In collaboration with
RMI and the Global Battery Alliance

Powering the Future: Overcoming Battery Supply Chain Challenges with Circularity

WHITE PAPER

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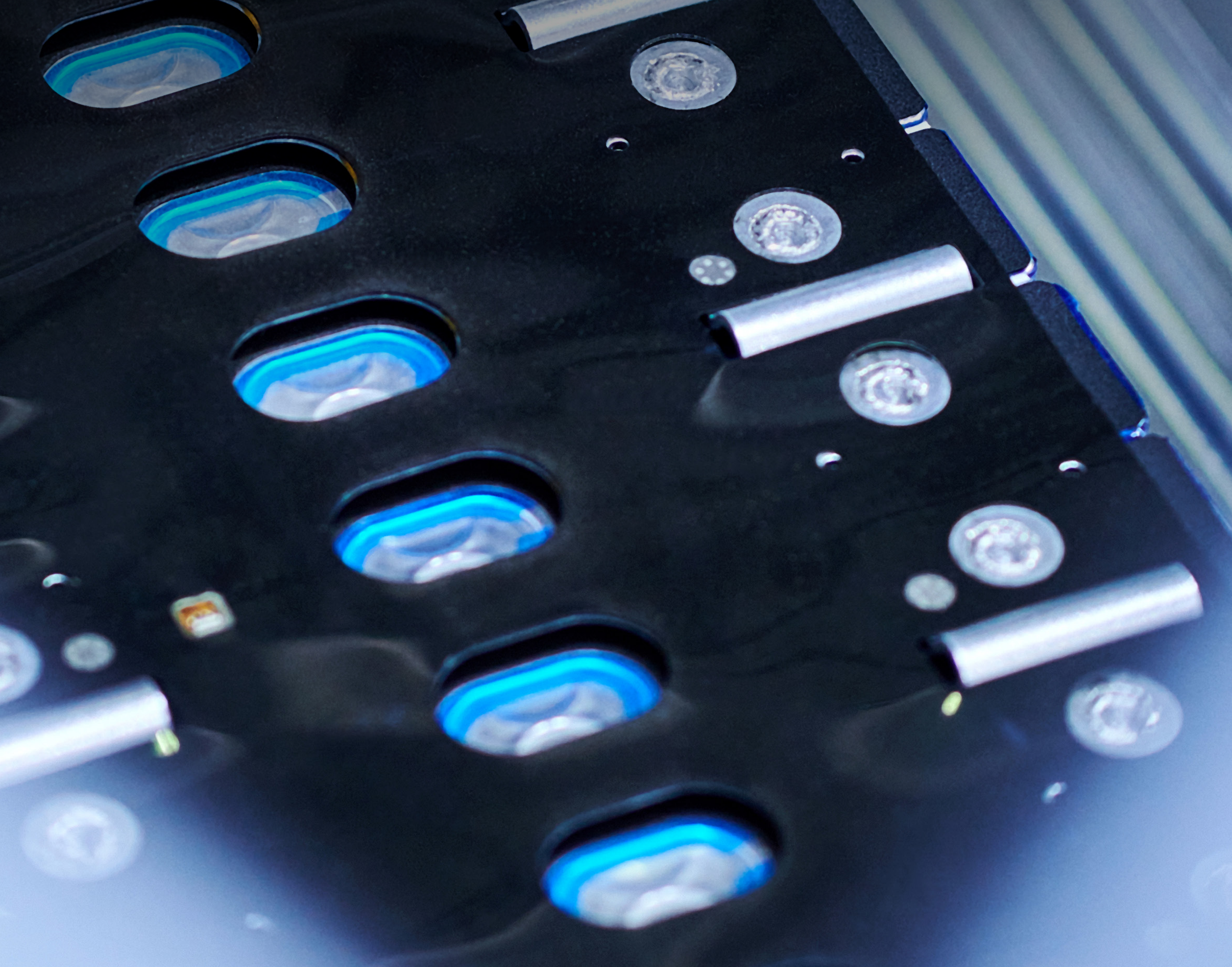

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Foreword

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As global electric vehicle (EV) sales continue to grow, so do concerns about the EV battery supply chain's ability to meet increasing demand. Although there is sufficient planned manufacturing capacity, the supply chain is currently vulnerable to shortages and disruption due to geopolitics, changing trade alliances, conflict, extreme weather and other factors. Many are also apprehensive about the supply chain's heavy reliance on the newly mined minerals that go into EV batteries – minerals whose extraction can involve human rights abuses and environmental degradation.

Another source of risk is the inadequate infrastructure in most parts of the world to manage the growing number of batteries reaching end of life. Addressing this challenge will require significant investment, intense stakeholder collaboration and effective policies.

It's clear that urgent action is needed.

But even in the face of these significant challenges, there are solutions. A *circular battery economy* – one in which EV batteries are repaired, reused, repurposed and recycled – can meaningfully address the challenges described above and deliver better outcomes in regions that have not previously generated value from the automobile industry.

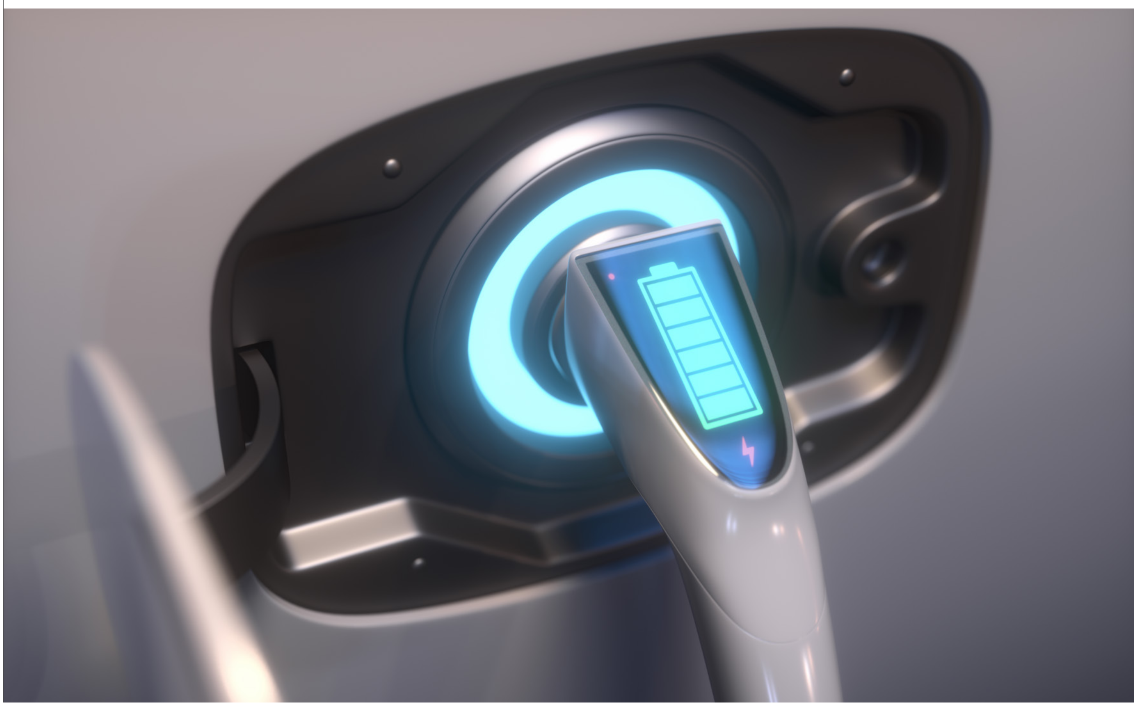
Battery circularity decreases the need for virgin materials, helping meet regional mineral supply gaps – which can increase the resilience of the supply chain and mitigate national security risks – while reducing the harms associated with mining. And it's important to note that a circular battery economy will not only lessen the supply chain's detrimental effects but will also create jobs and encourage economic growth in a diverse set of geographies.

In this report from the World Economic Forum, in collaboration with RMI and the Global Battery Alliance, we discuss the risks of continued reliance on a linear battery economy. We also present an alternative vision of the future, one in which we electrify transport at the pace and scale needed to meet global and national climate goals while respecting human rights and the environment. Perhaps most importantly, we suggest concrete steps that stakeholders around the world can take to make a circular battery economy a reality.

The good news is that we're not starting from scratch. Over the past few years, an increasing number of diverse stakeholders with varying interests have realized that we all have much to gain from a circular battery economy. They have been working to increase the supply chain's transparency, improve the performance and sustainability of batteries through new chemistries and build the infrastructure needed to manufacture and recycle batteries – but we need to do much more.

We must continue to accelerate this effort and adopt an attitude of informed optimism – one that makes clear that although the obstacles we face are significant, they are by no means insurmountable.

As we work together in pursuit of a common mission, we need to acknowledge that we have the chance to turn challenges into opportunities. Let's get started.



