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Circular waste management of electric vehicle batteries: Legal and technical perspectives from the EU and the UK post Brexit

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ABSTRACT

In light of the climate change, interdisciplinary solutions are needed to deal with end-of-life lithium-ion batteries (LIBs) that are used in Electric vehicles (EVs) in order to avoid a waste problem in the future. Building on both legal and technical perspectives, this paper criticises the current EU and UK frameworks and policies on batteries waste management which fail to address technological innovation, especially, in terms of the creation of a market for 'second life' of EV batteries which are subject to the electrochemical performance and durability and safety parameters, as well as LIB recycling in support of a circular economy. Most importantly, it also addresses recent developments in the EU in terms of a proposal for the EU new Batteries Regulation and the impact of Brexit in the UK for its future policy shape.

1. Introduction

Electric Vehicles (EVs) have the potential to contribute to decarbonising the transport sector and mitigate climate change, as EVs produce fewer greenhouse gas (GHG) emissions than conventional vehicles across their life cycle. This potential has been recognised worldwide, expecting that by 2030 there could be up to 125 million EVs on the road [1] with nearly 5 million tonnes of lithium-ion batteries (LIBs) used in EVs being sold by 2025 [2]. While this could be a great solution to decarbonise the transport system, yet, a new study found that recycling technologies for end-of-life lithium-ion batteries (LIBs) are lagging behind the brisk rise of EVs, which in turn will lead to a huge waste problem in the future [3]. Globally, over 11 million tonnes of spent LIBs are forecast to be discarded by 2030 [2], ending in landfills outside the EU. For instance, the EU internal market ends-up with approximately 190,000 tonnes of industrial batteries each year [4]. EVs batteries currently fall under the broad category of 'industrial batteries' under the EU Batteries directive (thereafter, the Directive) [5] and Waste Batteries and Accumulators Regulations 2009 (as amended) [6] in the UK (thereafter, the UK Regulations, implementing the named Directive), which are the main pieces of legislation on batteries waste. According to the Directive 'industrial battery' means any battery designed for exclusively industrial or professional uses or used in any type of EV (Article 3(6)). Due to the growing market of electric road transport vehicles, the European Commission (EC) has recently proposed to classify those batteries that are used for traction in road vehicles as a new category of electric vehicle batteries (EVB).

Currently, in the EU, the industrial batteries are not properly collected and recycled at the end of their life, with only 5% of lithium recovered by 2013 [7], surging the risk of releasing hazardous substances to the environment and pose major human health issues. It is estimated that in 2020 there were 250,000 tonnes of LIBs waste and no infrastructure to pair up the collection and recycling of it [8]. In addition, valuable materials are also lost, as result of poor recycling. There are escalating concerns over raw materials, especially, cobalt, nickel, and manganese which apart from lithium form essential part of the LIBs' composition. Recycling can offer a vital solution to raw material supply insecurity and price fluctuations. Indeed, through recovering critical raw materials from LIBs, manufacturers can shield themselves from supply disruptions and also create additional revenue streams [9]. For instance, it is predicted that by 2040 the global LIB recycling market will be worth $31 billion annually [9], as retired EV battery can either be repurposed for a second-life in alternative applications or recycled to obtain the raw materials [10]. Furthermore, this, in turn, would also improve the environmental performance of all operators participating in the life cycle of batteries, such as producers, distributors and end-users and, in particular, those

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operators directly involved in the treatment and recycling of waste LIBs [4]. Recycling and reusing (second-life) LIBs will reduce the life cycle environmental impacts associated to LIBs and products that rely on it (i.e. cars), in particular to those related to the extraction (i.e. mining) and manufacturing of raw materials and LIBs themselves, the largest contributors to impacts like climate change, primary energy demand and depletion of metals, since recycling and reusing will avoid the use of virgin materials [11, 12]. This is especially important since over 11 million tonnes of spent LIBs are forecast to be discarded by 2030 [2], which represents a total number of 58 million units. With a concentration of 8−15 kg of lithium per battery [13], the implementation of recycling would generate up to 58,000 tonnes of lithium, which could avoid mining virgin lithium and other metals. Mining of lithium is mostly dependant on a few large mines, either in South America (under salt lakes) or in Australia (rock mining), which involves approximately 1,900,000 liters of water per tonne of lithium when extracting lithium from brines, mostly in water impoverished areas of the world [14]. Therefore, mining negatively impacts local communities deteriorating health (e.g. air, soil and water pollution) and increasing inequalities due to income disparity, high pressures on infrastructure, housing and services, among others [15].

The challenges of moving toward a circular and sustainable economy are vast, but it is imperative to acknowledge them at early stage. There have been several scientific studies noting the importance of sustainable LIBs waste management [3, 11, 16-23], including how batteries performance and efficiency can be improved employing thermal management techniques [24, 25]. Research has also been performed to understand the role of battery design to enable the recycling and recovery of critical materials from LIBs, ensuring safe and economically viable processes [26]. However, there have not been any comprehensive studies undertaken from an interdisciplinary perspective embracing both legal (including the most recent developments) and technical aspects in the landscape of circular economy (CE). The EU Batteries directive (2006) was largely out-of-date and in great need of revision [5]. Therefore, in December 2020, a new 130-page EU Batteries Regulation was proposed covering all types of batteries also stressing that batteries are sustainable and safe throughout their entire life cycle, from production process, design requirements to recycling, reuse and giving batteries second life ensuring that valuable materials feed back into the economy [27]. If approved, this Regulation would replace the Batteries Directive, as there are currently no legal provisions in the EU level that address other aspects of the production and use phases of batteries, such as electrochemical performance and durability, GHG emissions, or responsible sourcing [27]. The EC has chosen a Regulation as the legal instrument, which in contrast to a Directive is directly applicable in the Member States, demonstrating the increased importance of this area. Specifically, it aims to strengthen the functioning of the EU internal market for batteries while simultaneously promoting the CE by closing the materials loop and reducing the environmental and social impacts of batteries throughout their life cycle. The importance on sustainable batteries in the EU is also visible in the EC's recent approval of State Aid of €2.9 billion for the "European Battery Innovation" covering twelve Member States to focus on a next generation of batteries along the entire battery chain. Along similar lines, the UK's government is also planning to review the UK Regulations 2009 to facilitate EV batteries recycle in the future. After Brexit the UK is no longer required to follow the EU rules and therefore, the proposed EU Batteries Regulation will not be applicable for the UK allowing more flexibility to design its waste statute book. Nevertheless, the UK will unlikely depart from the EU's approach to encourage circularity. Clearly, the UK Faraday Institute is playing a leading role in promoting the reuse and recycling of battery components, where one of the eight technical challenges set is to be able to recycle 95% of an EV battery pack by 2035 [28]. Regulatory frameworks are necessary for the transition towards a CE. Therefore, this paper will review the current EU and the UK legislations on batteries waste management, including the most recent developments. However, it is essential that the regulatory frameworks are in line with the technological development pace, especially, in terms of the creation of a market for 'second life' of EVB as well as LIB recycling, which will be explored in this paper.

