OCTOBER 2025

Strategic Pathways for Battery-Electric Container Handling Equipment Battery Circularity

Value add versus compliance risks

ZEPA Zero Emission Port Alliance

About this document

This document aims to help the container terminal industry anticipate and manage the growing challenge of **end-of-life (EoL) batteries from battery-electric container handling equipment** (BE-CHE), providing visibility into the **associated logistical, regulatory, and compliance risks and opportunities**. It shares insights on **extending lifetimes, reuse and recycling of batteries**, and concludes in four recommended actions for terminal operators and OEMs to **increase battery circularity.**

About ZEPA

The Zero Emissions Port Alliance (**ZEPA**) was formed expressly to **accelerate port decarbonisation**. Decarbonised ports are our vision. Container terminals are our focus because the electrification of container-handling equipment is a particularly powerful lever for decarbonising ports as it has interdependencies with other segments. ZEPA aims to **accelerate take-up of battery-electric container handling equipment** among terminal operators by making BE-CHE **affordable and accessible by 2030**.

The Secretariat is hosted by **Systemiq** and is responsible for managing ZEPA's day-to-day operations and coordinating member activities, including research and analysis, deliverable creation, project management, and industry engagement.

SYSTEMIQ

1

Container terminal industry must prepare for an increase in end-of-life batteries, which bring minimal economic impact but significant logistical and compliance risk.

2

Extending battery life is feasible yet operationally challenging.
Local Reuse offers value for LFP[1] but is more challenging for NMC[2] chemistries.
Recycling will be costly yet (legally) required in some geographies, leading to high gate fees (especially for LFP).

As the global container terminal industry is transitioning to Battery Electric Container Handling Equipment (BE-CHE), a growing number of battery systems will begin reaching their end-of-life from 2032 onwards, posing a small **economic** but significant **logistical and compliance** risk.

- **Small economic risk:** Circularity levers have limited impact on BE-CHE total cost of ownership (TCO), with a 10% gate fee or salvage value changing the TCO by only ±0.10–0.25%.
- **Significant logistical and compliance risk:** Global and regional regulations largely aim to incentivise and mandate battery reuse and recycling. For example, in the EU at least 50% of a battery's weight must currently be recycled—this will increase to 65% for lithium-ion from 2026 onwards.

	LFP	NMC
Extend: Smart charging, Battery Management System (BMS) upgrades, and predictive analytics can extend battery life and strengthen the business case—but implementation is operationally challenging, as port operations are optimised for container throughput and turnaround time, not battery lifetime.	⊗ Challenging strategy	⊗ Challenging strategy
Reuse: While reuse by OEMs and Terminal Operators (TOs) within ports is often operationally challenging, batteries can be sold to external reuse parties to pool end-of-first-life batteries, e.g., setting up Battery Energy Storage Systems (BESS). LFP's high cycle life makes it well suited for reuse. For NMC, batteries are difficult to reuse due to their complex chemical makeup and lower cycle life.	⊕ Advantageous strategy	⊕ Possible strategy
Recycle: Support – for example via Extended Producer Responsibility (EPR), where manufacturers are financially responsible for end-of-life treatment – will likely be needed. For NMC, assume 0 costs or low costs of ~EUR 0.5/kg as NMC batteries have a higher recovery value due to high-value cobalt and nickel content. For LFP, assume no salvage value, but price in high gate fees as the baseline. LFP batteries have more than 60% lower intrinsic value compared to other battery chemistries as they do not contain high-value metals such as cobalt or nickel. Unless lithium prices rise (which is unlikely) LFP will offer negative recycle economics. Few LFP recycling plants are economically viable, with only some (Chinese) recyclers recovering value without subsidy.	⊕ Possible strategy	⊕ Advantageous strategy

Note: [1] LFP is an abbreviation for lithium ferrous phosphate or lithium iron phosphate. [2] NMC stands for Nickel Manganese Cobalt.

⊗ Challenging strategy ⊕ Possible strategy ⊕ Advantageous strategy

3

Recommended actions for terminal operators and OEMs are to invest in understanding the space, build partnerships, pilot reuse and recycling models, and engage early with policy advocacy

Four recommended actions:

Understanding

The battery market & technologies and opportunities for circularity are marked by frequent changes and overall volatility, making it key to keep pace with developments.

Piloting

Explore second-life uses for retired BE-CHE batteries—such as onsite storage or regional backup power—by piloting with reuse specialists and other local EV users (as cross-border transport adds cost and complexity).

Partnering

Embed take-back or recycling clauses into purchase and/or leasing contracts and collaborate with logistics providers and recyclers to set up regional reverse logistics for used batteries. Terminal operators acting early will secure recycler partnerships and safeguard future access.

Policy advocating

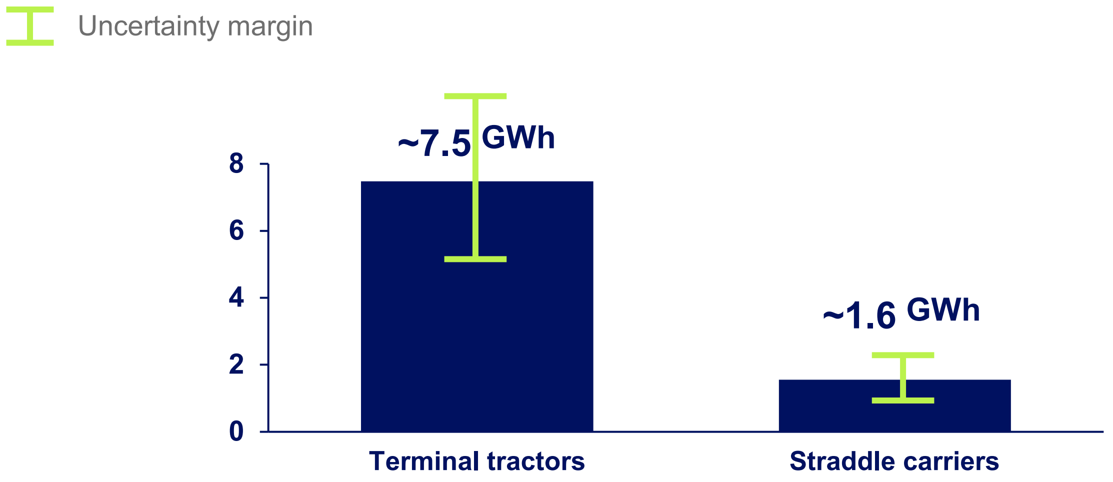
Collectively advocate for support for clear End of Life (EoL) standards, battery passports, and investment in local recycling and reuse infrastructure to shape a circularity-friendly regulatory environment.

