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RECYCLING USED CAR BATTERIES IN THE CONTEXT OF THE CIRCULAR ECONOMY

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Abstract: The profound transformation of the automotive sector, driven by the transition to electric mobility, has required a rethinking of the way in which the resources involved in this field are designed, used and managed. In the context of the exponential growth in demand for batteries for electric vehicles and the increasing pressure on critical mineral resources, the circular economy is asserting itself as an essential model for achieving the objectives of sustainability and economic resilience. By applying circular principles, the battery value chain is transformed from a linear system – based on extraction, use and disposal – into a regenerative system, in which materials, energy and economic value are kept in the circuit for as long as possible. By fully exploiting the potential of secondary raw materials, this model creates the premises for green mobility based on innovation, responsibility and a balance between economic progress and environmental protection.
Keywords: circular economy, batteries, waste, recycling, materials

INTRODUCTION

Lithium–ion batteries, widely used in electric vehicles, contain essential metals such as lithium, cobalt, nickel and copper. These are considered critical raw materials due to their economic importance and the risks associated with their supply. The European Union has identified these metals as vital for the energy transition and has implemented measures to ensure a sustainable and secure supply chain. The transition to electric mobility has significantly increased demand for lithium–ion batteries, which are essential for electric vehicles.

Over the past two decades, the global energy transition has driven a fundamental shift in the demand structure for critical mineral resources, particularly those used in the production of electric vehicle (EV) batteries. This transformation is fuelled by accelerating decarbonization policies, technological advances in energy storage, and commitments by major economies to reduce greenhouse gas emissions. In this context, demand for lithium–ion batteries has grown exponentially, becoming a critical component of the emerging energy infrastructure [1].

International estimates suggest that by 2035, global demand for lithium and nickel – two of the key components of these batteries – will increase by around 500% compared to current levels. This development is driven not only by the expansion of the electric vehicle market, but also by the expansion of battery use in related areas, such as large–scale renewable energy storage or portable electronics. As a result, supply chains for these resources are becoming increasingly strained, and global competition for access to strategic raw materials is intensifying [2]. In the context of the European Green Deal and the objective of achieving climate neutrality by 2050, the development of a sustainable value chain for batteries has become a strategic priority.

In this context, the adoption of Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 on batteries and waste batteries represents a major step towards strengthening industrial autonomy and environmental sustainability at European level [3,4]. This regulation introduces a single and ambitious legal framework covering the entire life cycle of batteries — from design and production to reuse, collection and recycling. A key element of the new legislation is the establishment of minimum material recovery rates in recycling processes, aimed at reducing dependence on primary resource extraction and encouraging a circular economy (figure 1) [4].

According to Article 71 of the regulation, Member States and economic operators must achieve minimum recovery rates of 90% for cobalt, copper and nickel and 50% for lithium by 31 December 2027. These thresholds will increase to 95% for cobalt, copper and nickel and 80% for lithium by 31 December 2031, reflecting the Union's ambition to maximise material efficiency and minimise the environmental impact of the battery sector [4].

The circular economy (figure 1) is a new model of economic and industrial development that seeks to maximize resource efficiency and minimize waste through reuse, repair, remanufacturing, and recycling. Applied to the context of car batteries, this approach involves redesigning the entire product life cycle so that component materials — especially critical metals such as lithium, cobalt, and nickel — can be recovered and reintegrated into production.

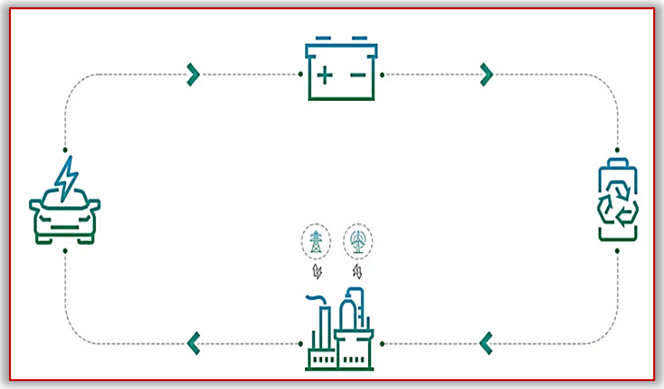

Figure 1. Circular economy

A first pillar of the circular economy in the field of batteries is recycling, a process by which valuable materials from used batteries are extracted and reintroduced into the industrial flow. Through modern hydrometallurgy and pyro metallurgy technologies, rare metals can be recovered with increasingly high efficiencies, thus contributing to reducing the pressure on primary resources and diminishing the ecological footprint of the industry.