Specifically, this paper is structured as followed. In Section 2 the current regulatory frameworks and policies related to LIB waste management in the EU and the UK will be reviewed. Section 3 will be devoted to various technical issues related to the creation of market for secondary materials, whereas Section 4 will summarise the discussion and Section 5 will conclude the paper.

2. Current regulatory frameworks and policies in the EU and the UK

2.1. Overview

The CE model has inevitably gained momentum changing systems from the linear approach "take-make-use-waste" to more circular ones, where resources are used and kept for longer to reduce and hopefully avoid wastages as much as possible. The CE model relies on a 'life-cycle thinking' approach to ensure sustainability, respecting the waste hierarchy, as defined by the EU Waste Framework Directive, commonly known as the WFD [29], as amended [30] with prevention being the most preferred option. As indicated by Price and Joseph [31] and Murray et al. [32] companies may subvert to an unsustainable business-as-usual model, if waste hierarchy is not explicit, therefore, without overhaul of the entire supply chain, mode of operation and the radical change in product materials.

The CE concept has been discussed in the EU for some time. Already in 2015, the EC issued a striving Circular Economy Action Plan [33], which included steps to encourage Europe's transition towards a CE, embracing measures covering the whole cycle: from production and consumption to waste management and the market for secondary raw materials, therefore, contributing to "closing the loop" of product lifecycles through greater recycling and re-use [34]. In 2020, the EC has issued a new Circular Economy Action Plan [35], which is one of the main blocks of the European Green Deal [36], Europe's new agenda for sustainable growth. Among other things, the new Circular Economy Action Plan calls to focus on the sectors that use most resources and where the potential for circularity is high, such as batteries and vehicles (point 3.2 of[35]). This plan also makes long-overdue commitments to introduce a new regulatory framework for batteries, to enhance the sustainability of the emerging battery value chain for electro-mobility and boost the circular potential of all batteries. Apart from rules on mandatory recycled content for certain materials or components, and improving recycling efficiency, the EC also aims to improve sustainability and transparency requirements for batteries, simultaneously considering the carbon footprint of battery manufacturing, ethical sourcing of raw materials and security of supply, and facilitating reuse, repurposing and recycling (point 3.2[35]). However, insufficient progress has been accomplished to address EV batteries recycling and reuse so far, as the average recycling rate across EU members of state is 48% [37], while lithium still gets lost with a recovering rates of 1−5% worldwide [7, 38].

2.2. EU batteries directive and related legislation

The WFD sets the foundation for any waste stream with a broad definition of waste, as "any substance or object which the holder discards or intends or is required to discard" (Article 3 WFD). In its landmark Vessoso and Zanetti decision (Cases C-206/88 and C-207/88 Vessaso and Zanetti ECLI:EU:C:1990:145), the Court of Justice of the

European Union (CJEU) held the notion of waste does not exclude substances and objects, which are capable of economic reutilisation. This sketchy definition of waste meant that it was difficult for the Member States to apply it to various practical situations, especially, in situations when a waste ceases to be a waste (and becomes a new or secondary raw material) [39]. In terms of hazardous waste, which consists of waste containing substances or properties harmful for humans and the environment (Article 3(2) WFD), the CJEU in its Lapin judgement (Case C-358/11, ECLI:EU:C:2013:142) indicated that REACH (in particular Annex XVII, as long as it authorises the use of certain chemicals) may be relevant for the purpose of determining whether hazardous waste ceases to be waste. The case further indicated that national bans can fail to ensure EU-wide protection, and would undercut the other objectives of REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals), such as the free circulation of substances on the internal market and enhancing competitiveness and innovation. Thus, this grey area of the classification of ‘waste’ and ‘secondary raw materials’ requires further clarity despite the end-of-waste criteria (i.e. the substance/object is commonly used for specific purposes; there is an existing market or demand for it; its use is lawful; and its use will not lead to overall adverse environmental or human health impacts, Article 6 WFD).

In addition to the general framework, there is the Batteries Directive [5], which is the main piece of EU legislation devoted to batteries so far. It is directed at the life cycle of batteries, from design, placing on the market to end-of-life collection, treatment and recycling of spent batteries. It covers three main categories: 1) portable batteries; 2) automotive batteries; and 3) industrial batteries. EV batteries fall under the latter category. The Directive's main objective is to reduce the negative impact of batteries and waste batteries on the environment (due to the presence of hazardous components) as well as to safeguard the fair functioning of the internal market in the EU. The management of chemicals used in batteries falls outside the scope of the Directive (and are covered under the specialised legislation, such as REACH), except the ban of using mercury and cadmium in batteries. It is illegal to landfill, incinerate or improperly dispose of spent batteries; and all spent batteries collected must undergo treatment and recycling (Article 12.1b Directive). These are reinforced in the proposal for a new Batteries Regulation [27].

