

Automotive Lithium ion Battery Recycling in the UK

Based on a feasibility study by Anwar Sattar,
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at WMG, University of Warwick



REPORT SUMMARY: SEPTEMBER 2020

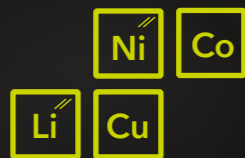
Produced by WMG, supported by the Advanced Propulsion Centre
Electrical Energy Storage Spoke and the High Value Manufacturing Catapult.

Key Findings

▶ THE ELECTRIC REVOLUTION IS WELL UNDERWAY AND THE **UK IS AMONGST THE BIGGEST ELECTRIC VEHICLE MARKETS IN EUROPE**



- ▶ By 2035, most passenger cars will contain a lithium ion chemistry traction battery. Lithium ion batteries contain rare and valuable metals such as lithium, nickel, cobalt and copper, many of which are not found in the UK.
- ▶ UK-based OEMs pay between £3 and £8 per kg to recycle end of life lithium ion batteries that are exported abroad for material recovery. The material must later be repurchased.



▶ **METALS** ARE THE MOST RECYCLABLE COMPONENTS WITHIN LITHIUM ION BATTERIES

- ▶ The average value in end of life automotive packs is £3.3/kg for BEVs and £2.2/kg for PHEVs.
- ▶ A huge opportunity exists for lithium ion battery recycling in the UK.
- ▶ By 2040, the UK will require 140GWh worth of cell production capability, representing 567,000 tonnes of cell production, requiring 131,000 tonnes of cathodic metals. Recycling can supply 22% of this demand (assuming a 60% recycling rate and 40% reuse or remanufacture).
- ▶ The break-even point for an automotive lithium ion battery recycling plant is 2,500 - 3,000 tonnes per year if the chemistry contains nickel and cobalt.
- ▶ The three greatest costs for recycling plants are transport (29%), purchase (29%) and hourly labour (23%).



▶ **BY 2040, 339,000 TONNES OF BATTERIES ARE EXPECTED TO REACH END OF LIFE**

Abbreviations used in this Report

NEDC: New European Driving Cycle
 LMO: Lithium Manganese Oxide
 LNO: Lithium Nickel Oxide

NMC: Nickel Manganese Cobalt Oxide
 NCA: Nickel Cobalt Aluminium Oxide



“Electric vehicles offer huge potential for decarbonising transport and improving air quality, but as we accelerate their early market we must equally be thinking about what happens at the end of their useful life. Batteries in particular contain significant quantities of materials which are costly to extract and refine and which could be hazardous to the environment if improperly disposed of.

Investment is needed to create suitable recycling facilities in the UK within the next few years, and beyond that, research is needed to allow economic recovery of much greater proportions of the battery material. In doing so we will protect the environment, secure valuable raw materials, and reduce the cost of transport.”

David Greenwood
 Professor of Advanced Propulsion Systems, WMG, University of Warwick

“WMG has been at the forefront of the development of battery technology for the future of electric mobility in the UK. Internal combustion engines and systems will be replaced by electric motors, power electronics and battery packs.

A key part of that future is how we responsibly recycle the materials contained in the batteries and thus create a commercially valuable circular economy. This report is one of the best that I’ve seen to present the challenges and the opportunities in such a clear way. It’s an excellent piece of thought leadership, from the leaders in their field”.

Dick Elsy
 CEO, High Value Manufacturing Catapult

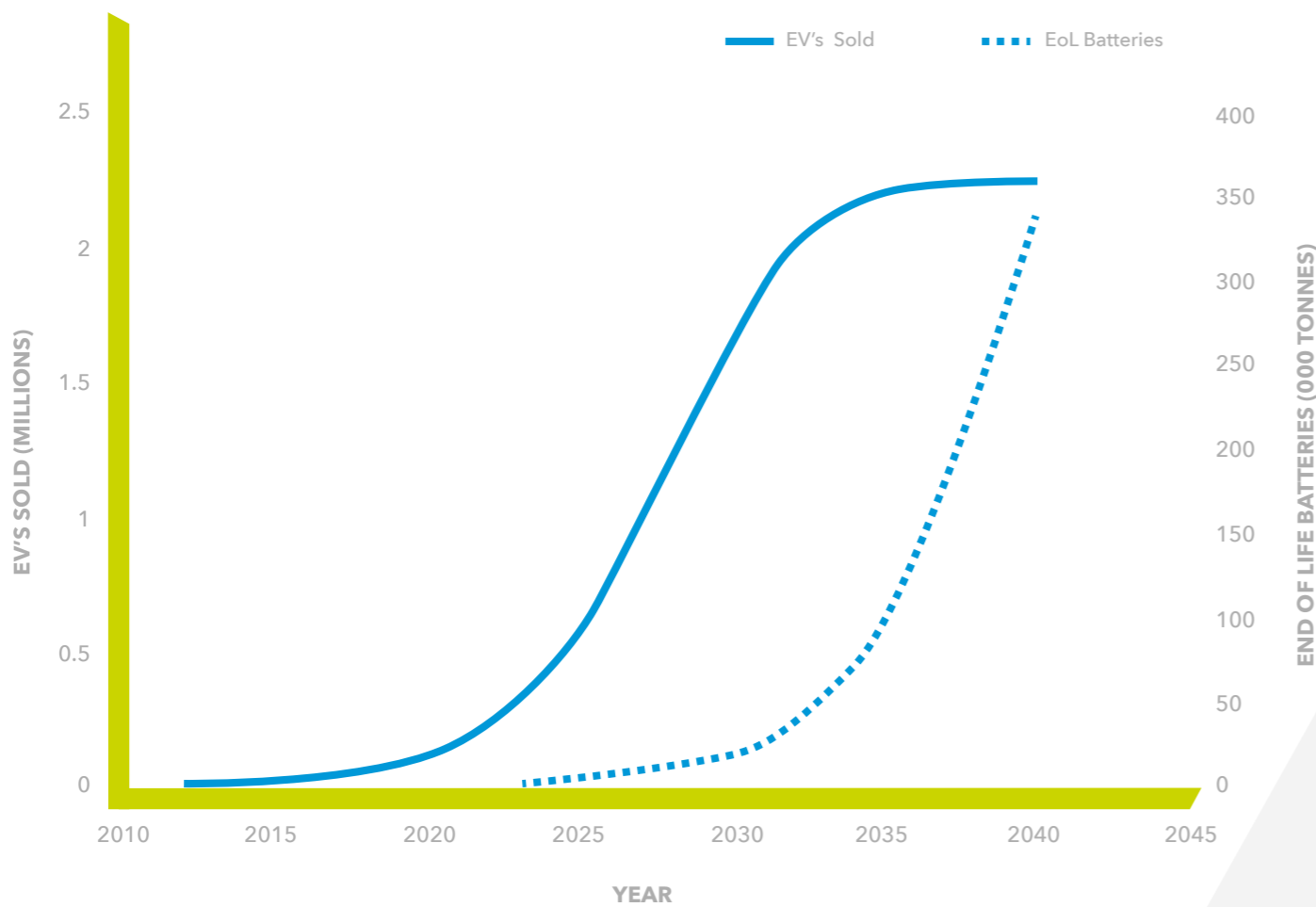
End of Life Batteries

From 2035 it is proposed that every new passenger car sold in the UK will be non-polluting - in practice, this means that new vehicles sold after 2035 will have a traction battery.

Electric vehicle traction batteries can range in mass from 50kg to >600kg. Each of these batteries contain a significant amount of rare and strategic metals, that must be imported as the UK has no economically viable deposits.

If all the vehicles sold in the UK are to contain a traction battery, the market penetration for such vehicles will follow a similar trajectory to that shown in Figure 1.

