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ECOLOGICAL RISKS OF RAW MATERIAL EXTRACTION AND ENRICHMENT FOR EV BATTERIES AND THE IMPORTANCE OF EXTENDED PRODUCER RESPONSIBILITY

Davydova Iryna Volodymyrivna,
Candidate of Agricultural Sciences, Associate Professor,
Associate Professor at the Department of Ecology and Environmental Technologies
Zhytomyr Polytechnic State University
ORCID ID: 0000-0001-6535-3948

Bondarchuk Vasyl Mykolaiovych,
Senior Lecturer at the Department of Robotics, Electric Power Engineering and Automation
named after Prof. B. B. Samotokin
Zhytomyr Polytechnic State University
ORCID ID: 0000-0003-2793-8720

Panasyuk Andriy Viktorovych,
Candidate of Technical Sciences, Associate Professor,
Associate Professor at the Department of Mine Surveying
Zhytomyr Polytechnic State University
ORCID ID: 0000-0001-7468-2022

Shlapak Volodymyr Oleksandrovych,
Candidate of Technical Sciences, Associate Professor,
Head of the Department of Mine Surveying
Zhytomyr Polytechnic State University
ORCID ID: 0000-0002-4183-1922

Kyrylenko Nina Pavlivna,
PhD in Technical Sciences, Associate Professor,
Associate Professor at the Department of Ecology and Environmental Technologies
Zhytomyr Polytechnic State University
ORCID ID: 0000-0001-7222-9320

The article analyzes the environmental risks of mining, enrichment and processing of mineral raw materials for the production of electric vehicle batteries and determines the importance of extended producer responsibility (EPR) to reduce this impact. The key materials of the battery industry are characterized – lithium, cobalt, nickel, manganese and graphite – and their role in modern types of batteries (NMC, NCA, LFP) is shown. Data on the geography of mining of critical minerals and the growth of global demand for them in connection with the development of electromobility are summarized. Special attention is paid to the impact on water resources, soils, ecosystems and atmospheric air, in particular the risks of depletion of aquifers, acid mine drainage, formation of enrichment tailings, dust and gas emissions. Based on the LCA approach, it is shown that the production of electric vehicles, especially batteries, forms a higher initial ecological footprint compared to cars with internal combustion engines, however, during operation, electric vehicles provide lower total greenhouse gas emissions. It is substantiated that RBB, eco-design, supply chain due diligence, recycling, second-life approaches and the implementation of battery passport are systemic tools for the transition to a circular economy. The methodological basis is the analysis of scientific sources, a comparative description of technological stages and the systematization of environmental risks. Recommendations are formulated for the standardization of sustainable production, the development of "green" processing technologies and strengthening international regulation in the field of EV batteries.

Key words: *electric vehicles, batteries, critical minerals, environmental risks, extended producer responsibility, circular economy, battery passport, LCA.*

Давидова Ірина, Бондарчук Василь, Панасюк Андрій, Шлапак Володимир, Кириленко Ніна. Екологічні ризики видобутку та збагачення сировини для акумуляторів для електромобілів та важливість розширеної відповідальності виробника

У статті проаналізовано екологічні ризики видобутку, збагачення та переробки мінеральної сировини для виробництва акумуляторів електромобілів і визначено значення розширеної відповідальності виробника (РВВ) для зниження цього впливу. Охарактеризовано ключові матеріали батарейної індустрії – літій, кобальт, нікель, марганець і графіт – та показано їх роль у сучасних типах акумуляторів (NMC, NCA, LFP). Узагальнено дані щодо географії видобутку критичних мінералів і зростання глобального попиту на них у зв’язку з розвитком електромобільності. Окрему увагу приділено впливу на водні ресурси, ґрунти, екосистеми та атмосферне повітря, зокрема ризикам виснаження водоносних горизонтів, кислотного дренажу шахт, утворення хвостів збагачення, пилових і газових викидів. На основі підходу LCA показано, що виробництво електромобілів, особливо акумуляторів, формує вищий початковий екологічний слід порівняно з автомобілями з ДВЗ, однак упродовж експлуатації електромобілі забезпечують нижчі сукупні викиди парникових газів. Обґрунтовано, що РВВ, eco-design, due diligence ланцюгів постачання, recycling, second-life підходи та впровадження battery passport є системними інструментами переходу до циркулярної економіки. Методичну основу становлять аналіз наукових джерел, порівняльний опис технологічних етапів і систематизація екологічних ризиків. Сформульовано рекомендації щодо стандартизації сталого видобутку, розвитку «зелених» технологій переробки та посилення міжнародного регулювання у сфері EV-акумуляторів.