The Directive incorporates the principle of producer responsibility, with the responsibility being placed on producers for the end-of-life management of the batteries that they place on the market; producers must cover the costs of collecting, treating and recycling all waste batteries (Recital 19 Directive). In terms of industrial batteries, producers, for instance, cannot refuse to take back spent industrial batteries from end-users (Article 8.3 Directive). However, the Directive does not set targets for the collection either of waste industrial or automotive batteries. This meant around 56,000 tonnes (11%) of industrial batteries placed on the market were lost on a yearly basis [40]. Specifically, industrial LIBs, popular in EVs, are currently classified as ‘other batteries’ within the Industrial battery category. With the recycling efficiency target for ‘other’ batteries being set at 50%, the legislation does not guarantee the recovery of lithium or any other valuable materials, such as cobalt contained in those batteries [41]. This should be rectified by the newly proposed Regulation which, first of all, recommends creating a new category of electric vehicle batteries, specifically designed to provide traction to hybrid and electric vehicles for road transport (Article 2(12) [27],). Secondly, the importance of lithium for the battery value chain is also addressed through new targets for LIBs, where the recycling efficiency target for LIBs is proposed at 65% by 2025 with the material recovery rates for Co, Ni, Li, Cu being suggested at 90%, 90%, 35% and 90% in 2025, respectively [42].

The current Batteries Directive has been criticised for failing to address all environmental impacts and risks of the different stages in a battery's life cycle [40]. Indeed, it does not take into consideration negative externalities on the environment, for instance, from the vast extraction of raw materials, or from recycling processes requiring extensive energy and water supplies. For instance, high amounts of GHG emissions result from the pyrometallurgical process of LIBs. Refining copper, cobalt and nickel is also an energy intensive process producing a substantial amount of GHG emissions ranging from 3.2 kg CO_2eq. per kg of copper to 12.8 kg CO_2eq. per kg cobalt. However, still lower when considering that around 3.6×10^{12} kg of CO_2eq. are associated to mining and metal production, which correspond to 10% of the global energy-related GHG emissions [43]. Therefore, the new Batteries Regulation proposes new rules on the carbon footprint of EVB with staged information requirements, a carbon footprint declaration; followed by carbon footprint performance classes; and ultimately, the compliance with maximum life cycle carbon footprint thresholds (Article 7, Annex II [27],).

Finally, the proposed Batteries Regulation (if approved) will operate in conformity with other legislation, such as the Directive on end-of life vehicles (known as the ELV Directive) [44] which sets dismantling and recycling of ELVs more environmentally friendly. For instance, it contains targets for reuse, recycling and recovery of the ELVs and their components. It also provides provisions for producers to manufacture new vehicles without hazardous substances (namely, lead, mercury, cadmium, and hexavalent chromium).

2.3. UK regulations

Given that the deadline to implement all the directives discussed above passed before the UK ceased to be the EU Member State, they all were transposed to the UK legal landscape. Specifically, the EU Batteries Directive was implemented in the UK Regulations [6], which aim to improve the environmental performance of batteries and specify requirements for waste battery collection, treatment, recycling and disposal of all types of batteries and affect producers, battery distributors, waste battery collectors, recyclers and exporters. Aligning with the Directive, it also covers the three categories of batteries, including industrial batteries with a ban of industrial batteries being disposed in landfills or by incineration (Section 56 Regulations). LIBs fall under the industrial batteries category and the UK currently does not have any specific legislation for LIBs.

Section 35(2) of Regulations provides that producers of industrial batteries must redeem waste industrial batteries free of charge and within a reasonable time from an end-user of industrial batteries. They must also guarantee that all identifiable waste batteries taken back (or collected) are transported to 1) an approved battery treatment operator for treatment and recycling (i.e. ABTO or ABE); or 2) an approved battery exporter for treatment and recycling outside the UK. Records must be kept of the amount in tonnes of industrial batteries placed on the UK market for the first time and the amount in tonnes of industrial batteries taking back or collected and delivered to an approved battery treatment operator for treatment or recycling, or to an approved battery exporter for treatment or recycling outside the UK. It must also specify the amount in tonnes of batteries by each category of battery; and by the chemistry type for each category of battery (Section 39 Regulations). In the context of chemistry type, similar to the Directive, the Regulations identify two main types, such as lead-acid and nickel-cadmium, referring to the remaining as any other chemistry. Therefore, LIBs would fall under ‘other’ category, meaning that there is insufficient encouragement to recover precious metals.

Furthermore, there are also obligations arising from the implementation of the ELV Directive, which was transposed in the ELVs Regulations 2003 (the ELVs (Amendment) Regulations 2010); the ELVs (Producer Responsibility) Regulations 2005 (the ELVs (Producer Responsibility) (Amendment) Regulations 2010) [45]. These require to limit the environmental impact of EVLs disposal, by reducing the amount of waste created when they are scrapped. Vehicle manufacturers and importers, among other things, are required to establish collection networks to take back their vehicles free of charge at end-of-life. They also require vehicles to be treated at Authorised Treatment Facilities to certain depollution standards, which also include removal of the batteries at an early stage before further treatment takes place.