Executive summary

This report identifies concerns about today's EV battery (EVB) value chain that contribute to negative environmental and social impacts and hinder the development of equitable socio-economic value. Using insights gleaned from an expert advisory panel, the Global Future Council on the Future of Responsible Resource Use, and secondary research, it identifies five changes needed to drive towards a circular battery economy and address these concerns. Priorities include:

1. **Developing standardized, interoperable track-and-trace platforms.**

   You can't manage what you can't see and measure. Following a battery and its materials from extraction to production to end of life (EOL) can help battery manufacturers and automakers make responsible purchasing decisions; ensure adherence to environmental and human rights principles and regulations; and provide critical information about repair, reuse, repurposing and recycling that stakeholders need to plan and invest effectively.

2. **Setting performance and data standards and financing R&D for design innovation that prioritizes disassembly and recyclability alongside safety, cost and range.**

   Battery design today prioritizes first-life performance – but choices made in battery design influence, if not determine, whether a battery can and will be repaired, reused, repurposed and recycled. Additionally, access to data about the battery's design, health and remaining useful life is crucial for enabling safe, efficient and economical second life and EOL management. Developing performance and data standards, implementing supportive policy, and finding innovative ways to finance R&D for battery design can help prioritize second life and EOL management in battery design and data-sharing.

3. **Using targeted policy interventions to help overcome economic and technical barriers faced in recycling and second life.**

   High capex requirements, insufficient feedstock volumes and volatile mineral markets subject EVB recycling to financial uncertainty and put the industry at risk. Similarly, declining new battery prices, uncertainty around the value of used batteries, and high costs and technical challenges of reuse and repurposing may prevent the second-life industry from scaling up. Policy intervention is needed to support these emerging industries at this critical moment as a wave of EVBs reaching end of first life approaches, creating the opportunity to increase resource efficiency, reduce the embedded environmental and social impacts of EVBs, and capitalize on the substantial socio-economic opportunities associated with second-life batteries.

4. **Developing regional, circular value chains within a global circular economy, and facilitating responsible cross-border movement of batteries and battery materials.**

   Today's EVB supply chain is both geographically concentrated and dispersed: concentrated because mining, refining, processing and assembly take place in just a few countries, and dispersed because battery materials travel tens of thousands of miles as they move through the value chain. These factors weaken the resilience of the value chain while driving up emissions. At the same time, today's movement patterns and international regulations related to EV batteries may cause inadvertent harm to the developing economies that import used vehicles and batteries. Enabling more countries to participate in the value chain, and facilitating responsible movement of batteries and battery materials can increase resilience, reduce emissions and prevent inadvertent harm to developing markets while building a circular battery economy.

5. **Investing in the workforce needed for a circular battery economy by training and reskilling for circular jobs, integrating and preventing development of informal markets, and prioritizing principles of just transition.**

   In a circular battery economy, the value chain will no longer rely on virgin minerals, resulting in job losses in mining-related industries. The workers displaced and others can take advantage of the many circular career opportunities that will become available if they receive upskilling and reskilling support. Governments, industry representatives, and educational institutions will need to work together to ensure that workers have the skills they need to succeed in the circular economy.

Batteries are an exceptional asset for humanity and will enable the energy transition. However, it is crucial to not replicate the errors of the past and not disregard the externalities generated by energy systems. The time to act is now, before the compounding of systemic environmental and social damage, to create a circular battery economy that serves communities worldwide, protects the environment and allows for economic growth.

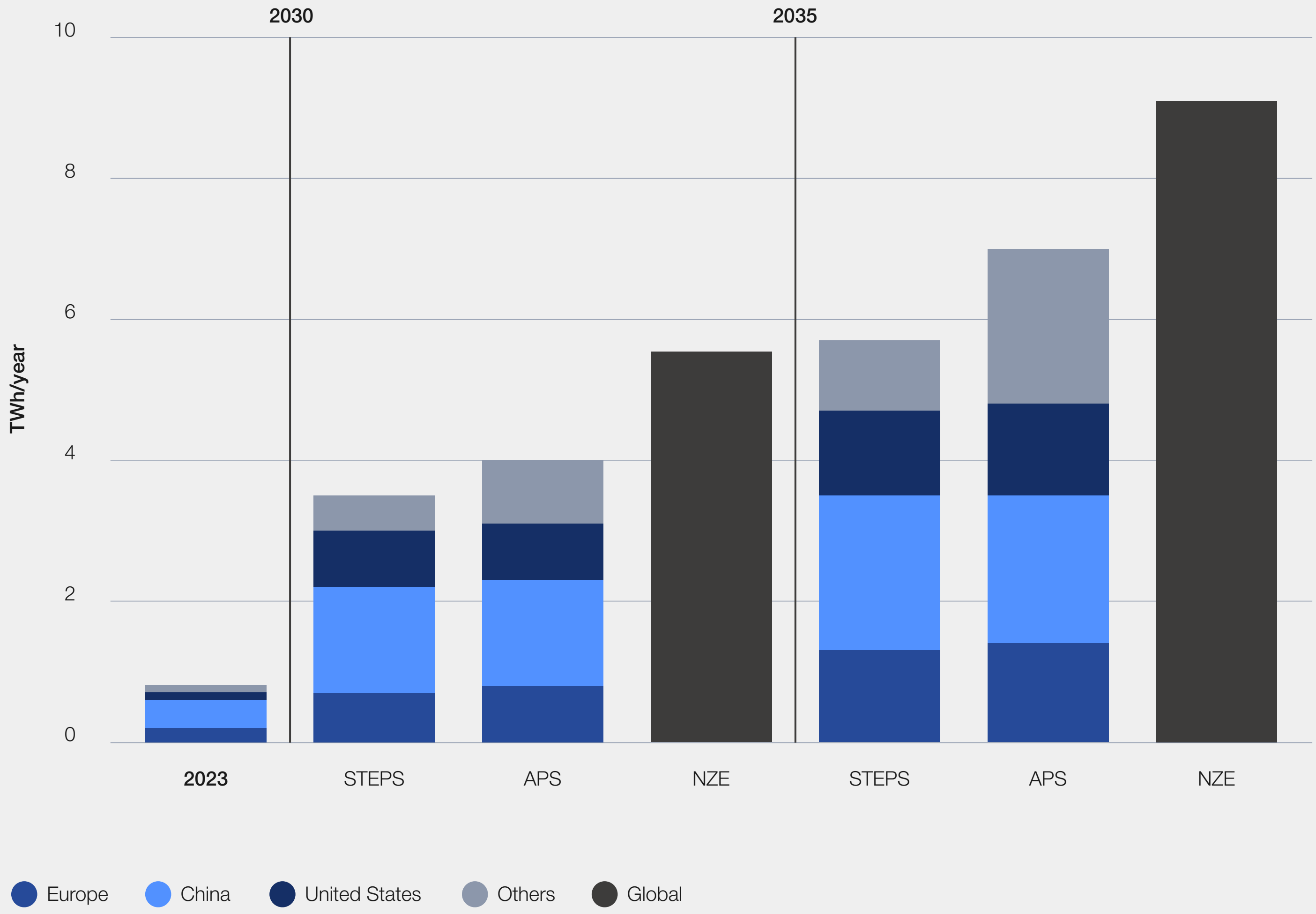
1 Introduction

A circular battery economy is needed to increase resilience, minimize environmental and social harms, and create equity in the battery value chain.

1.1 The implications of rising demand for EV batteries

The demand for EVBs[1] is rising, and with it, the need for critical minerals and other raw materials. According to the International Energy Agency (IEA), the global annual demand for EVBs is projected to grow to 5.5 terawatt-hour (TWh) in 2030 and 9.1 TWh by 2035[2] in a "net-zero emissions by 2050" scenario.