FIG 1 End of Life Batteries



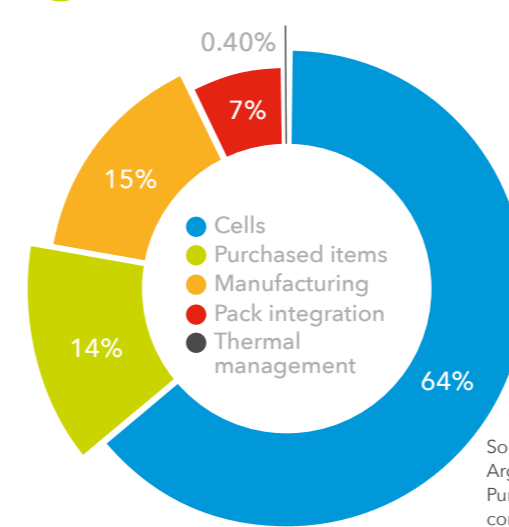
Assuming that the average lifespan of a battery is 11 years, the volume of batteries coming to 'end of life' is projected to be around 1.4 million packs per year by 2040. This translates to around 339,000 tonnes of batteries per year (based on the average pack mass of 238kg) and assuming 60% are recycled; 203,000 tonnes per year that will require recycling.

Where is the Value?

In 2018, the average values for end of life battery packs were around £1200 for BEV packs and £260 for PHEV packs. In BEVs the average value per pack for non-cell components was estimated at an average of £128 (source: WMG; International Dismantlers Information System (IDIS), vehicle manufacturer's websites).

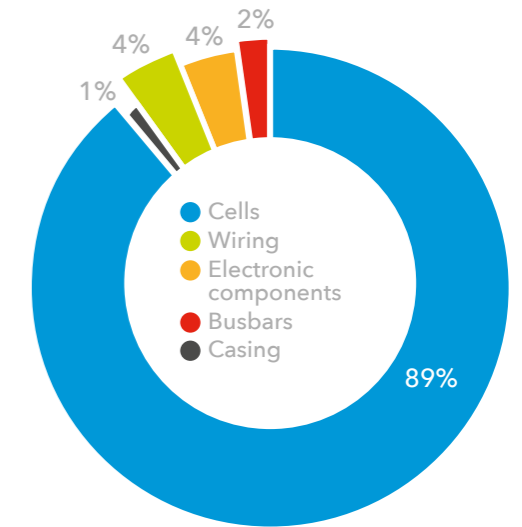
The value content in an end of life battery differs significantly from the cost breakdown for a new battery. The cost of cells in a new battery represents around 64% of the total cost whereas in an end of life pack the cells account for almost 90% of the value in the pack.

FIG 2 Cost of New Pack



Source: BatPaC Model Software, Argonne National Laboratory¹. Purchased items refers to connectors, busbars, etc.

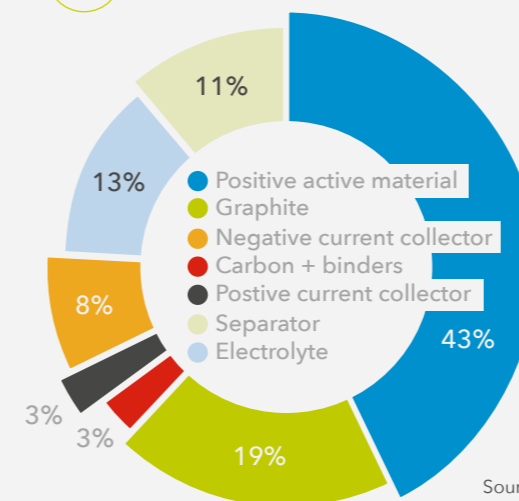
Value in EoL Packs



There is also a difference in the values between new cells and end of life cells. In new cells, the cathode material and the anode current collector make up 51% of the costs, but comprise 93% of the value in end of life cells. It must be noted that not every recycler will be able to realise the total value in the

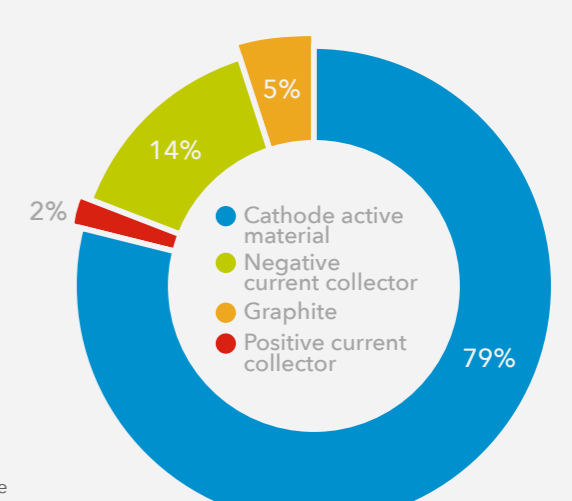
cells as only dedicated hydrometallurgical recovery processes are able to recover metals such as lithium and manganese. Recyclers which only recover the black mass and sell it onto a metal refiner will claim a much lower value.

FIG 3 Cost of New Cells



Source: BatPaC Model Software

Value in End of Life Cells



The value in the packs is affected by the quantity of the material within the pack and the chemistry of the cells. Figure 4 shows the value in three different vehicle packs.

FIG 4 Cell Value of Packs

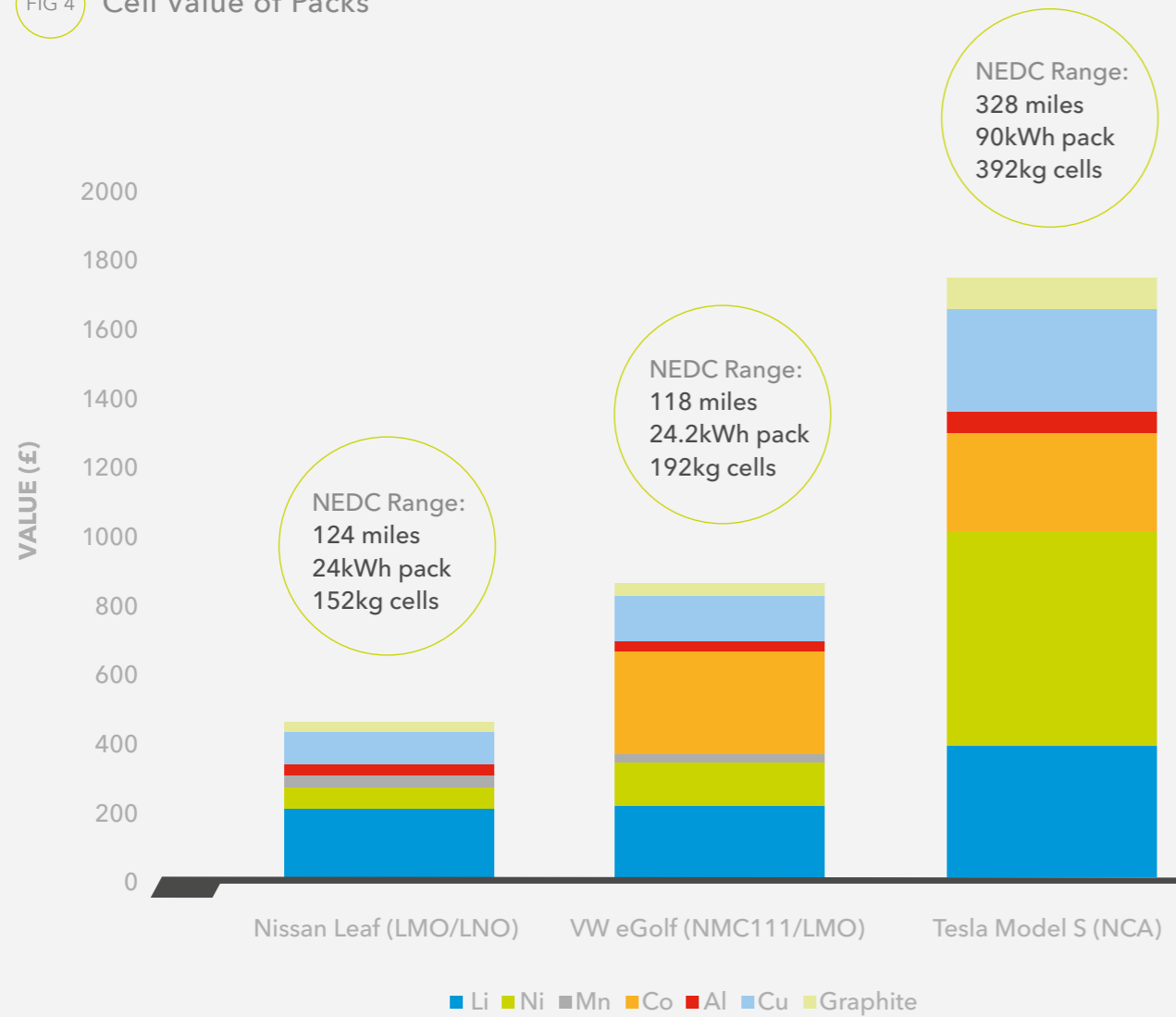


TABLE 1 Value of the Recoverable Components

Prices taken from London Metals Exchange (LME) in Q2 2019.

