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Recycling and Reuse of Lithium Batteries in Latin America and the Caribbean

Analytical Review of Global and Regional Practices

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► Analytical review of global and regional practices

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This report is part of the knowledge agenda developed by the Energy Division of the Inter-American Development Bank that aims to develop new knowledge products and technical assistance programs for the countries of Latin America and the Caribbean. The knowledge products generated are intended to inform, guide, and offer a menu of recommendations to policy makers and active participants in energy markets, including consumers, public utilities, and regulators. The report was prepared under the general direction of Marcelino Madrigal (Chief of the Energy Division). The leader of the work team is Carlos G. Sucre, and the team members are Carolina Ferreira Herrera, Martin Walter, and Lenin Balza. The authors of the report are Viviana López Hernández, Inga Hilbert, Lucía Gascón Castillero and Andreas Manhart from the Öko-Institut e.V; Diego García, Bertrand Nkongdem, and Raluca Dumitrescu from MicroEnergy International GmbH; Carolina Ferreira Herrera and Carlos G. Sucre from the Inter-American Development Bank.

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List of Abbreviations

ADR	Agreement concerning the International Carriage of Dangerous Goods by Road
Al	Aluminum
BEV	Battery Electric Vehicle
BMS	Battery Management System
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
Co	Cobalt
Cu	Copper
EoL	End of Life
EPR	Extended Producer Responsibility
EU	European Union
EV	Electric Vehicle
kg	Kilogram
kWh	Kilowatt-hour
LAC	Latin America and the Caribbean
LCO	Lithium-cobalt-oxide
LFP	Lithium-iron-phosphate
Li	Lithium
LIB	Lithium-ion Battery

List of Abbreviations

LMO	Lithium-manganese-oxide
LMT	Light means of transport
NCA	Lithium-nickel-cobalt-aluminum-oxide
NMC	Lithium-nickel-manganese-cobalt oxide
OECD	Organization for Economic Co-operation and Development
OPEX	Operational Expenditure
PHEV	Plug-in Hybrid Electric Vehicle
PRO	Producer Responsibility Organization
PV	Photovoltaic
RE	Renewable Energy
SLI battery	Automotive battery used for automotive starter, lighting or ignition power only
SNA	Social Network Analysis
ULAB	Used Lead-Acid Battery
ULIB	Used Lithium-Ion Battery
USD	United States Dollar
WEEE	Waste Electrical and Electronic Equipment
Wh	Watt-hour
ZEV	Zero Emission Vehicle

Glossary

Black Mass	Black powder obtained after mechanical pre-processing of used Lithium-ion batteries. It contains the active materials of the batteries´ anode and cathode. Depending on the battery chemistry, it contains graphite, lithium, and metals like cobalt, nickel or manganese in different compositions.
Decree	Written resolution of a normative nature issued by a person or body with authority to do so.
End-of-Life (EoL)	Product at the end of its useful lifetime, which requires further handling and proper management.
Extended Producer Responsibility (EPR)	An environmental policy approach, which extends a producer´s responsibility to the post-consumer phase of a product´s life cycle. Responsibility can be economically and / or physically, and can be placed fully or partially on the producer (OECD 2022). Producers might be defined to comprise those actors, who first bring a product into a defined market. In the context of EPR, manufacturers and importers are often summed up as producers.
Integrated waste management	The activities of source reduction, separation, reuse, recycling, co-processing, biological, chemical, physical or thermal treatment, collection, storage, transport and final disposal of waste, individually performed or combined in an appropriate manner, to adapt to the conditions and needs of each place, meeting the objectives of valorization, sanitary, environmental, technological, economic, social and social efficiency (SEMARNAT 2020).
Lithium-ion batteries (LIB)	Family of rechargeable battery types in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging (Qiao and Wei 2012a).
Portable batteries	Portable batteries are those which can be hand-carried by an individual without difficulty, and are neither automotive nor industrial batteries.

Glossary

Primary batteries	Single-use galvanic cells that store electricity for convenient usage. Examples are zinc-carbon cells, alkaline zinc-manganese dioxide cells, and metal-air-depolarized batteries (Kordesch and Taucher-Mautner 2009).
Producer Responsibility Organization (PRO)	PROs are organizations assigned to implement Extended Producer Responsibility (EPR) schemes on behalf of the producers.
Recycling	Collection, sorting and processing of disposed materials for use in other manufacturing processes. The recycling process is different for each material and location. In many places around the world there is an “informal sector” of recyclers that capture valuable disposed materials and reintroduce them into the economy (Circular Economy Practitioner Guide 2023).
Regulation	A rule or directive made and maintained by an authority.
Remanufacturing	Process of recovering, disassembling, repairing and sanitizing components for resale at “new product” performance, quality and specifications. Remanufactured products should not be understood as “used,” “refurbished,” “repaired” or “reused” (Circular Economy Practitioner Guide 2023).
Repurposing	Use of a product or material for different function than it was originally produced for (Circular Economy Practitioner Guide 2023).
Resolution	Formal statement of opinion or a decision to take an action. In the context of a legislative practice, “resolution” is just a form in which a legislative body expresses an opinion or a purpose with respect to a given matter or topic that is temporary in nature (LII 2023).
Reuse	The use of a previously used material or product, without any transformation process.

Glossary

Reverse logistics	Process of collecting and aggregating products, components or materials at the end-of-life for reuse, recycling and returns. Reverse logistics closes the loop. Take-back programs, warranties and product defect returns all require reverse logistics to get the product from the consumer back to the manufacturer (Circular Economy Practitioner Guide 2023).
Secondary battery	Secondary batteries are electrically rechargeable. The most common application is the use of lead-acid batteries in automobiles for starting, lighting, and ignition (SLI) purposes. Nickel-cadmium, nickel-metal hydride, and lithium batteries are gaining large market sections (Kordesch and Taucher-Mautner 2009).
Special handling waste	Waste generated in production processes that do not meet the characteristics to be considered as hazardous or municipal solid waste, or that are produced by large generators of municipal solid waste (SEMARNAT 2020).
Take-back schemes	Initiative organized by a manufacturer or retailer, to collect used products or materials from consumers and reintroduce them to the original processing and manufacturing cycle (Circular Economy Practitioner Guide 2023).
Used Lithium-Ion Batteries (ULIB)	Also referred to as waste batteries. Some of these batteries have the potential to be reused or repurposed for further material utilization.

Executive Summary

Background

The increasing demand for lithium-ion batteries (LIB), associated to energy storage for electric vehicles, electronics and renewable energy, has raised concerns about their proper disposal, recycling and end-of-life management (EoL). Currently, only half of all LIB reaching end-of-life globally are recycled, with the rest being disposed of. LIB are considered hazardous waste due to their content of hazardous substances, as well as flammable electrolytes. Unsound handling and disposal can lead to environmental pollution and fires. Effective and safe end-of-life management, lifetime extension, and material recovery are urgently needed, especially in those countries where best practices for disposal and recycling have not yet been implemented.

The demand for lithium-ion batteries is growing in Latin America and the Caribbean (LAC) due to increase in renewable energy generation and the uptake of electric vehicles. The region has ambitious targets for climate change mitigation and renewable energy generation, with solar and wind energy generation expected to increase by 550% by 2030 (with respect to 2015 levels). The use of battery-based storage systems is crucial to achieving these targets.

The region holds 67% of global lithium reserves. While mining is an important economic factor in some areas of the region, it also has impacts on the environment and local communities[1]. In that situation, a stronger focus on promoting reuse and recycling of used lithium-ion batteries (ULIB) can achieve both, more local value addition and resource recovery from end-of-life devices, as well as a reduced need to exploit mineral deposits.

The LAC region lacks a strong regulatory framework for the proper management of used and end-of-life lithium-ion batteries, which creates challenges for developing sound end-of-life management solutions. While such policy gaps must be closed in the near future, there is also a need to develop a regional approach aimed at improving capacities, facilitating transboundary movement of batteries and promoting investments for more efficient used lithium-ion battery (ULIB) collection, recycling, and reuse. This regional approach is particularly important for countries of limited size that will continue to lack sufficient end-of-life battery volumes to justify investments in their own end-of-life management capacities.

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[1] The extent of the social and environmental impacts of mining largely depends on the local context and the mineral extracted.

Objectives

The objective of this assignment is the conduction of an analytical assessment of global and regional practices for the reuse and recycling of LIB, with a specific focus on the Latin America and Caribbean region. The review aims to evaluate the current status of LIB end-of-life (EoL) streams in the region, identify growth perspectives, and propose strategies for the adoption of best practices in ULIB reuse and recycling.

The results will provide a comprehensive overview of the LIB EoL management value chain to investors, private sector stakeholders, national authorities, and international cooperation agencies. The assessment compared global best practices in terms of technology and regulatory frameworks with the current practices in the LAC region. Based on this analysis, recommendations were formulated to promote safe and environmentally sound ULIB recycling and reuse. The recommendations prioritize extending the lifetime of LIB, promoting material recovery and preventing unsound EoL management practices in the region, in addition to promoting regional cooperation, promoting the incorporation of LIB into existing regulatory frameworks and supporting the creation of Extended Producer Responsibility Systems (EPR).

Chapter 1 of the report provides background information on the concepts of circular economy, lithium-ion batteries and an overview of good practices for the end-of-life management of LIB; Chapter 2 provides an overview of the methodological approach followed through the study; Chapter 3 analyzes the global state-of-the-art technologies and practices for environmentally sound and safe management of lithium batteries, as well as the regulatory frameworks that enabled their introduction; Chapter 4 presents the results of assessing the current panorama of LIB reuse, repurposing, and recycling practices in the LAC region, the most relevant findings of this process are presented in Chapter 5.

Chapter 6 presents the regional outlook for LIB in the region, including the estimation of the battery volumes reaching their end-of-life in the period 2024-2050, along with estimations of the LIB volumes available for recycling and reuse in different scenarios, this section also presents estimations for the investment requirements to set up the required recycling and reuse infrastructure in each scenario. Chapter 7 finalizes the report by providing a series of recommendations in critical areas to support the implementation of best practices for EoL of ULIB in the region.

Methodology

This report was developed through desk research, field visits, case study analysis, and interviews with key stakeholders in the region. The assessment of ULIB reuse, repurposing and recycling practices in LAC was conducted through an initial desk research aimed at obtaining a not exhaustive regional screening on the topic. The screening criteria included regulatory frameworks, dedicated EPR schemes for batteries, recycling infrastructure for ULIB, and relevant developments in national E-mobility targets and rural/off-grid electrification strategies.

The desk research provided an overview of the current state of ULIB reuse, repurposing, and recycling practices in LAC. Based on this information, four countries were selected for in-depth case studies: Chile, Colombia, Costa Rica and México. Interviews with key stakeholders in each country were conducted using a semi-structured approach to gain a deeper understanding of the regulatory environment, EoL management capabilities, and ongoing developments. The goal was to gather further insights and to identify the most relevant stakeholders in the region. The information collected from these interviews helped to develop a more comprehensive understanding of the situation in each country. A gap analysis between the assessment of the current status of the LAC region and the global best practices allowed for the elaboration of recommendations and capacity needs for the region.

The report also included a stakeholder mapping, as part of the regional assessment using Social Network Analysis (SNA), a technique that visually represents social relationships and provides insights into stakeholder networks. The stakeholder mapping complemented the insights collected during the interview phase and was used to identify key actors in the network.

The estimations of battery volumes, required recycling and reuse capacities and investment requirements were elaborated through the analysis of the historical and expected behavior of three key battery generation sectors in the region: solar energy, wind energy and electric vehicles, the demand for energy storage associated to these sectors was converted to its equivalent in battery mass and then into battery mass reaching its EoL, this allowed for the formulation of a baseline case and the elaboration of three different scenarios for battery collection, recycling and repurposing rates.

Findings

- Currently, lithium-ion battery recycling processes in the Latin America and Caribbean (LAC) region are limited to mechanical pre-treatment and separation of different fractions.
- Additional investments will be required in the region to expand ULIB recycling plants, especially considering the expected increase in lithium-ion batteries reaching their end-of-life in the long term.
- The increasing volume and shares of LFP batteries could make recycling processes uneconomical as they contain less valuable raw materials than other Li-ion battery types. To mitigate such economic bottlenecks, additional financial instruments, such as extended producer responsibility (EPR) schemes, are necessary.
- There is a need for better information and support from governmental actors in the development of centralized measures for the safe storage, packaging and transport of used lithium-ion batteries (ULIB).
- Current efforts in the region for ULIB EoL management focus on recycling, while reuse initiatives (mostly at the start-up level) receive little support.
- Traceability of end-of-life EoL volumes is very low in the region due to the informal nature of large segments of the region's waste management and recycling sector.
- There is little regional cooperation between neighboring countries to improve end-of-life management practices for LIB, with the exception of some bilateral commercial agreements and ongoing cooperation for technology transfer.
- Small and medium-sized enterprises in LAC lack administrative capacities to apply Prior Informed Consent procedures for transboundary movements of collected ULIB. This procedure is required to organize movements of hazardous waste across international boundaries and is therefore an important pre-condition for well-regulated and controlled cross-border cooperation in end-of-life battery management.
- Battery collection in the region is hampered by the fact that most recyclers must charge gate fees to cover the costs of sound end-of-life management, which many users are reluctant to pay. This situation, along with widely absent disposal rules and enforcement, represents a barrier for boosting battery collection and sound end-of-life management. Additionally, these limitations result in a small number of players so that sound end-of-life management often results in substantial transport costs to the few active operators, further increasing the costs.
- It has been estimated that between 6.6 and 7.5 million tons of lithium-ion batteries will reach end-of-life in LAC in the period between 2024 and 2050.

- The implementation of best practices for ULIB reuse and recycling in the LAC region could reduce the amount of ULIB reaching their end-of-life by up to 2.1 million tons by 2050 (0.7 million tons in a more conservative scenario) and enable the region to recycle up to 2.8 million tons of LIBs between 2024 and 2050 (1.5 million tons in a more conservative scenario).
- The investment needs to establish the necessary recycling capacities for the entire region in the period 2024-2050 range between 353 and 462 million USD in capital costs alone (between 188 and 247 million USD in a more conservative scenario).
- The investment needs to establish battery reuse and repurposing capacities in the region in the period 2024-2050 range between USD 949 million and USD 1,243 million in investment and operational costs (between USD 237 million and USD 311 million in a more conservative scenario).

Recommendations

- Support public sector actors in the integration of lithium battery requirements into national waste management standards, the establishment of mandatory extended producer responsibility (EPR) systems and the implementation of battery-specific national regulatory frameworks.
- Promote the safe and environmentally sound management of lithium batteries through regulations promoting reuse/repurposing of batteries, mandatory recovery rates and the use of recycled materials in new batteries.
- Conduct regional conferences and workshops focused on end-of-life management, facilitating the exchange of best practices, particularly related to effective and practicable collection systems and collaborative platforms.
- Design a targeted communication strategy through social campaigns to raise awareness of the importance of proper battery management and the available take-back schemes.
- Encourage the creation of national circular economy solutions groups and regulatory working groups to foster knowledge sharing, cooperation between actors and the development of specific regulations for lithium battery management in countries with an increasing number of used batteries.
- Support the mobilization of investments and funds towards small and medium scale reuse and recycling facilities.
- Provide specific training to actors involved in the collection and transport of lithium-based batteries to ensure the implementation of good practices.
- Train national authorities, environmental agencies, collectors and transporters in the areas of good practice and compliance with relevant regulations, such as the Basel Convention, to facilitate the movement of used batteries within the region.

1. Background

The need for fostering reuse and recycling practices for lithium-ion batteries (LIB) has become increasingly important as the demand for electric vehicles (EV), electronics and renewable energy (RE) sources (among other sectors) continues to increase. LIB are currently used in a variety of consumer products (e.g., mobile phones, laptop computers, etc.), as LIB are the most widely used type of rechargeable battery. The use of lithium-ion batteries has been growing steadily over the last decade, boosted by the recent exponential growth of the EV sector, with global forecasts of 140 million EVs by 2030 and approximately 11 million metric tons of lithium-ion batteries by 2030 (Jacoby 2019; IEA 2023). Furthermore, LIB play a key role on the global energy transition, the global demand for lithium is expected to grow by 42 times between 2020 and 2040 under a climate scenario that is in compliance with the Paris Agreement, and even more under a scenario where net zero emissions are reached by 2050 (Blakemore et al. 2022). This situation has raised global concerns regarding the correct end-of-life (EoL) management of these batteries once they achieve the end of their useful life.

As of 2018, only half of all LIB reaching end-of-life globally reached recyclers, considering that the number of batteries in second life applications remains low. The installed capacity of second life batteries, which are LIB used in less demanding applications such as energy storage for small residential systems or larger grid-scale solutions, is below 100 MWh in Europe, and below 10 MWh in North America (Melin 2022). Thus, the urgent need to ensure their effective and safe end-of-life management, along with approaches to allow lifetime extension and promote material recovery, particularly for countries where best practices for EoL management of LIB have not yet been defined or implemented.

LIB are often classified as hazardous waste, even if they contain fewer toxic metals than other types of batteries, which contain higher concentrations of lead or cadmium. LIB are considered a hazardous waste by entities such as the United States Environmental Protection Agency (EPA) due to their high energy density and content of hazardous elements, including nickel, cobalt and other organic chemicals such as toxic and flammable electrolytes that make lithium cells and batteries a chemical and electrical hazard (Xu et al. 2008; U.S. Department of Transportation 2022). The improper EoL management of these batteries leads to environmental pollution by the infiltration of heavy metals to underwater bodies or the release of poisonous gases such as hydrogen fluoride (HF) into the atmosphere (Balasubramaniam et al. 2020). Furthermore, lithium-ion batteries are flammable, and their disposal into municipal facilities that are not equipped for their processing can lead to fires (EPA; OLEM 2019).

In Latin America and the Caribbean (LAC), the demand for LIB has been in constant growth, with several countries in the region seeking to increase their renewable energy production and promote the uptake of electric vehicles (López Soto et al. 2022). Motivated by the ambitious national targets for climate change mitigation and production of energy from renewable sources, by 2030, it is expected that solar and wind energy generation in the region will increase by 550% with respect to 2015 levels, reaching a share of 18.9% of overall electricity generation, together with the overall increase in the regional electricity demand, which is estimated to double from 2015 levels by 2040 (Graham et al. 2021). Furthermore, the requirements from solar power would be even larger in order to reach the 1.5° climate goal, with requirements of 20 GW additional solar power and 12 GW wind generation capacity per year until 2050 (IRENA 2022c), where LIB will play a major role as the most implemented stationary storage technology, reaching 50% of the share of energy storage in the existing and planned projects (Graham et al. 2021).

Regarding EV, their uptake is underway in some markets in the region. In 2021, 25,000 new EV were registered, doubling 2020 levels (BloombergNEF 2022). In 2020, 2.7% of the new passenger vehicles were EV in Costa Rica, followed by Colombia, with a 0.6% and Chile reaching 0.5%. The market will continue its growth, further supported from public sector initiatives and targets to incorporate zero emission vehicles (ZEV), which include, among others: reaching 100% sales of urban buses to be zero emissions by 2035 in Colombia, and reaching 100% new vehicle sales by 2050 in Mexico and by 2035 in Chile (Kohli et al. 2022), while in Costa Rica, by 2030, 8% of the light vehicle fleet (private and institutional) will be electric, as depicted in their 2020 NDC, these measures will be complemented with the introduction of electric passenger and freight trains.

Even though the number of lithium-ion batteries has significantly increased in the region, and it is expected to continue increasing, the alternatives for environmentally sound EoL management of batteries are scarce. Among other factors this is due to the lack of a strong regulatory framework targeting LIB and only 55% rate of proper solid waste management in the region. While there have been some efforts to address these issues, there has been limited research into the global and regional practices for the reuse and recycling of lithium-ion batteries in the Latin American and Caribbean region.

This situation calls for a regional approach to improve capacities and foster investment for more efficient ULIB collection, recycling and reuse. Moreover, without a specific regulatory framework in place, unsound management of these batteries can only be partially prevented and the pressure on the region's mining of virgin lithium resources will only increase.

Promoting reuse and recycling of lithium-ion batteries has many potential positive long-term environmental and social impacts in the region by reducing the demand for virgin lithium which must be obtained through mining. The exploitation of lithium resources is expected to increase in the LAC region, as 67% of the global reserves of this metal are concentrated in Bolivia, Argentina, Chile, Mexico and Peru (USGS 2021). The extraction of lithium resources in hard rock mining operations, which, in the LAC region, takes place in Brazil has impacts, such as soil and air pollution and the consumption of water resources, which are necessary for local surrounding communities,, including the increase in emissions product from mining and processing of ores, such as SOx emissions from smelting sulfide ores (Dunn et al. 2012; Rahman et al. 2017). Within this context recycling processes present a viable option for reintroducing lithium-ion battery components into the economic cycle, thus reducing the need from primary raw materials (Velázquez-Martinez et al. 2019).

The objective of this project is the analytical assessment on global and regional practices reuse and recycling of lithium-ion batteries. A particular focus of this review is set on best practices and technologies available, and regulatory instruments that enable the introduction of best practices. The review specifically focuses on the Latin America and Caribbean (LAC) region aiming to assess the current status of the lithium-ion battery end-of-life (EoL) streams, its perspectives for growth and provide strategies for the adoption of best practices for reuse and recycling within the region.

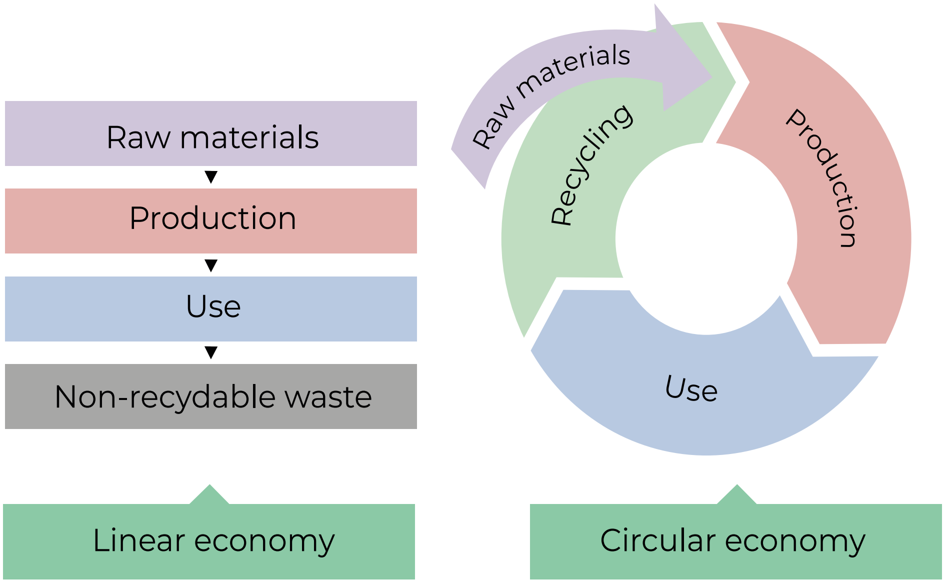
The outputs of this review will provide investors, stakeholders from the private sector and national authorities as well as international cooperation agencies with a comprehensive overview of the LIB end-of -life management value chain. The identified global best practices in terms of technology and enabling regulatory frameworks are contrasted with current practices in the LAC region. Finally, key recommendations are drafted with the aim of fostering safe and environmentally sound ULIB recycling and reuse which prioritizes extending the lifetime of LIB, promoting material recovery and mitigating the environmental impacts as well as preventing substandard EoL management of LIB in the region.

1.1 Circular economy considerations

A Circular Economy (CE) links the effective use of resources to economic growth and is a regenerative approach intended to reduce waste and aimed at ensuring the eco-sustainability of post -use products. Increasing demand for LIB has led to global supply chain and environmental concerns. Some problems stemming from current and future demand of LIB include geopolitical risks, environmental, and social issues as well as economic pressures:

- Critical materials used for anode and cathode of LIB such as lithium, nickel, cobalt etc. are finite and concentrated in countries that can have less strict human health and environmental regulations.
- Pollution linked to unsound EoL management of LIB which contains toxic materials.
- Water usage in extraction and processing of lithium
- Despite the pressing need to use lithium more efficiently, approximately 90% ends up in landfills, partly due to technical constraints, economics barriers, regulatory gaps, and logistics issues (Costa et al. 2021). As environmental issues continue to increase, stakeholders, policy makers, and regulators have started to identify barriers to a circular economy for LIB and solutions to drive and enable environmentally sustainable ULIB management.
- Circular economy for LIB in this context refers to transition from a “take-make-consume-dispose'' linear economic system to a circular system that allows for extended lifetime, high performance, and reuse or recovery of critical materials (see Figure 1-1) (Curtis et al. 2021).

Figure 1-1: From Linear economy (left) to circular economy (right)



Source: Government of the Netherlands (2016)

A lithium-ion battery is a family of rechargeable battery types in which lithium ions move from the positive electrode to the negative electrode during charge and back when discharging (Qiao and Wei 2012b). Each cell is formed by a transition metal compound as a cathode (positive electrode), graphite as the anode (negative electrode), aluminum and copper as current collectors, a lithium salt dissolved in organic solvents as electrolyte, a polymeric separator and a metallic cell casing (Tarascon and Armand 2001; Reddy 2011); a lithium-ion battery (or battery pack) is made from one or more individual cells packed together. As the focus of the ULIB recycling process is driven by market value, cobalt and metallic fractions are currently the main interest, with emerging recycling processes focusing also on recovering lithium, particularly in formations containing cobalt (Ober 2018; Velázquez-Martinez et al. 2019; Gaines and Dunn 2014).

1.2 Lithium-ion battery (LIB) types

Lithium-ion batteries are used in a broad variety of applications and come in different sizes, designs and sub-types. In terms of battery chemistry, Lithium-ion batteries can be differentiated in the major sub-types listed in Table 1-1. Lithium cobalt oxide (LCO) batteries are mainly used in mobile electrical and electronic equipment. For recycling, these batteries are quite attractive as they contain high concentrations of cobalt, which is one of the main value carriers of EoL Lithium-ion batteries. Lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA) batteries also contain cobalt, but at lower concentrations. Instead, the cathodes are composed of a mix of cobalt and other substances, whereof nickel (NMC-batteries) is also of considerable value to recyclers. Lithium iron phosphate (LFP) and lithium manganese oxide (LMO) batteries are entirely free from cobalt and nickel and refer to iron phosphate and manganese oxide as resources for cathode material production instead. The costs for the cathode material have considerable implications on the total battery production costs. Due to high raw material prices over the last months and years, price sensitive applications increasingly switched to using cheaper LFP batteries, leading to a rapidly increasing market share for this sub-type from 5% in 2019 to around 40% in 2022. This switch was also supported by improved energy-densities of this sub-type (Wunderlich-Pfeiffer 12 Oct 2022).

Table 1-1:.Major current sub-types of Lithium-ion battery chemistries

Battery chemistry		Energy densities	Common applications
LCO	Lithium cobalt oxide	150-200 Wh/kg	Mobile phones, notebooks, cameras
NMC	Lithium nickel manganese cobalt oxide	150-260 Wh/kg	Power tools, e-bikes, electric vehicles
NCA	Lithium nickel cobalt aluminium oxide	200-260 Wh/kg	Medical devices, industrial batteries, electric vehicles
LFP	Lithium iron phosphate	90-180 Wh/kg	Stationary applications (e.g., solar power storage batteries), electric buses, electric vehicles
LMO	Lithium manganese oxide	100-150 Wh/kg	Stationary applications, electric vehicles (no relevant market share)

Source: (Battery University 2021; Wunderlich-Pfeiffer 12 Oct 2022; electrive.net 1 Apr 2022)

Lithium-ion batteries also have a large variety in terms of sizes and designs, including flat or pouch cells used in mobile phones or tablets, cylindrical cells and larger battery packs composed of numerous cells and modules (see Figure 1-2).

Figure 1-2: Various types and designs of Lithium-ion batteries

Source: Oeko-Institut

1) Lithium-ion batteries from mobile phones

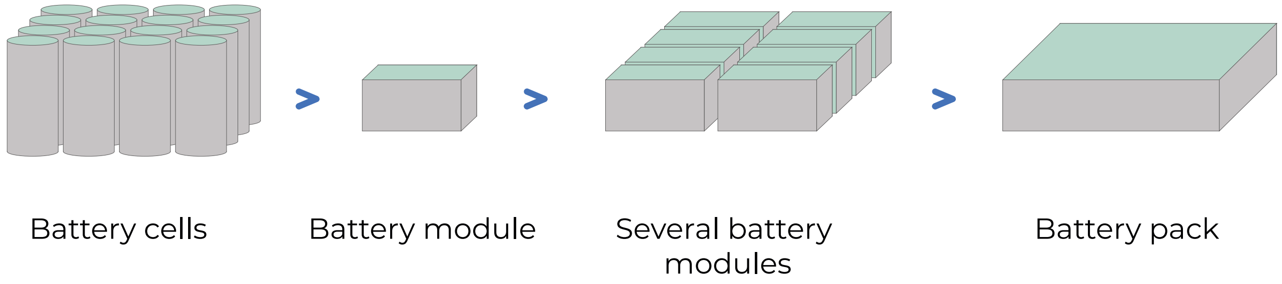
2) Lithium-ion battery pack from a power tool

3) Cylindrical cells assembled to larger battery packs (shrink-wrapped)

4) Cylindrical cells assembled to a larger battery pack with battery management system (BMS)

Electric vehicle batteries often weigh several hundred kilograms and are composed of numerous battery cells. Cells are often cylindrical but may have other forms (prismatic, blade design etc.) and are assembled into battery modules. Several modules are combined into a battery pack encased in a housing and equipped with a battery management system (see Figure 1-3). Such battery packs are commonly referred to as electric vehicle batteries. The casing does not only fulfil protective functions but must also conduct heat to the cooling system to protect from overheating. Therefore, many electric vehicle battery packs have aluminum elements that can take-up and remove heat generated at cell and module level.

Figure 1-3: Composition of electric vehicle battery packs (simplified)



Source: Oeko-Institut

1.3 Overview of good practice LIB end-of-life management

Figure 1-4 gives an overview about an optimized reverse supply chain for electric vehicle batteries:

- After the batteries have reached a remaining capacity that is too low for vehicle operation, the battery packs are safely removed, packed and shipped to an authorized battery testing and treatment facility.
- The receiving company conducts a state-of-health test of the battery packs and their modules. Reusable modules are used to assemble second-life storage solutions (a practice also referred-to as ‘repurposing’). Other modules and battery components are passed-on to recycling.
- After several more years of second-life use, batteries have no relevant reuse value anymore and are also given to recycling.
- Recycling starts with a manual dismantling of larger battery packs. Further processing is done under safe conditions in a sealed environment, including dust and emission controls. Most recycling processes entail mechanical pre-processing where the battery modules and cells are shredded and sorted into major output fractions, namely copper, aluminum, plastics and black mass[2].

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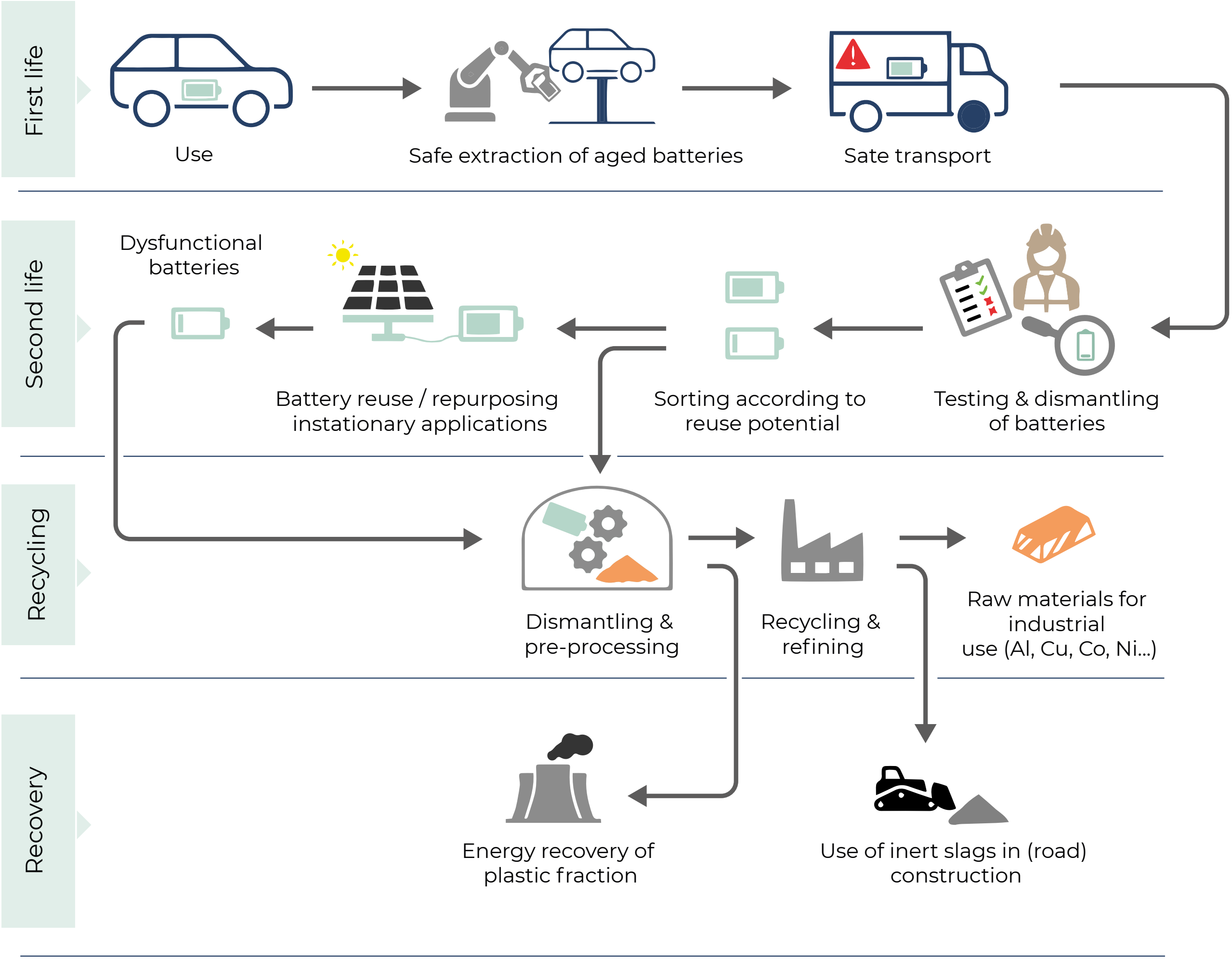
[2] Black mass refers to a black powder obtained after mechanical pre-processing of used Lithium-ion batteries. It contains the active materials of the batteries´ anode and cathode. Depending on the battery chemistry, it contains graphite, lithium, and metals like cobalt, nickel or manganese in different compositions.