FIGURE 1 **Global annual demand for EV batteries in three scenarios**



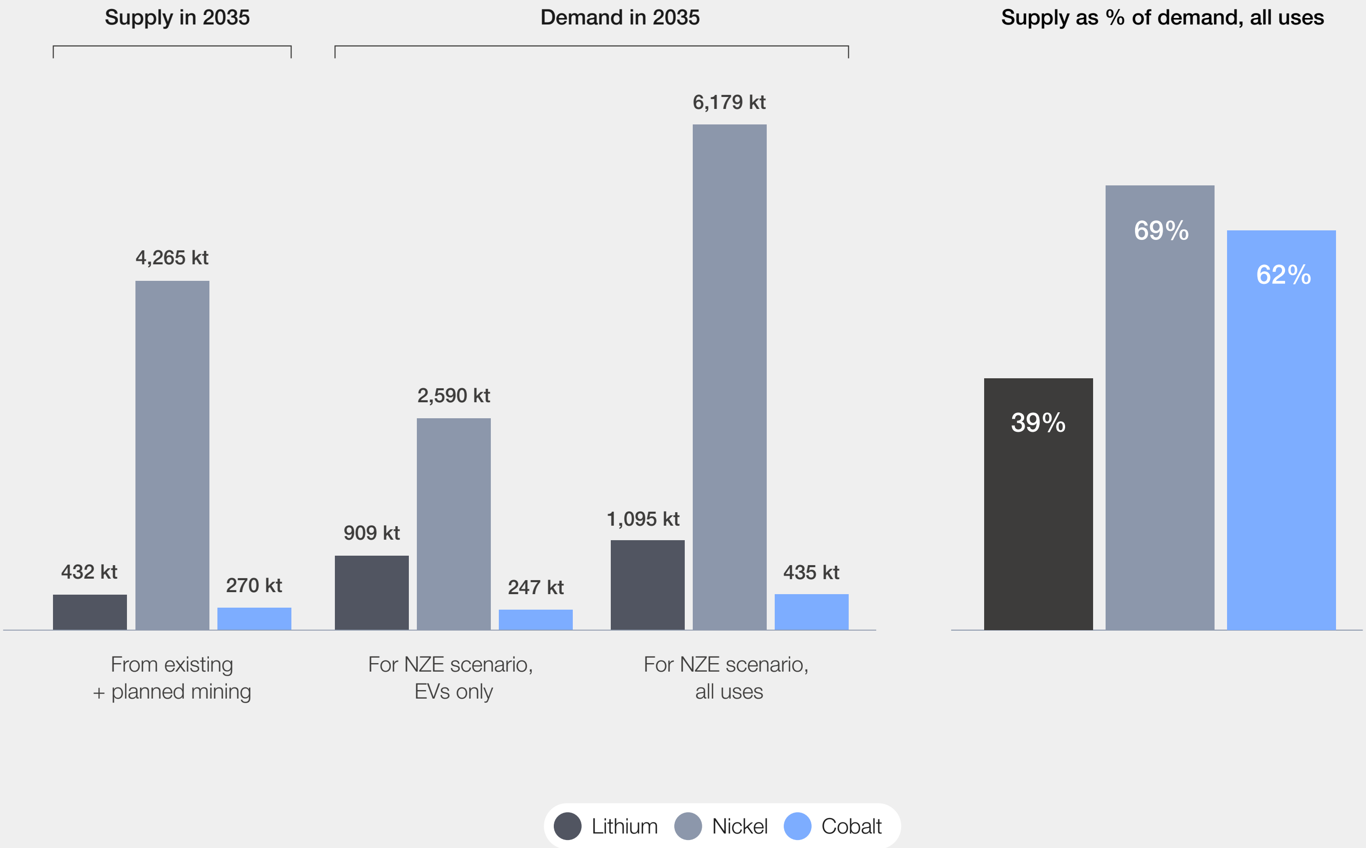
Note: The IEA forecasts annual demand for EVs in three scenarios: 1) The Stated Policies Scenario (STEPS) is based on the current policy landscape; 2) The Announced Pledges Scenario (APS) includes announced climate targets from countries around the world; and 3) The Net Zero Emissions by 2050 Scenario (NZE) is based on the change needed in the global energy sector to achieve net-zero carbon dioxide (CO_2) emissions by 2050

Source: IEA, Global EV Outlook 2024[3]

To meet this growing EVB demand, annual mineral demand can be expected to reach 909 kilotonnes (kt) per year for lithium, 2,590 kt per year for nickel and 247 kt per year for cobalt by 2035.[4] Battery chemistry innovations and density improvements have significantly reduced nickel and cobalt demand, and the trend is expected to accelerate in the future.[5] Demand for lithium – the common mineral for nearly all of today's EVB chemistries – is expected to grow significantly more than nickel and cobalt demand.[6]

According to IEA forecasts, supply from current and projected mining alone is insufficient to meet this growing demand: forecasted supply from existing and announced mining projects will meet only 39%, 69% and 62% of projected annual demand from EVBs and other uses of lithium, nickel and cobalt, respectively, for the year 2035 in a Net Zero Scenario.[7] This could put the EV transition at risk. (These forecasts do not include any supply from EVB recycling, which will meet part of the demand. Forecasts will continue to change with rapidly evolving battery and recycling technology, continually changing supply projections and regular re-evaluations of EV demand forecasts.)

FIGURE 2 **Critical minerals outlook for 2035**



Source: IEA Critical Minerals Data Explorer[8]

Growth in demand and production also means that an increasing number of EVBs will reach the end of their useful lifetimes in the decades ahead – creating a need to responsibly manage these EOL batteries to avoid the harms of improper disposal. It takes years to build infrastructure, enact and implement policy, change corporate practices, and redesign manufacturing, distribution and consumption processes. It also takes decades to create systemic change in global systems. It is imperative to act now to be ready to manage the wave of batteries that will begin reaching their end of life in the middle of the next decade.

In addition to the environmental and social risks of improper disposal, there are risks associated with the production of EVBs, and the increase in demand for EVBs will increase those risks if business-as-usual continues wherein the systems and processes for EVB production and EOL management remain largely unchanged from today.

Fortunately, alternatives are available.

1.2 A circular battery economy

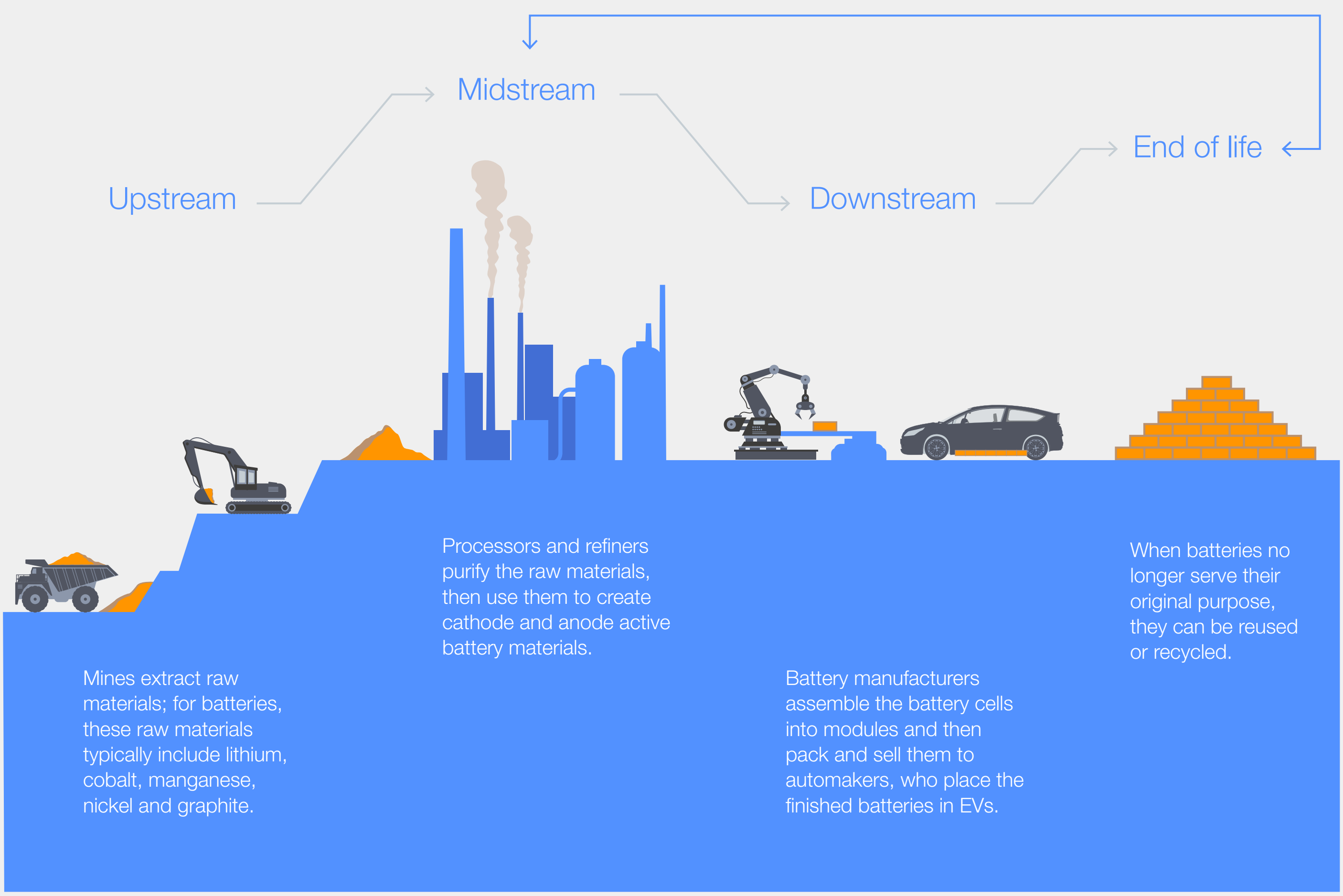
The definition of "circular economy" varies based on the use case and the perspectives of different stakeholders. Some may focus more on environmental benefit, and others on the economic implications. Some may emphasize closed-loop systems, while others emphasize efficiency. One definition based on an analysis of 221 definitions goes like this:

"The circular economy is a regenerative economic system which necessitates a paradigm shift to replace the 'end of life' concept with reducing, alternatively reusing, recycling, and recovering materials throughout the supply chain, with the aim to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations. It is enabled by an alliance of stakeholders (industry, consumers, policy-makers, academia) and their technological innovations and capabilities."[9]

As this definition indicates, it is important to take a holistic approach to circularity: one that encompasses sustainable development, environmental quality, economic development and social equity.