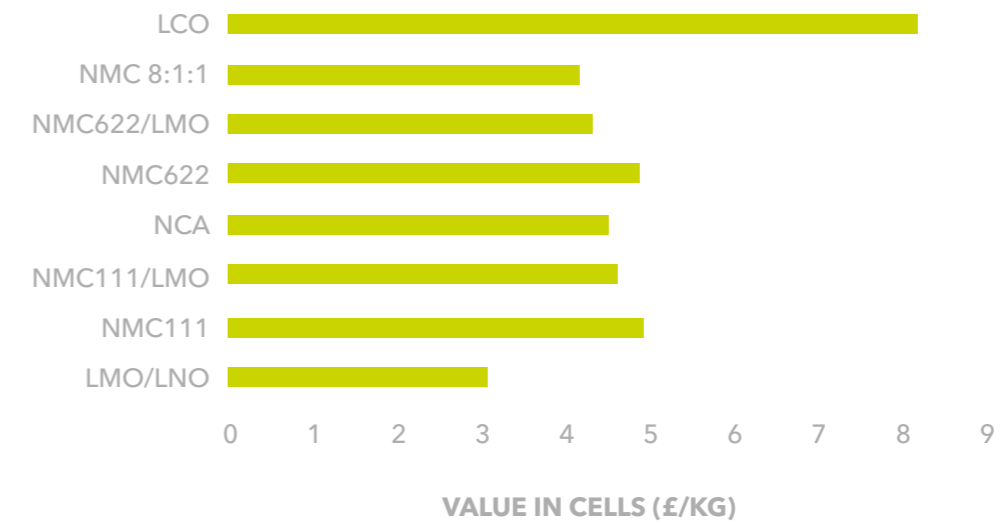
Metal/material	Value/kg (£)
Li	46
Ni	10.4
Mn	1.44
Co	25.6
Al	1.44
Cu	4.8
Graphite	1*

*Price for recycled graphite. Virgin battery grade graphite costs around £11/kg

Lithium ion batteries are used in a multitude of applications and therefore, a number of different chemistries have been developed to match the performance with the requirement. A recycler will want to process a number of different chemistries to maximise value.

Figure 5 shows the material value per kg in different cells. Note that lithium iron phosphate cells have been omitted as there is currently an uncertainty in their end of life value arising from a lack of European recycling facilities for such cell chemistries.

FIG 5 Value per kg of Cells (£)



"Recent times have seen the automotive sector focus on developing electric vehicles to drive a reduction in tailpipe greenhouse gas emissions. However, to deliver a truly decarbonised sector a whole lifecycle approach is required to ensure that emissions from one part of the vehicle lifecycle are not shifted to another. To achieve this the UK has an opportunity to think holistically; so that whilst it is investigating how to grow its battery manufacturing capacity to support the electrification agenda, it can in parallel build its recycling capability.

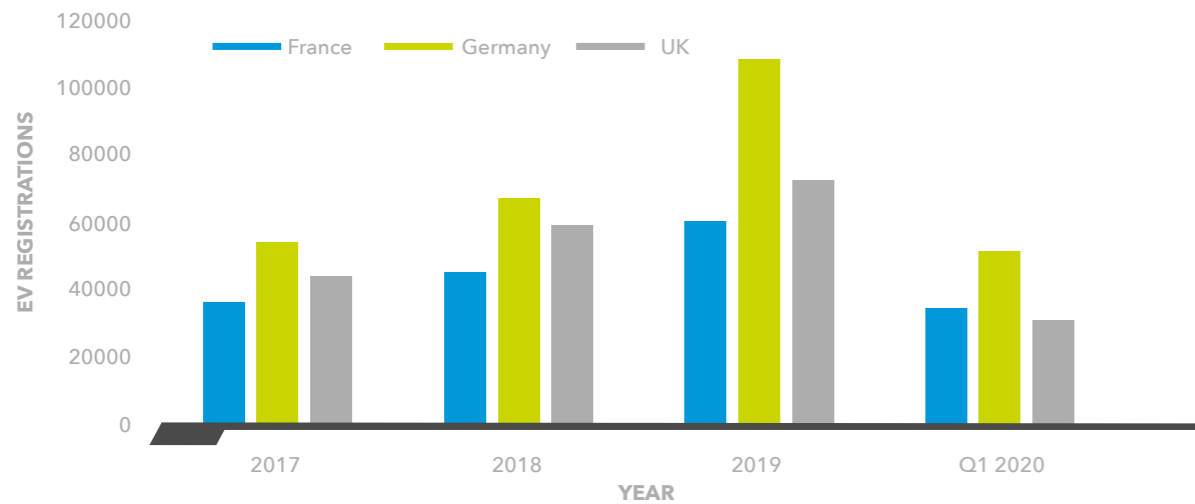
Successful delivery of this involves us going back to the start of the process by considering design for manufacturing, assembly, disassembly, reuse, remanufacturing and recycling. This will enable the development of a strategy for the UK to develop a sustainable and competitive supply chain that supports the delivery of an end-to-end process, which includes a viable and sustainable battery recycling industry, that retains the earth's valuable resources within the system."

Philippa Oldham
Head of National Network Programmes, Advanced Propulsion Centre

Why the UK?

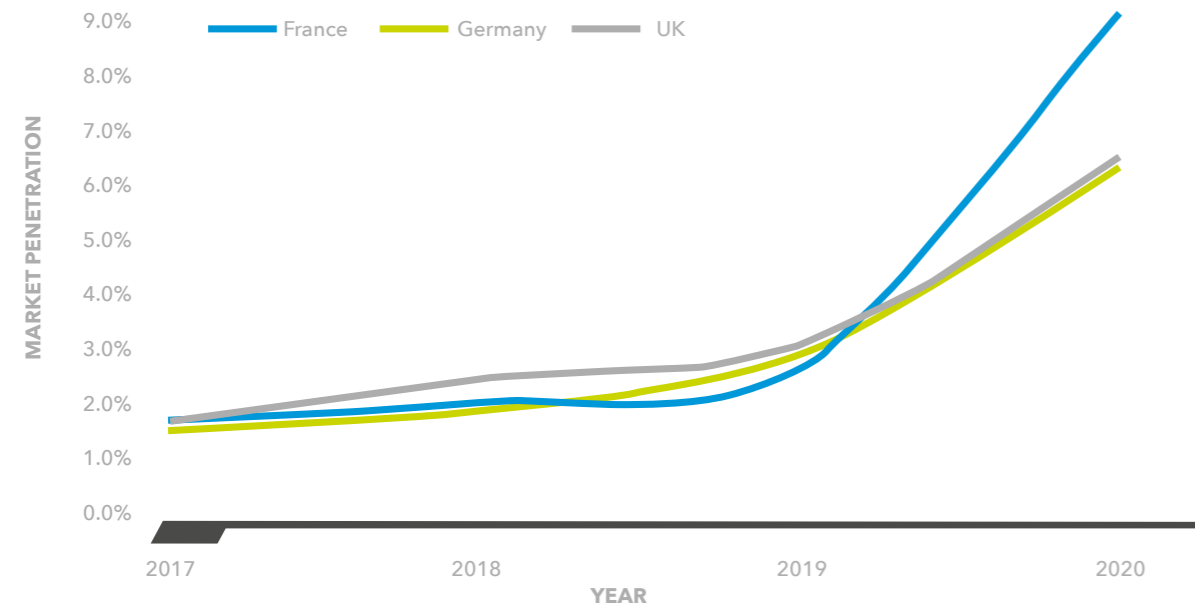
The UK is the second largest vehicle market in Europe with annual sales exceeding 2.3 million units in 2019. It is also amongst the top electric vehicle (BEV+PHEV) markets in Europe¹, with 32,000 EVs registered in the first quarter of 2020.