- The quality of recovered plastics is usually too low for recycling purposes so that this material is used for energy recovery[3] purposes.
- Aluminum, copper and black mass are passed on to specialized smelting and refining processes that generate raw materials for industrial production.
- Inert by-products of smelting operations (slags) can be used in road construction as gravel or sand.

Figure 1-4: Optimized reverse supply chain for electric vehicle batteries



Source: Oeko-Institut

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[3] Energy recovery is a standard term in waste management and entails all processes where the calorific value is used. Mostly through burning. This can happen in cement kilns, waste incinerators, coprocessing in coal plants among others.

The flowchart above represents a simplified model and does not account for possible additional steps, side streams and variations. Amongst others, this includes:

- End-of-life batteries must also be discharged prior to dismantling and processing. This can either be conducted prior to shipment (at the point where the batteries are taken out of the vehicles), or as first management step before dismantling. In any case, deep discharging of industrial and electric vehicle batteries is a high voltage operation and shall only be carried-out by trained personnel.
- Deep discharging of batteries is often challenging for various reasons: larger batteries have a protection against deep discharge, which would need to be disabled through access to the battery management system.
- Battery testing can either be based on a testing protocol for modules and cells or making use of recorded use-data saved on the battery management system (BMS) or a cloud storage solution. The latter option might allow battery reuse/ repurposing without dismantling activities (see section 3.2).
- There are various approaches to the recycling process. While most of them refer to mechanical pre-processing, others start the recycling with thermal or pyrometallurgic methods, which has consequences for various involved materials such as aluminum and plastics (also see section 3.3).

The model as indicated above can also be applied to other Lithiumlithium-ion battery types. Nevertheless, the following aspects must be considered:

- For smaller batteries (e.g., from smartphones) discharging is also difficult as contacts are often corroded or get corroded during discharging attempts (e.g., in saltwater baths).
- Small lithium-ion batteries (e.g., from electrical and electronic equipment) commonly have a low reuse potential. Thus, testing and reuse/repurposing is usually limited to other battery types such as industrial batteries and electric vehicle batteries.
- Small batteries (cells, small packs) also do not require dismantling prior to treatment.

Overall, take-back schemes, specifically those aligned with principles of Extended Producer Responsibility (EPR) play a key role to ensure that responsibilities and costs of sound end-of-life management of ULIB is clearly specified and effectively implemented (also see section 3.4.4). In countries where EPR schemes for used LIB are already in place, the collection and safe transport is mandated by existing legal obligations (see also section 3.4). Although the same approach can be taken in a voluntary manner in countries without existing EPR schemes, ensuring an effective EoL management of ULIB could be more challenging.

2. Methodology

The overview on global state of the art technology for ULIB recycling (chapter 3) was obtained through a desk research and review of technical literature. Due to Oeko-Institut´s previous project work and expertise in the field of battery recycling, the authors were able to complement the theoretical review with first-hand impressions and learnings gained throughout various field visits to different recycling plants and reuse operations worldwide (see pictures included in the report). The selection of regulatory frameworks (chapter 3.4) was based on a high level of experience in the respective jurisdictions. Either due to a high volume of used batteries (China), gradual evolvement of the framework over time (Germany), or due to an intense and up-to-date review process of the whole framework (EU).

The assessment of ULIB reuse, repurposing and recycling practices in LAC (chapter 4) was conducted through an initial desk research aimed at obtaining a not exhaustive regional screening on the topic. The screening criteria were determined by relevant enabling aspects in global best practices for Used lithium-ion batteries (ULIB) reuse and recycling. These include existing regulatory frameworks (including LIB), dedicated Extended Producer Responsibility schemes for batteries, recycling infrastructure for ULIB as well as relevant developments in terms of national E-mobility targets and rural /off-grid electrification strategies (as indicators for projected EoL LIB management needs).

With the information collected via desk research it was possible to obtain an overview of the current state of matters in LAC for the topic of reuse, repurposing and recycling of ULIB. As next step, the four (4) most interesting and relevant countries were identified in order develop deep-dive case studies. For the selected countries, further research was complemented through interviews with key stakeholders (see Annex I). Semi-structured interviews were conducted in order to gather further insights on the situation in specific countries and to identify the most relevant stakeholders in the region. The goal of this step was to gain a deeper understanding of the reality in terms of regulation efficiency, EoL management capacities and ongoing developments in each country.

As final step in the assessment of regional practices, a stakeholder mapping was conducted. The mapping of relevant stakeholders has been conducted through the methodology of Social Network Analysis (SNA). SNA is a method used to provide a visual representation of social relationships - location and grouping of actors - and gain insights into the boundary of actor networks and which has proved to be useful in a wide range of fields of the social sciences (Borgatti 2009). The basic premise of SNA is that actors who are indirectly connected in the context of thematical networks can influence each other (Marin & Wellman 2011). SNA is therefore useful in understanding network dynamics and identifying relevant stakeholders when applied to a specific context such as the subject of this assignment. In addition to the stakeholders identified in the regional screening (see 4.1), the stakeholder mapping was complemented by information collected during the interview phase.

The regional outlook (see chapter 6) was developed by gathering regional data for three sectors identified as critical for the generation of large-size LIB (Solar PV, wind Energy and electric vehicles). The collected data was used to estimate the behavior of these three sectors in the period 2024-2050 in terms of demand requirements (demand for PV or wind energy installed capacity and demand for new electric vehicles), along with the equivalent demand for LIB storage, which was subsequently converted into equivalent battery mass requirements. This allowed the estimation of the battery mass entering the LAC market every year during the forecasting period and the battery mass reaching its end-of-life. This assessment was further supported with the formulation of a baseline and three different scenarios, each one assuming different ULIB collection, recycling and reuse rates. Afterwards, the battery mass recycled and reused was utilized as an input to estimate the foreseen economic benefits and investment requirements of achieving the ULIB recycling and reuse requirements of each scenario. The entire methodological approach for the elaboration of this chapter and the detailed assumptions utilized are described in depth in Annex IV.

The recommendations and capacity needs (see chapter 7) were developed by identifying the main gaps between the regional outlook and the identified global best practices for reuse, recycling and repurposing. The recommendations were divided into four categories, and within each category the recommendations were divided in primary and secondary interventions.

3. Overview on global state of art technology and existing practices for lithium-ion battery EoL

3.1 Collection and transport

Collection of used and end-of-life lithium-ion batteries is strongly influenced by national legislation and waste management system. In general, many types of end-of-life LIB do not carry sufficient material value to be attractive for scrap dealers and recyclers. While some revenues from material recovery can be generated, they often do not cover the full costs of reverse logistics and recycling operations (Angliviel et al. 2021; Manhart et al. 2022). Collection therefore strongly depends on mandatory systems and rules that delegate the obligation for sound collection, transport and responsible treatment (encompassing reuse/repurposing and recycling) to clearly identifiable players. This is commonly done through legislation and enforcement based on the principle of Extended Producer Responsibility (EPR), where producers or importers of batteries and battery containing equipment are given the task to set-up and operate collection systems, and to ensure that collected volumes are treated according to defined criteria such as recycling rates, environmental performance and safety (also see section 3.4).

In terms of handling of used and end-of-life lithium-ion batteries, it is important to consider that such batteries contain various substances of concern, including substances that can cause skin burns and eye damage, that are classified as highly flammable, that are suspected of causing cancer and that may cause an allergic skin reaction (Stahl et al. 2018). In addition, used and end-of-life LIB carry significant fire and explosion risks, which basically result from their content of flammable substances, as well as potential residual charge. Overheating and fire outbreaks are mostly a result of overcharging, deep-discharging, high temperatures or physical stress to batteries. Lithium-ion battery fires may propagate from one cell to neighboring cells and modules and therefore carry the risks of larger fire outbreaks. In addition, such fires are often difficult to be controlled and extinguished as overheating may develop within few seconds and because overheating of some cathode materials releases oxygen, which can sustain a battery fire even under air exclusion (Manhart et al. 2018). For these reasons, end-of-life lithium-ion batteries are classified as dangerous goods under the Agreement concerning the International Carriage of Dangerous Goods by Road (ADR Convention) and considered as hazardous waste by many signatories to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal[4].

Storage and transport of used and end-of-life lithium-ion batteries are therefore subject to various international and national regulations aiming at minimizing risks for human health, infrastructure and the environment. The following gives an overview on the main international rules and common good practices. Further requirements might apply, depending on national legislation or standards and procedures required by other parties such as insurance companies and shipping agencies:

- Waste batteries are prohibited from air transport unless approved by the state of origin and the state of destination (RRC 2019).
- For transport, end-of-life batteries must be packed in a system that is heat-insulating, leak-resistant, stabilizing and/or shockproof. The selected packaging solution must comply with ADR safety requirements, which must be confirmed by an accredited certification body (Reneos 2022).
- Smaller lithium-ion batteries are commonly packed in UN-approved barrels, embedded in sand or vermiculite. The sand/vermiculite separates the batteries, prevents movements and impacts from shocks and absorbs heat from overheating cells. Valves facilitate the release of overpressure (see Figure 3-1).
- Damaged batteries heavier than 30 kg must be packed separately.
- Transport containers, as well as transport carriers must be labelled with the appropriate dangerous goods class (ADR-code No. 9) and UN-code (UN3480 Lithium Batteries for Recycling). Also see Figure 3-2.
- Transport across international boundaries must in many cases follow the prior-informed-consent procedure of the Basel Convention where the competent authorities (usually the authority responsible for the environment) of the exporting country notifies the competent authorities of the transit and receiving countries prior to the movement. Shipments of used batteries for reuse/repurposing may only be exempted from this rule when accompanied by a functionality test by a third party[5].

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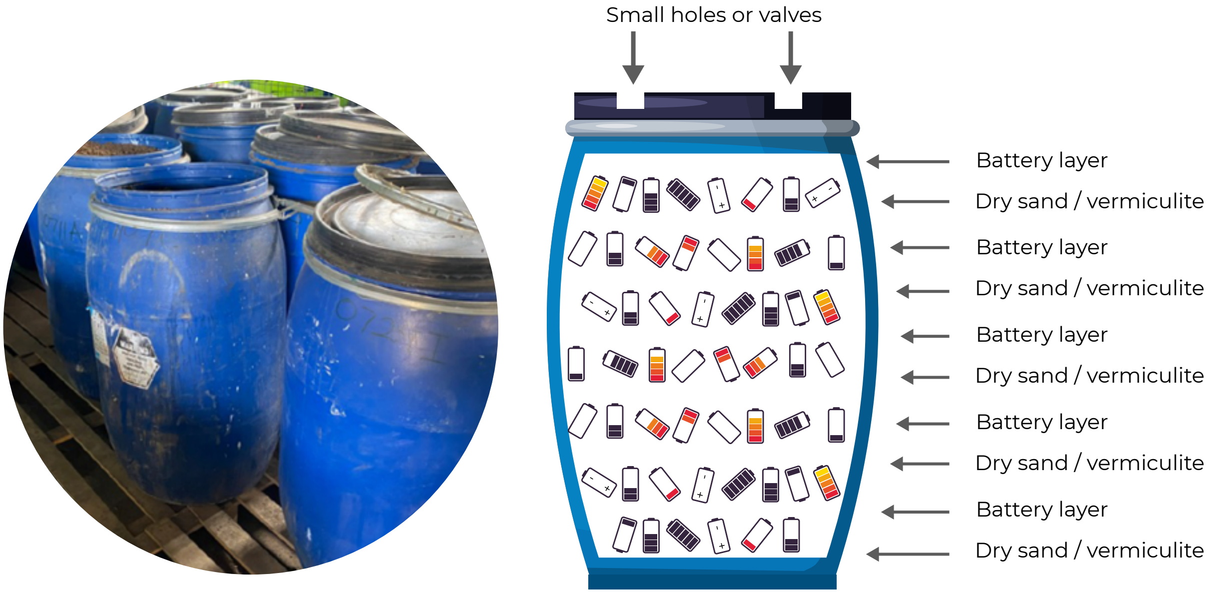
[4] Waste lithium-ion batteries are not explicitly listed in Annexes I and VIII to the Basel Convention, however, some substances and their characteristics contained in LIB (e.g., the electrolyte consists of hexafluorophosphate) are listed in the Annexes I and III.

[5] In-line with the Technical guidelines on transboundary movements of electrical and electronic waste and used electrical and electronic equipment, in particular regarding the distinction between waste and non-waste under the Basel Convention (2019).

Figure 3-1: Barrels commonly used for lithium-ion battery storage and transport (left) and concept of embedding batteries in sand or vermiculite (right)



Source: Oeko-Institut

Figure 3-2: Coding and decals required for transport of end-of-life lithium-ion batteries

Source: Public domain

Besides transport, logistical hubs for used and end-of-life LIB must take various precautionary measures to mitigate fire risks and to guarantee workplace health and safety. This involves (but is not necessarily limited to):

- Separation of battery storage areas from areas where other functions are conducted (e.g., residential, office);
- Minimization of fire loading from other materials (e.g., no structures or furniture from wood or plastics);
- Further fire safety measures (smoke detectors, appropriate fire extinguishers etc.);
- Measures to avoid excessive heat and moisture in storage areas;
- Emergency preparedness plans and trainings;
- Measures to avoid accumulation of potential leaking gases from batteries;
- Measures to minimize the risk of direct contact of personnel with hazardous battery materials (personal protective equipment, eye wash station etc.);
- Regular safety training of workers and all visiting personnel.

3.2 Reuse and repurposing

The capacity of lithium-ion batteries degrades over time, which commonly leads to situations where aged batteries are considered unsuitable for a certain application, while still being appropriate for others. This typically applies for batteries used in the mobility sector, where battery capacity correlates with a vehicle's milage. EV batteries are commonly considered unsuitable when capacity declined to 80% or 70%,depending on the battery and vehicle quality, among other factors, this is likely the case after more than 10 years of use (Zhu et al. 2021; Allred 2021). At this point in time, where EV batteries are either replaced, or the whole vehicle decommissioned, the battery can be tested and used for other (stationary storage) purposes (Tankou et al. 2023). This so-called 'repurposing' allows to extend the lifetime of batteries for several more years and can have multiple positive side-effects such as provision to affordable power storage solutions and the generation of business opportunities in local testing and reuse/repurposing operations (Angliviel et al. 2021).

Reuse and repurposing can also stretch beyond EV-batteries and, for example, be conducted with industrial battery packs from warranty returns (e.g., from solar power installations). Usually, only a minority of cells and modules of dysfunctional battery packs are damaged or unsuitable for reuse/repurposing (Kampker et al. 2021).

Reuse and repurposing start with a thorough visual and technical inspection of incoming battery packs, including the collection of all retrievable information on the batteries past applications and state-of-health. Larger batteries (EV-batteries, industrial batteries) commonly record use data (charging-discharging cycles, temperature regime, discharge current, etc.) onto the battery management system (BMS) or a cloud storage system. Access to such information can be instrumental to learn about a battery’s state-of-health and greatly facilitate reuse and repurposing efforts. Nevertheless, access to BMS data is not universal and requires specialized software and access usually available only to manufacturers and close cooperation partners (Zhu et al. 2021).

Independent reuse and repurposing must therefore refer to other testing methods that include a disassembly of battery packs down to module or even cell level, a visual inspection on mechanical properties (sort out damaged and leaking cells) and electrochemical performance testing (open circuit voltage, internal resistance, capacity) (Zhu et al. 2021). Testing may use the protocols of the UL 1974 standard, which is currently the only standard guiding battery evaluation for reuse and repurposing. Based on the test results, modules and cells are either rejected (for recycling) or sorted into groups with similar properties. The latter are reassembled into new battery packs and equipped with a new BMS.

As EV market penetration only became significant a few years ago, the generation of used EV batteries for repurposing is still very limited in most markets. Therefore, battery repurposing is still limited in scale (Allred 2021). In that context, the following additional aspects on future prospects are mentioned in the literature:

- Reuse and repurposing activities require an influx of similar or even identical batteries. In case a collection system generates a broad variety of different types and cells, reuse and repurposing are significantly limited (Kampker et al. 2021; Manhart et al. 2022).
- Access to battery state-of-health data is key to enable cost-efficient, high quality and safe reuse/repurposing of batteries. As access to such data is not universal, such type of repurposing is only possible for producers or close cooperation partners (see above). There are various attempts to establish a digital battery passport, but it is still unclear if such a passport will facilitate a more universal access to battery state-of-health data (Berger et al. 2022; Zhu et al. 2021).
- Battery disassembly, testing and reassembly is currently a labor-intensive process, which - depending on the labor costs of a certain setting - can impact economic viability (Zhu et al. 2021; Allred 2021).
- Automation in disassembly and testing may reduce manual labor requirements, and also allow improved inspection qualities. Testing may also be completed and improved with technologies such as X-ray computed tomography (XCT), neutron-scattering and in combination with better models of typical battery-degradation procedures (Zhu et al. 2021).
- Product safety of second-life batteries is of high importance and should ideally be at the same level as first-life batteries. Such safety levels are defined in application specific standards such as IEC 62619 or UL 1973.
- In terms of environmental and socio-economic benefits, the reuse and repurposing of locally generated batteries should clearly be preferred over imports of used batteries. Imports of lithium-ion batteries for reuse/repurposing should only be considered in cases where such imports allow access to high-quality storage solutions at a comparable low price and in-line with international conventions on the transboundary movement of used goods and hazardous waste[6] (Betz et al. 2022).

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[6] Importers need to consider (1) the classification of ULIB as (non-)hazardous waste in receiving or transit countries and (2) the ban amendment between (non-)OECD countries.

3.3 Recycling

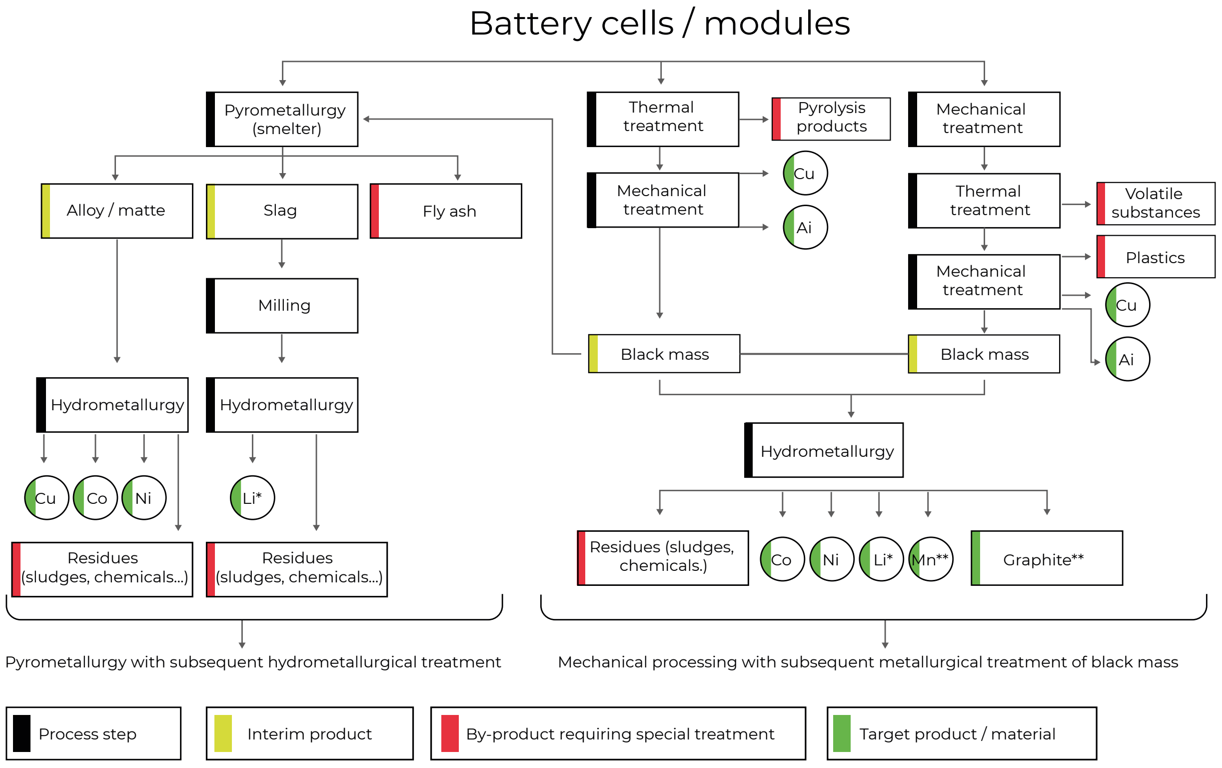
Recycling of lithium-ion batteries is a relatively new field with different methods and process routes being tested and optimized. Complex material compositions, including halogenic and organic compounds, as well as high energy densities of potential residual charge make lithium-ion battery recycling technologically challenging. While some parts of the recycling processes such as the mechanical processing steps are built-up in many world regions, fully integrated processes are currently only available in a limited number of countries in Asia (e.g. S-Korea, Japan, China) Europe (e.g. Belgium, Germany, France, Finland) and North-America (USA) (Sojka et al. 2020).

While there are several different process routes and variations, they can be classified in two main types, which are both described in more detail in the subsequent sections (Brückner et al. 2020):

- Pyrometallurgy with subsequent hydrometallurgical treatment
- Mechanical Processing with subsequent metallurgical treatment of black mass

The simplified flowchart for both options is illustrated in Figure 3-3 and some descriptions provided in the subsequent sections. In addition, direct recycling of recovered black mass is applied, but currently limited to the recycling of battery production waste (pre-consumer recycling), which is further elaborated in section 3.3.3.

Figure 3-3: Overview flowchart of major ULIB recycling pathways



* Recovery challenging(technically and/or economically)
**Not yet recovered on an industrial scale

Source: Adapted from (Brückner et al. 2020)

3.3.1 Pyrometallurgy with subsequent hydrometallurgical treatment

In pyrometallurgical processes batteries are directly fed into a smelting furnace. High temperatures and reducing agents melt and reduce the embedded metals, which form an alloy / matte that contains the batteries' copper, nickel and cobalt (see Figure 3-4). Aluminum, iron, impurities and some trace elements, including lithium, are forming a slag. The main challenges for pyrometallurgical treatment are linked to the batteries' fluorine and lithium contents, which can attack the furnace's refractory lining (Brückner et al. 2020). Fluorine, mostly converted to hydrofluoric acid (HF), can also corrode further parts of the (off-gas) system and create emission challenges (Brückner et al. 2020; Manhart et al. 2022). The LIB's organic contents (plastics, electrolytes, graphite) add considerable energy, which must be considered in the smelting process. The aluminum content of LIB also has implications as it increases the slags' viscosity (Brückner et al. 2020).

The produced alloy / matte is further treated with hydrometallurgical methods and electrowinning to recover the metals (Cu, Co, Ni) in a pure form. In general, the pyrometallurgical step of this type of lithium-ion battery recycling can be differentiated in two major types:

- Pyrometallurgy where lithium-ion batteries are co-processed with other furnace feeds
- Smelting processes fully dedicated to lithium-ion batteries

Co-processing is conducted by various smelters, including Nickelhütte Aue (Germany) and Glencore (smelting in Sudbury, Canada, hydrometallurgy in Kristiansand, Norway).

Dedicated ULIB smelting is, amongst others, conducted by Umicore (Belgium) and Ecomet (Italy). Both processes yield an alloy / matte, which is passed-on to hydrometallurgical treatment. These process sequences are quite efficient for the recovery of copper, cobalt and nickel with recovery rates of >95% in the pyrometallurgical processes and losses <5% in the hydrometallurgical processes (Brückner et al. 2020). Aluminum and lithium report to the slag. The LiO_2-concentration of slags from dedicated ULIB smelting is reported to be at around 8-10 %, which is similar to those of lithium-concentrates from spodumene mining. Subsequently, lithium (Li_2CO_3) can be recovered from such slags by milling, acid leaching, filtration and precipitation (Brückner et al. 2020). Li-concentration in slags from co-processed smelting is typically too low for recovery.

Figure 3-4: Alloy / matte as interim product of pyrometallurgical ULIB recycling

Source: Oeko-Institut

3.3.2 Mechanical Processing with subsequent metallurgical treatment of black mass

Mechanical processing of lithium-ion batteries (cells or modules) aims at separating the various materials (copper, aluminum, black mass) into defined output streams. While the copper and aluminum foils, as well as the ferrous metals fraction can be given to respective base metal processing / smelters, the separated powder ('black mass') with graphite, lithium, cobalt, nickel and manganese is given to specialized treatment for metal recovery.

Mechanical processing can be done with a variety of process sequences, some of them involving a thermal treatment step prior to separation. Thermal treatment (pyrolysis) aims at removing the electrolyte, solvents and other volatile substances and breaks down the batteries into their main metallic components, including the black mass (Velázquez-Martinez et al. 2019). These processes have the advantage that batteries lose their hazardous potential (fire and explosion risks) in this first treatment step under controlled conditions. To do so, the heat treatment is either conducted in an inert atmosphere (nitrogen, carbon dioxide or argon) or under vacuum. In addition, the inner lining of the oven must be made of corrosion resistant material and all extracted gases and particles captured in a well-designed and maintained off-gas treatment system (Manhart et al. 2022). The thermal removal of organic binders allows a quite clear separation of copper, aluminum and black mass, which is not possible with purely mechanical separation means (Brückner et al. 2020; Sojka et al. 2020). The downside of this process is its quite complex operation (batch-process), which needs high throughputs and economics of scale (Manhart et al. 2022).

To avoid the complexity of thermal treatment, various players start the recycling process with a mechanical shredding of batteries, followed by removal of volatile substances and automated sorting. This approach is also embraced by various small and medium-scale recyclers that aim at starting lithium-ion battery recycling at a limited scale and by supplying output fractions (copper, aluminum, black mass) to larger companies for further treatment.

To avoid fire and explosion risks in shredding, a dual strategy is commonly applied:

- Batteries are discharged prior to shredding[7];
- Shredding is conducted in inert conditions (e.g., nitrogen flooded shredding chamber).

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[7] Complete discharging of all batteries is often very difficult as inbuilt battery management systems prevent a complete discharge. Smaller batteries or cells without BMS are commonly discharged in a saltwater bath. This method also has limitations as the saltwater can corrode battery poles, which limits the dis¬charging rates.

The shredder output still contains volatile substances, which must be removed prior to further processing. This is done through heating and/or vacuum distillation where the evaporated compounds are captured. It is noteworthy that the shredding and this subsequent treatment generate highly corrosive and hazardous gases, which shall not be emitted to the workplace or the environment so that sound off-gas capture and treatment is a must (Sojka et al. 2020). The resulting mix of metals and black mass are separated in a sequence of mechanical steps. A third option is the shredding in water (alkaline pH). This option is used by the Canadian company Li-cycle in various of their “spoke” operations supplying retrieved black mass to one of their hubs, which, however, are not yet in operation (Li-Cycle 2022). Such wet shredding yields a moist black mass, which is likely limiting off-taker possibilities for this material. All shredding operations also yield a plastic output fraction suitable for energy recovery.

The black mass of all mechanical operation is passed-on to further processing. While the black mass can be treated in pyrometallurgic processes (see section 3.3.1), many operators apply hydro-metallurgical means to recover cobalt and nickel. Also, lithium can be recovered in the final stages of hydrometallurgical processing (e.g. in the form of Li_2CO_3), but process optimization is quite challenging (Allred 2021; Velázquez-Martinez et al. 2019). Hydrometallurgical methods also allow the recovery of manganese and graphite. Nevertheless, the complexity of involved processes is high, and recovery is not yet practiced at industrial scale and might conflict with high recovery rates for other metals (Brückner et al. 2020; Sojka et al. 2020).

3.3.3 Direct recycling

Direct recycling of ULIB aims at recovering cathode and anode material (and potentially also electrolyte) in a form they can be directly reapplied in lithium-ion battery production. Related approaches have been successfully tested on a laboratory scale[8] and it is hoped that such pathways may save energy and greenhouse gas emissions compared to the more established recycling pathways described in sections 3.3.1 and 3.3.2 (Zachary J. Baum et al. 2022). Direct recycling requires an input stream of batteries with identical cell chemistry and ideally uniform battery designs. While different battery designs may be tolerated but would be associated with additional efforts and costs for battery dismantling, diverging cell chemistries would (if treated in the same batch) cause mixed material outputs unsuitable for direct use in battery production.

[8] Research regarding direct recycling is inter alia conducted by the Faraday institution in the United Kingdom: https://www.faraday.ac.uk/research/lithium-ion/recycle-reuse/

Used and end-of-life batteries have a broad variety of shapes and chemistries and usually come as a mix to recyclers. Direct recycling is therefore not a realistic option in most cases but has a role in the recycling of battery production waste (pre-consumer recycling) and may be feasible and viable in cases of a steady incoming flow of uniform battery types and designs. This latter approach is followed by the Swiss electric vehicle company Kyburz that developed a direct recycling process for the LFP-cells used in their vehicles (Kyburz 2022).

A comparative overview of the (dis)advantages of the described recycling options can be found in Table 3-1.

Table 3-1: Overview of different ULIB recycling options

		Mechanical Processing + Metallurgy		
	Pyrometallurgy	**Large scale operations including thermal treatment**	**Small(er) scale operations without prior thermal treatment**	**Direct Recycling**
Advantages	▪ Efficient to recover copper, cobalt and nickel.	▪ If mechanical processing is combined with thermal treatment, LIBs lose their hazardous potential (fire and explosion risk). ▪ Thermal removal of binder allows clear separation of copper, aluminium and black mass.	▪ Complexity of the process is reduced without thermal treatment	▪ Saves energy and GHG emissions.
Disadvantages	▪ Aluminium and lithium are in the slag, lithium can only be recovered from dedicated LIB smelting, concentrations in slag from co-processing too low; aluminium is lost. ▪ Fluorine and lithium have corrosive properties; especially fluorine emissions need sound handling otherwise risk of corrosion of plant and contamination.	▪ Quite complex process which needs high throughputs and economics of scale.	▪ Only mechanical treatment does not allow clear separation of fractions. ▪ Shredding and subsequent treatment generate highly corrosive and hazardous gases; health and environmental risk if no sound off-gas treatment.	▪ Requires input stream with identical cell chemistry and ideally uniform battery designs, ▪ Currently limited to pilots and to the recycling of battery production waste (pre-consumer recycling).

Source: Own compilation

3.4 Regulatory frameworks enabling reuse & recycling of ULIB

Lithium-ion battery cathode materials are very diverse, and there are various LIB sub-types as e.g., lithium-iron-phosphate, lithium-nickel-manganese-cobalt-oxide, lithium-nickel-cobalt-aluminum-oxide and lithium-cobalt-oxide (see Table 1-1). Considering the current recycling technologies and raw material prices, the cobalt and nickel contents widely determine the material value of the battery, as lithium is not recovered in many processes yet (see section 3.3). For LIB with low cobalt and nickel contents, the material value is not yet high enough to cover the costs of recycling, although this could change in the future depending on raw material prices and technological development. In general, treatment costs are substantial in all practiced recycling approaches and lead to situations in where many recyclers charge gate fees for accepting certain types of ULIB for recycling. Growing end-of-life battery volumes are expected to allow economies of scale in battery recycling, which will likely reduce treatment costs in the future. Nevertheless, net-costs are believed to persist for LFP batteries (Brückner et al. 2020).

Therefore, not only available recycling techniques, but also regulatory frameworks are decisive parameters for ULIB recycling. The following sections present the regulatory landscape which frame reuse and recycling of lithium-ion batteries in three different jurisdictions. China is the country with the worldwide largest market share in used lithium-ion batteries recycling, and besides Europe, it is the jurisdiction with the most advanced regulatory framework (Obaya and Céspedes 2021). The German framework for EoL battery management was established more than three decades ago and has been further developed since then, whereas the extensively revised European legislation on batteries and waste batteries has been recently updated and addresses the latest developments along the battery value chain.

The following sections provide a short overview of the selected regulatory frameworks.

3.4.1 China´s regulatory framework for battery reuse and recycling

There has been a sharp increase of lithium-ion battery usage in China over the last years and the widespread and early use of electric vehicles currently results in significant amounts of comparably large LIB in need for sound end-of-life (EoL) management. As a result, the regulatory framework for EoL battery management has been complemented and further developed over the last years, with a specific focus on repurposing and recycling of ULIB coming from electric vehicles (Hampel 2022).

Development of the regulatory framework

In the beginning, the Chinese regulatory framework addressed waste batteries in the *Law on the Prevention and Control of Solid Waste Pollution (1995)* among other solid waste streams and requested a separate recycling of batteries. The following regulations addressing waste batteries merely focused on the proper EoL management of lead-acid batteries (Neumann et al. 2022).

Nevertheless, the constantly growing number of used LIB , and especially the deployment of electric vehicles, resulted in LIB-specific regulations from 2015 onwards (Bird et al. 2022). Since then, sound management of LIB gained increasing importance and plays an important role in various Chinese battery legislations. Some important examples are (Bird et al. 2022):

- Policy on Pollution Prevention Techniques of Waste Batteries (2016)
- The Implementation Plan of the Extended Producer Responsibility System (2016)
- Specifications for the safety measures, procedures, storage and management of vehicle batteries (2017)
- Standardizations for battery cells, modules and packs in order to facilitate recycling (2017)

The relevant regulations include recycling targets for major waste products, including LIB, of 40% by 2020 and 50% for 2025 (Neumann et al. 2022). Furthermore, there are mandatory material recovery rates for recyclers of electric vehicles for various raw materials typically contained in ULIB. Requested recovery rates address the composites of nickel, cobalt and manganese, as well as a composite recovery rate for rare earth elements and other metals of more than 95 % each. A lithium-ion recovery rate minimum 85% is requested (See Table 3-2).

Table 3-2: Mandatory material recovery rates for EV battery recycling in China

Raw material	Material recovery rate[9]
Composite recovery rate of nickel, cobalt and manganese	≥ 98%
Lithium-ion recovery rate	≥ 85%
Composite recovery rate of rare earth elements and other metals	≥ 97%

Source: (Wenbo Li et al. 2021)

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[9] The ambition level of the set targets might vary based on the definition of recovery used in this context. If e.g. the use of smelting slag in road construction is accounted for as recovery, material recovery rates might be easier to reach. The EU legislation differentiates between recycling and recovery targets (see section 3.4.3).

The responsibility for EoL battery management is legally assigned to the producers. Although Extended Producer Responsibility was not officially introduced before 2016, already the preceding regulation made battery manufacturers responsible for collection and labelling of waste batteries. Once the implementation plan of the extended producer responsibility system was enacted in 2016, battery producers were made responsible for EoL management beyond battery collection. The EPR regulation was complemented by EV manufacturers-specific requirements in 2018, making EV manufacturers responsible for setting up collection and recycling facilities for spent batteries. Furthermore, EV producers were made responsible for establishing a maintenance service network which allows repair and exchange of old batteries (Bej et al. 2022).