A circular economy for EVBs is one in which EVBs are used for as long as possible in their first application ("first life"); then reused in other EVs or repurposed for placement in other applications, like energy storage ("second life"); then recycled, when the materials in the battery are extracted and returned to the refining stage of the value chain to be used in new batteries. Taking a holistic approach, a circular battery economy must be designed with systems thinking to prioritize minimizing environmental harm and maximizing equity – ensuring that all can benefit from this new system, and none have to disproportionately bear the cost of change.

FIGURE 3 **The EV battery value chain**



Source: RMI

Circularity is about more than "closing the loop" and reusing materials. It is the tool that enables an efficient value chain while balancing environmental, social and economic priorities. A circular battery economy can:

- *Minimize the environmental and social impacts* associated with EVB production and improper disposal, and reduce the consequent negative perceptions of EVBs and EVs.
- *Enable widespread transition* to EVs by reducing supply gaps and strengthening the resilience of the value chain.
- *Decrease geopolitical tensions* by reducing competition for resources from the handful of countries with critical mineral reserves or processing capacity.
- *Increase geopolitical and economic standing* by involving more nations in the EVB value chain and capitalizing on value creation opportunities.
- *Increase access to clean energy* through repurposing of EVBs for renewable energy storage and grid stabilization.
- *Increase access to clean mobility* by enabling widespread EV transition through reduced supply gaps, lowering the cost of EVs with reused batteries, and increasing access to EV charging with repurposed EV batteries.

Moving from a linear economy to a circular economy will not eliminate all negative impacts, inequities and inefficiencies, and can itself cause unintended consequences if not designed thoughtfully and holistically and managed in a responsible, equitable manner. Transitioning to a circular economy necessitates change, and it is essential to ensure that countries heavily dependent on their current role in the EVB value chain are well-positioned for this transition and are not left behind. As the United Nations (UN) emphasized in its guiding principles on critical energy transition minerals, "Justice and equity must underpin mineral value chains."[10]

1.3 Report approach

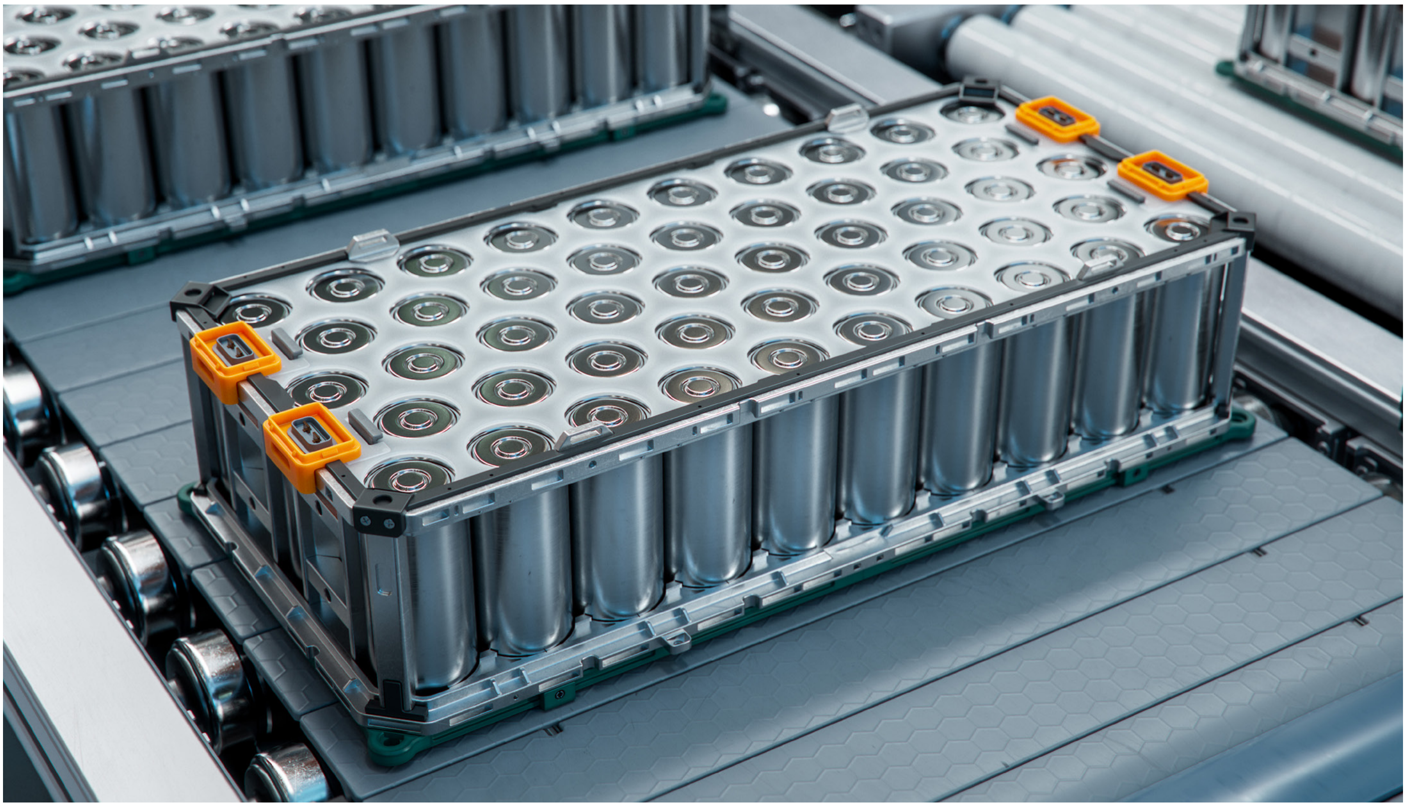
The World Economic Forum, RMI and the Global Battery Alliance (GBA) collaborated with experts from around the world and throughout the battery value chain to develop this report. The team gathered input and feedback from an advisory panel of experts from industries and sectors throughout the global EVB value chain; from the Forum's Global Future Council on Responsible Resource Use; and from members of the GBA.

This report first examines the most pressing concerns about today's battery value chain, the environmental and social impacts connected to those concerns, and the opportunities that can be captured or lost, depending on the actions taken or not taken. Though important, this report does not address issues linked to mining practices and how to transition to more environmentally and socially responsible mining practices as this aspect has recently been well discussed by the "Nature Positive Sector Transition for Mining and Metals" report of the World Economic Forum.

Using a combination of stakeholder input from an expert advisory panel, input from collaborating organizations and secondary research, this report delivers a set of recommendations to address these concerns to mitigate risk and capture opportunities in a way that benefits all. These recommendations aim to ensure the same risks in today's value chain are not replicated in a circular economy, and that new ones are not created. The report also aims to capture the opportunities at hand in an equitable manner so that all markets benefit from the transition to a circular battery economy.

2 Concerns about today's battery value chain

Business-as-usual practices threaten the resilience and efficiency of the EV battery value chain and carry environmental and social risk.



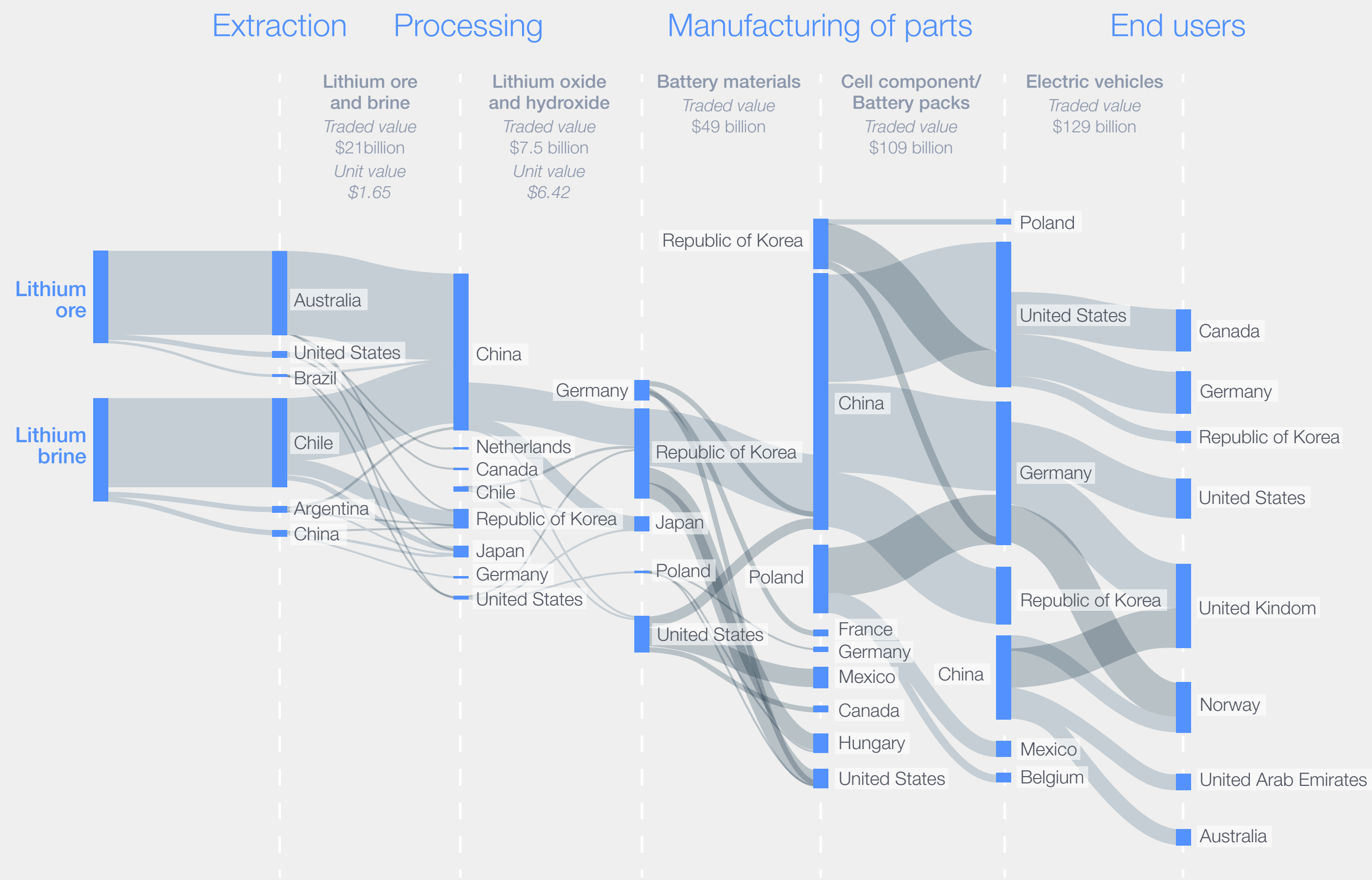
2.1 Lack of transparency across the full value chain