Ключові слова: *електромобілі, акумулятори, критичні мінерали, екологічні ризики, розширена відповідальність виробника, циркулярна економіка, battery passport, LCA.*

Introduction. The rapid development of electric mobility is currently regarded as one of the key directions in the global transition to a low-carbon economy [1]. Electric vehicles are designed to reduce greenhouse gas emissions, improve urban air quality, and decrease dependence on fossil fuels. In this context, demand for lithium-ion batteries – the primary energy storage technology for electric transport – is growing at an unprecedented rate [2]. This, in turn, drives a sharp increase in the extraction and enrichment of critical mineral raw materials, including lithium, cobalt, nickel, manganese, and graphite [3].

Despite the evident environmental advantages of electric vehicles during operation, the upstream stages of battery production exert significant ecological pressure. Mining operations are frequently accompanied by excessive water consumption, land degradation, ecosystem disruption, and contamination of soils and water bodies with heavy metals and chemical reagents [4]. Mineral enrichment and processing generate additional risks – ranging from toxic emissions to the generation of hazardous waste capable of causing prolonged environmental damage [5]. This raises a critical question: to what extent can electric mobility be considered "green" if its raw material supply chains impose a substantial environmental burden [6].

In this context, the concept of Extended Producer Responsibility (EPR) is gaining increasing significance. Its mechanisms are intended to ensure producer accountability for the environmental consequences of products throughout their entire life cycle – from raw material origin to end-of-life battery disposal. EPR incentivizes eco-design, responsible sourcing, supply chain transparency, and the development of a circular economy [7].

The purpose of this article is to provide a comprehensive analysis of the environmental impact of the extraction and enrichment of mineral raw materials used in electric vehicle battery production, as well as to substantiate the key role of Extended Producer Responsibility in fostering a more sustainable and environmentally responsible production cycle.

To achieve the stated objective, the article sets the following tasks: to characterize the principal types of mineral raw materials used in the production of modern electric vehicle batteries; to analyze the geography and scale of critical mineral extraction; to examine the environmental impact of mineral extraction and enrichment processes; to compare the ecological footprint of battery production with that of conventional automotive infrastructure based on life cycle assessment (LCA); and to formulate recommendations for improving Extended Producer Responsibility systems, enhancing supply chain sustainability, and implementing circular approaches in battery manufacturing.

Research methods and techniques. The study is grounded in a comprehensive interdisciplinary approach that integrates elements of ecological economics, institutional analysis, and the circular economy concept. The methodological foundation of the work is a systems approach, which enables the examination of the EV battery industry as an integral structure encompassing all stages of the battery life cycle – from critical mineral extraction to recycling and material reuse.

The research employs an analysis of scientific publications, regulatory acts, and strategic documents in the fields of sustainable development and Extended Producer Responsibility (EPR), as well as a comparative analysis of contemporary regulatory practices. To assess environmental aspects, a life-cycle thinking approach was applied, enabling the identification of key ecological impact points and the potential for implementing circular mechanisms, including eco-design, recycling technologies, and the battery passport system. The synthesis of the results enabled the formulation of conclusions and practical recommendations to enhance the effectiveness of EPR implementation in the battery industry.

Results and discussion. The rapid growth of the electric vehicle market is driving a sharp increase in demand for minerals used in lithium-ion battery production. The key materials include lithium, cobalt, nickel, manganese, and graphite (Fig. 1). These minerals determine the energy density, operational stability, longevity, and safety of batteries. According to international energy research estimates, global demand for battery-grade minerals may increase several-fold by 2030 compared to early 2020s levels, thereby intensifying the burden on the mining industry and elevating environmental risks.

Lithium is the fundamental element in nearly all modern electric vehicle batteries, as it facilitates charge transfer within the cell and enables high energy density at a relatively low mass. The principal lithium deposits are concentrated in the so-called "Lithium Triangle" of South America (Chile, Argentina, Bolivia), as well as in hard-rock deposits in Australia (Fig. 2). Over the past decade, lithium demand has increased several-fold. Projections indicate that the electric vehicle sector may consume over 80% of extracted lithium within the next decade.

