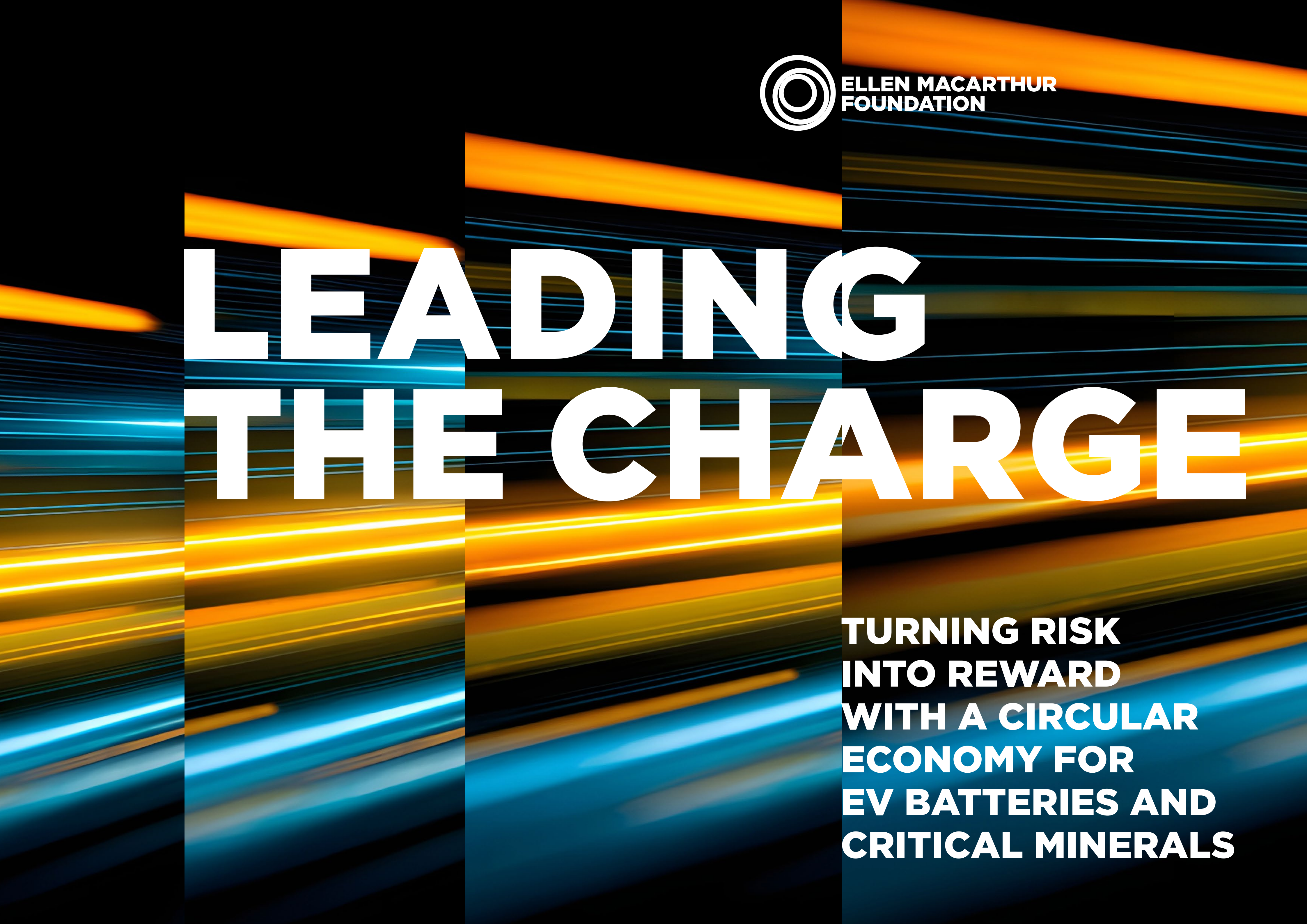

ELLEN MACARTHUR
FOUNDATION

# LEADING THE CHARGE

## TURNING RISK INTO REWARD WITH A CIRCULAR ECONOMY FOR EV BATTERIES AND CRITICAL MINERALS

# CONTENTS

# FOREWORD

Electric vehicles are scaling fast, and with them, the batteries and critical minerals that underpin the transition. **This shift is creating major commercial opportunity, but it is also moving the automotive industry from fuel-centric to material-centric value chains**, exposing businesses and economies to price volatility, supply bottlenecks, and growing environmental and social risks.

Researched and written by the Ellen MacArthur Foundation, **this report sets out how a practical, structural, and system-level view of circular economy can reshape the EV battery economy** to unlock economic value while building resilience. It articulates a system-level vision framework in which batteries deliver the greatest possible mobility and energy services; are kept in high-value use through maintenance, repair, refurbishment, and remanufacture; and are ultimately collected and recycled at high quality so critical minerals never become waste.

**This report translates this ambition into five reinforcing circular loops** (from intensive use, life extension and cascading to second-life applications, high-quality recycling, and the information exchange that enables them) **and three levels of circular action**: product and component design, business models, and the wider systems of infrastructure, finance, and policy. Our vision framework has been informed by over 15 years of circular economy research, advocacy, and collaboration across public and private sectors, and in a wide array of sectors and industries.

**Grounded in practical examples and 'bright spots'** already emerging across the value chain, and **informed by direct engagements with stakeholders and leaders** across the EV battery value chain, it offers commercially focused recommendations for the EV battery industries and associated stakeholders — original equipment manufacturers (OEMs) and battery manufacturers, recyclers and logistics providers, energy and mobility players, policymakers, and investors — to accelerate a competitive, scalable, and fair circular battery economy. It distils the most decision-relevant levers to act on now, and provides a platform for organisations to deepen analysis and implementation in their own context.

## Scope and intent

It is important to be mindful of scope. This report is not intended to be an exhaustive catalogue of every circular intervention, business mechanism, or policy instrument. The omission of specific approaches does not imply they are unimportant. In addition, this report intentionally does not replicate the quantitative forecasting and scenario modelling provided in critical minerals outlooks and recycling studies. Rather, **the report is written for a cross-value chain audience and prioritises commercially actionable themes** that can be advanced through collaboration, investment, and policy advocacy — and that can be strengthened by the Ellen MacArthur Foundation's circular economy expertise and convening role.

We see this publication as **one of the many early steps for the Ellen MacArthur Foundation in a multi-year campaign committed to accelerating a circular economy for critical minerals in the EV battery value chain.** Building from the bright spots highlighted here, we will work with partners, members, and wider stakeholders to develop deeper insights, sector-specific implementation pathways, and detailed proposals for industry collaboration, with the aim of mobilising further action at scale.

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# EXECUTIVE SUMMARY

## Electric vehicle batteries: a growing strategic priority

**Electric vehicle (EV) batteries are becoming the strategic asset class of the energy transition.** As adoption accelerates, the automotive transition shifts from fuel-centric to material-centric vehicles. A typical EV, by some estimates, contains over 200 kg of critical minerals — around six times more than an internal combustion engine (ICE) vehicle. And, more specifically, EV batteries contain and are reliant on a wide range of valuable critical minerals, such as lithium, graphite, cobalt, and nickel.

**However, today's EV battery value chain remains highly material-intensive, geographically concentrated, and structurally linear, creating systemic risks as demand grows.** Potential supply shortfalls for key minerals, exposure to environmental and social harms, and challenges in mining, processing, manufacturing, and recycling could increase costs, destabilise markets, increase price volatility, and slow deployment. Together, these dynamics increase the fragility of the EV battery value chain precisely at the moment when the system needs to rapidly scale.

**A systemic circular redesign is needed across the value chain.** A broader redesign of products and components, business models, and the energy-mobility system is essential to strengthen resilience and reduce systemic risks. Scaling a circular EV battery transition therefore requires moving beyond incremental and end-of-pipe fixes towards a system-level redesign. One that generates economic value across the value chain, reduces material intensity, mitigates supply risks, and lowers environmental and social impacts.

## The circular economy: turning risk into competitive advantage

**A circular economy approach can convert these challenges into a competitive opportunity.** By keeping batteries and the critical minerals in high-value use across multiple life cycles, and by designing the surrounding mobility, energy, data, and policy systems, a circular EV battery economy is economically viable at scale. For business leaders across the value chain, such an approach is not an add-on, but a board-level strategic lever to:

- **Protect margins** by increasing utilisation, extending battery life, and avoiding premature replacements
- **Reduce exposure** to volatile mineral markets and concentrated supply chains
- **Create new revenue pools and business models** by managing batteries and materials as assets (service, upgrade, second-life, and circular-mineral streams)
- **Strengthen resilience and licence to operate** amid geopolitical disruption and tightening regulation.

**How critical minerals in EV batteries are sourced, used, and recovered determine the predominant value and risk for the EV value chain — making a circular economy a strategic imperative for industry leaders.** Business decisions governing the management of these minerals — through strategy, business models, and design — will have profound impacts on both the commercial value businesses can capture, and the exposure they face to supply disruption, cost, and other risks across the EV battery value chain. As the EV market enters a phase of rapid scale-up, the window to shape these operating systems is now: early investment in circular economy approaches can offer the greatest opportunity to unlock resilience, competitiveness, and long-term value.

## Moving beyond silos: towards a system-level strategy

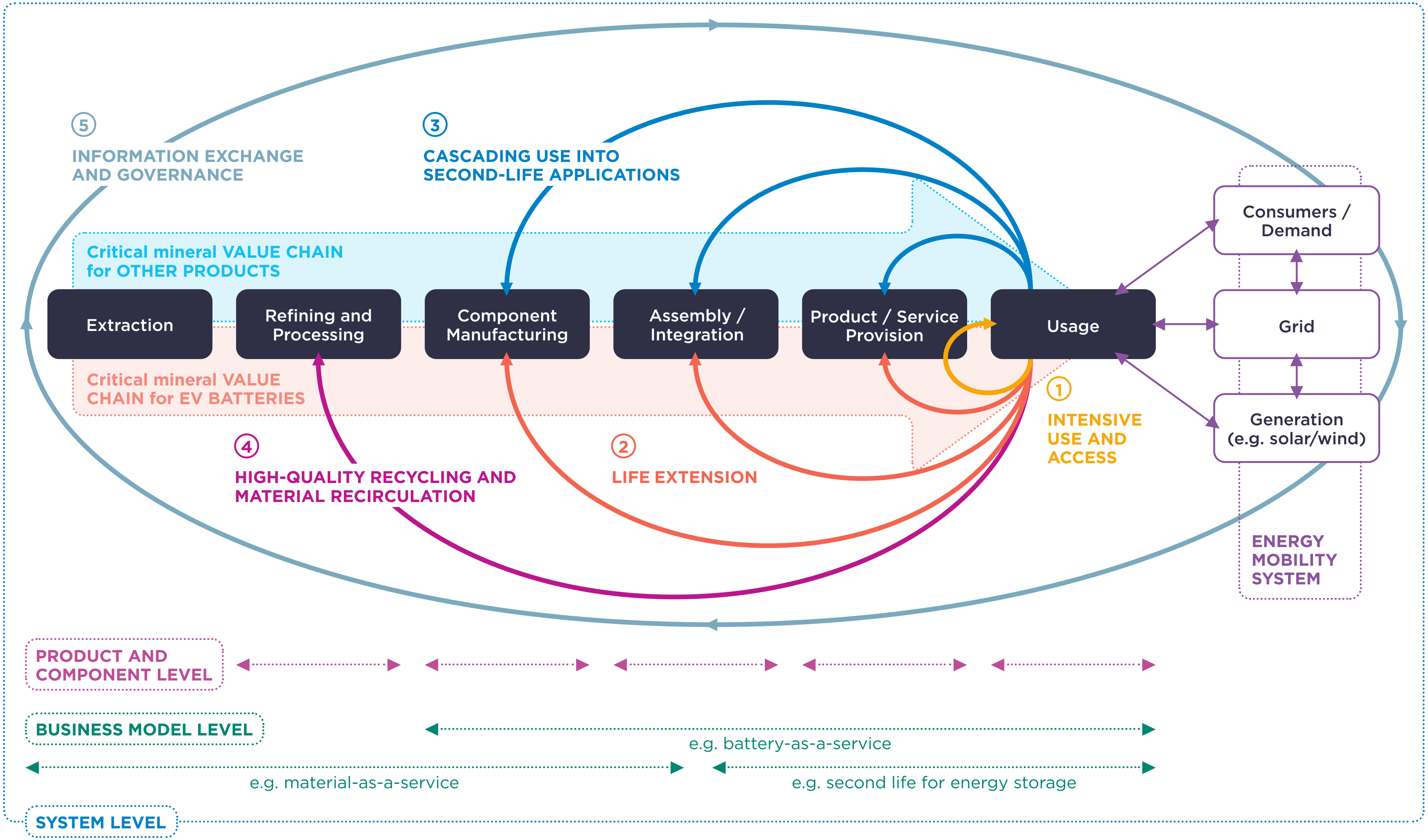
**The current circular economy narrative and efforts remain fragmented and often focused on end-of-life.** Credible analyses on EV demand growth, mineral constraints, recycling capacity, and policy pathways have been developed, and industry action has been mobilised – mostly focused on recycling, and to a lesser extent second life. However, this narrow focus can crowd out meaningful, innovative, and high value-add levers that could be applied ahead of recycling. At the same time, issues with the supply-demand gap remain unaddressed in the short-term given the significant time lag between battery production and the end of the battery's first life, while disproportionate pressure is being placed on rapid recycling-infrastructure scale-up when a broader set of end-of-life solutions are not considered.

**The circular economy vision set out in this report deliberately rebalances the conversation and ambition from end-of-life optimisation to system-level redesign.** The economic benefits of the circular economy for EV batteries are realised through aligned and collective action between actors in the EV battery value chain, rather than through siloed efforts. The decisions made at each stage of the value chain can constrain or enable circular economy activity at every other stage. For example, upstream decisions on battery design and architecture, data access, and ownership determine how batteries can be practically circulated downstream. Similarly, market access, standards, and signals determine how well upstream players are able to innovate and invest in circular activities with confidence. The exact dependencies, trade-offs, and open questions will need to be modelled and tailored to local market and regulatory realities to enable business leaders and policymakers to effectively manage batteries and their critical minerals as the strategic assets they are.

**The result is a commercially relevant framework that helps leaders turn circular economy ambitions from scattered pilots into a coherent value chain strategy,** highlighting the tangible financial value and broader strategic upsides. It provides a common language for aligning investment, partnerships and capability building, and for identifying value leakage, risk accumulation, and the interventions that unlock the greatest system returns. The report translates this into action through two lenses:

1. **Five circular loops for EV batteries**, illustrating the 'inner loops' where highest value can be retained (intensive use, life extension, and cascading use), the 'outer loop' of high-quality recycling, and the overarching loop of information exchange and governance, which act as key enablers across the system
2. **Three levels of action** that bring the circular economy to life, presenting how circular thinking can be applied to create system-level change at each level:
   - Product and component design,
   - Business models, and
   - Systems

## Figure 1 How the circular economy drives innovation and value creation across the EV battery critical minerals system



## Mobilising system change: five bright spots for leadership action

**Five major 'bright spots' — high-potential opportunity areas for cross-value chain collaboration — were identified** based on insights gathered from value-chain stakeholders and real-world case studies. For each, the report sets out immediate first steps that relevant system actors can take to drive meaningful progress.

Leaders across the EV battery value chain can act now by focusing on five strategic actions:

1. **Design batteries for circularity, not disposal**
   Rethink EV batteries not as single-purpose assets, but as durable components of a broader mobility and energy system, intentionally designed to last, be taken apart, and reused in different applications across multiple lives. To achieve this, the system must build in modularity, safe disassembly/debonding, diagnostics, and traceability from day one, so repair, remanufacture, second life, and high-quality recycling are technically and economically viable at scale.

