. Recyclers charge an OEM over £5k per battery to recycle but logistic costs could exceed this owing to packaging and transport requirements for a damaged battery.

Dismantling

Dismantling is conducted by hand and requires trained high voltage technicians. A study by Nomura Research Institute (NRI) estimated dismantling costs at £12 per kWh, meaning a typical 60kWh battery costs around £720 to dismantle. For comparison, labour costs in China reduce this to £145.

Economic viability of recycling

The Nomura Research Institute (NRI) study showed that recycling is not currently profitable in Europe because of high running costs of labour and energy cited as the main issue. In China, labour costs and economies of scale mean recycling is commercially viable.

In the UK we have world-leading R&D in recycling that can be leveraged to bring down costs and increase the revenue generated from recycling. We have an ecosystem enabling automotive OEMs, battery manufacturers, recyclers, and CAM manufacturers to be in close proximity, therefore significantly reducing transport costs. The ecosystem needs to grow to build economies of scale, and this is likely to need intervention to support the first players in the market.

Recommendation 3

Recycling and Re-use regulation and permitting review

Recommendation 4

Education on emissions from raw materials versus recycled materials to aid decision-making on investment

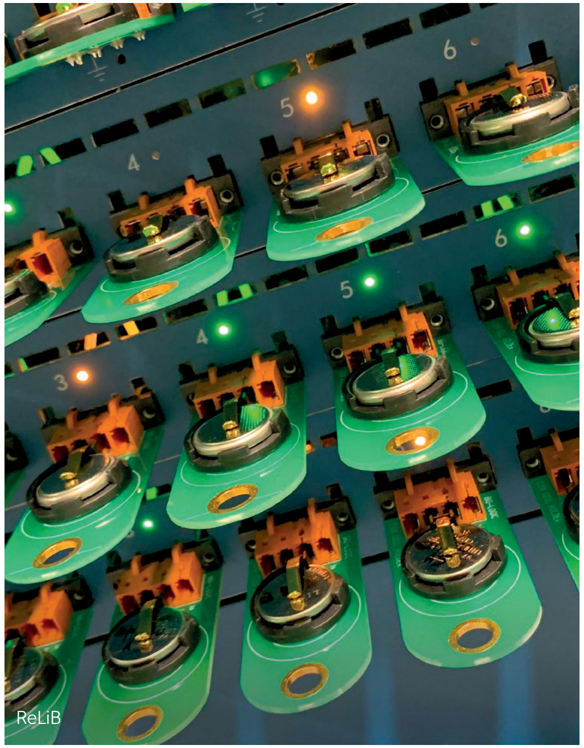
Vermiculite used in packaging to combat thermal runaway of damaged battery provided by SER

Battery dismantling provided by Autocraft

Innovation projects in UK

There are already some great innovative recycling projects in the UK, some of which have the potential to completely overhaul the current value chain.

Here are two examples of UK projects which have received funding from the Faraday Institution and Advanced Propulsion Centre.



ReLiB

1. ReLiB – Sustainable Management of Lithium-ion Batteries
2. EMR – RECOVAS – Advanced Propulsion Centre (apcuk.co.uk)

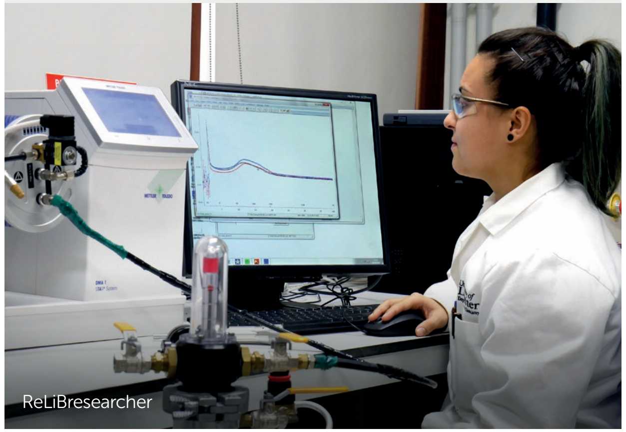
ReLiB

Recycling and Reuse of EV Lithium-ion Batteries – The Faraday Institution

"ReLiB's vision is to provide a UK EV battery recycling industry with a pipeline of scalable technologies that are responsive to regulatory drivers, new battery designs and chemistries, and the opportunities afforded by Industry 4.0."

Project highlights:

- Automation of battery dismantling using robotics which would greatly reduce cost of dismantling
- Development of bioleaching processes as an alternative or complimentary technology to hydrometallurgy
- Direct recycling of common cathode materials bypassing shredding and metallurgy to provide direct recovery of cathode material from dismantled cells
- Provide facilities to aid scale-up and development of skills



ReLiBresearcher

RECOVAS

RECOVAS – EMR – RECOVAS – Advanced Propulsion Centre (apcuk.co.uk)

The RECOVAS project looks at introducing a new circular supply chain for electric vehicle batteries in the UK, by developing the infrastructure, at scale, to collect and recycle electric vehicles and their batteries.