In order to support producers with the assigned responsibility, and to channel ULIB to sound recycling facilities, the Chinese government established a whitelist for lithium-ion batteries recyclers fulfilling Standard Requirements for the Comprehensive Utilization of Decommissioned NEV Power Batteries (Bej et al. 2022). Whereas in the beginning only five facilities were listed, the responsible Ministry of Industry and Information Technology (MIIT) added more facilities in various updates of the list (Hampel 2022).

In addition to the regulations addressing ULIB recycling, the responsible Chinese Ministries jointly issued measures to promote “downcycling” of ULIB. The measures published in 2021 aim to facilitate repurposing of electric vehicle batteries for second-life applications as energy storage or backup power supply. To ensure safe operation the measures are accompanied by industry standards which have to be complied with (Kenji 2022).

Current challenges

Besides the above-described extensive regulatory framework, it is reported that there are significant challenges to ensure (EV) ULIB are recycled according to the national standards in place (Wenbo Li et al. 2021). As for many other waste streams, sub-standard recycling can - with a narrowly defined economic scope - help reduce costs for some individual players in the management chain. Such economic advantages usually go hand in hand with substantial negative side effects (e.g., pollution) affecting other players such as nearby communities and the wider society.

If technical minimum standards are not in place and/or enforced, then it will be very challenging for facilities that follow good practices to compete with sub-standard recyclers.

Furthermore, low collection rates of ULIB have been identified as one main challenge. Although there are detailed and ambitious material recovery rates for raw materials in EV batteries for each individual battery recycler (see Table 3-2), non-compliance for the collection targets of ULIB from EV have been identified as one obstacle to upscaling of ULIB recycling in China (Wenbo Li et al. 2021).

3.4.2 The German Battery Act[10]

The German Battery Act (BattG) regulates the distribution, take-back and environmentally sound end-of-life management of batteries and accumulators within Germany. It was commissioned in 2009 and translates the EU Directive 2006/66/EC into the national law. The preceding Battery Regulation (BattV) was already commissioned in 1998. It aimed to reduce the input of hazardous materials in waste from batteries and contained only few requirements regarding the EoL management as collection of batteries (BattV 1998).

Over the years legislative amendments and practical experiences allowed an iterative development of today´s battery take-back systems. The latest update of the Battery Act in 2020 comprised increased minimum collection rates, included additional requirements for the calculation of collection rates, and a requirement that makes producers of automotive and industrial batteries financially and organizationally responsible for the collection and recovery of batteries brought into the market (IHK Karlsruhe 2020; Bej et al. 2022).

This currently valid framework will be overruled as soon as the EU Battery Regulation comes into force[11] (see section 3.4.3). Nevertheless, its current constitution and practical experiences from previous years still allow to draw relevant conclusions.

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[10] Some sections of the following text are taken from the author´s so far unpublished report “Developing a regulatory framework for Extended Producer Responsibility and take-back scheme for batteries in Ethiopia” n.d.

[11] Whereas an EU directive sets goals for the member states which need to be translated into national law to become applicable, EU regulations are laws that apply directly ((Citizens Information 2022).

Scope & requirements

As stated above, the German Battery Act translates the EU Battery Directive into national law. Therefore, its scope comprises the same three battery categories also used in the EU Directive: (1) portable (2) automotive and (3) industrial batteries. In line with the EU battery directive, it assigns:

- The responsibility of producers of batteries to register before batteries are brought into the market (Article 4)
- The responsibility of producers to take waste batteries from distributors and voluntary collection points back free of charge (Article 5)
- The responsibility of distributors to take back waste batteries from the end user free of charge and to hand over collected waste portable batteries to a take-back system (Article 9)
- The responsibility that all collected and identifiable waste batteries are to be treated according to the state of the art and materials are to be recovered (Article 14)
- Beyond to the predefined requirements from the EU Battery Directive, the German Battery Act complements the following requirements:
- The responsibility of producers to take back also industrial batteries (Article 8)
- The responsibility of distributors who supply automotive batteries to end-users to charge a refundable deposit of €7.50 including VAT per vehicle battery if the end-user does not return a waste automotive battery at the time of purchase of a new vehicle battery (Article 10)
- Since 2021 a minimum collection rate of 50% for portable waste batteries (Article 16)[12], which is 5% higher than the 45% currently requested in the EU Directive (European Commission 2006) and which is foreseen to remain constant until the end of 2023 in the Draft EU Battery Regulation (see section 3.4.3).
- An ecological design of fees (eco-modulation): Take-back systems are required to include monetary incentives to minimize the use of hazardous substance for production of portable batteries. They are further requested to differentiate fees according to the durability, reusability and recyclability of portable batteries (Article 7a).

Although the German Battery Act does not use the term Extended Producer Responsibility, the translation of predefined requirements of the EU Directive into German legislation inevitably leads to the set-up of an EPR system for batteries (see section 3.4.4 for further information on EPR). In this context it describes an administrative framework of the battery EPR system in Germany, leaving the design of take-back mechanisms and the details of practical implementation to be developed by the producers and distributors (or their authorized representatives).

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[12] The minimum collection rate requested in the BattG for portable batteries increased over time: 35% till 2012, 40% till 2015, 45% till 2016, 50% since 2021

In order to monitor the effectiveness of take-back schemes, Article 15 includes requirements how the weight of collected batteries shall be documented and reported to the competent authority. To ensure enforcement of the EPR system, this control mechanism is complemented by Article 29 which specifies violations against the Battery Act and possible fines.

Impact of the regulatory framework on battery collection rates

As the German Battery Act was preceded by a German Battery Regulation, at the time of its commission there were already three take-back schemes actively operating in Germany. Due to their practical experiences and established processes the collection rate in 2009 - the first year of commission - was almost 10 % higher than the requested 35% (UBA 2011). In 2019 the collection rate increased to 52.2% but decreased the following year to 45.6% (UBA 2022)[13]. In 2021 the requested minimum collection rate of 50% was not met, and only 48,2% of portable batteries were collected (see Table 3-3).

Table 3-3: Development of requested and actual collection rates of waste portable batteries in Germany

Year	Minimum collection rate requested in the Battery Act	Actual collection rate of portable batteries
2009	35 %	44.4 %
2019	45 %	52.2 %
2020	45 %	45.6 %
2021	50 %	48,2 %

Source: Own compilation based on (UBA 2011) and (UBA 2022)

The numbers indicate that collection rates were already quite high at the time the Battery Act was introduced in 2009. A lack of continuously increasing minimum requirements allowed practical collection rates to widely stagnate over the last decade.

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[13] The declining collection rate in 2020 was inter alia based on a 20% increase of battery volumes placed on the market, which was not complemented by the necessary larger quantity of collected waste batteries.

3.4.3 The EU Batteries Regulation

Until 2023, EU regulations relevant for batteries included the Battery Directive (Directive 2006/66/EC) and the Waste Electrical and Electronic Equipment (WEEE) Directive (Directive 2012/19/EU) (Neumann et al. 2022). In order to adapt the legislative framework to current developments and to harmonize the EU-wide handling of batteries, the legislative framework was amended with the new EU Battery Regulation (EU) 2023/1542 adopted by the European Parliament and the Council in 2023. The initial proposal published in 2020, was subject to extensive discussion, and in December 2022 the EU Commission, Council and Parliament announced to have reached provisional agreement on the regulation. The final text of this regulation concerning batteries and waste batteries was published in July 2023 (European Parliament; Council of the European Union 2023) amending Directive 2008/98/EC and Regulation (EU)2019/1020 and repealing the Batteries Directive (2006/66/EC).

The new EU Battery Regulation contains an extensive set of requirements applicable for batteries placed on the European market, and for their end-of-life management.

New batteries will have to contain certain **shares of recycled raw materials** (Article 8). For those batteries containing cobalt, lead, lithium or nickel, a material specific recycled content rate will become mandatory. The recycled content may come from (1) battery manufacturing waste or (2) post-consumer waste. Article 8 defines an initial phase where the recycled content has only to be documented. Moreover, this article defines mandatory minimum values to be introduced and increased over the years. As can be seen in Table 3-4, recycled percentages between 6 - 16 % are indicated as a first step for those raw material relevant for lithium-ion batteries[14]. Compared to the 2020 published regulation draft of the Commission, in the final text of the Regulation the minimum percentages for cobalt, lithium and nickel were increased, as now battery manufacturing waste, and not only post-consumer waste, accounts as recycled content (European Parliament; Council of the European Union 2023).

After a few years requested percentages relevant for lithium-ion batteries will be increased to 12 - 26 %. The calculation and verification of compliance with the requested shares will follow a methodology yet to be developed by the European Commission.

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[14] Due to their intrinsic material value and well-established recycling techniques, the great majority of lead-acid batteries is already recycled in most countries and the recovered lead inter alia used to produce new batteries.

Table 3-4: Minimum content of recycled raw materials for new batteries placed on the European market according to (EU) 2023/1542

Minimum recycled content	Batteries in scope
From 18 August 2031	
▪ 16% cobalt ▪ 85% lead ▪ 6% lithium ▪ 6% nickel	Industrial, electric vehicle and SLI batteries
From 18 August 2036	
▪ 26% cobalt ▪ 85% lead ▪ 12% lithium ▪ 15% nickel	Light means of transport, industrial, electric vehicle and SLI batteries

Source: European Parliament; Council of the European Union (2023)

The minimum content does not apply to reused, repurposed or remanufactured batteries that had already been placed on the market before. The minimum thresholds are planned to be reviewed few years after the regulation has comes into force. Targets might be adapted (in both directions) and further raw materials might be added. The information of the recycled content of batteries must be made accessible among other information via an QR code on the battery (Article 13).

The requirements regarding a defined minimum share of secondary raw materials are complemented by **supply chain due diligence** for primary raw materials (Chapter VII: Articles 47-53). The final requirements mandate that operators putting new batteries onto the market shall be assigned with due diligence requirements. Batteries intended for reuse and repurposing are excluded from this obligation.

In order to reduce the amount of waste batteries turning into waste, the Regulation contains specific **performance and durability** requirements for portable batteries of general use (Article 9) and for light means of transport (LMT) batteries, rechargeable industrial batteries and electric vehicle batteries (Article 10).

The Regulation also sets important prerequisites for the **reuse and repurposing** of batteries (Article 14). It requests information on the state of health and expected lifetime of batteries to be made accessible to the buyer of the battery. The requirements of this article indicate that from August 2024 battery management systems shall contain up-to-date data on parameters relevant for determining the state of health and expected remaining lifetime of batteries, indicating its capability for further use. These requirements are intended to apply to light means of transport and electric vehicle batteries, as well as batteries used in stationary energy storage.

The regulation contains numerous requirements regarding the management of waste batteries, including the assignment of responsibilities and specific targets for collection and treatment (Chapter VIII). A strong focus is set on the implementation of **Extended Producer Responsibility** (Article 56) and mostly encompasses requirements already in place under national legislation in each member state The most relevant requirements in this context are:

Article 55: EU "member states shall set up a register of producers which shall serve to monitor compliance of producers with the requirements [...]". Producers shall be obliged to register - either directly or through a Producer Responsibility Organization (PRO). The Article also specifies the information required for registration with a competent authority.

Article 56: "for batteries that they make available on the market for the first time within the territory of a Member State. [...]" This means that producers are obliged to organize and promote separate collection of waste batteries (including subsequent transport and management), provide information on batteries made available on the market and those collected and managed, and finance all these activities. These obligations may either be fulfilled individually, or collectively through a PRO.

The EU Battery Regulation also specifies all relevant administrative procedures for implementing the EPR systems, including obligations for members states, competent authorities, producers, distributors, end users and treatment facilities.

Either producers or appointed Producer Responsible Organizations acting on their behalf are responsible to reach minimum **collection rates** for waste portable batteries (Article 59). The minimum rates foresee a collection rate of 45% by end of 2023, and an increase up to 65% after six, and up to 70 % after eight years (see Table 3-5).

Table 3-5: Collection rates requested for waste portable batteries in (EU) 2023/1542

Collection rate	Timeline
45 %	by 31 December 2023
63 %	by 31 December 2027
73 %	by 31 December 2030

Source: Own compilation based on (European Parliament; Council of the European Union 2023)

Collected waste batteries shall not be disposed of or be treated in an energy recovery operation (Article 70), instead all collected waste batteries shall undergo preparation for reuse, repurposing or recycling (Article 71).

In order to support higher collection rates of portable batteries over time, requirements regarding the **removability and replaceability** by end-users are foreseen (Article 11). Removability shall be possible with the use of commercially available tools. Specialized tools may only be needed if they are provided free of charge with the product.

Recycling efficiencies and material recovery targets are specified in Parts B and C of Annex XII. The regulation imposes weight-based recycling efficiencies for all types of batteries. Table 3-6 shows the values discussed for lithium-based batteries.

Table 3-6: Requested recycling efficiency by average weight of lithium-based batteries[15] in (EU) 2023/1542

Recycling efficiency	
65 %	No later than 31 December 2025
70 %	No later than 31 December 2030

Source: Own compilation based on (European Parliament; Council of the European Union 2023)

Even more specific are the material recovery rates, which give fixed percentages of the contained raw materials which will have to be recovered in the future. The figures indicated in Part C of the regulation can be found in Table 3-7.

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[15] The battery regulation does also contain recycling efficiencies for lead-acid, nickel-cadmium and other waste batteries.

Table 3-7: Requested material recovery rates in (EU) 2023/1542

Material recovery	
▪ 90 % for cobalt, copper, lead, nickel ▪ 50 % of lithium	No later than 31 December 2027
▪ 95 % for cobalt, copper, lead, nickel ▪ 80 % of lithium	No later than 31 December 2031

Source: European Parliament; Council of the European Union (2023)

As with current technologies lithium is only recovered in some of the existing recycling facilities, the foreseen percentages of 50% or even 80% would put a lot of pressure on systematically expanding such approaches.

The new EU Battery Regulation entered into force on the 17th of August of 2023. The material specific recovery rates, and the mandatory use of recycled raw materials in new batteries mandated in the Regulation are expected to have an important impact on the development of lithium-ion battery recycling in the European Union. Additionally, the Regulation sets favorable framework conditions for reuse and repurposing activities for batteries on the European market.

All in all, the three regulatory frameworks provide a good overview of political instruments and specific collection and recycling requirements, which can be used to support and enable lithium-ion battery reuse and recycling. As all three selected frameworks put a strong emphasis on the environmental policy approach Extended Producer Responsibility (EPR), the following chapter will provide a brief overview of the concept and possible organizational set-ups.

3.4.4 The role of Extended Producer Responsibility systems

Extended Producer Responsibility (EPR) extends a producer´s[16] responsibility to the post-consumer phase of a product´s life cycle (see Figure 3-5).

Figure 3-5: The concept of Extended Producer Responsibility

Source: Oeko-Institut

Responsibility can be economic and / or physical and can be placed fully or partially on the producer (OECD 2022). “Physical responsibility refers to ensuring the treatment of waste products, including collection, transport, sorting, reuse, recycling, and disposal [...]. The financial responsibility relates to the financing of the aforementioned activities and allows producers to internalize the costs of waste treatment and incorporate them into their prices.” (Neumann et al. 2022).

Physical responsibility, including the compliance with minimum collection rates of waste batteries, can be fulfilled individually, and each producer can build up an its collection and end-of-life management system (see Figure 3-6).

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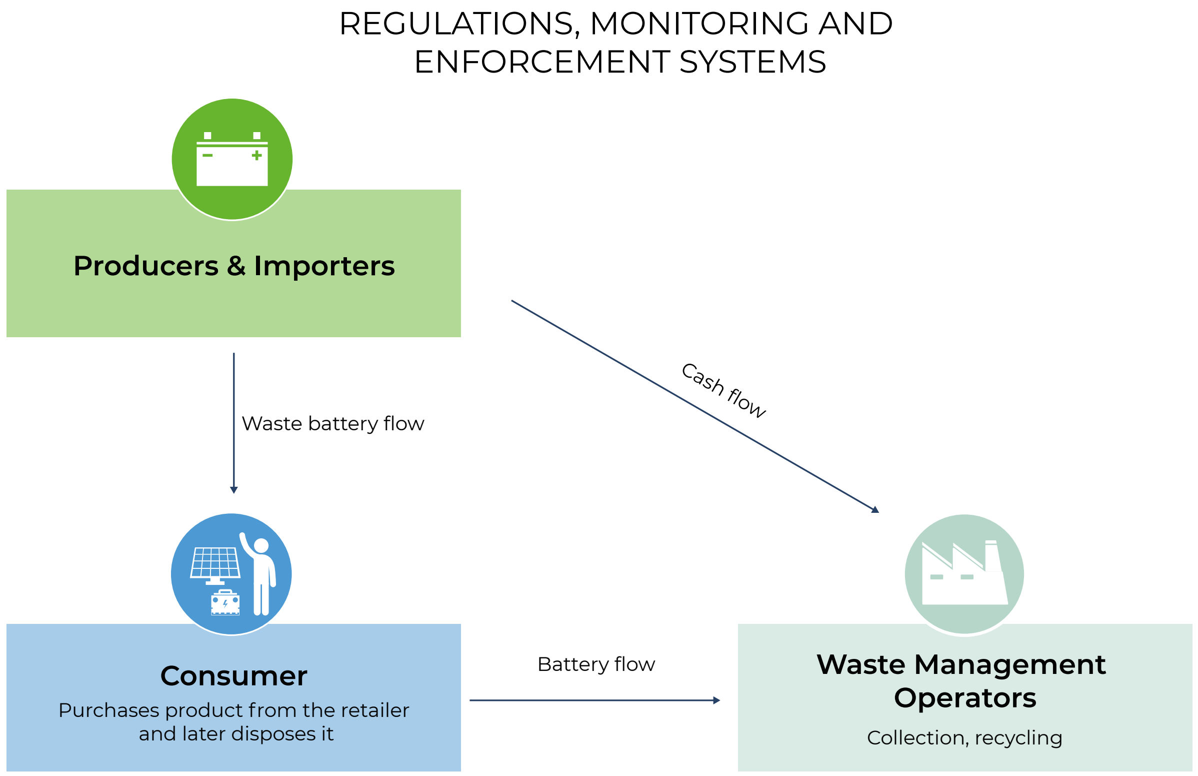
[16] In order to develop effective EPR schemes, the term “producer” needs a clear definition. Normally it comprises those stakeholders, which first placed a product onto the respective market. This might be manufacturers or importers.

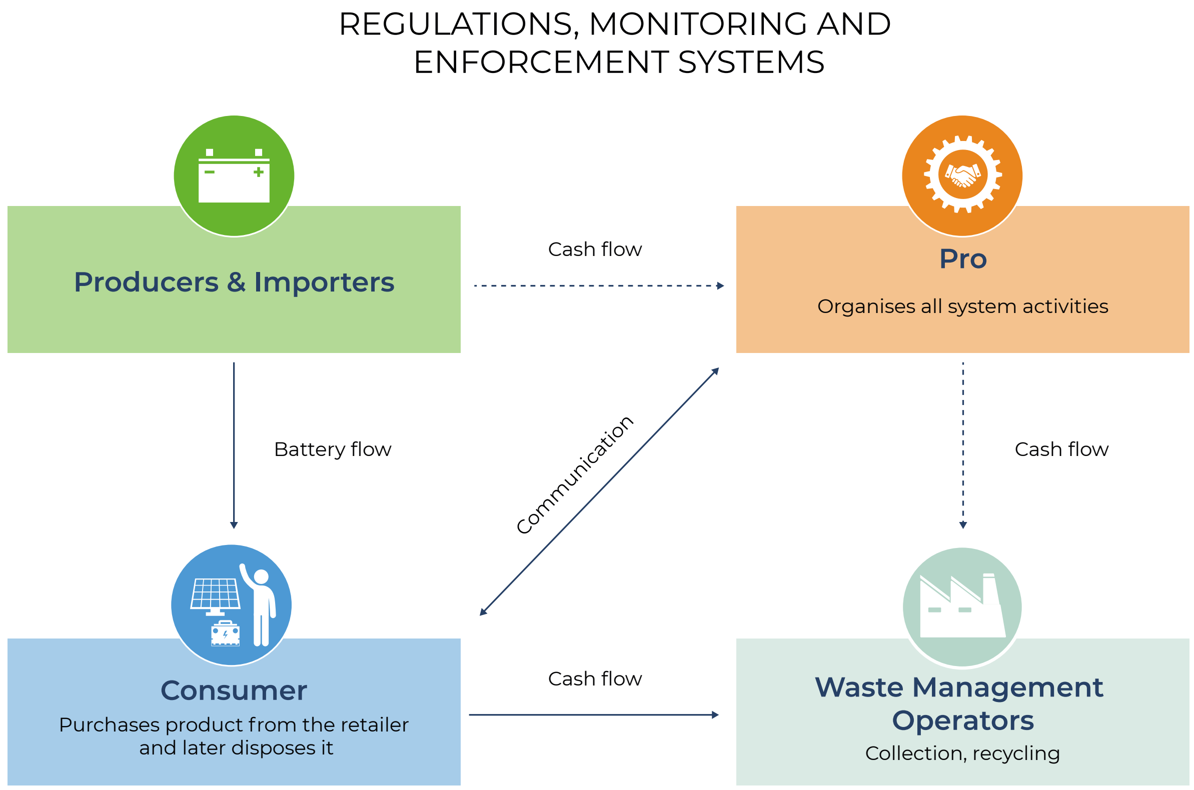
Figure 3-6: Individual compliance with physical responsibility for waste batteries



Source: Adaptation of (PREVENT Waste Alliance 2020)

Alternatively, responsibility can be fulfilled collectively. In the latter case, various producers assign a Producer Responsibility Organization (PRO) to conduct the task of collection and end-of-life management on their behalf (see Figure 3-7).

Figure 3-7: Collective compliance with physical responsibility for waste batteries involving a Producer Responsibility Organization



Source: Adaptation of (PREVENT Waste Alliance 2020)

In this case, producers pay a PRO to take over their (extended) responsibility for sound EoL management. The PRO is then responsible to:

- Register producers which are members of the PRO and their product (battery)volumes brought onto the market;
- Take over responsibilities for implementing EPR requirements e.g., ensuring to meet minimum collection rates and sound end-of-life management of the collected batteries, or conducting public awareness campaigns for consumers;
- Coordinate and monitor the implementation of EPR-requirements (e.g., by assigning waste collectors and recyclers);
- Document efforts and provide transparent documentation to the responsible authority.

By making sound end-of-life management of waste batteries mandatory for producers, EPR can be used to ensure the recycling of all sub-types of ULIB (see economic challenges for recycling of certain sub-types in section 3.1). Overall, EPR was found to play an important role in making ULIB recycling effective (Bird et al. 2022; Neumann et al. 2022).

4. Assessment of ULIB reuse, repurposing and recycling in Latin America and the Caribbean

4.1 Regional overview

In Latin America and the Caribbean (LAC), ULIB recycling and reuse are currently at an early stage. The volumes of LIB in the market continue to increase, resulting from established and new applications such as E-mobility. Meanwhile, neither the regulatory frameworks nor the capacities and management infrastructure have evolved at the pace of the battery volumes reaching end-of-life. A general awareness about the need for EoL solutions for this growing waste stream has only become visible in recent years but this has mainly been linked to the global demand for lithium and the attention given to the region in terms of lithium reserves. Although many countries already have regulations for the management of hazardous waste and Waste Electrical and Electronic Equipment (WEEE), only few of these address batteries or ULIB as a specific waste stream in focus.

At present a major share of ULIB is subject to unsound or no management in most LAC countries. This is the result of the absence of dedicated regulations and operational EPR systems, as well as missing ULIB collection and the lack of recycling infrastructure. In most countries battery EoL management is still covered by broader solid waste management regimes. This is not particularly encouraging in a region where only 55% of solid waste is properly managed (Obaya and Céspedes 2021). For ULIB resulting from WEEE management activities (e.g., disassembly for pre-treatment) and post-consumer programs, some authorized operators used to export them for treatment overseas. However, due to fire and safety risks during storage and transport, ULIB are subject to various international and national regulations such the Basel convention which restrict the transboundary movement of hazardous waste (see section 3.1). In order to enable the export of used LIB to other countries with recycling capacities (EU, North America, Asia), WEEE management operators must prepare and comply with a series of formal and technical requirements. Many local waste management operators reported to not have the legal capacities to apply for the required permits and documentation.

In terms of infrastructure, only few countries in the LAC region currently have companies performing on-site EoL management of LIB. These companies are working to scale their technology and expand their capacities, as well as trying to collaborate in exchanging experiences to overcome legal and bureaucratic hurdles. Meanwhile, the first foreign ULIB-recycling investment projects have been announced for the region for the coming years. Furthermore, a couple of start-ups and national actors are currently developing business models for ULIB reuse or repurposing applications.

For the study, a first regional screening was conducted to develop a general overview of the regional ULIB recycling and reuse practices, but also further aspects (regulatory framework, market develop¬ments) that are important for the selection of more detailed case studies. The regional screening included the following criteria:

- Existing regulatory frameworks addressing EoL management of LIB,
- Existing EPR schemes for batteries,
- Existing or planned ULIB recycling infrastructure,
- Projected EoL management needs for LIB, namely E-mobility targets and rural/off-grid electrification strategies[17].

It is worth mentioning that for the purpose of the case studies, recycling infrastructure is being referred to as processing only until the stage of separation of fractions through electromechanical processes, and not until the stage of hydro- or pyrometallurgy, given that the latter is still inexistent in the region.

Table 4-1 presents an overview matrix of selected Latin American countries with regards to the selection criteria listed above. In general, South America is where the most progress in terms of regulatory framework and development of capacities for EoL management of LIB were identified. Currently Colombia and Ecuador have regulations for the environmental sound management of batteries which also explicitly address ULIB. Bolivia, Perú and Colombia have established mandatory EPR schemes for collection of batteries (including ULIB). Meanwhile, Colombia, Chile and Brazil are the frontrunners for operational ULIB recycling infrastructure in the region. In the same countries, some initiatives and start-ups for repurposing of ULIB are already operating at small scales.

Mexico, the only Latin American country located in North America, is relevant due to the size of its market and the ambitious national targets for E-mobility which will translate into significant volumes of LIB requiring EoL management. In the Caribbean region as well as in Central America, little to no developments were found. Costa Rica is the only country with relevant developments in terms of regulatory framework, existing ULIB recycling infrastructure, and ambitious E-mobility plans.

Based on this preliminary findings, four countries were selected for in-depth case studies: Colombia, Costa Rica, Chile and Mexico. These countries represent relevant and interesting cases from different regions in LAC.

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[17] Ambitious e-mobility goals and / or national off-grid electrification strategies are most probably linked to growing volumes of EoL LIB in the future.

Table 4-1: Latin America overview matrix

Country	Population	Virgin lithium value chain	Lithium battery regulation	Mandatory EPR Scheme for batteries	Recycling infrastructure	Projected End-of-Life management needs for ULIB		
	World Bank (2021)			(excl. E-mobility batteries)	(Processing until stage of black mass production)	E-mobility targets		Off-grid decentralized renewable energy (2021)
	Million inhabitants	yes/no	- / + / ++*	no / in development / yes	- / + / ++ / +++**	Year	Target	Systems installed ***
Argentina	45.8	yes	-	in development	+	2030	4,500 E-buses in Buenos Aires	193
Bolivia	11.8	yes	+	yes	-	2030	20% of vehicle fleet is electric	n/d
Brasil	213.9	yes	+	no	++	2030	1,000 E-buses (conservative scenario)	269
Chile	19.2	yes	+	in development	++	2035	100% urban public transport is zero-emission	6,000
Colombia	52.3	no	++	yes	+++	2030	600,000 E-vehicles on Colombian roads	n/d
Costa Rica	5.1	no	+	in development	++	2030	8% of light vehicle fleet electric	2,000
Ecuador	17.9	no	++	no	-	2025	10,000 E-vehicles	n/d
El Salvador	6.5	no	-	no	-	n/d	n/d	38
Guatemala	17.1	no	-	no	-	2032	30% increase in E-vehicle sales	3,600

Country	Population	Virgin lithium value chain	Lithium battery regulation	Mandatory EPR Scheme for batteries	Recycling infrastructure	Projected End-of-Life management needs for ULIB		
	World Bank (2021)			(excl. E-mobility batteries)	(Processing until stage of black mass production)	E-mobility targets		Off-grid decentralized renewable energy (2021)
	Million inhabitants	yes/no	- / + / ++*	no / in development / yes	- / + / ++ / +++**	Year	Target	Systems installed ***
Honduras	10.1	no	-	in development	+	2030	50% urban public transport is electric	n/d
Jamaica	2.9	no	-	no	-	2030	16% share of electric public transport fleet	n/d
Mexico	130.3	no (but unexploited lithium reserves)	+	no	++	2030	800,000 E-vehicles	130,000
Panama	4.4	no	-	in development	+	2025	10% of vehicle fleet is electric	893
Peru	33.3	yes	+	yes	-	2032	6,700 E-buses and 171,000 E-cars	n/d
Uruguay	3.5	no	+	no	-	2035	100% electrified vehicle fleet	700

* '-' = no regulations, '+' = batteries included in waste management regulations, '++' = lithium battery-specific regulation

** '-' = none found, '+' = planned / pilot recycling plants, '++' = at least one recycling company doing treatment on-site, '+++'= more than one company doing treatment on-site

*** The sizes and capacities of the summarized systems vary and are not directly comparable between countries.

Source: Own compilation

4.2 Current practices and policies in selected countries

4.2.1 Colombia

Colombia is one of the countries in the region with the most progress in terms of reuse and recycling for ULIB. Besides, the country has one of the most advanced regulatory frameworks in Latin America for promoting collection and environmental sound management of EoL ULIB. In the following sections[18] the current state of ULIB reuse and recycling practices will be described covering different aspects: regulatory framework, existing infrastructure and capacities and national developments.

4.2.1.1 Policies, Regulations and EPR Schemes

In Colombia EoL battery management was first regulated by Resolution 1297 of 2010 of the Ministry of Environment. These regulations were the basis for the establishment of selective collection systems and environmentally sound management of waste portable batteries and accumu¬lators with the objective of preventing environmental degradation. The scope of application was defined for primary cells and primary batteries (including lithium-ion batteries) as well as Nickel-cadmium, Nickel-iron accumulators and spent electric accumulators. Before this resolution, almost all waste portable batteries were disposed of in landfills, open dumps or other unregulated areas (Ministerio de Ambiente, Vivienda y Desarrollo Territorial 2010).

As a result, the first collection and environmental management systems for batteries started to operate from 2011 onwards. Within the first six years, 31 collection systems were approved by the responsible authority, the National Environmental Licensing Authority (ANLA). In addition, more than 12,000 collection points were installed throughout the country (Ministerio de Ambiente y Desarrollo Sostenible 2017).

In 2017, after practical experiences with battery management systems had been collected for a few years, Resolution 2246 was passed to complement the 2010 Resolution 1297. It added a set of management indicators, allowed better monitoring and evaluation of the different collection and management systems.[19] Both resolutions applied to all producers[20] which market more than 3,000 or more batteries in the country. The product scope included primary and secondary portable batteries or accumulators. However, industrial and electric vehicle batteries were excluded from the early regulatory framework.

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[18] Some sections of the following text come from the author´s so far unpublished report “Developing a regulatory framework for Extended Producer Responsibility and take-back scheme for batteries in Ethiopia” n.d.

[19] These include indicators for collection and management, consumer information and awareness, increased geographic coverage, and direct consumer incentives. For example, the collection and management indicator is defined in this resolution as the ratio between the amount of waste batteries and accumulators collected and managed with respect to the target weight to be collected in the year of evaluation. The evaluation of the collection systems in terms of these indicators is obtained by adding the values achieved in each one, so that compliance is achieved with a minimum score.

[20] Producers are defined to include manufacturers, distributors and importers (Article 3, Res 1297).

In 2022, a new sole Regulatory Decree of the Environment and Sustainable Development Sector addresses WEEE, batteries and accumulators (Res 851 of 2022) was issued. As of 1st of January of 2023, the previous regulations for WEEE and battery collection were dero¬gated by Resolution 851.

This resolution sets national targets for the collection and long-term management of waste from electrical and electronic equipment (WEEE), based on the principle of Extended Producer Responsibility (see section 3.4.4) and taking into account the lifetime of each equipment (Ministerio de Ambiente y Desarrollo Sostenible 2022). The products in scope for this resolution are defined according to the tariff lines of imported goods. Lithium-ion batteries are included under the harmonized tariff schedule (HTS) code 8507.60.0000 (Annex 1 in Res 851 of 2022). In contrast to the previous resolutions, Res 851 includes some specific requirements for larger ULIB (industrial and vehicles). Among other dispositions, it makes the collection of ULIB from electric vehicles mandatory from 2024 onwards.

Overall, the Colombian regulatory framework makes Extended Producer Responsibility (EPR) an important instrument for waste battery management in the country. Although Resolutions 1297 and 2246 did not explicitly referred to EPR, their requirements led to the set-up of an EPR system for batteries. In contrast, the current Resolution 851 of 2022 uses the concept of Extended Producer Responsibility as guiding principle for defining national targets for collection and management of WEEE (including batteries and accumulators). Articles 6 and 11 detail the obligation for producers (importers and national manufacturers) of EEE and batteries of mass consumption to implement a collection and management system, either individually or collectively, which will be subjected to evaluation, approval and monitoring by the National Authority of Environmental Licenses. For producers of EEE and batteries for industrial use (which include batteries from electric vehicles) Res 851 requests to implement collection and management systems but these are not subjected to monitoring. Instead, producers of industrial batteries are requested to establish information channels for consumers about collection conditions at end-of-life.

Resolution 1297 introduced minimum collection rates for waste portable batteries, increasing from 4% in 2012 until 45% in 2022 (Ministerio de Ambiente, Vivienda y Desarrollo Territorial 2010). However, these targets were not achieved by major collection systems in the past (see Table 4-3). In the new resolution 851 of 2022, the mandatory collection rates for batteries and accumulators were reset starting from 37% in 2022 with a 1% increase until 45% in 2030. Starting 2024 R851 of 2022 also establishes mandatory collection rates for batteries from electric vehicles and other industrial batteries[21] starting at 0.5% of the quantities introduced to the market in 2024 and increasing to 65% in 2044 (see Table 4-2).

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[21] Res 851 of 2022 categorizes LIB (HS code 8507.60.0000 as identified in Annex I) used in Electric Vehicles as items of industrial use with long lifetime and therefore, targets for collection rates are differentiated from short lifetime batteries and accumulators. The same applies for LIB used in industrial applications such as stationary energy storage for photovoltaic systems.