Cobalt plays a vital role in stabilizing cathode materials and extending battery service life. It ensures the structural stability of batteries and enhances their performance. Approximately 60–70% of the global cobalt supply is mined in the Democratic Republic of Congo, which gives rise not only to economic but also to environmental risks associated with intensive extraction, generation of toxic waste, and contamination of soils and water resources. Consequently, many battery manufacturers are progressively seeking to reduce the cobalt content in next-generation batteries.

Nickel is one of the key elements that enables higher battery energy density and extended electric vehicle driving range. Modern batteries increasingly employ cathodes with elevated nickel content. Demand for battery-grade nickel is expected to increase several-fold by mid-century. The principal producers are Indonesia, the Philippines, and several other countries.

Manganese is used in cathode materials to enhance battery stability and reduce costs. Unlike cobalt, this element is more abundant in nature; however, its extraction and processing can also have adverse environmental effects, including soil contamination, acid mine drainage, and elevated levels of airborne particulate pollution. In contemporary battery systems, manganese is frequently used in combination with nickel and cobalt to achieve a balance between performance, safety, and economic viability.

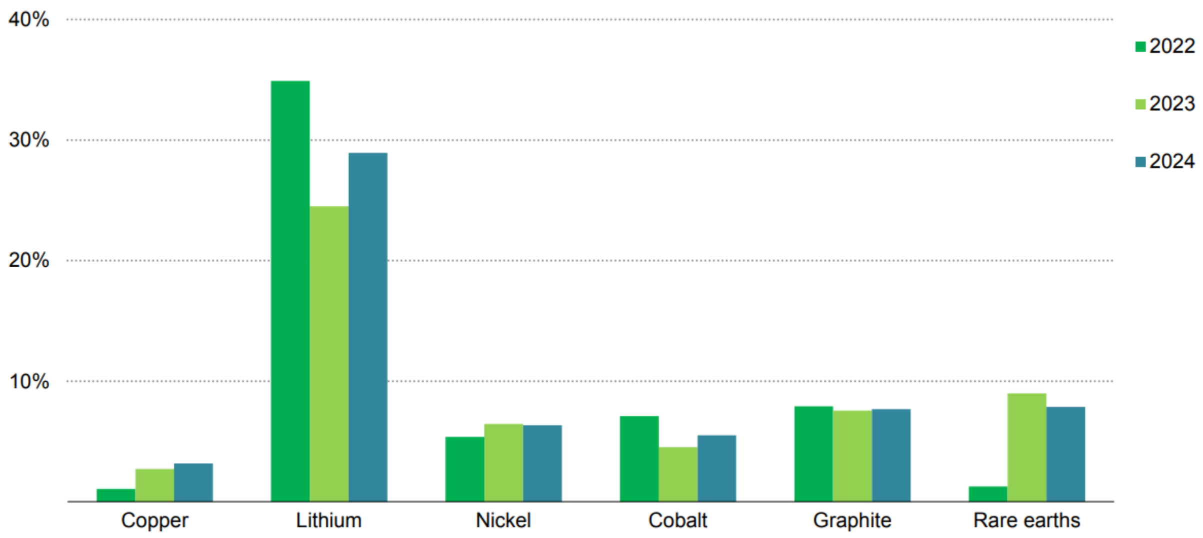

Fig. 1. Global demand dynamics for key electric vehicle battery minerals (lithium, cobalt, nickel, graphite) in 2022–2024 [9]

Graphite is the primary anode material in most lithium-ion batteries. Notably, producing a single electric vehicle battery typically requires more graphite by mass than lithium. A significant share of global natural graphite production is concentrated in China, creating a degree of global market dependence on a single region.

It is also essential to consider that different types of electric vehicle batteries utilize various combinations of these minerals (Fig. 3). For instance, NMC (nickel-manganese-cobalt) batteries are among the most widely used, as they combine high energy density with operational stability. NCA (nickel-cobalt-aluminum) technology emphasizes high nickel content, enabling greater vehicle driving range. In contrast, LFP (lithium iron phosphate) batteries contain neither cobalt nor nickel, are characterized by enhanced safety and lower cost, and consequently, their adoption in the mass-market electric vehicle segment has been growing rapidly in recent years.

These minerals form the foundation of the modern battery industry, yet simultaneously pose significant environmental challenges associated with their extraction and enrichment. For this reason, issues of environmental risk, as well as mechanisms for responsible resource management, including Extended Producer Responsibility, are becoming central to the sustainable development of the electric mobility sector.