Project highlights

- Creation of a circular supply chain for electric vehicle batteries in the UK
- Construction of processes, design guidelines and a physical pilot facility to recover vehicle batteries, allowing packs and materials to be re-used or recycled
- Development of a process for analysis of used batteries, directing materials to the most appropriate recycling stream – from pack and cell re-use to recycling of materials
- Requirements definition to enable recyclability to be designed into future vehicle battery packs

recovas™

Glossary and definitions

Logistics
A battery needs to be delivered to site either as part of the vehicle or after removal. If the battery is visually damaged extra precautions are required which increase cost of logistics.

LCE
Lithium Carbonate Equivalent

Re-Use
An automotive battery can be repurposed by replacing or repairing damaged cells or modules depending on the design. Batteries are tested to determine the state of health and which cells/modules need replacing. After repair batteries are tested to determine suitability for onward use in another vehicle or stationary storage application from domestic to energy infrastructure.

Recycle
Typical automotive batteries containing nickel and cobalt are recycled to recover these high-value materials. Increasingly lithium is being recovered and this is likely to increase in part due to the value of lithium and in part due to policy and regulation aimed at securing local supply. Although it is possible to recover many materials other materials of note such as anode materials, plastics and electrolyte are often within the waste of the recycling process.

Discharge
Batteries are discharged to reduce the risk of short-circuit and self-ignition. This can be done in a number of ways, for example via electronic load.

Dismantle
Casing is removed and can be separately recycled, modules or individual cells might be removed depending on process. This is challenging to automate due to variety in battery, module and cell designs and the use of adhesives which can be used as a structural and thermal management component.

Wet Shred
The shredding of batteries in a solution, e.g., water. Wet shredding potential enables the shredding of charged batteries. Wet shredding also eliminates generation of airborne particulates and fire hazards, making it potentially safer. However, the waste solution will contain hazardous compounds requiring treatment.

Dry Shred
Dry shredding requires no specialist chemicals and is easily scaled up. Dry crushing can be carried out in cryogenic or inert environments to reduce the risk of fire and release of hazardous gases. Dry shredding requires an electrolyte treatment step, for example by combustion or evaporation and condensation. Dry shredding can allow the recovery of electrolyte whereas in wet shredding it is destroyed.

Separation
Separation of the particles generated by shredding can include a number of steps including further milling of the particles. The shredded material can be separated into plastic, separator material, steel, nickel and aluminium tabs, aluminium and copper current collectors and black mass. Not every recycler will produce all of these products. Separation can be via:

- sieving based on particle size
- magnetic separation to remove steel structures and other ferrous metals
- electrostatic separation to remove plastics from the metallic components
- eddy current separation to separate based on material conductivity which can separate copper, aluminium and plastics
- density separation either via vibration, rotating table air or fluid can separate metal from plastic as well as the current collectors from the cathode and anode materials

Black Mass
Black mass contains the high-value materials from the cathode and anode. It may also contain other materials, such as PVDF, $LiPF_6$, steel, copper, and aluminium depending on shredding and separation processes employed which means that the percentage of high-value materials can vary.

Pyro-metallurgy
Material is put into a high temperature furnace. Plastics, polymers, and electrolyte are burned away leaving a metal alloy of cobalt, copper, iron, and nickel and a slag containing aluminium, manganese, and lithium. Pyrometallurgy does not require batteries to be sorted or material of a certain size, however it is advantageous to sort batteries beforehand to reduce impurities which can distort the downstream hydrometallurgical refining. However, energy use is high and therefore so is cost and CO_2 emissions (depending on energy source). The alloy and slag require additional processes to recover the raw materials and materials such as graphite cannot be recovered.

Hydro-metallurgy
Hydrometallurgy can involve a number of steps depending on battery chemistry and required materials. Material is dissolved using corrosive liquids. Once dissolved, organic solvents are used to separate the metals. Pyrometallurgy can be used as a pre-treatment step for hydrometallurgy, potentially improving the recycling efficiency, or hydrometallurgy can be performed on black mass material from shredding.

Refine and Remanufacture
The metallurgy step can produce raw materials which constitute 19 percent of value of a cell however these materials cannot be used directly in a battery cell. Refined metal compounds, such as nickel and cobalt hydroxide, are used to manufacture CAM material which constitutes approximately 45 percent of the cost of the cell

CAM
Cathode Active Material. Constitutes 45 percent of value of a cell.

AAM
Anode Active Material. Constitutes 14 percent of value of a cell.