Table 4-2: Collection rates for batteries and accumulators and lithium-ion batteries from electric vehicles in Colombia[22]

Evaluation year	Collection rate Lithium-ion Batteries and accumulators	Collection rate Industrial batteries and Electric vehicles	Base years for the calculation of the indicator
2022	37%	-	2021, 2020, 2019
2023	38%	0%	2022, 2021, 2020
2024	39%	0.5%	2023, 2022, 2021
2025	40%	1%	2024, 2023, 2022
2026	41%	2%	2025, 2024, 2023
2027	42%	4%	2026, 2025, 2024
2028	43%	6%	2027, 2026, 2025
2029	44%	9%	2028, 2026, 2025
2030	45%	12%	2029, 2028, 2027
2031	45%	15%	2030, 2029, 2028
2032	45%	19%	2031, 2030, 2029
2033	45%	23%	2032, 2031, 2030

Source: (Ministerio de Ambiente y Desarrollo Sostenible 2022)

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[22] Calculated on the basis of the total weight of EEE placed on the market annually; in this case, the average of the three base years indicated.

Furthermore, the current Colombian EPR system also has a strong focus on awareness-raising for end-consumers and geographical coverage of take-back schemes. In this context, established take-back schemes are evaluated based on a multi-criteria system. Each scheme should define a strategy for achieving a minimum score and should provide supporting information. This system includes five indicators:

- Collection and management
- Consumer information and awareness.
- Geographical coverage
- Applied research and experimental development in the use of waste
- Promotion of the circular economy

Producers (importers and national manufacturers) can meet the described responsibilities either individually or collectively (also see chapter 3.4.4).

In Colombia, there are currently three collective take-back schemes for waste portable batteries: Pilas con el ambiente, Recopila and ARBAM-(Motorola)[23]. In addition, there are 27 individual schemes registered.

Practice example 1: Pilas con el Ambiente

Legislative requirements are translated into action

Pilas con el Ambiente is one of the take-back schemes which is part of "Grupo Retorna" and one of the registered collective schemes with higher coverage in the country. Grupo Retorna is an environmental initiative made up of six post-consumer programs: Cierra el Ciclo, EcoCómputo, Pilas con el Ambiente, Red Verde, Recoenergy and Rueda Verde. Each program was established with the purpose of creating channels for recycling devices or objects that have completed their life cycle such as: household insecticide containers, computers and peripherals, used batteries, white goods, used lead-acid batteries and tires. The idea is to promote environmental awareness through recycling as a common goal of all Colombians. Pilas con el Ambiente is organized as a non-profit cooperation and represents some of the main distributors and importers of portable batteries in Colombia. It started to collect batteries in 2012 and has increased the collection rate to 20 % in 2021 (see Table 4-3).

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[23] Spanish acronym from "Acuerdo de recolección de baterías Motorola".

Table 4-3: Development of requested and actual collection rates of Pilas con el Ambiente

Year	Minimum collection rate requested in Res 1297	Actual collection rate of portable waste batteries
2012	4 %	1,9 %
2013	8 %	5,6 %
2014	12 %	6,7 %
2015	16 %	6,2 %
2016	20 %	7,6 %
2017	25 %	12,2 %
2018	30 %	18,8 %
2019	35 %	17,6 %
2020	35 %	17,6 %
2021	40 %	19,5 %

Source: Own compilation based on data provided by Pilas con el ambiente

Despite increasing collection rates over the years, the amount of collected batteries was not in line with mandatory minimum collection rates. From the perspective of Pilas con el Ambiente as EPR scheme main challenges encountered included:

- The competition between different take-back schemes; from practical experiences one joint collection system is expected to result in higher collection rates.
- Missing awareness and commitment of end-consumers to hand back waste portable batteries to designated collection points
- Missing support from national and local authorities for the development of necessary awareness-raising actions

Besides focusing on collection and awareness raising, since 2018 Pilas con el Ambiente also dedicated resources for the development of technology for the treatment of projected volumes of ULIB from mobility and has therefore contributed to upscaling capacities for reuse and repurposing of ULIB.

From 2023 onwards, the activities of Pilas con el ambiente will focus on adapting the current management system to meet the new requirements regarding larger LIB coming into force in 2024. For this, it is foreseen that Recoenergy, another PRO from Grupo Retorna, will step in as the responsible organization for the collection of ULIB from E-mobility. This PRO was until now in charge of the collection scheme for ULABs but will expand its scope to attend the growing volumes of EoL LIB in the automobile and transport sector.

4.2.1.2 Existing recycling infrastructure and reuse initiatives

In terms of LIB EoL management initiatives, Colombia has the most developments the region. As of today, the country has two active ULIB recycling plants in two of the main industrial regions. Altero, located in the vicinity of Medellín, and Innova Ambiental in the metropolitan region of Cali. Both companies apply small scale mechanical recycling processes to obtain separated metal and plastic fractions as well as black mass (also see chapter 3.3.2). The black mass is exported for further processing and valorization through cobalt or nickel recovery.

Two further companies were identified operating under business models dedicated to repurposing of ULIB, namely BatX and Recobatt. BatX offers energy storage services, integrating recycled and reused components in the design and manufacture of batteries. Recobatt is a recent initiative resulting from a strategic partnership between a national battery manufacturer (Tronex) and a WEEE and ULIB recycling company (Innova Ambiental). This company focuses on the development of second life applications derived from used LIB from electric mobility (see Practice example 2 for more information).

In the context of the activities of one of the EPR schemes, since 2022 a working group on circular economy solutions for lithium-ion batteries and other technologies was coordinated. This group includes representatives from producers, waste managers, PROs and sectorial actors. The activities in this group have focused on exchanging experiences about ongoing initiatives and possible technological solutions for EoL management of ULIB in Colombia. Moreover, it was reported from one of the experts participating the working group that legal, technical and economic obstacles for developing local models to recover the material flows resulting from ULIB precursors have been discussed and identified within the group.

Besides the private companies mentioned above, other members of the working group also have ongoing negotiations and agreements for cooperation with other regional actors (in Costa Rica, Chile and Brazil). These partnerships are oriented to complement competences at different stages of the recycling processes for ULIB, including supply agreements (black mass for cobalt recovery) or technology transfer. For example, in collaboration with a Chilean company, Gaia Vitare, a Colombian WEEE management operator, has established an ULIB shredding process with the objective of exporting black mass to Chile as precursors for Cobalt refining at Ecominería (see Practice example 5).

Practice example 2. Innova Ambiental & Recobatt

Integration of ULIB Repurposing and Recycling business models

Innova Ambiental is a company located in the vicinity of Cali, in Colombia. It was created in 2010 to supply services for hazardous waste management for the industrial sector (WEEE, luminaries). In 2018 as a response to the global problem of growing waste ULIB and the interest in the markets for critical materials such as Co and Ni, a new line for processing ULIB started being developed.

Innova Ambiental was licensed in 2020 to process secondary batteries. Initially, only Ni-Cd and NiMH were processed, but shortly after the scope was expanded also to lithium-ion batteries. The process is an electromechanical recycling in which batteries are separated in three stages:

1. Classification by chemical composition, battery type and battery condition
2. Two-stage shredding
3. Three -stage separation by magnets, particle size and density

The process has different variables that can be modified according to the chemistry of the batteries and the characteristics of the batch. Emissions control is ensured through central and local ventilation and extraction systems in the isolated operation areas for the line of ULIB processing. At its full capacity, this complex is designed to process 10 tons of batteries a day. Today, the company processes about 30 tons per month.

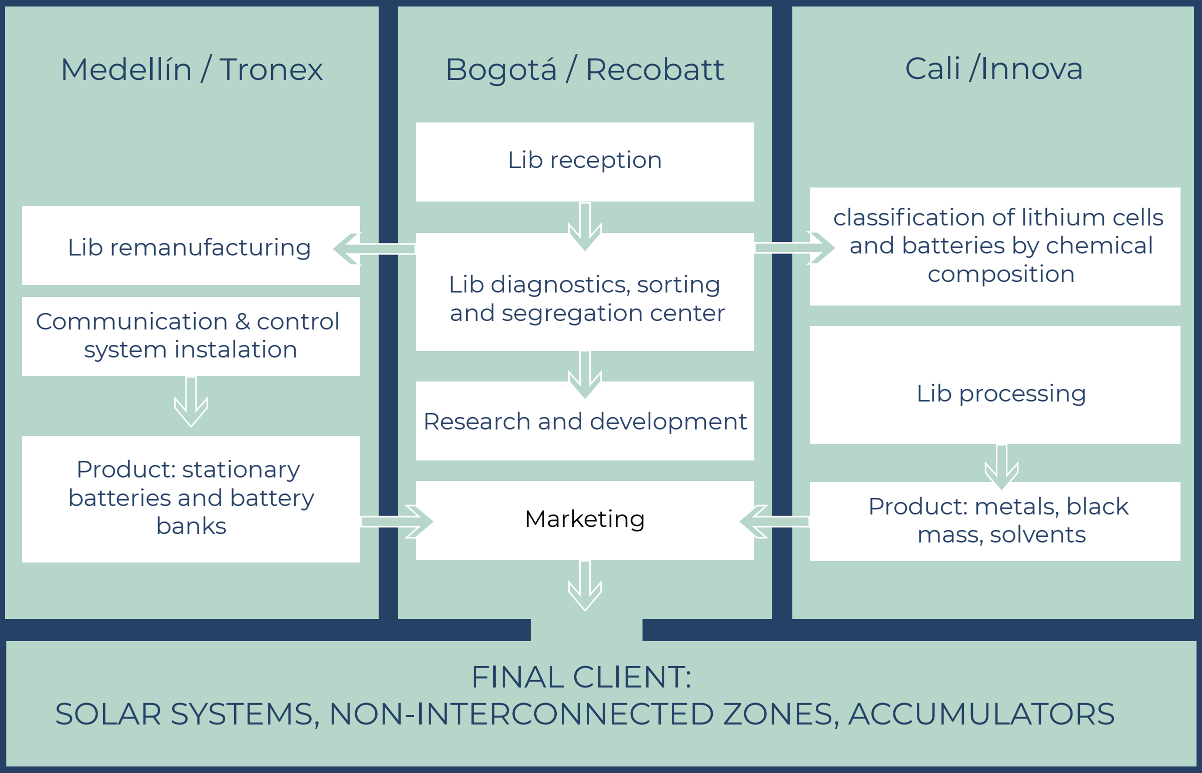
With increasing amounts of collected ULIB from resulting from electric mobility, Innova in partnership with **Tronex**, a Colombian manufacturer of alkaline (primary) batteries and founder of the collective take-back scheme “Recopila”, identified the need for developing additional solutions for reuse and repurposing of these type of batteries. As a result of an intensive research process, **Recobatt** was established as a circular economy business model for diagnosing, remanufacturing and valorization of batteries from electric mobility in second life applications. Recobatt operates as a complex of complementary services and processes to those already established in the portfolios of solutions from Innova and Tronex (see Figure 4-1).

The business model of Recobatt is designed to manage incoming ULIB from electromobility. Recobatt's process includes the classification and characterization of the electrochemistry of the batteries to determine their state of health and state of charge.

Depending on the initial diagnosis, disassembled modules will be shipped to Cali or Medellin for further processing. Functional modules will be remanufactured by Tronex Industrial and those classified as non-functional will be sent to Innova (Cali) for recycling. The batteries repurposed by Tronex are commercialized as second life solutions for backup and power compensation systems in applications that require a reliable, safe and uninterrupted power supply as well as temporary energy accumulators in solar or wind generation systems.

As the study was being conducted, Recobatt's facility in Bogotá was being built and the process was not fully scaled. However, Recobatt has been operating the facilities and infrastructure from its partner companies Innova and Tronex. This business model is projected to manage growing volumes of collected EoL batteries from electromobility in line with increasing collection targets set by Resolution 851 of 2022. The Colombian EPR system for batteries is currently not mandatory for electric vehicle batteries. For this reason, the volumes currently received are of a voluntary nature.

Figure 4-1: Integrated business models of ULIB repurposing and recycling in Colombia



Source: Recobatt 2023

Practice example 3: Altero

Modular and replicable ULIB recycling technology

Altero is a Colombian company working on recycling of ULIB. The process is a self-developed recycling technology, which integrates different systems for a safe and dry processing of battery waste, recovering high-value materials. The batteries are transformed through an electromechanical process that does not use chemical reagents and operates under inert atmosphere which neutralizes the batteries during shredding and further stages of the process. The gas mixture, pressures and remanence times according to each stage are the core of the patent (pending). The gas mixture allows shredding the batteries without prior discharge and controls the volatilization of the electrolyte.

The resulting materials are separated into three strategic products: precursor material for the manufacture of new batteries (black mass), copper/aluminum mixture, and a mixture of organic solvents and lithium salts (Electrolyte). Altero's technology is equipped to process all types of lithium-ion batteries, originating from cell phones, computers, electronic toys, electric mobility (with prior manual dismantling) and energy storage systems. The batteries are segregated and processed in batches according to chemical composition to ensure significant amounts of the desired minerals. Altero receives waste ULIB both from battery manufacturers as well as batteries collected by post-consumer programs (EPR schemes) and WEEE managers.

Altero’s plant is located in Guarne - Antioquia in the vicinity of Medellín. At its full capacity, this complex is designed to process 90 tons of batteries per month (~1,000 tons per year). Today, the company processes about 5 tons per month.

Figure 4-2: Modular ULIB recycling facility in Colombia

Source: Altero 2023

One of the main characteristics of this technology is the fact that the whole process is built into ship containers so that the system is isolated from soil and external atmosphere. Different process stages (preparation, shredding and storage) are placed in different containers and can be distri-buted according to area availability. This makes Altero’s technology an interesting modular solution which could eventually be replicated in other countries in need of ULIB EoL management capacities.

4.2.1.3 Relevant national developments

The National Strategy for Electric Mobility (2019) defines the objective of having 600,000 electric vehicles on Colombian roads by 2030, and deploy five charging stations in main urban areas by 2022 (Ministerio de Ambiente y Desarrollo Sostenible 2020). In addition, the country’s capital Bogotá is one of the cities in Latin America with the most progress in terms of electrification of its public transportation system. The ambitious targets set for 2022 were achieved and as of beginning 2023 Bogotá has now a total of operational 1,.485 E-buses. The city has also set minimum purchase requirement of 30% electric vehicles for public transportation by 2025 and 100% E-bus purchasing by 2035 (TUMI E-Bus Mission 2022b). Besides the capital, there are other cities in the country with likely ambitious goals and making fast progress in terms of electric public transport (TUMI E-Bus Mission 2022a; 2022c).

While these developments are very encouraging, there will be the time where E-buses and their batteries are worn down and must be decommissioned. E-buses are equipped with several hundred kilograms of batteries, which will be classified as hazardous waste at their end-of-life. Therefore, progress on this topic also indicate expected increased volumes of ULIB in need for EoL manage¬ment solutions at national level.

4.2.1.4 Country summary

Colombia has the strongest regulatory framework of the analyzed case studies as well as most developments in terms of reuse and recycling practices. There are many active stakeholders in comparison to other countries, both in ULIB recycling, as well as in ULIB repurposing. Nevertheless, the current recycling companies in the country operate way below their capacity, meaning that there is more potential beyond the volumes currently collected via EPR systems and commercial agreements with manufacturers.

4.2.2 Costa Rica

4.2.2.1 Policies, Regulations and EPR Schemes for LIB

The Law for Integral Waste Management (Asamblea Legislativa de la República de Costa Rica 2012) addresses EPR in Article 42, obliging producers and importers of goods whose waste is declared as 'special' (incl. LIB) to implement at least one of the following measures:

- Establish an effective program of recovery, reuse, recycling, energetic use or other means of valorization;
- Participate in a sectoral waste program for its integral management;
- Adopt a deposit, return and refund system in which the consumer, when acquiring the product, will leave a monetary amount in deposit that will be recovered with the return of the packaging or product;
- Develop products or use packaging that minimize the generation of waste and facilitate its recovery, or allow its disposal in the least harmful way for the environment; or
- Establish strategic alliances with the municipalities to improve the collection and integral waste management systems.

Decree N° 38272-S which regulates the declaration of special handling waste also mentions in Article 4 that producers or importers of such waste must offer options to ensure its recovery and thus reduce the volumes reaching final disposal sites (Presidencia de la República; Ministerio de Salud 2014). Annex I of this decree includes ULIB, among many other materials such as automobile tires, mattresses, and light bulbs (Presidencia de la República; Ministerio de Salud 2014)

Finally, Decree No. 35993-S on Regulation for the Integral Management of Electronic Waste, which includes LIB of portable computers, cellular phones and uninterruptible power supply units (UPS) in Annex I, addresses EPR in Article 12, by attributing producers responsibility throughout the entire life cycle of the product (Presidencia de la República; Ministerio de Salud; Ministerio de Ambiente, Energía y Telecomunicaciones 2010). This decree declared the creation of an executive committee[24], which currently functions as an advisory council coordinated by the Ministry of Health with various representatives from ministries, non-governmental organizations, academia and the private sector. The functions of this committee include defining, reviewing and publishing annual waste recovery goals and ensuring that producers comply with them (PREAL 2022).

Despite the existence of a regulatory framework for the treatment of batteries and WEEE, there has been no effective implementation of the mechanisms described in the legislation, nor has there been effective follow-up and control of those that have been implemented (Domenech Cots and Guillén Miranda 2021). The lack of mandatory collection and recovery goals means that neither the importers, distributors nor the brands or original manufacturers of the equipment are required to ensure adequate final disposal (Domenech Cots and Guillén Miranda 2021).

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[24] Comité Ejecutivo de Gestión Integral de Residuos Electrónicos - CEGIRE

Another mechanism which has not been implemented so far is the automation via software for the reporting of the companies that have EPR scheme. From the perspective of consulted stakeholders, the revision and results evaluation are questionable, slow, manual, and depends on only a few individuals. This is preventing the system from giving the necessary statistics in order to measure the effectiveness of the EPR. Also, stakeholders active in ULIB recycling in Costa Rica identified the lack of enforcement of the regulatory framework as one of the main obstacles. Interviewed experts evaluated the responsible Ministry of Health to lack resources for an effective follow up. This would lead to a lack of motivation for companies to comply with national laws. The absence of sanctions was confirmed by experts from different organizations as an obstacle for the registration of obliged parties in Costa Rica. Furthermore, it was said that the current legislation frames ULIB recycling as an opportunity for the generation of revenues. As a consequence, many municipalities did not foresee any budget for the sound EoL management of ULIB in their planning of activities. This led to the situation, in which collection was not mandatory for importers, and municipalities did not have any money budgeted for this task. This complements the findings of (Domenech Cots and Guillén Miranda 2021), who wrote that the main challenge for ULIB recycling operations in Costa Rica "is not the availability of LIB waste, which is expected to be sufficient, taking into account the possibility of integrating volumes generated in other countries in the region, but the implementation of a formal collection system for this type of waste, which will allow high percentages of coverage at the national level, and especially in Central America".

Some of the current shortcomings might be eliminated once the reform of the Law for Integrated Waste Management (Law 10031 of 2021) is enacted. This reform defined priority product categories for which EPR responsibilities will apply (Asamblea Legislativa de la República de Costa Rica 2021). At the moment it is missing an ordinance to become applicable, but when the respective ordinance is finalized, the law will no longer leave most EoL measures for batteries voluntary, but inter alia make the sound treatment of spent EV batteries mandatory in Costa Rica.

4.2.2.2 Existing recycling infrastructure and reuse initiatives

The Ministry of Health (MINSA) and the Ministry of Environment and Energy (MINAE) developed a roadmap for an efficient management of electric vehicle batteries in Costa Rica during the first half of 2022 (Urcuyo Solórzano et al. 2022), which included a diagnosis of the current state of the country in terms of infrastructure. Some of these results are extracted below:

As of February 28, 2022, 19 authorized waste managers registered for the management of LIB or similar batteries were detected (MINSA; MINAE 2022). It is important to mention that this could be exclusively lead acid battery managers. However, these enterprises have the potential (and initial infrastructure) to become ULIB managers. Almost all of them carry out collection, transport, and storage of waste, whereas nine carry out pre-treatment. Seven perform valorization activities, which are not specified, but could include reuse and/or recycling. 30% of these companies export the waste.

It was also found in the assessment that none of the above-mentioned enterprises perform any kind of valorization process on electric vehicle batteries, being most likely that these are exported. In the context of this study, it was found that in the meantime Fortech has started working with EV batteries as well. The company is not only engaged in the recycling of different kinds of ULIB, but is currently developing a reuse business model for used battery cells as well (see more information in Practice example 4). Another waste-managing company interviewed is Solirsa, and even though they do not recycle ULIB, they are interested in exploring the topic of ULIB repurposing.

Practice example 4: Fortech

Costa Rican expertise on ULIB recycling as regional knowledge hub

The recycling company Fortech in Costa Rica has more than two decades experience in WEEE recycling, and started to develop and optimize a ULIB recycling process several years ago. Inter alia with the support of the Technical University Aachen, Fortech developed a mechanical treatment process for ULIB, which results in separated fractions of aluminum, copper, plastics and black mass. A thermal treatment after the shredding evaporates the electrolyte, which is then condensed recovered for reuse as well.

Fortech identified off-takers for all of the recovered materials. Whereas Aluminum and copper are given into the Al- and Cu-recycling routes Fortech already established when working with WEEE, the black mass is sold to off-takers in the US or Europe. The plastic fraction is converted to refuse derived fuel (RDF) for energy recovery.

Fortech´s business case is not solely based on the revenues from sold materials, but also on the existing EPR system in Costa Rica, which covers batteries amongst several other types of waste (see challenges of the current legal framework in section 4.2.2.1). Even in the absence of manda-tory collection rates some battery importers were willing to pay for the sound collection and treat-ment of generated waste batteries.

Since Costa Rica became an OECD member in 2021, the import of used batteries is easier, also for larger batteries coming from electric vehicles[25]. Fortech discharges the batteries before transport, disassembles them in the facility and can treat them mechanically in the same plant which is otherwise processing portable ULIB. Fortech has an arrangement with an EV manufacturer to collect and treat their old vehicle batteries not only originating in Costa Rica, but from other countries of the region as well.

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[25] The transboundary movement of batteries still need to follow international regulations like the Basel Convention.

The company is a member of E-waste LATAM, a network in Latin America and the Caribbean which fosters exchange between actors along recycling networks (see chapter 4.3). Fortech is well connected in the region and has ambitions to share expertise and knowledge to further interested parties, either through consultation or a franchise concept. Currently there are ongoing discussions with interested parties from various LAC countries including Colombia, Chile and Mexico.

In the context of a collection pilot conducted from Nov 2022 to Jan 2023, strategic alliances and agreements with various Costa Rican municipalities, local governments and producers could be established. As result of the pilot, 120 tons of ULIB were collected and channeled to reuse initiatives or Fortech´s recycling facilities.

4.2.2.3 Relevant national developments

CAs part of its National Decarbonization Plan[26], Costa Rica aims to be carbon-neutral by 2050, and part of the action plan is oriented precisely to transportation and sustainable mobility. The initial ambitions were to achieve 70% of the bus and taxi fleet and 25% of the private vehicle fleet to be zero-emission by 2035; by 2050, 100% of the bus and taxi fleet and 60% of the private vehicle fleet should be zero-emission.

However, for the year 2020, MINAE's Climate Change Directorate presented its Nationally Deter-mined Nationally Determined Contribution (NDC) report where the original targets were adjusted - the new goal being to achieve 8% of all bus, taxi and private vehicle fleets to be zero-emission by 2030 (MINSA; MINAE 2022). For other vehicle categories, such as motorcycles, targets and measures shall also be developed to migrate towards EVs.

Figure 4-3: Charging station for electric vehicles in Uvita, Costa Rica

Source: Oeko-Institut

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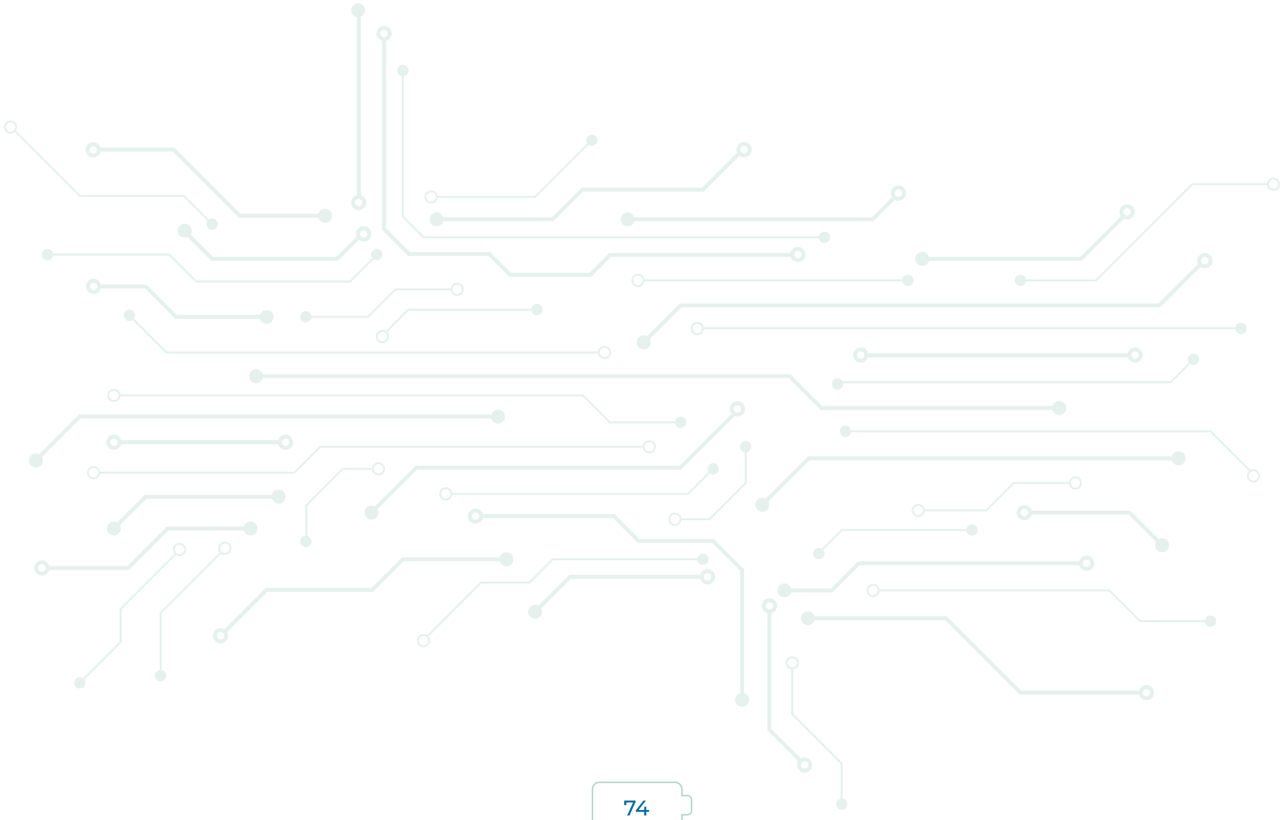
[26] Descarbonicemos Costa Rica Compromiso País 2018-2050

With the approval of Law N° 9518 in 2018, the acquisition of electric vehicles is incentivized in public tenders of the state and establishes the goal to electrify, at least, 5% of the bus fleet every two years (MINSA; MINAE 2022). A National Plan for Electric Transport was published the same year, which includes concrete steps towards electrification of vehicles (MINAE 2018).

Additionally, the roadmap for an efficient management of electric vehicle batteries in Costa Rica developed by the MINAE presents challenges, environmental and social impacts, best practices, and a plan of action for the short (2030), medium (2040) and long term (2050) for the efficient and adequate management of electric batteries in Costa Rica (MOVE 2022). As part of this roadmap it was estimated that by 2030, around 1000 tons of battery waste could be produced in Costa Rica and by 2040 around 3,000 tons (MINSA; MINAE 2022).

4.2.2.4 Country summary

Costa Rica has existing WEEE and battery regulation, as well as EPR established in the integrated waste management law, but is not mandatory. Therefore, the de facto management of EoL LIB remains far from sound. However, recent studies carried out in the country (Domenech Cots and Guillén Miranda 2021; MINSA; MINAE 2022) confirm that there is abundant knowledge on the topic in the country and serve as a foundation towards better practices. The National Decarbonization and Electric Transport Plans prove that Costa Rica wants to become a pioneer in the region, but not enough attention is being put to the consequences of decarbonized transport i.e., the increasing generation of EV battery wastes that will have to be managed. With a single plant, a project of the enterprise Fortech, as only recycling infrastructure for ULIB, there is a need to export the batteries. However, Fortech is already a good example for development of ULIB recycling in the Central American region.



4.2.3 Chile

Together with Bolivia and Argentina, Chile is part of the “lithium triangle”, a region with salt flats whose concentration levels make its exploitation highly profitable in relation to other deposit. This is currently one of the top lithium exporting countries in the world (López et al. 2019) despite having only two companies that currently exploit the mineral (SQM & Albemarle). In the following sections the current state of ULIB reuse and recycling practices will be described covering different aspects: regulatory framework, existing infrastructure and capacities and national developments.

4.2.3.1 Policies, Regulations and EPR Schemes for LIB

In 2004, Decree 148 was published, which establishes the minimum sanitary and safety conditions to which hazardous waste must be subjected (Ministerio de Salud 2004). Even though this decree is still in force and includes batteries, there is no explicit mention of lithium-ion batteries or waste electrical and electronic equipment.

Since 2016, Chile has a legislation specifically addressing WEEE, which requests the introduction of an EPR scheme for various priority products. The Framework Law for Waste Management, Extended Producer Responsibility and Recycling Promotion (“Ley REP”)[27] (Ministerio del Medio Ambiente 2016), aims to reduce the generation of waste and promote its reuse, recycling and other types of recovery, through the establishment of EPR and other waste management instruments. Although lead-acid car batteries and alkaline batteries are two of the six priority products included in the EPR scheme, no category includes LIB. Small LIB are covered by the category of electrical and electronic equipment, as they are components of such. However, there is a regulatory gap for electromobility batteries, which are currently excluded from the obligations of the current regulatory framework.

According to the EPR law, producers of priority products must organize and finance the collection of waste from priority products throughout the national territory, as well as their storage, transportation and treatment, through individual or collective management systems (see section 3.4.4). Producers must also ensure that waste management of priority products is carried out by authorized and registered managers (Ministerio del Medio Ambiente 2016).These obligations shall be enforceable with the entry into force of the respective supreme decrees that establish goals and further associated requirements for each of the priority products.

In 2022, Resolution 207 approved the proposed draft for supreme decree establishing collection and valorization targets and associated obligations for portable batteries and electronic and electronic appliances (Ministerio del Medio Ambiente 2022). According to this draft, the collection and valorization targets will gradually increase over time from the year in which it comes into force, as shown in Table 4-4.

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[27] Law 20920 that establishes Framework for Waste Management, EPR and Promotion of Recycling

Table 4-4: Collection and valorization targets for electric and electronic appliances according to Resolution 207

Year	Collection / valorization target
First year	3%
Second year	5%
Third year	8%
Fourth year	12%
Fifth year	16%
Sixth year	20%
Seventh year	24%
Eighth year	30%
Ninth year	37%
From tenth year onwards	45%

Source: Ministerio del Medio Ambiente 2022

4.2.3.2 Existing recycling infrastructure and reuse initiatives

In terms of ULIB recycling, Chile has some active initiatives. By the time of this study was conducted, only one company was identified to be performing ULIB recycling in operational phase and one other at pilot scale. Ecominería is a company with an established processes for recycling waste LIB (See Practice example 5) As of 2023 the start-up Relitia was developing a pilot ULIB recycling process (see Practice example 6).

In the topic of ULIB reuse, another start-up, Andes Electronics was identified. This company has plans to develop reuse options for ULIB in smaller electric vehicles (see Practice example 7). Furthermore, it is worth mentioning that the Chilean mining enterprise SQM has signed agreements with other actors, such as LG Energy Solution and the Universidad Católica del Norte (UCN), to promote and develop ULIB recycling infrastructure in the country (SQM Media Center 2022; pv magazine 2022).

Practice example 5: Ecominería

Recovery and valorization of materials from black mass

Ecomineria is a Chilean company specialized in ULIB recycling. The plant processes 10 tons per month of ULIB of all types. One of the target outputs of the process is black mass is obtained from Li-Co batteries, present in devices such as cell phones, tablets and drones. Ecomineria already receives batteries from electric vehicles, and the long-term plan is to obtain black mass from them as well. Although important materials such as copper, cobalt sulfate, graphite and aluminum are recovered, Ecomineria does not recover lithium as the quantities are very small.

The company has a circularity agreement with Samsung Latin America, which means that it processes 3 tons per month of batteries from the telephone company and resells the material to them to produce new batteries. It also has an agreement with Gaia Vitare, a Colombian waste-management company, to recycle cell phone batteries from Colombia. Furthermore, this company has an active partnership with the start-up Andes Electronics which evaluates their collected batteries and retains those which are still suitable for stationary energy storage applications.

With its current processing capacity of 1200 tons per year, Ecominería would be in a position to process the total amounts of EoL ULIB in Chile which are estimated to be 734 tons yearly (ANIR 2021). However, with higher increasing numbers of e-vehicles entering the national market, this capacity will not be enough for future amount of EoL ULIB. According to the company, there is a lack of investment to scale up this type of technology to attend EoL management needs in other regions of the country and in Latin America.

Practice example 6: Relitia

ULIB recycling aiming to recover lithium

Relitia is a start-up focused on recycling all kinds of ULIB and recovering the contained materials in order to reinsert them into the value chain of new batteries. Relitia has a pilot process for recycling, in which manual disassembling and hydrometallurgical processing is used for recovery of battery fractions., Currently, the company recovers graphite, metallic salts and lithium salts, and separates them from the inert components.

In the facility, the collected batteries are discharged using an electrolytic solution to reach voltages below 1V. Once the batteries are discharged, they are manually disassembled. The cathode, anode and separator are treated in a hydrometallurgical process, separating the graphite in solid form and the metals, which are dissolved in an aqueous solution. Finally, the metals are precipitated in the form of hydroxide or oxide. The lithium can be recovered by precipitating it in the form of carbonate.

Relitia is supported by the company Sustrendlab and currently has a two-year government fund for scaling up the process. In the current pilot phase, batteries from cell phones and electric scooters are processed. It is planned for the near future to conduct tests with the first large vehicle cells, such as LG-Chem's Pouch and Tesla's 18650. Nevertheless, the company expects that there won´t be enough raw material (value) recovered to work exclusively with e-vehicle batteries in the coming years.

Still at laboratory scale, the current processing capacity of Relitia is 50 to 80 batteries per month, with an average of 5 kg per battery cell. However, investment is being sought to build a plant with a capacity of between 500 kg and 1 ton per hour. Relitia also stated that they don´t aim at just obtaining black mass, but instead separate the materials and obtain them at the right grade to reinsert them into the value chain. This has already been achieved with graphite and cathode salts.