2. **Rethink battery service within optimised energy-mobility systems**
   Redefine battery value not as maximised capacity in every vehicle, but as delivering the right performance for the right use, with mobility systems designed to support access to services rather than ever-larger batteries. This can be achieved by moving away from oversized and over-specified products and towards rightsizing and optimising for real needs. This shift must be supported by the redesigning of the energy-mobility system to reset the 'default' expectations of vehicle requirements, and allow users to access more or equal functional utility through innovation in service models across the rest of the EV battery value chain.

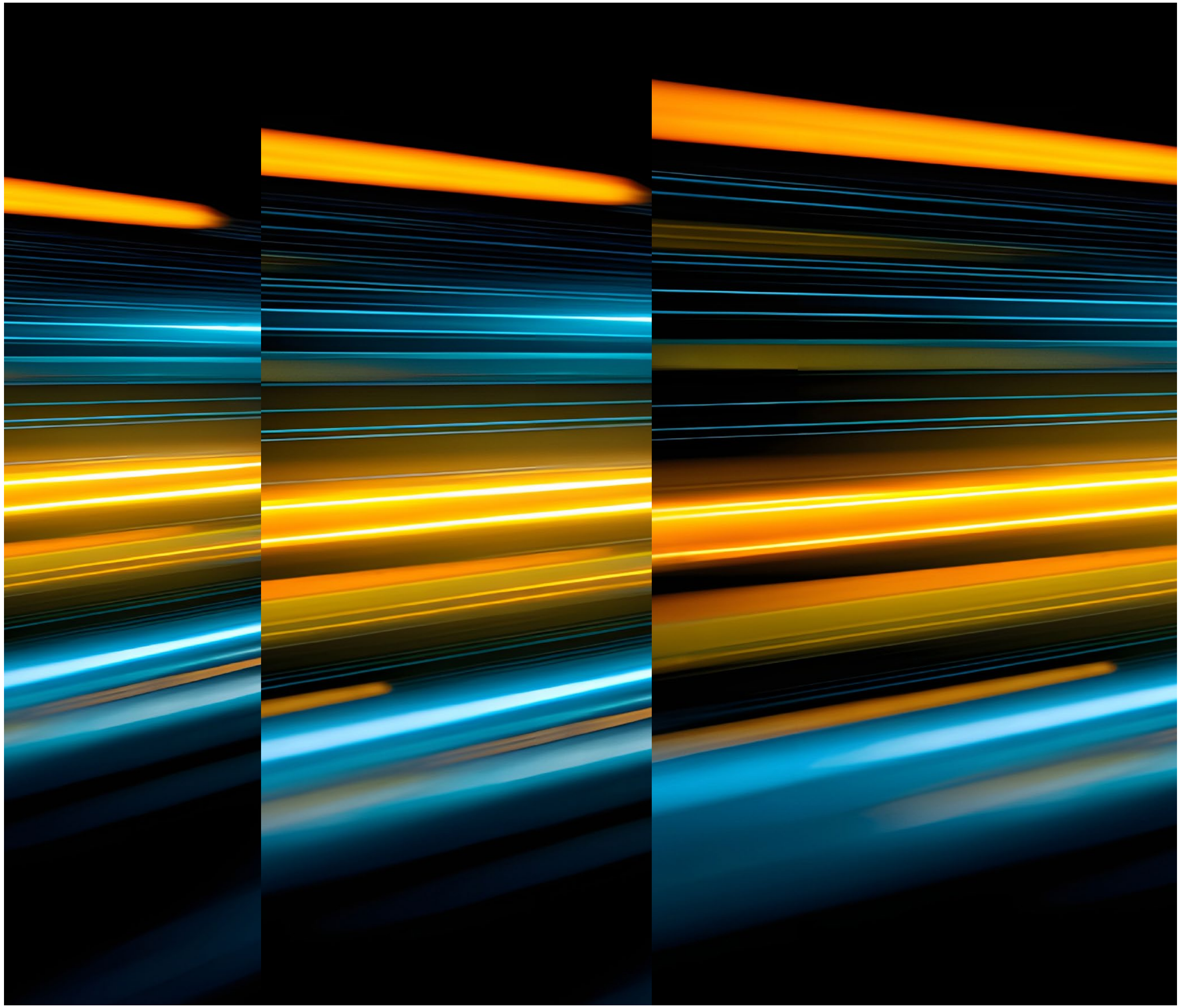
3. **Scale circular business models**
   Reframe batteries and materials not as products sold once, but as assets managed over time through models that reward durability, performance, recovery, and deployment into second-life applications, across multiple cycles of use. This includes expanding Battery-as-a-Service, upgrade/maintenance subscriptions, performance-based warranties, structured second-life offerings, and Material-as-a-Service pilots so durability, uptime, recovery, and residual value become commercial incentives and bankable outcomes rather than afterthoughts.

4. **Build and co-invest in regional circular infrastructure**
   Reimagine the battery value chain as an intentionally designed network of regional and inter-regional infrastructure that enables materials to circulate efficiently, resiliently, and transparently. This means treating collection, triage, testing/grading, repair/remanufacture, repurposing, and recycling as core infrastructure; and de-risking capacity via shared investment models and long-term feedstock/offtake contracts that make circular flows predictable.

5. **Make the circular operating system work**
   Reduce transaction costs and give businesses and investors the confidence to operate repair, reuse, and recycle loops at scale by creating the necessary transparency and traceability of currently hidden flows in the EV battery economy. This can be done by deploying interoperable battery passports and common data standards; aligning definitions and requirements (e.g. end-of-life classification, transport and treatment rules); and strengthening assurance mechanisms so secondary battery and material markets can function at scale with lower transaction costs and risk — going beyond compliance and structuring market infrastructure.

**For 15 years, the Ellen MacArthur Foundation has aligned a powerful business and policy network around a vision of an economy that works differently.** To catalyse implementation at scale the Foundation connects actors across value chains who can move quickly, learn, adapt, and sustain progress. In this context, we have already engaged over 30 EV battery industry actors representing each section of the value chain — from extraction and processing, to manufacture, service provision, and end-of-life reprocessing — to develop a future-proofed circular economy vision for the sector. From our unique position at the intersection of business and policy, our aim is to drive three types of action in the EV battery value chain: setting clear direction and alignment for business action, of which this report marks an early step; enabling effective collaboration to mobilise investment and innovation through new, localised networks, joint ventures, shared infrastructure, and co-investment; and advancing collective advocacy to reshape the policy and regulatory conditions needed for a circular EV battery system to succeed.

**Reframing EV batteries as high-value circular assets has the potential to be transformative. With a coherent view of where value is created or lost, where risks are accumulating, and which interventions unlock the greatest system-level returns, the industry can move beyond fragmented circular initiatives to build long-term resilience and value — protecting margins, shifting business models and profit pools, reducing supply exposure, and keeping critical minerals in circulation.**



# 01

# SYSTEMIC RISKS IN THE EV BATTERY VALUE CHAIN

**Electric vehicles (EVs) are moving from the margins to the mainstream, and batteries are becoming the strategic backbone of the energy transition.** The prize is large — growth, jobs, innovation, consumer benefits, and major emissions cuts — but the campaign depends on a value chain that can scale with discipline. Today's EV battery value chain is still largely linear, material-intensive, and potentially exposed to supply shortfalls and disruptions. This section sets out the five systemic risks that could slow or destabilise progress, and outlines the reasons ramping up recycling and second life is necessary but not sufficient.
A broader redesign is needed that makes circular models for batteries reliable and investable.

## 1.1

# THE EV TRANSITION OFFERS SIGNIFICANT POTENTIAL FOR ECONOMIC GROWTH AND EMISSION REDUCTIONS

**EV adoption is surging.** In 2024, approximately 20% of new cars sold worldwide were electric, totalling more than 17 million vehicles globally. Depending on governmental policies, technological advances, and consumer adoption rates, the market share of EVs is expected to reach around 65% to 75% of global car sales by 2050.[1]

**The transition is generating substantial economic opportunities.** The EV sector is a driver of global economies, creating new investment and jobs, and contributing significantly to GDP.[2] Although growth rates vary by region, the global EV market is forecast to experience strong and steady growth from approximately USD 892 billion in 2025 to over USD 2.1 trillion by 2032.[3] The industry as a whole is ushering in a new era of strategic opportunities for growth, innovation, and industrial transformation across countries.

**It is also already delivering meaningful impacts for global greenhouse gas (GHG) emission reductions.** The EV transition is fundamentally disrupting the oil market and leading to substantial impacts on global GHG emissions.[4] The adoption of EVs has displaced over 1.3 million barrels of oil per day in 2024, equivalent to Japan's entire oil demand for the transport sector.[5] By 2035, this number is expected to rise to over 6 million barrels of oil per day.[6]

# 1.2 HOWEVER, TODAY'S EV BATTERY VALUE CHAIN IS EXPOSED TO FIVE MAIN SYSTEMIC RISKS

**The EV battery sector depends on a value chain that can scale reliably and responsibly.** Today's system is still largely linear, material-intensive, and concentrated. That creates five systemic risks that could slow the transition unless addressed. Together, these five risks raise costs and increase fragility precisely as the system needs to scale. That is why circular economy strategies are not 'nice-to-have' add-ons. Circular economy solutions are both practical risk-management and competitiveness levers, and a key route to making battery loops investable at scale.

## » Supply-demand gap

The EV transition is driving unprecedented growth in demand for critical minerals. The production of an average EV contains over 200 kg of critical minerals, six times more than what is needed to produce an internal combustion engine (ICE) vehicle.[7] Over the next two decades, the electrification of passenger vehicles is projected to drive approximately half of the demand for critical minerals — like lithium, graphite, cobalt, and nickel — among all clean energy technologies.[8] Achieving net zero by 2050 means a six-fold increase in the production of these minerals from 2022 levels.[9] Despite recent increases in the number of mining and refining project announcements, major shortfalls in supply are still expected for some minerals by the mid-2030s, particularly for lithium and copper due to rapidly rising demand, natural declines in ore grades, rising capital costs, limited resources for discoveries, and long lead times for new mines.[10]

In addition, the current material feedstock for battery recycling largely stems from manufacturing scrap. This is forecast to continue in the coming years, with scrap from manufacturing processes still accounting for two-thirds of available recycling feedstock in 2030.[11] End-of-life EVs and storage batteries are expected to take over from 2035 onwards, once large enough volumes reach the end of their service life.[12] Therefore, in the short term, growth in recycling is structurally limited as it is tied to new battery production and manufacturing yield losses. Without a mature secondary supply from end-of-life batteries, the recycling practices of today — largely reliant on scrap alone — cannot close the near-term supply-demand gap.

## Environmental harm

The demand for critical minerals and the subsequent processing required to transform them into EV battery products also create burdens on the environment.

At the mining stage, most activities coincide with the world's most valuable biodiversity hotspots and threaten thousands of unique species and habitats found nowhere else on Earth.[13] Mining activities were responsible for a global loss of 1.4 million hectares of tree cover between 2001 and 2020,[14] affecting up to a third of the global forest ecosystem, a figure projected to increase in the coming years.[15] They also generate substantial biodiversity impacts in ecosystems thousands of kilometres away from where they take place, notably through waste tailings that infiltrate soils and water systems, carrying large amounts of heavy metals and severely impacting species and local communities.[16]

The extraction, processing, and refining activities of raw materials are also highly emissions-intensive,[17] even more so with critical minerals, which have a higher emissions intensity than other metals and commodities. For instance, the emissions from producing the average tonne of Class 1 nickel or lithium carbonate are, respectively, ten- and three-times higher than those from producing a tonne of steel.[18] The post-extraction stages of processing and refining minerals are also highly water-intensive and use chemicals that leak into the air and water systems, affecting both animal and human populations.[19]

Finally, though recycling is advancing and reaching high volumes of end-of-life EV batteries,[20] many regions still face limited collection infrastructure and weak economic incentives, causing a risk of leakage in the linear system, where end-of-life batteries are not always captured and processed appropriately. The high costs associated with recycling infrastructure further exacerbate the effective recycling uptake, diverting a large number of batteries to informal markets, where they are poorly managed and processed without adequate environmental and safety controls. This poses ongoing environmental and health risks.

## Social issues

Across the value chain, from resource extraction to refining, cell manufacturing and end-of-life treatment, communities face persistent challenges, including land degradation, pollution, unsafe working conditions, and socio-economic disruption. Many of these impacts remain insufficiently addressed.[21,22] In the case of mining — while it can deliver social benefits, including stimulating the local economy, increasing incomes, and creating local jobs — it can also raise a myriad of social issues when poorly governed. These can include uneven distribution of benefits and risks, land expropriation and displacement, damage to human health from environmental impacts, reduced water supplies, and water contamination.[23] These risks are often most acute in mineral-producing regions in emerging and developing economies (many in the Global South), where oversight capacity can be uneven and where communities may bear significant impacts without proportional economic ownership, value, or participation. Poor governance in mining for critical minerals has also been linked to widespread human rights violations.[24] Meanwhile, the waste collection stage preceding recycling also makes use of hazardous work practices in some areas, or even child labour.[25]

## Product and system inefficiency

During their use phase, batteries are often underutilised, spending large proportions of the time idle, not always connected to electricity grids, and losing performance through ageing.[26] Additionally, automakers are prioritising vehicles with large, long-range batteries to meet consumer expectations, increasing demand for critical materials.[27] However, many cars are used in urban contexts[28] with no need for such long-range battery capabilities, thereby missing an opportunity to increase material-use efficiency by deriving more value from a reduced amount of materials, and to reduce pressure on supply chains.

These inefficiencies are reinforced by battery designs and architecture which often prioritise first-life performance over modularity and repairability. While improvements in performance are vital, in some new, higher-integration architectures — such as certain cell-to-pack and cell-to-chassis designs — modularity, repairability, and serviceability can be reduced further, making it difficult for downstream end-of-life actors to open, repair, upgrade, or reconfigure batteries, limiting opportunities to extend their use and to recover materials at the end of life.[29,30]

## Supply chain bottlenecks and disruptions

Another issue is not only whether minerals exist, but whether they can be reliably converted to battery-grade materials and cells and moved through the supply chain. Today's mining, material processing, battery manufacturing, and end-of-life recycling are highly geographically concentrated.[31,32] This concentration increases the risk of supply bottlenecks and disruptions caused by extreme weather events, operational outages, logistical failures, regulatory delays, or trade disruptions. As a result, governments and regulators have increased their focus on supply security, trade deals and incentives, and introducing new policy and economic incentives for access to critical minerals.[33] However, these policies on their own do not resolve underlying supply chain disruption threats and may both inflate prices and slow the EV and renewable energy transitions through creation of additional friction, added cost, and complexities.[34]

These supply chain risks, in conjunction with growth in demand for EV batteries and their associated minerals, and potential risks of future supply-demand gaps, are leaving markets prone to spikes or sharp swings in critical mineral prices. This price volatility causes wide-ranging impacts on global supply chains: manufacturers have difficulty securing long-term contracts, committing to scaling production, and forecasting costs; and mining companies and recyclers face increased uncertainty when making large and long-term investment decisions. This results in margin pressure for supply chain players, such as battery producers, and affordability risks for consumers, with price hikes of potentially up to 40% to 50% in the event of a sustained battery metals supply shock.[35]

# 1.3 WHILE RECYCLING AND REPURPOSING EFFORTS ARE SCALING UP RAPIDLY, A COMPREHENSIVE SYSTEM TRANSFORMATION IS NEEDED

**Efforts to recycle EV batteries are ramping up.** Companies are recognising the role of recycling in reducing material costs, lowering waste management burdens, and limiting exposure to volatile commodity markets. Advances in asset tracking, AI-enabled sorting, and more efficient processing technologies are making recycling increasingly viable and scalable. The rapid expansion of global EV fleets and battery lifespans of eight to 12 years are expected to generate huge volumes of recycling. According to some estimates, global battery recycling could increase sharply, from USD 13 billion in 2025 to USD 114.66 billion by 2035.[36] In parallel, governments worldwide are prioritising recycling as a pillar of secure and resilient supply chains. For example, the EU has introduced minimum recycled-content requirements for key minerals;[37] China has enacted stringent regulations and built extensive recovery infrastructure;[38] and ambitious targets for EV adoption in Southeast Asia are creating indirect momentum for the battery recycling industry (e.g. Thailand is aiming for 30% of vehicle sales to be electric by 2030, while Indonesia and Vietnam are aiming for total adoption by 2050).[39]

**Initiatives to keep retired EV batteries in use are already underway.** As the first large waves of EVs reach the end of their useful life, companies and governments are attempting to scale solutions to repurpose and recycle their batteries. Even after an EV battery can no longer power a vehicle efficiently, it typically retains 70-80% of its original capacity — enough for a wide range of less-demanding applications. This opens up significant opportunities for investment in second-life markets, such as stationary energy storage, backup power systems, microgrids, and renewable integration.