A lack of transparency pervades the EVB value chain. This often obscures the environmental and social impacts of EVB materials sourcing and manufacturing to the end of life and prevents the mitigation of, and accountability for, these impacts.

The current EVB value chain is both geographically concentrated and dispersed: a small number of countries dominates each segment of the EVB value chain, requiring minerals to travel tens of thousands of miles. Economically viable deposits of required minerals are found in just a handful of countries – primarily Australia and Chile in the case of lithium, Indonesia for nickel and the Democratic Republic of Congo for cobalt.[11] These minerals typically travel to China for processing and manufacturing into cell components before being assembled into EVs in China, Europe or the United States (US).[12]

In total, minerals often travel more than 50,000 nautical miles from the mine to the battery-cell factory.[13] This complexity and geographic distribution, coupled with a lack of harmonized regulations, contributes to an opaque EV value chain – and that opacity can mask and perpetuate the environmental impacts and social inequity associated with battery materials.

FIGURE 4 | **Movement of critical minerals around the world**



Source: UNCTAD secretariat calculations based on data from UN Comtrade[14]

For instance, depending on the source of raw materials, the carbon intensity of the electric grid supply for refining and manufacturing, and the distance travelled by battery minerals from origin to assembly, common lithium-ion battery (LIB) chemistries can have a carbon footprint between 65 and 100 kg of CO_2 equivalent per kilowatt-hour (CO_2eq/kWh).[15] Without disclosure of these factors, it is not possible to determine a battery's carbon footprint. Similarly, without visibility into the origin of raw materials; the labour and environmental practices used at each stage of the value chain; and how the battery is managed at EOL, it is not possible to understand the social and environmental impacts of a battery.

Mining without adhering to due diligence standards can lead to human rights abuses; violations of free, prior and informed consent; and land and water pollution, impacting the health and livelihoods in surrounding communities. Understanding the social impacts of a battery also requires knowing if and how the raw materials benefitted local populations, or if they were extracted and exported solely for the benefit of other markets. Finally, it is essential to ensure batteries are reused, repurposed and eventually recycled at EOL – which requires visibility into EOL management – to reduce reliance on mining and avoid the harms of improper disposal.

Without visibility into all these factors, buyers have less ability to differentiate and procure lower-impact batteries, hindering due diligence efforts; producers have less incentive to reduce their impacts; consumers have less information to make purchasing decisions; and regulators and civil society have less ability to hold all parties accountable. Efforts to increase transparency have begun, as seen in the digital product passport requirement of Regulation (EU) 2023/1542 of the European Parliament or the "EU Battery Regulation," but more work is needed to advance widespread implementation of such approaches and to standardize data tracking and disclosure frameworks.

2.2 Battery design and data access

Battery design that prioritizes first-life performance, combined with limited access to battery management system data, hinders repair, second life and recycling.

Recycling, reusing and repurposing EOL batteries have significant environmental benefits. Extending the lifespan of LIBs through reuse and repurposing increases the resource efficiency and reduces the need to produce new batteries, reducing the environmental and social impacts associated with battery production and EOL management. Second-life batteries can also fulfil numerous roles in energy and mobility applications, as outlined on the following page, providing enormous potential benefit to markets around the world. When the battery reaches end of second life, recovering the battery minerals and using the recycled content in new batteries can potentially reduce the carbon footprint of battery manufacturing by 20-30%.[16]

Batteries have traditionally been designed to maximize performance (durability, vehicle range, battery safety and battery lifespan) during their first life, while minimizing cost. These design choices influence everything from selection of battery chemistry to battery weight to form factors,[17] and necessitate trade-offs between how the battery performs in its first life and how the battery lends itself to repairability, second-life use and recyclability.

A battery cell is the basic building block for EVBs; these cells are combined into modules, which are then assembled into battery packs, which are fitted into EVs. The materials, form factor and assembly technique chosen determine performance, weight, safety and ease of repair, recycling and second life. For example, permanent bonding techniques like irreversible adhesives and welding provide batteries more structural integrity and make them more compact, but also make their disassembly difficult. This poses a challenge for repair and second life and can potentially lead to premature recycling, as recycling via shredding may be the only feasible option at the end of first life if the battery cannot be disassembled.[18]

The diversity of battery designs also impacts management at end of first life. Automation could be helpful in avoiding the inherent safety risks of disassembly and saving time – but it is made more challenging because there is little battery standardization.[19] Additionally, the range of battery designs makes screening, safety evaluation and certification of EVBs for second life challenging and increases the cost of transport and warranties for second life. Given that this is a nascent field, there is a lack of standardized tests, performance standards and statistical information that can provide end customers the confidence to support second-life products. For example, accessing data about a battery's health and usage in first life can help evaluate viability of second life; but concerns about data privacy and liability often prevent sharing of this data via the battery management system (BMS). The design issues described above, paired with limited or no access to original BMS data, can lead to significant remanufacturing efforts and costs.

Finally, in addition to design choices, battery labelling – or the lack thereof – impacts second life and EOL management. The lack of clear labelling indicating key battery components and substructures, and limited or non-existent access to information about the battery's SOH hinder the safe and effective handling of retired batteries.

While safety and performance during first life are critical priorities, batteries must also be designed (and labelled) with consideration for repair, second life, and eventually, recycling. This will help extend battery life and avoid premature recycling, improper disposal and unsafe handling.[20]

BOX 1

Key terms

- **State of health (SOH):** A measure of a battery's capacity, expressed as a percentage of the battery's original capacity.
- **Battery management system (BMS):** An electronic system that monitors the operating state of modules and cells in a battery pack; calculates and reports performance data; and manages the performance of individual cells and modules.
- **Experimental SOH diagnostics:** A method of evaluating a battery's SOH by directly testing it.
- **Model-based SOH diagnostics:** A method of evaluating a battery's SOH by monitoring physical parameters such as the current, voltage, temperature, number of cycles and charge/discharge behaviour of cells, modules and the battery pack over time, and then using these parameters to predict not only current SOH but also the battery's degradation rate and remaining useful life.