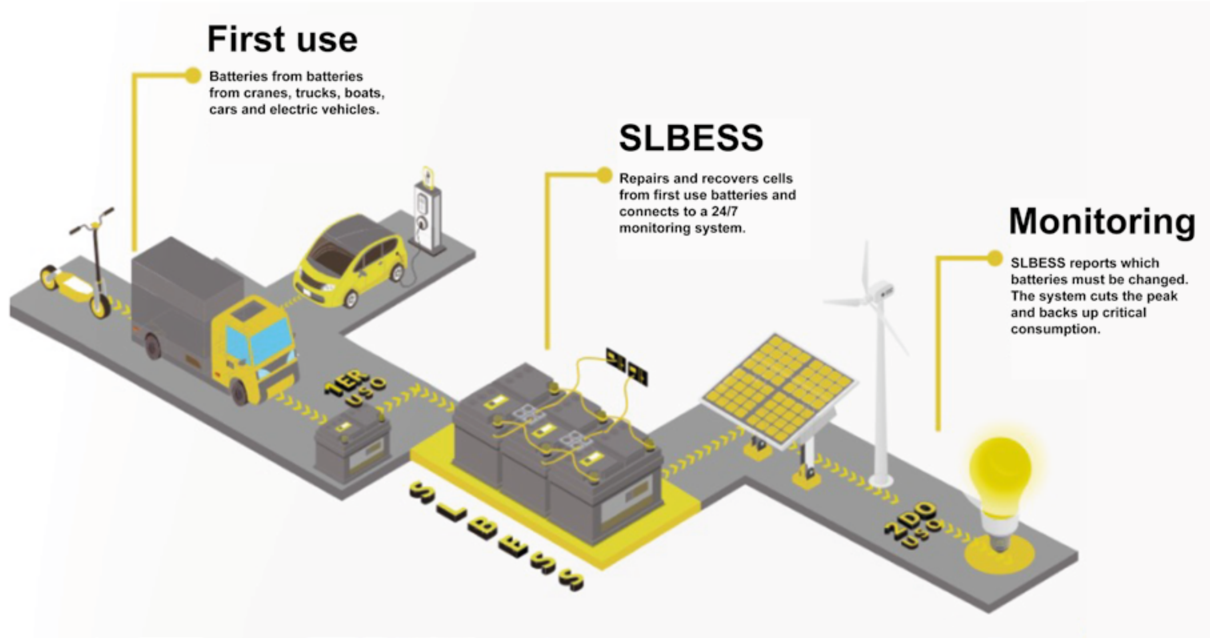
Practice example 7: Andes Electronics

ULIB repurposing for second life applications

Andes Electronics is a Chilean start-up that creates second life batteries storage systems (SLBESS), battery management systems (BMS), and other services dedicated to battery repur-posing. For the development of their technology, the founders had the support of academic insti-tutions as well as state funding through the Startup Ciencia 2021 program.

Due to availability of waste batteries, Andes Electronics currently processes lead-acid batteries. However, their long-term goal is to focus on ULIB. Currently, the company is developing technologies to replace lead-acid batteries in transport and industrial applications with second-life portable ULIB (e.g., electronic device batteries). Moreover, the company already started working with second life batteries for small electric vehicles such as e-bikes and e-scooters.

Figure 4-4: Business model for second life applications of ULIB in Chile



First use

Batteries from batteries from cranes, trucks, boats, cars and electric vehicles.

SLBESS

Repairs and recovers cells from first use batteries and connects to a 24/7 monitoring system.

Monitoring

SLBESS reports which batteries must be changed. The system cuts the peak and backs up critical consumption.

Source: Andes Electronics 2023

4.2.3.3 Relevant national developments

Chile is one of the most advanced countries in Latin America in terms of legislation related to electric mobility (MINSA; MINAE 2022). Chile has a National E-Mobility Strategy (Estrategia Nacional de Electromovilidad), which has the goal "to ensure that 100% of new additions to urban public transportation are zero-emission vehicles by 2035, 100% of sales of light and medium vehicles are zero-emission by 2035, and 100% of sales of vehicles for interurban passenger and freight transportation are zero-emission by 2045" (Ministerio de Energía 2021).

In terms of electrification strategy, the Chilean population's access to electricity is almost absolute. In fact, the electric grid provides coverage to 99% of the population (Ministerio de Energía 2020). As of 2021 Chile had installed 6,000 decentralized renewable energy systems, many of which include batteries for energy storage. After reaching its EoL these batteries will also require environmentally sound management. (Soler Guzmán et al. 2021).

4.2.3.4 Country summary

The national EPR law does not include LIB as priority product category, but rather as a component of electrical and electronic equipment (for which there is a specific category). However, a growing awareness on the correct EoL management has been observed in Chile. In terms of existing capacities, a facility in operational phase and a startup exclusively specialized in ULIB recycling were identified as along with a startup for second life applications of ULIB. These three actors are well networked, and all of them have expansion plans, not only in Chile but in the region (e.g., Ecomineria has agreements with companies in other South American countries). Regarding the development of second life business for EoL batteries, the main problems in Chile are the lack of capacity for quality certification of batteries, and the lack of support for second life business models. Interviewed stakeholders identified the geographic conditions in the country and transportation distances as a major barrier which make reverse logistics for LIB more complex.

4.2.4 Mexico

Although Mexico has unexploited lithium reserves, the country has not yet developed a value chain for this mineral. In 2022, the Mexican Senate approved a presidential initiative to nationalize lithium, which is to be exploited exclusively by the state through its recently founded company LitioMx (SEGOB 2022). In the following sections the current state of ULIB reuse and recycling practices will be described covering different aspects: regulatory framework, existing infrastructure and capacities and national developments.

4.2.4.1 Policies, Regulations and EPR Schemes

At this stage, Mexico has no specific regulations for end-of-life management of batteries and WEEE. However, LIB are covered by the General Law for the Prevention and Integral Management of Waste (LGPGIR of 2003), which classifies them as "special" but not hazardous waste[28] and establishes a framework of shared responsibility among various industry players. LIB are indirectly covered by the Mexican official standard[29] for the management of hazardous waste, which includes some electronic products (containing batteries) in its lists (SEMARNAT 2012).

The Mexican official standard NOM-161-SEMARNAT-2011 establishes the criteria to classify such special waste and to determine which are subject to a management plan. Although the elements and procedures for the formulation of management plans are well defined, these plans are voluntary and there are no repercussions if they are not in place.

In 2020, a baseline study for the integral management of waste was published (SEMARNAT 2020). This study mentions batteries as an emblematic case in Mexico for which there only a temporary policy was developed, but had no real effect on the country's environmental quality.

The same document identified challenges for the implementation of sound waste management practices. One main challenge is the absence of a defined institution in charge of follow-up and control of the national waste management plans. Moreover, the coordination of several states for implementing and monitoring these plans at regional level is mentioned as a further challenge. (SEMARNAT 2020).

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[28] LIB included in Article 19 of LGPGIR of 2003 under: “Batteries containing lithium, nickel, mercury, cadmium, manganese, lead, zinc, or any other element that allows the generation of energy in them, at levels that are not considered as hazardous waste in the corresponding official Mexican standard”.

[29] NOM-052-SEMARNAT-2005

To address this challenges, a National Program for the Prevention and Integral Management of Special Handling Waste (PNPGIRME)[30] was developed and published in 2022 (SEMARNAT 2022). The priority objectives of the PNPGIRME are:

- Generate information on special handling waste in the country, in order to strengthen decision making at the three levels of government. decision-making at the three levels of government.
- To promote the prevention of the generation, as well as the adequate management and use of special handling waste. management and use of special handling waste.
- Promote an adequate legal framework that establishes clear attributions and competencies for the management of special handling waste.

Although the publication of this program is an improvement in the regulatory framework for Mexico, there is still not enough available information about the quantities of waste batteries generated in the country. The lack of progress in Mexico's regulatory framework dedicated to waste batteries, makes the implementation of good practices for reuse or recycling of EoL LIB especially difficult.

4.2.4.2 Existing recycling infrastructure and reuse initiatives

In Mexico the only known company which currently operates a ULIB recycling plant is SITRASA. Due to the lack of first-hand information obtained in the course of this study, no further data on the process or capacities can be reported at this stage. Reverse Logistics Group Latin America (RLG LATAM) also has operations in Mexico concerning reverse logistics of WEEE; however, it was not confirmed whether these involve ULIB. Further initiatives for developing recycling infrastructure involve other relevant national actors such as the Mexican Chamber of Lithium (CaMexLi) who announced in 2021 the construction of a ULIB recycling plant in the state of Querétaro. In the same year, two electric mobility companies announced infrastructure projects for the future (Florencia Guglielmetti 15 Jun 2021; Ailen Pedrotti 8 Nov 2021).

Since 2021, no further information has been published regarding the current state of implementation for the announced projects, therefore it has not been confirmed whether these facilities are in development. Regarding ULIB repurposing, an initiative called REMSA was identified. This company uses EoL LIB from electric vehicles to convert them into solar power units (see Practice example 8).

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[30] Programa Nacional de Prevención y Gestión Integral de Residuos de Manejo Especial - PNPGIRME

Practice example 8: REMSA

Repurposing used ULIB into solar power units

REMSA (Recicla Electrónicos México), so far active in WEEE recycling, has developed a new business line for reuse and repurposing of ULIB. The company aims at repurposing used ULIB into autonomous (mobile) solar power units and stationary energy storage banks. Moreover, the company engages in collection programs with automotive companies, and offers its own collection service for citizens and businesses through a mobile application.

4.2.4.3 Relevant national developments

At this point in time, Mexico’s government has great interest in exploring options to exploit their own lithium reserves and become a producer of batteries for electromobility. For this, the Mexican Chamber of Lithium is a visible actor aiming to facilitate investments in Mexico dedicated to lithium processing (Becerra 21 Apr 2022). In contrast to developments in other countries in the region regarding capacities for reuse and recycling of EoL LIB, no major progress has been observed for Mexico.

Mexico has a National E-Mobility Strategy (Estrategia Nacional de Movilidad Eléctrica - ENME) in development phase, which aims at 10% of vehicle sales being electric by 2030 and a 100% electrified vehicle fleet by 2050. Additionally, the strategy prioritizes the implementation of a EoL regulation for e-vehicle batteries by 2030, which should include recycling schemes and second life as energy storage units (Altamirano 18 Aug 2022). In 2021, the Ministry of Foreign Affairs initiated a cooperation with the University of California to develop a strategy for the electrification of the automotive industry in Mexico. This initiative “proposes an orderly transition to electromobility not only at the national level, but also at the regional level, by coordinating productive integration with [Mexico’s] most important trading partner, the United States” (Secretaría de Relaciones Exteriores; University of California 2022). The goal is to present in 2023 a bi-national roadmap for the creation and implementation of clear and defined policies for the Mexican automotive industry towards the manufacture and use of electric vehicles. It was also mentioned by the interview partners that the country is rapidly engaging in the fabrication of batteries and electric vehicles, but not at all in the EoL management of these.

Regarding off-grid electrification, as of 2021 Mexico had installed 130,000 decentralized renewable energy systems, whose batteries must be managed at the EoL phase (Soler Guzmán et al. 2021).

4.2.4.4 Country summary

In Mexico barely any ULIB recycling or reuse capacities were identified, and very little information was publicly available. The country has no dedicated regulations addressing LIB; neither a mandatory national EPR scheme, nor a circular economy law. Only one ULIB recycling company in operational phase was detected, but no contact could be established. Developments regarding second life for ULIB were found to be at a very early stage, with one company currently starting to engage in this sector. Actors interviewed for this study identified Mexico's market characteristics to be one important factor that explain the scarce awareness about the need for environmentally sound EoL management of growing volumes of LIB. The federal constitution and lack of institutional coordination of this country are also probable barriers to national developments in terms of ULIB reuse and recycling.

The coordination between states to achieve regional agreements was considered a factor which presumably adds complexity to the country's progress in terms of regulatory implementation. Moreover, stakeholders described the changes in federal and regional administration as challenge and one important reason for shifting interests about announced infrastructure projects (e.g., cancellation). A possible reason for the lack of progress could be a dependency of the country on the USA, Mexico's main commercial partner and where technology and infrastructures to recycle ULIB are already available.

4.3 Overview of relevant Stakeholders for ULIB reuse, repurposing and recycling in LAC

In promoting better end-of-life management practices for lithium-ion batteries it is critical to understand the current landscape of stakeholders in the region. Therefore, in parallel to the desk research and interviews for this study, the actors active in Latin America and the Caribbean for the topic of reuse and recycling of ULIB were identified. The resulting stakeholder mapping is presented in Figure 4-5. The full list of actors identified to be active in the four selected countries is presented in Annex II.

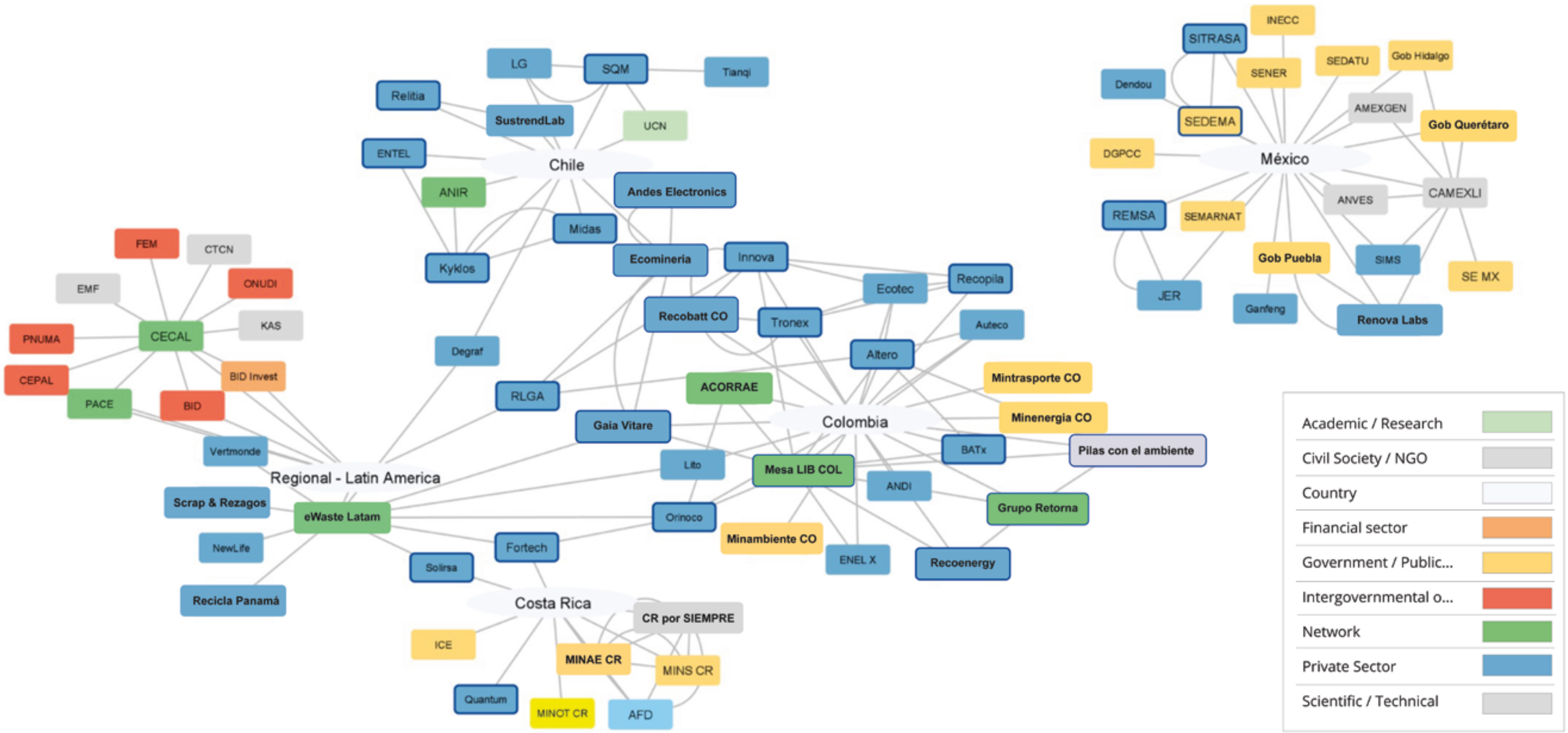
Moreover, the actors identified to have operating capacities related to reuse and recycling of ULIB in the four countries in focus have been summarized in Table 4-5.

Table 4-5: Actors with existing initiatives and capacities for EoL management in selected countries

Type of Activity	Colombia	Costa Rica	Chile	México	Regional
ULIB Collection and reverse Logistics	▪ Grupo Retorna (including Pilas con el Ambiente & Recoenergy) ▪ Recopila		▪ ENTEL (in alliance with Kyklos)	▪ Movistar (in alliance with REMSA)	▪ Reverse Logistics Group (RLG)
ULIB Recycling	▪ Innova Ambiental ▪ Altero	▪ Fortech	▪ Ecominería ▪ Relitia	▪ SITRASA	
ULIB Reuse / Repurposing	▪ Recobatt ▪ BATX	▪ Fortech	▪ Andes Electronics	▪ REMSA	
Other interesting actors (currently exploring or developing related initiatives/ projects)	▪ Orinoco ▪ Tronex ▪ Gaia Vitare	▪ Solirsa ▪ Quantum Lifecycle Partners ▪ LabVolta (Universidad de Costa Rica)	▪ SQM ▪ LG Energy Solution ▪ Universidad Católica del Norte	▪ CaMexLi ▪ Renova Labs	▪ E-Waste LATAM

Source: Own compilation

Figure 4-5: Stakeholder mapping in the four selected case studies in LAC



Source: Own elaboration

Most identified actors are mainly networked within countries, and not within the region. Specially Mexico has so far very limited connections to other countries or regional networks. Missing capacities for upscaling and expansion of business models are also evaluated as important challenge by involved stakeholders (see chapters 4.2.1 to 4.2.4).

* Connections represent interactions, active participation partnership or visibility around the topic of LIB for selected countries.

** Actors with active work in LIB recycling or repurposing are highlighted with a different border width

*** Double connections among actors indicate reported links from both sides or close cooperation.

5. Findings from LAC technology and regulatory framework

Considering the experiences in the countries selected for case studies, the following aspects summarize the findings and challenges for better ULIB reuse and recycling practices in the region:

Technology for ULIB reuse and recycling

- Current ULIB recycling processes in LAC are mostly until the stage of mechanical treatment (shredding) and the following separation of different fractions (black mass, plastic, copper, aluminum). Recyclers still depend on smelters from the global north (Europe, North America, Asia) to export and recover valuable materials.
- There is currently no (significant) recovery of lithium from waste batteries taking place in the LAC region. As the black mass is mostly exported for further treatment (see above), the potential for Li recovery is shifted to these regions. If the black mass would be treated within the region in the future, the process of secondary lithium production from slag will be completely different from the regional primary lithium production from brines (as applied in mining industries).
- Current LIB volumes in need of EoL management are still mainly composed by LCO and NMC batteries. Increasing volumes of LPF batteries are anticipated in the coming years, inter alia resulting from electric vehicles. One implication of this development is that recycling processes might no longer generate sufficient revenues from recovered materials to cover treatment costs (since neither cobalt nor nickel will be present in significant amounts in the black mass). In this case, to ensure recycling capacities in the region, additional financial instruments would be necessary to cover costs. As shown in the global review, EPR systems could be a viable solution to close this gap. As an example, the not yet mandatory EPR system in Costa Rica is already an important pilar in the business model of a local recycler.
- The recycling of ULIB is mostly perceived as possible source of income by actors in the region. This is possibly explained by the fact that current volumes of ULIB contain comparably high shares of “valuable” materials such as nickel and cobalt (see above). Also, the framing in some of the relevant regulations was described to be focused on possible revenues, and does not consider that municipalities should reserve respective budget for EoL management. Nevertheless, some of the recycling companies do already differentiate between battery chemistries, and make sure to charge gate fees for the treatment of battery chemistries like LFP.

- The traceability of the amounts of LIB at end-of-life is very low in the region. The informal market for waste management is a significant issue in all focus countries. Due to informality, the waste handled through these channels cannot be quantified.
- There is a lack of investment in the region to scale up existing pilot or smaller plants (e.g., Fortech, Ecomineria, Altero). From the perspective of consulted stakeholders, the focus on short-term results of Latin American investors is a major barrier to such developments. Consequently, there is still little investment for establishing or expanding LIB recycling capacities in the region.
- Current efforts in the region to improve sound EoL management of ULIB mainly focus on recycling options, whereas initiatives for reuse receive very little support (both from governments and potential investors).

Regulatory framework

- With respect to the legal framework, there are few LIB specific regulations in the region. In the majority of countries, LIB are managed under hazardous or special waste laws, as in the case of Mexico, or under WEEE management laws, as in the case of Costa Rica and Chile. In Colombia, the legal framework is more specific, and LIB are regulated under a category for batteries and accumulators. The regulatory framework even includes some specific requirements for larger lithium-ion batteries (industrial and vehicles).
- Existing regulatory frameworks are still mainly based on voluntary measures and often lack mandatory requirements. According to local stakeholders, those mandatory measure which are in place are often not sufficiently enforced. As confirmed by the global good practice review, the existence of regulatory frameworks is a necessary pre-requisite for development of effective reuse and recycling practices, as lithium-ion battery recycling is not per se a business case. A comparison within the region shows, that from the four focus countries Colombia is the most advanced in terms of sound EoL LIB management. At the same time Colombia is the country with the most robust regulatory framework with many mandatory requirements. On the other hand, Mexico, Chile and Costa Rica either have no specific regulation or only voluntary schemes in place.
- The selected countries have (either published or in development phase) national electromobility strategies, engaging in decarbonization aiming to grow EV markets. However, a lot of attention is focused on the operation of EVs and little to no attention is paid to the EoL management of their components, including batteries. So far LIB from elective vehicles had not been directly addressed in waste regulations in the focus countries. Colombia is the only exception where these batteries will be included in mandatory collection schemes from 2024 onwards. Costa Rica also has plans to address this type of batteries in the near future.

Other findings

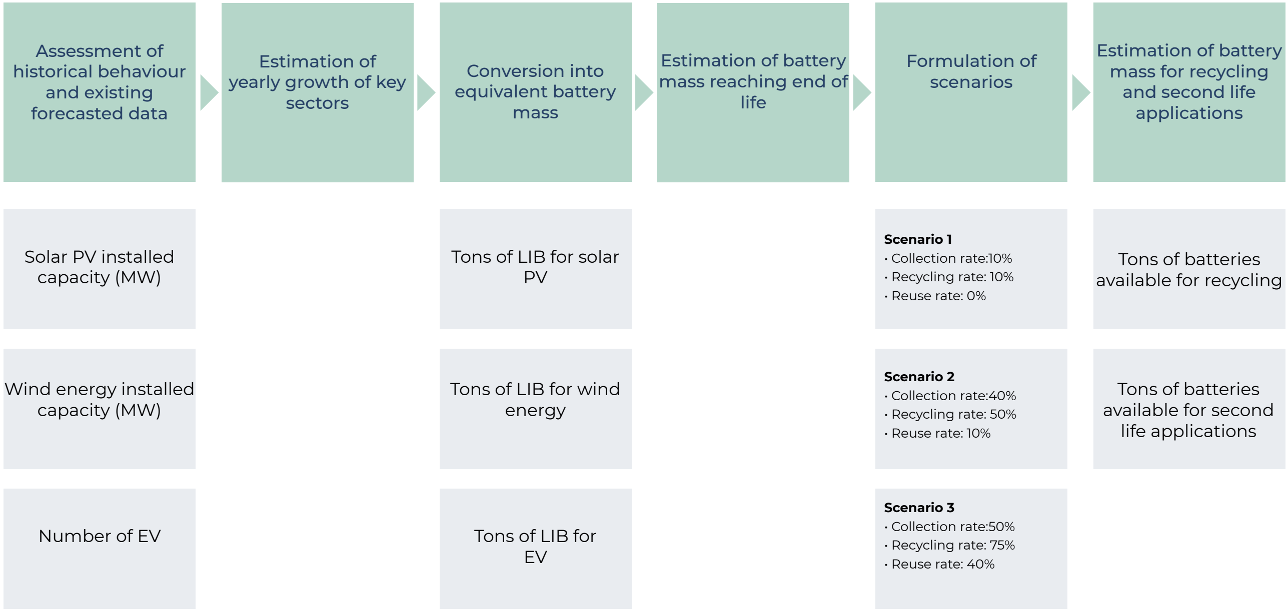
- It has been found that there are many misconceptions and caution among the actors such as transport companies and manufacturers which currently delay or prevent significant battery volumes from reaching national recyclers in the examined countries. In this context, there is a need for better and harmonized information on the risks of LIB as well as support from governmental actors in developing centralized measure for safe storage, packaging and transport of ULIB.
- There is little regional cooperation between neighboring countries for improving EoL management practices for LIB, apart from some ongoing bilateral commercial agreements. This was confirmed by one of the experts consulted on the subject. WEEE LATAM is one of the few exceptions, a network of WEEE managers in several Latin American countries seeking to promote good waste management. This network also has an established working group on LIB. Some companies are currently evaluating the options to share and distribute their knowledge and technology in the region, which will possibly increase cooperation in the future.
- Complying with the Basel convention constitutes a challenge for regional cooperation in EoL management of LIB. The mainly small and medium sized companies active in ULIB reuse and recycling in LAC do not have the administrative capacities for undergoing the formalities and legal efforts required to apply a Prior Informed Consent procedure for transboundary movements of ULIB. This situation reduces motivation for collecting ULIB in countries with non-existing national recycling capacities. The option of exporting used LIB to recycling companies in the region which theoretically are in the position to process higher volumes as they already do is also limited by the administrative hurdle. Legal support as well as solutions for collective consolidation of LIB volumes at storage, transport and export were mentioned by various stakeholders as possible ways to tackle this challenge.

6. Regional outlook

This section presents the most relevant results of the estimations of the battery volumes for the entire Latin America region in the period 2024-2050, along with a scenario analysis of the potential battery volumes available for recycling and reuse and the investment requirements necessary to set up the infrastructure required to manage these volumes.

The estimations consider only batteries associated to three key sectors: Energy storage for solar photovoltaics (solar PV), energy storage for wind energy and energy storage for electric vehicles (EV), including light EV (electric cars) and electric buses. These sectors were selected in accordance with the project requirements, and considering that these sectors: i) employ large size LIB, ii) are associated to applications that are critical to the decarbonization efforts of the region, and iii) are expected to have a significant uptake in the region in the upcoming years (López Soto et al. 2022). The section below focuses on the estimation results, an overview of the methodological approach can be seen in Figure 6-1 below, and the methodology and assumptions are explained in detail in Annex IV.

Figure 6-1: Overview of methodology for ULIB estimations



Source: Own elaboration

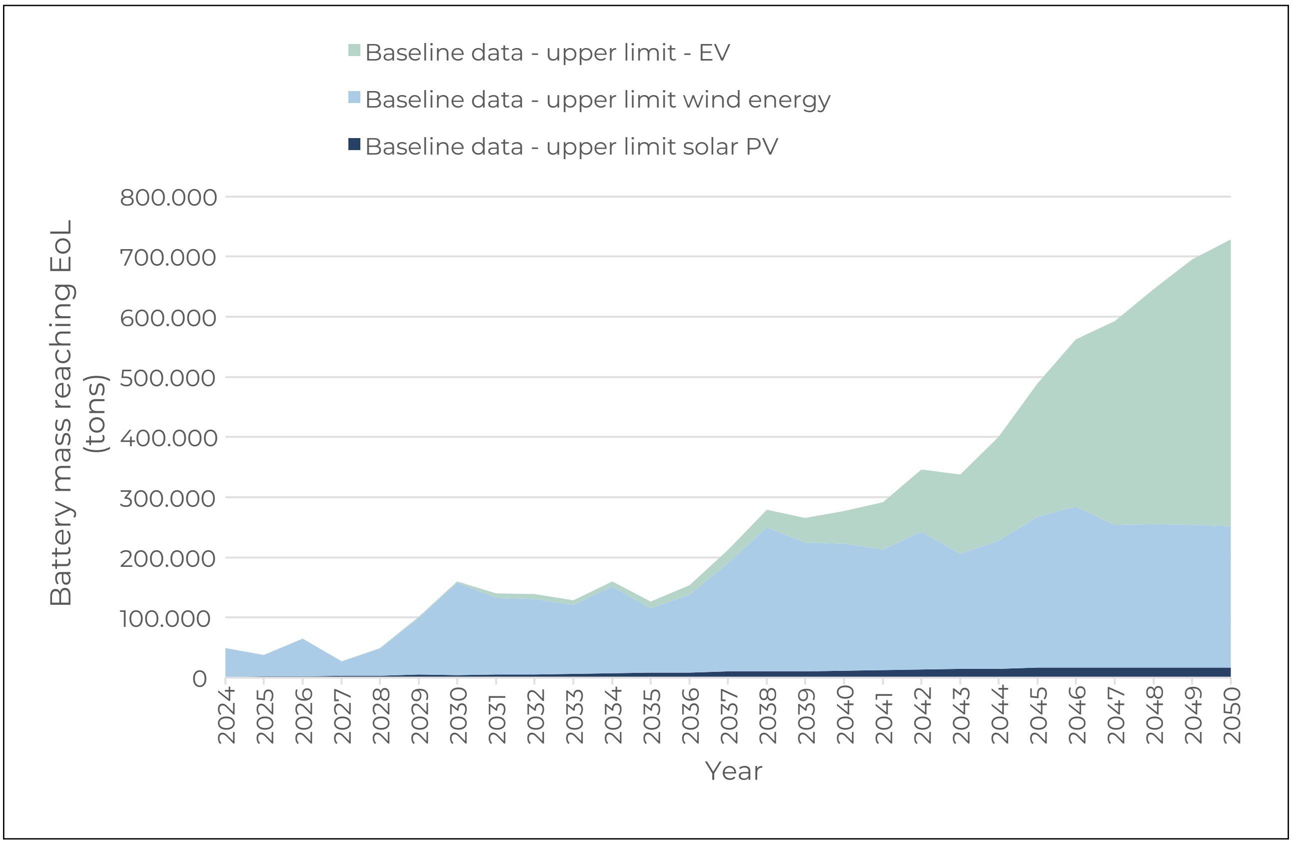
6.1 Estimation of ULIB volumes

6.1.1 Baseline estimations

Figure 6-2 and Figure 6-3 below provide an overview of the upper limit values of the baseline data showing the yearly and cumulative mass of batteries (in tons) reaching their end-of-life (EoL) during the period 2024 - 2050 for the LAC region. The baseline scenario does not consider any battery reuse applications.

As it can be seen in Figure 6-2. The batteries for solar PV represent a small share of the batteries reaching EoL, with most of the waste batteries imported by the EV sector in 2050. Table 6-1 below provides the upper and lower limits of the yearly battery volumes reaching their EoL estimated for the years 2030, 2040, and 2050 per sector.

Figure 6-2: Yearly ULIB mass reaching end-of-life (EoL) - Baseline



Source: Own elaboration

The battery volumes have an increasing trend, explained due to the increase associated to the number of EV entering the market and to the increase in the installed capacity for wind energy, it has been estimated that between 660,000 and 730,000 tons of batteries will reach their end if life in the LAC region in the year 2050.

Table 6-1: ULIB mass reaching EoL per year (tons) - Baseline

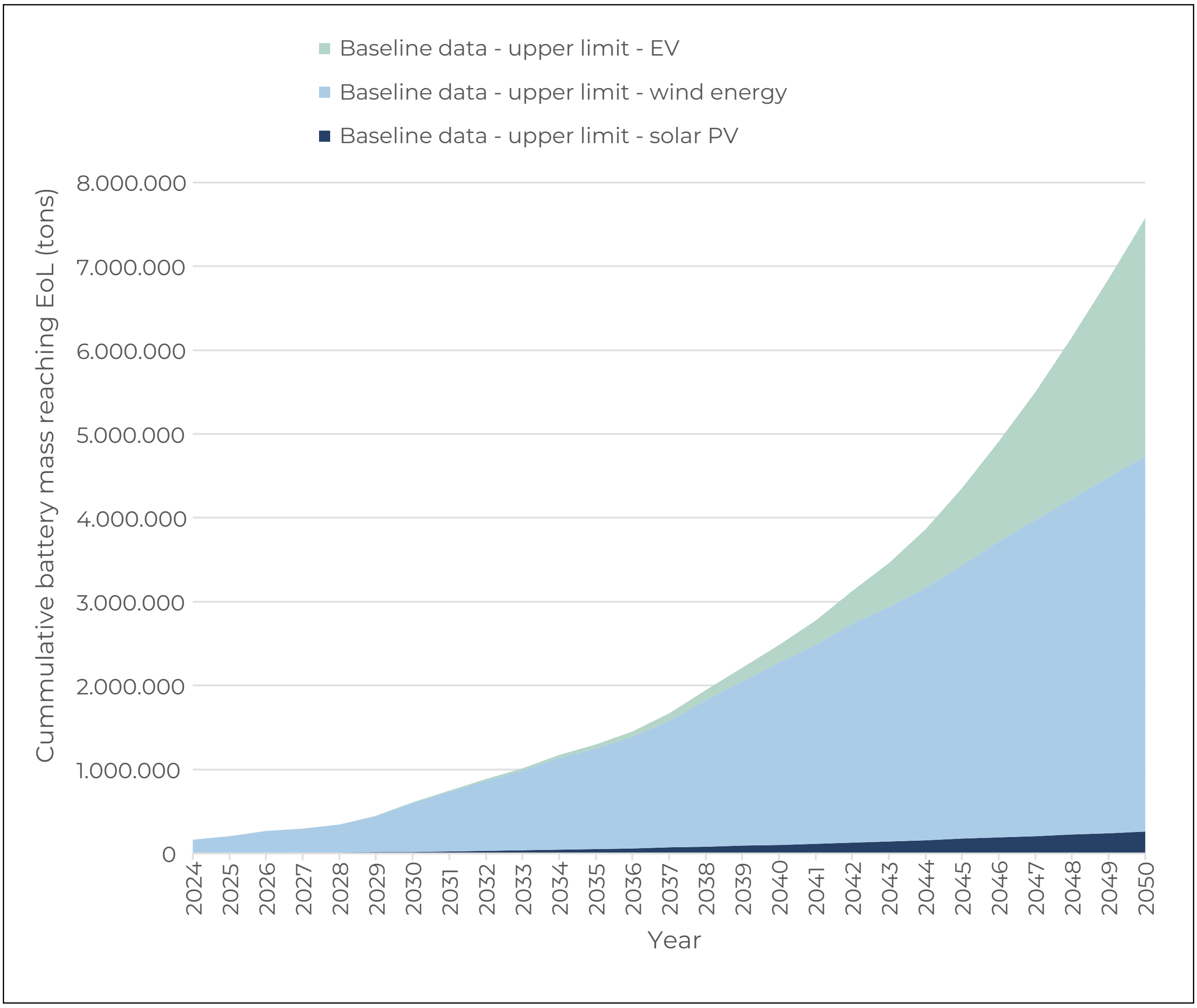
Year	**2030**		**2040**		**2050**	
Limit	Superior	Inferior	Superior	Inferior	Superior	Inferior
Solar PV	900	4,500	7,400	11,400	10,100	17,000
Wind energy	108,600	153,700	171,500	211,500	174,100	235,300
EVs	1,800	1,800	41,100	53,900	372,000	476,700
Total	**111,200**	**160,000**	**232,800**	**276,800**	**660,800**	**728,900**

Source: Own elaboration

The decrease in the battery mass reaching EoL in certain years can be explained due to the behavior of the data available from the selected battery-importing sectors. For example, the decrease in the years 2025 and 2027 is associated to a smaller additional installed capacity for wind energy added in the region in the years 2017 and 2019, which translates to smaller battery volumes entering the market in those years, and thus reaching their EoL in 2025 and 2027. Upward peaks in the estima¬tions, such as the ones observed in 2034, 2038 and 2042 are associated to the EoL management of batteries that entered the market as replacement of batteries reaching EoL. For example, the peak in 2034 corresponds to the additional battery volumes reaching their EoL that entered the market in 2026, as a replacement of batteries installed for wind energy systems in 2018.