**However, these solutions alone cannot resolve underlying supply-chain challenges — doing so requires a system redesign.** For the world to meet global decarbonisation goals, EV battery use and the stock of critical minerals required for them will have to grow tremendously in the coming years. Yet scaling the current linear system would exacerbate environmental degradation, social risks, and supply chain vulnerabilities, making the transition increasingly costly and unstable. For the shift to be economically viable, environmentally sound, and socially just, a fundamental redesign of the EV battery system is required. Decisions made today will either lock in the linear system or accelerate one that keeps critical minerals in high-value use over multiple lifetimes. The time is now to ensure the coming wave of EV battery demand is met in ways that generate positive economic, environmental, and social outcomes.

# 02

# A SYSTEM-LEVEL TRANSFORMATION TOWARDS A CIRCULAR EV BATTERY ECONOMY

## 2.1

# A CIRCULAR ECONOMY VISION FOR EV BATTERIES

**In an ideal circular economy, EV batteries deliver the greatest possible value across their use phases, and the critical minerals used to make them never become waste.** This is the core ambition of a circular economy for EV batteries. This vision is aligned with the principles of a circular economy and is centred on four core pillars:

- **The mobility and energy storage services EV batteries provide are maximised** in their use phase by being fully integrated into mobility and energy systems.
- **EV batteries are employed at their highest value for as long as possible** by being designed to be maintained, repaired, refurbished, and recycled.
- **The materials used to make EV batteries are kept in circulation for as long as possible, delaying their eventual disposal as waste**, through high-quality, economically attractive collection and recycling systems.
- **The value generated by EV batteries is fairly distributed** by employing high-value business models across the value chain.

**Realising this vision would bring benefits across the value chain, including:**

- **Curb the demand for virgin critical minerals** by making more effective use of EV batteries and the materials embedded in them.
- **Strengthen supply chain resilience** by circulating EV batteries and critical minerals in the economy, thereby reducing the exposure of players across the value chain to virgin material price volatility and supply bottlenecks.
- **Unlock substantial economic value** by making more effective use of existing materials and components, leading to lower costs for materials and waste management across the value chain, better services for EV battery users, and new revenue streams for producers.
- **Support goals on climate, biodiversity, and pollution** by reducing the requirement for newly mined minerals, supporting the scaling of renewable energy, and reducing EV battery waste generation and its associated environmental harms.
- **Distribute economic opportunity to mineral-producing countries** which can move up the value chain, ultimately ensuring that the countries and local communities endowed with these resources are the ones to benefit the most, in accordance with the UN principles guiding the energy transition minerals towards equity and justice.[40]

**This vision complements the current focus on recycling and cascading use by introducing systemic solutions.** To date, circular economy activity in the EV battery sector has focused largely on material recycling and cascading EV batteries to secondary uses once they can no longer perform their primary function. By contrast, upstream opportunities that prioritise system redesign and the use of higher value ‘inner loops’ of reuse, remanufacturing, and refurbishment have received less attention. Recycling and repurposing through cascaded uses will remain crucial elements of a circular economy for EV batteries, though the design of batteries can be further improved on to make their adoption more technically feasible and economically viable. However, the vision outlined above expands the concept in equally important ways to ensure the benefits it generates are expanded and maximised. The levers described below — which represent opportunities to put the different elements of the vision into action — constitute the steps necessary for such a system-level transformation.

## BOX 1 The circular economy

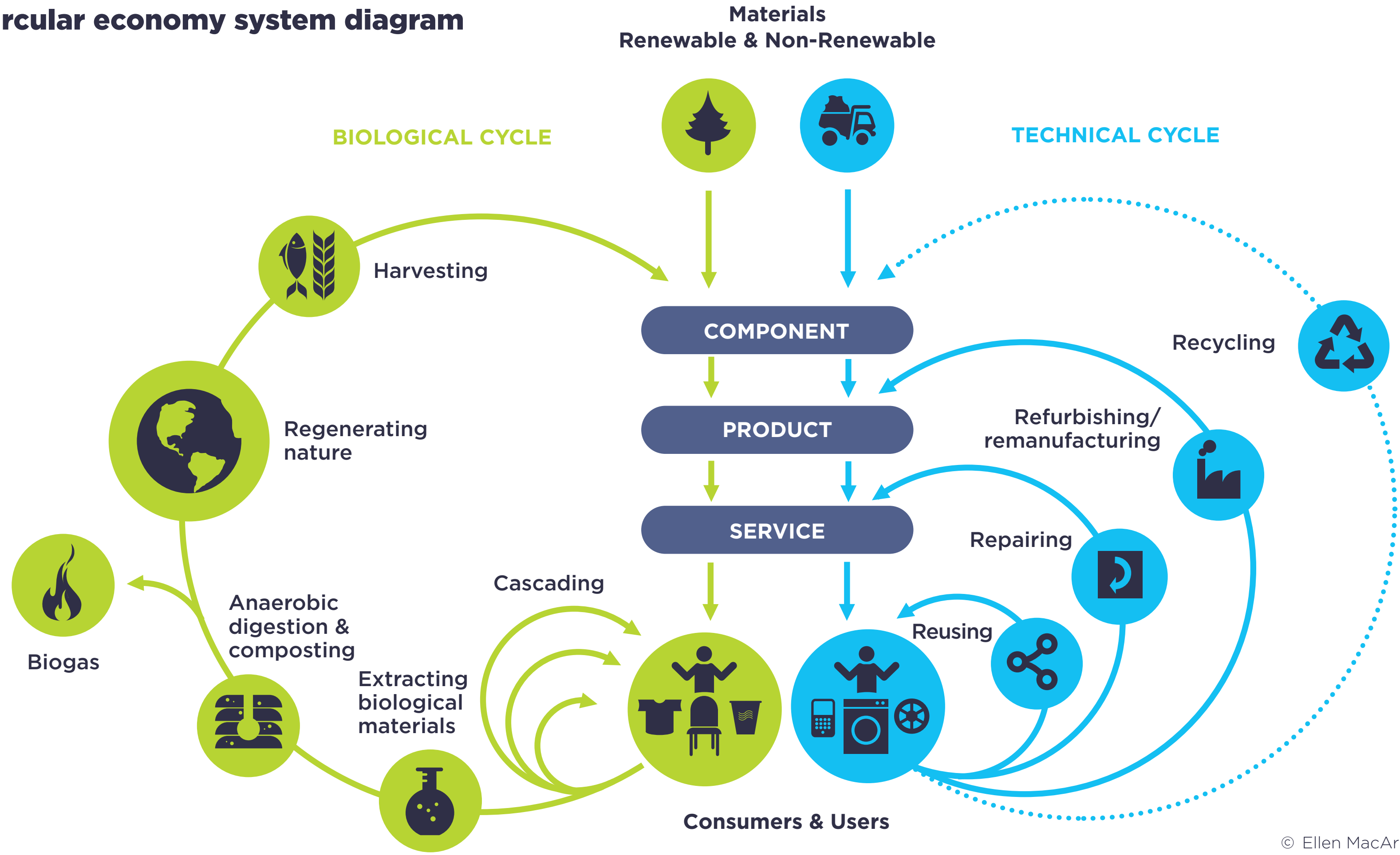
The circular economy is a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. The circular economy tackles climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources.

The circular economy is based on three principles, driven by design:

- Eliminate waste and pollution
- Circulate products and materials at their highest value
- Regenerate nature

Underpinned by a transition to renewable energy and materials, the circular economy is a resilient system that benefits business, people, and the environment.

## The circular economy system diagram



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Drawing based on Braungart &
McDonough, Cradle to Cradle (C2C)

# 2.2 THE FIVE CIRCULAR ECONOMY LOOPS FOR EV BATTERIES

**In a circular economy for EV batteries, interventions can be distilled into a small set of circular loops in which EV batteries and the critical minerals embedded in them can circulate through the economy instead of being used once and discarded.** These loops are often mutually reinforcing. For instance, design for disassembly (DfD) facilitates repair, second life, and recycling; high-quality recycling creates a dependable secondary supply that makes circular business models more attractive; while data and policy coherence underpin all other loops.

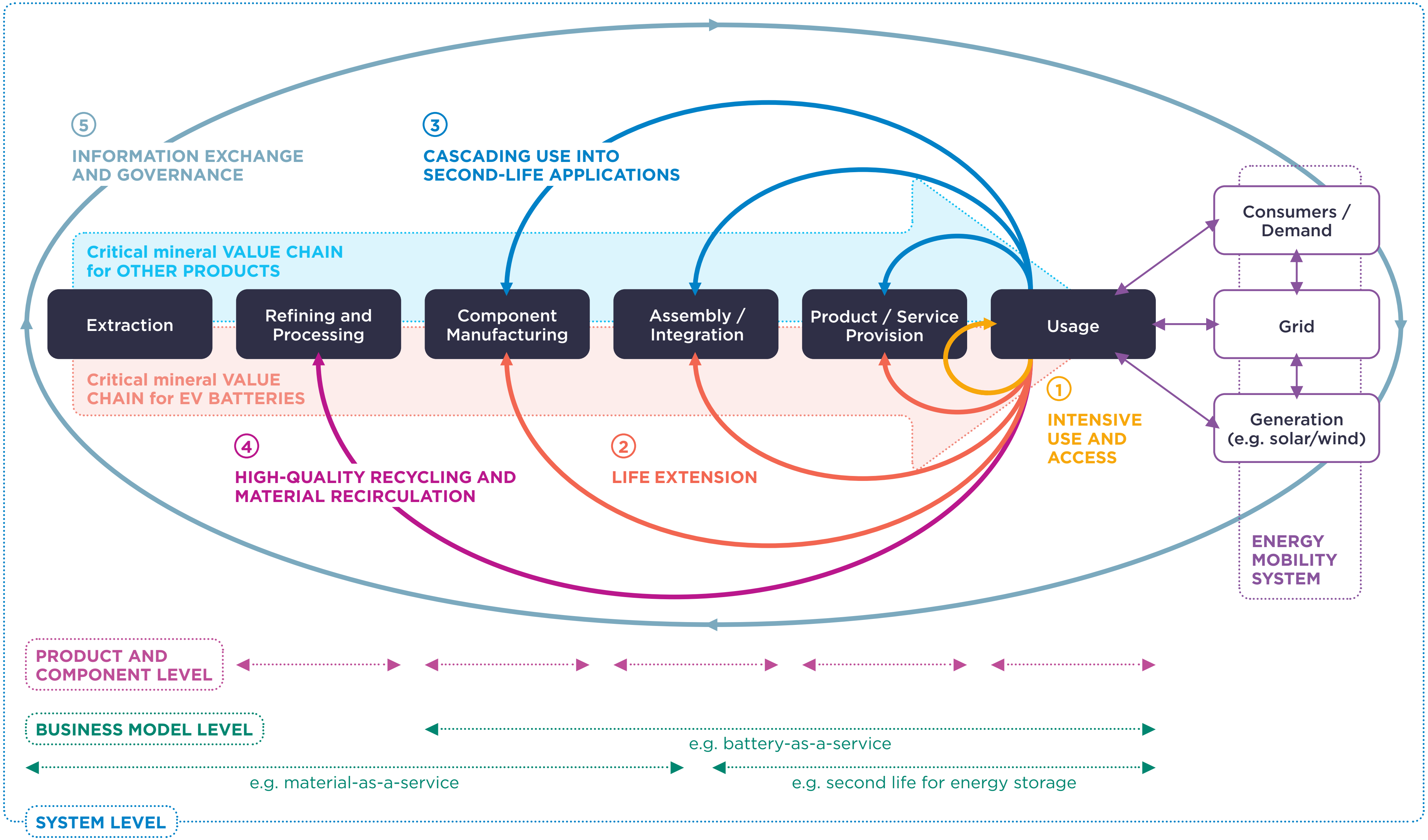
At the same time, the loops are deliberately stylised. They are not a detailed system model or a full representation of all risks and trade-offs. It is worth noting also that they are not always automatically additive — for example, higher utilisation or Vehicle-to-Grid (V2G) services can accelerate degradation if not managed, and second-life use can delay the return of materials for new batteries. Therefore, scenario analysis, standards, policy, and industry priorities can help determine which pathway is preferable in which context, and reduce the risk that local loop optimisation undermines circular outcomes overall against policy or economic objectives.

**These loops do two things when it comes to discussions of a circular economy for EV batteries:**

- Provide a simple language for describing how different opportunity areas work
- Help show where different actors (from miners to original equipment manufacturers [OEMs] to cities) are in fact contributing to the same underlying dynamics, even when they act at different points in the value chain.

Building on the circular economy framework and system (or ‘butterfly’) diagram (see Box 1), the five circular loops of particular relevance to EV batteries are listed below. Four loops describe physical circulation of batteries and materials; the fifth is an enabling loop that determines whether the physical loops can happen at scale.

**Figure 1** How the circular economy drives innovation and value creation across the EV battery critical minerals system



## 01 Intensive use and access

**This loop encompasses strategies that increase the amount of mobility and energy services delivered per battery,** such as shared and on-demand mobility systems that reduce idle time and improve utilisation, as well as the use of EVs as distributed energy storage through V2G or Vehicle-to-Home (V2H) services, enabling each battery to deliver more passenger-kilometres, freight-tonne-kilometres, or kilowatt-hours over its life. It shows how higher utilisation can reduce the material intensity of mobility and storage (less mineral input per unit of service), and highlights that the core ratio is between services delivered and critical minerals circulating in the system.

**Important considerations:**

- **Demand effects and potential rebound effect risks** in mobility and energy services
- **Urban planning, behavioural shifts, and governance** needed to move away from private car dominance (including multimodal integration and charging availability)
- **Interoperability across vehicles, charging, and service platforms,** including physical charging compatibility, roaming/payment, data sharing, and (where relevant) V2G communication and market participation, such that assets can be shared, charged, and monetised across operators and borders
- **Equity and distributional impacts,** including who gains access first and how benefits and burdens fall across users and regions.

## 02 Life extension through repair, refurbishment, and remanufacture

**This loop covers strategies that slow the rate at which batteries move through their first life by keeping them in good condition and returning them to high-value use when they fail**, including better operation and maintenance, repair and module replacement, and more intensive refurbishment and remanufacture, enabled by modular design, debonding solutions, and embedded diagnostics. It shows an increase in the average technical and economic lifetime of batteries in their primary application, and therefore fewer new batteries — and less virgin mineral input — needed to deliver a given level of services, thereby building supply chain resilience.

**Important considerations:**

- **Real-world economics, capabilities, and safety frameworks** needed to provide these services at scale
- **Conditions under which life extension may be sub-optimal** compared with accelerated replacement and high-quality recycling (e.g. when new chemistries are vastly more efficient)
- **Allocation of responsibilities, warranties, and liabilities** across OEMs, independent repairers, remanufacturers, recyclers, insurers, and regulators
- **Approaches to modularity and standardisation that preserve innovation,** addressing concerns regarding design lock-in, reduced competitive innovation, differentiation, or slower technology improvements.

## 03 Cascading use into second-life applications

**This loop includes how batteries transition from high-performance automotive use into second-life applications with lower performance requirements** — such as behind-the-meter storage, microgrids, or backup systems — once they fall below automotive performance thresholds. It relies on the ability to assess the state of health; sort and aggregate used packs and modules; and then match them to appropriate stationary use-cases and business models. It shows how the number of useful life cycles per battery can increase before dismantling and recycling, and how well-designed cascades can reduce demand for new packs in stationary storage and thereby ease pressure on primary mineral supply.

