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Timeline for establishing a circular economy for lithium-ion batteries

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The electrification of road transport is not in doubt. Still, its rate of adoption and the concomitant waste handling issues accompanying it are a matter of conjecture. While practical solutions have been proposed and, in some cases, trialled, the timeline for technology adoption has not been set out. Some regions have policies for dealing with waste, but there is significant doubt whether the targets are achievable. This review outlines the factors affecting technology adoption and a proposed timeline for achieving circularity. Many factors affecting the adoption timeline involve the quality and sustainability of the product itself and the ability of the market to adapt to improved battery chemistries. This is tensioned by the need of the industry to exploit the invested capital and to retain consumer confidence. Given a 12–15 years lag between production and recycling, many of the changes required to deal with a large market by 2040 need to be implemented by standards or policy. All stakeholders drive the direction of future battery chemistries, affecting the sustainability of materials and the success of achieving circularity. This review highlights the issues in developing international recycling policy with projected waste mass flow projections and issues with current policy with the projected apparent timeline.

Broader context

Lithium-ion batteries are a vital technology for decarbonising road transport and energy storage. The use is only useful if they are part of a true circular economy. This study offers the first comprehensive overview on a timeline of when these changes would occur. It also highlights challenges to achieving this timeline due to the lack of techno-economic information and legislative barriers particularly around material and information transfer. The perspective article provides manufacturers, policy makers and recyclers with clear conclusions about the barriers to circularity. It highlights the constraints for recyclers caused by lack of standardisation of pack labelling and architecture. Differences in the legislation governing waste in different producer and consumer nations leads to confusion about recycling responsibility. The article also shows that some of the targets in battery directives are unachievable due to the flows of markets and the immaturity of recycling markets. Many of the issues highlighted could be reduced by establishing fora which bring together pack designers and recyclers to look for quick wins in pack disassembly. The article concludes that all stakeholders can affect the trajectory of product adoption, and only by working together can policy targets be met.

1. Introduction

Establishing a circular economy for any product requires a successful product, a facile recycling protocol, and an economic or legislation driver to ensure the collection of end-of-life (EOL) products for processing to acceptable quality for use in remanufacturing. Traditionally, the creation of a circular approach to product lifetimes has come after the establishment of a mature product. While many large-scale products already exist in a circular economy, this often occurs when the ability to recycle a product depends on the financial savings gained from using recycled materials. These instances often mirror the complexity of the product and the purity of the recycled material. For example, the extraction of steel and aluminium from their primary ores is highly energy-intensive. Still, the metals can easily be separated from mixed waste streams. In this case, the main driver for recycling is the energy savings from recovery *versus* extracting them from the

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ores.[1] Changes to process economics can also increase recycling rates, as was seen recently for glass recycling in the UK when renewable electric or hybrid systems replaced gas furnaces and when the steel industry replaced blast furnaces with electric-arc furnaces for the treatment of secondary scrap.[2,3] In cases where the feedstock is complex, such as in plastic packaging, large amounts of material are downcycled into lower-value products or incinerated.[4]

Decarbonising the energy sector introduces more complex materials that will ultimately need to be recycled, including wind turbines, solar cells and lithium-ion batteries (LIBs). Expanding global policy to facilitate a circular economy in energy materials requires understanding the potential products and their ongoing development and an appreciation of the product lifetime and the barriers preventing transportation and treatment of these materials at EOL. Changes to regulatory policy can be used to kickstart markets, control material flows, and promote circularity. However, if handled poorly, it can also hamper investment in the industry and prevent the adoption of the original product. This study proposes a potential timeline for establishing a circular economy for LIB materials within the framework of a flexible product and process regulation policy. The factors affecting the circularity of LIB materials are summarised in Fig. 1.

Battery technology is continually evolving, and developments in the EV market need to learn from past products. Many different battery types still find their place on the market, largely dependent on their cost, energy and power densities. Due to their relatively low energy density, Zn/C batteries are single-use and low-cost for small portable devices.[5] The complexity of the cell design makes them notoriously difficult to recycle economically due to their low-value components.[6] In contrast, lead acid batteries, LABs, have the highest recovery rates of any recycled product, allowing recovery of ≈99% of the battery components for reuse in new batteries due to their simplicity of separation.[7] This has stabilised the amount of lead mined over the past few years, as the recycling sector contributes a significant amount of the materials required for LAB manufacture. The design of LABs is fairly monolithic, with a basic structure of lead, lead oxide, and sulfuric acid, housed within a polypropylene container. Typically, the polypropylene container is crushed to drain the electrolyte, allowing the remaining components to be recovered *via* density separation. The ease of separation and the relative amount of material recovered make collection and logistics relatively easy and economically worthwhile. Additionally, due to component toxicity and the relative environmental impact of their disposal, legislation surrounding the collection and recycling of these cells is extensive. Historically, these batteries were used to power the earliest forms of electric vehicles (EVs). However, they still have significant usage in the automotive industry as ignition sources for vehicles using internal combustion engines (ICE). Nickel cadmium- and nickel metal hydride-based battery chemistries also saw use as early EV batteries due to their relatively longer-life recharging characteristics. However, as the cell chemistries were more complex, recycling rates are much lower at approximately 50–60%.[8] For similar complexity reasons LIBs also possess a much lower recycling rate to LABs. While battery legislation surrounding recycling is now relatively mature, updates are still frequently required. Recent changes have been applied to battery labelling to prevent LIBs from entering the LAB recycling process.