Despite leaving the EU, the UK government has stated that this has not changed its world leading ambitions on the environment and its commitment to moving towards a more CE by maintaining resources as long as possible, obtaining maximum value from them, minimising waste and promoting resource efficiency [46]. For instance, it is planning to bring forward the end date for the sale of petrol, diesel and hybrid cars and vans to 2035, or earlier if that transition appears feasible [47]. Therefore, the importance of LIBs recovery will increase significantly in the UK. This is why it is essential that regulatory frameworks and policies embed the principles of a CE, ensuring that the value of materials is maintained for as long as possible, for instance, by creating a market for secondary materials. The UK has international commitments, for instance, under Paris Agreement, to address the climate change, It is the first major economy to legislate for net-zero emissions by 2050. After Brexit, the UK will not have an obligation to implement the newly proposed Batteries Regulation. Yet, it is unlikely that the UK will ignore the EU Regulation and its circularity approach, especially in terms of Northern Ireland, as the proposed EU Regulation will apply to Northern Ireland because of the Ireland/Northern Ireland Protocol annexed to the Withdrawal Agreement [48]. To ensure co consistency on the UK internal market, the government most likely will try to avoid any legislative divergence between Northern Ireland and Great Britain. Furthermore, according to the EU-UK Trade and Cooperation Agreement, EVs are regarded differently from combustion engine cars, as neither the UK nor the EU currently has the capacity to supply them with battery cells. To qualify for tariff-free trade between the UK and EU, up to 60% of the components in EVs can originated from outside the EU (or the UK) by the end of 2023, which is reduced to 55% by 2026 and to 45% from 2027. This means that EVBs will have to be sourced in the EU or UK. Therefore, building a market for secondary materials is essential.

3. Market for secondary materials

3.1. Building a market for secondary materials: overview

Secondary materials will not work unless there is a market for it. A market for the second life of used EVBs is emerging, as the uptake of EVs is sharply increasing. However, currently, neither the Batteries Directive nor the UK Regulations address second life of batteries; they do not define the legal framework within which the second life of batteries can be developed with further opportunities to improve environmental, economic and social impacts. In relation to environmental impact, it can reduce waste disposal and increase recycling rate. Lithium hexafluorophosphate (LiPF6), an electrolyte used in these batteries, is hazardous and highly flammable [40]. Replacing primary materials with secondary recycled materials could also help offset the environmental impact of different stages in a battery's life cycle, protecting natural ecosystems and biodiversity [49]. In terms of competitiveness of recovered materials compared with raw materials, the emissions caused by recycling metals (lead, lithium or nickel) are offset by the savings in emissions due to the lower need for extractive activities, as recycling processes produce lower environmental burdens than raw material extraction [40]. Challenges still remain in the collection and recycling processes, as so far the quality of the materials recovered translates to economic savings between −5% to 20% [26]. Therefore, it is estimated that final balance is positive, especially if the environmental damage is considered as negative externality. For example, McManus [50] assessed the metal depletion of six battery production systems in the UK, namely Lead-acid, Nickel cadmium, Nickel metal hydride, Lithium ion (with NMP as solvent), Lithium-ion (with water as solvent) and Sodium Sulphur. In this study, the production of LIBs showed the highest depletion of resources between 100.8 and 158.4 kg Fe eq. per kWh capacity, global warming potential between 61.2 and 72 kg CO_2eq. per MJ capacity, and high human toxicity between 10.8 and 18 kg 1,4-DB eq. per kWh capacity, which comes mainly from the mining processes. Lithium-ion and the nickel metal hydride batteries also exhibited high cumulative energy demand when assessed by mass of product, estimated at ~90 MJ per kg battery. Sodium sulphur and the lead acid batteries excelled across the technologies analysed; however, the author did acknowledge the lack of available and reliable data for the Sodium Sulphur. Ellingsen et al. [51] also carried out a cradle-to-gate LCA assessing a comprehensive set of 13 environmental indicators using three functional units (e.g. battery unit, mass, kWh). When looking at the capacity of the batteries (kWh), they have estimated that the global warming potential ranges from 172 to 487 kg CO_2eq. per kWh while the depletion of resources ranges from 154 to 157 kg Fe eq. per kWh. Wang and Yu [11] assessed not only the manufacturing of LIBs including battery evolution, but also the impact of recycling in the life cycle. They found that the evolution of the batteries, according to Chinese market and technologies, will per se decrease the impacts associated to the batteries' life cycle by around 4% in the case of global warming potential and by 8% in the case of depletion of fossil fuels. The depletion of resources is the greatest benefit, as the estimations shown a reduction of 46%. However, the inclusion of recycling at the end-of-the life of the batteries is by far the most beneficial activity. The authors found that recycling decrease global warming potential by 56%, the depletion of fossil fuels by 45% and the depletion of resources by 92%.

As far as economic impact is concerned, repurposing and second use applications can be cost effective, or even profitable, depending on gains obtained using (repurposed or refurbished) batteries, on the cost of disassembly and remanufacturing (treatment of hazardous and flammable components required ad hoc facilities and highly skilled personnel) and on the differences in cost with production of new equally-performant batteries. Wang and Yu determined that when considering battery evolution, there is a decrease in the profit of recycling companies along the time, due to constraint of cobalt as batteries will use less cobalt, however the recycling business will be still profitable. They also highlighted the issues related to collection of batteries, which could be more detrimental than the recycling technology evolution. Increased resource efficiency also reduces the risk of supply chain disruption due to lower reliance on imports [52]. As noted by the EC, "the supply chain of these materials is potentially vulnerable to disruption. In view of the large quantities needed in the future (...) recycling of materials will increasingly become important for reducing the EU's dependency on third country markets and should be encouraged in the framework of the transition to a circular economy" [30].

Finally, in terms of social impacts, a market for secondary materials can create new job opportunities along the supply chain, improve environmental and health conditions, and facilitate further collaboration among different stakeholders and authorities, building cooperative supply chains and promoting industrial symbiosis [53]. Additionally, it can also reduce dependency on foreign primary resources (resource security), with further social impact on reducing child labour and conflict (i.e. cobalt extraction from Democratic Republic of the Congo largely relies on armed aggression and child labour) [54]. Building on the above, there is no surprise that the EC in its newly proposed Batteries Regulation aims to impose the responsible sourcing of raw materials (due diligence), addressing the social and environmental risks related to raw material extraction, processing and trading for battery manufacturing purposes.

3.2. Pathways for the generation of secondary raw materials

Promoting CE practices for EVBs require the development and implementation of a supply chain together with infrastructure that consists of collecting and sorting, dismantling, materials recovering and remanufacturing including reusing, upcycling, downcycling, and the development of new markets for recycled materials, and remanufactured batteries. Therefore, the following sub-sections will discuss some of these key activities in terms of legal requirements and technological implications.