FIG 6 EV Registrations



Market penetration of EVs is accelerating, reaching 6% in Q1 of 2020. But, it will need to grow at an annual rate of 25% to enable all passenger cars to be ultra-low emission by 2035.

FIG 7 Market Penetration



Road transport accounts for a fifth of the UK's greenhouse gas emissions². Electric vehicles offer a 72% reduction in fuel-generated CO₂ emissions (based on the current UK electricity mix) and a 50% reduction in embedded carbon³. Battery recycling will help this further, as 1kg of recycled material saves the equivalent of 1kg CO₂ versus manufacturing from virgin material⁴.

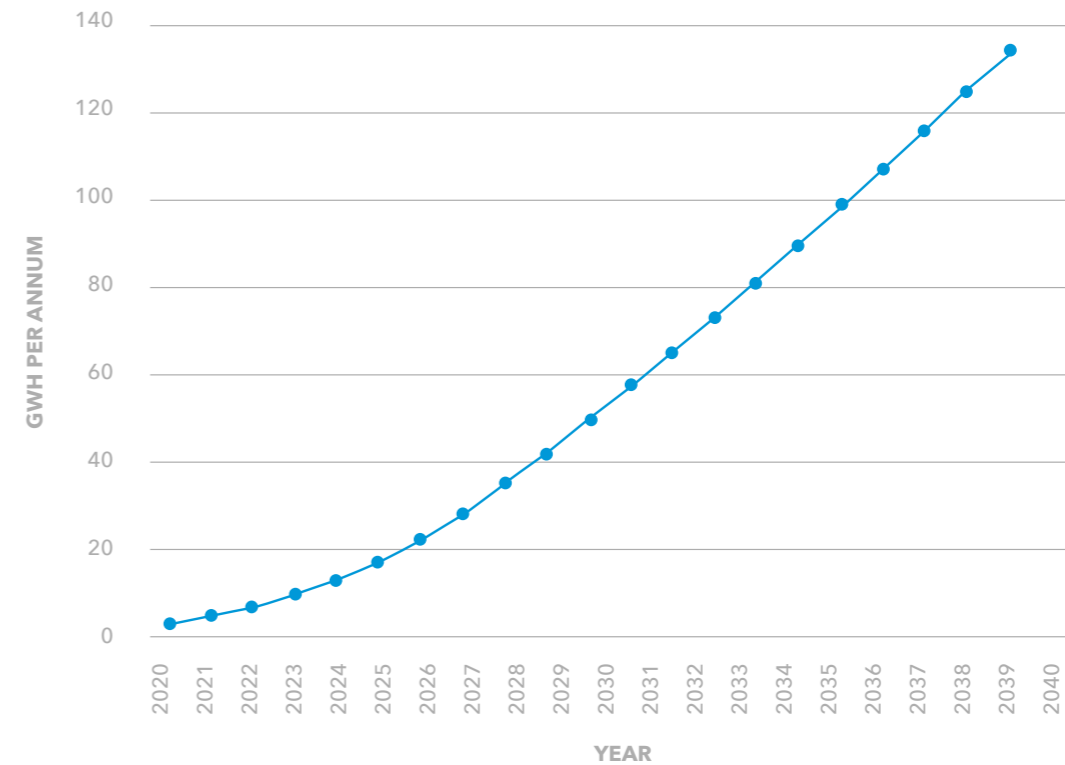
The UK exports its end of life lithium ion batteries to Europe and other parts of the world for recycling and material recovery. This is not an economically sustainable position for the UK. Establishing material recovery processes in the UK would provide a supply of ethically sourced material.

* 2020 data is for Q1, 2020

The Faraday Institution estimates the UK requires around 140GWh worth of cell production capabilities by 2040.

The average Gigafactory has around 20GWh of capacity and produces 81,000 tonnes of cells per year, a total of 567,000 tonnes of cells per year (using Tesla 2170 cell format).

FIG 8 Projected Demand for UK-produced Batteries



Modified from a Faraday Institution report⁵

To satisfy 2040 demand, the UK will need 133,000t of cathode metals per year. Much of this material can be supplied by recycling end of life batteries.

TABLE 2

Metal	Demand (tonnes per year)	Supply from Recycling (tonnes per year)
Lithium	14,000	3,000
Nickel	96,000	20,600
Manganese	11,000	2,400
Cobalt	12,000	2,600

Based on 8:1:1 chemistry assuming 60% of end of life batteries are recycled in 2040.

Each Gigafactory produces approximately 6% defective cells and modules plus thousands of tonnes of 'dry' anode and cathode scrap, all of which requires recycling. It is vital that recycling plants are located near Gigafactories to reduce

transport costs and rapidly reintroduce the material into the supply chain. Established recycling facilities will be a requirement for attracting battery manufacturers to the UK.

¹ More electric vehicles have been sold in Norway to date but Norway has an EV market penetration of 75% and its total vehicle market is around 6% of the UK's vehicle market.

² Office for national statistics; <https://www.ons.gov.uk/economy/environmentalaccounts/articles/roadtransportandairmissions/2019-09-16#toc>

³ Nikolas Hill. Determining the environmental impacts of conventional and alternatively fuelled vehicles through Life Cycle Assessment. Ricardo Energy and Environment; https://www.uepi.org/images/Vehicle_LCA_Project_FinalMeeting_All_FinalDistributed.pdf

⁴ Rebecca E. Ciez & J. F. Whitacre; Examining Different recycling Processes for Lithium ion Batteries. Nature Sustainability, 2, 148156 (2019).

⁵ The Faraday Institution. UK electric vehicle and battery production potential to 2040. Faraday Report - March 2020. Annual Gigafactory Study

Battery Recycling Process

This map details the major lithium ion battery recycling centres in Europe and their capacities.

Please note that this is not an exhaustive list.

- 1 **Duesenfeld** – Pilot scale (commercial operation)
- ▶ 3,000t batteries per year
 - ▶ Recycling efficiency of 85% - includes an electrolyte recovery step
 - ▶ Cells shred in an inert atmosphere, created using N₂. Patent also has the provision of shredding in a vacuum
 - ▶ Process has hydrometallurgical capabilities and recovers the cathode metals as metal salts to go back into the supply chain

- 3 **Umicore** – Commercial process
- ▶ 7,000t batteries per year
 - ▶ High temperature (pyrometallurgical) process. Batteries mixed with coke and slag forming agents and dropped into a giant furnace where preheated air is fed through sides and the volatile material within the batteries is used to produce some of the energy required for the process.
 - ▶ Process has hydrometallurgical capabilities and also produces new cathode powders from the recycled metal salts

- 5 **Valdi (Eramet Group)** – Commercial process
- ▶ 20,000t batteries per year but, Li ion only small portion of this
 - ▶ Pyrometallurgical
 - ▶ Process produces a metal alloy that can be recovered hydrometallurgically

- 7 **SNAM** – Pilot scale process
- ▶ 300t batteries per year, looking to expand to 10,000t per year
 - ▶ Pyrolysis followed by shredding process
 - ▶ Black mass is sold to refiners. Installation of hydrometallurgical plant is planned

- 9 **uRecycle** – Pilot scale process
- ▶ 100t batteries per year
 - ▶ Shreds lithium ion batteries in a CO₂ atmosphere to neutralise the lithium and avoid ignition of flammable electrolyte
 - ▶ Process recovers anode and cathode material as black mass which is sold to refiners

- 2 **Accurec Recycling GmbH** – Pilot scale (commercial operation)
- ▶ 2,500t batteries per year
 - ▶ Cells placed in pyrolysis chamber and heated to 250°C evaporating electrolyte before shredding
 - ▶ Process treats recovered black mass pyrometallurgically to produce an alloy and a slag which contains the lithium. The alloy can be treated hydrometallurgically to recycle the metals

- 4 **Euro Dieuze Industrie (EDI)** – Pilot scale process (commercial operation)
- ▶ 1,800t batteries per year
 - ▶ Cells shredded in a closed system - vapours and gases coming off cells are captured and treated
 - ▶ Process has hydrometallurgical capabilities and recovers the cathode metals as metal salts to go back into the supply chain