A circularity approach for LIBs is essential, learning from the efficient recycling and effective legislation and regulation around the LAB sector. However, LIBs are larger, more hazardous to handle, and contain many more components; hence,

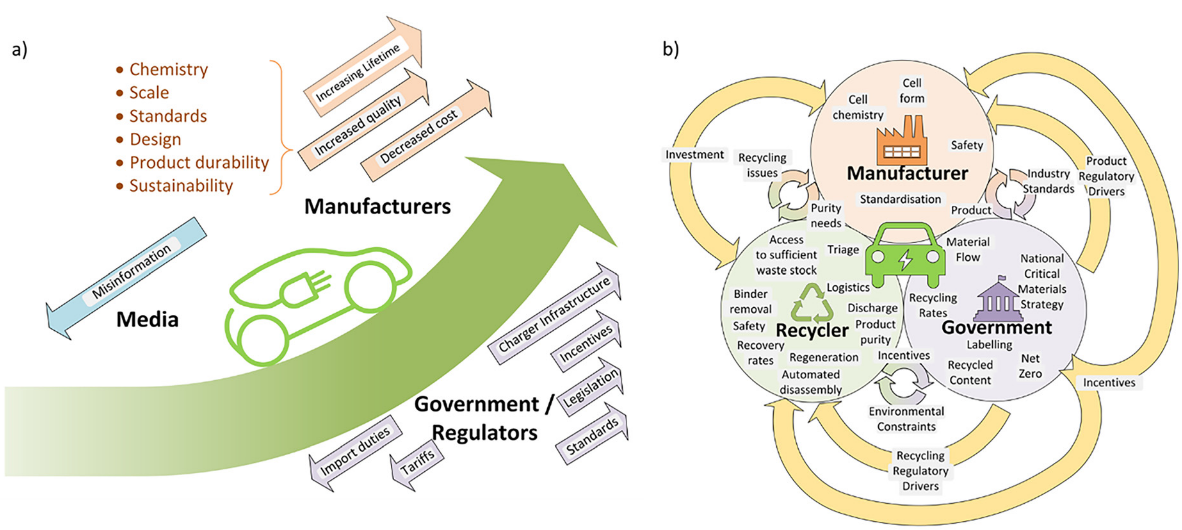

Fig. 1 Diagrammatic representations of (a) factors affecting the market establishment and (b) issues with creating a circular economy supporting domestic manufacturing.

simple density separation is not an option. Additionally, due to the higher performance expectations for LIB applications, any form of recycled product needs to be specifically high purity and high performance, meaning the requirements of LIB recycling processes are much more stringent than those of other battery chemistries.[9]

Adopting electrified road transport will cause the largest change in waste material handling since the advent of the ICE. LIB waste materials will mainly take the form of production scrap and quality control reject materials until 2030, as the early EV models are just coming to the end of their predicted battery lifespan. This was originally predicted to be 10 years liefespan, however it has been found that it is more typically 12–15 years – only slightly shorter than the average lifetime of an ICE vehicle at *ca.* 18 years.[9,10] EOL batteries will only become about 50% of the waste to be processed after 2044 when it is predicted that an equilibrium will be reached between EV demand and the availability of EOL material. Therefore, developing the recycling infrastructure for both EOL and production scrap materials is necessary to retain value within the battery supply chains. The present study outlines a possible route to circularity for LIB technology, discussing the external factors that may affect this timeline, including product development, recycling processes, the cost of components and the changing market, and the geography of the supply chain, as well as consumer confidence in EVs and battery technology. In this study, the effect of only Light duty electric vehicles is considered as it is the major part of the market and the part which is least easy to regulate. Also the effect of alternative EVs, such as those powered by fuel cells, are ignored since global numbers are significantly smaller than LIB-powered EVs (*ca.* 50k).[11]

2. Proposed timeline to circularity

This timeline discusses the key challenges towards a mature and stable global circular economy for EV battery production and recycling. Fig. 2 shows a schematic representation of this predicted timeline. The *Y*-axis shows the actual and predicted tonnage of private electrified vehicles in the global vehicle fleet, and the *X*-axis shows the anticipated time scale for each key stage of market maturity. Numerous external factors will affect this timeline, as discussed below. The timing of each of these steps is also dependent on local markets. For example, waste processors will only enter the market when there is an appreciable amount of material to process. It has been estimated that functioning recycling plants will need to process 10 to 30 kt p.a. for a profitable hydrometallurgical process.[12]

Assuming a notional 10 kt of spent LIB is needed to warrant a recycling facility, then that equates to approximately 25 000 EVs p.a. The dates when waste processors will enter the market can be estimated at 12 years after sales exceed 25k vehicles p.a. China already has sufficient volume, whereas countries such as France and Germany will surpass this threshold in 2029 (although they already have suitable recycling capacity).[11] However, other countries may not see these volumes until later, *e.g.* UK (2031) and Australia (2034), and some regions may require combined facilities, *e.g.* Central and South America combined may not see these volumes until 2035. Economic considerations such as energy and labour costs may also make some countries earlier or later to develop recycling markets. The suggested dates in Fig. 2 are therefore guides and may differ by ±6 years depending on the size of the national or regional EV market.