Although electric vehicles are regarded as a tool for transport decarbonization, the initial stages of their life cycle, including the extraction and processing of mineral raw materials, are associated with substantial environmental burdens (Table 1).

Impact on water resources. Lithium extraction from brine deposits in the South American region encompassing Salar de Atacama, Salar de Uyuni, and Salar del Hombre Muerto is particularly water intensive. The technology involves pumping underground saline water followed by multi-month evaporation in open-air ponds. This process leads to a decline in groundwater levels in aquifers, disrupting the hydrological balance of desert ecosystems. In regions experiencing chronic water scarcity, this creates competition between mining companies' water needs and the water supply for local communities and traditional agriculture.

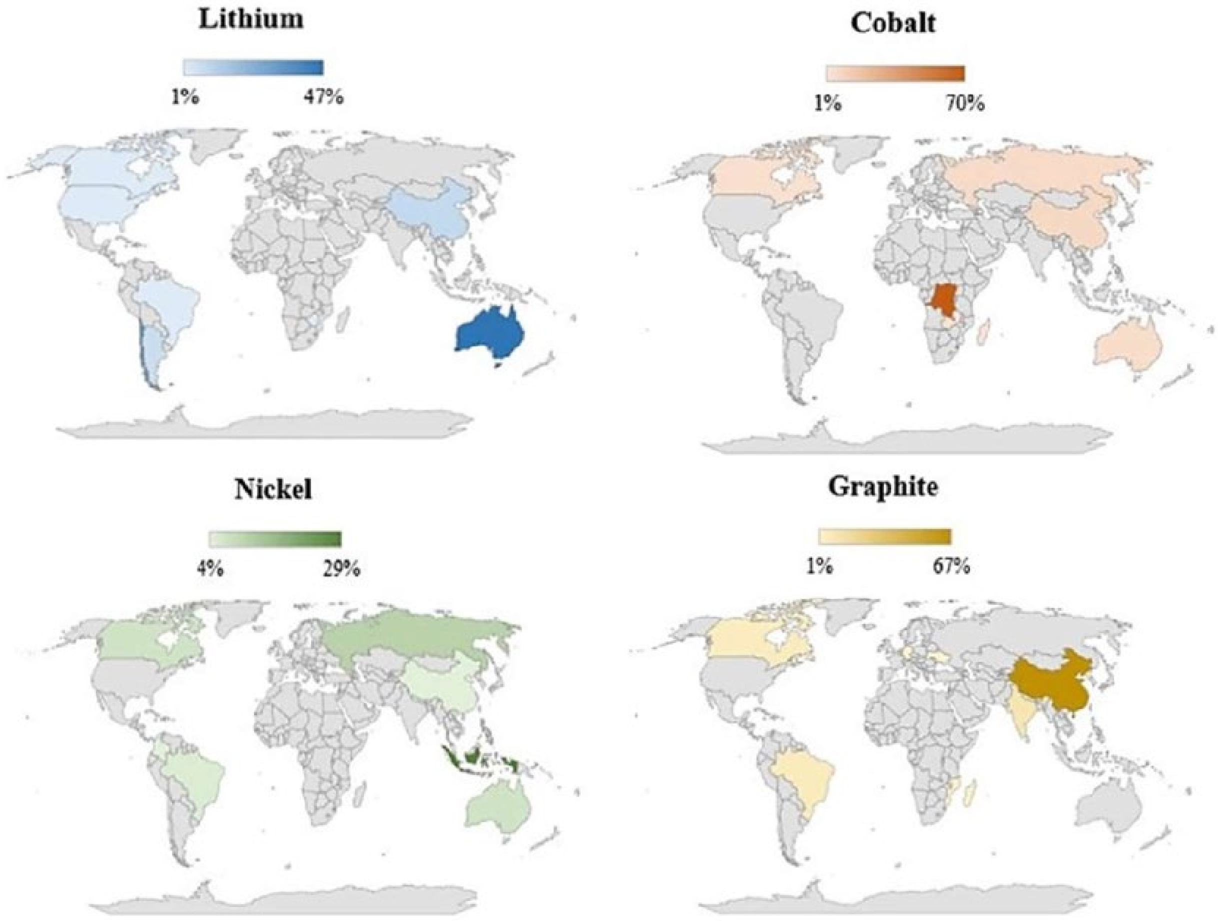

Fig. 2. Global Distribution of Critical Battery Minerals [10]

The extraction of nickel and cobalt, which are widely used in NMC (nickel-manganese-cobalt) battery cathodes, poses a risk of acid my drainage. Oxidation of sulfide ores results in acidic effluents that can dissolve and transport heavy metals into surface and groundwater. Tailings storage facilities and enriching waste impoundments pose an additional hazard, as they may serve as sources of chronic or accidental contamination. Thus, the water footprint of battery raw material production represents one of the key environmental challenges facing the electric vehicle industry.