Table of contents

From 2032 onwards, end-of-first-life port equipment batteries will emerge, creating risks for OEMs and operators

Based on ZEPA demand projections, an estimated ~7.5 GWh of batteries will be purchased for terminal tractors (TT's) and ~1.6 GWh for straddle carriers (SC's) between 2025-2035, reaching end-of-first-life from 2032 onwards

Battery volume from CHE electrification expected to be purchased between 2025-2035[1], GWh



- A typical battery could have a 'first-life' of about **7-12 years** before it reaches a 'State of Health' below 80%
- This is **heavily dependent on duty cycle**, **charging strategy** and **environmental conditions**
- Overall, one could therefore assume volumes **reaching end-of-first-life from 2032 and onwards**

Without strategic planning, these purchased batteries will increase risks for OEMs and operators

Small economical risks

Lack of circular planning may increase handling and recycling costs, though they remain a small share of total cost of ownership.

Deep-dive on following pages

Legal and compliance risk

New regulations (e.g., Battery Regulation, Basel Convention, etc.) tighten end of life (EoL) responsibility and cross-border waste rules – complicating the shipment of end-of-life batteries across borders.

Deep-dive on following pages

Logistical bottlenecks

Without sufficient collection, storage, and recycling infrastructure, used batteries and components may accumulate, creating delays and potential breaches of regulatory obligations.

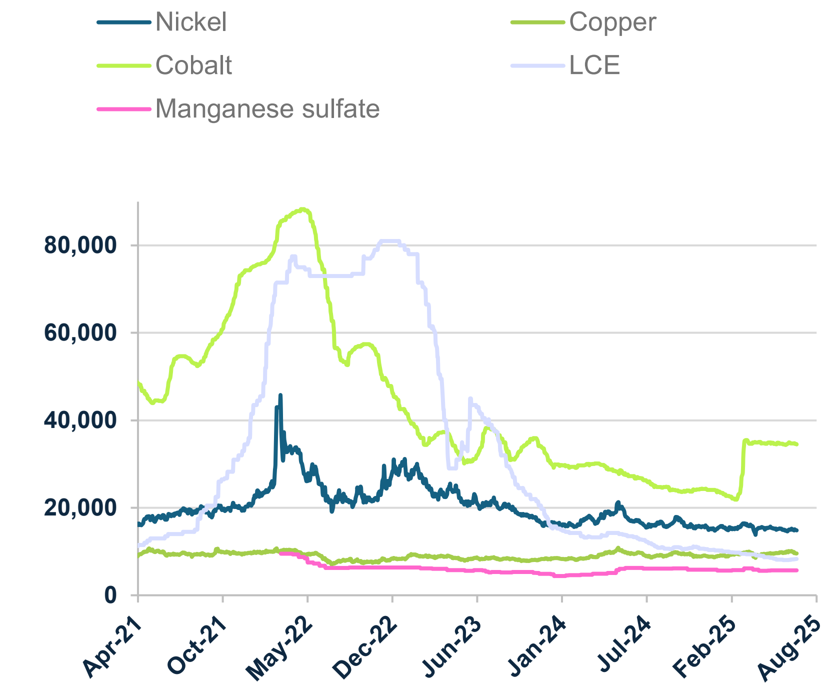
Notes: [1] Please note, this is based on estimations from 2024 and is highly illustrative as values are likely to increase further. Anonymous surveys from 2024 highlighted 4310-4660 Terminal Tractor's (TT's) and 390-540 Straddle Carrier's (SC's) are expected to be purchased from 2025-2035 by ZEPA members. Assuming an SC has 500 kWh battery size and a TT has 250 kWh battery size, an estimate is made on the total GWh battery capacity. The total estimate of equipment projections is then based on the assumption that ZEPA Members make up 15% of the market. Total market volumes are obtained by scaling ZEPA member figure .

Source: Based on demand assumptions from ZEPA 2024 Workstream 1 report

The economics of battery value remains extremely uncertain due to fluctuating metal prices and changing market dynamics

The battery metals market has been volatile and is expected to stay uncertain

Historic prices key battery materials[1], USD/t



Source: Fastmarkets

Future developments and volatility in material availability and battery prices lead to uncertain changes in the economics of battery recycling & reuse

Key (volatile) drivers of battery economics:

Primary supply changes lead to price developments	Supply for key battery metals is expected to exceed demand until 2030, supporting low market prices and limiting the value proposition of recycling in the near term. However, forecasts highlight that cobalt, lithium and nickel markets could move into a deficit by 2033
Mining capacity	New mining capacity from 2030 could mitigate price runaway, tempering recycled material value. Nevertheless, this is extremely uncertain. As an example, lithium prices made a jump as CATL shut down a their major Jianxiawo mine in China
Secondary supply	End-of-life battery supply is not expected to become a primary scrap source until around 2030/2033. When volumes increase, an oversupply of scrap could emerge, which would weigh on resale prices
Recycling market dynamics	Many recyclers outside China currently face unprofitability in refining capacity. In Europe and North America, heightened competition for scrap and limited refining capacity further erode margins
Individual battery specifics	Salvage value also depends on the battery's State of Health (SoH), usage patterns (e.g. cycling depth, temperature exposure), and whether it is suitable for reuse, repurposing, or only raw material recovery. However, the market is not yet mature enough to assess this consistently

Note: [1] Data from graph are from Fastmarkets analysis.

Source: ABN AMRO (2024), ESG Economist - Copper remains very essential in energy transition, Circular Energy Storage price data, IEA (2025), Global Critical Minterals Outlook 2025; CarbonCredits.com (2025), Lithium Prices Jump as CATL Shuts Major Jianxiawo Mine in China; Fastmarkets; Systemiq Analysis

Circularity levers have limited economical value, as either a gate fee or salvage value for end-of-life batteries impacts the total cost of ownership by 0.10–0.23%

Depending on market developments, an end-of-life battery can have either a gate fee or a salvage value

Gate fee

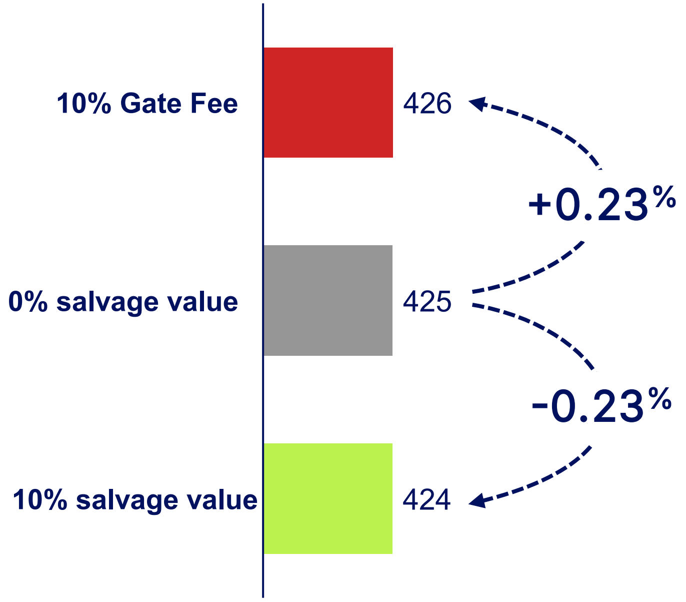
Gate fees are charged by recyclers to cover sorting and processing of end-of-life batteries.