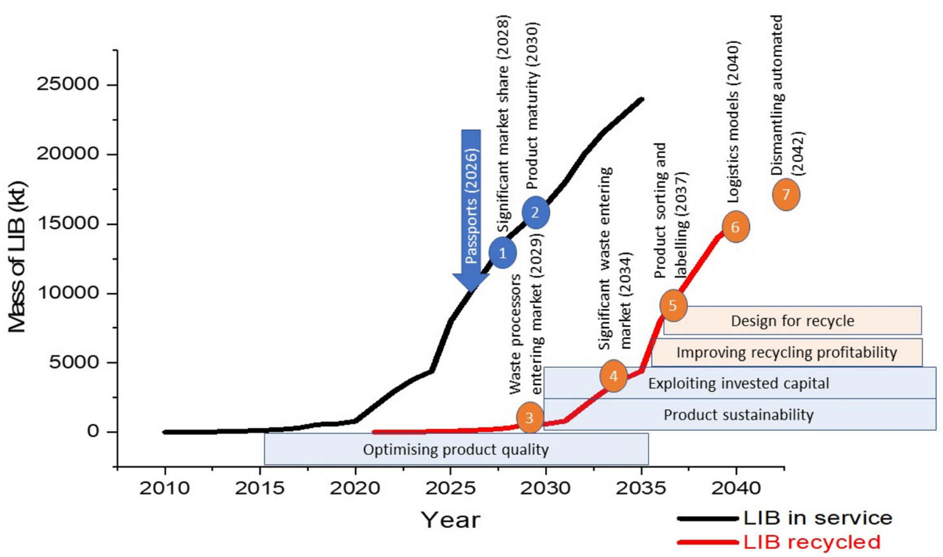

Fig. 2 Schematic representation of the EV market trajectory towards a circular economy. Timeframes for each process (boxes) and milestones (numbers) are estimates based on the length of research and time taken for product-to-market, as well as expected recycling equipment and EV battery lifetimes. The numbered circles are associated with important events/milestones, and the boxes are the development processes that must occur. LIB in service data taken from IEA[11] and BloombergNEF.[13] Recycled data assumes LIB have a 12 years service life and an average mass of 400 kg.

Ensuring product quality

Optimised energy density, lower charging times, and extending cell lifetimes are essential for a flourishing EV market, along with a reduced carbon footprint for batteries through their manufacture, use, and recycling *vs.* the ICE. Product reliability and safety are also paramount to a product's reputation, with constant developments in battery chemistry and cell/pack conformations.

Battery chemistries may diverge towards specific applications. Consumers see ICE cars as generic products, whereas, in truth, each consumer will probably use their vehicle in fairly regular duty cycles. Consumers who use their vehicles for multiple short journeys will have different requirements for battery range and capacity compared to those engaged in long-distance travel, partially due to the usage patterns and partially due to the availability of charging stations in remote areas.[14] It should be noted that vehicles and their batteries may also be tailored to the geographic region, as larger countries will inherently require EVs with better range and regularity of charging stations. Some countries may prefer battery chemistries that contain readily available materials to drive down manufacturing costs. Fast charging capabilities will also impact the choice of battery chemistry, and hence the energy and power densities of the batteries being produced.

Market trends are already showing that cathode chemistries are segregating between different applications; lithium iron phosphate (LFP) cells typically possess longer lifetimes, lower energy density and superior safety characteristics compared to lithium nickel manganese cobalt oxide (NMC) based chemistries.[15] This means that LFP is typically better utilised for shorter-range vehicles such as buses and may also lend itself to stationary energy storage systems where battery weight is less of an issue.[16] Therefore, where lightweight, high-energy-density systems are required, it is assumed that cobalt- and nickel-based batteries will be used in longer-range vehicles, whereas consumer electronics will be dominated by lithium cobalt oxide for a number of years. However, this may change with faster-charging technologies. It is unlikely that either chemistry will find a second use in domestic applications.[17] Still, LFP packs may find some reuse in remote off-grid storage where extending the life of a lower-value pack may be more valuable than immediately recycling it. Mixing these cathode chemistries will be problematic for recyclers, and surprisingly, some original equipment manufacturers and OEMs are now producing packs containing both LFP and NMC cells. It is also an issue that disruption to material supply chains could affect the adoption of different battery chemistries.[18,19]

Nevertheless, the most important aim is to establish a reliable, safe product that customers confidently use. OEMs need to have a product that can be mass-produced without major changes in design. Standardisation will reduce costs, simplify maintenance, and simplify the recycling/reuse market. Still, with the wide range of use cases and battery manufacturers present within the space, it is unlikely to occur like the LAB market. A full-scale recycling infrastructure, however, needs a mature battery market with a limited number of incoming chemistries and conformations and a defined set of outgoing products to standardise processes to minimise process costs.

From 2025 to 2035, it is probable that NMC and LFP-based chemistries will dominate the electric vehicle battery market. The former will decrease in cobalt content over time, while the latter may start to introduce Mn into the formulation.[20,21] Anode chemistries such as graphite are likely to remain roughly constant for the foreseeable future as silicon or lithium titanium oxide (LTO) have not made significant inroads into modern EV batteries due to limitations surrounding calendar life and energy density, respectively. Lab-scale research has shown that used graphite can be recycled into new cells, and material that is too damaged for reuse can be upcycled into graphene.[22] LTO can be upcycled to titanium-doped niobate compounds for further use as anodes in high-power LIBs.[23] A major factor in adopting new battery chemistries will be whether they enable "drop-in" technology.

By the late 2020s, EVs will form a significant part of the transportation fleet. This is expected to be mainly driven by governmental legislation for the decarbonisation of transport. The UK government has stated that 80% of new cars sold by 2030 must be zero emission at the point of use, increasing to 100% by 2035.[24] Many manufacturers have begun this change and invested in new production lines. Jaguar Land Rover, UK, ceased the production of three popular ICE models (XE, XF and F-type) in mid-2024 as it prepares for its EV future. The USA has a much longer timeline for decarbonisation by 2050.[25] However, this blueprint covers all forms of transport rather than just sales of new vehicles.