Impact on soils and ecosystems. The extraction of nickel, cobalt, and manganese is frequently carried out through open-pit mining, resulting in large-scale landscape transformation. Removal of the fertile soil layer, formation of quarries and waste dumps disrupt

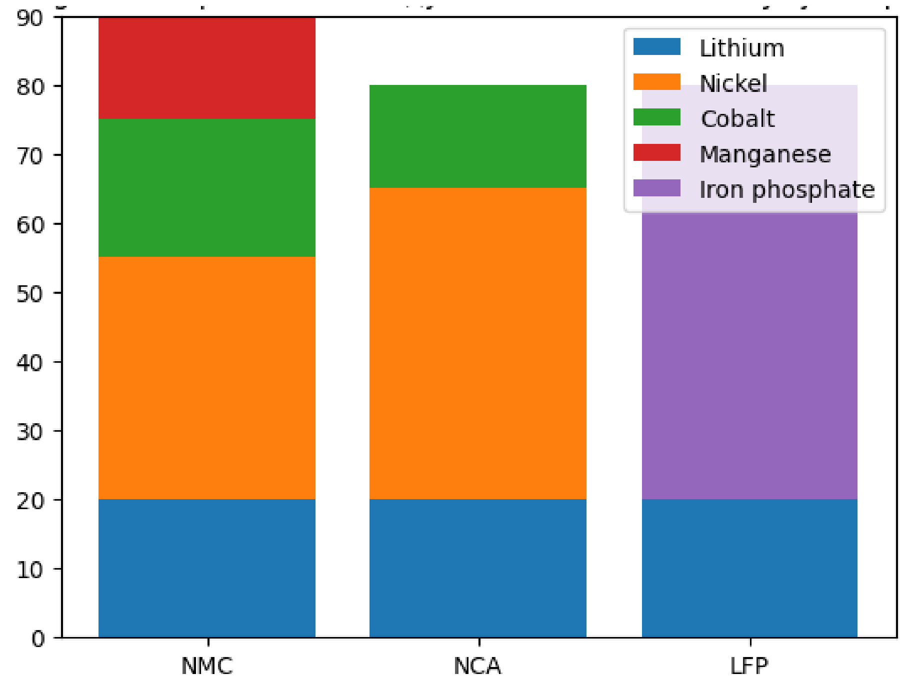

Fig. 3. Composition comparison of the main types of electric vehicle batteries (NMC, NCA, LFP), Relative material share (%) [11]

Table 1

Comparative characteristics of the environmental impact of mineral resource extraction for electric vehicle battery production on environmental components

Mineral Resource	Impact on Water Resources	Impact on Soils and Ecosystems	Impact on Air
Lithium	Intensive brine pumping; groundwater level depletion; risk of salinization of freshwater aquifers; alteration of regional hydrological balance	Disruption of salt flat ecosystem structure; degradation of topsoil layer; alteration of natural water-salt regime	Dust during transportation and drying; emissions from chemical processing of lithium carbonate
Cobalt	Acid mine drainage; heavy metal infiltration into surface and groundwater; leakage risks from tailings storage facilities	Soil degradation from open-pit mining; accumulation of toxic waste; fragmentation of natural biotopes	Metal-containing dust; toxic aerosols during enrichment and smelting; sulfur oxide emissions
Nickel	Water contamination by effluent solutions; acidification of water bodies; increased turbidity due to erosion processes	Large-scale removal of vegetation cover; tropical soil erosion; formation of waste dumps	Significant SO□ and NO_x emissions during pyrometallurgical processing; metallic dust
Manganese	Potential contamination by mine water; localized increase in metal concentrations	Landscape transformation; formation of waste dumps; disturbance of soil cover	Dust emissions during crushing; emissions from thermal ore processing
Graphite (natural)	Water use in flotation processes; contamination by slurries and reagents	Land disturbance from open-pit mining; accumulation of enrichment waste	Fine-dispersed graphite dust; emissions from high-temperature purification

the natural structure of territories and lead to land degradation.