The second pillar is the reuse, or recovery, of batteries that have completed their life cycle in vehicles but retain sufficient residual capacity for other uses. These batteries can be used for stationary energy storage applications, contributing to balancing electricity grids and integrating renewable sources such as solar and wind energy. Reuse extends the useful life of the product and reduces the amount of waste generated, while providing an economically efficient solution for the energy transition [6].

A third pillar is remanufacturing, which involves reconditioning and recalibrating used batteries for reuse in vehicles or other performance applications. This stage involves checking, replacing and testing damaged components, giving batteries a "second life" with performance comparable to new products. Remanufacturing is an important step towards complete closure of the life cycle, reducing the need for primary materials and optimizing industrial costs.

By integrating these processes, the circular economy applied to batteries is not limited to waste management, but redefines the very architecture of the production chain, transforming waste into resources and strengthening the sustainability of the European energy system. Applying circular economy principles to the automotive battery industry generates multidimensional benefits – ecological, economic and strategic – that go beyond the strictly industrial sphere.

METHODOLOGIES

In line with the objectives of the European Union, each Member State is responsible for implementing national circular economy policies, adapting the general measures to the local context and to the industrial and social specificities. In Romania, the national strategy aims to develop a sustainable value chain for car batteries, integrating collection, recycling, reuse and remanufacturing, thus supporting the transition to electric and sustainable mobility.

A central objective of the national strategy is the collection and recycling of car batteries. This involves the development of a mandatory collection system that ensures the takeover of all used lithium–ion batteries from electric and hybrid vehicles. In parallel, the aim is to create efficient processing centres equipped with advanced technologies, including hydrometallurgical and pyro metallurgical processes, for the optimal recovery of cobalt, nickel, copper and lithium [1,3,8].

The strategy also promotes the reuse and remanufacturing of batteries, providing support to projects that allow the reintegration of used cells into energy storage systems. This approach not only extends the lifespan of batteries, but also reduces the pressure on primary raw materials, contributing to the circular economy and reducing the carbon footprint.

Life cycle analysis of lithium–ion batteries highlights that the initial stages of production – particularly the extraction and refining of raw materials such as lithium, cobalt and nickel – are responsible for the majority of the carbon footprint and primary energy consumption. Mining and the associated chemical processes are energy intensive and generate significant emissions, making the recycling stage of batteries a strategic step in reducing the overall environmental impact [12].

Recent studies based on LCA methodology show that recycling used batteries can significantly contribute to reducing total CO2 emissions and saving energy resources. By reintegrating recovered materials into industrial flows, the dependence on primary extraction is reduced and the impact associated with the production of new batteries is significantly reduced. According to comparative analyses carried out at European level, the reuse of lithium and nickel from electric vehicle batteries can lead to a reduction in carbon dioxide emissions by approximately 30–40%, depending on the efficiency of the process and the energy source used. At the same time, primary energy consumption can be reduced by up to 25–35%, thus strengthening the economic and ecological argument for recycling.

The LCA results also highlight the importance of integrating remanufacturing and reuse processes into the battery life cycle. Batteries with a second life, for example in stationary applications, extend the service life of active materials and reduce the pressure on recycling infrastructure. In addition, the adoption of Eco design practices – such as modular design and the use of easily separable materials – simplifies disassembly processes and increases the energy efficiency of recycling, with direct benefits on the overall performance assessed by LCA.

As the electric vehicle market expands and the number of end–of–life batteries increases, recycling is becoming a central component of the circular economy and a key condition for the sustainability of the battery value chain. The recovery of critical metals such as lithium, nickel, cobalt and copper helps to reduce the pressure on natural resources and the environmental impact of primary extraction. At the same time, recycling supports the European Union's objectives of strategic autonomy and low carbon emissions, thus strengthening the material basis of the energy transition.

Currently, the main technologies used for recycling lithium–ion batteries can be grouped into three broad categories – hydrometallurgical processes, pyrometallurgical processes and direct recycling – complemented by a series of emerging technologies in advanced stages of research and development (figure 2).

Hydrometallurgical recycling involves the use of chemical solutions to dissolve the metals contained in used batteries and their subsequent separation through controlled reactions. This process typically involves leaching, precipitation and electrolysis steps, which allow the selective extraction of cobalt, nickel, manganese and lithium.

Pyro metallurgical recycling relies on melting batteries at high temperatures (often above 1,200°C) to separate the component metals based on their melting points. In this process, the active materials are converted into metal alloys, slag and fumes, which can then be refined to extract cobalt, nickel and copper.