**Important considerations:**

- **Trade-offs between delaying recycling and the timely availability of secondary materials** for new EV batteries (particularly in fast-growing markets)
- **Technical and regulatory challenges linked to recombining heterogeneous used components**, such as different packs or modules (including testing protocols, standards, warranties, certifications, and safety considerations)
- **Market access and value realisation for second-life assets**, such as for grid-scale storage system, examining interconnection rules, dispatch or aggregation requirements, and revenue mechanisms in different system contexts
- **Logistics, storage, and transport compliance for used batteries**, including safe handling, interim storage rules, and cross-border shipment constraints (and the risk of leakage into poorly regulated channels)
- **Economic competitiveness of second-life systems versus new storage options**, such as impacts of new-battery price declines, new chemistries, warranty expectations, and other costs associated with testing, balance-of-system, and integration.

## 04 High-quality recycling and material recirculation

**This loop represents the recovery of critical minerals from end-of-life batteries at high yield and in forms suitable for battery-grade applications**, via hydrometallurgical, pyrometallurgical, or emerging direct-recycling routes, assuming that collection, logistics, and pre-processing reliably connect end-of-life batteries to appropriate facilities. It shows how a growing share of secondary materials in cell and battery production can progressively reduce dependence on virgin extraction, and how 'tight' loops — with minimal losses to slag, low-grade products, or unmanaged waste — help stabilise supply and support circular business models.

**Important considerations:**

- **End-of-life timing constraints and feedstock lag** in a rapidly growing market (including the additional delay created by second-life use). Aligning economic, operational, and policy considerations between **recycling capacity ramp-up and available feedstock volumes**, including uncertainty in feedstock access and quality, return rates, utilisation risk, and investment bankability
- **Environmental and social impacts of recycling operations**, including energy use, emissions, local pollution, and the governance needed to manage them
- **Competitive dynamics and quality risk** (e.g. low-yield or low-cost routes undercutting high-quality recovery in the absence of clear standards and incentives)
- **Regulatory classification and shipment rules for recycling intermediates (particularly black mass)**, including hazardous/non-hazardous status, waste codes, and implications for cross-border flows and domestic refining capacity
- **Harmonised calculation, verification, and reporting of recycling efficiency and material recovery**, including documentation requirements and definitions of usable output fractions
- **Convergence risks between evolving battery chemistries and recycling business models**, including how changing material compositions alter recovery value, yields, and the economics of 'battery-grade' refining.

## 05 Information exchange and governance (enabling loop)

**This enabling loop underpins all the prior physical loops by capturing the circulation of data, rules, and incentives for material flows which determine how batteries and materials can be located, assessed, moved, and treated to achieve circular outcomes.** For example, this may include digital product passports and traceability systems, common data standards, aligned definitions of waste and end of life, and financial, contractual, and regulatory mechanisms that reward durability, repairability, and high-quality recovery. It shows how better information and governance can close accountability gaps, make responsibilities visible along the chain, and create the conditions for investment in circular business models and infrastructure.

In practice, information and data access and governance shape how decisions are made about routing batteries through repair, repurposing, or recycling pathways. For example, without trusted, portable battery health information, it is difficult to value used batteries, verify suitability for second life, or route packs efficiently to the highest-value pathway.

**Important considerations:**

- **Political economy and legitimacy of rule-setting and standard-making**. Decisions about data, reporting, and traceability shape who can participate, who bears costs, and who captures value across the EV battery value chain. Ensuring legitimacy requires inclusive governance processes that represent upstream producers, manufacturers, recyclers, workers, and affected communities.
- **Trust, confidentiality, and data-sharing arrangements between actors**. Information circulation depends on trusted data-sharing frameworks that protect commercial sensitivity, clarify access and ownership, and prevent data withholding that undermines traceability and system performance.
- **Interoperability and fragmentation risks in digital passports and traceability systems**. Multiple, uncoordinated battery passport and traceability initiatives risk creating fragmented systems, increasing compliance costs, and limiting cross-border circulation of batteries and materials.
- **Data quality, verification, and auditability mechanisms**. For battery data to be trusted, it must be accurate, verifiable, and auditable over time. This requires agreed protocols for data collection and reporting, independent assurance mechanisms, and robust chain-of-custody systems that track materials and components across life cycles.
- **Cross-border regulatory alignment and legal complexity**. EV battery data flows are subject to multiple regulations, including trade law, waste and end-of-life definitions, transport rules, and financial regulation. Misalignment across jurisdictions can block circular loops, such as cross-border reuse or recycling.
- **Incentive coherence and pathway ‘routing’ rules**. Data systems increasingly influence how batteries are directed toward repair, repurposing, cascading, or recycling. Routing rules and incentives must be aligned with system-level objectives, ensuring that higher-value loops are prioritised over suboptimal pathways or premature recycling.
- **Broader social licence and justice dimensions**. Transparency around sourcing, labour conditions, environmental impacts, and community consent is critical to maintaining public trust and social licence. Data governance should ensure that the benefits of circular EV battery systems are shared fairly and do not reproduce existing inequities.

## Table 1 How circular economy loops address systemic risks in the EV battery value chain

Systemic risks to the EV battery value chain

| **Circular Loops »** | **Intensive use & access** | **Life extension (repair, refurbishment & remanufacture)** | **Cascading use into second-life applications** | **High-quality recycling & material recirculation** | **Information exchange & governance (enabling loop)** |
|---|---|---|---|---|---|
| **Supply-demand gap** | Increases services delivered per unit of installed capacity (shared/on-demand mobility, V2G), lowering mineral input per unit of service. | Slows the replacement rate of existing batteries so more service is delivered from the same stock before new production is required. | Redirects used batteries into stationary storage and other applications, substituting for new packs and easing pressure on mineral demand in those sectors. Though it can delay recycling. | Returns critical minerals to the supply pool as secondary material, progressively curbing material demand over time (with lag). | Improves visibility of battery stocks and material flows (e.g. via passports and traceability) and aligns rules and incentives so investment flows to the highest-value circular options easing supply pressure. |
| **Environmental harm** | Reduces overall demand for new batteries, easing pressure on mining, processing, and manufacturing activities — the most environmentally damaging processes in the value chain. | Reduces production emissions and land/energy footprints associated with new pack manufacturing thanks to fewer replacements and better-cared-for batteries. | Avoids the production of additional batteries and the emissions associated, by using remaining capacity in second-life applications, ultimately reducing the total volumes likely to become waste. | Displaces part of primary mining demand with secondary feedstock, reducing cumulative extraction and enabling stricter environmental standards in managed facilities. Reintroduces materials into the production cycle instead of losing them to landfills, lower-quality uses, or leakage. | Embeds environmental standards, reporting, and incentives into regulations, encouraging actors in the value chain to adopt low-impact and cleaner practices for production and recycling. |
| **Social issues** | Reduces overall demand for new minerals and the need for new extraction frontiers, limiting associated risks to communities and workers. | Reduces the pressure to open or expand mines in high-risk areas, easing social and human-rights burdens at the margin. | Shifts some value creation away from primary extraction towards downstream service activities that can be more tightly regulated. | Builds a more regulated secondary supply base which, if well managed, replaces some high-risk primary sources (e.g. artisanal and small-scale mining in sensitive regions). | Makes social performance visible throughout the chain (due diligence; passports; free, prior, and informed consent; labour standards) and ties access to markets/finance to better practices. |

**Systemic risks to the EV battery value chain**

| **Circular Loops »** | **Intensive use & access** | **Life extension (repair, refurbishment & remanufacture)** | **Cascading use into second-life applications** | **High-quality recycling & material recirculation** | **Information exchange & governance (enabling loop)** |
|---|---|---|---|---|---|
| **Product and system inefficiency** | Tackles under-utilisation head-on by rightsizing batteries, promoting shared use and enabling EVBs to provide both mobility and energy services (e.g. V2G). | Improves real-world performance and reliability through better care and timely repair, reducing periods of downtime and under-performance. | Puts 'stranded' capacity from retired EVBs to work in new applications, turning what would be idle or wasted capacity into useful services. | Encourages more deliberate material choices and modular designs that avoid inefficient lock-ins, thanks to feedback on design and system planning (when high-quality recycling is expected and valued). | Informs product design, business models, and regulation, by using data on utilisation, performance, and degradation — discouraging oversizing, idle assets, and rewarding efficient use. |
| **Supply chain bottlenecks and disruptions** | Reduces exposure to volatile primary commodity markets by lowering the demand growth for new minerals through more intensive and efficient use of existing capacity. | Dampens the need to constantly expand primary supply, easing pressure on tight markets that can otherwise translate into sharp price swings. | Adds flexibility into the system by providing an additional 'buffer' of usable capacity that can be deployed in response to shocks without immediately ramping new production. | Creates a geographically more distributed, secondary resource base that can cushion price shocks and reduce dependence on a small set of primary suppliers and regions. | Supports diversification and resilience through transparent data, stable long-term contracts, and policy frameworks that encourage new entrants, shared infrastructure, and more balanced value capture across regions. |

# 2.3

# THE THREE LEVELS OF ACTION OF THE CIRCULAR ECONOMY FOR EV BATTERIES

**To move from vision to implementation, these loops are translated into three distinct, but interdependent, levels of action.** These two concepts can be explained as follows:

- **Loops** describe *what happens* to batteries and minerals over time — the ways they are used longer, used more intensively, cascaded into new applications, or finally recycled.
- **Levels** describe *where decisions* are made that either enable or block those loops — in the design of **products and components**, in **business models** and ownership structures, and in the wider **systems** of policy, infrastructure, and finance.

**A circular economy intervention or mechanism can therefore be understood as activating one or more loops, and at one or more levels of action.** This framing help to clarify (i) how different interventions complement each other, and (ii) how they address scaling challenges by revealing where limiting factors arise in decisions shaping products, markets, and systems.

## 01 **Products and components level**

— where the technical potential of the circular economy is set

**This level is about how batteries, vehicles, and components are designed, sized, assembled, and specified — including chemistry choices, pack architecture, joining and bonding solutions, and embedded diagnostics.**

Design choices at this level determine:

- **How effectively inner loops (maintenance, repair) can be carried out**, for example, through modular pack designs, debondable adhesives, and standardised formats
- **How easily batteries can be repurposed or cascaded into second-life applications** such as stationary storage
- **How efficiently materials can be recovered at end-of-life, and at what cost**, through design for disassembly and high-quality recycling
- **How much critical mineral demand is generated in the first place**, through battery rightsizing, energy-density improvements, and material substitution.

In other words, product and component design is where the technical ceiling of the circular economy is set: it governs which loops are even possible, how high-value they can be, and with what economic and environmental payoff.

## 02 **Business models level**

— where value from the circular economy is created and captured over time

**This level is about how value is incentivised, generated, shared, and de-risked across the battery life cycle, for example through Product-as-a-Service (Paas), Battery-as-a-Service (Baas), and Material-as-a-Service (MaaS) models, second-life markets, service-based logistics and reverse-logistics, or data-driven fleet optimisation.**

Business models at this level shape:

- **Ownership structures and incentives**: who owns the battery or the embedded materials at each stage, who is rewarded for designing for longevity and recovery, and who is responsible for end of life
- **Activation of loops in practice**: service/lease and performance-based models (e.g. BaaS, MaaS, and structured second-life offerings) enable high utilisation, planned maintenance/upgrade, and predictable return flows for repair, remanufacture, repurpose, and recycling
- **Risk and reward distribution** across the value chain, especially between mineral-producing countries, battery manufacturers, vehicle OEMs, and operators.

Business models are therefore where circular loops become tangible investable propositions rather than technical options — they determine whether the circular economy is profitable enough, for enough actors, to scale.

## 03

## Systems level

— where the enabling conditions to the circular economy are created

**This level is about how infrastructure, policy, finance, and cross-value-chain collaboration are fundamentally configured (or reconfigured) to accelerate and enable the circular economy, including:**

- **Mobility and energy systems,** for example, on-demand mobility, V2G, grid-integrated swapping infrastructure
- **Regional circular infrastructure** for repair, remanufacturing, and recycling, as well as the workforce, skills and capabilities, and safety and quality standards needed to operate this infrastructure at scale
- **Rules for moving batteries and recovered materials across borders, and for classifying waste** versus secondary resources
- **Transparency and traceability mechanisms**, such as battery passports and standards for ESG performance in mining and processing.

Decisions at this level determine:

- **Whether circular solutions can scale in practice**, for example, whether cross-border rules and logistics allow batteries to move to where capacity exists, or whether policy and finance support regional recycling and repurposing infrastructure
- **How the benefits and burdens of a circular EV battery economy are distributed across regions**, especially mineral-producing countries and emerging economies
- **How far the circular economy can reduce systemic risks**, such as those identified earlier — supply-demand gap, environmental harm, social issues, product and system inefficiency, and supply chain bottlenecks and disruptions.

System-level actions help prevent circular initiatives from remaining isolated pilot projects, and transform loops and business models into a coherent and resilient global EV battery value chain.

## Table 2 How circular economy loops operate across product and component, business model, and system levels

Each loop requires coordinated interventions at the product and component level, business-model level, and system level; while gaps at any level can prevent circular pathways from scaling.

Level of action

| **Circular Loops** » | **Products & components** | **Business models** | **Systems** |
|---|---|---|---|
| **Intensive use & access** | • Rightsized packs for real duty cycles<br>• Bidirectional charging and robust thermal management<br>• Embedded telemetry (usage, degradation) for optimisation | • Shared/on-demand mobility and fleet optimisation<br>• Range-flexible access (subscription, swapping, leasing)<br>• V2G aggregation and revenue-sharing contracts | • Multimodal planning and charging/swapping networks<br>• Grid rules/tariffs for V2G (interconnection, aggregation)<br>• Interoperability standards (charging, communication) |
| **Life extension (repair, refurbishment & remanufacture)** | • Modular architectures; reversible fasteners/debonding<br>• Accessible components; repair documentation; standard interfaces<br>• Diagnostics and state-of-health data; chemistry transparency (passport) | • Service contracts and extended warranties<br>• Core-return/exchange and upgrade programmes<br>• Markets for repaired/refurbished modules; clear liability allocation | • Repair/remanufacturing hubs and trained workforce<br>• Right-to-repair: access to spares and repair information<br>• Safety and certification standards; compliant transport rules |
| **Cascading into second-life applications** | • Design for safe disassembly and repurposing<br>• Standardised state-of-health grading and interfaces (voltage, comms)<br>• Repurposing-ready Battery Management System (BMS) and safety features | • Second-life storage services (leasing, pay-per-kWh)<br>• Aggregation and matching platforms for used packs/modules<br>• Warranties and performance guarantees for second-life assets | • Grid incentives and market access for distributed storage<br>• Qualification, safety, and warranty standards for second life<br>• Streamlined permitting and interconnection; passport adoption |
| **High-quality recycling & material recirculation** | • Clear material/chemistry labelling; design for automated disassembly<br>• Joining choices that enable high-yield separation and sorting<br>• Chemistries/material choices that support high-quality recovery | • Take-back and collection embedded in sales/service contracts<br>• Long-term feedstock and offtake agreements (closed-loop procurement)<br>• Pricing and contracts that reward yield, quality, and traceability | • Regional collection, pre-processing, and recycling capacity<br>• Recycled-content requirements and material quality standards<br>• Aligned end-of-life/end-of-waste definitions and compliant movement rules |
| **Information exchange & governance (enabling loop)** | • Unique battery ID and digital product passport<br>• Common data set: chemistry, provenance, use history, state of health<br>• Cybersecurity and controlled-access design | • Data-sharing agreements and trusted intermediaries<br>• Contracting for responsibilities, residual value, and liability<br>• Assurance/audit services for claims (recycled content, ESG) | • Interoperable standards and governance for access/consent<br>• Coherent definitions and rules (end of life, waste/end of waste)<br>• Policy signals that de-risk investment and reduce friction |

**BOX 2**

## The value generated by a circular economy transition for EV batteries must be fairly distributed across regions and the value chain

The highly centralised and fragile EV battery value chain presents economic uncertainty for all countries, as none are self-sufficient and all are exposed to supply chain disruptions.[41] At the same time, building fully independent, end-to-end value chains will not be feasible in the near term, as the geological distribution of resources is uneven, and for resource-rich regions, moving up the value chain requires access to capital, technology, and skills, a set of factors that depend on international cooperation.[42] Therefore, increased collaboration is essential to both distribute value more equitably across regions and reduce systemic risks. Shifting from managing scarcity and risks to promoting collaborative systems can enhance resilience and innovation across the EV battery value chain.[43]

Achieving this shift requires rethinking how cooperation is structured to ensure linear extractive practices are not replicated. As the circular economy for EV battery advances, additional mining will still be required in the interim to support a successful EV transition. In doing so, international cooperation must ensure it is done responsibly, emphasising transparency, environmental stewardship, social responsibility, and ethical governance throughout the mining life cycle.[44,45] However, such practices remain far from the industry norm.[46] While voluntary standards and initiatives have helped advance responsible mining practices,[47] they should be complemented by binding regulation to ensure these expectations are consistently enforced.