Rehabilitation of such areas requires prolonged reclamation efforts and does not guarantee the restoration of original ecosystems. Tropical regions are particularly vulnerable, as the expansion of mining areas is accompanied by deforestation, habitat fragmentation, and biodiversity loss. Similar problems arise in nickel extraction areas within tropical and subtropical ecosystems, where heavy rainfall intensifies erosion processes following vegetation removal. Land subsidence associated with underground mining and secondary erosion after operations poses long-term geoecological risks.

Emissions and air pollution. Battery raw materials undergo a complex cycle of enrichment and metallurgical processing, which is accompanied by dust and gaseous pollutant emissions. Delicate particulate matter containing nickel, cobalt, or other metals can disperse through the atmosphere and accumulate in the human body. Exposure to such aerosols is associated with an elevated risk of respiratory and toxicological disorders. Metallurgical processes used to obtain high-purity cathode materials involve energy-intensive furnaces and chemical reagents, which can form sulfur oxides, nitrogen oxides, and other harmful compounds.

Environmental consequences of mineral enrichment and processing for battery production. The enrichment and chemical-metallurgical processing stages of mineral raw materials intended for lithium-ion battery manufacturing constitute one of the most environmentally intensive segments of the entire electric vehicle value chain. It is at this stage that the transition occurs from ore or brine to high-purity compounds of lithium, nickel, cobalt, manganese, and graphite suitable for the synthesis of cathode and anode materials.

Flotation, leaching, precipitation, and purification processes involve the use of substantial volumes of acids, alkalis, organic solvents, and specialized reagents. During hydrometallurgical processing of nickel and cobalt ores, sulfuric acid, ammonia solutions, and extractants are widely employed to ensure selective metal recovery from concentrates. In the production of lithium compounds, reagents are used to precipitate high-purity lithium carbonate or lithium hydroxide.

Improper handling of chemical reagents can cause localized contamination of soil and water, as well as the generation of toxic air emissions. Attention should be paid to facilities located in countries with less stringent environmental standards, where emission controls and wastewater treatment may be inadequate. On a global scale, a significant share of graphite and lithium compound processing is concentrated in China, intensifying the regional concentration of environmental burdens.

The enrichment process generates a substantial volume of waste in the form of tailings – fine-dispersed ore residues remaining after the extraction of valuable components. These materials are stored in specialized slurry impoundments or tailings storage facilities, which are retained by dams. Tailings may contain residual concentrations of heavy metals, sulfides, and reagents that pose environmental hazards. Failure of tailings dam integrity can lead to a large-scale release of slurry into river systems and adjacent territories. Even without an accidental breach, prolonged seepage of filtrate from tailings facilities can cause chronic groundwater contamination. For raw materials used in battery production, the tailings problem is particularly acute due to the large volumes of low-grade ore processing, particularly for nickel and cobalt.

In addition to enrichment tailings, the processing stage generates slag, filtration sediments, spent reagents, and contaminated aqueous solutions. Improper management of such waste can cause secondary environmental contamination and the accumulation of toxic substances in the biosphere.

An additional challenge is the limited availability

Table 2

Environmental consequences of mineral enrichment and processing for electric vehicle battery production

Processing Stage	Principal Environmental Risks	Impact Type
Flotation and enrichment	Use of chemical reagents; generation of tailings; risk of water and soil contamination	Water, soils
Hydrometallurgical leaching	Acidic effluents; toxic solutions; potential seepage of reagents into groundwater	Water, soils
Pyrometallurgical smelting	High CO_2 emissions; formation of SO_2 and NO_X; metal-containing dust	Air, climate
Refining and purification	Generation of highly concentrated chemical waste; risk of secondary contamination	Water, air
Storage of tailings and industrial waste	Risk of tailings dam failure; long-term contamination of soils and water	Water, soils

of technologies for the complete disposal or reuse of waste. In some cases, waste is stockpiled without adequate stabilization, increasing the risk of its migration into the environment. At the same time, the development of a circular economy and spent battery recycling technologies may reduce the need for primary extraction and decrease the volume of industrial waste in the future.

The assessment of the environmental impact of electric vehicles compared to internal combustion engine vehicles is typically conducted using the Life Cycle Assessment (LCA) approach [12]. This approach encompasses all stages of a vehicle's existence – from raw material extraction and component manufacturing to operation and end-of-life disposal or recycling. In the case of electric cars, the most significant environmental impact occurs during the initial production stage, particularly in lithium-ion battery manufacturing, which requires substantial volumes of minerals, energy, and water. Conversely, in conventional vehicles, the majority of emissions are generated during operation through the combustion of fossil fuels.