Salvage value

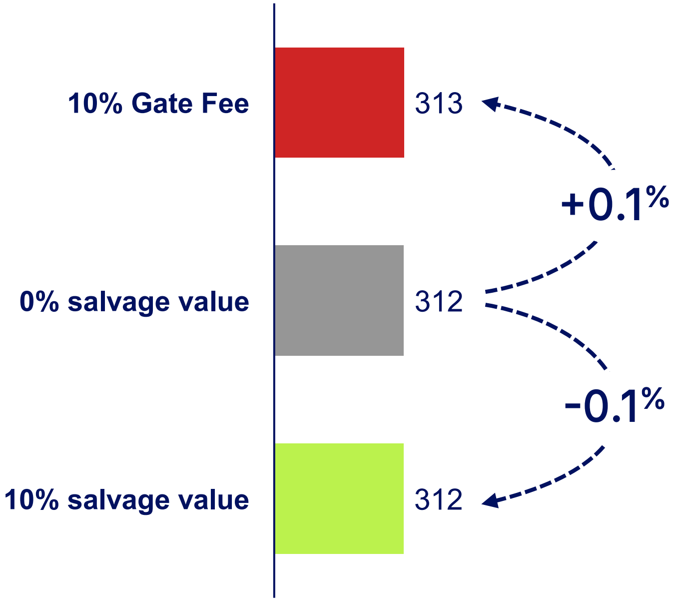
Salvage value refers to the residual value recovered from materials or components (e.g., lithium, cobalt, casing metals) after processing end-of-life batteries, often through recycling. Under certain market conditions recycling or disposal facilities provide a salvage value for end-of-life batteries.

Whether disposal results in a 10% gate fee or 10% salvage value has 0.10-0.23% impact on the Total Cost of Ownership (TCO)

TCO for straddle carrier – Rotational setup incl. Labour, million USD



TCO for terminal tractor – Rotational setup incl. Labour, million USD



Source: Based on sensitivity analysis of the Total Cost of Ownership (TCO) model of ZEPA 2024 Workstream 2 report

Environmental regulations worldwide are tightening around battery disposal and reuse (1/2)

Geography	Policy	Description (Policy Scope, Status & Timeline)	Impact for TOs and OEMs
International/Global	**IEC 63330[4] & IEC 63338[5]**	Updated in 2024. IEC 63330 specifies requirements for repurposing of secondary cells, modules, battery packs and battery systems, which are originally manufactured for applications such as electric vehicles; IEC6338 specifies guidance on reuse/ repurposing of secondary cells & batteries.	Informs and de-risks battery re-use; enables standard-based procurement.
International/Global	**UL 1974[6]**	Updated in 2023. Standard to evaluate the performance of used batteries. It covers processes for grading, sorting, and evaluating for second-life applications. First published in 2018; recent update improves clarity on diagnostics and quality assurance.	Supports quality assurance for reuse (Recognized by US DOE and major utilities).
North America[1]	**Inflation Reduction Act[1]**	Passed in August 2022 with key 2023-24 IRS guidance. Offers tax credits (45X, 30D) for battery materials sourced or recycled within North America. Focuses on localizing EV and battery supply chains.	Major incentives for recycling if upheld; risk of rollback under new administration.
North America[1]	**One Big Beautiful Bill Act (U.S.)[7,8]**	Signed July 2025. Repeals most clean energy tax credits from the IRA including for EVs, clean energy, and recycling. Credits remain only for projects started before June 2026 or online by Dec 2027.	Removes core tax incentives for battery reuse and recycling.
China	**Various[3]**	MIIT have issued revised guidelines for battery recycling companies titled "Industry Standard Conditions for Comprehensive Utilization of Waste Power Batteries of New Energy Vehicles (2024 Edition)", including mandatory recycling recovery rates (98% for Co/Ni, 85% for Li), and environmental standards. China has also introduced a national standard for black mass (recycled derivative from Li-Ion batteries), which is no longer regarded as waste.	Pushes battery OEMs and recyclers in China to comply with higher recovery mandates. Mandates design traceability; simplifies repurposing for compliant OEMs and terminal operators. Black mass standard allows for import of high-quality black mass (previously not allowed).

Note: While the US lacks federal regulations, several states are in the process of implementing "extended producer responsibility" laws, mandating battery recycling.

Source: 1 – IRA, 2 – FBIL, 3 – rhomotion (2024), China releases proposed standards for battery recycling, IEA (2024), Specifications for the Comprehensive Utilisation of Waste EV Batteries 2024, - rhomotion (2025) China releases legislation allowing the import of black mass, IEC63330, 5 - IEC63338, 6 - UL1974, 7 – Fastmarkets, 8 – L&W; Rhomotion (2024), LFP battery recycling, the challenges and opportunities

Environmental regulations worldwide are tightening around battery disposal and reuse (2/2)

Geography & Policy		Description (Policy Scope, Status & Timeline)	Impact for TOs and OEMs
Europe	**Regulation (EU) 2023/1542[1]** *(repealing Directive 2006/66/EC and amending No 2019/1020)*	Enforced Aug 2023. Introduces mandatory recycled content, Battery Passport (2027), carbon footprint rules, and dismantling design.	OEMs must digitize product data and redesign for circularity. TOs can leverage battery passports to validate second-life viability and remaining useful life.
Europe	**Taxonomy Regulation (EU) 2020/852[2]**	In force since 2020. Defines environmental criteria for sustainable investments, including recycling and reuse activities.	Opens access to green financing for OEM/TO investments in repurposing and recycling. May influence procurement and reporting frameworks.
Europe	**End-of-Life Vehicles Directive Review (Draft)[3]**	Proposal submitted July 2023. Requires higher material recovery, traceability, and extended producer responsibility for EVs.	OEMs must account for end-of-life logistics early in design and may face penalties for non-recovered batteries. TOs may gain responsibility—and opportunity—in certified dismantling.
Europe	**Critical Raw Materials Act[4]**	Council position adopted June 2023. Targets 15% annual recycling and max 65% import dependency for strategic materials.	Increases strategic value of localized recycling. OEMs may prioritize partnerships with EU-based recyclers. TOs handling used batteries can play a role in raw material recovery loops.

Countries such as India, South Korea, and Nigeria are also developing battery recycling frameworks. Growing regulatory pressure is expected to support the development of the battery recycling market.