3.2.1. Collection and sorting- recycling targets

As stated above, the existing Directive does not set specific collection targets or reporting obligations for industrial batteries, which embrace EVBs. It also fails to define targets for the recovery of vital materials, such as those contained in LIBs, which is truly problematic. The lack of specific target for LIBs recycling efficiency disincentives the recovery and exacerbates the imbalance. Therefore, great opportunities for business are lost, as it has been estimated that the value of recovered materials (cobalt, nickel, aluminium and lithium) in 2030 could amount up to EUR 408 million [55], provided a collection rate is set at 65% and a recycling efficiency for lithium batteries of 57%. This in turn would help to retain these materials in the EU economy and create 2618 new jobs [40]. Furthermore, some studies have also noted that the collection targets should not be limited to only one type of batteries (i.e. portable batteries), as it is not effective [56]. It can also imply that some batteries are not worth recycling.

Nonetheless, there are some promising developments. In May 2020, the EC published its Inception Impact Assessment [42] to modernise the Directive. Furthermore, in the European Strategic Energy Technology Plan, there is also a proposal to collect 70% of LIBs of any kind by 2030 [57]. Most recently, in December 2020 the proposed Regulation does not contain any provision LIBs collection rates. Yet, it is expected that all EVBs would be collected in full (Article 49 [27]). In addition, it also suggests introducing a gradual recycled content of valuable material in EVBs, which will be further discussed in the following sub-sections.

3.2.2. Recycling/upcycling/downcycling and material recovery

The recent evaluation of the Directive has identified that the current provisions on 'material recovery' are insufficient (Section 3.2.4 [40]), as they do not fully reflect the importance gained by resource efficiency and CE policies. It has also been noted that the current definition of recycling efficiency in the Directive is orientated towards determining the efficiency of processes rather than towards material recovery [58]. Given that high-quality recycling is not defined as a priority, compliance with some current targets could be achieved by downcycling or 'cherry picking' (i.e. choosing which battery parts or materials to recycle) [40]. For instance, there are currently only targets for the recycling efficiencies of lead and cadmium but not for other valuable components; without further specification of other recycling obligations, life cycle thinking is undermined. To address this, the new Regulation imposes obligations to provide detailed technical documentation with information about the amount of cobalt, lead, lithium or nickel recovered from waste present in active materials which will have to accompany EVBs (as of 1st January 2027); and from January 2030 the EVBs will have to comprise of specifically defined levels of recycled content (i.e. 12% cobalt; 85% lead, 4% lithium and 4% nickel, which will be further increased to 20% cobalt, 10% lithium and 12% nickel by January 2035 (Article 8, [27]).

In terms of CE, recycling has several advantages. First, recycling reduces depletion of raw materials and resource insecurity, especially if materials are scarce and/or imported from potentially 'unethical' sources. Extraction of raw materials has large environmental burdens. Therefore, replacing primary/virgin production of metals, such as cobalt and nickel, totally or partially, would greatly reduce those impacts. Secondly, LIBs contain high value materials; thus, recovering, for example, high-grade steel and other precious metals, such as nickel, cobalt and manganese from the dismantling process creates additional economic and environmental advantages. A battery composition generally consists of an aluminium (Al) casing, the battery management unit (BMU) and cables. In general, around 55 wt% of a battery system are dedicated to the battery cells containing the electrolyte, separator (plastics), cell housing (Al), and the electrodes. While the anode is a copper (Cu) foil mainly coated with graphite, the main component of the cathode coating is a transition metal oxide containing different ratios of lithium, nickel, cobalt and manganese oxide. To have a better understanding of the amount of metals present in an EV battery system with average weight and formulations similar to $LiNi_{0.33}Co_{0.33}Mn_{0.33}O_2$, 3.5 kg of lithium (Li), 10.9 kg of nickel (Ni), 10.9 kg of cobalt (Co), and 9.8 kg of manganese (Mn) can be calculated [59].

However, recycling of LIBs from a technical point of view is far from simple due to their extremely variable formulation (i.e. high mixture of materials and small dimensions of such mixture that complicates physical separation) and engineering design. Therefore, this means that a series of high energy intensive processes are required to recover parts of materials used in LIB which are described below, detailing steps and methods (see Fig. 1).