The results of numerous LCA studies indicate that electric vehicle production, particularly battery manufacturing, can generate 30–70% more greenhouse gas emissions compared to the output of a gasoline or diesel vehicle (Fig. 4). This is attributable to the energy intensity of lithium, nickel, cobalt, and graphite extraction and processing. However, during the operational phase, the situation reverses: electric vehicles produce no direct tailpipe emissions, and consequently their cumulative carbon footprint progressively decreases relative to conventional transport (Fig. 5).

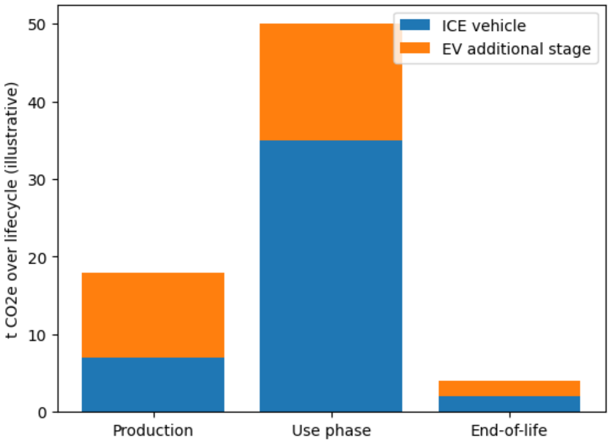

Fig. 4. Life-cycle greenhouse gas emissions of internal combustion engine (ICE) vehicles and electric vehicles (EVs) [12]

A critical question is how long, or after what mileage, an electric vehicle "compensates" for the additional emissions associated with battery production. Most current estimates indicate that this occurs after approximately 20,000–40,000 kilometers of driving, depending on the country's energy mix. In regions with a high share of renewable energy, this period is shorter, whereas in countries where electricity is generated predominantly from coal, the advantage of electric vehicles diminishes. Beyond this "break-even point," the total life-cycle emissions of an electric vehicle are typically 40–60% lower than those of an internal combustion engine vehicle [14].

Beyond climate-related aspects, it is essential to consider other environmental factors, such as land degradation in mining areas, water resource consumption, generation of mining waste, and potential heavy metal contamination. These factors are often the primary subject of debate regarding the sustainability of EV battery production. In this context, battery recycling technologies, material reuse, and the implementation of Extended Producer Responsibility principles acquire particular significance.

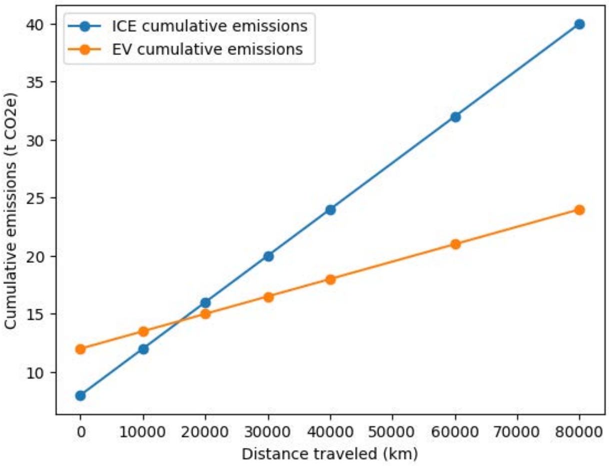

Fig. 5. Break-even point of cumulative greenhouse gas emissions between EVs and ICE vehicles [13]

Extended Producer Responsibility (EPR) is becoming one of the key mechanisms for managing environmental risks associated with the production and use of electric vehicle batteries. Since lithium-ion batteries contain a significant quantity of valuable yet environmentally sensitive materials, producer responsibility must extend beyond the manufacturing stage to encompass the entire product life cycle - from raw material extraction to disposal and material reuse. For this reason, contemporary regulatory approaches, particularly in the European Union, envisage establishing systems that incentivize companies to account for the environmental consequences of their products as early as the design stage.

One of the key elements of EPR is the promotion of eco-design. In the context of batteries, this entails creating batteries that are easier to repair, disassemble, and recycle. For example, current research shows that up to 95% [14] of certain battery metals can be recovered, provided that proper design and recycling technologies are in place. The implementation of eco-design principles not only reduces the adverse environmental impact but also enhances production cost-efficiency, as secondary materials can be reintroduced into the manufacturing cycle (Table 3).