- 6 **Batrec Industries AG** – Pilot scale process (in commercial operation)
- ▶ 200t batteries per year
 - ▶ Shreds lithium ion batteries in a CO₂ atmosphere to neutralise the lithium and avoid ignition of flammable electrolyte
 - ▶ Process recovers anode and cathode material as black mass which is sold to refiners

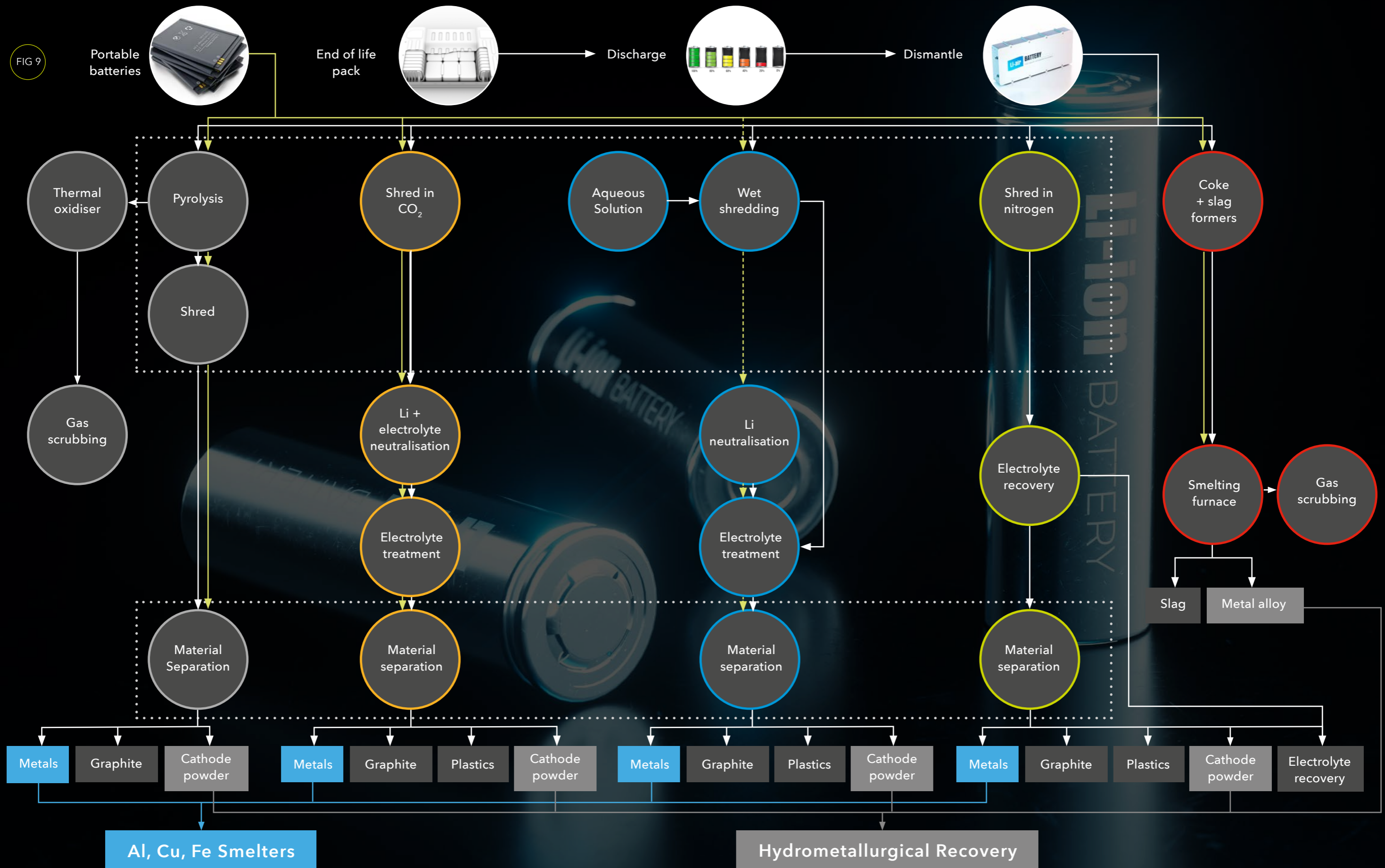
- 8 **Recupyl** – Pilot scale process
- ▶ 110t batteries per year
 - ▶ Shreds cells in a controlled atmosphere using a mixed CO₂ and Ar atmosphere
 - ▶ Process recovers anode and cathode material as black mass which is sold to refiners

- 10 **REDUX** – Commercial process
- ▶ 10,000t per year. Cells deactivated in a thermal treatment step prior to shredding and material separation
 - ▶ Process recovers anode and cathode as black mass which can be treated pyrometallurgically and hydrometallurgically to recycle the metals

- 11 **Akkuser** – Commercial process
- ▶ 4,000t per year (estimate). Cells shredded in a two-stage process assumed to occur in an inert atmosphere. Material separation is followed by acid leaching
 - ▶ Process is able to recover anode and cathode as black mass which is treated hydrometallurgically to recover the metals as metal salts



Commercial Processes for Battery Recycling



Pros and Cons of Different Recycling Methods

(includes processes that are still in development)

TABLE 3 Pre-process Methods

Method	Advantages	Disadvantages
Discharge	<ul style="list-style-type: none"> ▶ Takes electrical energy out of cells making them safe ▶ Process is mature and scalable ▶ Electricity can be fed back into the grid ▶ Negates the need for post lithium neutralisation 	<ul style="list-style-type: none"> ▶ Only applicable for large modules and packs ▶ Difficult to discharge portable cells without using salt water solution, which generates toxic and flammable gases ▶ Rebound can occur if discharged too rapidly ▶ Rapid discharge of high capacity cells can lead to overheating and thermal runaway ▶ Non-standardised parts make it difficult to connect to load bank
Thermal treatment	<ul style="list-style-type: none"> ▶ Allows charged cells/modules to be processed ▶ Energy expended in a safe environment ▶ Burns off electrolyte taking away biggest hazard ▶ Process is mature and scalable ▶ Negates the need for post process neutralisation ▶ Low temperature vacuum thermal treatment allows for recovery of some electrolyte carbonates ▶ Makes easier to process hydrometallurgically 	<ul style="list-style-type: none"> ▶ Inert atmosphere required - increasing process operating costs and reducing throughput ▶ Large quantities of toxic gases produced increasing processing costs ▶ Lower recovery efficiency ▶ Large input of energy required for process ▶ Produces CO₂ through combustion process ▶ Temperature gradients can exist in larger modules, which may lead to incomplete reactions ▶ Aluminium components within cell can melt at high temperatures causing agglomeration within the reactor
Freezing	<ul style="list-style-type: none"> ▶ Allows charged cells and modules to be processed as immersion in a cryogenic liquid, typically liquid nitrogen, freezes the electrolyte, reducing cell reactivity to zero 	<ul style="list-style-type: none"> ▶ Only suitable for batch processing, making it difficult to scale up ▶ Expensive reagents used ▶ Only gives a short time for processing before cells become live again ▶ Li and electrolyte must be neutralised post processing

TABLE 4 Process Methods

Method	Advantages	Disadvantages
Pyrometallurgical	<ul style="list-style-type: none"> ▶ Allows for selective targeting of metals ▶ Extracts most valuable components ▶ Volatile components within the cells are combusted, reducing external energy demand ▶ Makes easier to process hydrometallurgically 	<ul style="list-style-type: none"> ▶ Difficult to feed continuously as high temperatures vaporise electrolyte, forming explosive mixtures ▶ Metals such as aluminium, manganese and lithium not recovered (although could be recovered from slag) ▶ Various additives required to make process work ▶ Extensive scrubbing required to treat off-gases ▶ Components such as electrolyte, graphite and plastics combusted so not recovered
Shredding in saturated lithium chloride solution	<ul style="list-style-type: none"> ▶ Easier to scale-up than dry inert shredding methods ▶ Allows charged cells to be processed 	<ul style="list-style-type: none"> ▶ If shredding is done submerged, complex feeding and equipment operation required ▶ Large quantities of expensive lithium chloride is required ▶ Contamination of products with lithium chloride ▶ Lithium to be neutralised post-process which can cause exothermic reaction ▶ Chloride ions can cause corrosion to process equipment ▶ Acid not dealt with ▶ Electrolyte recovery and removal very challenging