Source: Mobility Open Blockchain Initiative[21]

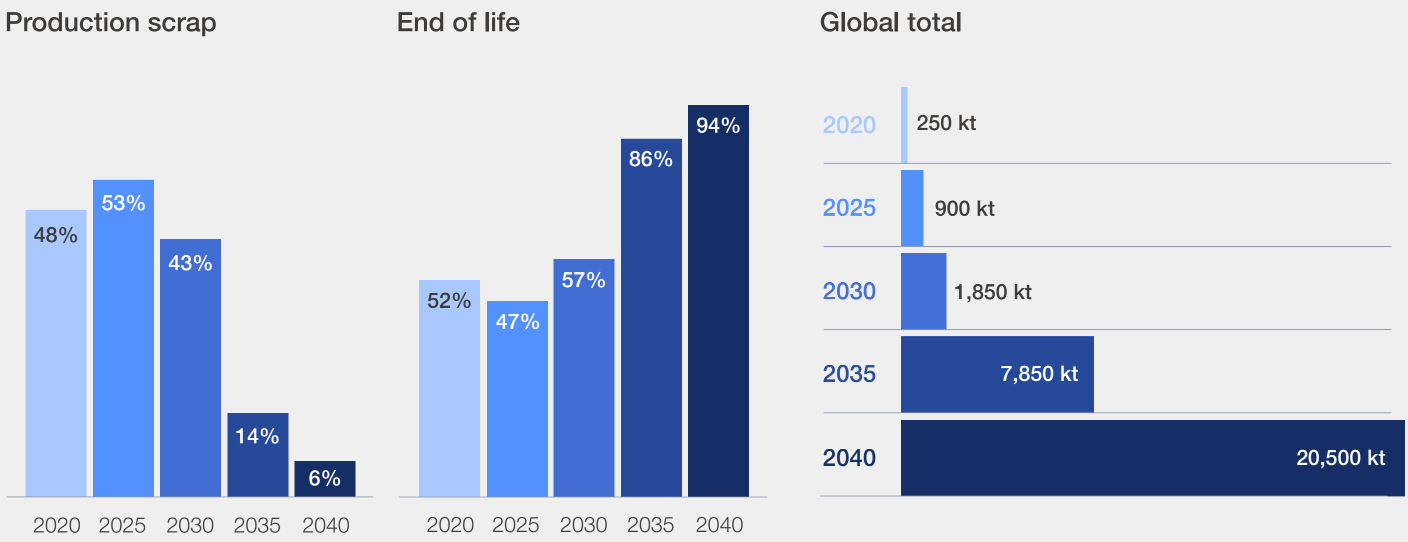
2.3 Challenging economics of recycling and second life

The economic challenges pertaining to EVB recycling and second life may hinder the scale-up needed to meet demand.

While the IEA expects recycling capacity to outpace recycling demand for EVBs and battery production scrap in the short term (by 2030), based on both the Stated Policies Scenario and the Announced Pledges Scenario,[22] there is reason for concern about the long-term outlook of recycling capacity. These forecasts are based on current recycling capacity and company announcements for planned additional capacity, and these plans do not always come to fruition; in fact, current overcapacity may contribute to the reduction, cancellation or consolidation of additional planned capacity, even as the number of EVBs reaching EOL grows exponentially starting in the mid-2030s[23] and an increasing number of regions need EVB recycling. Given that it takes years to secure permits and construct and commission recycling facilities, investment must continue apace.

Considering the significant capex required for new recycling infrastructure, the uncertainty associated with shifting minerals markets and evolving battery chemistries poses an additional obstacle for recyclers. Volatile mineral markets subject the battery recycling industry to potential negative profit margins when mineral prices are low.[24] Additionally, as lithium iron phosphate (LFP) batteries increasingly displace nickel manganese cobalt (NMC) batteries, the lower residual value of LFP (due to the lower prices of the minerals contained in the battery) will probably further challenge the profitability of recycling.

FIGURE 5 **EV batteries reaching end of life, globally**



Source: McKinsey & Company[25]

Current forecasts for batteries reaching EOL typically focus on end of first life, and do not factor in the potential for second life; however, recycling should be viewed as the last step of a battery's life, after reuse or repurposing as suggested by the waste management hierarchy derived from the European Union (EU) Council Directive 75/442/EEC.[26] The second-life industry – currently in even earlier stages of development than the recycling industry – must scale up significantly to meet impending global demand, but this growth may be impeded by falling prices of new batteries, the perceived value of used batteries, and the cost of battery diagnostics, remanufacturing, logistics and warranties.[27]

Since batteries are a portfolio product, with battery manufacturers offering several product lines that are fine-tuned for their customers' application, the battery reuse, repurposing and recycling industries must develop sufficient resilience to maximize value from the ever-growing suite of products that are entering the market.

BOX 2 | Giving EVBs a second life

A battery is typically considered fit for use in a new EV for as long as it maintains 80% of total usable capacity and loses no more than 5% of its charge per day when not in use.[28] This initial phase of use in an EV is referred to as a battery's "first life" and typically lasts 8-12 years,[29] and potentially 10-15.[30]

This means that when an EVB no longer meets its original performance specification, the battery still has 75-80% of its usable capacity left.[31] At this point it may be "repurposed" (i.e. used in other applications, such as energy storage, which do not require as much power density). There may also be opportunity to "reuse" the battery in another EV under certain circumstances. Together, reuse and repurposing are considered a battery's "second life." Second life may allow the battery to be used for an additional 10-20 years beyond its first life.[32]

Second-life opportunities include:

– *Renewable energy storage, on and off the power grid*: Repurposed batteries can store renewable energy for later use – e.g. storing solar power for times when the sun's not shining – providing reliable electricity and grid flexibility while lowering emissions. Second-life batteries can also be used for off-grid energy storage in the form of standalone microgrids or other distributed energy resources, which can increase access to electricity in regions with limited electricity infrastructure.[33]

– *Grid stabilization*: Repurposed batteries on the electric grid can help a utility maintain power reliability and displace more expensive, less efficient, ageing assets that are currently used to maintain power reliability,[34] thereby accomplishing the same goal for lower cost and with lower emissions. This opportunity may be particularly beneficial in the Global South. For example, a 2023 study by the University of California, Davis, highlights the potential for second-life batteries to be used as backup power and off-grid energy storage in Kenya, which experiences power outages, and concludes more generally that second-life batteries could provide a more affordable energy storage solution for lower- and middle-income countries.[35]

– *Expansion of EV charging infrastructure*: Repurposed EV batteries may be used directly in EV charging infrastructure to provide supplementary power to fast chargers.[36] Additionally, by stabilizing the grid, providing renewable energy storage and increasing access to electricity, second-life batteries can enable development of EV charging infrastructure and help balance grid loads from EV charging.

– *Reuse in EVs*: EVBs are being designed for increasingly longer lifetimes – sometimes as long as one million miles or 15 years.[37] This increases the probability that EVs will retire before their batteries reach the end of their useful life. (For reference, passenger cars in the US typically last 12-15 years.[38] The average driver in the US drives 13,500 miles a year,[39] meaning it would be several decades before an EVB reaches one million miles. In countries with lower average driving rates, the battery may outlast the vehicle even further. As a result, there may be potential for EVBs to be reused in other EVs.) Additionally, a used EVB may be suitable for use in another EV with lower range requirements.

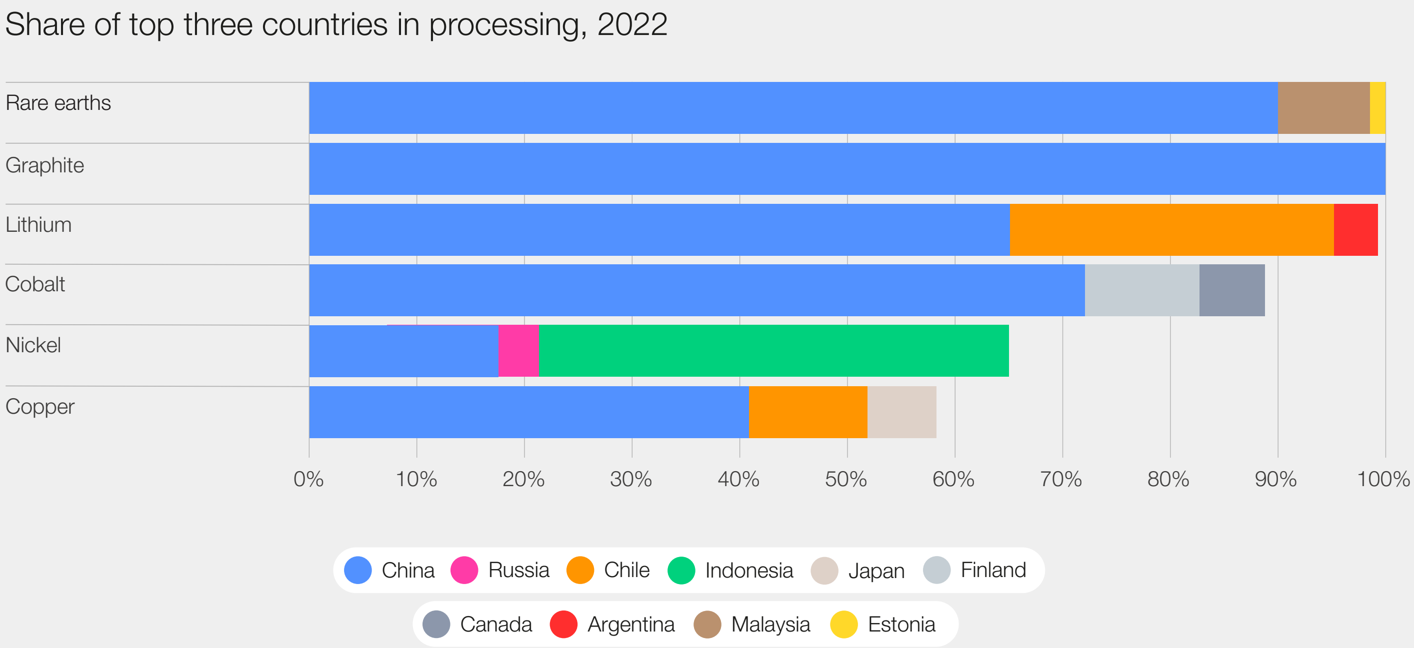
On a global scale, the supply of second-life lithium-ion batteries could exceed 200 gigawatt-hours per year by 2030,[40] and the second-life battery market could surpass $7 billion by 2033.[41]