Product sustainability

The sustainability of a pack depends on the availability of the electrode active materials and their recyclability, as well as on how the cells are manufactured to ensure that as many non-active materials are captured and reused as possible. Significant attention has gone to the higher charge density of NMC compared to LFP cells, which contrasts with the sustainability of iron-based chemistries compared to cobalt and its well-documented socio-political issues.[26] The current predictions suggest the market share for LFP-based LIBs will increase compared to NMC chemistries, with LFP overtaking NMC by 2035, driven by use in public transport or smaller private EVs. Densely populated countries such as the UK (with a median daily mileage in the UK of 20 miles[27]) may see an increased market share of smaller EV cars. It is also widely expected that the cobalt content of cells will continue to decrease. Non-fluorinated binders and decreased use of epoxy-based adhesives could make packs easier to repair/recycle, increasing their sustainability.[28,29]

Lithium supply chain issues are also well documented, where demand is expected to grow fivefold by 2030 and 14-fold by 2040 compared to 2020 levels.[30] Lithium from hard rock mines and brines heavily burdens water consumption, especially in certain geographical regions such as the South

American salars (salt lakes).[31] However, the scale and impact of these environmental burdens remain poorly understood, further complicating efforts to ensure sustainable production and policy development. The demand for lithium often exceeds supply due to the different rates at which gigafactories can be established compared with the exploitation of a lithium reserve, which can take up to 15 years to reach full production. While flows and prices of lithium may fluctuate by 2035, the lithium supply will likely keep track of the overall predicted growth. Advancements in alternative battery types are essential towards 2050, when the overall lithium supply may become more critical. Cobalt is primarily produced as a by-product of copper and nickel mining, making its availability dependent on the market dynamics of these primary materials and the global demand for cobalt. Additionally, documented human rights issues associated with cobalt extraction in the Democratic Republic of Congo (DRC) raise significant concerns about its sustainable supply.[32]

Sodium-ion batteries are one of the largest of these alternative battery types. They could rapidly change many aspects of battery recycling, not least the cost of production and the value of the end-of-life (EoL) material. The time taken to market has decreased considerably compared to LiBs, and, as of 2024, there are reports of prototype vehicles already coming to the market.[33] A recently published roadmap on sodium-ion batteries[34] highlights the technical advancements made with this technology. While the power density is significantly reduced, recent cells have shown performances akin to LFP cells at a significantly reduced cost. Fig. 3 shows the cost, power density and proportion of technology-critical metals in the various cathodes.

In addition to new battery chemistry, new charging protocols could significantly affect consumer uptake. Smaller packs, which are more rapidly charged, could positively impact battery costs and accelerate car production, producing a more sustainable market. This may be particularly important for future sodium-ion batteries with lower energy densities.

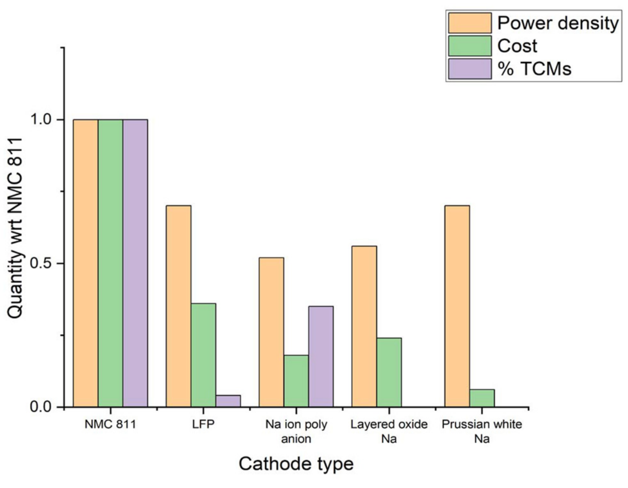

Fig. 3 Shows the cost, power density and proportion of technology critical metals in the various cathodes. Note: numerous metals can be used in layered oxide cathodes. The figure uses data from the literature.[35]

Other aspects of battery pack innovations for sustainability include decreasing permanent adhesives between cells and modules, simplifying disassembly, and switching from fluorinated binders to biopolymers for electrode manufacture. The shape, layout and tooling of cells, modules, and packs can simplify automated disassembly. Overall, the sustainability of the cell must also include its longevity.

Exploiting invested capital

Establishing a giga-factory is a capital-intensive process, and it is essential to ensure a maximum return on any investment, which in this instance would be the manufacturing equipment. By 2030, it is expected that the EV market will have some level of maturity, and OEMs will be working towards optimising product manufacturing into the future to maximise the lifespan of the equipment. OEMs are generally reluctant to alter a working process once optimised, especially as newly developed technologies may require a new production line. While sodium-ion technologies may be able to use portions of existing LIB production lines, other technologies such as solid state or lithium–sulfur batteries will require new production equipment and environmental controls. Any improvements to the current technologies must be designed to be dropped to an existing process. This is also true for emerging battery recycling facilities, where the processes being implemented are mainly based around pyro/hydrometallurgy, often with a shredding step to make the battery safe and comminute it to manageable sizes for processing.[36,37] This technology is expected to be utilised until enough economic, environmental, or legislative drivers are present to push recyclers to explore alternative end-of-life processing methods. Redesigning batteries with recycling in mind will help streamline this transition by reducing cost and energy requirements and ensuring that batteries can be disassembled safely and economically.[38] Legislation of a "battery passport" for new EVs will help facilitate disassembly and recycling.[39] However, the beneficial effects of clear labelling will not be seen on the recycling market until these new EVs reach end-of-life in 12–15 years.