Process Methods (continued)

Method	Advantages	Disadvantages
Shredding in an alkaline solution	<ul style="list-style-type: none"> ▶ Easier to scale up than dry inert shredding methods ▶ Allows harmful chemicals to be neutralised ▶ Some alkali solutions treat electrolyte making it easier to process downstream 	<ul style="list-style-type: none"> ▶ Hydrogen is generated if aluminium is present ▶ Addition of alkali reagent to water increases costs ▶ Alkali ions can be corrosive to process equipment ▶ No electrolyte recovery possible
Shredding in a vacuum	<ul style="list-style-type: none"> ▶ Cheaper to operate than using inert gas ▶ Can be coupled with a vacuum extraction unit to evaporate and condense electrolyte carbonates ▶ Relatively mature technology used in other recycling operations 	<ul style="list-style-type: none"> ▶ Only suitable for batch processing, making it difficult to scale up ▶ Other parts of shredder may need to be placed under vacuum to avoid fires post shredding ▶ Safety not as high as shredding in an inert atmosphere ▶ Not suitable for shredding charged cells
Shredding in a nitrogen atmosphere	<ul style="list-style-type: none"> ▶ Relatively mature technology used in recycling of other flammable material ▶ Continuous shredding possible with right feeding mechanism 	<ul style="list-style-type: none"> ▶ More expensive than vacuum shredding ▶ May need inert conveyance line post shredding to avoid fires/explosions ▶ Not suitable for shredding charged cells and modules
Shredding in a CO ₂ atmosphere	<ul style="list-style-type: none"> ▶ Allows for shredding of charged cells ▶ Mature technology in operation for over 15 years 	<ul style="list-style-type: none"> ▶ Lithium beneath the surface of the particle is not reacted ▶ Reaction takes a long time to complete ▶ Unreacted lithium needs to be neutralised post shredding ▶ Expensive to operate

TABLE 5 Electrolyte Recovery Methods

Method	Advantages	Disadvantages
Liquid extraction	<ul style="list-style-type: none"> ▶ Allows all electrolyte components to be extracted ▶ Very mature technology 	<ul style="list-style-type: none"> ▶ Volatile low boiling point solvents required ▶ Energy intensive process ▶ Difficult to find right solvent for each chemical ▶ More than one solvent may be required to recover all electrolyte components ▶ Solvent loss likely to occur ▶ Solvent likely to dissolve plastics creating problems in extraction
Supercritical CO ₂ extraction	<ul style="list-style-type: none"> ▶ Recovery of electrolyte relatively simple compared to liquid solvents ▶ Can be used to neutralise the lithium if charged cells are shredded 	<ul style="list-style-type: none"> ▶ Additives may be needed to recover all electrolyte components ▶ Cannot recover lithium hexafluorophosphate ▶ Very difficult to scale up the process as high pressures are involved
Vacuum extraction	<ul style="list-style-type: none"> ▶ Recovery of electrolyte is simple ▶ Relatively mature technology 	<ul style="list-style-type: none"> ▶ Cannot recover lithium hexafluorophosphate ▶ May not be suitable to recover all carbonates ▶ Only suitable for batch processing, making it difficult to scale up ▶ Final product could require further processing

Recyclability of Materials

Lithium ion batteries are made up of a variety of materials that can cost a significant amount when new.

At the end of a battery's life, some of these materials retain their value but others do not, and some even have a negative value. The table below shows the recyclability of the materials, given current recycling processes and possibility of future recycling.



TABLE 6

Component	Material	Current Recyclability	Future Recyclability
Casing	Steel	Steel is highly recyclable. Steel is most likely to be down-cycled into an alloy.	Steel will continue to be recycled
	Aluminium	Aluminium is highly recyclable, but recyclers prefer 'chunky' pieces to thin foil, such as from pouch cell casings. Aluminium is down-cycled into an alloy	The aluminium recycling industry is considering recycling high grades of aluminium rather than down cycling, but this is likely to be for high-volume scrap and not thin foils.
Positive current collector	Aluminium	As above	As above
Negative current collector	Copper	Highly recyclable, but may need to be baled or briquetted beforehand. The high value of copper allows for complete recycling.	Copper will continue to be recycled
Anode active material	Graphite or graphite-silicon	Limited recyclability. Graphite's structure and morphology changes with cell use, making it difficult to recycle back into cells.	Graphite will continue to be difficult to recycle into cell-grade graphite, but it may be converted into other materials such as graphene.

Component	Material	Current Recyclability	Future Recyclability
Cathode active material	Lithium	There are two options for cathode recycling: <ul style="list-style-type: none"> ▶ Commercial refiners use elevated temperatures alongside additives to selectively discard certain metals (such as Li, Al, Mn) to leave the more valuable and abundant metals such as Ni, Co and Cu which are then recycled using hydrometallurgical processes. ▶ In-house processes are more tailored so can recover more of the metals including lithium. The main issue for lithium recycling is the low concentration of lithium per cell, at around 2% by mass. 	More in-house hydrometallurgical processes will be developed or large-scale centralised refining specifically designed for cathode material will allow for the recovery of all cathode metals. Next-generation cathode recycling processes will recycle the entire cathode rather than break it down to its base metals. Standardisation of cell chemistry is required for this to become commonplace.
	Manganese	Similar to lithium, manganese is not recycled by commercial recyclers owing mainly to its low price. In-house hydrometallurgical processes are able to recycle the manganese.	As above
	Nickel	Nickel is a high-value metal that can be completely recycled back into cells.	As above
	Cobalt	Cobalt is a high-value metal that can be completely recycled. Some LIB recyclers have the capability to recycle the cobalt back into cathode material.	As above
	Oxygen	Oxygen accounts for around 33% of the cathode or ~11% of cell mass. The Battery Directive has a provision for the recycling of oxygen if it can be proven that it is involved in the chemical conversion of the metals. This gives pyrometallurgical recyclers an advantage. Direct hydrometallurgical recycling of the cathode leads to the production of oxygen gas, which, unless utilised, cannot be accounted for.	Next-generation cathode recycling processes will recycle the entire cathode (including the oxygen). Standardisation of cell chemistry is required for this to become commonplace.
Other cathodes	Lithium iron phosphate (LFP)	Alternative processes such as direct recycling or chemical processes that strip the lithium from the LFP have been demonstrated at small scale.	Direct recycling methods will be further developed, which will allow for the recycling of the LFP powder to go back into new cells.
Separators	Polymers	Limited recyclability. Commercial plastic recyclers prefer chunky plastics as the high temperature melting and extrusion process is not suitable for plastic films. Many recyclers choose to combust the plastics.	Plastic separators will continue to be challenging to recycle, particularly back into new cells. They could potentially be down-cycled and used in other applications in the future.
Electrolyte	Organic carbonates	Recyclers are able to recover at least some of the organic carbonates fraction of the electrolyte. This may be sold into the chemicals industry if the purity is high enough. Some recyclers claim to be able to recover the electrolyte from the aqueous solution in wet shredding processes. Most recyclers either combust the electrolyte or treat it with chemicals to destroy it.	Recyclers will be more inclined to recover and recycle the electrolyte if the cells used a standardised electrolyte composition. It is difficult to design a process that can recover the variety of different carbonates that go into the various lithium ion batteries.
	Lithium hexafluorophosphate (LiPF ₆)	Limited recyclability. The LiPF ₆ composition within the cell changes as the cell ages. Difficulty recycling LiPF ₆ is due to a number of factors: It decomposes at temperatures above 80°C, it hydrolyses in the presence of moisture and, finally, it requires a solvent extraction process to enable its recovery. Currently either destroyed thermally or hydrolysed using water and neutralised.	Limited recyclability in the future, as the conditions required for its recycling are likely to be too stringent for most recyclers.

Economic Analysis

Currently the UK lacks industrial capacity for lithium ion battery recycling, therefore batteries are shipped to mainland Europe for material recovery. This can be a very expensive process, dependent on state of health of the pack, chemistry of the pack and size of the pack.