Source: 1 – Regulation (EU) 2023/1542, 2 – Regulation (EU) 2020/852 , 3 - End-of-Life Vehicles, 4 – Critical Raw Materials Act

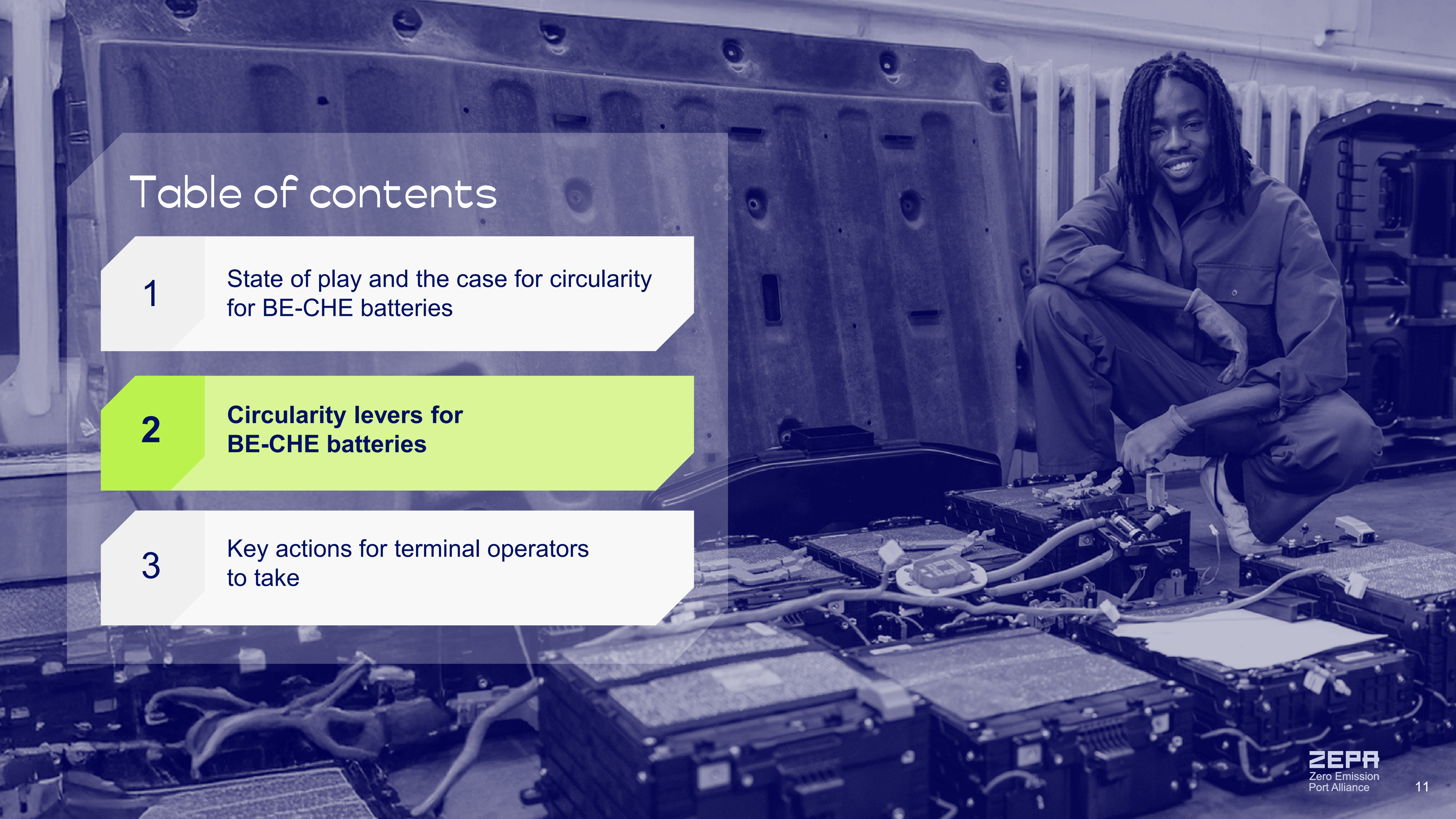
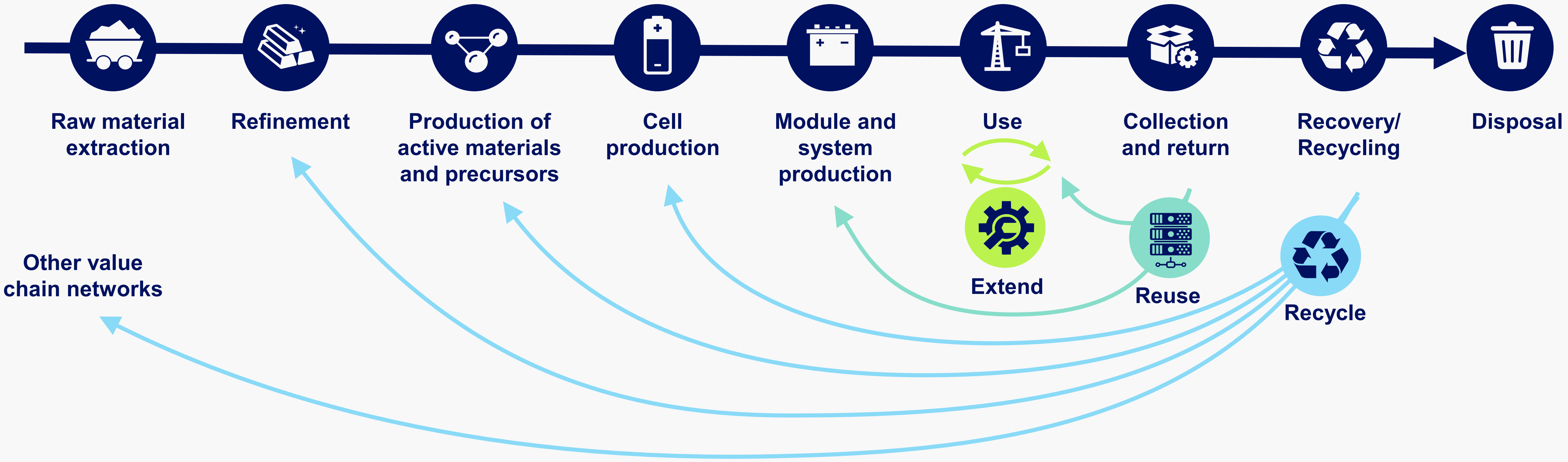


Table of contents

There are three circular levers for batteries: Extend, Reuse and Recycle



Extend

Operational strategies (e.g., smart charging, BMS[1], thermal control) to prolong battery life in its original application and delay retirement. This also entails repair.

Reuse

Repurposing used batteries (~80% capacity) for second-life applications such as backup power or commercial and industrial storage.

Recycle

Processing end-of-life batteries to recover critical materials (e.g., Li, Co, Ni) for reintegration into new battery production.

