

TOWARD ADVANCED CIRCULAR STRATEGIES IN AUTOMOTIVE ENGINEERING: THE CASE OF EV BATTERIES RECYCLING IN ROMANIA AS A MEDIUM-SIZED EMERGING MARKET

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Abstract: *As a medium-sized emerging market, Romania has demonstrated an interesting trend in relation to the transition from internal combustion engine (ICE) vehicles to electric vehicles (EVs). Compared to other emerging markets in the region, the rate of adoption has been higher and the dynamics particularly noteworthy. Customers understood the importance of switching to EVs, while the reduction in financial support provided through the Rabla Plus programs in 2025-2026 was partially offset by the energy crisis of April 2026, which manifested itself in rising fuel prices. A novel aspect addressed in this research concerns the analysis of the feasibility of implementing recycling systems in emerging markets. Romania has entrepreneurial specialists interested in new recycling technologies that would reduce the life-cycle cost of EV products.*

Keywords: internal combustion engine (ICE), electric vehicles (EVs), ICE-EV green transitions, sustainability, Circular Economy Strategies (CES)

1. Introduction

The global transition to electric mobility represents a technological shift and a modernization of industrial ecosystems, supply chains and energy systems. Authorities and manufacturers are increasingly forced to adopt long-term strategies that combine environmental goals with technological resilience and economic competitiveness [1, 2]. The success of the transition depends on the economy's ability to adapt its industrial and infrastructure policies to the requirements of an electric transportation system [3].

Recent events in the energy market have shown that price fluctuations and supply disruptions lead to a quick adoption of alternative propulsion solutions by consumers [4]. This is why governments have started to adapt their mobility strategies and support investments in infrastructure for

electric vehicles and battery production.

The transition to electric mobility in emerging economies depends on industrial capacity, workforce skills, and technological innovations [5].

2. ICE-EV circular green transition

The automotive sector is going through a circular green ICE-EV transition, driven by environmental requirements, new technology and legislative framework. This transition is determined by the necessity to minimize greenhouse gas emissions, increase energy efficiency and comply with international climate policies [6]. EVs have a key role in achieving the climate goals set by the Paris Agreement and sustainability strategies such as the European Green Deal promoted by the European Commission.

At the same time, the circular green transition and associated technologies present new sustainability challenges related

to battery production, the sourcing of raw materials, end-of-life battery management and the recycling of rare metals [7].

Given these challenges and especially the importance of managing end-of-life batteries, the implementation of circular economy principles is a natural step, as they are essential during the ICE-EV transition [8]. These principles aim to maximize the use of materials and minimize waste generated through the entire life cycle, focusing on:

- sustainable battery production;
- extending battery lifespan;
- second-life battery applications;
- recycling of rare materials.

These aspects describe the transition to electric vehicles in a way that reduces dependence on the extraction of primary resources and supports industrial development [9, 10].

3. Circular strategies for EV batteries

Electric vehicles differ from conventional vehicles with internal combustion engines in that they use electric motors for propulsion, power electronics, and high-capacity rechargeable batteries.

Circular economy strategies for electric vehicles are aligned with the principles mentioned above regarding the sustainable production of batteries, maximizing their service life, alternative end-of-life solutions, and methods for recycling critical materials. Even though electric vehicles produce **zero tailpipe emissions**, battery production and

the extraction of raw materials can have a significant impact on the environment, with the main concerns relating to:

- the production of high-energy-consumption batteries;
- the extraction of critical materials;
- greenhouse gas emissions generated by the extraction of materials.

The main raw materials used in the production of lithium-ion batteries for electric vehicles are lithium, cobalt, nickel, manganese, and graphite, the extraction and processing of which often involve social and environmental challenges [11, 12].

One of the strategies of the circular economy is to extend the lifespan of batteries, which can be achieved using management systems designed to optimize charging and discharging cycles. Long-lasting batteries reduce the frequency of replacement and lower resource consumption.

Another strategy involves repurposing batteries for other uses before the end of their life cycle, when their capacity drops to approximately 70–85% and they are no longer suitable for use in vehicles. Examples of applications for reusing batteries with reduced capacity include:

- stationary energy storage systems;
- renewable energy storage systems for solar and wind power;
- backup power systems for buildings.

Companies such as Nissan have developed battery reuse programs for batteries from Nissan Leaf electric vehicles.

Table 1. Recycling processes for electric vehicle batteries

Recycling process	Description and role
Pyrometallurgical recycling	The method uses high-temperature furnaces to recover metals such as cobalt, nickel, and copper.
Hydrometallurgical recycling	The method is based on the use of chemical solutions to extract metals with greater efficiency and lower energy consumption.
Direct recycling	The method aims to recover components without altering their chemical structure, thereby enabling their direct reuse in the manufacture of new batteries.

Battery recycling is also another key strategy for recovering valuable materials at the end of a battery's life cycle. Recycled materials can be reused in the production of new batteries, thereby reducing the need for raw material extraction [13, 14]. The main recycling processes are detailed in Table 1. The main stages in the life cycle of an

electric vehicle battery are illustrated in Figure 1, from the extraction of raw materials to recycling and reuse applications, clearly demonstrating the use of the circular economy to optimize resource efficiency and support sustainability in their use.