The cells and modules are sent to mainland Europe for recycling. The process is as follows;

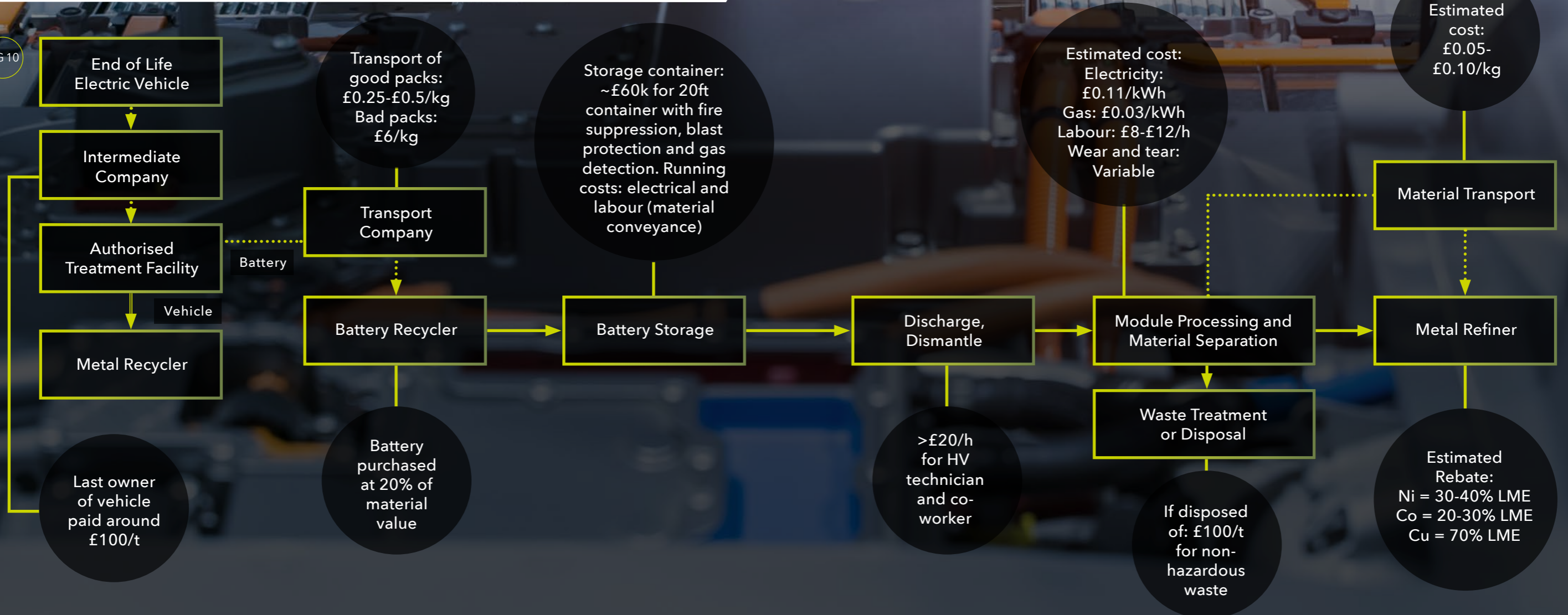
- ▶ End of life electric vehicles are returned to the dealership where the battery is removed from the vehicle using high voltage technicians
- ▶ The vehicle is sold to a metal recycler whilst the battery is given to a battery disposal company
- ▶ The battery is discharged, dismantled into modules which are packaged in containers alongside fire-proof material
- ▶ The packaged modules are shipped to Europe to a recycling facility which levies a processing charge to recycle the batteries and gives a rebate based on the LME price of nickel, cobalt and copper
- ▶ Costs can range from £3/kg to £8/kg depending on the state of health and chemistry of the battery
- ▶ Up to 75% of the total cost of recycling can be attributed to the transportation costs if the pack is damaged or its state of health is unknown
- ▶ Only cells and modules which are in a good state of health can be transported to Europe, damaged cells and modules cannot be taken to Europe

Pack discharging and dismantling is one of the most challenging parts of automotive battery recycling.

- ▶ Lack of standardised connectors makes it difficult to connect pack to the load bank
- ▶ Some packs use epoxy resins to seal the lid, making it hard to access the cells and modules
- ▶ Module removal can be difficult if the screws and connectors are located in obscure locations



FIG 10

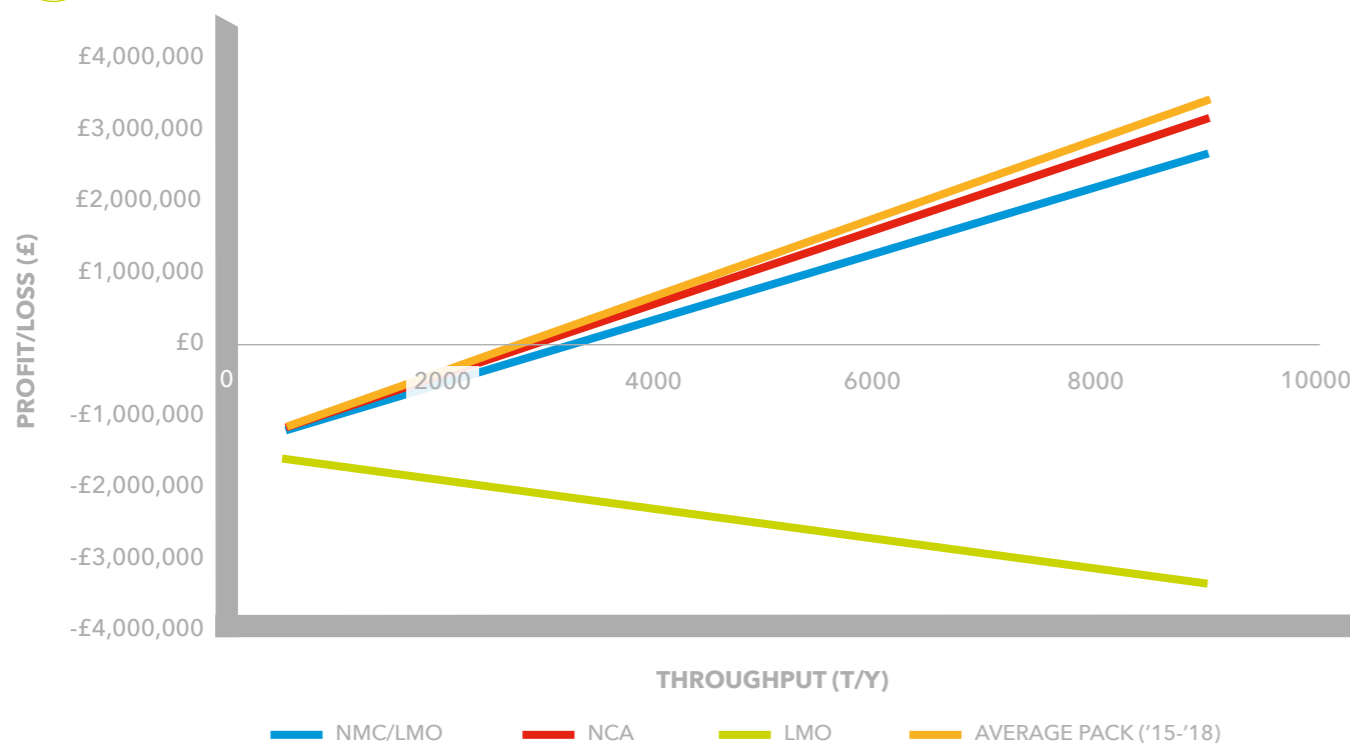


Battery Recycling Plant Economics

Process economics for a 1.5t/h automotive lithium ion battery recycling plant were modelled on Microsoft Excel.

Assumptions were as follows; average packs weigh 238kg with gross values varying from £550 (LMO) to £733 (average) per pack. Process is limited to separation of black mass, which is sold to refiners, allowing the recycler to attain 40% of the value for packs containing Ni and Co and only 20% for LMO packs. Transport costs were assumed to be £50 per pack. Other costs are shown in Figure 10. Cost of capital and depreciation were not included in the model.

FIG 11 Break-even Point



Note that average pack chemistry includes many NMC 1:1:1 packs which have a higher value

The cost of processing decreases as throughput increases since plant capacity is utilised more efficiently. The break-even point for such a plant is between 2,500 and 3,000 tonnes per year if the chemistry contains Co and Ni.