International cooperation must also enable developing countries, where most of these resources are found, to not be limited to exporting low-value raw materials, but to fully participate in the development of a circular supply chain for EV batteries, adding value to their exports through processing materials and developing end-of-life technologies in recycling, repurposing, and repairing.[48] This can be done through technology transfer agreements, foreign direct investment, fairer trade deals, and support in capacity building.

Finally, international cooperation efforts must explicitly recognise and engage with the informal sector, which plays a significant role both upstream in artisanal and small-scale mining, and downstream in end-of-life activities such as collection, dismantling, and recycling.[49,50] In many developing countries, informal actors provide livelihoods for millions and supply a substantial share of critical minerals and secondary materials, yet often operate outside regulatory frameworks, facing unsafe working conditions, environmental harm, and economic precarity.[51] A just transition to collaborative circular economy systems, therefore, requires policies that support gradual formalisation, improved labour conditions, access to finance and technology, and integration into responsible supply chains,[52] potentially through cooperative organisational schemes, public-private partnerships, and inclusive recycling models.[53] This can enhance the resilience of EV battery value chains and ensure that their expansion delivers more equitably distributed value across regional actors.

# 03

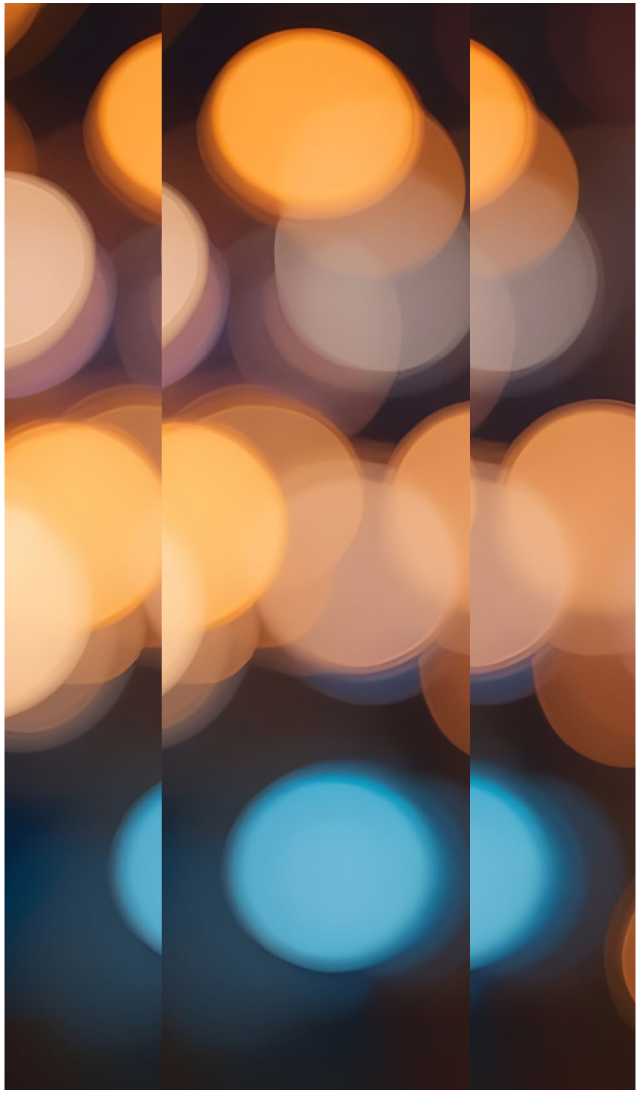
# FIVE BRIGHT SPOTS TO ADVANCE CIRCULAR EV BATTERY LEADERSHIP

**Siloed approaches to circularity are increasingly recognised as a limitation in the EV battery value chain**. As EV batteries scale rapidly, there are different ways to respond. One is to treat circularity as a set of end-of-life fixes — necessary, but ultimately reactive. Another is to recognise a deeper shift: a circular economy framework can function like a master key for the battery era, because it changes what the system is optimised for — from throughput to utilisation, from one-life products to managed assets, from isolated interventions to reinforcing loops. Used well, it does not open a single door; it opens many: design decisions, commercial models, reverse logistics, data architectures, investment cases, and policy alignment.

**Five 'bright spots' for circular economy activity that are already emerging and demonstrating promise were identified** through structured industry engagement with more than 30 organisations across the EV battery value chain. Opportunities where coordinated action by industry, investors, and policymakers could accelerate progress and the effective implementation of circular loops across the different levels were in particular focused on. These areas do not indicate a comprehensive list of all actions needed to realise the vision described in Chapter 2, but rather highlight the immediate and high-leverage opportunities that can propel meaningful change towards a circular economy for EV batteries.

**The following opportunities show not only *what* needs to happen to batteries and minerals, but also *where* decisions must shift in and across the system** — in design studios and engineering teams, in boardrooms and contract negotiations, and in policy, infrastructure, and international cooperation. They also highlight who needs to act to unlock the benefits of the circular EV battery economy and ensure that it becomes the norm rather than the exception.

But the emergence of early bright spots does not mean we have reached the final answer, nor that the remaining work is merely incremental. The battery system is complex, and the outcomes leaders care about — such as cost, resilience, emissions, and sourcing — are shaped upstream and across multiple interfaces: where incentives sit, how value is shared, and what information and infrastructure make looping bankable. This report offers not a definitive conclusion, but a **replicable analytical framework and a starting set of priority bright spots** as a launchpad for cross-value chain and cross-sector collaboration: a common language to convene conversations today, and a practical foundation on which deeper analysis, pilots, and industrial collaboration can be built next.



# 3.1

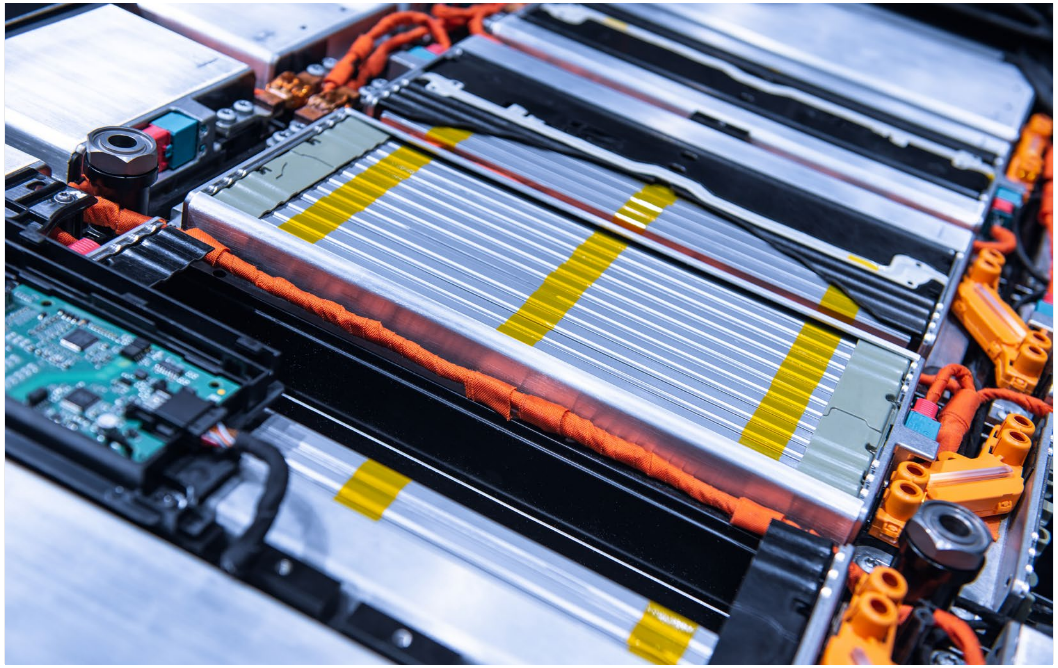
# DESIGN BATTERIES FOR CIRCULARITY, NOT DISPOSAL

## What benefits this opportunity unlocks

**Redesigning EV batteries for diagnosis, disassembly, modularity, and traceability makes it technically and economically viable to operate the repair, refurbishment, second-life, and high-quality recycling loops at scale.** It is a foundational enabler of a circular EV battery economy, shifting batteries from single-purpose design into durable components of a broader mobility and energy system, intentionally made to last, be taken apart, and reused across multiple lives and applications. It lowers lifetime cost by avoiding premature replacements, enabling more effective repair and repurposing of products and materials (e.g. by making it possible for the service providers of these loops to practically and efficiently reprocess materials), and preserving higher residual value in packs and modules for longer. It also strengthens resilience by enabling more regional repair, remanufacture, and material recovery, reducing exposure to primary supply shocks. By extending service life and improving recovery yields, battery redesign reduces emissions per kWh delivered and supports responsible sourcing through clearer, more traceable material composition that eases compliance and improves transparency.

## Which loops are enabled

- Life extension through repair, refurbishment, and remanufacture
- Cascading use into second-life applications
- High-quality recycling and material recirculation
- Information exchange and governance (enabling loop)



## 3.1

## How it can be applied at each level

| | |
|---|---|
| **Products and components** | • Introduce modular pack and module architectures that allow faulty cells or modules to be isolated and replaced without discarding entire packs.<br>• Replace permanent, hard-to-separate bonds with solutions that enable efficient debonding and disassembly, reducing repair time and unlocking higher recovery rates in recycling.<br>• Integrate diagnostics and traceability (for example through embedded sensors and digital product passports) so that battery condition, chemistry, and design are visible to repairers, second-life integrators, and recyclers to enable greater looping and unlock efficiencies. |
| **Business models** | • Enable service models based on repair and upgrade (rather than premature replacement), improving total cost of ownership and extending revenue from each pack.<br>• Lower the cost and complexity of reclaiming packs and components for second-life and recycling, strengthening the business case for BaaS and similar models that depend on efficient reverse flows. |
| **Systems** | • Underpin regulatory requirements for minimum durability, repairability, and recyclability, and for the use of digital product passports.<br>• Make regional repair and recycling infrastructure more available and efficient, thereby improving resilience and reducing environmental impact per tonne of material processed. |

## Who needs to act

» **Cell and battery manufacturers:**
Lead on setting new design standards aligned with circular economy requirements, including modularity of battery cells and components (such as standardised or interoperable pack fasteners); the use of debonding solutions; and the adoption of integrated diagnostics. Collaborate with repairers, remanufacturers, and recyclers to understand how current designs constrain these processes, and to set appropriate new standards that can enable new batteries to be looped through their systems with greater efficiency and cost-effectiveness.

» **Vehicle manufacturers (OEMs):**
Incorporate circular battery design criteria into platform decisions and supplier requirements. Design vehicles to allow battery removal and reinstallation.

» **Repairers, remanufacturers, and recyclers:**
Provide feedback on design barriers to efficient repair, remanufacture, and recycling, and collaborate on shared design guidelines with actors further up the value chain.

» **Standard-setting bodies and policymakers:**
Create common standards and regulations for durability, repairability, recyclability, and data provision that support these design changes and create economic incentives needed to encourage adoption.

# 3.2 RETHINK BATTERY SERVICE WITHIN OPTIMISED ENERGY-MOBILITY SYSTEMS

## What benefits this opportunity unlocks

**Designing EV batteries 'fit for purpose' for the utility or functions they need to deliver — coupled with reshaping mobility and energy systems to support mobility requirements — reduces structural overprovision of capacity and overspecification of technology, thereby lowering mineral demand.** At the same time, service quality and utility are maintained or improved (e.g. in critical minerals tonnage per passenger kilometres). This means rethinking battery value from maximising capacity in every vehicle, towards delivering the right performance for the right use, with mobility systems designed to support access to services rather than ever-larger batteries.

The energy-mobility system can be redesigned so that access to 'more' passenger kilometers is provided through services and infrastructure, rather than additional, larger batteries. This shifts the market away from a one-size-fits-all oversized consumer preference, towards more targeted offerings. This can sometimes require creativity in product, brand, and service design — for example, making 'enough' range feel premium and frictionless by default, and reframing performance and user experience.

## Which loops are enabled

- Intensive use and access
- Life extension through repair, refurbishment, and remanufacture
- Information exchange and governance (enabling loop)

## 3.2 How it can be applied at each level

| | |
|---|---|
| **Products and components** | • Rightsize batteries according to realistic usage profiles rather than defaulting to large, long-range packs for each application. Innovate to make 'enough range' be seen as the default consumer choice.<br>• Tailor chemistries and pack designs by use-case: for example, high-performance batteries for long-distance fleets and smaller, more material-efficient packs for urban vehicles. |
| **Business models** | • Expand shared, on-demand mobility services (including those with demand-shaping mechanisms and interventions) that increase vehicle and battery utilisation, making smaller batteries viable for many users.<br>• Deploy battery swapping, subscription services, or other business models that enable access to vehicles with different range options when needed, so users do not rely on owning — or paying for — oversized batteries. |
| **Systems** | • Invest in charging and battery swapping infrastructure — particularly in cities — that allows frequent, convenient charging and reduces range anxiety.<br>• Integrate V2G and V2H solutions so batteries deliver both mobility and energy storage services, maximising kWh delivered per unit of critical minerals. |

## Who needs to act

» **Battery manufacturers and OEMs:**
Embed rightsizing into product planning and vehicle design. Adopt circular business models like subscription and battery swapping to enable more cost-effective use of battery minerals per mile driven. Communicate transparently with end users about real-world range needs to help alleviate range anxiety and support right-sized battery choices.

» **Cities and mobility providers:**
Plan and deploy shared mobility services, charging networks, and multimodal transport strategies that support intensive use of appropriately-sized vehicles. Require charging point operators to enhance interoperability between different batteries and charging infrastructures and to set up bidirectional chargers. Communicate the benefits, and enable the adoption of multimodal systems to encourage end user adoption of these offerings. Introduce variable pricing (e.g. varying parking fees to battery and vehicle weight) to incentivise users to prioritise rightsized vehicles.

» **Energy providers and grid operators:**
Develop frameworks and tariffs that unlock V2G and related services. Engage with regulators, charging point operators, and city authorities to anticipate grid upgrades and develop charging infrastructure that unlocks efficient and extensive use of EV batteries.

» **Policymakers:**
Align urban planning, transport, and energy policies to enable rightsizing, shared mobility, and grid integration, and make these more economically viable. Revise public procurement rules across each of these sectors to create demand signals.

# 3.3 SCALE CIRCULAR BUSINESS MODELS

## What benefits this opportunity unlocks

**Circular business models turn EV batteries and their materials into long-term assets rather than products sold only once**. These models reward durability, performance, recovery, and deployment into second-life applications, across multiple cycles of use, allowing more value to be generated from the same stock of batteries and minerals. Models such as MaaS, BaaS, upgrade and maintenance subscriptions, performance-based warranties, and structured second-life offerings can align crucial commercial incentives around durability, uptime, recovery, and residual value, rather than premature replacement. By retaining ownership with one actor, these models can also help monitor the whereabouts of products and materials and prevent them from going unaccounted for.