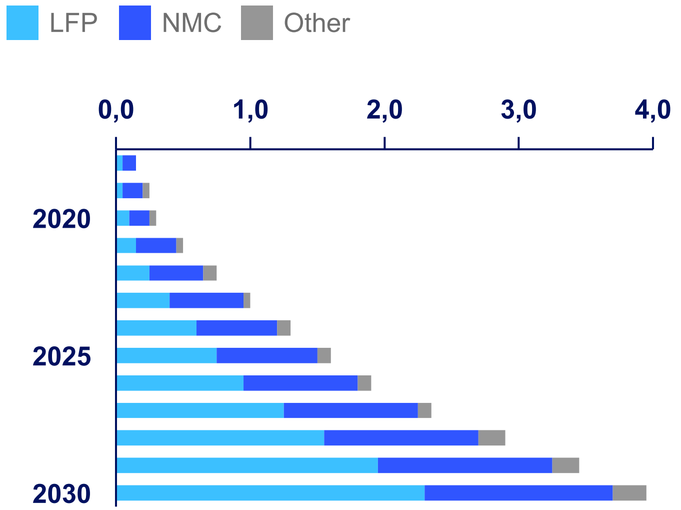
Note: [1] Battery Management System (BMS)
Source: Systemiq expert input

LFP and NMC batteries already dominate the EV market and are expected to grow further; they are therefore the focus of this document

Overall, lithium-ion battery chemistry is focused on NMC and LFP

NMC and LFP are seen as the dominant chemistry in the total EV market, representing ~>90%. Although other batteries such as LTO are also used, NMC and LFP are therefore the key scope of this document.

Global battery cell demand by source in EV's[1], TWh



Unlike LFP, NMC batteries are more recyclable due to valuable cobalt and nickel, but less suited for reuse given their shorter cycle life

	LFP (Lithium Iron Phosphate)	NMC (Nickel Manganese Cobalt)
Average Price (2024)[2]	~ USD 60/kWh for a cell	~ USD 75/kWh for a cell
Performance[3]	~2000-4000 cycle life Low energy density	~1500 cycle life High energy density, at both cell and battery pack level
Reuse	✓ **Better suited:** Long cycle life; tested in Battery Energy Storage Systems applications	✗ **Limited potential:** Short cycle life; batteries suffer from degradation and reduced efficiency and reliability as they age – limiting reuse
Recycle	✗ **Negative to low value at EoL due to absence of Co/Ni –** e.g., in Europe gate fees of ~USD 3.3-4.5/ kg scrap LFP batteries being paid to recycler[4]	✓ **High value at EoL due to recoverable Co/Ni/Cu –** e.g., in Europe ~USD 0-0.5 / kg scrap NMC batteries being paid to recycler[4]

Note: NMC = Nickel-Manganese-Cobalt; LFP = Lithium-Iron Phosphate; **[1]** Depicted from Exhibit 2 McKinsey data; **[2]** Prices based on S&P Global Jan 2025 data, data might have changed from then. **[3]** Based on Advanced Propulsion Centre Insights report. **[4]** Fastmarkets noted that they have 'recently heard' these figures, suggesting the estimates are based on informal industry insights rather than published data. Formal data is not available.

Source: McKinsey (2024), The battery chemistries powering the future of electric vehicles; BloombergNEF (2023), Lithium-ion Batteries: State of the Industry; CEID; Fastmarkets (2024), European LFP recycling vital for future but facing economic barriers: LME Week; S&P Global (2025), Where are EV battery prices headed in 2025 and beyond?; Advanced Propulsion Centre (2025), Insights report L(M)FP batteries for EV adoption from a UK perspective; McKinsey (2024), How batteries will drive the zero-emission truck transition

Battery strategies face trade-offs: life extension is challenging, reuse suits LFP better than NMC, and recycling is expensive but mandatory in some regions, with high gate fees especially for LFP due to limited material recovery value

	1. Extending (80-90% SOH[1])	2. Reusing (50-80%/80% SOH)	3. Recycling (<50% SOH)
Description	• Smart charging to reduce degradation • Use of battery analytics to optimize cycle depth and thermal conditions • Retrofit Battery Management System (BMS) upgrades for asset life extension • Ongoing repairs to reduce environmental impacts from damaged batteries	• Battery packs disassembled to modules and cells, repacked and equipped with new BMS for 2nd-life use • EV batteries redeployed in less demanding applications (e.g., backup powered)	• Black mass is produced by mechanically shredding and sorting end-of-life Li-Ion batteries • It is then refined using hydrometallurgical, pyrometallurgical, or combined processes to recover valuable materials to use in production of renewed batteries
Emerging technologies	• Advanced predictive BMS • Deep cycle & usage optimization software • Battery analytics using physics-based models	• Modular repurposing • Integrated diagnostics + automated disassembly	• Direct recycling of Cathode Active Materials (CAM) • Electrochemical recovery methods for selective metal extraction from black mass or battery waste
Advantages +	• **Low-cost, near-term benefits** via smart charging and BMS upgrades • Extends battery life, **reducing Total Cost of Ownership** and deferring replacement	• Retired batteries can either be reused on-site or sold to industrial reuse vendors; **reuse vendors are likely to be the best option** • **LFP chemistry is well placed** for reuse due to its long cycle life, unlocking **additional value**	• **Mandatory -** Several regions have extended producer responsibility (EPR) laws for EV batteries or other mandatory recycling efficiency targets • **NMC is more suitable for recycling**, as the cobalt/nickel content enables **higher recovery values**
Disadvantages −	• **Operational constraints limit optimisation,** factors such as shift schedules and optimized logistics make it difficult to consistently align charging windows with optimal battery health practices • **Dependent on software integration and user compliance**	• For **NMC**, **batteries are difficult to reuse** due to their complex chemical makeup and lower cycle life • **Overall,** reuse could be **operationally complex** (e.g., due to disassembly, testing). Terminal operators may avoid 2nd-life LFP BESS on-site **due to safety, reliability, and integration concerns.** It could also be less attractive due to declining new battery costs	• **LFP batteries offer limited economic recovery** potential, as they lack high-value metals like nickel and cobalt, and often require **gate fees to offset recycling costs** • **China remains the exception,** with established low-cost, high-efficiency infrastructure, while recycling LFP elsewhere is often economically unviable due to higher costs and limited scale

Deep-dive on following pages

Note: [1] State of Health (SOH) SOH is the percentage of a battery's original capacity that remains. **[2]** Pyrometallurgical battery processing requires additional refining steps before recovered materials can re-enter the supply chain.""Hydrometallurgical processing yields outputs that can directly enter the cathode manufacturing process.

Sources: Relectrify, TWAICE, Zitara official websites and case studies; McKinsey Battery Circularity Insights.