By the year 2050, it has been estimated that the Latin America and Caribbean region would potentially have an approximate of between 6.6 million and 7.5 million metric tons of lithium-ion batteries from the RE and EV sectors that would have reached the end of their lifespan. The management of this volumes will - already long before 2050 - require interventions to ensure their environmentally sound and safe management.

Figure 6-3: Cumulative ULIB mass reaching EoL - Baseline



Source: Own elaboration

6.1.2 Scenario 1

Scenario 1 is the least ambitious of the three scenarios formulated, this scenario assumes a lower collection rate of used ULIB, 10%. Without any applications for the reuse of these batteries, it is assumed that 10% of the collected batteries will be recycled. This means that the number of batteries reaching the end of their life will remain the same as the baseline scenario. Table 6-2 and Table 6-3 provide the amount of battery mass that will be available for recycling in the years 2030, 2040, and 2050, both annually and cumulatively.

Table 6-2: ULIB mass available for recycling per year (tons) - Scenario 1

Year	2030		2040		2050	
Limit	Lower	Upper	Lower	Upper	Lower	Upper
Total (tons)	1,100	1,600	2,300	2,800	6,600	7,300

Source: Own elaboration

Table 6-3: Cumulative ULIB mass available for recycling (tons) - Scenario 1

Year	2030		2040		2050	
Limit	Lower	Upper	Lower	Upper	Lower	Upper
Total (tons)	4,400	4,900	20,200	23,700	65,000	74,600

Source: Own elaboration

According to the estimates, the amount of battery material that would be available for undergoing a recycling process by the year 2050 ranges from 65,000 to 74,600 tons. After estimating the overall battery mass available for recycling and assuming typical percentages of metal content in each battery (considering the battery chemistries) for the most relevant metals in an ULIB (Al, Cu, Co, Ni and Li) along with recycling efficiencies for each one of these metals, it is possible to estimate the metal content of the batteries available for recycling. The assumptions for metal content and recycling efficiencies can be found in Annex IV. The estimated material content in the batteries available for recycling over the period 2030, 2040 and 2050 is provided in Table 6-4 below.

Table 6-4: Cumulative metal content of ULIB available for recycling (tons) - Scenario 1

Year	2030		2040		2050	
Limit	Lower	Upper	Lower	Upper	Lower	Upper
Al (tons)	100	110	430	510	1,240	1,610
Cu (tons)	200	220	910	1,080	2,610	3,400
Co (tons)	60	70	270	320	780	1,020
Ni (tons)	40	50	180	220	520	680
Li (tons)	40	50	170	200	480	630

Source: Own elaboration

It must be noted that the amounts provided above indicate the material contents and do not directly translate into recoverable amounts., particularly in the case of lithium, which, under current conditions, is often not recovered.

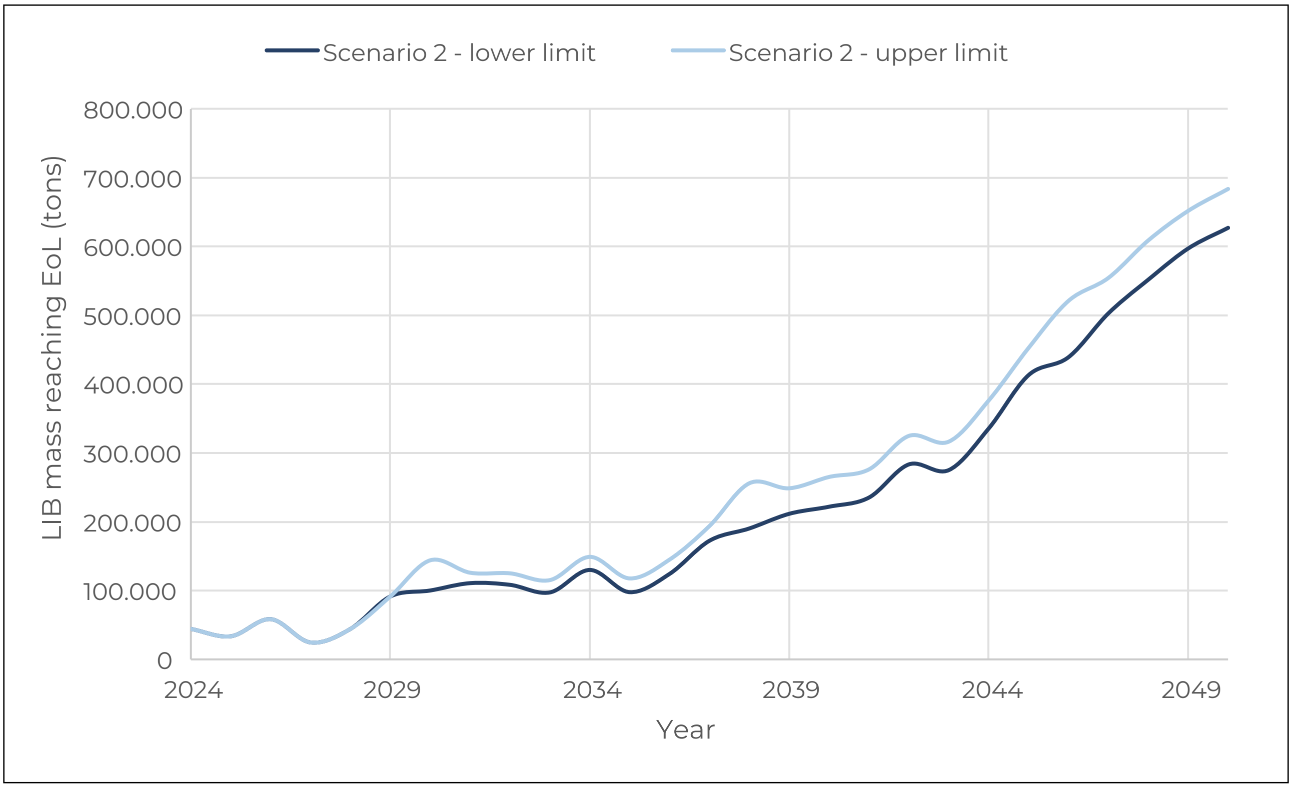
6.1.3 Scenario 2

This scenario assumes:

- A higher collection rate when compared to Scenario 1 - 50% (Compared to 10% of Scenario 1)
- Battery reuse at a small rate - 20% of the collected ULIB reaching EoL each year
- A higher recycling rate compared to Scenario 1 - 40% of the collected ULIB recaching EoL each year

The use of repurposed batteries will reduce the demand for new batteries, considering that the use in second life applications can extend the life of a battery up to ten years (NITI Aayog and Green Growth Equity Fund Technical Cooperation Facility 2022). However, in this case, as the collection and repurposing rates are relatively low, its effect is not very significant. Figure 6-4 and Figure 6-5 below show the yearly and cumulative battery mass at the end-of-life for this scenario including the lower and upper limits.

Figure 6-4: Yearly ULIB mass reaching EoL - Scenario 2



Source: Own elaboration

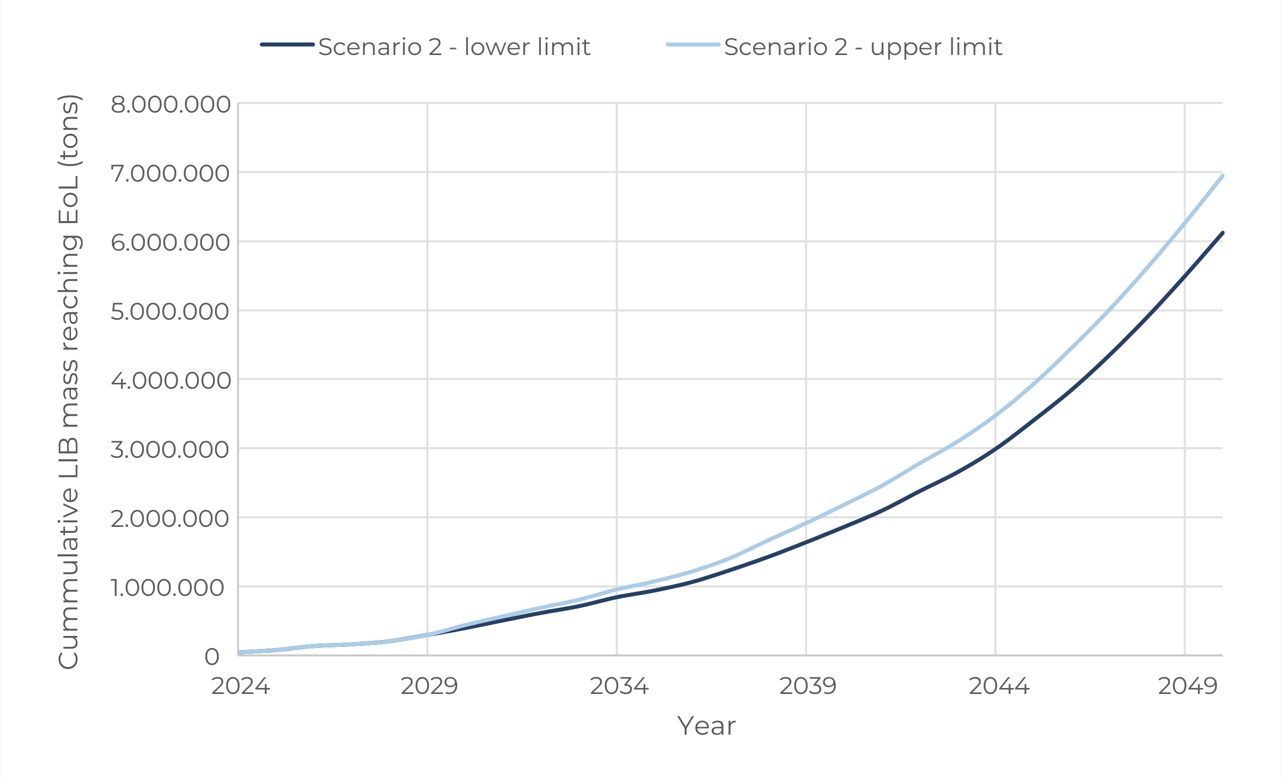
Regarding potential battery volumes available for recycling, Table 6-5 below shows the cumulative metal content in the battery mass available for recycling in the years 2030, 2040, and 2050. It has been estimated that in Scenario 2 by 2050 there will be a maximum content of 68,000 tons of copper in the batteries available for recycling, followed by 32,200 tons of aluminum.

Table 6-5: Cumulative metal content of ULIB available for recycling (tons) - Scenario 2

Year	2030		2040		2050	
Limit	Lower	Upper	Lower	Upper	Lower	Upper
Al (tons)	1,900.00	2,100.00	8,600.00	10,200.00	24,700.00	32,200.00
Cu (tons)	4,000.00	4,500.00	18,100.00	21,600.00	52,200.00	68,000.00
Co (tons)	1,200.00	1,300.00	5,400.00	6,500.00	15,700.00	20,400.00
Ni (tons)	800.00	900.00	3,600.00	4,300.00	10,400.00	13,600.00
Li (tons)	700.00	800.00	3,300.00	4,000.00	9,600.00	12,500.00

Source: Own elaboration

Figure 6-5: Cumulative ULIB mass reaching EoL - Scenario 2



Source: Own elaboration

Table 6-6 and Table 6-7 below show the estimated amount of accumulated battery mass that can be used for secondary applications (reuse) each year, as well as the battery mass available for reuse in the years 2030, 2040 and 2050, while By 2050 there will be a cumulative mass of batteries available for second-life applications between 572,800 and 745,800 tons.

Figure 6-6 shows the battery mass available for second life applications each year.

Table 6-6: Yearly ULIB mass available for reuse (tons) - Scenario 2

Year	2030		2040		2050	
Limit	Lower	Upper	Lower	Upper	Lower	Upper
Total (tons)	11,100	16,000	22,000	27,700	55,600	72,900

Source: Own elaboration

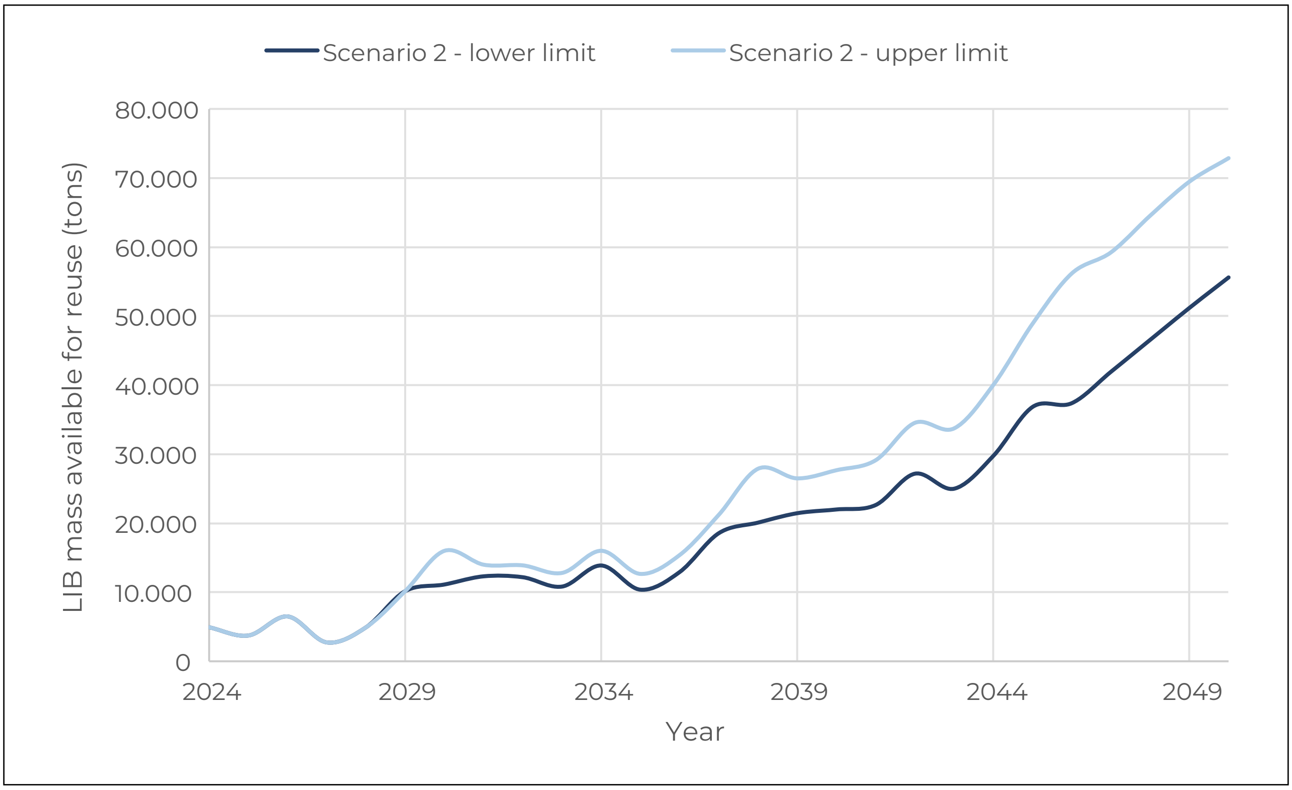
Table 6-7: Cumulative ULIB mass available for reuse (tons) - Scenario 2

Year	2030		2040		2050	
Limit	Lower	Upper	Lower	Upper	Lower	Upper
Total (tons)	44,100	49,000	198,700	237,000	572,800	745,800

Source: Own elaboration

By 2050 there will be a cumulative mass of batteries available for second-life applications between 572,800 and 745,800 tons.

Figure 6-6: Yearly ULIB mass available for reuse - Scenario 2



Source: Own elaboration

6.1.4 Scenario 3

This scenario assumes:

- A collection rate of 90% of the ULIB reaching their EoL
- A reuse rate of 44% of the collected ULIB reaching EoL each year
- A recycling rate of 42% of the collected ULIB reaching EoL each year.

This is the most ambitious of the three scenarios, where best practices for battery collection, reuse, and recycling are implemented in the LAC region.

In terms of recycling potential, Table 6-8 below shows the cumulative metal content in the batteries available for recycling the years 2030, 2040 and 2050. It has been estimated that in Scenario 3 by 2050 there will be a maximum potential content of 127,520 tons of copper in the batteries available for recycling, followed by 60,410 tons of aluminum.

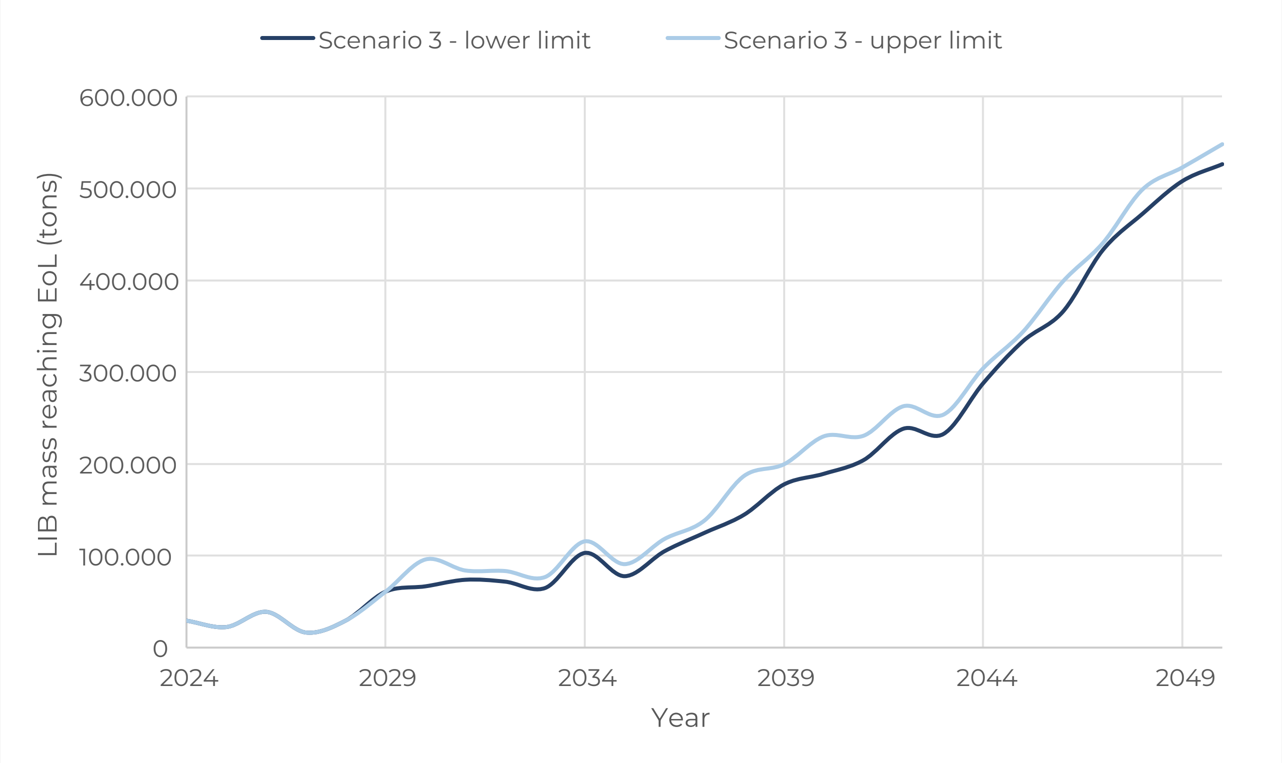
Table 6-8: Cumulative metal content of ULIB available for recycling (tons) - Scenario 3

Year	2030		2040		2050	
Limit	Lower	Upper	Lower	Upper	Lower	Upper
Al (tons)	3,570	3,970	16,090	19,200	46,400	60,410
Cu (tons)	7,540	8,370	33,980	40,530	97,950	127,520
Co (tons)	2,260	2,510	10,190	12,160	29,390	38,260
Ni (tons)	1,510	1,670	6,800	8,110	19,590	25,500
Li (tons)	1,390	1,540	6,260	7,470	18,040	23,490

Source: Own elaboration

Figure 6-7 and Figure 6-8 and show the yearly and cumulative mass of batteries reaching their end-of-life in the period 2024 - 2050.

Figure 6-7: Yearly ULIB mass reaching EoL - Scenario 3



Source: Own elaboration

Table 6-9 and Table 6-10 below show the most relevant values for Scenario 3 in terms of the yearly and cumulative battery mass available for second life applications in the years 2030. 2040 and 2050.

Table 6-9: Yearly ULIB mass available for reuse (tons) - Scenario 3

Year	2030		2040		2050	
Limit	Lower	Upper	Lower	Upper	Lower	Upper
Total	44,500	64,000	88,000	110,700	222,500	291,600

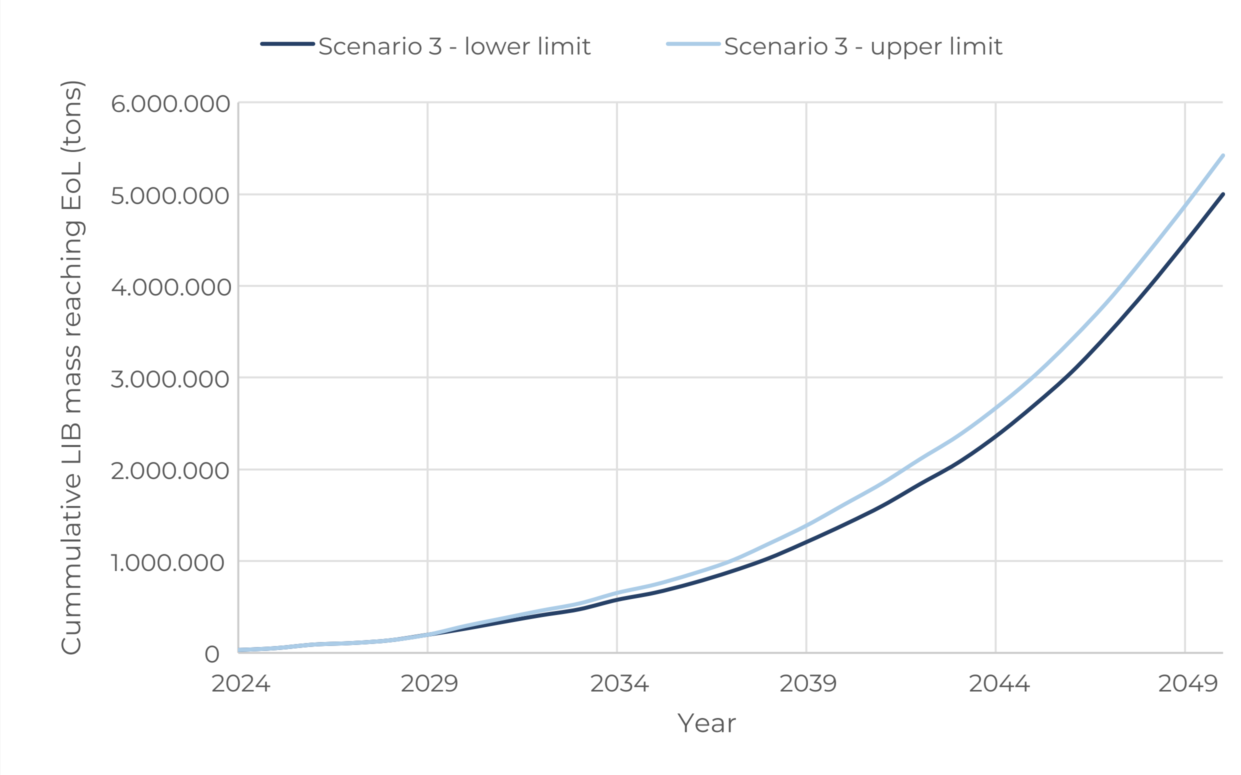
Source: Own elaboration

Table 6-10: Cumulative ULIB mass available for reuse (tons) - Scenario 3

Year	2030		2040		2050	
Limit	Lower	Upper	Lower	Upper	Lower	Upper
Total	176,400	195,900	794,800	948,100	2,291,300	2,983,000

Source: Own elaboration

Figure 6-8: Cumulative ULIB mass reaching ULIB - Scenario 3

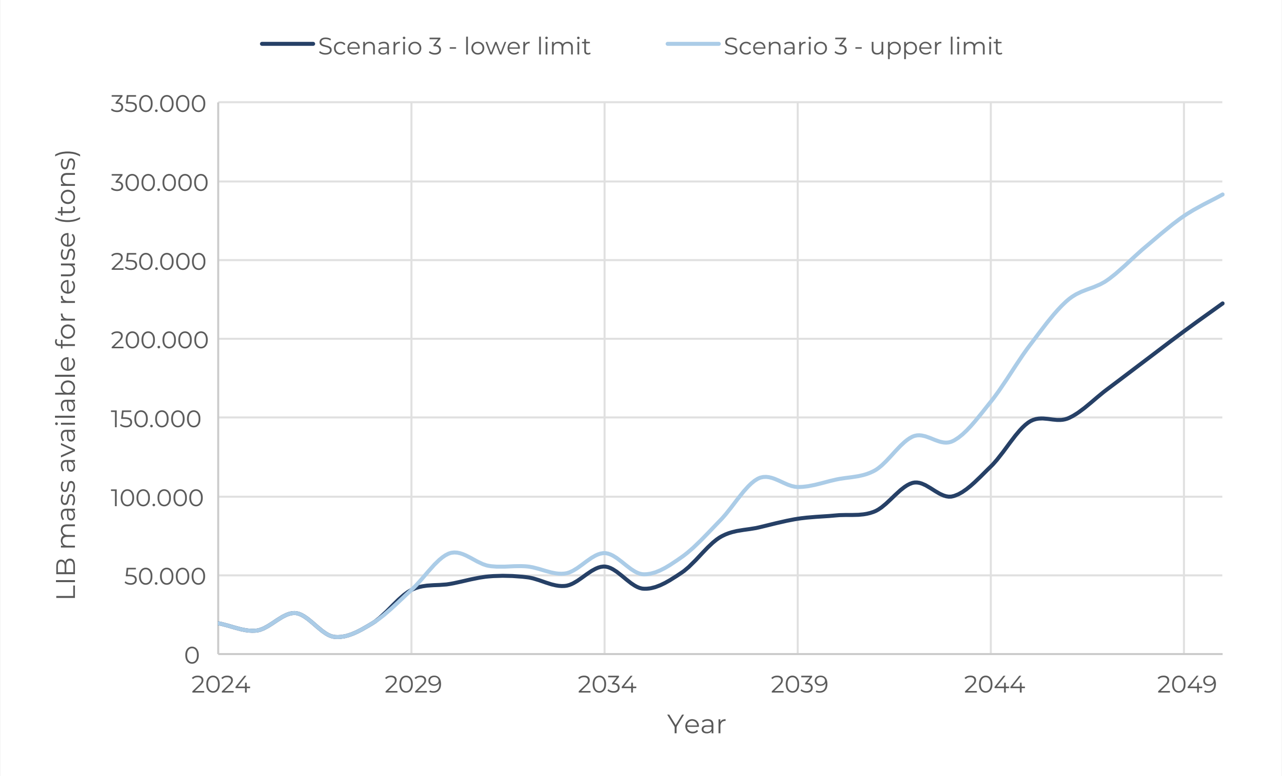


Source: Own elaboration

Figure 6-9 below shows the battery mass available for second life applications each year.

The baseline case has estimated that within the period 2024-2050 between 6.5 and 7.5 million tons of batteries from the solar PV, wind energy and EV sectors will reach their EoL. In scenario 3, by fostering good practices for collection, recycling and reuse, between 2.3 and 2.9 million tons of these batteries would have the potential to be reused in second life applications, which in turn would reduce the demand for new batteries, resulting in Scenario 3 having a reduced cumulative volume of batteries reaching their EoL in the period 2024-2050, within a range between 5.0 and 5.4 million tons.

Figure 6-9: Yearly ULIB mass available for reuse - Scenario 3



Source: Own elaboration

6.1.5 Comparison of scenarios

Table 6-11 to Table 6-14 below provide a comparison between scenarios with the baseline data, in terms of ULIB mass reaching EoL, potential battery mass collected, battery mass available for recycling and battery mass available for reuse. The values are cumulative up to the years 2030, 2040, and 2050 and consider the upper limits of the estimations.

Table 6-11: Comparison of ULIB mass reaching EoL across scenarios (tons)

Year	2030	2040	2050
Baseline (tons)	606,700	2,487,400	7,574,500
Scenario 1 (tons)	606,700	2,487,400	7,574,500
Scenario 2 (tons)	440,700	2,182,300	6,948,800
Scenario 3 (tons)	293,800	1,618,100	5,422,600

Source: Own elaboration

Table 6-12: Comparison of ULIB mass collected across scenarios (tons)

Year	2030	2040	2050
Baseline (tons)	-	-	-
Scenario 1 (tons)	60,700	248,700	757,500
Scenario 2 (tons)	195,900	948,100	2,983,000
Scenario 3 (tons)	244,800	1,185,200	3,728,800

Source: Own elaboration

Table 6-13: Comparison of ULIB mass available for recycling across scenarios (tons)

Year	2030	2040	2050
Baseline (tons)	-	-	-
Scenario 1 (tons)	4,900	23,700	74,600
Scenario 2 (tons)	97,900	474,100	1,491,500
Scenario 3 (tons)	183,600	888,900	2,796,600

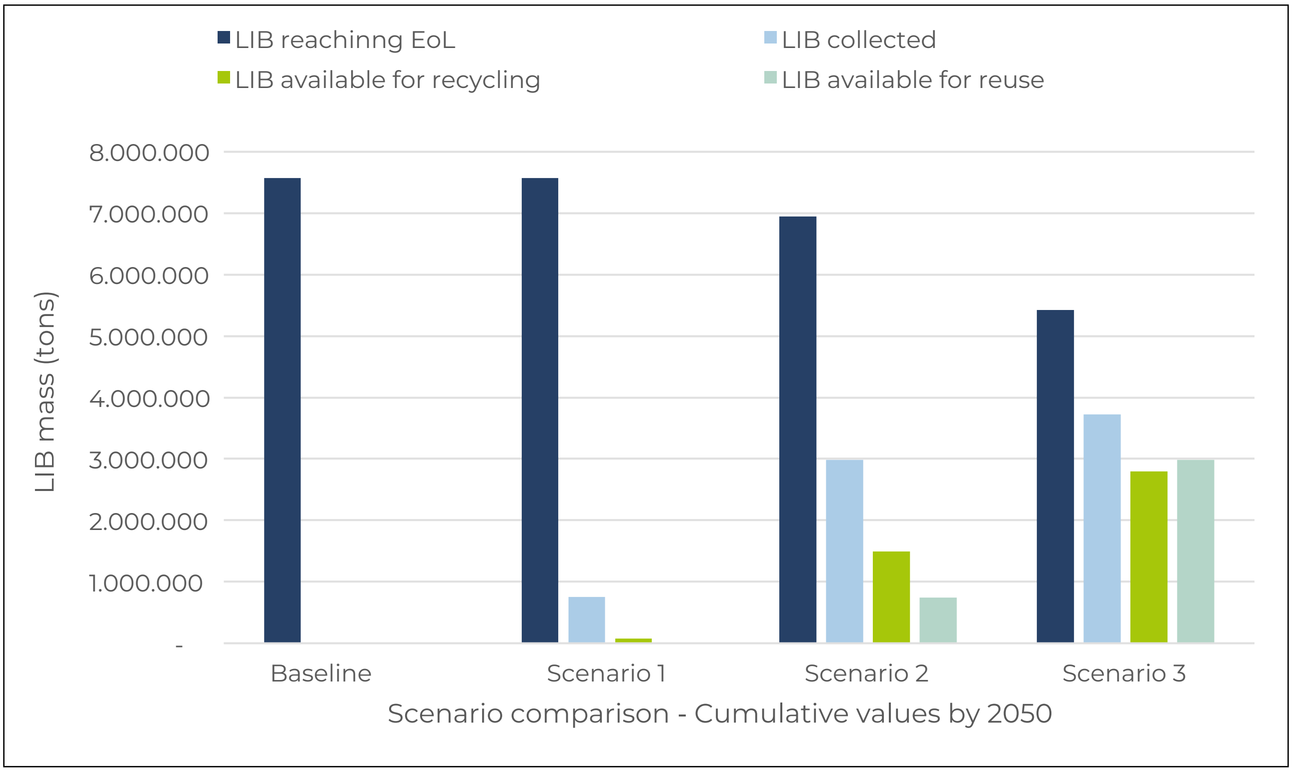
Source: Own elaboration

Table 6-14: Comparison of ULIB mass available for reuse across scenarios (tons)

Año	2030	2040	2050
Baseline (tons)	-	-	-
Scenario 1 (tons)	-	-	-
Scenario 2 (tons)	49,000	237,000	745,800
Scenario 3 (tons)	195,900	948,100	2,983,000

Source: Own elaboration

Figure 6-10: Scenario comparison



Source: Own elaboration

Figure 6-10 above presents a graphical comparison of the accumulated volumes of ULIB reaching EoL, collected and available for recycling and reuse applications by the year 2050 in the region.

The findings show that the adoption of best practices for the reuse and recycling of ULIB in the LAC region (Scenario 3) can lead to a reduction of 2.1 million tons of ULIB reaching the end of their life by the year 2050. In addition, the same practices will potentially enable the region to recycle up to 2.3 million tons of ULIB over the period 2024 to 2050.

6.2 Estimation of ULIB investment requirements

The values obtained in section 6.1 constitute the base for estimating the investment requirements, in particular, the yearly ULIB mass available for recycling and reuse in the years 2030, 2040 and 2050 represent the necessary recycling and reuse capacity required in the region for each scenario. These recycling and reuse (repurposing) capacities were used, along with literature data, to estimate the costs required to set up the required infrastructure.