Waste handlers and significant waste entering the market

Most countries currently have some capability for neutralising waste LIBs, and countries that were earlier to adopt larger EVs generally have more advanced recycling facilities. In the early 2030s, more waste processors are expected to enter the market. Up until this point, the majority of material processed was production scrap. Due to the currently guaranteed lifespan of an EV battery being 8 years or 100k miles,[40,41] the earlier models of EVs will be the main materials processed. However, modelling by the British Geological Survey indicates that the average lifespan of an EV car is closer to 14 years, delaying EoL material entering the recycling market. Battery feedstocks will be mixed, and product quality and profitability will be low. However, the recovery of higher cobalt content will offset this.

The long-term economics of recycling will need process efficiencies as the cobalt content falls. Numerous processors are already on the international market, albeit on a modest scale, producing products with varying efficiencies and forms. The outputs of the processes have been compared using a Strategic Materials Weighting And Value Evaluation (SWAVE), which compares the importance and value of the products obtained from each process.[42] By 2035, a significant number of EV batteries (estimated to be *ca.* 340 000 from EV cars alone) will need to be recycled, *i.e.*, the pre-2020 stock. Less valuable battery chemistries will also enter the recycling market, especially when large volumes of LFP cells from buses come. Battery directives will start to dictate the amount of recycled material that needs to be in cells by 2031.

By 2030, a position will have been established whereby approximately 20–30% of all vehicles sales are electric.[11] A significant amount of EoL stock is entering a recycling market, which is producing safe black mass, enabling some materials to re-enter the battery market. It is unlikely that there will be sufficient stock with the requisite purity to meet current battery directives. Still, it could be claimed that some material comes from recycled sources, albeit not from used EV batteries. Modelling suggests that if the UK wishes to comply with current EU targets, even assuming 100% recycling efficiency of EoL EV batteries, there will be a deficit of about 2000 tonnes of secondary lithium for the UK market alone until 2040.[43] In the case of cobalt, the deficit is predicted to be in the order of 3000 tonnes but likely to reach an equilibrium from 2035 onwards. A significant proportion of the recycling economics will be driven by processing gate fees.

A significant issue is that the chemistry of the cathode active material for many batteries will have changed. EoL material in the mid-2020s is mostly LMO/NCA, NMC111, and NCA, which are not commonly used in most modern applications. So, methods of converting this to more modern chemistries must be constantly reviewed. One method to increase the value of these end-of-life materials is to upcycle them into modern cathode chemistries through complete dissolution of the active material and modification of the metal ratios.[36] Other examples of upcycling methods include the selective leaching of one component. Ascorbic acid can be used to selectively leach LMO from LMO/NMC or LMO/NCA blends, where the leached LMO can be used as a precursor for producing different types of cathode chemistries, and the NMC or NCA phase can be regenerated.[44] A eutectic solvent made from choline chloride and oxalic acid dihydrate has been shown to selectively leach Co and Mn from NMC, resulting in a Ni-enriched solid.[45] Alternatively, multiple active materials can be leached together and precipitated to form higher-value materials such as lithium manganese iron phosphates.[46] More unusual upcycling methods include using bacteria to produce Co and Ni nanoparticles from battery leachates[47] or converting lithium-ion battery cathodes to sodium-ion battery cathodes.[48]

Maintaining the inherent value of the active material is also important. Once manufacturers have settled on a specific battery chemistry, the cathode's direct regeneration or relithiation is desirable. Relithiation has been shown for various cathode materials using hydrothermal, non-aqueous, and molten salt methods.[49–51] Production scrap and quality control reject materials will be available for processing much sooner than EV batteries. They will be composed of the current battery chemistries. In these instances, recovering the active materials as-is for direct reuse is preferable. In the case of graphite anodes, the active materials coating is delaminated from the copper foil current collector *via* a reaction of the lithiated SEI layer formed during cycling with water.[52]

Improvements in recycling efficiency

In the late 2030s, as roughly 50% of scrap cars are EVs, gate fees will need to be decreased, and process efficiencies will need to increase. Reverse logistics models have been used to determine the need for recycling plants.[53] Increased numbers of batteries with similar forms and chemistries will enable product sorting, driven by improved labelling. With battery passports introduced in 2027 (Fig. 2), these vehicles will probably not be recycled until *ca.* 2040. This will help logistics models and assist in the automated disassembly of packs. Depending on the available material volumes, battery recyclers can then specialise in specific battery chemistries. It is particularly important to separate LFP from NMC chemistries initially and then sodium ion batteries as they enter the market. The specialist recyclers may be linked to supply-specific OEMs to ensure quality feedstocks and purities. The importance of traceability has recently been discussed.[40] With some OEMs mixing battery chemistries in the same pack, simple colour coding of LFP and NMC chemistries may be a quick fix.

Cell and module shredding is currently the only viable option from a safety perspective.[42] Manual disassembly is time-consuming,[54] and exposes human workers to significant health hazards and high voltage environments. Automated disassembly has many benefits, from economic and safety perspectives,[55] and purer product streams. Since all battery assembly is automated, it seems logical that dismantling should be the same to improve disassembly times and reduce costs.[56]

By the early 2040s, battery pack forms should be more standardised, permitting automation of battery dismantling[41,57–59] However, this will only benefit the recycling market in about 2055. In conjunction with the dismantling, the battery modules will need to be assessed quickly to see if they are in good enough health to be refurbished and reused.[60] Any power remaining in the battery cells will be recovered before recycling, partially for safety and to minimise processing costs. Controlled cell discharge will also avoid dissolution of the copper current collectors, as copper is detrimental to cathode performance and would prevent direct recycling if present.