1. Extend

Process improvements can extend battery life and improve the business case, although this might be operationally challenging

Key advantages and considerations

5 key process improvements and their advantages:

- **Smart charging and discharging** within 20–80% state-of-charge (SoC) windows significantly reduce wear and prolongs battery lifespan. Additionally, studies highlight that a ‘slow charge’ once a week up to 100% SoC is also beneficial for preventing battery degradation.
- **Effective thermal management systems** maintain batteries within the optimal 20–30°C range, preventing degradation during idle time or extreme weather.
- **Cell-level battery management systems (BMS)** provide accurate SoH/SoC readings, detect imbalances early, and prevent overcharge, deep discharge, or thermal events.
- **Predictive analytics platforms** such as Zitara and Accure track asset-level degradation patterns, optimize charging, and enable condition-based maintenance over fixed-cycle servicing.
- **Repair services** offered by battery manufacturers can reduce the environmental impacts of damaged batteries.

- **Operational constraints limits optimisation** — smart charging can conflict with operational demands (e.g., shift schedules, optimized logistics), making it difficult to consistently align charging windows with battery health practices.
- **Relies on system integration and operator behaviour** — effective life extension depends on BMS-software integration and staff consistently following charging and maintenance protocols.

Key examples of projects

RELECTRIFY
MAKING ENERGY STORAGE AFFORDABLE

Relectrify (AU) extended second-life battery lifespan by ~30% in commercial storage projects through advanced cell-level BMS integration.

TWAICE

TWAICE (DE) reduced EV battery failure rates by up to 25% for OEMs using digital twin analytics and predictive diagnostics.

zitara

Zitara (US) enabled optimized charging strategies and O&M planning across fleet-scale micromobility and industrial applications.

elysia
BATTERY INTELLIGENCE

Elysia Cloud enables remote monitoring of battery health and life forecasting in electrified mining trucks, with safety ensured by prognostic algorithms that analyse each parallel cell group.

Note: **[1]** Battery Management System (BMS)
Source: Expert input, Relectrify, TWAICE, Zitara; elysia; McKinsey Battery Circularity Insights.

2. Reuse

Reuse models are early-stage but may be more cost-effective than recycling; industrial reuse vendor strategy is most favorable

Key advantages and considerations

+

- **Reuse potential varies by chemistry** — LFP is safer and better suited for reuse due to high cycle life (~4,000 cycles), while NMC has lower cycle life (~1,500), hindering reuse.
- **Retired batteries can either be reused on-site as BESS system or be sold to industrial reuse vendors; reuse vendors are likely to be the best option as ports could lack capacity to safely inspect, disassemble, and redeploy degraded batteries** (see table):

	Pack Inspection & Remanagement Capability	Infrastructure for Deployment	Insurance & Compliance Readiness
On-site reuse (e.g., port repurposing)	Poor – ports lack skills/tools and would have to hire externals	Mixed – depends on local space/grid access	Poor – reuse often uninsurable
Industrial reuse vendor (e.g., B2U, Connected Energy, Ace)	Good – SoH testing and QA processes	Good – deploy in prepared facilities	Mixed – improving but still evolving

–

- **The scale of reuse for one terminal might not be sufficient** for it to be economically feasible.
- **Falling battery prices and cheap new cells threaten reuse margins.** Refurbishment must compete with falling battery costs; only efficient, modular second-life players remain competitive.
- **Export is rarely an option.** Hazardous waste rules and high shipping costs mean **reuse and refurbishment must happen locally**; reuse in APAC **is more mature**, while Europe, US reuse faces issues.
- **Second-life battery deployment face insurance barriers**, as safety risks make coverage difficult or unavailable.

Key examples of projects

- Connected Energy (UK): Deploys second-life EV batteries in 300 kW / 360 kWh BESS units at commercial and industrial site.
- B2U Storage Solutions (USA): Operates a 25 MWh second-life battery storage site in California using retired EV battery packs for energy arbitrage.
- Johan Cruijff Arena (Netherlands): Operates a 3 MW / 2.8 MWh energy storage system using 148 second-life Nissan Leaf battery packs and 340 new ones for backup and peak shaving.

Startups focusing on 2nd life use-cases

Evyon™ Voltfang Connected Energy

Sources: Company websites (B2U, Connected Energy, Mobility House), BloombergNEF, Benchmark Mineral Intelligence, Expert Interviews

3. Recycling

The clearest compliance pathway for EoL batteries, but economics of LFP batteries introduce a new financial risk

Key advantages and considerations

+

- **Recycling allows for circular value chains:** renewed batteries can be produced from recycled battery materials.
- **Recycling aligns with evolving regulatory requirements and supports compliance** with extended producer responsibility (EPR) frameworks.
- **To avoid unpriced end-of-life risks, early coordination on contracts, partnerships, and infrastructure is essential** — when structured well, recycling can support green job creation and strengthen port legitimacy.
- **NMC is more suitable for recycling**, as the cobalt/nickel content enables **higher recovery values.** *Deep-dive next page*

–

- **LFP batteries have over 60% lower intrinsic value compared to NMC and other chemistries,** as they do not contain high-value metals such as cobalt or nickel — this limits their economic attractiveness for recycling. *Deep-dive next page*
- **Logistics add further cost.** Batteries are classified as UN3480 hazardous materials and require UN-certified, fireproof packaging for transport — especially for standalone shipments.
- **Geographical differences are significant.** China holds ~69% of global battery recycling capacity, Europe ~18%, and North America ~9% (all mainly NMC). Western markets are expanding capacity, but for LFP batteries China remains the only economical location. *Deep-dive next page*
- **Assume no salvage values for LFP batteries, but price in high gate fees as the baseline. For NMC, assume 0 costs or low costs of EUR 0.5/kg.** For example, in Europe gate fees of USD 3–4.5/kg scrap are common for LFP, making disposal a cost. Without a lithium price spike or policy support—such as Extended Producer Responsibility (EPR), where OEMs are required to cover end-of-life treatment—terminal operators will likely bear these costs unless OEMs agree to take back at zero cost or for a specific price.

Key examples of projects

Regional developments in Hubei, Jiangxi and Fujian Provence (China): Initiatives representing 100 millions USD in investment and hundreds of thousands of tones in annual processing capacity.

Cylib (Germany): Low-chemical, water-based hydrometallurgy process recovering lithium and graphite; targets low-waste CAM production.

Redwood Materials (US): 20 GWh/year using pyro-hydro hybrid; raised $2B+; focused on anode/cathode recovery.

Ace Green Recycling (US/India): Non-pyro, low-emissions recycling for lithium-ion and lead-acid batteries; expanding capacity in Texas and Gujarat; has infrastructure for LFP.