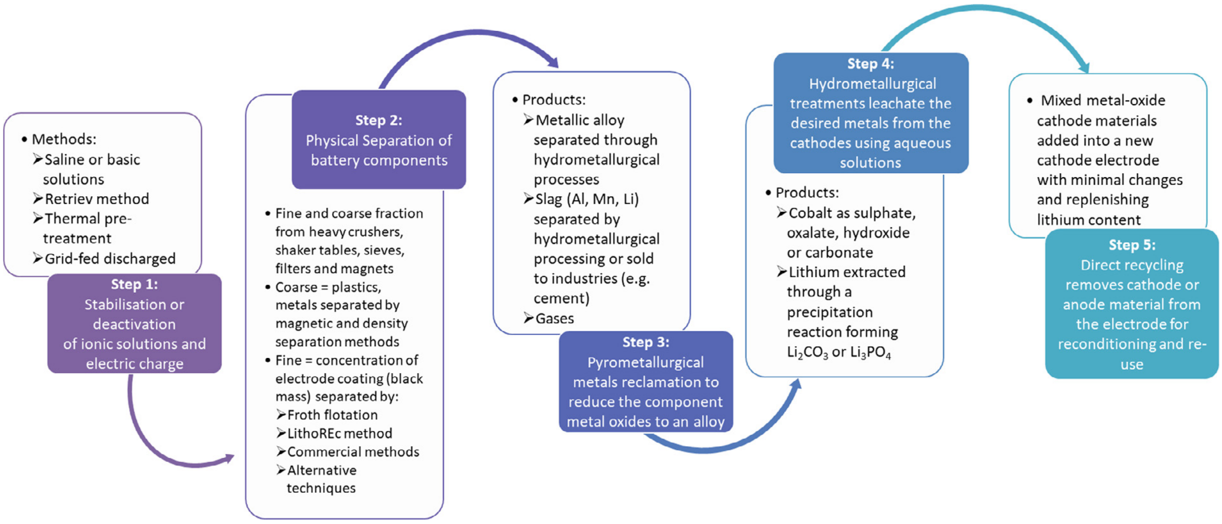
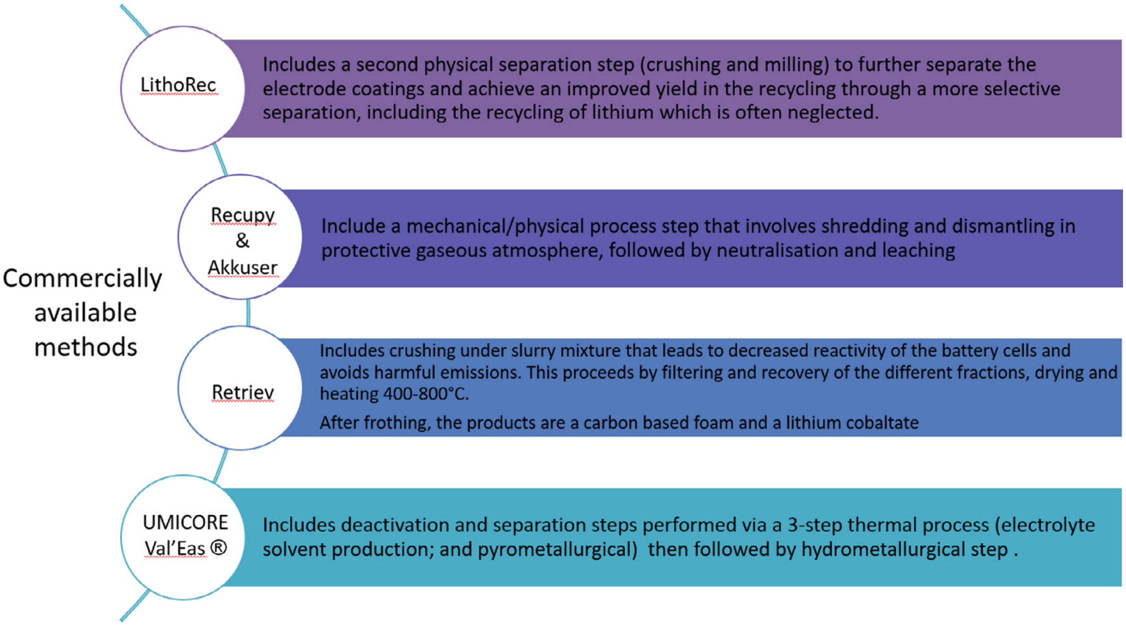


Fig. 1. Schematic of the stages and relevant steps available for the recycling of battery components [3, 60-72].



Includes a second physical separation step (crushing and milling) to further separate the electrode coatings and achieve an improved yield in the recycling through a more selective separation, including the recycling of lithium which is often neglected.

Include a mechanical/physical process step that involves shredding and dismantling in protective gaseous atmosphere, followed by neutralisation and leaching

Includes crushing under slurry mixture that leads to decreased reactivity of the battery cells and avoids harmful emissions. This proceeds by filtering and recovery of the different fractions, drying and heating 400-800°C.

After frothing, the products are a carbon based foam and a lithium cobaltate

Includes deactivation and separation steps performed via a 3-step thermal process (electrolyte solvent production; and pyrometallurgical) then followed by hydrometallurgical step .

Fig. 2. Summary of the existing commercial methods for battery recycling [62, 64, 65, 67, 69, 70].

Step 1: Stabilisation or deactivation. Prior to entering batteries in the recycling cycle, an initial step is required to stabilise the charge to avoid uncontrolled electrical and thermal discharge, which can be achieved by performing a controlled discharge in ionic solutions. Initially, seawater was the main medium used for this task. Different ionic solutions (saline and basic) were also tested [66], in particular, for the evaluation of the optimal point between discharge capability and corrosiveness levels of some of the solutions on the units. This type of process is also used in the Retriev method [67] where the crushing of the batteries is performed within a slurry that diminishes the reactivity of the material. Another deactivation method consists of a thermal pre-treatment [72]. During this process batteries are heated up to maximum temperatures around 300 °C. Currently, a promising idea of discharging the batteries in the grid to re-use part of the electricity in peak hours is being developed and optimised.

Step 2: Physical separation. The mixture of lithium-rich solution, low density plastics and papers, magnetic casings, coated electrodes and electrode powders forming the battery undergoes a series of processes that include heavy crushers, shaker tables, sieves, filters and magnets. The result is generally a fine fraction containing a concentration of electrode coatings and a coarse fraction consisting of plastics, casing materials, and metal foils. Those coarse fractions can undergo magnetic separation processes to set apart the magnetic material (i.e. steel casings) and a density separation process to separate plastics from foils. The finer fraction is referred to as the 'black mass' and includes the electrode coatings (metal oxides and carbon). The carbon can finally be separated from the metal oxides by froth flotation.

A further advancement on the physical separation processes is offered by the LithoRec process [62], which includes a second physical separation step (crushing and milling) to further separate the electrode coatings and achieve an improved yield in the recycling through a more selective separation, including the recycling of lithium which is often neglected in favour of the other metals. This second crushing steps also reduces the high temperature processes (the pyrometallurgical steps), hence, moving towards a more energy efficient process.