## Which loops are enabled

- Intensive use and sharing
- Life extension through repair, refurbishment, and remanufacture
- Cascading use into second-life application
- High-quality recycling and material recirculation

## 3.3

## How it can be applied at each level

| | |
|---|---|
| **Products and components** | • Design for longevity, repairability, second life, and recyclability to enable more effective value retention when shifting to business models that allow providers to retain ownership of batteries or embedded materials.<br>• Establish contractual arrangements that require transparency on design choices and support investments in appropriate repair and recycling capabilities. |
| **Business models** | Adopt:<br>• **Battery-as-a-Service models** that shift battery ownership to specialised operators who manage charging, maintenance, upgrades, and end of life, often using standardised, swappable packs and centralised monitoring.<br>• **Material-as-a-Service models** that allow mining, processing, and recycling companies to lease critical minerals downstream, retaining ownership as they circulate through multiple product life cycles.<br>• **Second-life business models** that create new revenue streams by redeploying batteries into stationary storage and other applications once automotive performance thresholds are no longer met. There is particularly strong potential for demand for these solutions in the Global South in areas where power grid infrastructure is more nascent. |
| **Systems** | • Use the contract-based, circular business models to underpin long-term, predictable flows of materials and products, supporting planning for regional infrastructure, investment, and policy design.<br>• Adopt circular business models across the value chain to redistribute economic opportunity, allowing mineral-producing countries and other currently low-margin actors to capture more value from the same resources.<br>• Deliberately design business and systems to ensure optimal material and efficiency trade-offs and avoid unintended consequences when adopting BaaS/swapping type models. For example, while battery swapping models can boost utilisation and lifetime value, these models can also drive demand up through the impact of lowered upfront prices or increased convenience, and potentially require additional ‘buffer’ battery stock in swapping networks. Therefore, the net mineral outcome depends on system plus business model design choices, and is not a given outcome based on the service model. |

## Who needs to act

» **Mining and processing companies:**
Pilot and scale MaaS arrangements that keep materials in predictable loops and incentivise high-quality recovery.

» **Battery manufacturers and OEMs:**
Expand BaaS and other service-based offerings, including swap-based systems and integrated mobility and energy services. Once batteries reach the end of their useful life in EV applications, set up offerings to resell the products for secondary applications, for example in energy storage systems.

» **Energy companies and utilities:**
Partner with OEMs, supply chain players, asset managers, and investors on second-life applications and integrate these into grid planning.

» **Financial institutions and insurers:**
Design instruments that recognise the asset value of batteries and materials across multiple life cycles.

» **Policymakers:**
Enhance cross-border collaboration and work towards aligned rules for end-of-life classification and transport of batteries, to enable the creation of an effective second life marketplace.

# 3.4

# BUILD AND CO-INVEST IN REGIONAL CIRCULAR INFRASTRUCTURE

## What benefits this opportunity unlocks

**Reimagine the battery value chain as an intentionally designed network of regional and inter-regional infrastructure that enables materials to circulate efficiently, resiliently, and transparently.** Scaling regional reverse-logistics and processing capacity — and doing so through collaborative investment — can ensure that batteries and critical minerals are able to circulate efficiently, resiliently, and transparently, while diversifying economic opportunity across regions. Building regional capacity can be important for time sensitivity, improving bankability, and policy coherence. In some instances, by shortening transport distances and improving processing efficiency, it can reduce emissions per tonne handled. However, inter-regional scale can be more attractive for activities with deep specialisation and high capex. Circular infrastructure is complex, and it is important to convene cross-value chain actors to build an evidence base and shared decision heuristics for what needs to happen locally, regionally, and internationally.

## Which loops are enabled

- Life extension through repair, refurbishment, and remanufacture
- Cascading use into second-life application
- High-quality recycling (through regional processing hubs)
- Information exchange and governance (through shared planning and investment signals)

## 3.4

## How it can be applied at each level

| | |
|---|---|
| **Products and components** | • Develop regional facilities for diagnostics, repair, remanufacture, and repurposing to make it viable to keep products and components in circulation closer to where they are used. This is particularly important when considering that the cascaded second-life applications of batteries may take place in vastly different geographies than where the first life occurs; enabling collection and recirculation of materials in the regions where these materials practically come to their end of life allows their circulation to be more cost effective and avoids potential for leakage out of the system.<br>• Tailor co-located or networked recycling facilities to the chemistries and designs most prevalent in the region. |
| **Business models** | • Pool investments in infrastructure to lower risks and costs for individual actors and can be structured around long-term contracts that secure feedstock (for recyclers) and supply (for manufacturers and OEMs).<br>• Introduce new service offerings around transport, aggregation, diagnostics, and processing of batteries at end-of-first-life and beyond. |
| **Systems** | • Set up regional hubs strategically for collection, repair, second-life integration, and recycling to reduce dependence on a small number of global processing centres, increasing resilience to shocks and trade disruptions.<br>• Co-develop and make necessary infrastructure available in partnership with mineral-producing countries, to support these regions' move up the value chain into processing, remanufacturing, and recycling activities. |

## Who needs to act

» **Battery manufacturers, OEMs, and recyclers:**
Co-invest in regional facilities and logistics networks, sharing risk and expertise. Develop regional hubs in the right places which can handle the right volumes for all necessary stages of the recirculation process to make the activities economically viable; from collection to sorting to recycling and reprocessing minerals. In the first instance, collaborate with others in the value chain using similar battery chemistries to unlock greater efficiencies in recycling. Consider forming buyers alliances to secure demand for circular critical minerals. Engage mining and processing companies to learn from their expertise on material handling and build regional capacity for reprocessing of materials.

» **Logistics providers:**
Develop specialised, compliant services for transporting used and end-of-life batteries within and across regions.

» **Governments and development finance institutions:**
Provide enabling policy frameworks, de-risking instruments and public finance to catalyse private investment, especially in emerging and developing economies, to build regional collection, sorting, recycling, and processing infrastructure. Support the development of transparency and traceability frameworks that can create certainty on projected material flows to de-risk investment in regions and at volumes that will be needed (see more on this in chapter 3.5).

» **Policymakers:**
Align rules and policy incentives so batteries can be moved to the right facility for the optimum circular outcome (whether it be for repair, second life, recycling), while preventing leakage and supporting the development of, and investment into, local or regional capacity where it adds value. Facilitate conversations on inter- versus intra-regional investments and capacity by creating forums for identification of regional priorities, constructing evidence-led forums for bottlenecks and capacity gaps, and discussing where distributed, regional capacity is more essential, versus where specialised hubs deliver the most efficient outcome.

» **Education and training providers:**
Partner with businesses and governments to develop training and research and development programmes for circular economy jobs in the EV battery value chain.

# 3.5 MAKE THE CIRCULAR OPERATING SYSTEM WORK

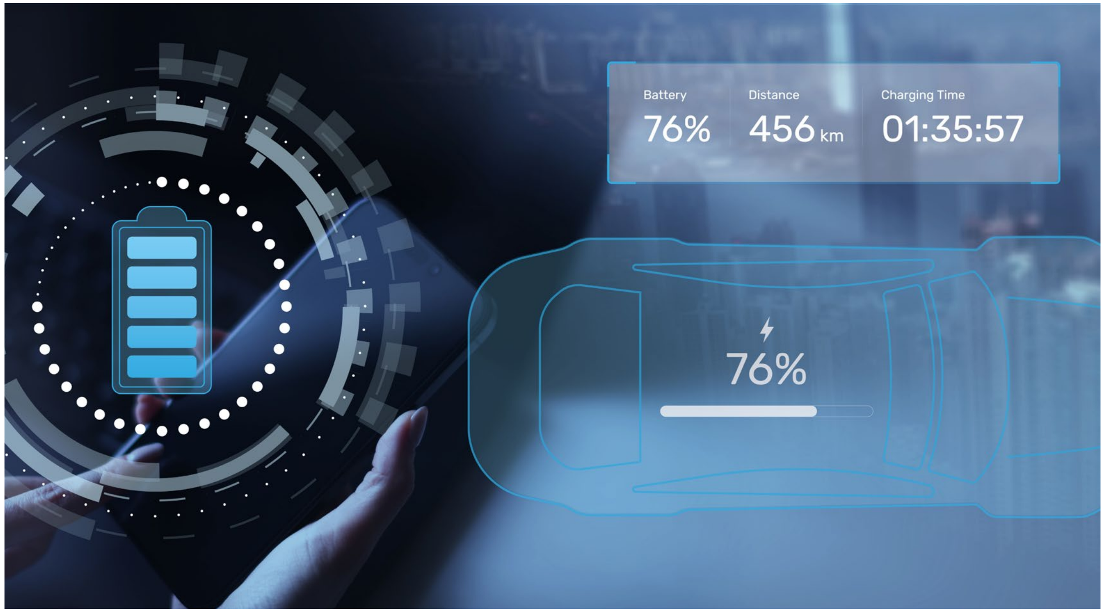
## What benefits this opportunity unlocks

**Data and policy are the operating system of a circular EV battery economy.** Aligning data, definitions, and rules across borders is essential to unlock investment and make all other loops work in practice. Without coherent policy, and visibility on product, component, and material data, batteries become 'dark assets' — hard to locate, classify, and technically circulate in the different loops. Value chain players lack access to crucial information needed to be able to practically recirculate batteries (e.g. information on how to technically and safely repair a battery), and moving them for repair, second life, or recycling remains costly and risky.

By creating the necessary transparency and traceability of currently hidden flows in the EV battery economy, transaction costs are lowered, secondary product and mineral markets are enabled to function at scale, and businesses and investors have the confidence to finance infrastructure and new business models. The enhanced transparency on environmental and social performance also strengthens responsible sourcing and supports customer trust. Making the circular operating system work in this way also strengthens resilience and boosts commercial success by improving planning for future material flows and reducing 'stranded' assets caused by regulatory uncertainty.

## Which loops are enabled

- Information exchange and governance (enabling loop)
- All other loops



## 3.5

## How it can be applied at each level

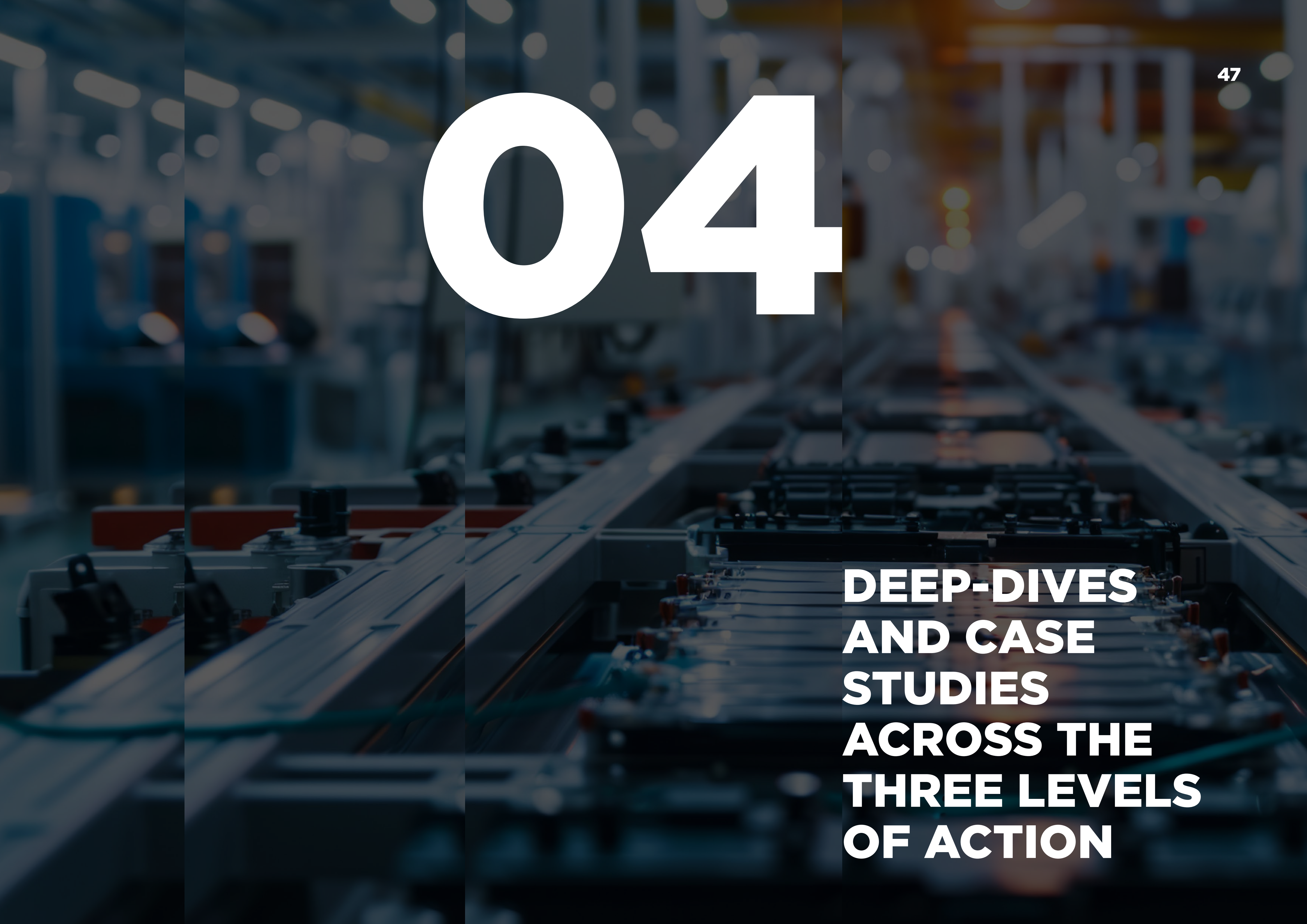
| | |
|---|---|
| **Products and components** | • Use digital product passports and related tools to record design, chemistry, use history, and state of health of batteries. Make this information available to all relevant actors when needed to enable effective decision-making about repair, second life, and recycling. |
| **Business models** | • Collect reliable data on battery location, condition, and availability to underpin BaaS, MaaS, and second-life markets, and allow actors to plan business models around predicted streams of used batteries. |
| **Systems** | • Harmonise definitions for waste, end-of-life, and 'end-of-waste' status, along with consistent rules for transporting batteries and recovered materials, to reduce friction and uncertainty across borders and unlock inter-regional circulation where scale is needed.<br>• Provide clear and coherent policy signals to give investors confidence to build circular infrastructure and test new business models at scale.<br>• Increase market confidence by demonstrating trusted governance and assurance mechanisms (auditing, certification, and data integrity) can increase market confidence. |

## Who needs to act

» **Policymakers and regulators:**
Work towards aligned cross-border rules for end-of-life classification, transport, and treatment. Mandate and support digital product passport, and data-sharing framework adoption across the value chain. For example, in the case of black mass and waste code classification, regulatory definitions are not merely misaligned, but can demonstrably increase transaction costs and burdens that undermine the business case for recycling.

» **Industry coalitions and standards bodies:**
Define common data requirements, governance models, and assurance mechanisms for battery passports and traceability tools. Work to ensure that these are adopted globally and across all battery passport providers to minimise fragmentation and divergence.

» **Companies across the value chain:**
Share relevant data (within agreed governance frameworks) across the value chain to enable efficient looping of batteries (e.g. through repair, remanufacture, and recycling). Participate in pilots that aggregate information to inform infrastructure planning and policy design.



# 04

# DEEP-DIVES AND CASE STUDIES ACROSS THE THREE LEVELS OF ACTION

**EV batteries sit at the heart of the electrification transition, bringing together some of its most challenging resource, cost, and sustainability trade-offs.** A true circular battery economy is not a single technology switch or an end-of-life fix. It is a full-life cycle discipline: keep batteries delivering value for as long as possible, recover that value through repair and repurposing, and return materials into new production at high quality.