"Design for recycling" principles must be adopted to improve recycling efficiency and enable automated disassembly.[29,57,61] Connecting or fastening systems must be simplified to minimise human intervention and the associated health risks. Depending on the battery design, automated disassembly can decrease tear-down time from 8–10 h to 1–2 h.[58]

Rapid triage of end-of-life modules and cells can be integrated into disassembly if form factors are standardised.

Alternative electrode binders are a major enabler to sustainable cell production and recycling. The use of biopolymers such as gelatin,[62] guar gums,[63] polyacrylates, poly/oligo-saccharides,[64] and others have been covered in reviews by Bresser *et al.*,[65] and Bichon *et al.*[66] Additives such as phosphoric acid have been added to counteract hydroxide formation, or a protective coating, such as carbon or aluminium oxides, has been applied to the NMC particles.[67]

More comprehensive suggestions on cell design have also been made,[29,68] and these include:

- Fewer but larger cells
- Minimal use of thermoset adhesives
- Fewer fixing types
- Cells that are more easily opened
- Cells that can be rejuvenated by flushing out the old electrolyte and replacing with new
- Electrode binders that can be fully dispersed using water.
- Debondable adhesives (discussed further in Mulcahy *et al.*[28])

3. Factors affecting the timeline

Cost of product

By far, the largest factor affecting the EV market is cost. Governments and manufacturers can encourage the adoption of electric vehicles by offering new vehicle purchase subsidies, decreasing road tax, using bus lanes, subsidising charging points and workplace charging schemes, and penalising fossil fuel-burning vehicles with taxes for city driving. These subsidies can taper off as product adoption increases. Many countries and OEMs declare moratorium dates when they will stop manufacturing ICEs.[24] EV purchase costs have decreased from *ca.* 600 to 100 $ per kWh from 2012 to 2022.[69] Still, when EVs become the dominant proportion of the transport market, additional taxes will be needed to compensate for the decreased tax revenue from petroleum-based fuels.[11] Fuel duties typically represent about 1% of most national incomes, so electrification will change taxation policy and, in turn, the rate of electrified vehicle adoption. A delicate balance is needed between the cost of purchase, maintenance, and operation of the vehicle. However, this also needs to be viewed from a free-trade perspective as national governments impose import tariffs to limit imports and protect local manufacturing. This could be one of the largest barriers to EV adoption.

Misinformation & consumer confidence

Misinformation and miscommunication are major issues influencing the adoption of EVs. This can depend on how customers search for information prior to purchase. These can include fire safety, perceived green metrics, and information about ease of use,[65,66] particularly regarding the availability of charging points and charging times. Concerted social marketing programs backed by reliable data can boost consumer confidence as technology changes become familiar. Most drivers of ICE vehicles understand parameters such as engine size, power rating, range and fuel efficiency. Still, it takes time to translate kWh to fuel volume as a marker for range. Simplified traffic light systems could engender consumer confidence in the short term. Implementing battery passports should help alleviate consumer concerns about battery quality, reliability, and the ethicality of the sources of the material.[39,70] As vehicles become more dependent upon web-based functions such as remote charging, and it is important to future-proof communications with them. For example, phasing out 2G and 3G wireless communications is making some functions impossible on only 10-year-old vehicles.

Geography

While each consumer may have a different requirement for an EV based on their day-to-day usage, *e.g.* short supermarket round-trips *vs.* long commutes, the geographic location of those consumers will significantly impact whether they are willing to adopt EVs. Therefore, the types of batteries (chemistry and size) may need to differ in these markets. Probably the largest factor in the recycling market is the cost of processing which will have a large geographic factor, most notably in the cost of labour and energy. It may be cheaper to export the batteries for processing if labour is the major factor. This will, however, have a significant impact on the life-cycle assessment depending on the main source of electricity. This could concentrate manufacturers to certain markets. Geography will also impact how batteries are recharged, *i.e.*:

- Ensuring charging stations are available in remote areas may require upgrading the grid and storage infrastructure.
- Method of electricity production will affect the carbon footprint of EVs: where and how is the electricity produced? Is electricity generated nearby or on-site, or must it be "transported"? Schemes to link service station charging with solar farms must ensure that any carbon footprint gains are not outweighed by the dewilding brought about by the photovoltaic arrays.
- Charging technology: rapid charging would be preferable for remote locations. At the same time, the ability to switch battery packs would work best in high-traffic areas. However, storing fully charged battery packs will present safety and containment issues.

Battery ownership models

One model to ensure circularity is for batteries leased from EV (or battery) manufacturers. The battery could be replaced at end-of-life or swapped at designated refill points for smaller vehicles. This would have the added benefit of prolonging the life of the EV, as mechanical parts are easy to replace. Standard form factors are needed for the battery pack and the EV to achieve this. This concept of leasing batteries has already been implemented in the Chinese market, where two major manufacturers, Nio and Geely, make EVs with interchangeable battery packs, with some expansion into the European market.[71] The EV would need to be designed so that:

(a) the battery pack was quick and easy to remove and replace, *i.e.* not a structural component of the chassis, (b) take a standard battery pack shape and voltage, with a compatible Battery Management System, and (c) have standardised connectors at standardised locations.

This intriguing concept is unlikely to achieve significant market share before 2035 due to the high variability in battery pack design and a lack of backward compatibility. Storage infrastructure and technical assistance would make setup and maintenance expensive. Leasing batteries also fuels consumer mistrust/misuse of a used product. However, it could decrease initial costs and overcome battery lifetime and safety issues. Other factors that require optimisation include power density and battery range, environmental sustainability of material sources, recyclability of the product, and minimising costs. Geopolitical factors affecting the availability of component elements could also affect the trajectory of Fig. 2.