6.2.1 Investment requirements for ULIB recycling

In the case of investment costs required for battery recycling, the values were estimated taking as a reference values estimated through surveys of ULIB recycling units in India conducted by the Indian Council for Research on International Economic Relations (ICRIER) and the International Institute of Sustainable Development (IISD) for facilities with a capacity between 5,000 and 7,000 tons per year where hydrometallurgical ULIB recycling takes place. It was established that a recycling unit of these characteristics require a capital expenditure (CAPEX) of approximately USD 10.15 Million (Dai et al. 2023). The same study provided an estimated of yearly operational expenditure (OPEX) costs of approximately USD 1,560 per ton of cathode material processed (Moerenhout et al. 2022; Neometals 2021). Table 6-15 and Table 6-16 below provide the CAPEX and OPEX required to recycle the battery mass estimated in section 6.1.

Table 6-15: CAPEX required to achieve the potential ULIB capacity (USD)

Year	2030		2040		2050	
Scenario	Lower	Upper	Lower	Upper	Lower	Upper
Scenario 1 (USD)	1,882,000	2,706,800	3,937,600	4,683,200	11,178,900	12,331,000
Scenario 2 (USD)	37,639,400	54,135,600	74,416,300	93,663,800	188,156,800	246,619,100
Scenario 3 (USD)	70,573,800	101,504,200	139,530,600	175,619,600	352,793,900	462,410,800

Source: Own elaboration

Table 6-16: Yearly OPEX required to achieve the potential ULIB recycling capacity (USD)

Year	2030		2040		2050	
Scenario	Lower	Upper	Lower	Upper	Lower	Upper
Scenario 1 (USD)	416,500	599,100	871,500	1,036,500	2,474,100	2,729,100
Scenario 2 (USD)	8,330,400	11,981,300	16,469,800	20,729,700	41,642,900	54,581,800
Scenario 3 (USD)	15,619,400	22,464,900	30,881,000	38,868,200	78,080,400	102,340,800

Source: Own elaboration

Under the scenario with the highest collection and recycling rates (Scenario 3) the required investment in recycling infrastructure by 2050 ranges between USD 353 million and 462 million, with estimated total operational costs for that year ranging between USD 78 million and 102 million. These values were calculated considering 2022 costs and are only indicative, as investment requirements are highly likely to change in the long term.

6.2.2 Investment requirements for ULIB reuse

Regarding the estimation of investment requirements for battery reuse, these were calculated considering values obtained from industry consultation for average costs for battery collection, transport and repurposing per ton of battery (Element Energy Ltd 2019). The values can be seen in Table 6-17 below.

Table 6-17: Reference values for ULIB reuse investment requirements (USD)

Values for investment calculations - ULIB reuse		
ULIB collection costs	333	USD/ton
ULIB transport costs	333	USD/ton
ULIB repurposing costs (for LFP batteries)	20	USD/kWh

Source: Element Energy Ltd (2019)

Using the reference values above and the yearly battery mass available for reuse, the required investment costs necessary to manage these ULIB volumes were estimated for each scenario as it can be seen in Table 6-18 below.

Table 6-18: Investment costs required to manage the ULIB available for reuse (USD)

Year	2030		2040		2050	
Scenario	Limit		Limit		Limit	
	Lower	Upper	Lower	Upper	Lower	Upper
Scenario 1 (USD)	-	-	-	-	-	-
Scenario 2 (USD)	47,459,000	68,258,800	93,830,600	118,099,400	237,244,400	310,958,700
Scenario 3 (USD)	189,836,000	273,035,300	375,322,300	472,397,700	948,977,500	1,243,834,800

Source: Own elaboration

According to these estimations and considering the necessary capacity to reuse the battery mass reaching end-of-life by 2050, the total investment cost required in battery reuse (repurposing) will range between USD 950 million and 1,240 million in the most ambitious scenario (Scenario 3). As in the case of battery recycling cost, this is an indicative estimation based on 2023 data and is highly likely to vary in the long term.

6.3 Assessment of potential economic benefits of adopting a safe and environmentally sound EoL management of ULIB

6.3.1 Potential economic benefits of ULIB recycling

The estimation of the economic benefits of ULIB recycling was conducted by assuming recycling efficiencies for each one of the relevant metals present in ULIB: Al, Cu, Co, Ni and Li and the average content of these metals in ULIB (See Annex IV). Using these values, it was possible to estimate the recoverable metal content in the batteries available for recycling in each scenario. These values were multiplied with the market values of each metal, presented in Table 6-19 Table below, to estimate their overall value.

It must be noted that these estimations are indicative based on data obtained in 2023, and only reflect the value of the metals contained and potentially recoverable in the batteries. It must be taken into consideration that raw material prices can vary significantly over time, along with the metal concentrations in the batteries, which have been assumed constant for these estimations. Furthermore, lithium is currently not often recoverable from a recycling process.

Table 6-19: Market price of metals present in ULIB (USD)

Metal	Price (USD/ton) (2021)
Al	2,658
Cu	9,688
Co	61,550
Ni	20,171
Li[31]	30,930

Source: Lima et al. (2022)

The estimations for the cumulative value of the metal content potentially recoverable from the ULIB mass available for recycling in the years 2030, 2040 and 2050 can be found in the Table 6-20 to Table 6-22 below. Each table represents one of the proposed scenarios.

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[31] Under current conditions, lithium is not often recovered from LIB recycling operations

Table 6-20: Cumulative value of metals in ULIB available for recycling (USD) - Scenario 1

Metal	2030		2040		2050	
	Lower	Upper	Lower	Upper	Lower	Upper
Al	253,100	281,100	1,140,700	1,360,900	3,288,800	4,281,600
Cu	1,947,700	2,163,100	8,777,600	10,471,500	25,306,000	32,945,300
Co	3,709,000	4,122,800	16,726,700	19,958,400	48,229,100	62,792,500
Ni	811,000	900,700	3,655,100	4,360,500	10,537,700	13,718,800
Li	1,145,500	1,272,100	5,162,200	6,158,400	14,882,800	19,375,500
Total (USD)	**7,866,400**	**8,739,900**	**35,462,400**	**42,309,700**	**102,244,300**	**133,113,700**

Source: Own elaboration

Table 6-21: Cumulative value of metals in ULIB available for recycling (USD) - Scenario 2

Metal	2030		2040		2050	
	Lower	Upper	Lower	Upper	Lower	Upper
Al	5,062,500	5,622,300	22,814,800	27,217,600	65,775,300	85,631,300
Cu	38,954,000	43,261,900	175,552,700	209,430,500	506,119,600	658,905,100
Co	74,244,900	82,455,700	334,597,500	399,167,400	964,646,900	1,255,850,800
Ni	16,220,900	18,014,800	73,102,300	87,209,400	210,754,300	274,376,000
Li	22,909,300	25,442,800	103,244,700	123,168,600	297,655,200	387,510,200
Total (USD)	**157,391,600**	**174,797,500**	**709,311,900**	**846,193,400**	**2,044,951,300**	**2,662,273,500**

Source: Own elaboration

Table 6-22: Cumulative value of metals in ULIB available for recycling (USD) - Scenario 3

Metal	2030		2040		2050	
	Lower	Upper	Lower	Upper	Lower	Upper
Al	9,492,100	10,541,800	42,777,800	51,033,000	123,328,700	160,558,700
Cu	73,038,700	81,116,000	329,161,300	392,682,100	948,974,300	1,235,447,100
Co	139,209,300	154,604,400	627,370,300	748,438,800	1,808,712,900	2,354,720,300
Ni	30,414,200	33,777,700	137,066,700	163,517,600	395,164,400	514,455,100
Li[32]	42,954,900	47,705,300	193,583,800	230,941,200	558,103,400	726,581,600
Total (USD)	**295,109,200**	**327,745,400**	**1,329,959,900**	**1,586,612,600**	**3,834,283,800**	**4,991,762,700**

Source: Own elaboration

These values show that under the most ambitious scenario (Scenario 3). The overall economic value of the potentially recoverable metals in the ULIB available for recycling in the period 2024-2050 ranges between USD 3,800 million and 5,000 million, based on the market price of these metals in 2021.

6.3.2 Potential economic benefits of ULIB reuse

The assessment of economic benefits of ULIB reuse was estimated exclusively for the EoL batteries from electric vehicles, as EV batteries are the most commonly battery type used for second life applications. The economic benefits were estimated by assessing the market value of the batteries available for second life applications and comparing it with the costs of purchasing an equivalent amount of batteries at the market price of a new battery. For each scenario where ULIB reuse was assumed (Scenario 2 and Scenario 3) four parameters were estimated:

- **Battery repurposing costs:** obtained my multiplying the overall capacity of the EV zatteries available for reuse (obtained from the battery mass and the energy density of EV batteries) and the battery repurposing cost of each kWh of ULIB storage. These costs include used ULIB testing, assembly, transportation and capital investments in infrastructure.
- **Market value of the second life batteries:** obtained my multiplying the overall capacity of the EV batteries available for second-life applications and the selling price of a second life battery.

- **Market value of new batteries:** obtained by multiplying the overall EV battery capacity available for second-life applications and the selling price of a new EV battery.
- **Additional value from EV battery reuse:** Obtained from the difference between the market value of new batteries and the market value of second life batteries after considering the repurposing costs.

These four parameters were estimated for the cumulative battery volumes from EVs available for second life applications in the years 2040 and 2050. This assessment was based on cost data from the year 2019 and provided by the United States National Renewable Energy Laboratory (NREL) Battery Second-Use Repurposing Cost Calculator (NREL 2023; Ambrose 2020). The cost values assumed can be found in Table 6-23 below.

According to this assessment by 2050, in the most ambitious scenario (Scenario 3), the EV batteries available for second life applications in Latin America and the Caribbean will have a market value of 16,800 million USD, incurring in repurposing costs of 4,100 million USD.

In comparison, the market value of an equivalent amount of new EV batteries in this period would be of 32,100 million USD, under these circumstances, the promotion of the reuse of EV batteries will have an additional value of approximately 11,300 million USD. It must be noted that these values are indicative and were calculated based on reference values from 2019. Therefore, these values are highly likely to change in the long-term.

Table 6-24 below presents the most relevant results of the assessment of economic benefits of repurposing ULIB from EV in the LAC region. The values for the key parameters are provided in USD and are cumulative up to the years 2040 and 2050 for the scenarios 2 and 3. Figure 6-11 illustrates the same parameters up to the year 2050. The values presented are based on the upper limit of the formulated scenarios.

Table 6-23: Reference values for estimating the economic benefits of ULIB reuse (USD)

Values for assessment of economic benefits of ULIB reuse		
Price of a new EV battery	157	USD/kWh
Selling price of a second life battery	82	USD/kWh
Repurposing costs (for LFP batteries)	20	USD/kWh

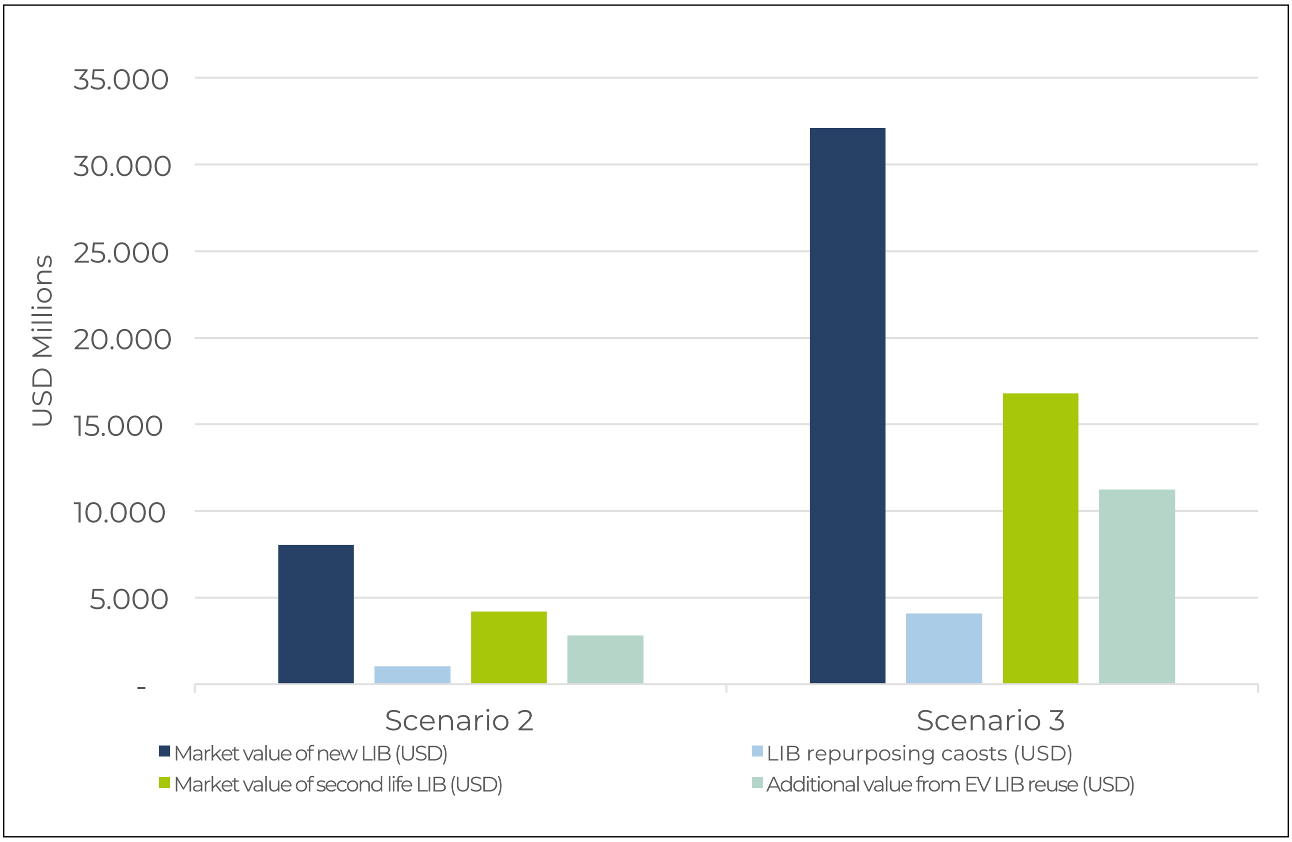
Source: (NREL 2023; Ambrose 2020)

Table 6-24: Assessment of cumulative economic benefits from ULIB reuse in the LAC region (USD)

Year	Parameter	Value	
		Scenario 2	Scenario 3
2030	Market value of new batteries (USD)	14,144,200	56,576,800
	Battery repurposing costs (USD)	1,801,800	7,207,200
	Market value of second life batteries (USD)	7,387,400	29,549,700
	Additional value from EV battery reuse (USD)	**4,955,000**	**19,819,900**
2040	Market value of new batteries (USD)	590,872,300	2,363,489,300
	Battery repurposing costs (USD)	75,270,400	301,081,400
	Market value of second life batteries (USD)	308,608,500	1,234,433,900
	Additional value from EV battery reuse (USD)	**206,993,500**	**827,974,000**
2050	Market value of new batteries (USD)	8,029,517,100	32,118,068,300
	Battery repurposing costs (USD)	1,022,868,400	4,091,473,700
	Market value of second life batteries (USD)	4,193,760,500	16,775,042,000
	Additional value from EV battery reuse (USD)	**2,812,888,100**	**11,251,552,600**

Source: Own elaboration

Figure 6-11: Overview of potential economic benefits of ULIB reuse by 2050



Source: Own elaboration

6.4 Potential environmental & social benefits from sound EoL management of ULIB

Sound end-of-life management of end-of-life lithium-ion batteries has various environmental and socio-economic benefits that cannot be quantified in economic terms. This mostly to the following fields:

6.4.1 Mitigation of social and environmental costs from pollution and fire risks

ULIB contain various substances of concern that, in case they are released from the batteries in an uncontrolled manner, may cause damage to human health and the environment (Sojka et al. 2020; Stahl et al. 2018). Moreover, various chemical reactions within the batteries can lead to the formation and emission of highly corrosive gases with significant eco- and human-toxicity potential. Sound EoL management of ULIB with effective emission prevention along the entire EoL management value chain can notably reduce such risks.

Moreover, ULIB with residual charge may be subject to thermal runaways[32] causing fires or even explosions (Dragonfly Energy 2022). Thermal runaways are commonly caused by damages to battery cells, e.g., through overcharging, deep-discharging, overheating or other physical stress and may occur immediately or with delays of several hours, days or even weeks. Subsequently, EoL ULIB are a high-risk waste stream and may cause significant (fire) damage if not managed properly.

While global data on related risks is not available, numerous anecdotical evidence indicate that EoL ULIB are a major concern of waste managers all over the world and repeatedly cause fire outbreaks and damages in waste transport and management facilities. Risks are commonly highest in situations where used ULIB are not collected and managed separately but are comingled with other waste streams, so that battery specific handling and waste treatment is difficult or even impossible.

In the United Kingdom waste LIB cause around 201 fire outbreaks annually, causing significant damages to waste operating facilities. Furthermore, 48% of the annual waste fires in the United Kingdom are caused by ULIB, which costs the country more than USD 200 million every year (Eunomia 2021). In 2018, the United States Consumer Product Safety reported over 25,000 overheating or fire incidents in the period 2013-2018, with at least 40 known fires within large-scale LIB energy storage systems (TÜV SÜD).

Secondary effects of such fire incidents are the loss other recyclable materials, significant greenhouse gas emissions and formation and emission of a wide range of pollutants to air, soil and water. Furthermore, ULIB fires and the release of toxic gases are a direct threat to the health of humans and other organisms, the surrounding areas can be affected by air transportation of fire debris and pollutants (Mrozik et al. 2021).

Therefore, effective EoL management of LIB, including the segregation of batteries from other waste types at source, the introduction of good practices for battery storage and fire safety and emission control measures is a necessary intervention to mitigate the health and environmental risks associated to the sub-standard management of LIB, especially in light on the increasing LIB volumes in the LAC region.

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[32] Chain reaction within a LIB cell that occurs when the temperature inside a battery reaches the point that causes chemical reactions to occur inside the battery and further producing more heat.

6.4.2 Development of associated value chains and employment generation

Beyond the economic benefits of promoting ULIB reuse and recycling, the adoption of global best practices for the EoL management will provide additional benefits to the region in terms of the development of value chains associated to LIB and the creation of employment.

Deploying the necessary infrastructure for the EoL management of LIB in the region will create both direct and indirect employment for battery collectors, recyclers, and companies in waste management and ULIB recycling and reuse applications. Globally, employment in the LIB value chain is expected to increase to a total of 10 million jobs by 2030, with more than half of these jobs in developing countries (Global Battery Alliance; WEF 2019). Furthermore, the value chain associated to the use phase and recycling (including electric vehicles and stationary applications) of ULIB has a potential for job creation of 5 to 10 times higher than the number of jobs directly or indirectly associated with battery (materials, cells to pack) production (Fraunhofer; EIT Raw Materials 2021).

Estimations from Tesla and the European Institute of Innovation and Technology (EIT) state that for each GWh of battery production, 140 jobs will be created in terms of manufacturing of cells and batteries, including the upstream value chain (material production) (Fraunhofer; EIT Raw Materials 2021; Tesla 2020), leading to estimations of between 700 and 1,400 jobs associated to use and recycling phases of ULIB per each GWh of battery manufacturing capacity.

Beyond 2030, the number of jobs required in applications associated to the use phase and recycling of ULIB, will increase beyond 10 million, while LIB manufacturing (from materials to cell and pack manufacturing) reaching 2 to 3 million jobs.

The introduction of recycling and reuse of ULIB will increase the demand for skilled labor in the areas of academic and technical know-how, including economists, environmental experts, technical staff and engineers in areas that include broad electro mobility applications, stationary storage applications, battery management systems (BMS), battery control and system integration, battery testing, battery application, handling of batteries and safety (Fraunhofer; EIT Raw Materials 2021).

The number of jobs in areas that are non-academic and non-technical is also growing, these jobs include sales and marketing of applications and end-products associated lo LIB. As of 2021, the rate of employed staff is divided in 20% academic and 80% technical to non-technical staff. As a result, there will likely be a long-term demand for professionals in the field of batteries, in Europe between 100,000 and 200,000 experts with academic background and longer-term experience in the battery sector will be required (Fraunhofer; EIT Raw Materials 2021).

Comparison of benefits of ULIB recycling and reuse with those generated by mining of lithium deposits

This panorama can be contrasted with the creation of jobs associated to the mining industry in LAC region, particularly in the lithium triangle region. The labor force required for mining requires both non-skilled and highly skilled personnel. The demand of skilled personal has increased due to an increase in the number of start-ups emerging from the mining sector in applications such as the use of biotechnology for mineral extraction and process automatization (Geref et al. 2016).

In the case of Chile, engineering services for the mining industry are transforming into engineering consultancy and the provision of services for the mining sector, with a focus on the enhancement of productivity and the reduction of costs. Examples of these services include equipment maintenance, repairs and overhaul of mining machinery. Furthermore, labor demand has increased as mining companies have their own repair centers for equipment maintenance and have extended them to neighboring countries (Geref et al. 2016).

The demand for skilled labor in the region has benefited from Research and Development (R&D) in new processes, along with the tendency of mining firms to shift their focus to their core business, while relying on strategic alliances with equipment manufacturers, suppliers and research centers for the development of innovative solutions and development of new technologies (Sánchez and Hartlieb 2020).

Furthermore, studies from the World Bank have confirmed the positive socio-economic impact of mining at the regional level. By 2018, the economic growth rate and per-capita income in the mining region of Antofagasta doubled the national average and contributed to the creation of jobs, contributing to the increase in income and the reduction of poverty.

The promotion of ULIB recycling and reuse has also the potential to reduce the pressure in the mining of raw material markets, particularly lithium, thus, supporting the alleviation of the problems associated to social conflicts associated to mining activities.

7. Recommendations and capacity needs

The challenges associated with the end-of-life management of lithium-ion batteries (LIB) in the LAC region have been divided into four main categories: i) policy and regulations; ii) awareness raising; iii) domestic recycling infrastructure and repurposing capacities and iv) capacity building. Based on these challenges and the best practices identified under the global review, several recommendations have been elaborated to contribute to the long-term sustainable EoL management of LIB.

The proposed recommendations have been categorized in two groups: primary interventions, which should be implemented in the short term and are meant to set the basis for the implementation of the secondary interventions, which are proposed within the medium to long term and aim to consolidate best practices in the region and require of a more solid regulatory framework and a more mature market.

As an overview, relevant recommendations include the incorporation of specific provisions for the management of lithium batteries as part of national policies and existing regulations in the region; the introduction of mandatory Extended Producer Responsibility (EPR) schemes; the creation of general awareness on the importance of an environmentally sound end-of-life management for lithium batteries; the establishment of cooperation among key stakeholders at the national and regional level and the creation of local capacities along the lithium battery value chain. The specific recommendations within the four categories are further elaborated in sub sections 7.1 to 7.4 below..

7.1 Policy and Regulations

Problem:

In the LAC region, many countries have laws and regulations in place for the handling and management of hazardous waste and e-waste, which are indirectly applicable to batteries[33]. However, there are only a few countries such as Colombia, Ecuador and Chile that have developed provisions that address the management of lithium batteries, and even in these countries, requirements such as collection systems, are mainly voluntary. Provisions for the collection and management of batteries from EVs are yet to be introduced.

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[33] In such cases, the regulations apply to various product groups, and often with few/limited LIB specific requirements

Furthermore, the existing regulations lack enforcement mechanisms to ensure compliance. Without a clear, consistent and mandatory set of requirements, most stakeholders lack motivation to engage and invest in sound EoL management operations. As ULIB repurposing and recycling is not per se a business case, companies do not develop an effective strategy for collecting, transporting, recycling, and reusing ULIB. In that context, it is important to introduce mandatory rules that producers and importers of batteries and battery powered equipment and installations (entities that bring batteries onto a national market for the first time) are held responsible to organize and finance environmentally sound collection and management of such batteries, in-line with the concept of Extended Producer Responsibility.

Specific challenges:

Until recently there had been no specific regulation in the region that addressed the proper EoL management of lithium batteries. This has led to poor management of their end-of-life, particularly in countries such as Mexico that lack regulations on battery EoL management as a whole. Furthermore, important instruments such as mandatory and enforced national or regional EPR systems are yet to be implemented, while in other countries, including Costa Rica, Colombia and Chile partly voluntary EPR schemes have already been introduced as part of their waste management laws.

Second life battery applications suppose additional challenges, as these approaches are new to the regional market and their use in applications such as energy storage still lacks regulation and standardization, making it difficult to develop business models which involve their use. Moreover, obtaining the necessary permitting requirements is a major obstacle to a regional solution for battery management in the region, as many local waste management operators lack the legal capacity to apply for them.

Recommendations - Primary interventions:

- Support public sector stakeholders in the integration of requirements for lithium batteries into the existing national regulatory framework for waste management, including the development of national strategies for the long-term safe and environmentally sound management of lithium batteries.
- Support key stakeholders (battery producers, governmental agencies, retailers, waste management companies, recyclers, and environmental organizations) in establishing and upgrading mandatory EPR systems for batteries, with clearly defined responsibilities and measurable collection, reuse/repurposing and recycling targets. This process requires stakeholder consultation and the establishment of incentives, penalties and provisions for the practical implementation of take-back schemes.

Recommendations - Secondary interventions:

- Support the implementation and enforcement of the regulatory framework for batteries, including provisions for the monitoring of EPR systems, the elaboration of technical standards for ULIB reuse and recycling and the achievement of national targets.
- Creation of specific provisions to regulate the use of second-life batteries that guarantee that these batteries are tested for compliance with quality standards before being resold. This regulation will assure end-users that second-life batteries comply with minimum quality requirements.
- Support public stakeholders in introducing mandatory recovery rates and elaboration of regulations which ensures that new batteries put on the market in the LAC region contain a certain share of recycled raw materials.

7.2 Awareness raising

Problem:

The increasing number of lithium batteries reaching their end-of-life in Latin America calls for the urgent development of national and regional approaches to ensure that these batteries will be collected and managed in a safe and environmentally sound manner. Addressing this problem and implementing appropriate solutions requires action from stakeholders along the entire value chain of lithium batteries, including battery, importers, regulators and end-users, which need to understand the nature of the situation and the need to take action.

Colombia and Costa Rica are good examples of good practices to raise awareness on the need for environmentally sound management of lithium batteries, with the establishment of a national working group on circular economy solutions for batteries in Colombia and the establishment of an executive committee e-waste integrated management integrated by local authorities in Costa Rica. These initiatives have potential for replication in other countries to facilitate stakeholder cooperation and the development of a sound regulatory framework.

Additionally, regional cooperation is a relevant factor in the development of solutions for the management of batteries, as it has the potential to facilitate the exchange of lessons learned and the development of regional approaches to the end-of-life management of LIB. There are already regional initiatives in place, which can be further supported, such as E-waste LATAM, which gathers Waste Electrical and Electronic Equipment (WEEE) managers and aims to improve waste management practices through and a collaborative working group dedicated to LIB.

Specific challenges:

The introduction of sustainable solutions for the management of lithium batteries requires a general awareness of key stakeholders on the current status of lithium battery management in the region, as well as the need for a long-term strategy and well-defined policy instruments to deal with this issue.

In the particular case of battery end-users, awareness raising is required on the available options to dispose of their used batteries. This situation must be addressed through social campaigns conducted by responsible stakeholders, such as PROs managing waste batteries[34]. These campaigns should sensitize end-users about the need to properly dispose of lithium batteries, the risks and consequences of unsound battery management and the available options for battery collection.

Recommendations - Primary interventions:

- Conduction of regional conferences and workshops dedicated to ULIB end-of-life management. These events will facilitate the introduction of best practices and new technologies, along with the discussion of challenges and the creation of regional platforms for collaboration and knowledge exchange.
- Design of a communication strategy to introduce the importance of proper management of lithium batteries and the available take-back schemes and other options for their collection through social campaigns. This strategy can be first implemented in those countries where the regulatory framework already addresses batteries and where there are EPR systems already in place (e.g., Colombia) using channels such as social media, websites and other communication materials. In the case of countries where the regulatory framework is not yet in place, national governments should design and finance communication strategies.

Recommendations - Secondary interventions:

- Encourage the creation of national groups for circular economy solutions for batteries and local policy-working groups. These groups are particularly relevant in those countries where the amount of ULIB will increase significantly in the next years and the regulatory framework for the management is insufficient. These national groups should promote discussions and facilitate cooperation between the private and public sector, including national authorities in the areas of environment, technology, business models, health and work, among others, thus promoting knowledge exchange, setting the base for stakeholder cooperation along the entire value chain for lithium batteries, and supporting the development of specific regulations for ULIB management.

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[34] PROs will only be responsible for awareness raising, if the applicable EPR regulation includes respective mandatory requirements.

7.3 Domestic recycling infrastructure and repurposing capacities

Problem:

Countries in the region have a limited infrastructure for reusing and recycling ULIB. There are few actors active on the local recycling and repurposing market, with some of them being new market players and others still at a pilot stage. As a consequence, used batteries must be transported long distances, with the additional transport costs increasing the overall recycling and repurposing costs, or exported for processing in other countries.

Additionally, there is a lack of functioning collection schemes, which represents a challenge to meet the collection rates of those countries that have already established them. Colombia is an example for this challenge, and even as the collection rate for portable batteries in the country increased by 20% in the period 2012 to 2021, the mandatory minimum collection rates were not met.

Battery collection remains a challenge for the region due to several reasons, including the lack of enforcement of mandatory collection rates, and in other cases, the absence of collection rates (in the case of large-scale batteries, such as the batteries for e-mobility, collection targets are just being introduced); Additionally, there is a limited number of active actors in ULIB recycling and repurposing, which face the challenge of obtaining enough ULIB volumes, this increases the distances the ULIB need to be transported, along with the transportation costs.

Specific challenges:

Even though in each case study country (Mexico, Costa Rica, Colombia, and Chile) at least one company is already recycling or repurposing ULIB, additional capacity will be required in the long-term to fulfill the region's requirements, particularly considering the region targets for the introduction of electric vehicles and additional capacity for solar and wind energy.

Some of the stakeholders interviewed highlighted the lack of investment for scaling existing pilot or small-scale plants as a challenge.

Recommendations - Primary interventions

- Support new and existing pilot projects for battery reuse and recycling in the region. The scope of support can include the provision of technical assistance for knowledge transfer and capacity building, these initiatives can be conducted in collaboration with national and international cooperation partners, universities and private sector stakeholders.
- Support the mobilization of investment and funding towards existing small and medium scale facilities which have proven to be able to conduct environmentally sound recycling or reuse for scale-up of their operation. At the same time technical assistance to ensure technology and knowledge transfer on operational best practices for ULIB end-of-life management should be provided.

Recommendations - Secondary interventions

- Support the existing regional networks for exchange of knowledge such as e-waste LATAM, including the provision of technical assistance to leverage resources, expand their outreach and further promote the creation of public-private partnerships and cooperation with local communities and non-governmental organizations.
- Establish mandatory standards which outline sound recycling and reuse operations. The develop-ment and enforcement of standards will ensure that only soundly operating facilities are approved and supported. Ideally, these standards should be designed and implemented at an early stage, while the infrastructure is still under development.

7.4 Capacity building

Problem:

Batteries for large-scale renewable energy generation and electric vehicles are relatively new to the regional market and have yet to reach their end-of-life, and ULIB recycling and reuse are still on their early implementation stages. Therefore, capacity building of stakeholders plays a relevant role in the development of appropriate regulations and the development of procedures for the collection, transport and EoL management of batteries and the establishment of such systems.

Specific challenges:

Many actors along the reverse value chain for ULIB lack sufficient knowledge on lithium batteries and the measures required to ensure a safe storage and transport. This has led to a series of misconceptions and is one of the challenges which prevents that batteries are collected and transported to recycling or reuse facilities.

Additionally, the development, enforcement and monitoring of a regulatory framework for used lithium-ion batteries requires significant capacity building along public sector stakeholders such as environmental agencies, ministries and enforcement agencies on best practices for the EoL management of LIB and how to monitor their compliance. The development of capacity among regulators is critical to the design of adequate regulation and the capacities to enforce it.

Recommendations - Primary interventions

- Organization of regional conferences and sessions with key stakeholders from the public, private and civil society sector along the value chain for ULIB to introduce the fundamentals of lithium batteries and best practices for a safe and sound end-of-life management.
- Offer specific training to stakeholders involved in the collection and transport of lithium-batteries on guidelines and procedures for a safe transport.
- Support to research and development initiatives and pilot projects that allow for the identification of mechanisms, methodologies and innovative approaches for the environmentally sound and safe EoL management of LIB.

Recommendations - Secondary interventions

- Training of national authorities and environmental agencies on best practices for the EoL management of ULIB and how to assess and enforce these best practices along the national regulatory frameworks, including monitoring and reporting criteria.
- Capacity building of collectors, transporters and public sector stakeholders on the due diligence and requirements on the Basel Convention for transboundary movement of waste, with the aim of streamlining and supporting the process and facilitate movement of used batteries to facilities in the region.