This chapter takes a practical, *'how it works in the real world'* approach to provide a snapshot of what are already relatively established, versus nascent, practices. It examines how three levels of action reinforce each other. In line with the circular economy framework introduced in Chapter 2, it starts with the **product**, because design sets the constraints; moves to **business models**, because incentives determine what gets done; and then zooms out to **systems**, because networks decide what scales. Put simply, products make the circular economy possible, business models make it profitable, and systems make it widespread.

To ground these pathways in operational reality, short case studies are included on debonding and soluble binder innovation (GRST and Bostik), reverse logistics and battery repair enablement (DHL), recovered-material battery cells (Altilium and JLR), and standardised swapping with grid integration (CATL's Choco-Swap ecosystem). Together they show what circularity looks like when design, operations, and commercial incentives align.

# 4.1 PRODUCTS AND COMPONENTS

## Designing EV batteries for disassembly, modularity, and traceability unlocks the economic potential of high-value in-use services and after-use pathways

Manufacturers are increasingly designing batteries integrating features such as modularity, standardisation, traceability, and diagnostics to enhance repair, reuse, and recycling at the end of life. Modular pack systems made of removable cell clusters with diagnostic sensors enable targeted, faster, and more affordable repairs, avoiding full-pack replacements and reducing downtime. DfD not only cuts maintenance costs and waste, but also enhances the efficiency of material recovery, ultimately reducing material use and environmental impact. Compared to traditional battery designs, modular designs have been shown in some instances to improve overall recyclability by 15-20%.[54] Standardisation of components across different models, and the use of mechanical fasteners (bolts, screws) instead of permanent joints, which enable automated interventions, are other design strategies that can further enhance battery lifespan. When paired with traceability tools, such as blockchain or digital product passports, DfD encourages battery repurposing in second-life applications and the adoption of circular business models like battery swapping or leasing, opening new revenue streams beyond the initial vehicle sale. Although DfD is not yet common practice in the battery industry today, technological advances and regulatory requirements aimed at establishing a circular economy will greatly facilitate its adoption.

### Benefits:

- Modular battery designs, compared to traditional designs, have been shown to improve overall recyclability by 15-20%.
- Although the initial investment of design for disassembly may be higher, it generates numerous economic benefits such as: reduced labour costs, improved material recovery, extended product life through repair and upgrading, and regulatory compliance.
- The use of specific design features (number of modules and fasteners, design complexity and accessibility) can significantly lower end-of-life processing costs by up to 75% per pack, depending on the design.[55]

## Case study: GRST and Bostik's debonding solutions

Emerging technologies are transforming EV batteries and boosting recyclability by simplifying disassembly through debonding solutions.

GRST (Green, Renewable and Sustainable Technology) is a lithium-ion battery technology company that specialises in binders, a high-tech 'glue' for sticking the active materials to the electrodes, utilising PFAS-free and water-soluble materials designed for easy repair and recycling. The binder is a simple drop-in to existing battery manufacturing and works for all major chemistries without changing performance or cost. In the recycling phase, GRST's binders can be dissolved in recyclable water, bypassing heat, chemical, or mechanical grinding processes required by conventional binders. As a result, GRST claims a recovery rate of high-purity black mass at over 99.9%, and carbon emissions reductions of up to 90%. This removes the need for recyclers to handle PFAS-fluorinated materials. In addition to recovering battery minerals, GRST's binders can be filtered out from the black mass and recycled for use in other industries. By streamlining battery dismantling, maximising mineral recovery, and minimising environmental impact, GRST's technology enables the effective implementation of a closed-loop system for the battery life cycle.

Bostik, a global adhesive company within the Arkema Group, also develops bonding and debonding solutions tailored for EV batteries. The company's thermal interface materials, especially the thermally conductive gap fillers, are designed to be removable and repositionable. They are non-curing and silicone-free materials that maintain the same liquid viscosity throughout their lifespan, improving efficiency during disassembly, as well as repairability and recyclability. The materials could also extend battery lifespan through high-performance heat management. In addition, Bostik has launched Prep DB, an innovative disassembly primer designed for the automotive industry. The solution ensures strong structural bonding during use while enabling clean, heat-triggered separation at end of life. This approach simplifies repair processes and facilitates material recovery, improving recyclability and reducing waste.

See GRST and Bostik websites for more details.

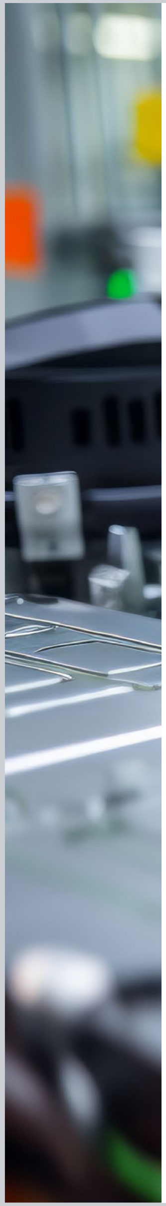
## Enabling EV battery repair offers high economic payback by preventing premature replacement and substantially reducing costs and material demand

Repairing faulty, damaged, or degraded batteries is essential to extend the battery lifespan, reducing premature battery retirement and recycling, and avoiding emissions from new battery production. Scaling repair is as much about compliance and logistics as it is about engineering. EV batteries are regulated as dangerous goods, and defective or damaged packs that pose heat, fire, or short-circuit risks are difficult to transport and handle. This means triage, safe discharge, compliant packaging, and certified reverse-logistics routes are prerequisites for repair at scale. It is estimated that 92% of the modules in failed battery packs in warranty are still considered functional,[56] underscoring the enormous material waste if batteries are prematurely replaced.

Globally, OEMs and battery manufacturers are adopting circular business model solutions that enable them to repair parts of batteries on a module or cell level to make their batteries last longer. Once an EV battery is identified to be faulty or damaged, technicians from OEMs or battery manufacturers can perform diagnostics on the battery, repair or replace faulty parts, and return the battery to the user. By some estimates, a 95% share of repaired faulty batteries could be reached by 2030 (up from 80% in 2019), with associated cost savings of USD 2 billion and $CO_2$ emissions reductions of 2Mt achievable.[57] To the end customers, these repair services provide a financially optimal solution, as vehicle usage lifespan is extended. For OEMs and battery manufacturers, high-quality repair services help improve their reputation among customers and, when combined with BaaS solutions, unlock cost efficiencies by enabling more value to be attained from a battery for a longer period of time.

### Benefits:

- Repair of faulty batteries prolongs the lifespan of critical minerals in EV batteries, increasing material value utilisation.
- Repair of batteries with high residual value could unlock cost savings of USD 2 billion by 2030, while offering cheaper solutions to customers.
- Battery repair consumes significantly less energy than producing a new battery, resulting in a direct reduction in associated GHG emissions.



## Case study: DHL’s EV batteries logistics services

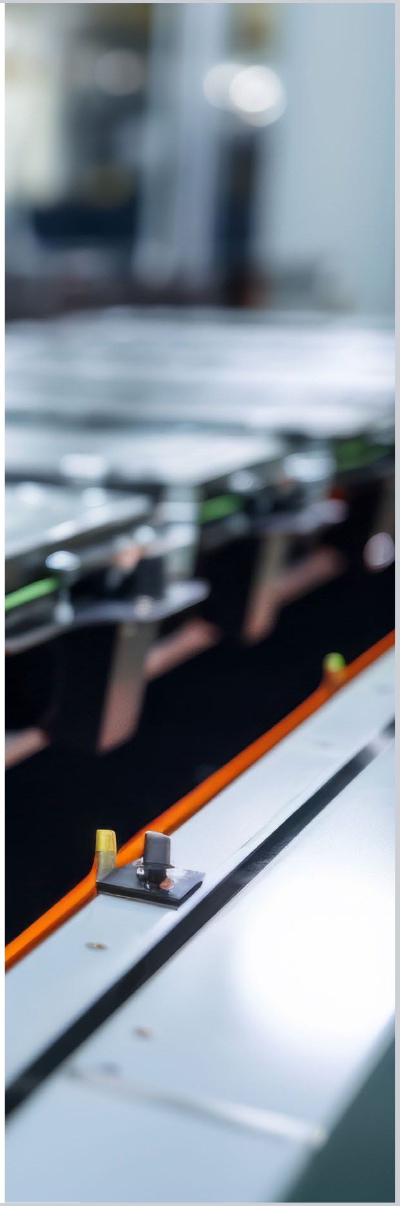
A circular economy for EV batteries requires efficient transportation services and reverse logistics infrastructure, including collection, transport, and storage of faulty, damaged components, or end-of-life batteries. Capturing this trend, DHL reports a growing network of over 15 EV Centres of Excellence (CoEs) globally, with one specifically tailored to the circular logistics of EV batteries in Europe, offering integrated, end-to-end solutions for the aftermarket battery life cycle.

The CoEs address key logistics challenges related to EV batteries. As EV batteries are classified as dangerous goods when shipped, DHL assists its customers with the certification process and helps them navigate the various compliance requirements across different regions. For cross-border movements, battery diagnosis and classification, as well as the management of unpredictable volumes, are carried out at DHL network storage sites, thereby ensuring compliance and optimising transport options.

In a partnership with Cox Automotive, DHL offers battery triage and repair logistics services at the UK CoE. The facility has 35,000 square feet of dedicated battery repair space and could handle thousands of batteries annually. As part of the partnership, DHL has invested over GBP 800,000 in a Battery Energy Storage System to discharge batteries and recirculate energy back into the facility. In addition, DHL ensures any damaged batteries are safely discharged and stored and prepares them for repair.

Through specialised logistics, regulatory expertise, and circular economy-focused solutions, DHL could efficiently support circular business solutions for EV batteries.

See DHL website for more details.



## Increasing the scale and efficiency of EV battery recycling is key to returning critical minerals to the economy after batteries have exhausted other after-use options

Significant advances in battery recycling technologies are improving the recovery rates of critical materials like lithium, cobalt, and nickel. Innovations including pyrometallurgy and hydrometallurgy, electrochemical extraction, and graphite recovery enhance the efficiency of recycling processes. The opportunities are significant: under optimal conditions, one material flow analysis estimates that recycling retired batteries could supply 60% of cobalt, 53% of lithium, 57% of manganese, and 53% of nickel of lithium-ion batteries globally in 2040.[58] In addition, recycled minerals such as nickel, cobalt, and lithium release approximately 80% less GHG emissions than virgin materials produced from mining.[59]

As ore grades naturally decline, the cost of extracting the same amount of minerals will rise over time. Without increases in recycling, the total investments in mining to achieve net zero emissions by 2050 would need to be approximately 30% higher, further intensifying the challenge of mobilising the necessary financing.[60] On the other hand, scaling battery recycling offers major socio-economic advantages — from mitigating price and supply volatility to creating high-quality domestic jobs. Taking a holistic approach (accounting for economic impact, job creation ability, carbon abatement, water and land use reduction) battery recycling could create a net value between USD 11.3 billion to USD 40.3 billion in benefits by 2040, a significantly higher return on investment than conventional mining, according to a study focused on the US.[61]

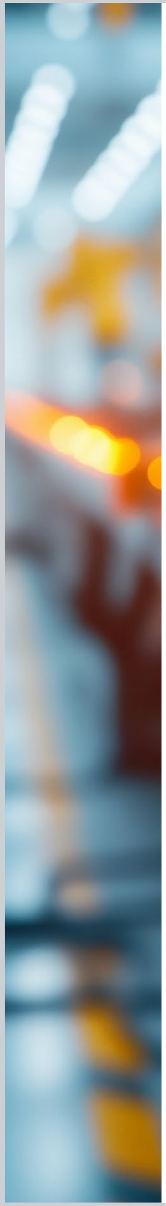
Despite these advantages, scaling battery recycling across regions remains limited due to constrained feedstock availability, as most batteries are still in their first use cycle. In addition, batteries can end up in other regions when reaching end of use, diverting materials away from local recycling facilities. Many sources have cited near-term recycling constraints, as manufacturing scrap is still expected to dominate feedstock through 2030. At the same time, rapidly evolving battery chemistries complicate investment decisions by increasing uncertainty around future feedstock composition and volumes. These challenges are compounded by battery designs that increasingly prioritise performance over modularity, making disassembly and recycling more difficult, as well as the lack of visibility across the value chain experienced by downstream recyclers, which undermines their ability to predict volumes of retired batteries.

In the longer term, developing an efficient and competitive recycling value chain will require comprehensive efforts to maximise collection rates, promote design for easier disassembly and recycling, ensure that industrial processes can adapt to evolving battery chemistries, and improve battery visibility across the value chain.

In support of these efforts, several countries are creating conditions for a robust EV battery recycling ecosystem, seeking to ensure a more resilient supply chain and reduce emissions linked to the use of raw materials. The new EU Battery Regulation is a key policy driver for EV battery recycling, imposing minimum recycled material content requirements (16% for cobalt, 85% for lead, 6% for lithium and 6% for nickel from 2031), ambitious material recovery targets (e.g. 80% for lithium by 2031) and digital ‘battery passports’ for greater transparency.[62] Elsewhere, the UK is also promoting Extended Producer Responsibility (EPR) and targeting high recycling rates (95% of EV battery packs by 2035),[63] while countries such as the US and China are implementing policies focused on EPR, collection, and material recovery.

### Benefits:

- Recycling helps reduce dependency on virgin resources and strengthens the EV battery supply chain by creating a more resilient and closed-loop source of critical materials.
- The recycling industry is already beginning to help lower the cost of EVs and energy storage systems.
- The recycling industry itself creates new economic opportunities and jobs in collection, processing, and manufacturing.



## Case study: Altilium and Jaguar Land Rover partnership on recovered-material batteries

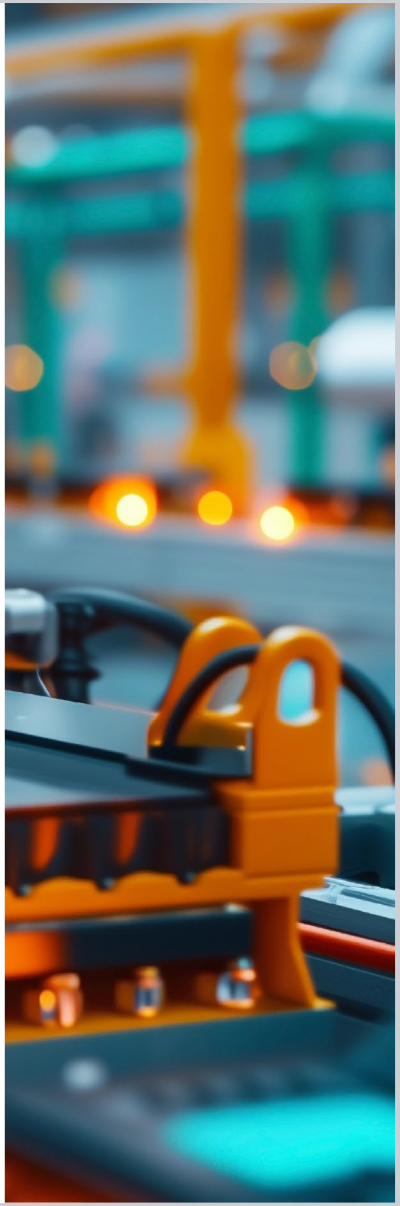
Altilium, a UK clean-tech company, and Jaguar Land Rover (JLR) unveiled the UK's first EV battery cells made from recovered cathode active materials (CAM) at the Cenex Expo 2025.

Using Altilium's EcoCathode process, the newly developed, automotive-grade NMC 811 multilayer pouch cells were successfully designed and manufactured at the UK Battery Industrialisation Centre (UKBIC) using CAM (including cobalt, lithium, nickel, and manganese) recovered from end-of-life EV batteries. According to the companies, the proportion of recovered CAM in the battery cells meets the EU's 2036 Battery Regulation target for minimum recovered content (26% cobalt, 12% lithium, 15% nickel). Their initial electrochemical testing indicates that cells made with recovered materials perform comparably to those produced using virgin materials, an important step in validating the suitability of recovered materials for high-performance EV applications.