FIG 12 Cost Breakdown for Recycling Plant

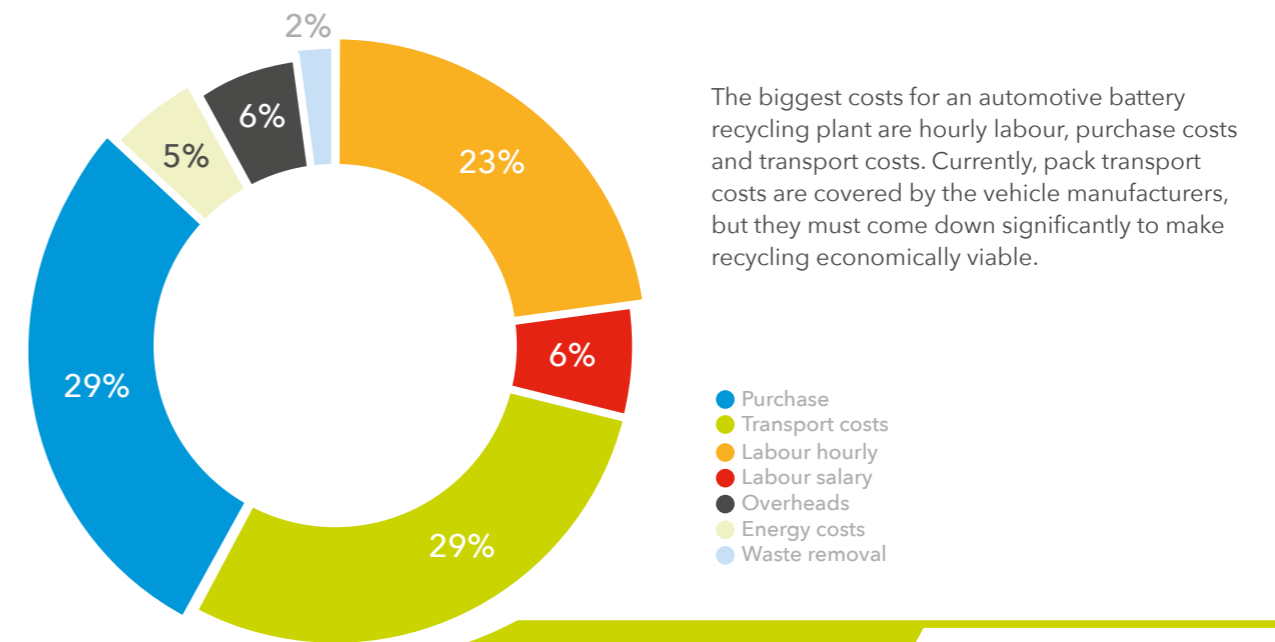
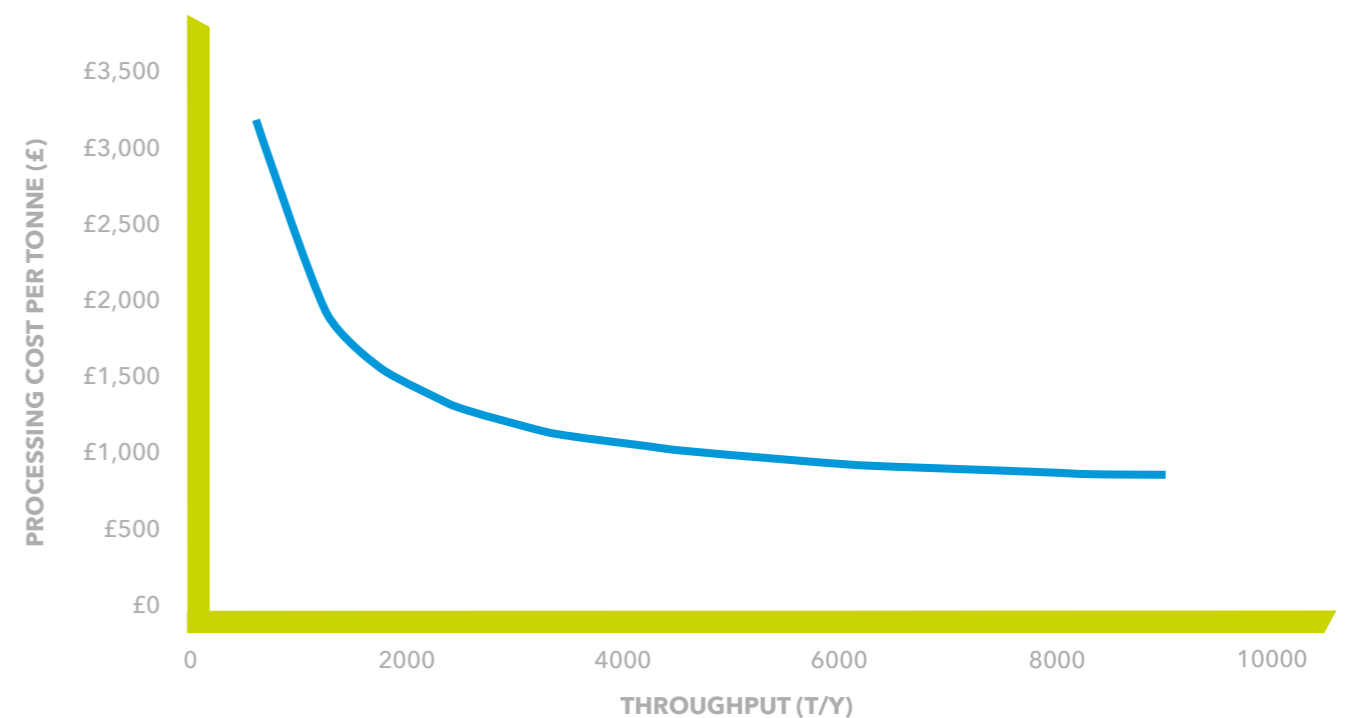


FIG 13 Processing Cost Vs Throughput



Based on average packs sold in the UK between 2015 and 2018



Recommendations

The UK needs to establish commercial scale recycling for automotive lithium ion batteries.

This will ensure sustainable disposal and capture valuable raw materials to sustain UK battery manufacturing. Today's volumes of end of life batteries are insufficient to sustain a commercially viable plant, but plants are needed nonetheless to ensure sustainable disposal.

Volumes will become sustainable in around 5-8 years when tens of thousands of tonnes of material will require processing. Processing of trade waste from UK battery factories will provide early revenue streams in the meantime.

The UK does not have legacy processes and could challenge for highest recycling efficiencies - enabling revision of Battery Directive towards >80% recovery by mass (from 50% today).




RECYCLING EFFICIENCIES COULD REACH **70% BY 2025** AND **80% BY 2035**


The following points are recommended to ensure a viable and sustainable battery recycling industry in the UK:

- 1 Support the installation of recycling facilities until volumes reach sufficient levels to make battery recycling sustainable.
- 2 Link recycling plants to planned Gigafactories in UK.
- 3 Work with battery recyclers and transport companies to develop and update the battery transport regulations.
- 4 Streamline permitting process for battery recycling.
- 5 Vehicle manufacturer must provide battery passporting data to vehicle/battery recyclers allowing for accurate triaging.
- 6 Greater clarity around the transfer of liability at end of life.
- 7 Develop and standardise discharging and dismantling training for end of life battery technicians.
- 8 Update Battery Directive to reflect the increased material recycling capabilities of new processes.
- 9 Begin to standardise parts of the battery packs such as high voltage connection ports to allow for easier discharging and dismantling.
- 10 Create a distinction between automotive traction batteries and other batteries to allow for ambitious targets to be set, such as 70% by 2025 rising to 80% by 2035 for battery packs.
- 11 Only processes with high recycling rates for critical metals should be permitted - for example 98.5% for cobalt to stop inefficient processes from being installed.
- 12 **R&D into the following areas;**
 - ▶ Design of 'easy to recycle' battery packs
 - ▶ Recycling of cathode metals using, green solvents, that reduce the CO₂ footprint of the process
 - ▶ Recycling of non-cathode components
 - ▶ Direct recycling of production scrap
 - ▶ Research into the life cycle analysis of lithium ion battery recycling processes in the UK.

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