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Annex

Annex I. List of interviews and contact with regional stakeholders

INTERVIEWS	
Name of organization / company	Date of interview
Colombia	
Altero S.A.S.	January 18th, 2023
Orinoco	February 20th, 2023
Grupo Retorna	February 20th, 2023
Recobatt	February 21st, 2023
Costa Rica	
Fortech	November 28th, 2022
Soluciones Integrales en Reciclaje S.A. (Solirsa)	January 31st, 2023
Chile	
Kyklos	January 31st, 2023
Andes Electrónica	February 1st, 2023
Relitia	February 9th, 2023
Mexico	
Cámara Mexicana de Litio (CAMEXLI)	January 30th, 2023
Regional	
Reverse Logistics Group LATAM (RLGA)	25 de enero, 2023
OTHER PERSONAL COMMUNICATION	
Name of organization / company	Via e-mail/telephone
Recicla Electrónicos México (REMSA)	telephone
Inversiones Ecomineria SPA (Chile)	telephone
e-Waste LATAM	e-mail

Annex II. Stakeholder mapping - Full list of all identified actors in four selected countries

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
COLOMBIA					
Comisión Intersectorial de Cambio Climático	CICC	Government / public sector	Regulation		
Ministerio de Ambiente y Desarrollo Sostenible	Minambiente CO	Government / public sector	Regulation		
Ministerio de Energía y Minas	Minenergía CO	Government / public sector	Regulation		
Ministerio de Transporte	Mintransporte CO	Government / public sector	Regulation		
Ecocómputo	Ecocómputo	Civil Society / NGO	WEEE recycling	Collection	Grupo Retorna member
Pilas con el ambiente	Pilas con el ambiente	Civil Society / NGO	PRO	Collection	Grupo Retorna member

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Tronex	Tronex	Private Sector	Other		Primary battery manufacturer; partner of Innova and Recobatt; founder of Recopila
Asociación Nacional de Empresarios de Colombia	ANDI	Private Sector	Other		
Altero	Altero	Private Sector	ULIB recycling	Recycling (black mass level)	For more information, see Practice example 2
Auteco Mobility	Auteco	Private Sector	Other		
BATx	BATx	Private Sector	Reuse/ second life	Repurposing / Reuse	Startup for ULIB second life
Empresa de Energia de Bogotá (ENEL)	ENEL X	Private Sector	E-mobility promotion		
Gaia Vitare	Gaia Vitare	Private Sector	ULIB recycling	Sorting	Partner of Ecomineria (CL)

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Innova Ambiental	Innova	Private Sector	ULIB recycling	Recycling (black mass level)	Partner of Tronex and Recobatt. For more information, see Practice example 1.
Lito Colombia	Lito CO	Private Sector	WEEE recycling		
Orinoco	Orinoco	Private Sector	WEEE recycling		
Pcshek	Pcshek	Private Sector	WEEE recycling	Sorting	
Recobatt	Recobatt CO	Private Sector	Reuse/ second life	Repurposing / Reuse	Partner of Tronex and Innova. For more information, see Pratice example 1
Reconergy	Recoenergy	Private Sector	PRO		Grupo Retorna member
Recopila	Recopila	Private Sector	PRO	Collection	Founded by Tronex
Tecnologias Ecologicas SAS	Ecotec	Private Sector	WEEE recycling	Sorting	Altero supplier

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Comité Nacional de Residuos de Aparatos Eléctricos y Electrónicos (RAEE)	ACORRAE	Network	WEEE recycling		
Grupo Retorna	Grupo Retorna	Network	PRO	Collection	Includes Pilas con el Ambiente, Recoenergy, Ecocomputo
Mesa Baterías de Litio Colombia	Mesa ULIB COL	Network	Advocacy		
COSTA RICA					
Instituto Costarricense de Electricidad	ICE	Government / public sector	Regulation		
Instituto Nacional de Aprendizaje	INA	Government / public sector	Research	Repurposing / Reuse	Research on second life projects for electric vehicle batteries

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Ministerio de Medio Ambiente y Energía	MINAE CR	Government / public sector	Regulation		Project member: "hoja de ruta para gestión de baterías en CR"
Ministerio de Obras Públicas y Transportes	MINOT CR	Government / public sector	Regulation		
Ministerio de Salud	MINS CR	Government / public sector	Regulation		Project member: "hoja de ruta para gestión de baterías en CR"
LabVolta, Universidad de Costa Rica	LabVolta	Academic / Research	Research	Repurposing / Reuse	Research on second life projects for electric vehicle batteries
Asociación Costa Rica por Siempre	CR por Siempre	Civil Society / NGO	Advocacy		Project member: "hoja de ruta para gestión de baterías en CR"
Agencia Francesa de Desarrollo	AFD		Financing		Project member: "hoja de ruta para gestión de baterías en CR"

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Fortech	Fortech	Private Sector	ULIB recycling	Recycling (black mass level)	For more information, see Practice example 3
Instituto Automotriz ECACtrónica	ECAC	Private Sector	Research	Repurposing / Reuse	Research on second life projects for electric vehicle batteries
Lighting resources LLC	Lighting resources	Private Sector	ULIB recycling	Recycling (black mass level)	RLGA downstream company in CR
Quantum Lifecycle Partners	Quantum	Private Sector	WEEE recycling		Canadian company that bought plant in CR. Makes pre-treatment of batteries
Servicios Ecológicos MBBSA	MBBSA	Private Sector	WEEE recycling	Sorting	
Solirsa	Solirsa	Private Sector	ULIB recycling	Sorting	

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
CHILE					
Ministerio de Energía	MinEnergia CL	Government / public sector	Regulation		
Ministerio de Medio Ambiente	MMA CL	Government / public sector	Regulation		
Ministerio de Transporte y Telecomunicaciones	MTT CL	Government / public sector	Regulation		
Pontificia Universidad Católica de Chile (PECLAB)	PECLAB	Academic / Research	Research		ULIB-related research through Power & Energy Conversion Laboratory (PECLAB)
Universidad Católica del Norte	UCN	Academic / Research	Research		Project "Creation of a research and development pole in the lithium battery value chain" with SQM.

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Andes Electronics	Andes Electronics	Private Sector	Reuse/ second life	Repurposing / Reuse	For more information, see Practice example 6
Empresa Nacional de Telecomunicaciones S.A.	ENTEL	Private Sector	Other	Collection	Campaign "Reutiliza" with Kyklos
Inversiones Ecomineria SPA	Ecomineria	Private Sector	ULIB recycling	Recycling (material recovery)	For more information, see Practice example 4
Kyklos	Kyklos	Private Sector	Other	Collection	Works with Entel on collection campaign; initiated the CIR (Centro Inclusivo de Reciclaje) where some pre-treatment is done
LG Energy Solution	LG	Private Sector	Financing		Recycling investment project with SQM

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Midas	Midas	Private Sector	WEEE recycling	Recycling (sorting / pre-treatment)	
Recobatt	Recobatt CL	Private Sector	WEEE recycling	Sorting	Authorized WEEE manager that receives ULIB
Relitia	Relitia	Private Sector	ULIB recycling	Recycling (material recovery)	For more information, see Practice example 5
Sociedad Química y Minera de Chile S.A.	SQM	Private Sector	Financing		One of the biggest producers of lithium salts in CL; wants to promote lithium recycling in CL
SustrendLab	SustrendLab	Private Sector	Financing		Materials innovation company financially supporting Relitia
Tianqi Lithium	Tianqi	Private Sector	Financing		Chinese mining corporation that bought part of SQM

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Asociación Nacional de Reciclaje	ANIR	Network	ULIB recycling promotion		Collaborates with Kyklos
MEXICO					
Dirección General de Políticas para el Cambio Climático MX	DGPCC	Government / public sector	Regulation		
Gobierno de Hidalgo	Gob Hidalgo	Government / public sector	Regulation		ULIB recycling infrastructure projected in this state
Gobierno de la Ciudad de México: Secretaría de Medio Ambiente	SEDEMA	Government / public sector	PRO	Collection	Responsible for the "Ponte Pilas con tu Ciudad" campaign, batteries are delivered to SITRASA for processing
Gobierno de Puebla	Gob Puebla	Government / public sector	Regulation		ULIB recycling infrastructure projected in this state; financed by Renova Labs

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Gobierno de Querétaro	Gob Querétaro	Government / public sector	Regulation		Electromobility battery recycling infrastructure project with CAMEXLI, ANVES, and private investment
Instituto Nacional de Ecología y Cambio Climático	INECC	Government / public sector	Regulation		
Secretaría de Desarrollo Agrario, Territorial y Urbano MX	SEDATU	Government / public sector	Regulation		
Secretaría de Economía MX	SEC	Government / public sector	Regulation		
Secretaría de Energía MX	SENER	Government / public sector	Regulation		
Secretaría de Medio Ambiente y Recursos Naturales MX	SEMARNAT	Government / public sector	Regulation		

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Asociación Mexicana de Empresas de Gestión Energética	AMEXGEN	Civil Society / NGO	ULIB recycling promotion		Promoter group for ULIB recycling plant
Asociación Nacional de Vehículos Eléctricos y Sustentables	ANVES	Civil Society / NGO	E-mobility promotion		Promoter group for ULIB recycling plant
Cámara Mexicana de Litio	CAMEXLI	Civil Society / NGO	ULIB recycling promotion		Promoter group for ULIB recycling plant
Dendou Bikes	Dendou	Private Sector	Financing		Electric vehicle battery recycling plant announced
Dian Procesos Metalúrgicos S.A. de C.V.	Dian	Private Sector	WEEE recycling	Sorting	RLGA downstream company in MX
Ganfeng Lithium	Ganfeng	Private Sector	Financing		Chinese company that announced ULIB recycling plant project in Mexico

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Junta Entrega y Recicla	JER	Private Sector	PRO	Collection	App for collection of WEEE that is later processed by REMSA
Recicla Electrónicos México	REMSA	Private Sector	Reuse/ second life		For more information, see Practice example 7
Renova Labs	Renova Labs	Private Sector	Financing		Working with Government of Puebla to inaugurate recycling plant
Sistema Inteligente de Movilidad Sustentable	SIMS	Private Sector	E-mobility promotion		Promoter group for ULIB recycling plant
SITRASA		Private Sector	ULIB recycling	Recycling (black mass level)	
Telefónica Movistar México	Movistar	Private Sector	Other	Collection	WEEE collection in alliance with REMSA

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
REGIONAL / OTHER LATIN AMERICAN COUNTRIES					
Banco Interamericano de Desarrollo	BID	Intergovernmental organizations	Advocacy		
Comisión Económica para América Latina y el Caribe	CEPAL	Intergovernmental organizations	Advocacy		
Foro Económico Mundial	FEM	Intergovernmental organizations	Advocacy		
International Transport Forum	ITF	Intergovernmental organizations	Advocacy		
Movilidad Eléctrica Latinoamérica y el Caribe	MOVE	Intergovernmental organizations	E-mobility promotion		
Organización de las Naciones Unidad para el Desarrollo Industrial	ONUDI	Intergovernmental organizations	Advocacy		

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Programa de Naciones Unidas para el Medio Ambiente	PNUMA	Intergovernmental organizations	Advocacy		
Sustainable Cycles Programme	SCYCLE	Intergovernmental organizations	Research		
Centro y Red de Tecnología del Clima	CTCN	Scientific / Technical	Research		
Fundación Ellen Mac Arthur	EMF	Civil Society / NGO	Advocacy		
Fundación Konrad Adenauer	KAS	Civil Society / NGO	Advocacy		
BID Invest	BID Invest	Financial sector	Financing		
Global Environmental Facility	GEF	Financial sector	Financing		
Degraf	Degraf	Private Sector	WEEE recycling		eWaste LATAM member

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
NewLife	NewLife	Private Sector	WEEE recycling		eWaste LATAM member
Recicla Panamá	Recicla Panamá	Private Sector	WEEE recycling		eWaste LATAM member
Reverse Logistics Group Latin America	RLGA	Private Sector	Reverse logistics	Entire reverse logistics	Regional presence in AR, CL, CO, MX and PE
Scrap & Rezagos	Scrap & Rezagos	Private Sector	WEEE recycling		eWaste LATAM member
Vertmonde	Vertmonde	Private Sector	WEEE recycling		eWaste LATAM member
Coalición de Economía Circular de America Latina y el Caribe	CECAL	Network	Advocacy		
eWaste Latam	eWaste Latam	Network	WEEE recycling		Regional network of WEEE management companies in LAC
International Council on Clean Transportation	ICCT	Civil Society / NGO	E-mobility promotion		

Name	Acronym	Sector	Activity	Process level (ULIB)	Comments
Plataforma para la Aceleración de la Coalición de Economía Circular	PACE	Network	Advocacy		
Transformative Urban Mobility Initiative	TUMI	Network	E-mobility promotion		
Zero Emission Bus Rapid-deployment Accelerator	ZEBRA	Network	E-mobility promotion		

Annex III. Interview questionnaire (original - Spanish; adapted for individual interview partners)

Subject	Subtopic	Questions
End-of-life management practices	Recycling	What type of recycling process is implemented at the facility? **1.** Which steps take place (pre-treatment / treatment)? **1.1** What type of batteries are recycled at the facility? What is the most common type? **2.** Is there a significant number of batteries from electric vehicles or renewable energy storage processed at the facility? **2.1** What is your current processing capacity? Are there any plans for upgrading or expanding the facility? **3.** Is there enough demand for the setting of more LIB recycling facilities in the region in the upcoming years? **4.** Are the recycled materials sold locally or exported? If they are exported, where to? **5.** Are there further LIB recycling facilities in the country?
End-of-life management practices	Repurposing	**6.** Are there any other initiatives in the region (MX,CO,CL,CR) for the reuse or repurposing of lithium batteries? **6.1** If yes: What reuse/repurposing is conducted? (Which batteries are reused for what application?) **6.2** What scale/size do these initiatives have (pilot/ established business etc.)? **6.3** Could you provide us a contact to the initiative?

Subject	Subtopic	Questions
End-of-life management practices	Other EoL practices	**7.** What happens to those LIBs which are not recycled / reused? (Unsound disposal, export, not known etc.)
Regulatory environment	State of implementation and efficiency of national regulations and EPR schemes for batteries	**8.** What is the current regulatory framework for EoL management of LIBs (recycling + reuse) in the country? - EPR system for batteries - existing collection/recycling targets - safety requirements for reuse, etc… **8.1** Which implementation challenges (beyong regulatory framework) currently hinder the implementation of recycling / reuse businesses (best practices)?
Enabling environment and investment requirements		**9.** What is the current regional regulatory framework lacking to promote the implementation of best practices for the reuse and recycling of lithium batteries in the region?
Further contacts		**10.** Do you have contact recommendations for further interviews?

Annex IV. Methodology and approach for the development of ULIB regional outlook

An evaluation of the volume of lithium-ion batteries (LIB) that will reach their end-of-life (EoL) was conducted by gathering past and projected figures that reflect the behavior of the key sectors selected for the estimations: solar PV, wind energy and electric vehicles (EV). In the case of the projected values, these were given a lower and upper limit to take account of uncertainty and were then converted into battery capacity and mass (in tons) based on the energy density of a specific battery type.

1. Estimation of behavior of key sectors associated to the uptake of batteries

Three key sectors were selected as drivers for the demand for large-size batteries (solar PV, wind energy, and EVs). The historical data for these sectors were obtained from different sources, including the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), and the E-bus radar platform (IEA 2022b; IRENA 2022a; C40 Cities; P4G; ICCT 2023), and were collected for the entire region.

Renewable Energy

The approach taken to estimate data for the period of 2023-2050 for renewable energy applications differed depending on the application. Data from sources such as the International Renewable Energy Agency (IRENA) and the Asia-Pacific Economic Cooperation (APEC) for the years 2030, 2040, and 2050 were used in conjunction with historical data to create a polynomial regression.

This regression was then used to calculate the yearly growth of installed capacity for solar PV and wind energy. To account for any uncertainty, lower and upper limits were provided for the values based on different scenarios (IRENA 2022b; APERC and The Institute of Energy Economics, Japan 2019), specifically the scenarios developed by IRENA in the Global Renewable Outlook report, the Planned Energy Scenario (PES) and the Transforming Energy Scenario (TES).

The polynomial equations that describe the yearly growth of the installed capacity for solar and wind energy are provided below, due to the sensitivity of the equation, it is necessary to use many decimal points to obtain accurate values.

- Solar energy installed capacity - lower limit
  $y = -4.9299930363E+00x3 + 3.0061640354E+04x2 - 6.1095379690E+07x + 4.1384184896E+10$
- Solar energy installed capacity - upper limit
  $y = -8.2115686604E+00x3 + 5.0121581109E+04x2 - 1.0196527137E+08x + 6.9136871505E+10$
- Wind energy installed capacity - lower limit
  $y = -2.5074478249E+00x3 + 1.5267081488E+04x2 - 3.0980274555E+07x + 2.0951798080E+10$
- Wind energy installed capacity - upper limit
  $y = -4.4576172250E+00x3 + 2.7162001001E+04x2 - 5.5162402633E+07x + 3.7337760666E+10$

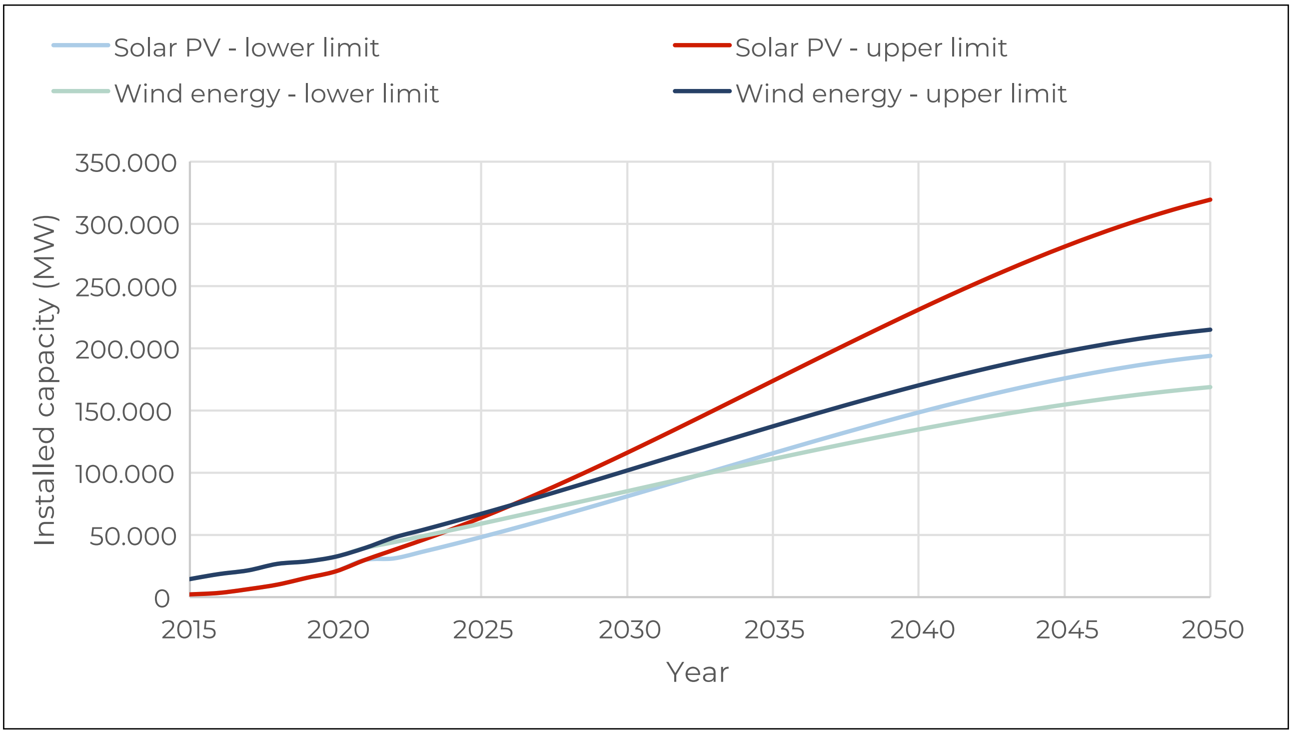
The resulting installed capacity values are presented below by providing the estimated installed capacity until 2050 for wind and solar PV, considering the lower and upper limits.

Estimated installed capacity for solar PV and wind energy in the LAC region

Year	2030	2040	2050
Solar PV installed capacity (MW) - lower limit	87.700	143.000	195.300
Solar PV installed capacity (MW) - upper limit	126.300	224.300	321.000
Wind energy installed capacity (MW) - lower limit	90.700	131.000	169.700
Wind energy installed capacity (MW) - upper limit	111.300	164.300	216.300

Source: Own elaboration

Estimated installed capacity for solar PV and wind energy in the LAC region



Source: Own elaboration

Electric vehicles

In the case of electric vehicles, the estimated values were divided into two sectors: light vehicles and electric buses. Light vehicles include battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). The approach for estimating the sector behaviors were similar to the one implemented for renewable energy, using historical data and available forecasted data to estimate the yearly growth. In this case, the sales of light EVs in the entire region by 2050 are forecasted as 45 Million according to the United Nations Environment Programme (UNEP 2016). The research conducted by the consultants showed that by 2021 there were approximately 33,300 EVs in the region, considering both light EVs and e-buses.

The yearly growth of light EV sales was estimated using a method that combines a regression of the baseline data with a forecasting equation that uses an S-Curve function[35], this method was designed specifically to estimate the uptake of EVs as it considers both the regression of the historical data with the approach of the S-Curve function, which forecasts the uptake of technologies that are new to the market, which is the case for electric vehicles (Islamovic and Lind). The overall form of the equation, along with the key parameters it entails, is presented below:

$$FC(t) = ((T_f - t)/(T_f - 2017))^5 * FC_{pol}(t) + (1 - ((T_f - t)/(T_f - 2017))5) * Sales_{tot} /(1 + e^{-a(t - T_0)})$$

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[35] An S-shaped curve (or adoption curve) represents the cumulative rate at which a population adopts a product, service or technology over time.

Where:

- FC(t) = forecasted value of a particular year t
- T_f = final year (2050)
- t = particular forecast year (i.e., 2022-2050)
- 2017 - the first year of recorded historical data
- FC_{pol} (t) = the trend line equation of the polynomial time series function obtained from the historical data from 2017-2021 $y = 5.4222222222E{+}02x^3 - 3.2817713452E{+}06x^2 + 6.6209167444E{+}09x - 4.4525287943E{+}12$
- $Sales_{tot}$ = Expected sales by the final year (2050) - assumed 45 million
- α = the increase of sales when 50% of total sales is reached, which is equivalent to the gradient of the S-curve function.
- T_0= The year when sales are 50% of the $Sales_{tot}$ value.
- This equation requires the assumption of two key parameters, a and T_0.
- α represents the increase of sales when 50% of total sales is reached and
- T_0 is the year when sales are 50% of the total value,

Different values were assumed for these parameters to represent the upper and lower limit of the estimated values shown in the table below.

Parameters used to define lower and upper limit of the estimation of the number of EV

Limit	T_0	a
Lower	2042	0.29
Upper	2040	0.33

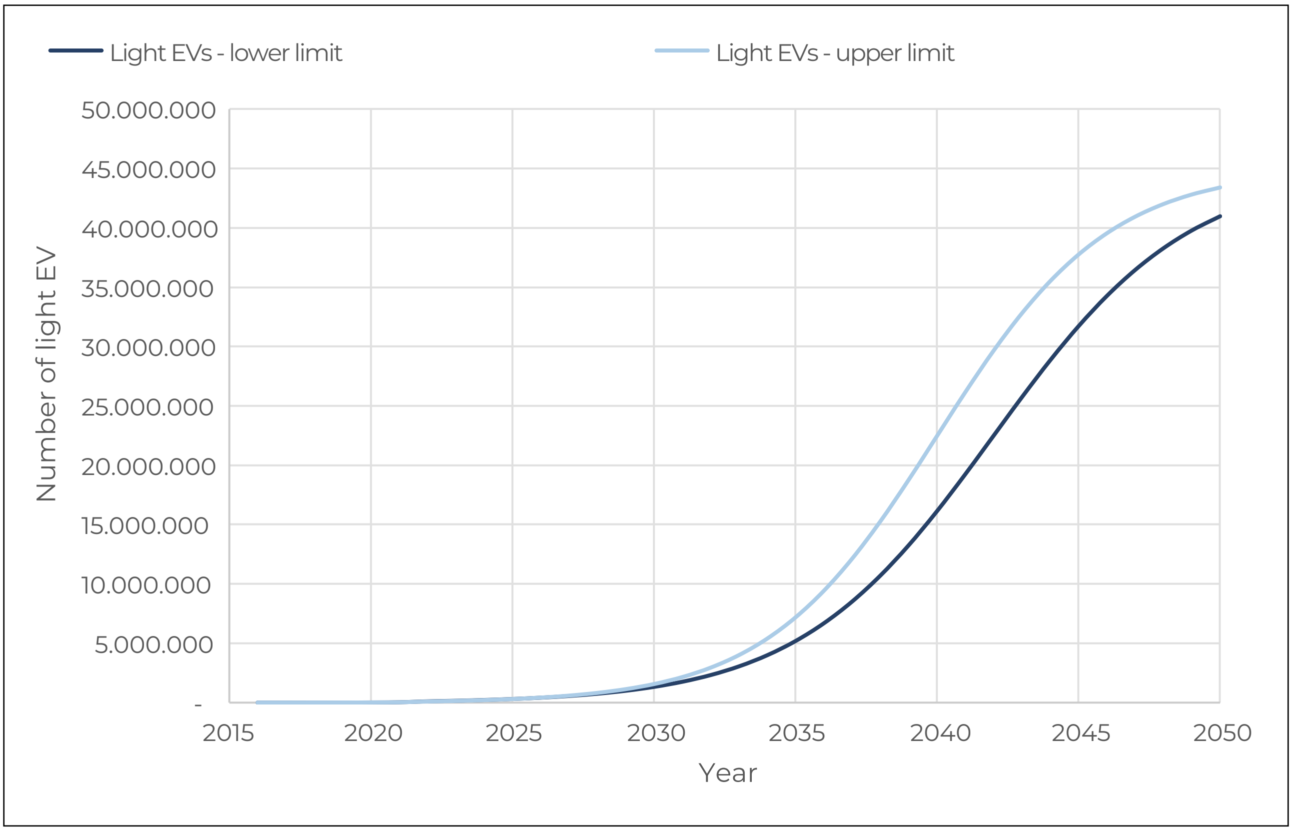
Source: Own elaboration

The figure below shows the upper and lower limit of the estimated number of light EVs in the LAC market.

In the case of E-buses, due to a lack of information consolidated at the regional level, the values were estimated by assuming different compound annual growth rates (CAGR) based on available market information and on the available country goals for the introduction of EVs into the public transport fleet (Mordor Intelligence 2023).

- The lower limit assumes a CAGR of E-buses in the region of 15% in the period 2022-2028, based on the CAGR forecasted for the region in the period 2018-2028 (Mordor Intelligence 2023), this annual growth is mainly driven by Colombia and Chile, the regional leaders in the introduction of E-buses, reaching their national targets (see chapters 4.2.1 and 4.2.3, after achieving these goals the CAGR decreases to 10% for the period 2028-2040, and then to 5% in the period 2040-2050. Assuming that after the market leaders achieve their targets the yearly growth will decrease and be driven by other countries, such as Mexico, and by 2040, when most of the countries have achieved their goals the growth will further decrease.
- The upper limit assumes that the 15% CAGR lasts longer (until the year 2037), as other countries modify their targets towards a more ambitious introduction of E-buses, followed by a steeper reduction towards a CAGR of 5% in the period 2037-2050.

Estimation of the number of light EV in the LAC region



Source: Own elaboration

2. 2. Estimation of battery mass from key sectors

Following the estimation values for the three main sectors over the period 2022-2050, the yearly change in each one of the key sectors was then calculated. This calculation looked at the yearly added new solar PV and wind energy installed capacity and the number of new electric vehicles being introduced to the market. This data was then converted into the respective battery capacities and, based on the type of battery (chemistry), converted into the respective battery mass.

▶ Battery mass from solar PV

To convert the new projected solar PV installed capacity into LIB storage requirements, it was assumed that the batteries will be mainly used as grid-scale storage, providing several system services, from short-term balancing and operating reserves and ancillary services for grid-stability (IEA 2022a).

As next step the ratio between new PV installed capacity globally and additional LIB grid storage was calculated (IEA 2022a; IRENA 2022a), this rate resulted in approximately 0.02395 Megawatt (MW) LIB storage per MW of solar capacity added globally, including a 90% factor to account for the share of newly added energy storage that corresponds to lithium batteries as of 2018 (excluding hydropower storage) (IEA 2020), this rate was then assumed to remain constant until 2050.

The total MW of battery storage[36], expressed in terms of system size were then converted into Megawatt-hour (MWh) of battery storage capacity[37] by using a ratio of 4 MWh of battery capacity per MW of battery system size for utility-scale battery storage (Lazard 2018).

The battery storage in MWh was then converted into mass using an energy density of 180 Wh/Kg, assumed as an average density for LFP batteries (Battery University 2010).

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[36] Power rating of the system (i.e. system size)

[37] Energy content on a single battery at 100% charge

Battery mass from wind energy

The volumes of LIB associated to wind energy were estimated using two different approaches, as lithium batteries are used with two purposes, one of them is for grid-scale storage, associated with providing general system services to the grid, as it is the case with solar PV, by estimating the global ratio between newly added wind energy capacity and newly associated grid-scale storage, this range was assumed to be replicated in the LAC region.

However, batteries are also employed at the turbine level to store the excess energy generated by the turbine, prevent overloads and maintain the turbines working at an optimally established range, the ratio of LIB storage requirements per MW of wind energy capacity installed was obtained from a battery manufacturer (Tycorun Energy 2023).

For those battery volumes associated to grid-scale storage of new wind energy installations, the same approach as for solar PV estimations was used, with a ratio of 0.0036 MW LIB storage required for each MW of additional wind energy capacity. The battery storage in MWh was then converted into mass using an energy density of 180 Wh/Kg, assumed as an average density for LFP batteries (IEA 2020; Battery University 2010).

For the battery mass associated to the turbine operation, the wind energy installed capacity was converted directly into battery mass, with a ratio of 12.5 Kg of LIB mass required for each MW of wind energy capacity installed for LFP batteries, as provided by a battery manufacturer (Tycorun Energy 2022).

Battery mass from electric vehicles

The estimation of LIB mass was separated in estimations for light vehicles and estimations for E-buses. In the case of light vehicles, it was conducted assuming that the market shares for Battery Electric Vehicle (BEV) and Plug-in Hybrid Electric Vehicle (PHEV) will remain constant until 2050 at the same values they had during the period 2016-2021, being approximately 43% BEV and 57% PHEV (IEA 2022b).

After estimating the number of light EV per technology, the number of vehicles was multiplied with the average battery capacity for each type of vehicle, 43 kWh for BEV and 10.6 kWh for PHEV (Statista 2023). The battery capacity was then divided by an energy density of 215 Wh/Kg assumed for EVs, based on an average value for NMC and NCA batteries (ArenaEV 2022).

In the case of E-buses, it was assumed that each bus requires a battery capacity of 480 kWh (used for a 12 m electric bus), obtained from a manufacturer (MAN Truck & Bus 2023), the capacity was then divided by an energy density of 180 Wh/Kg.

3. Estimation of LIB entering the market as replacement

After estimating the new LIB mass entering the regional market each year, the volumes of batteries reaching their end-of-life (EoL) were calculated by assuming LIB lifetimes for the different applications.

In addition to converting the key sector data into battery mass and estimating the battery mass reaching EoL every year, it is necessary to consider the replacement of these batteries. This entails assuming the frequency of replacement of LIB for the key applications, as shown in the table below:

Assumed lifetime and number of replacements for LIB used in key sectors

Type of battery application	Battery lifetime before replacement	Number of replacements during application lifetime	Overall lifetime of application
Renewable energy (RE) storage	8 years	2	24 years
Electric vehicles (EV)	10 years[38]	1	20 years

Source: Own elaboration

As an example, the LIB mass entering the regional market for EV applications in 2023 will be used for 10 years, until 2033, when that battery mass will reach its EoL, and an equivalent battery mass will enter the market to replace the batteries in those EV, this batteries, in turn, will reach their EoL in 2043, after when it is assumed that the EV will be taken out of circulation and no further EV replacement will be required.

Once the battery lifetime and the number of replacements has been accounted for it is possible to estimate the battery mass reaching its EoL every year as well as the cumulative material volumes for each year. The battery mass (in tons) reaching their EoL every year in the period 2024-2050, assuming that no ULIB reuse takes place, constitute the baseline data for the estimations and the scenario analysis.

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[38] EV battery lifetime of 10 years assumed considering the typical warranty period offered by EV manufacturers (8-10 years) and to account for both BEV and PHEV batteries, as PHEV batteries have a shorter lifespan.

Three different scenarios were then developed, each with varying rates of battery collection, recycling, and reuse. This allowed for the estimation of the potential battery volumes available for second-life applications (reuse) as well as the potential material mass available for battery recycling.

4. Formulation of scenarios

After obtaining the baseline data, three different scenarios were formulated to provide different estimations for the ULIB mass collected, available for recycling, and available for reuse. Three parameters were assumed to formulate the scenarios, as follows:

- ULIB collection rate: The percentage of the total ULIB mass that will be collected every year and used for battery recycling and second life applications.
- ULIB recycling rate: The percentage of the collected ULIB mass that will be available for recycling every year.
- ULIB reuse rate: The percentage of the collected ULIB mass that will be available for second life applications (reuse) every year.

These parameters have been assumed to remain constant throughout the period 2024-2050.

By assuming values for the three parameters, three scenarios were formulated, and the battery mass collected, available for recycling and available for reuse were estimated for each scenario. The table below provides an overview of the assumptions for each scenario.

Parameters assumed for the definition of scenarios

Scenario	ULIB collection rate (%) of the total EoL LIB	ULIB recycling rate (%) of the collected EoL LIB	ULIB reuse rate (%) of the collected EoL LIB
Scenario 1	10%	10%	0%
Scenario 2	50%	40%	20%
Scenario 3	90%	42%	44%

Source: Own elaboration

The three scenarios were formulated to provide a wider set of estimations:

- Scenario 1 estimating a lower collection rate, a low recycling rate and no reuse of batteries
- Scenario 2 with an intermediate collection rate between scenarios 1 and 3, considering both recycling and reuse of ULIB, with a larger battery mass undergoing more recycling than reuse.
- Scenario 3 with a larger collection rate and a larger battery mass undergoing reuse and recycling applications.

5. Estimation of metal content in the ULIB available for recycling

After the battery mass reaching EoL has been estimated, the percentages of batteries collected and available for recycling were used to estimate the volumes of batteries that would be available for recycling in each scenario.

The battery mass available for recycling is obtained by multiplying the battery mass (in tons) and the assumed percentages for battery collection and battery recycling.

Afterwards, knowing the battery mass available for recycling, it is possible to estimate the metal content of the batteries by assuming percentages of metal content (according to the different battery chemistries) and the potential recycling efficiencies of the recycling process. However, **these value reflect the potentially recoverable metal content in the ULIB, and not materials directly derived from the recycling process**. As additional considerations, such as the type of recycling method and the economic feasibility of the process should be accounted for.

The table below provides the assumed percentages on metal content (in LFP and NMC batteries) and the material recovery efficiencies of the recycling process.

Metal content in ULIB cells and material recovery efficiency from the ULIB recycling process

Metal	Content in LFP battery cells	Content in NMC battery cells	Material recovery efficiency
Al	4%	3%	100%
Cu	8%	7%	100%
Co	0%	6%	95%
Ni	0%	4%	95%
Li	2%	2%	70%

Source: (Weyhe and Yang 2018; Zheng et al. 2018)

6. Estimation of ULIB reuse applications

After the yearly tons of ULIB available for reuse were estimated, it was assumed that these batteries will have a lifetime of ten years, based on the typical lifetime of second life battery applications (NITI Aayog and Green Growth Equity Fund Technical Cooperation Facility 2022). After this period, these batteries will reach their EoL.

To account for battery reuse applications in the yearly estimations for scenarios 2 and 3, the battery mass available for second life applications every year was subtracted from the yearly mass of batteries reaching their EoL in the baseline case, resulting in smaller battery volumes reaching their EoL every year and reflecting the reduction in the demand for new batteries resulting from reuse applications.

The yearly number of reused batteries (from second life applications) reaching EoL was then added to the included to account for the EoL of reused batteries in scenarios 2 and 3, as it is depicted in the equation below:

ULIB reaching EoL in scenarios 2 and 3 (tons) = ULIB reaching EoL in baseline - ULIB available for reuse + reused ULIB reaching EoL[39]

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[39] All values provided in tons and for every year in the period 2024-2050