Third-party assessments showed that, while achieving comparable quality, recovered-material battery cells also demonstrated significant reductions in GHGs. An independent Life Cycle Assessment (LCA) by Minviro, based on Altilium's process and the UKBIC cell design and build, concluded that the NMC 811 pouch cells using 100% recovered CAM could reduce emissions by ~32% relative to cells made with virgin materials. Besides emission benefits, the assessment also suggested that the cells could lead to a 30% lower particulate matter formation, 58% less freshwater ecotoxicity, and 38% fewer metal and mineral resource impacts.

Showing that recovered materials can deliver high-quality performance with significantly lower environmental impact not only helps meet regulatory requirements, but also paves the way for more sustainable and resilient EV battery supply chains, making it a compelling model for future battery recycling efforts.

See Altilium and JLR websites for more details.



# 4.2 BUSINESS MODELS

## BaaS models increase EV battery use-rates, generate economic value, and reduce the structural waste of batteries sitting idle and degrading over time

Business models such as BaaS — which includes leasing, renting, and swapping — shift ownership, health, efficiency, and end-of-life management of batteries from users to providers. Increasingly, car manufacturers are adopting BaaS models, in which users purchase the vehicle but subscribe to, lease, or pay for the use of the battery capacity. This reduces the initial purchase price of EVs for users, while offering flexible upgrade options and continuous access to well-maintained batteries. With such business models, automakers or battery manufacturers retain ownership and oversight of a large volume of batteries, encouraging designs that enable prolonged use, upgrading, repair, and repurposing, while facilitating efficient materials recovery at the end of life without incurring collection costs.

BaaS models enable the deployment of swap stations where customers can quickly and easily exchange their batteries, while also facilitating full life cycle management, from charging and maintenance to reuse and recycling. To ensure efficient replacement at these stations, standardised battery designs are becoming increasingly common. Additionally, battery swapping stations can also function as distributed energy storage units. When connected to the grid, they enable smart charging during off-peak hours to reduce costs and provide secondary support for peak load management and frequency regulation (see CATL case study). As a way to reduce ‘range anxiety’ and charging time, battery swapping infrastructure is seeing a significant expansion — particularly in Asia — with the market projected to reach USD 22.72 billion by 2035, from USD 1.46 billion in 2025, at a CAGR of 31.5%.[64]

### Benefits:

- BaaS models incentivise battery providers to design batteries for the circular economy, thereby extending battery lifespan and performance. Through centralised monitoring, maintenance, and collection, BaaS solutions improve resource efficiency.
- BaaS models create new business opportunities for battery providers, automakers, and financial services.
- By decoupling the purchase of the battery from the vehicle, car manufacturers can reduce upfront purchase prices (by as much as 30 to 40%),[65] and with flexible payment options for batteries (pay-as-you-go or subscription), EVs can become more accessible to a wider range of consumers.

## MaaS models allow mining and processing players to generate greater economic returns and pass cost savings up the value chain

Under MaaS, mining companies lease the extracted minerals to downstream stakeholders, retaining ownership of the material through its life cycle, breaking away from the single use of raw materials and promoting their circular flow. Material lease expands new business opportunities for mining companies, as prolonged service agreements create recurring revenue streams — as long as the product is in use — rather than one-time sales. MaaS can also create revenue for recyclers and reprocessors. They can work as contracted recovery partners, paid via tolling or service fees and sometimes a share of recovered-material revenues. Overall, MaaS implies asset traceability and circular design for easy battery disassembly, collection, and mineral recovery.

By facilitating material loops, MaaS not only helps build a domestic or regional secondary supply source, it also encourages the development of local processing, remanufacturing, and recycling industries within the mining country. This can foster economic diversification and create skilled jobs. Inherently, given the contractual nature of MaaS, supply chain participants adhere to circular economy design principles (DfD, life extension, etc.) and higher environmental, social, and governance (ESG) standards. BaaS and MaaS can potentially reinforce each other, but this would certainly require deliberate commercial design and collaboration. In taking a cross-value chain perspective, it is important to recognise how emerging business models interact with each other, and how the industry can be convened to explore win-win options.

### Benefits:

- MaaS models strengthen the circular flow of critical minerals, ensuring that the leased materials have fixed destinations once batteries are retired, greatly increasing the reusability and recyclability of end of life batteries.
- Fixed loops of critical minerals in given regional and domestic markets can offset the potential vulnerability in the mineral supply chain.
- Through MaaS models, extractive countries can develop local industries beyond mineral sales, shifting focus from material extraction to management and creating diversified revenue streams, thereby fostering new skilled job creation in data management, logistics, or second-life applications.

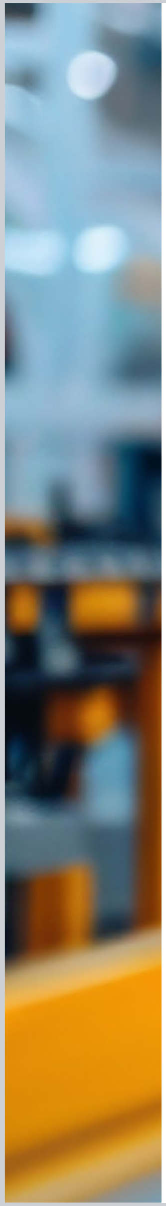
## Second-life battery business models keep batteries in use even when they can no longer fulfill their primary purpose

Repurposing used EV batteries for less-demanding applications, such as stationary energy storage, backup power systems, and grid stabilisation, creates new value streams and extends battery life, thereby keeping materials in use and reducing waste. Key models include direct resale, battery-leasing programmes, and strategic partnerships across the energy and automotive sectors. By selling used batteries to a repurposer or to an end user (e.g. a storage company), battery manufacturers can spread the cost of the battery over an extended period of revenue generation and reduce waste management costs. The adoption of batteries in second-life energy storage applications can also provide grid-stabilising benefits in regions where power grid infrastructure is not as developed, giving more people and businesses access to the energy they require more reliably and at a lower cost.

Marketplaces and B2B platforms are emerging to facilitate the reuse and repurposing of retired EV batteries, connecting auto OEMs, second-life integrators, and recyclers to maximise life cycle value while ensuring responsible handling. Conversely, by retaining ownership of products and materials through models such as leasing and rental, OEMs have the flexibility to become asset operators themselves, or to enter into partnerships with energy specialists, allowing them to capture the battery's second-life revenue stream. As second-life markets mature, automakers and battery producers are increasingly likely to view these models as strategic opportunities from the outset — retaining ownership of valuable assets, capturing additional revenue streams, and enhancing resource efficiency across the battery life cycle. Market projections suggest the sector could reach around USD 7 billion by 2033.[66]

### Benefits:

- Business models that promote second-life EV batteries are essential for reducing battery waste and the demand for new battery minerals.
- Car manufacturers and mobility service providers can generate revenue from new business models by creating a robust market for second-life batteries.
- Extending the lifespan of batteries through second-life applications substantially reduces the overall carbon footprint of batteries (per unit of capacity over time) and in a much more significant way than in an immediate recycling scenario.[67]



## Case study: CATL's Choco-Swap ecosystem

CATL, in cooperation with nearly 100 partners, launched an ecosystem combining a BaaS model with standardised batteries and maintenance systems, alongside grid-integrated swapping infrastructure in China. This innovative circular business model for EV energy management benefits consumers, automakers, and the energy system.

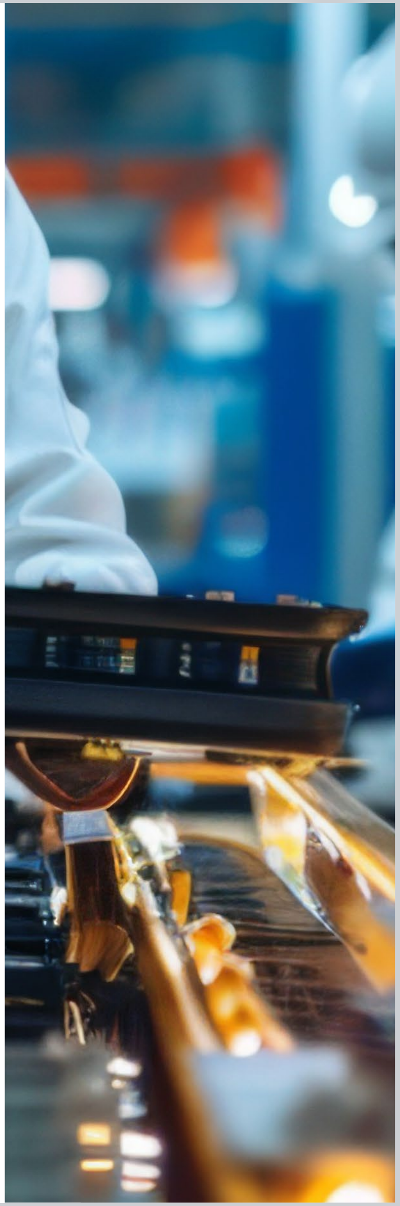
**BaaS model:**
While supporting battery purchase and buyback, the 'Choco-Swap' system enables the development of a BaaS model. This service allows users to purchase an EV without the most expensive component, the battery, and instead pay a monthly subscription fee for battery use and swapping services. Users can choose between charging, swapping, leasing, or upgrading batteries as needed. Including inspections as part of the service helps maintain batteries at high power capacity, extending their lifespan. In this model, revenue is tied to use, creating incentives to maximise the time batteries and components remain productive.

**Maintenance and standardisation:**
CATL leverages the world's largest battery database to monitor the real-time performance and degradation of each swappable battery cell. According to CATL, this data-driven approach ensures optimal usage and predictive maintenance, achieving an estimated 30% increase in battery lifespans. Moreover, by introducing standardised and modular battery packs that are compatible with many different vehicle models, the adoption of swapping infrastructure can become widespread. With centralised battery management, end-of-life collection is facilitated as used batteries can be recovered in bulk from stations rather than from individual owners — a key step toward closed-loop recycling.

**Distributed energy storage:**
CATL announced the deployment of 30,000 battery swap stations across China with their partners from 2025 onwards. These will not only support EV battery swapping but also integrate charging and energy storage functions, effectively acting as distributed energy storage units. Each station, connected through a cloud-based dispatching platform, will interact with the power grid, enabling battery-to-grid (B2G) capabilities. Stations can perform smart charging during off-peak hours at a reduced cost and provide real-time responses to grid load fluctuations. CATL claims that the system could collectively store up to 33.6 million kWh, with an additional 1.12 billion kWh stored in vehicles — a powerful distributed network supporting grid resilience and renewable energy integration in the regions where they operate.

By aligning industrial partners under a shared framework, CATL's Choco-Swap ecosystem enhances convenience for users, strengthens supply security for manufacturers, and contributes to the creation of a circular, data-driven, and material-efficient mobility and energy system.

See CATL website to learn more



# 4.3 SYSTEMS

## Rightsizing batteries and increasing energy density reduces the structural waste of idle battery capacity and material costs

Improving batteries' energy density and optimising their capacity to match intended use can help cut critical mineral demand. Through innovation in battery chemistry and design improvements, the energy density of batteries has increased significantly in recent years, leading to material efficiency and cost savings. For example, one study found that between 2015 and 2019, projected 2030 mineral demand per battery fell by a factor of more than 3.6 for cobalt and 1.4 for lithium.[68] At current rates of innovation, battery energy density is expected to increase by more than 25% by 2050,[69] with further implications for material demand.

While battery density has increased significantly since they first came onto the market, the average battery size is also increasing as manufacturers seek to extend vehicle range and meet consumer demand for larger models such as SUVs and pickups.[70] This trend, fueled by consumer range anxiety, risks undermining battery-efficiency efforts while simultaneously increasing mineral demand. Designing batteries that are appropriately sized for their function — by adapting vehicle range to consumers' travel habits and freight transport, rather than adopting a 'one-size-fits-all' large battery — could cut costs and material demand. Manufacturers could facilitate the appropriate sizing of batteries in order to meet different requirements in terms of range and passenger capacity. For example, in shared passenger transport fleets such as taxis, car-sharing services, and on-demand mobility services, high use rates and long range requirements would require high-specification, high-performance batteries. Conversely, in compact, densely populated cities, where commuting distance is reduced — typically in European cities daily travel distance is just 12.4 km per person[71] — smaller batteries are better suited. Communications campaigns to encourage adoption of shorter-range EVs will be important to reduce range anxieties and rightsize expectations. A study estimates that reversing the current trend towards larger EV batteries would have the most significant and immediate material impact — a 20% reduction in the average battery size compared to current levels would reduce global annual demand for batteries and minerals by 28% in 2035 and 27% in 2050.[72]

### Benefits:

- Optimising battery efficiency and rightsizing can cut 2050 mineral demand by half.[73]
- For urban and rural drivers, doubling the battery size could increase the total cost of ownership by 20% to 23%, implying that correct sizing offers substantial savings.[74]
- Battery rightsizing fits within a circular mobility system of making greater use of each vehicle via on-demand systems, designing each vehicle for its particular use-case, and distributing journeys effectively across modes, including public transport and walking and cycling.

## On-demand, digitally-enabled transport systems can help maximise the number of miles of mobility provided by each EV battery over its lifetime

Providing a digitally-enabled, on-demand, zero-emission, multi-modal transport system is an important aspect of the circular economy in cities. Such an urban mobility system would employ digital technologies to integrate transport modes, letting people shift between personal, shared, and public transport options in an optimised system. It would be supported by a digital platform that enables trip planning and a single payment solution, creating a convenient experience for the user. This would also help reduce range anxiety and subsequent demand for larger batteries by enabling access to different EV types. The resulting increase in vehicle utilisation rates would lead to reductions in the number of vehicles on the road and a decrease in traffic congestion. It would also free up significant urban land, which could be reallocated to green spaces, parks, housing, or commercial areas, bringing considerable nature, climate, and social benefits — as outlined in the Foundation's *Building Prosperity* report.[75]

Furthermore, with most private cars parked for around 90% of the time,[76] on-demand mobility can increase the materials productivity of batteries, maximising the utilisation of embodied resources. Additional key elements of city-wide mobility system design include: compact city development for effective mobility; charging infrastructure and battery swapping stations; and big data solutions to optimise mobility systems.

### Benefits:

- A less vehicle-dependent transport system can reduce global mineral demand by 6-8% in 2035 and by 17% in 2050.[77]
- A shared mobility system in Europe could lower demand for raw materials by 26 to 54% by 2050.[78]
- On-demand mobility options offer substantial savings for households and disproportionately benefits members of the most disadvantaged communities.

## V2G systems extend the energy storage services EV batteries provide over their lifetime by playing an important role in renewable electricity grids

Through V2G technology, EV batteries can feed electricity back into the grid during peak demand, effectively turning each car into a mobile storage unit. At scale, this creates a distributed energy system that enhances grid stability and resilience while lowering electricity costs for users. When thousands of EVs operate together, they can provide flexibility services to the power grid, reducing the need for costly infrastructure upgrades and large centralised storage facilities. This also helps avoid the material and environmental costs of building new high-capacity transmission and distribution networks. A study suggests that equipping just 50% of EVs with V2G technology could decrease the European Union's total primary material demand for stationary storage by up to 7.5% between 2020 and 2050.[79] Such measures could mitigate geopolitical risks and enhance material security. China has already announced 30 V2G pilot projects across nine cities, underscoring the real-world potential of this solution. These benefits could be especially important in areas with more nascent power grid infrastructure, creating more resilience to the energy systems particularly in the Global South.

### Benefits:

- V2G solutions help meet energy storage needs, thereby avoiding the material demand associated with the production and installation of new transmission and distribution infrastructure.
- Energy providers avoid costly infrastructure upgrades while households and fleets earn new income by charging vehicles during off-peak hours and selling electricity to the grid during peak hours.
- By displacing the need for fossil fuel 'peaking' plants to meet energy demand at peak times, V2G solutions can help avoid additional GHG emissions.

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