There are commercially available methods, which use the first two steps defined above (see Fig. 2). For instance, Recupyl [65, 69, 70] and Akkuser [64] include a mechanical/physical process step, embracing shredding and dismantling in protective gaseous atmosphere and further neutralisation followed by leaching. Similarly, the Retriev method [67] proposes a crushing under slurry mixture (i.e. this wet crushing leads to decreased reactivity of the battery cells and avoids harmful emissions) which is followed by filtering and recovery of the different fractions, drying and heating 400–800 °C. These steps also produce a carbon containing foam retrievable via frothing and a lithium cobaltate. In the UMICORE Val'Eas® process, on the other hand, the deactivation and separation are performed via a thermal process by heating the cells in three steps: i) electrolyte solvent production; ii) pyrolysis step that removes the polymeric fraction; and finally, iii) a pyrometallurgical step at higher temperature (>1400 °C) to collect the remaining metals followed by a hydrometallurgical step.

Alternative techniques use the combination of two processes. For instance, mechano-chemical recovery methods show that lithium/cobalt oxide can be firstly co-grinded with various additives in a hermetic ball milling system, then Co and Li can be recovered by a water leaching procedure [3, 72]. Alternatively, high temperature and magnetic separation can be used in combination for the recycling of cobalt, lithium carbonate and graphite from $LiCoO_2$/graphite lithium batteries. This method makes a direct use of the chemistry of the battery to benefit the recycling reaction, in particular the use of the graphite as reducing agent of the metal bearing component into a recyclable salt [63].

Step 3: Pyro-metallurgical method. Pyrometallurgical metals reclamation uses a high-temperature furnace (>1400 °C) to reduce the component metal oxides to an alloy of Co, Cu, Fe and Ni metal, similarly to a smelting process of a mineral ore [3]. The products of such process are: a metallic alloy, slag and gases. The metal alloy can be further separated through hydrometallurgical processes (described below) and the slag, which generally contains aluminium, manganese and lithium, can also be reclaimed by further hydrometallurgical processing, or can be directly used in other industries, such as the cement industry. In the pyrometallurgical process no real consideration is given to the reclamation of the electrolytes and the plastics (approximately 40–50% of the battery weight) or other components, such as the lithium salts [3] but it is, in fact, mostly focused on the collection of the cobalt and nickel fraction only.

Step 4: Hydrometallurgical methods. Hydrometallurgical treatments leachate the desired metals from the cathodes with the use of an aqueous solutions. By far the most common combination of reagents reported is H_2SO_4/H_2O_2; however, a variety of research of different reagents, ratios or conditions, such as temperature have been carried out, in particular, regarding the optimal conditions in relation to the different batteries' compositions. Once leached, cobalt is usually extracted either as the sulphate, oxalate, hydroxide or carbonate, and then lithium can be extracted through a precipitation reaction forming Li_2CO_3 or Li_3PO_4 [3].

The hydrometallurgical step can be used in specific battery formulations for the direct synthesis of the cathode material; this, especially, works well with NiMnCo batteries and the precursor hydroxide is formed during the hydrometallurgical step [3]. However, the material re-synthesised often shows chemical and crystalline characteristics that differ from the original material, affecting the electrochemical properties and finally the performance [68].

Step 5: Direct Recycling & direct regeneration. Similar to the last step described above, the removal of cathode or anode material from the electrode for reconditioning and re-use in a remanufactured LIB is known as direct recycling. In principle, mixed metal-oxide cathode materials can be reincorporated into a new cathode electrode with minimal changes to the crystal morphology of the active material, hence, avoiding any risk of decreased performance. Yet, this requires the lithium content to be replenished (lithium is "lost" during the use of the battery). This is done through addition of fresh Li_2CO_3 or hydrothermal treatment with a solution containing $LiOH/Li_2SO_4$ before annealing [3], or with the support of ultrasound [73]. Direct regeneration method proves a very high yield process also for battery with the $LiFePO_4$ chemistry [74].

Biotechnology approach [60]. This is an emerging technology for LIB recycling and metal reclamation and is potentially complementary to the hydrometallurgical and pyrometallurgical processes currently used for metal extraction. Cobalt and nickel are especially difficult to separate and require additional solvent extraction steps [3, 60, 75].

Overall, the variability of approaches described above, indicate that to reach a higher recycling yield and consequently, a sustainable end-of-life strategy for battery, it is necessary to work on different geometries, potentially more standardised designs that could support the automation of the disassembly of the batteries, as well as develop novel binders, based on materials that are soluble in water, hence, favouring the separation of the smaller fractions, and finally optimise battery chemistries that favour the amount and quality of recovery and direct re-synthesise of the cathodes seem to be the way to go to make the end of life of batteries sustainable and improve safety of processes.

3.2.3. Building a second life of batteries: reuse

Currently, a second life of advanced batteries is not properly addressed; the Directive does not support re-use approaches, especially in terms of industrial batteries [40]. The performance of new LIBs usually diminishes with their use. For instance, EVBs are unable to perform as expected when their performance drops to 75−80% of its original value. Yet, this does not mean that the battery does not have any value. Second life of batteries for energy storage could help lower their environmental impact, assuring a longer and more efficient use of resources provided certain conditions are met [76, 77]. The new Regulation aims to address this regulatory gap, by introducing several obligatory measures, including the so-called "battery passports", a novel electronic information exchange system for the traceability of EVBs and their management (Article 65 [27]). This will enable second life operators to make informed decisions about responsible repurposing of used batteries (i.e. for a different purpose as stationary energy storage batteries) while simultaneously considering the precautionary principle and ensuring safety of use for end users. The Regulation contains a specific provision (Article 59) on requirements related to the operations of repurposing and remanufacturing for a second life of EVBs, including the access to the battery management system to establish the state of health of a battery to repurposing operators (i.e. the electrochemical performance/durability; safety parameters). There are currently two options proposed: i) whether repurposing is considered a waste treatment operation; or ii) repurposed (second life) batteries are considered as new products. The latter should be favoured as it is more in line with the CE principles.