Another important aspect is the reduction in primary raw material consumption. Currently, the extraction of lithium, cobalt, and nickel has significant environmental consequences, including landscape disruption, water resource consumption, and the generation of mining waste. According to forecasts by international energy organizations, demand for certain critical minerals for clean energy technologies may increase several-fold by 2040. Under such conditions, the use of secondary materials from spent batteries can substantially reduce pressure on natural resources and mitigate the environmental risks of extraction.

Another critical component of EPR is supply chain control, or due diligence. Battery and electric vehicle manufacturers are increasingly required to verify the origin of minerals to avoid using raw materials extracted in violation of environmental or social standards. This approach enhances transparency in global supply chains, particularly when extraction occurs in regions with elevated ecological or social risks.

An important innovation in battery management is the introduction of the so-called "battery passport." This is a digital system containing information on the battery composition, material origin, production carbon footprint, and the battery's usage history and technical condition. Such a system enables significantly improved control over the battery life cycle, simplifies recycling, and enhances long-term resource efficiency. The implementation of battery passports is expected to become mandatory under international regulations in the coming years.

EPR is one of the principal mechanisms for transitioning from the linear "extraction – production – use – waste" model to a circular economy, which envisions the return of materials to the production cycle and the maximum extension of their useful life.

In the battery industry, this is manifested through the development of recycling systems and the reuse of battery components. Modern technologies enable the recovery of a significant proportion of valuable materials, including lithium, cobalt, nickel, and graphite, at a high degree of purity suitable for reuse in the production of new batteries. In this way, a closed material loop is formed, in which spent batteries become a resource for the next generation of energy technologies.

Conclusions and Recommendations. Extended Producer Responsibility (EPR) is a critical tool for ensuring the sustainable development of the electric vehicle battery industry. The implementation of EPR enables the reduction of adverse environmental impacts, enhances the efficiency of the utilization of valuable materials, and facilitates the transition from a linear production model to a circular economy. Modern recycling technologies and digital tools, such as the "battery passport,"

Table 3

Role of Extended Producer Responsibility (EPR) in the EV Battery Life Cycle

Stage	Key Activities	EPR Mechanisms	Environmental / Circular Economy Impact
Raw Material Extraction	Lithium, Cobalt, Nickel mining	Material sourcing due diligence	Reduces environmental degradation; ensures ethical sourcing
Design & Manufacturing (Eco-design)	Battery design for disassembly, repair, and recycling	Eco-design principles	Up to 95% of metals recoverable; enhances recyclability
Usage in Electric Vehicles	Operation and performance monitoring	Lifecycle tracking	Extends battery life; informs reuse strategies
Supply Chain Transparency	Verification of material origins	Due diligence reporting	Ensures compliance with social and environmental standards
End-of-Life Management / Recycling	Collection, sorting, material recovery	EPR-mandated recycling programs	Recovery of Li, Co, Ni, graphite; reduces dependence on primary resources
Battery Passport / Digital Tracking	Digital records of composition, carbon footprint, usage history	Regulatory enforcement and reporting	Improves resource efficiency and enables closed-loop recycling

provide control over the battery life cycle and create conditions for resource reuse.

At the same time, implementing EPR faces several significant barriers, including low recycling rates, the lack of standardized technologies, complex logistics for spent battery collection, and limited transparency in global supply chains. These challenges require coordinated action among manufacturers, regulators, and international organizations.

To overcome existing challenges and ensure the sustainable development of the EV battery industry, the following recommendations are proposed:

1. Establishment of global standards for sustainable extraction that guarantee compliance with environmental and social norms at all stages of production.
2. Development of more environmentally friendly battery chemistries that reduce adverse environmental impact during manufacturing and recycling.
3. Support for "green" recycling technologies that ensure a high degree of valuable material recovery and their integration into secondary production.
4. Incentivizing manufacturers to adopt EPR through regulatory, economic, and informational mechanisms.
5. Implementation of the battery passport system across all EU member states and beyond to enhance battery life cycle transparency and material provenance control.
6. Development of secondary markets for second-life batteries is an essential element of the circular economy and a means of reducing dependence on primary resources.

The application of these recommendations will enable balanced development of the battery industry, enhance resource security, reduce environmental burdens, and create resilient economic models on a global scale.

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