With thanks to

Altilium Metals

Autocraft SG

EMR group

Faraday Battery Challenge

Material Processing Institute

RECOVAS

ReLiB project

SER group

WMG (Warwick Manufacturing Group)

Annex: The Regulatory Landscape

Regulation – what is confirmed

There is already regulation in place in the UK and in Europe that has set targets as part of the drive to reach net zero. For vehicle tailpipe emissions the following regulation is approved and in place:

The EU Green Deal/Fit for 55

Approved in October 2022, and applies to both cars and vans, targeting:

- 55 percent CO_2 emission reduction for new cars and 50 percent for new vans by 2030 (compared to 2021 levels)
- 100 percent CO_2 emission reduction for both cars and vans by 2035

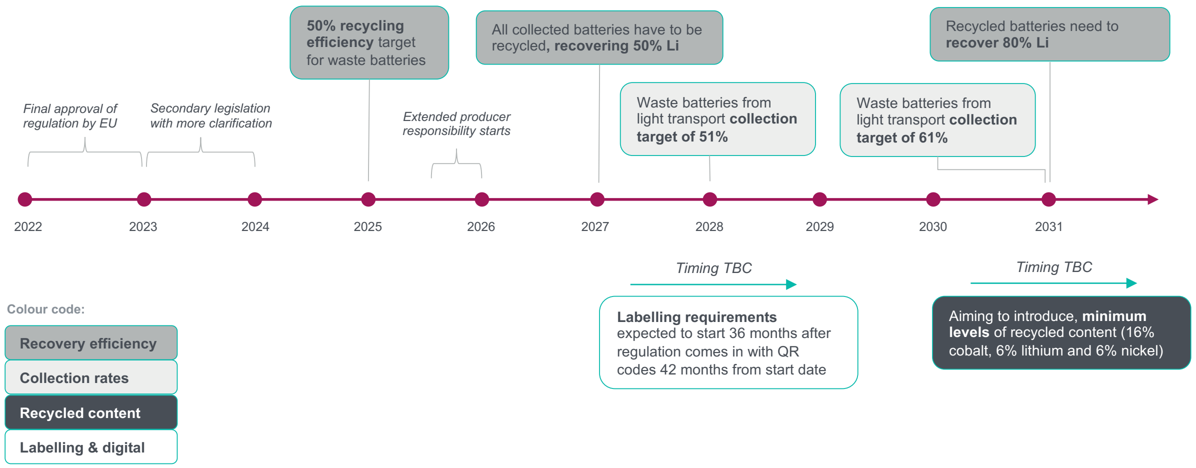
The UK Transport Decarbonisation Plan (TDP), Net Zero Strategy and New Road Vehicle CO_2 Emissions Regulatory Framework, approved July 2021 and October 2021, targets:

- End the sale of new petrol and diesel cars and vans from 2030
- From 2035 all new cars and vans much be zero emission at tailpipe
- Introduce a zero-emission vehicle mandate setting targets for a percentage of manufacturers' new car and van sales to be zero emission each year from 2024
- End the sale of new petrol and diesel HGVs from 2040, with <26t vehicles from 2026

For battery related carbon footprint, the following regulation is confirmed and in place:

EU Battery Regulation, provisionally agreed December 2022 (final legislation expected 2023), and prohibits the disposal in landfills or by incineration of waste industrial and automotive batteries and accumulators with the following metrics:

- Waste battery collections
- Material recovery rates targets
- Minimum recycled content
- Labelling and battery passport



What is confirmed continued...

Hazardous Chemicals and Effluent

Comprising of:

- REACH Regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals) – helps protect human health and the environment from risks posed by chemicals used or placed on the EU market
- RoHS Directive (Restriction of Hazardous Substances in Electrical Equipment) – more specific for electrical goods
- HSE's COSHH regulation (Control of Substances Hazardous to Health) protects employees and others from exposure to hazardous substances
- Environmental Permitting (DEFRA) – regulates effluent wastewater discharge and treatment

Upcoming regulation

There are currently two pieces of legislation under development, or in early adoption phase, which will support the introduction of wider LCA. These are:

EU Fit for 55

Full life cycle assessment framework which:

- will see the EU look to develop a common methodology by 2025 to assess the full life cycle of CO_2 emissions of cars and vans placed on the EU market
- will include the fuels and energy consumed by these vehicles
- manufacturers may voluntarily, report to the Commission on the life cycle emissions of new vehicles they place on the market.

EU Circular Economy Action Plan (CEAP)

Which was adopted in March 2020 and covers multiple industries including batteries and vehicles. It provides the framework for achieving the EU's 2050 climate neutrality target and to halt biodiversity loss:

- targeting sustainable products and circularity
- promoting reduced waste and secondary raw materials
- enabling conditions for increased circularity.

EU Corporate Sustainability Reporting Directive (CSRD)

- publication/reporting of sustainability information across all ESG topics alongside financial information in directors' reports
- EU-wide audit requirement for reported sustainability information
- companies must digitally tag sustainability information for onward transmission into the European single access point database.

Further regulation, which covers the whole cradle to cradle concept, under consideration include:

EU Zero Pollution Action Plan (ZPAP)

Adopted May 2021 with 2030 targets set to:

- reduce the number of premature deaths caused by air pollution by 55 percent
- improve water quality by reducing waste, plastic litter at sea by 50 percent and microplastics released by 30 percent
- improve soil quality by reducing nutrient losses and chemical pesticides use by 50 percent
- reduce the EU ecosystem threats to biodiversity by 25 percent
- reduce transport noise by 30 percent
- significantly reduce waste generation and municipal waste.

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