Material supply

As the LIB recycling market is relatively young, the supply of EoL materials is likely initially low but expected to rise rapidly. For example, in 2030, in the UK, there may be only a few hundred thousand EV LIBs. In contrast, it is predicted that there will be about 1.4 million LIBs requiring recycling in 2040, rising further to 2.7 million LIBs in 2046.[72] Significant investment in waste management infrastructure will be required to manage these volumes, both from processing and environmental protection perspectives.

One critical EU regulation mandates a certain percentage of recycled materials in batteries by 2030. For example, LIBs must contain at least 12% recycled cobalt by 2030 and 20% by 2035. In contrast, at least 4% of Li must be from recycled sources by 2030, going up to 10% by 2035.[73] Referring back to the case of the LAB market, where a very mature technology with a simple recycling protocol is available, it should be noted that a new LAB only contains about 70% recycled material due to the expanding nature of the LAB market.

Given the newness of the LIB recycling market, it is therefore infeasible to set regulations for LiBs before 2050, mandating anywhere close to 50% recycled materials. Suppose only the UK stock of potential EoL LIBs is considered for recycling. In that case, analysis indicates that even with a 100% recycling efficiency, the EU targets for 2030 and 2035 are unachievable due to insufficient stock availability.[72]

4. External policy challenges to achieving circularity

Holistic analyses of barriers and enablers for circularity in the battery sector are limited. Still, legislation and policy significantly impact the pathway to circularity.[74] Some of the main challenges are materials sourcing, safety, logistics and energy/transport costs. Transportation accounts for almost half of total disposal costs.[75] Cross-border transhipment of EoL batteries is subject to regulatory controls under the Basel Convention.[76] The Convention is important in preventing waste dumping. Still, the inconsistent interpretation of its rules and differing hazardous waste classifications across countries add significantly to the costs of LIB recycling and reuse.[77] Although legislation is jurisdiction-specific, the production, use and recycling of LIBs is a global issue. Intergovernmental agreements can significantly ease the burden of complex regulatory requirements and facilitate traceability of products, registers of contents, waste management logistics and safety protocols. Several jurisdictions are addressing these challenges to circularity (Table 1).

China is among the leading EV adoption nations, producing 1.2 million EVs in 2024. Still, concerns have been raised that its regulatory infrastructure remains underdeveloped for recycling the decommissioned batteries that will be falling out of use.[78] Most decommissioned power batteries in China, for example, still flow through informal channels, which remain poorly integrated in regulatory frameworks.[79] On the other

Table 1 International regulations for EV waste handling

Region	Regulation	Ref.
	Li recovery rate 90%, Ni, Co, Mn, Cu, Al and REE 98%. Energy consumption for 1t Li_2CO_3 < 18 MWh. Fluorine recovery > 99.5%	87
	Li recovery rate 80 %, Ni, Co and Cu 95% 2031 – New cells must contain 16% Co, 6% Li and 6% Ni from recycled sources 2036 – New cells must contain 26% Co, 12% Li and 16% Ni from recycled sources 2027 – Digital Battery Passport required	87
	No EPR regulations for WEEE or EV batteries. 9 states have some battery recycling regulations	88,89
	EVs are not differentiated from other vehicles. All demand recycling rates are >95%. The buyer pays a fee to cover EOL processing at the point of sale.	90

hand, China is predicted to reach full electrification earlier than other nations, and data suggests that this gives it significant potential to achieve full battery circularity faster.[80] As part of the effort to achieve this, The Ministry for Industry and Information Technology in China has 2024 published a new draft document for tighter battery regulations, which sets higher standards for LIB recycling and reuse.[81,82]

The USA, which has never had any federal nationwide collection or recycling targets for end-of-life batteries, committed in January 2025 to develop a national Extended Producer Responsibility (EPR) framework for batteries[83] (although it is now uncertain that this commitment will be fulfilled, given the deregulatory impetus and rollback on climate policies from the new administration).[84] In the meanwhile, it has been left to individual states to develop their governance frameworks for end-of-life batteries: New Jersey in January 2024 passed the Electric and Hybrid Vehicle Management Act, which applies only to EV batteries,[85] while states such as California, Vermont and Washington have, within the last few years, passed EPR laws targeting a broader range of batteries.[86] The administration change in the US also highlights how policy can rapidly change and this can affect technology adoption almost more than any other factor discussed above.

The EU, by contrast, has relatively well-established regulatory mechanisms for end-of-life batteries, which are further strengthened by new 2023 batteries legislation that is expected to support circularity and improve safety across the entire battery lifecycle.[73] This replaces the Batteries Directive 2006[91] and contains provisions for sustainable sourcing, production, labelling, recycling and materials recovery. These provisions will have phased application over the coming decade so that the full impacts will become more apparent over the coming years. Despite its comprehensive approach and innovative measures such as digital battery passports (DPP) from 2027 to enhance supply chain transparency,[73] the Regulation has important gaps: it is weak on ecodesign requirements and is unclear on details of data sharing mechanisms,[74] leaving some unanswered questions around risks and liabilities from second use.[92]

EU law no longer automatically applies in the UK post-Brexit, so the UK batteries landscape continues to be governed by old batteries legislation from 2009 (based on the 2006 EU Batteries Directive) until it is replaced by new UK-specific legislation.[93] Under the 2009 rules, which predate the move to electric mobility and are unsuited to address the challenges it raises, EV batteries in the UK are classified as 'industrial' rather than automotive batteries. This means there are no specific collection or recycling targets for these in current UK battery regulation – producers must only take back the battery if asked to do so. Batteries, once collected, are, however, subject to a 50% recycling efficiency target. Some governance measures are also provided by a ban on landfill/incineration on EV batteries and a separate set of regulations for end-of-life vehicles, which mandate a 95% recovery target and 85% recycling rate by weight for end-of-life vehicles.[94] Nonetheless, the weak mechanisms for EV battery circularity in current UK regulation is a recognised problem. The UK Government launched a review and consultation of its battery legislation in 2023.[95] At the time of writing, it is unclear when new UK regulations will be published.