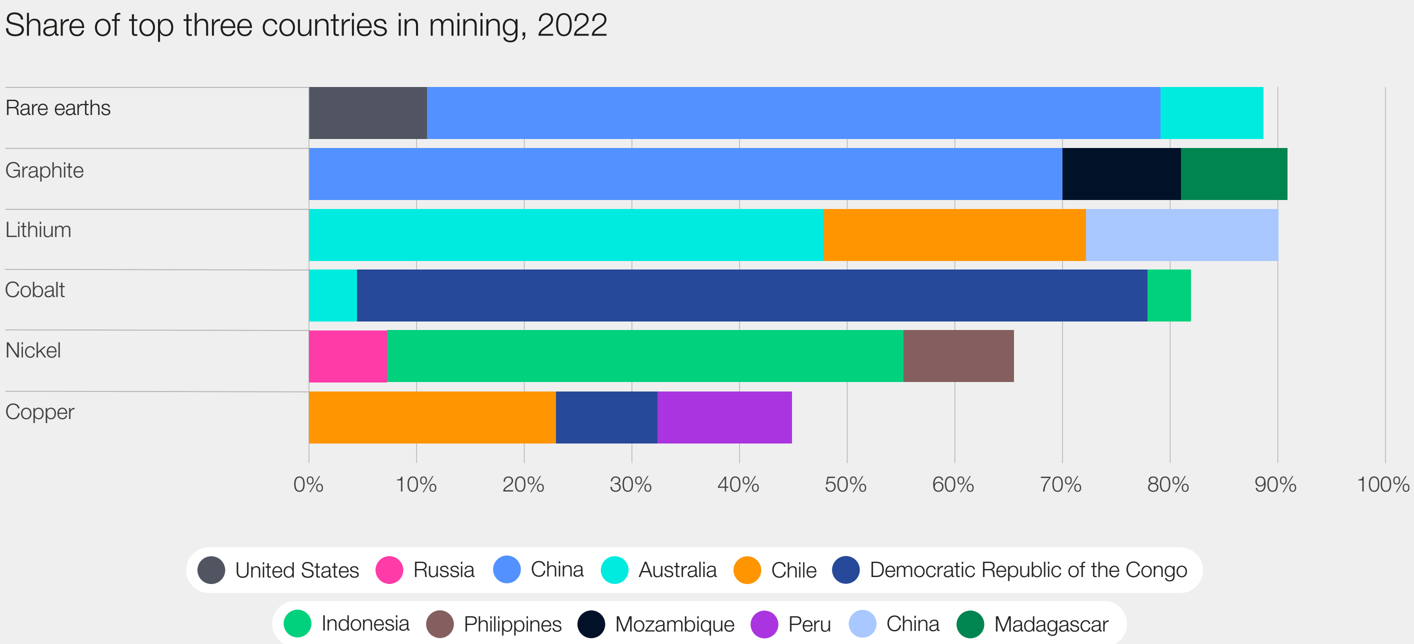
2.4 Vulnerabilities and inequitable harms and benefits of value chain design

The current global movement of batteries and battery materials generates vulnerabilities and may perpetuate or exacerbate inequities by leading to improper EOL management and preventing sharing of the benefits of a circular battery economy.

Extraction and processing are highly concentrated in a few countries. This generates vulnerabilities in the value chain as voluntary or involuntary disruptions from a single actor can significantly affect global markets. This concentration of supply and refining, coupled with the expected supply shortages, has led to a proliferation of trade alliances and restrictions.[42]

FIGURE 6 **Top three countries for mining and processing of critical minerals**



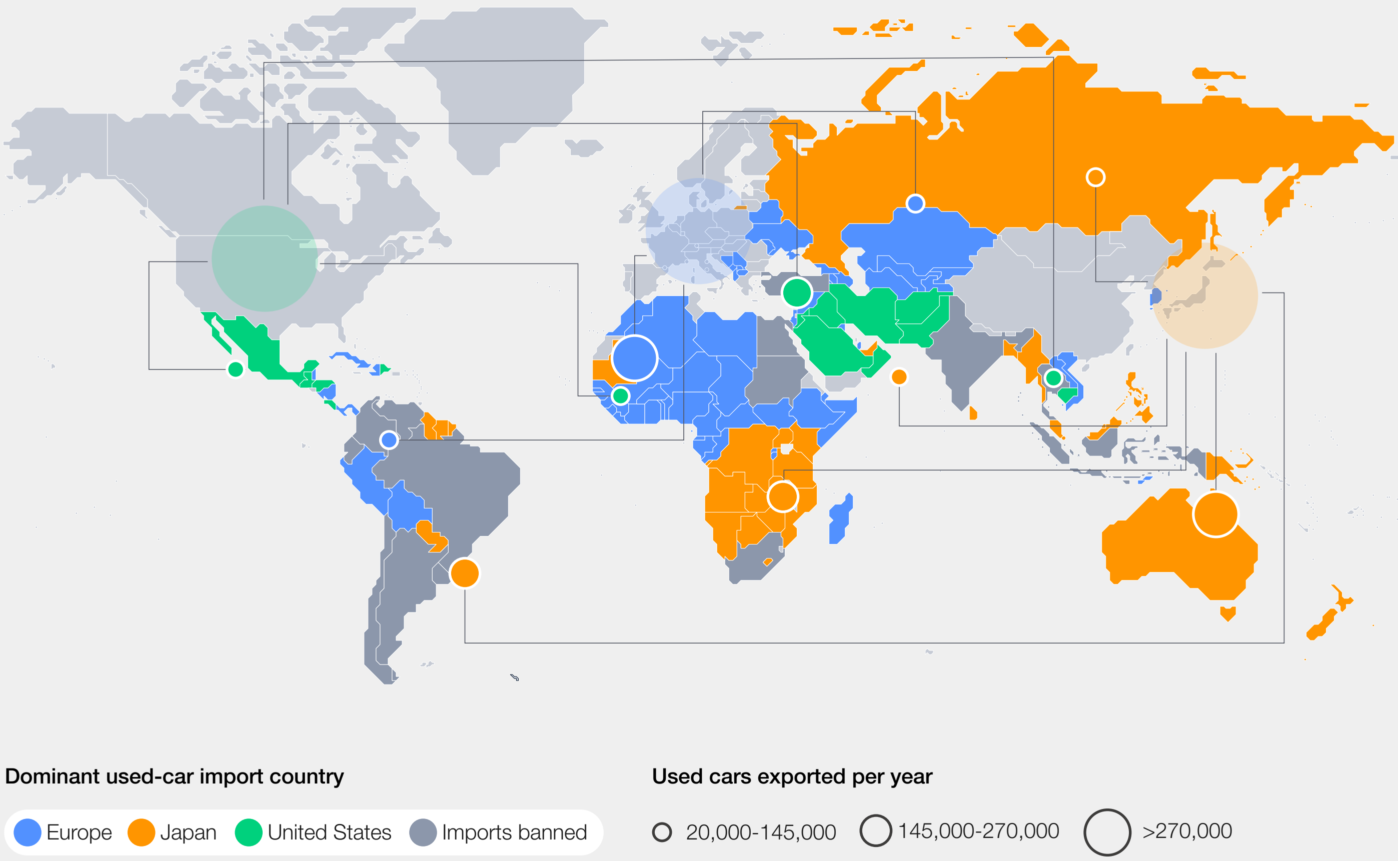


Source: IEA Critical Minerals Market Review 2023[43]

Additionally, countries in the Global South have almost exclusively been part of the raw material extraction segment of the value chain and have not seen the benefits of their endeavours, as the materials are extracted to produce EVs that generate value and benefit primarily other countries. As noted by the United Nations in its guiding principles on critical energy transition minerals, "The dependence of mineral-producing developing countries on exports of mineral commodities has resulted in vulnerability of their economies to mining cycles, and limited their realization of the economic benefits of mining."[44]

Lower-income countries often rely on second-hand vehicle imports, and EVs will continue to make up a growing share of vehicles in exporting countries.[45] Therefore, many EVBs will reach their eventual EOL in lower-income countries – many of which lack the necessary infrastructure and regulatory frameworks to safely and responsibly manage EOL batteries.

FIGURE 7 **Used vehicle imports and exports**



Source: UNEP

Without infrastructure and trained workers to enable reuse, repurposing and recycling, or affordable transport options to move batteries for EOL management, second-hand markets may resort to landfilling, stockpiling or informal recycling that are harmful to the environment and human health and pose safety risks. These practices increase the safety hazards inherent in LIBs, including chemical toxicity and fire risks, which endanger both workers and surrounding communities.[47] Furthermore, the risks of informal or improper EOL disposal may be exacerbated by the import of low-quality batteries with limited remaining useful life, made possible by unclear, inadequate or unenforced international regulations governing the import and export of used EVs, used EVBs and EOL battery materials.