An innovative and emerging approach is *direct recycling*, which involves dismantling batteries and recovering the cells or active materials without chemical dissolution or melting. The goal of this method is to preserve the structural integrity of the cathode and anode materials, so that they can be reconditioned and directly reintegrated into the production of new batteries.

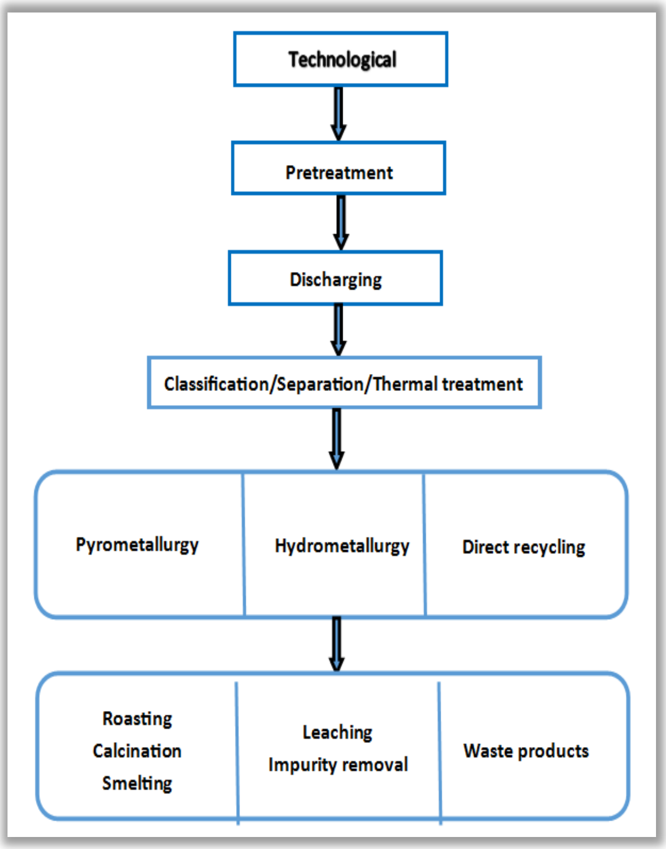

Figure 1. Classification of used car battery recycling technologies

This method is particularly promising because it requires low energy consumption and maintains the value of the active materials, eliminating costly purification and remanufacturing steps. However, its widespread application is conditional on modular and standardized battery design, which allows for automatic and safe disassembly of the cells. Currently, research in the field of eco–design ("design for disassembly") is essential for direct recycling to become an industrially viable solution.

In addition to established methods, emerging technologies have emerged in recent years that promise to revolutionize battery recycling by increasing efficiency and reducing environmental impact [14].

One of these is bioleaching, which uses microorganisms capable of dissolving metals from the battery structure through natural biological processes. This technology has the potential to replace aggressive chemical processes, significantly reducing the consumption of reagents and the generation of toxic waste. Although still in the experimental stages, bioleaching offers a sustainable alternative for the recovery of lithium and cobalt.

Another research direction is automated recycling, which integrates robotics, artificial intelligence (AI) and computer vision for the automated and safe dismantling of batteries. These systems can identify, separate and handle hazardous components with high precision, reducing risks for workers and increasing the speed of the process. Combined with machine learning algorithms, these technologies allow for the optimization of recycling chains in real time, contributing to a transition to smart and circular factories.

Overall, the evolution of battery recycling technologies reflects a complex dynamic between innovation, sustainability and economic efficiency. While traditional methods continue to dominate the market through technological maturity, emerging solutions offer a glimpse into the future of recycling – one in which processes will become cleaner, more automated and more integrated into the logic of the European circular economy [15–18].

RESULTS

At the national level, Romania has started implementing pilot projects for the collection of used batteries from electric and hybrid vehicles, in collaboration with authorized distributors and specialized services. These initiatives aim to establish efficient and safe logistics flows, allowing the transport and processing of batteries in a sustainable manner and in accordance with European norms.

Another example is the support program for investments in recycling infrastructure, which includes the development of hydrometallurgical and pyro metallurgical recycling lines. These investments allow for the increase of industrial capacity and the integration of advanced technologies necessary for the efficient recovery of critical materials.

Romania is also exploring the integration of second–life batteries into renewable energy storage systems. Pilot projects include the use of used batteries in smart grids and residential solar panels, demonstrating how reuse can contribute to energy efficiency and the stabilization of local electricity grids [9].

The implementation of the national strategy faces several challenges, starting with the need to harmonize regulations at European level and adapt them to the local context. This involves building a coherent legislative framework, applicable to all industry actors, and developing an efficient monitoring and reporting system.