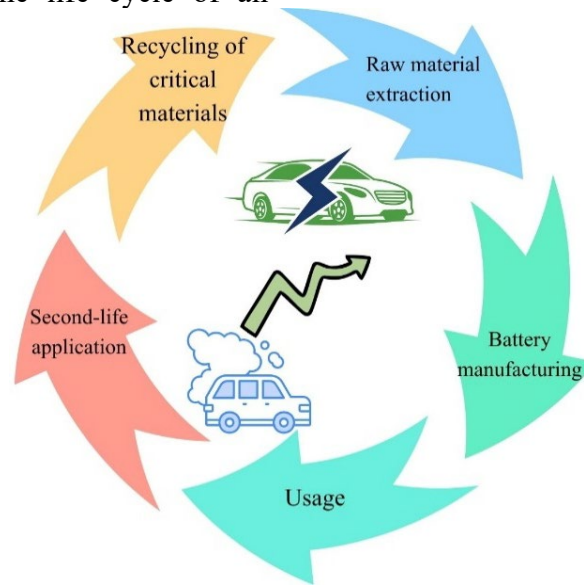


Figure 1: The circular life cycle of an electric vehicle battery in the context of the ICE-EV transition

4. Battery recycling technologies in emerging markets

4.1. A greater focus on the principles of the circular economy

Future battery technologies are increasingly being designed with the principles of the circular economy in mind. They aim to achieve sustainable industrial processes and the recovery of materials at the end of their life cycle. Key design strategies include:

- reducing the use of critical materials such as cobalt;
- developing battery architectures that are easy to recycle;
- increasing battery durability.

4.2. Recycling Electric Vehicle Batteries: Costs, Benefits, and Limitations

Recycling involves recovering valuable materials from used batteries through chemical or thermal processes.

There is also significant interest in advanced battery recycling technologies [15]. For example, Redwood Materials focuses on recovering rare metals from lithium-ion

batteries and reintroducing them into battery production supply chains. Similarly, Umicore operates advanced recycling facilities that recover valuable metals from electronic waste and electric vehicle batteries. These initiatives demonstrate how circular economy strategies can significantly reduce the environmental impact of battery production.

Recycling costs depend on the technology used and the scale of the project. Typical costs range from \$50 to \$100 per kWh. The main cost components include battery collection and transportation, disassembly, shredding, chemical processing, and waste treatment.

Battery recycling is important both from the perspective of recovering rare materials and in terms of cost, technological difficulty, environmental impact, and feasibility. Therefore, recycling technologies are selected based on target materials, costs, complexity, environmental impact, and suitability for emerging markets and a comparative assessment in this regard is presented in Table 2.

Table 2. Comparative Assessment of Battery Recycling Technologies

Recycling technology	Main recovered materials	Cost level	Technical complexity	Environmental impact	Suitability for emerging markets
Pyrometallurgical recycling	Cobalt, nickel, copper	High	Medium	High energy consumption	Medium
Hydrometallurgical recycling	Lithium, cobalt, nickel, manganese	Medium	High	Lower energy use than thermal routes	High
Direct recycling	Cathode materials, active compounds	Medium–high	Very high	Potentially lowest impact	Low–medium
Second-life use before recycling	Remaining battery capacity	Low–medium	Medium	Delays waste generation	High

The benefits of recycling consist in the recovery of rare materials such as lithium, cobalt, nickel, copper, and aluminum, as well as the positive environmental impact resulting from reduced mining activity and lower resource consumption.

The recovered materials can be reused in the production of new batteries, contributing to a **closed-loop supply chain**.

The development of industrial sectors in developing economies through battery recycling contributes to the creation of new jobs, which is particularly important for these economies.

The global expansion of EVs production is leading to a dramatic increase in the number of end-of-life batteries over the next decade, which will require a large-scale recycling infrastructure.

Battery recycling processes also have limitations, including:

- high energy consumption;
- incomplete recovery of lithium in some processes;
- economic dependence on metal market prices.

Lithium-ion batteries contain expensive rare earth metals, for which global supply is limited. This highlights one of the main benefits of recycling, which allows these materials to be recovered and reused in new batteries.

4.3. Recycling strategies in emerging markets

Emerging markets present unique conditions for the recycling of electric vehicle batteries, as they are typically characterized by:

- a rapidly growing urban population;
- booming transportation demand;
- developing industrial sectors;
- limited environmental infrastructure.

In addition, the major emerging economies (China, India, and Brazil) are involved in various stages of the battery value chain, including mineral extraction, battery production, vehicle assembly, and waste processing [16].

4.4. Recycling opportunities in emerging markets

A key opportunity is linked to the development of local recycling industries, and the establishment of local recycling facilities can create jobs, reduce dependence on rare materials, and support domestic production of electric vehicles. In this way, investments in recycling infrastructure can transform used batteries into valuable industrial resources [17].