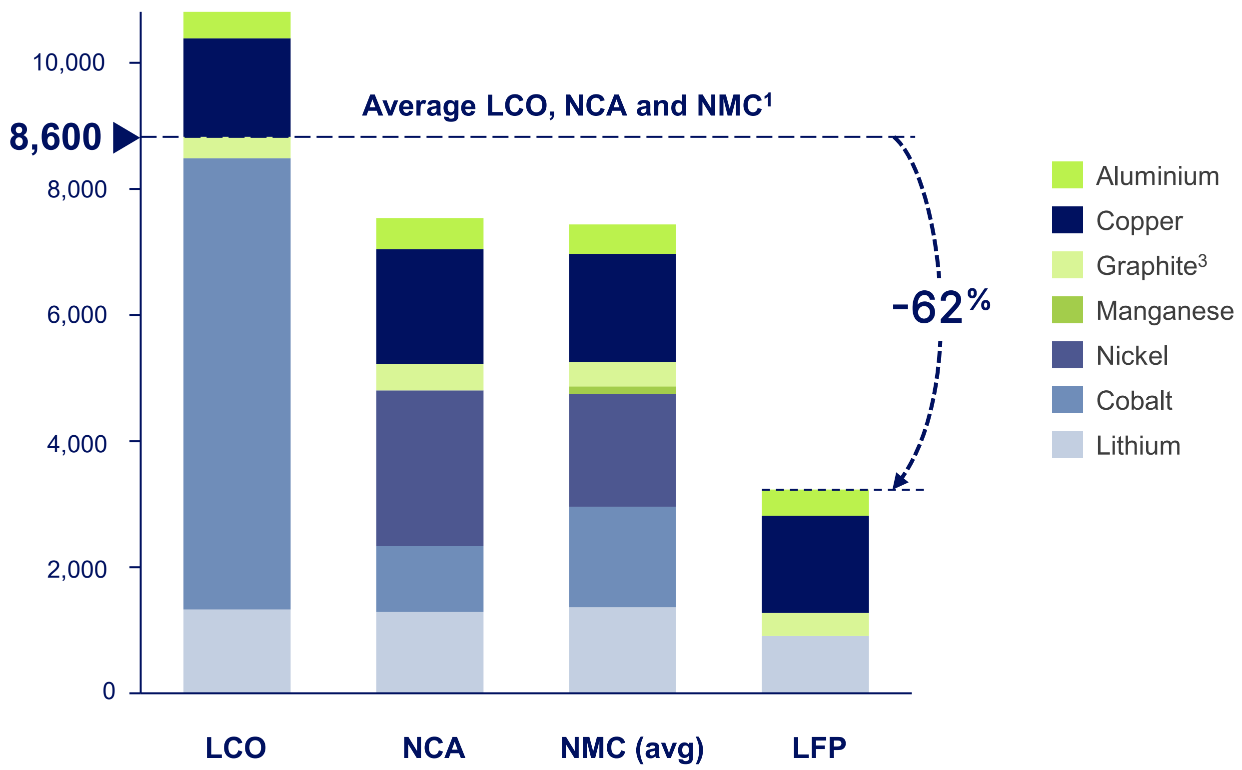
Source: ZEPA expert interview with Fastmarkets (July 2025), Fastmarkets battery recycling pricing data, Cylib/Redwood/Li-Cycle official websites, IEA Global EV Outlook 2024, Argonne National Lab publications, Volta Foundation report; Discovery Alerts (2025), China's Lithium Battery Recycling Projects Driving Sustainable Growth; Pang, D., Wang, H., Zeng, Y., Han, X., & Zheng, Y. (2025). Sustainable Recycling of Lithium-Ion Battery Cathodes: Life Cycle Assessment, Technologies, and Economic Insights. Nanomaterials, 15(16), 1283. ; Eureka (2025), How to Implement Effective NMC Battery Recycling in Industry

3. Recycling

LFP batteries have over 60% lower intrinsic value compared to NMC and other chemistries, this limits their economic attractiveness for recycling

Deep dive

Metal value in battery cells, by chemistry, $ per tonne (2025)[2]



- **LFP cells are ~20% cheaper than NMC** due to the absence of nickel and cobalt.
- **However, as LFP batteries have >60% lower intrinsic value compared to NMC and other chemistries,** recycling incentives are limited, which weakens the business case for end-of-life recovery.
- **Additionally, LFP recycling economics depend entirely on lithium prices**, which are currently too low to make recycling economically viable. Overall, lithium price are highly volatile – challenging a consistent business case.
- **On the other hand, the presence of cobalt/nickel content in NMC chemistries enables higher recovery values, strengthening its business case for recycling.** Additionally, NMC recycling facilities are also more widely available.

Note: [1] LCO: Lithium Cobalt Oxide, NCA: Nickel Cobalt Aluminum Oxide, NMC: Nickel Manganese Cobalt Oxide. [2] Based on Fastmerkets' data. [3] Although Graphite is technically not classified as a metal, it is included in this overview as it does exhibit some metallic properties and is widely used in batteries.

Source: Fastmerkets' battery recycling long term forecast; Benchmark (2025), The road to a circular economy; Fastmarkets (2025) Battery recycling long term forecast, European LFP recycling vital for future but facing economic barriers: LME Week

3. Recycling

China leads with low-cost, high-yield LFP recycling operations, while most global LFP recycling plants remain uneconomical due to infrastructure and cost barriers

Deep dive

China: Profitable & scalable recycling

- China controls **~78% of global lithium-ion battery pre-treatment** and **~89% of global refining capacity.**
- **Recovery yields:** up to 85–90% lithium for LFP (92% nickel and 88% cobalt for NMC/NCA black mass).
- **Costs 30-40% lower** than global peers due to scale, domestic logistics, and integrated infrastructure.
- **New regulations (from July 2025)** set standardized black-mass purity, allowing China to **import and process black mass efficiently.**
- **Global black mass flows**: Outside China, most recycling stops at black mass production, which is then exported to Southeast Asia or South Korea for further refining due to cost advantages and high recovery efficiency.

Economically viable recycling
due to scale, infrastructure, and high lithium recovery.

Rest of World: Challenges remain

- **LFP recycling concentration in China:** Today, almost all economic LFP recycling occurs in China. Outside China, facilities face low lithium yields, immature and fragmented infrastructure, and lack of regulatory incentives.
- **High logistics costs:** long-distance transport, imports, gate fees due to immature recycling networks.
- **LFP-specific hurdles:** low-value lithium recovery, lack of cobalt/nickel, leading to **net- negative economics**, unless alternative reuse loops are applied.

Most LFP recycling operations are **unprofitable or break-even at best** without any subsidy or regulatory support**. Early recycler partnerships** help avoid cost spikes and secure capacity as demand for processing rises[1].

Note: [1] Publicly to date 2 partnerships have been announced. ABEE is among the few to plan an LFP recycling facility in Europe/North America, though still in development. In Germany, Vitesco and Kyburz formed a recycling partnership. The latest status of these projects is unclear.