From a technical point of view, second life or reuse of LIBs are still not a widespread practice. The main reason for such low uptake is that most of LIB are still serving their first life in most of their current applications (e.g. cars and buses) worldwide. For instance, in Europe, reuse of LIBs has not yet reached 100 MWh of installed capacity, while in the USA, second life LIBs have just reached an installed capacity of 10 MWh [78]. In countries, like China, the reuse of LIBs has recently started, as LIBs were widely installed only since 2015 in electric buses [78]. Second life LIBs have been mainly used for small stand-alone applications, such as residential stationary energy storage to back-up storage systems in telecom installations or other ancillary applications to large off-grid installations in rural and remote areas [78, 79]. To promote and establish the use of second life LIBs, infrastructure and well-defined procedures are required. For example, in China, second life LIBs from EVs are starting to be used in telecom infrastructure companies replacing back-up lead-acid batteries in base stations. Car and battery manufacturers need to ensure that their designs and final products comply with the characteristics required to enable a well-managed end-of-life, enabling a second-life usage. Additionally, end-users of second life batteries, such as telecom providers require participating in framework development, to establish practices, logistic, regulations, etc.

Finally, there is a need to establish different strategic partnerships to enable the uptake of secondary life of products. For instance, third party institutions, such as start-ups can also play a critical role, as multiple-end users would create a stronger market to extend the life of LIBs.

3.2.4. Strategy for secondary materials

The discussion on the access and importance of secondary raw material, in particular for critical raw material, such as lithium, has been developing in different fields. For instance, in 2020, the Critical Mineral Association (CMA) in the UK developed a discussion/consultation on the potential link between electrical and electronic equipment waste (WEEE) and a CE. The main focus of such discourse was the importance of a sustainable supply; this is mostly in relation to independence from other countries for the supply of essential mineral material, such as the ones used for electricals and electronics components, including batteries that take a primary role in the move towards green transport. The second focal point for the CMA is to set the UK as a leader in the CE. Indeed, only a CE model can guarantee the essential change for the UK economy to transform to a greener society which includes full vehicle electrification, while, simultaneously, achieving a full resilience in material supply. Consequently, recycling becomes of uttermost importance and is the main tool for (secondary) raw material procurement. The CMA overview states that "75% of the value of an electric car battery is in its minerals. As an importer of critical minerals, it should be a core objective to keep these critical minerals in the UK's economy through circular economy practices". The CMA concludes that the lithium recycling and the complexity of battery designs needs to be addressed [80].

4. Summary of the discussions

The battery landscape is continuously evolving with new battery technologies, emergence of new chemistries in the battery market and growing tonnage of battery waste. The success of CE approaches in terms of batteries waste management depends on many factors, inter alia, technological and legal considerations. The paper argued that the current regulatory frameworks, such as the EU Batteries Directive and the UK Regulations are unsuitable for handling the

Table 1
Summary of the technologies and their advantages and disadvantages.

Technology	Advantages	Disadvantages
Physical methods	Simple method (already available at recyclers)	Low yield (if only one step); high energy
Pyrometallurgical methods	Simple method (already available at foundries)	High energy requirements
Hydrometallurgical methods	Recovery of high yield of metals	Hazardous solvents required
Combined Methods	Higher yields; more metals retrieved	Energy requirements due to the double step
Direct recycling	Low energy	Potential loss of properties; Replenishing of Li required
Biotechnology	Low energy	Small scale

expected rise in EVBs. The lack of specific provisions on treatment and recycling of LIBs or on ‘reuse’ create uncertainty for producers and users on the end-of-life conditions for these batteries implying that recycling or reuse of LIBs is not worth pursuing. This is about to change due to the recent proposed EU Batteries Regulation discussed in this paper.

However, these changes cannot happen if technical solutions are not provided together with support for implementation and development of new business and supply chain models. Given that the paper calls for the incorporation of technical innovation in the regulatory framework (i.e. in a form of accompanied guidelines/best practices), it has also reviewed the recent technological solution of battery recycling, which are summarised in Table 1.

It has been demonstrated that technical solutions for recycling of LIBs and consequent metal recovery are still limited by the variety of geometries (automated disassembly) and formulation (optimisation of a recycling protocol). However, some technological approaches presented seem to show a route towards a good metal recovery, for instance, such as Lithorec offers a positive solution towards skipping the high temperature pyrometallurgical method. Overall, simpler geometries and simpler formulations would help both the disassembly and recovery steps increasing the yield and limiting the costs of treatment and processing. New EVBs designs with future reuse/recycling in mind will have to be employed in order to be placed on the EU market in compliance with the newly proposed EU Batteries Regulation (once approved). Along the minimum content of recycled materials (i.e. cobalt; lead; lithium and nickel), other new requirements embrace exploitation of responsibly sourced materials with restricted use of hazardous substances, a carbon footprint declaration (and the future compliance with maximum life cycle carbon footprint thresholds), the introduction of batteries passport and other information on the electrochemical performance and durability to facilitate a second life of batteries. These are essential for the development of more sustainable and competitive battery industry. Yet, the industry warns that an all-round methodology to calculate the total carbon footprint (ensuring that GHG impacts are captured from all actors in the supply chain) aligned with different applicability to each technology and application is much needed [81].

5. Conclusions

Overall, implementing successful waste management for batteries that would increase recycling depends on a strong relationship between technological and legal considerations. The drawbacks experienced to date and presented in this paper, hence, depend on both a weak regulatory framework and a complex multi-material design of the batteries, which limit the recycling process because the material separation is often too laborious and the final result too impure to be re-used.

Innovative technologies fostering metal separations, standardisation of designs and geometries, and policies pushing towards legal responsibilities for end-of-life re-use of the batteries are necessary to overcome the existing barriers.

The proposal of the new EU Regulation is a welcome step to boost the CE of the battery value chains, encourage more efficient use of resources with the aim of curtaining the environmental impact of batteries. However, it should better align with technological evolution in battery technologies and recycling processes. The UK is yet to announce its developments in batteries waste management, which most likely will employ a similar approach to the EU due to Northern Ireland’s commitment to this Regulation, therefore, ensuring consistency in the UK internal market. The near future will demonstrate how the circularity in terms of batteries waste will develop in both jurisdictions in practice.

Declaration of Competing Interest

None.

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