Minimum recycled content targets

One significant driver towards battery circularity in the new EU Regulations is mandatory targets for minimum recycled content (specifically, lithium, nickel, cobalt and lead – Table 1). Some EU targets for recycled content have been criticised for being unrealistic and potentially counterproductive,[96] given forecasts of insufficient secondary material feedstocks. Nonetheless, despite the need for better data and ongoing review to inform specific targets, mandatory recycled content requirements can kickstart a fledgling LIB recycling industry and level the playing field for recycled materials, which are often more expensive than virgin materials. Regulatory intervention is especially important given that volumes of battery materials available for recycling are expected to be fairly modest until at least the mid-2030s,[75] which will make recycling more costly until economies of scale can be realised.

The intentions and timelines of the EU and China are relatively similar, although China has earlier deadlines. The products generated from the recycling processes must match the battery manufacturers' feedstocks. Direct recycling is the most economically favourable proposition but this can only be achieved if the battery chemistry of the recycled product is the same as that of the end of life material. This is an additional factor in favour of LFP.

Circular economy policy beyond recycling

Battery legislation and policy have focused heavily on recycling and waste management regulation to achieve circular economy ambitions through, for example, recycling targets, landfill bans and EPR for end-of-life batteries. Extending resource life or reducing critical materials use through repair, repurposing for second life applications, remanufacture, and better product design have received insufficient legislative attention or action.

Additionally, systemic interventions and circular business models (such as batteries-as-a-service or EV battery leasing schemes) also have significant potential to steer the transition towards a battery circular economy.[97] Apart from enabling effective collection and recycling, a further advantage of EV battery leasing is that it can help accelerate the transition to electric mobility by reducing the upfront costs of EV purchase – a known barrier to EV sales. Full electrification will, in turn, enable circularity by increasing secondary materials feedstock and making recycling more profitable.[80] Despite their potential to improve sustainability across the EV battery value chain, circular business models have been under-utilised in policy action.

Local sourcing and processing of battery materials can significantly reduce the environmental footprint of battery manufacturing while also enhancing future materials security. This has led to a renewed interest in mining and extraction in

Europe, where this industry declined until recently. The discovery of lithium deposits in South-West England has, for example, led to a renaissance in UK mining projects. Still, these geological resources can only be effectively harnessed with supportive policies and need improved planning/permitting processes.[98] Evidence suggests that UK infrastructure development is also significantly hampered by protracted local community disputes. However, legislation is planned to prevent unnecessary legal blocks.[99] While EV manufacture is a global concern, cell component manufacture is currently localised, and efforts to locate recycling and manufacturing plants closely have the potential to reduce overall carbon footprint by reducing impacts from transportation. While LIB cell manufacturing is becoming a global industry, electrode manufacture is still predominantly carried out in East Asia, making integrating active recycled material in some regions difficult.

Attention also needs to be given to developing more robust standards for battery design. EV batteries come in various chemistries, with various shapes and disassembly mechanisms for battery packs. Improving design for easier disassembly and recycling is an important area for future battery policy,[100] as the urge to retain competitive advantage may mean that manufacturers are unlikely to prioritise this without regulation. Improved standards around the labelling of batteries would also be beneficial.[101]

5. Conclusions

This study has revealed several clear recommendations designed to aid the establishment of a timeline for LIB recycling.

1. Many countries saw an increase in EV sales during the late 2010s and these vehicles will come to end of life in the period 2030–2035. While some countries have a recycling infrastructure in place, many do not but the timeline gives an indication of when these changes are required.

2. The volumes of EVs currently coming to market will require a different infrastructure for handling in 2035–2040, *e.g.*, pack labelling and standard pack architecture. OEMs need to think about the change in handling protocols brought about by the increased volume. Economies of scale will only be achieved with automated disassembly.

3. Significant differences in the legislation governing waste in different producer and consumer nations may lead to confusion about recycling responsibility.

4. Some of the targets in battery directives are unachievable due to the flows of markets and the immaturity of recycling markets.

5. Forums must be established to bring together pack designers and recyclers to look for quick wins in disassembly. Design for recycle needs to be more overtly discussed.

6. All stakeholders can affect the trajectory of product adoption, and only by working together can policy targets be met. National and regional policy changes can rapidly affect adoption and influence consumer confidence.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

Jennifer M. Hartley: writing – original draft, writing – review & editing, visualization, Sean Scott: writing – original draft, writing – review & editing, visualization, Jake M. Yang: writing – review & editing, Paul A. Anderson: writing – review & editing, Gavin D. J. Harper: writing – original draft, visualization, Jyoti Ahuja: writing – original draft, writing – review & editing, Evi Petavratzi: writing – review & editing, Harikrishnan Tulsidas: writing – review & editing, Andrew P. Abbott: writing – original draft, writing – review & editing, conceptualization, supervision.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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