Another opportunity involves repurposing low-capacity batteries for other uses and applications, such as energy storage. Before recycling, electric vehicle batteries can be reused even if their performance falls below the minimum level required for use in vehicles. Applications like rural electrification, microgrids for small

communities or backup power supply systems are other solutions for regions underdevelopment.

Integration with renewable energy systems represents another viable solution, given that emerging economies are rapidly expanding their renewable energy capacity and the potential to store solar, wind or hybrid microgrid energy in batteries. Therefore, battery reuse supports both energy transition goals and those of the circular economy.

A current and important challenge relates to digital tracking and battery passports, as new digital tools are being developed to increase the traceability of batteries through their entire lifecycle. A battery passport is essentially a digital record, containing information about the composition, manufacturing history, usage information and recycling instructions. These systems can help improve the efficiency and transparency of recycling processes in global supply chains [18].

4.5. Recycle limitation in emerging markets

Despite of existing opportunities, several technical, economic and institutional challenges are limiting the development of recycling systems in emerging markets.

The main constraints are:

- limited recycling capabilities;
- logistical constraints in battery collection;
- insufficient standardization;
- economic viability;
- regulatory and institutional barriers.

In many markets there are not any specialized facilities capable of safely processing batteries, activity that requires chemical treatment and controlled environments with specialized equipment. In the absence of these facilities, batteries can be exported to developed countries, stored indefinitely or disposed of improperly.

Battery collection requires an optimization of logistics and transportation networks, particularly because lithium-ion batteries are classified as dangerous materials and that involves strict regulations for handling and transporting.

Batteries for electric vehicles are different in

terms of chemical composition, dimensions and production architecture, due to a lack of standardization. For these reasons, automated disassembly and recycling processes are difficult to achieve and different chemical compositions such as NMC, LFP and LCO also require different technologies for each one of them.

In terms of economic viability, the profitability of recycling activities depends on the value of the recovered materials. While certain materials such as cobalt and nickel are highly valuable, others like manganese or lithium do not always offer profitable conditions, especially in regions with limited industrial technology.

Most emerging economies do not have clear regulations regarding battery recycling, which is why recycling methods can be performed with risks to the environment and human health may be affected. Consequently, the main challenges relate to:

- unclear responsibilities regarding battery collection;
- the lack of extended producer responsibility (EPR) systems;
- insufficient enforcement of environmental regulations.

5. Life Cycle Assessment of Electric Vehicles

Life cycle assessment (LCA) is a standardized method for evaluating the environmental impact of electric vehicles throughout their entire life cycle. This method is useful because it provides an analytical framework for comparing technologies used in the automotive sector and their environmental impacts, thereby supporting data-driven decisions in emerging markets [19].

The stage in the life cycle of an electric vehicle with the greatest environmental impact is battery production, which is one of the major activities generating greenhouse gas emissions. Over the entire life cycle, battery production accounts for over 30% of total emissions, depending on the technology used. One aspect of the vehicle operation phase is that EVs produce fewer emissions than those with ICE [20].

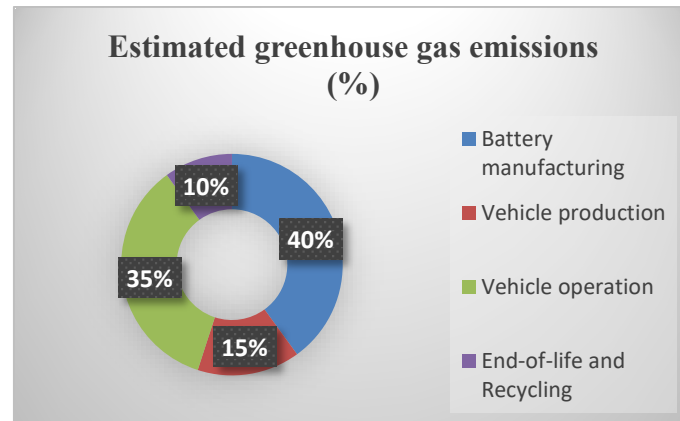


Figure 2. Greenhouse gas emissions at different stages of the life cycle [19, 20]

Figure 2 illustrates the overall environmental impact of the main stages in the life cycle of electric vehicles, specifically the distribution of greenhouse gas emissions [19, 20].

6. Conclusions

The global transition toward sustainable mobility requires not only the electrification of transportation, but also the development of new technologies capable of improving resource efficiency, reducing emissions, and supporting the principles of the circular economy.

The analysis confirms that the management of production and the end-of-life cycle of an electric vehicle battery plays a decisive role in the future evolution of electric vehicle markets in emerging economies within the context of a global transition.

The circular economy applied to electric

vehicle batteries in emerging markets will depend on several strategic actions, such as the development of regional recycling centers, the implementation of producer responsibility mechanisms, or substantial investments in advanced recycling technologies. Furthermore, standardization and international cooperation regarding supply chains are essential steps to take, in order to achieve sustainable battery ecosystems.

Future research in the field of circular mobility systems will focus on:

- sustainable chemistry composition for batteries;
- recyclable battery materials;
- hydrogen production from renewable sources;
- advanced recycling technologies.

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