Source: S&P Global; Fastmarkets; Rho motion (2024), LFP battery recycling, the challenges and opportunities; Rho Motion (2025), How much of the battery recycling industry does China control?; Expert input

Table of contents

Recommended actions for terminal operators and OEMs are to invest in understanding the space, build partnerships, pilot reuse and recycling models, and engage early with policy advocacy

	Terminal Operators - TOs	Original Equipment Manufacturers - OEMs
Understanding	**Battery circularity is marked by frequent changes and volatile markets, making it key to keep pace with developments.**	
Partnering[1] De-risk circularity through shared agreements between TOs and OEMs	• **Embed circularity, take-back, and reuse clauses** into contracts to enable repair and renew of damaged/depleted batteries, in collaboration with OEMs. • **Jointly negotiate with recyclers** to minimise gate fees and (where possible) secure minimum salvage value, especially for LFP chemistries. • **Coordinate and partner with reuse logistics providers (and recyclers)** to build regional reverse logistics for used batteries. • **Align with other port and regional stakeholders** to build shared regional reverse supply chain infrastructure.	• **Build incentive-based contract structures to support reuse/recycling** (e.g., shared salvage value agreements, take-back guarantees), in collaboration with TOs. This will be obligatory in some regions (e.g., the EU). • **Support (port) reuse by supporting piloting of pooled battery reuse models,** e.g., onsite energy storage or testing degraded cells for second life. • ***For battery producers*** **- Design battery systems with end-of-life recyclability and modularity in mind** – e.g., designing battery packs for ease of dismantling and supporting interoperable digital infrastructure (battery passports, state-of-health reporting, UL3601, design battery systems based on recycled materials).
Piloting Collaborate with OEMs to test/scale viable reuse and recycling models	• **Test circularity models through small-scale pilots** with first 'batch' of end-of-life batteries, evaluating against key metrics including degradation profiles, reuse revenue potential, and cost per kWh. • Collectively **pool end-of-life batteries across the region** to improve reuse/recycling economics. • **Launch coordinated battery reuse pilots** and agree to **share learnings** within ZEPA or industry associations.	• **Support with handling end-of-life batteries safely,** building on existing logistics and safety protocols. • **Contribute to aggregation and collection schemes** that benefit from scale. • Support **critical mass for reuse testing** by aggregating batteries from multiple stakeholders and/or terminal operators. • ***For battery producers*** **- Test the use of recycled battery materials** in manufacturing.
Policy Advocating Shape future standards and regulation	• **Advocate for port-ready reuse and recycling infrastructure** in specific regions. • **Align with Battery Passport roll-out** to shape industry-wide traceability norms. • **Collaborate with OEMs and regulators to co-develop compliance or subsidy mechanisms** that minimise gate fees and enable cost-effective takeback and reuse schemes.	• **Endorse and adopt interoperable standards for battery design, labeling, and traceability** (e.g., digital product passports such as Battery Passport, state-of-health reporting, and second-life grading), to reduce end of life fragmentation and support terminal operators in efficient battery take-back and reuse. → In EU mandatory. • **Advocacy** in shaping regulation on takeback, reuse, and digital traceability.

Ports can coordinate between battery owners, OEM's, reuse applications, and recyclers

Note: Examples of already existing partnerships include; CATL and APM Terminals; GM and Redwood Energy for reuse; SK tes and BMW Group; Lime and Redwood Materials;
Sources: Expert interviews

ZEPA Zero Emission Port Alliance

New battery chemistries, falling battery prices, new business models and geopolitical dynamics are key uncertainties for battery circularity strategies

Indicative size of impact on battery circularity

	Watchpoint	Indicative potential impact on the voluntary standards[1]	
Technical	**Emerging chemistries** (sodium-ion, solid-state)	Longer-term shift toward sodium-ion (abundant, lower-value materials) may reduce reuse/recycling incentives. Nevertheless, these chemistries are more likely to be used in stationary storage than EVs due to their lower energy density, costs, and weight/volume ratio.	
Economic	**Cost decline in first-life batteries**	Overall battery cost declines reduce the economic case for second-life solutions. As battery prices continue to fall—dropping below $100/kWh for new LFP packs—this compresses the margin available for repurposed batteries, especially where performance degradation and testing costs are high. This may limit the viability of second-life models in cost-sensitive applications, such as stationary storage at ports or backup power.	
	OEM-led Battery-as-a-Service / leasing models	As-a-Service models help retain ownership and traceability of batteries across first and second life. It also shifts incentives toward controlled reuse and defers recycling.	
Geo- Political	**China's dominance in battery recycling**	China controls ~78% of global lithium-ion battery pre-treatment and ~89% of global refining capacity, resulting in significant industry dependence on a single-country recycling value chain. This concentration heightens systemic exposure to regulatory or supply chain disruptions.	
	Critical minerals access and trade restrictions	More inward-focused national strategies may fragment supply chains and limit access to critical battery materials, increasing the strategic value of recycled, locally sourced inputs.	

Source: Insights based on ZEPA expert interviews; SYSTEMIQ analysis; EU Battery Regulation'&P Global (2025), Where are EV battery prices headed in 2025 and beyond?; IAE (2025), Critical Minerals Outlook 2025; Benchmark Mineral Intelligence; Rho Motion (2025), How much of the battery recycling industry does China control?;

Disclaimer

The ZEPA Secretariat provides this report for informational purposes only. The data and comprehensive analysis it contains reflect our commitment to delivering accurate, insightful findings. While we have worked diligently to make sure the report is reliable and clear, we recognize it may have areas needing further refinement. Information contained in this report is made as at the date of publication. The ZEPA Secretariat does not have any obligation to update or otherwise revise any information reflecting circumstances arising after the date of publication.

To the extent permitted by law, nothing contained in this report shall constitute any representation or warranty and no responsibility or liability is accepted by the ZEPA Secretariat as to the accuracy or completeness of any information supplied herein.

Decisions made by individuals or entities based on information in this report are their own responsibility. The ZEPA Secretariat shall not be held accountable for any outcomes resulting from the use of this information. Users are encouraged to conduct their own research and consult with qualified professionals before making decisions related to this material.

Acknowledgements

The Zero Emissions Port Alliance (ZEPA) is a cross-value-chain port alliance set up by its members to tackle BE-CHE adoption challenges together. ZEPA has multiple members for the 2025 Work Programme, whose activities span the container handling sector.

This report has been developed by Systemiq and constitutes a collective view of participating organizations in the Zero Emission Port Alliance. ZEPA members have supported and validated the analyses, and have agreed to endorse the findings as presented in this report.

We would like to thank other expert collaborators for providing valuable contributions to this report, especially:

ZEPA Zero Emission Port Alliance

For further information

see www.zepalliance.com

or email zepalliance@systemiq.earth

Confidential and proprietary.
Any use of this material without specific permission of ZEPA is strictly prohibited.