Another issue is increasing industrial capacity to cope with the growing volume of used batteries, estimated to triple in the next 10–15 years as the electric vehicle market expands. This requires strategic infrastructure planning, investment in recycling technologies and development of technical skills of personnel.

In terms of collaboration, the success of the strategy depends on the simultaneous involvement of industry, public authorities and academia. Partnerships are essential for the development of innovative solutions, such as modular battery design, optimization of recycling processes and integration of second–life batteries in energy applications. This integrated approach can transform current challenges into opportunities for a circular, efficient and competitive automotive industry [10].

Recycling Li–ion batteries will have a significant positive impact on the environment, by avoiding the emission of greenhouse gases, which will be used to reduce emissions that would normally be produced by mining and processing minerals.

CONCLUSIONS

The accelerated development of the electric vehicle battery industry and the transition to a circular resource use model generate not only opportunities, but also a series of complex challenges, which influence the entire technological, economic and social ecosystem.

These difficulties are interdependent and require systemic approaches, combining scientific innovation, political cooperation and ethical responsibility. The main categories of challenges can be identified in technical, economic, legislative and ethical–social terms.

From a technical point of view, the chemical and structural diversity of batteries represents one of the greatest difficulties of recycling and reuse. Numerous types of lithium–ion batteries coexist on the market (NMC, LFP, NCA, LMO, etc.), each with a different metal composition and specific design. This variation makes it difficult to standardize the dismantling and separation processes of materials, affecting the efficiency of recovery and the quality of recycled materials.

In addition, many battery designs were not originally designed for recycling, which makes access to the cells difficult and increases the risk of damage during disassembly. The lack of a modular design ("design for disassembly") constitutes a major obstacle to the implementation of automated recycling technologies, including those based on robotics and artificial intelligence. Also, the chemical separation processes involved in hydrometallurgy remain complex and resource–intensive, requiring technological optimizations to become more sustainable from an energy and environmental point of view.

Economically, the high costs of recycling processes continue to be a significant barrier to widespread implementation. In many cases, primary extraction of raw materials remains cheaper than recovering them from used batteries, especially in the context of fluctuating global metal prices.

The initial investments required to build dedicated recycling facilities, develop collection infrastructure and implement advanced technologies are considerable. In the absence of clear economic incentives – such as environmental taxes, recycling subsidies or extended producer responsibility (EPR) policies – the profitability of recycling may be low. However, technological advances and the increasing value of recovered materials could offset these costs in the medium term, especially in the context of growing global demand for lithium, nickel and cobalt.

On the legislative front, although Regulation (EU) 2023/1542 on batteries and waste batteries creates a uniform legal framework at European level, its implementation at national level remains a significant challenge. Member States need to adapt infrastructures, collection systems and reporting mechanisms to comply with requirements on traceability, digital labelling and minimum recycling rates.

There is also a need for coherent harmonisation between European legislation and national regulations on hazardous waste, transboundary transport and producer responsibility. The lack of uniform application of the rules can generate disparities between countries, affecting the competitiveness of the market and the overall efficiency of the recycling chain. In this regard, institutional cooperation and the exchange of good practices between Member States become essential to achieve the objectives set by the European Commission.

Beyond the technical and economic dimensions, the ethical and social aspects of the battery value chain are increasingly pressing issues. Working conditions in areas where raw materials are extracted – especially cobalt and lithium – are often precarious, involving major health risks, forced labor or child exploitation, especially in regions such as the Democratic Republic of Congo. These realities contradict the principles of sustainable development and undermine the "green" image of the energy transition.

At the same time, resource extraction in ecologically sensitive regions (such as the lithium mines of South America) generates significant social and environmental impacts, including habitat degradation and competition for water resources. The European Union therefore promotes ethical and transparent supply chains, based on due diligence, certification and full traceability of raw materials, in line with the principles set out in the OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict–Affected and High–Risk Areas.

In addition, the transition to a circular battery economy also has an internal social dimension, aiming at reskilling the workforce and creating new green jobs in emerging sectors. The challenge is to ensure a just transition that combines technological progress with social equity.

Overall, the challenges associated with the circular economy of automotive batteries are not reduced to technical barriers, but form a complex system of interdependencies between technology, economics, politics and ethics. The success of the transition to a sustainable battery industry depends on the ability of the actors involved – governments, companies and research institutions – to collaborate in an integrated framework, based on innovation, coherent regulation and social responsibility. Only such a holistic approach can transform current challenges into opportunities for truly sustainable and equitable mobility.

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