While a circular battery economy has the potential to reduce the environmental impact of EVBs and bring about significant socio-economic opportunities, this new economy must be designed with equity in mind to ensure all markets benefit, and that none are disproportionately burdened. To help achieve this, more countries must get involved in the value chain and facilitate responsible cross-border movement of batteries and battery materials.

2.5 Workforce development and transition needs

The workforce needed to repair, reuse, repurpose and recycle the number of batteries expected to reach end of life in the decades ahead has not yet been developed. Also, raw material markets will need to transition much of their workforce to other industries or other segments of the value chain.

Enabling a circular economy and enacting the changes discussed in this report requires a skilled and well-trained workforce – presenting both a challenge and an opportunity. In the transition to a circular battery economy, workers will be needed in new or expanded segments of the value chain, such as recycling, reuse and repurposing. Additional workers may also be needed in existing segments of the value chain, such as manufacturing, as a result of a stronger, more resilient value chain that enables greater EVB production. Recruiting and training workers to fill these jobs will be essential to enabling both a widespread transition to EVs and the development of a circular battery economy.

As raw material extraction needs decrease in the future, the workforce engaged in extraction would need to transition into new roles. The extent to which raw material extraction will be needed in the future is strongly dependent upon the degree to which the circular battery value chain is realized. Scenarios range from net-zero extraction (in a fully circular economy)[48] to one in which extraction needs continually increase to meet growing material demand.[49]

This uncertainty necessitates adaptability and requires that extraction markets, in particular, be prepared to recruit, train and reskill workers into various segments of the value chain as needs evolve. This presents both an acute challenge and a meaningful chance for these markets to develop in a way that avoids the inequities of the past and capitalizes on the socio-economic opportunities of a new, circular value chain.

An additional concern in developing markets is the potential for informal EOL industries, in which individuals collect, sort, repurpose or recycle waste without proper training or regulation. This has happened with lead-acid batteries[50] and e-waste,[51] and the Indian government has observed that it is happening with LIBs in India today.[52] Therefore, integrating these informal processes into the formal economy presents an opportunity for positive change.

3 Recommendations

An array of changes is needed across the EV battery value chain.

This section outlines what changes can, and must, be made to help address these concerns, in turn reducing environmental impact and capitalizing on the opportunity in a way that benefits all. This is not a comprehensive list of all changes needed to create a circular battery economy, but a prioritized set of interconnected recommendations that take a holistic approach to that end.

3.1 Track-and-trace platforms

Develop standardized, interoperable track-and-trace platforms.

What is this change, and why is it needed?

"Track and trace" (T&T) refers to two related approaches to increasing visibility across the value chain. "Tracking" involves following a battery from the time it is manufactured until it reaches an EOL management system (e.g. a recycling plant); this can be achieved through technology such as QR codes, radio-frequency identification and near-field communication. "Tracing" involves following battery materials from their origin (e.g. the mine) through EOL, and back into the supply chain; this requires blockchain, mass balance or other chain-of-custody techniques. Together, T&T provides the transparency needed to enable responsible decision-making and accountability at every step of the value chain.

Combining elements of both tracking and tracing, a digital product passport (DPP) "establishes a digital twin of the physical battery that conveys information about all applicable sustainability and lifecycle requirements based on a comprehensive definition of a sustainable battery."[53] GBA conceptualized a DPP for batteries as the principal instrument to map, measure and manage sustainability risks and impacts related to mineral value chains in its 2030 vision report brought out in collaboration with the World Economic Forum.[54]

DPPs may introduce upfront costs for businesses related to data collection, integration and compliance, which may ultimately be passed on to the final consumer but can potentially drive long-term efficiencies, reduce regulatory burdens, and unlock new revenue streams through enhanced product transparency and life-cycle management. For example, a quantitative analysis of impacts of the proposed EU battery passport found that availability of composition and dismantling data could reduce costs for preprocessing and treatment by 10-20%. Use of the battery passport in vehicle recycling and export procedures could potentially reduce battery leakage (illegal exports and treatment)[55] and increase the availability of active materials, fulfilling 5-20% of material demand for projected European passenger vehicle demand by 2045.[56]

T&T and DPP requirements are increasingly being introduced in multiple jurisdictions to bring transparency to battery value chains. For example, the European Union (EU) Battery Regulation explicitly requires use of a DPP for light-duty vehicles, industrial batteries and EVBs by 2027.[57] In California, vehicle manufacturers are required to provide digital identifiers for sharing information on battery composition and battery disposal instructions.[58] Given the business opportunities associated with this activity, commercial T&T solutions are proliferating. Harmonizing data governance for these platforms is vital to ensure that they are interoperable across value-chain segments and jurisdictions. Additionally, the metrics used must be rigorous and comprehensive to provide a full understanding of a battery's lifetime environmental and social footprint.

What levers can be used to facilitate this change?

Collaborate to harmonize T&T metrics and approaches across regions.

The US, Japan, China and other jurisdictions beyond the EU are at various stages of introducing due diligence, environmental footprint and traceability requirements for batteries. This creates an opportunity now to address challenges of traceability across global supply chains. Policy-makers across these jurisdictions can develop common methodologies for data collection and verification of the supply chain, making traceability systems interoperable, and creating harmonized data architectures. Harmonizing data governance for these solutions is critical to ensure interoperability across value chains, jurisdictions and diverse technologies.

While progress is being made at the regional level, global coordination remains limited. Organizations such as the UN Centre for Trade Facilitation and Electronic Business (UN/CEFACT) are contributing to these efforts in other sectors such as fisheries, garments and footwear and could serve as platforms for driving more global alignment in EVB-focused T&T initiatives.[59] In addition, policy-makers will need to promote data security and tamper-proofing requirements.

Doing this effectively will require greater collaboration between countries linking T&T to the relevant national or international registries to reduce both illegal export and illegal treatment of EOL batteries. For instance, DPPs may be interconnected with national vehicle registration offices. Additionally, these requirements must remain dynamic and adaptable to emerging use cases, which often develop unevenly across regions. It is crucial that they involve both demand centres and resource extraction countries.

Questions that must be addressed include:

– How do T&T solutions collect, manage, exchange and verify data? How should commercially sensitive data be handled? Who should have access to what data?

– What rules should apply to product carbon footprint calculations? How is the data verified? What statements may providers make as part of their solutions? (Guidance to help answer these questions can be found in the recommendations made by the COP26 Roundtable for Harmonized Principles for Data Authentication and Protection to Realize the Paris Goals.)[60]

– How can it be ensured that T&T does not become a vehicle for exclusion of artisanal and small-scale mining (ASM) supply, since the instruments are tailored for large-scale mining operators? How can it be ensured that access to a market of responsibly sourced ASM minerals, which are critical in many regions as a source of income and livelihoods?

– How should costs of implementing T&T solutions (collecting and aggregating data) be distributed across the value chain?

Build industry consortia and public-private partnerships.

Multistakeholder public-private consortia are instrumental in pioneering DPPs for EV batteries. Industry actors in the manufacturing and EOL portions of the value chain, data platform providers, civil society, consumer protection groups and regulatory agencies need to collaborate on developing secure data exchange and aggregation platforms to enable transparency and circularity through T&T.

For instance, different public-private alliances in the EU are working on developing standards for data exchange, storage and reporting to enable compliance with the EU Battery Regulation's traceability requirements. GBA has worked on developing guidelines for T&T providers reporting on ESG data, and a rulebook for reporting greenhouse gas emissions through an extensive stakeholder engagement process. It has also conducted pilots to demonstrate capability for complying with regulations.

Other initiatives to support data standardization include Catena-X, which leverages digital twins and blockchain to promote secure, interoperable data exchange within the automotive industry;[61] MOBI, which focuses on developing data infrastructure and an implementation framework for a decentralized battery passport system;[62] and BatteryPass, which supports compliance with EU regulations by standardizing data reporting for sustainability and circular economy goals. By collaborating with governments and industry, these initiatives have the potential to accelerate the standardization of T&T systems, driving transparency, regulatory compliance and sustainability across the global value chain.

Other regions across the globe need to build on these existing efforts by initiating similar partnerships to develop T&T solutions tailored to their specific region, value chain segment, use cases, and current or anticipated regulation. For instance, in the US, an evolved version of DPP can help demonstrate compliance with the Inflation Reduction Act's 30D foreign entity of concern (FEOC) regulation,[63] though the regulation does not require any particular tracing system at this time.

Require additional circularity metrics reporting to encourage sustainable practices.

DPPs can provide additional value when metrics beyond the scope of a battery's manufacturing footprint are incorporated. Tracking durability and performance of a battery in terms of lifespan, energy delivered and carbon footprint enables automakers to choose more sustainable batteries that meet their performance needs while contributing to their emissions reduction and sustainability goals – in turn helping build demand for lower-emissions batteries. While the 2023 EU Battery Regulation requires carbon footprint declaration of EV battery manufacturing to inform assessment of carbon threshold levels and to shift the market towards lower footprint products,[64] there are no requirements to track metrics such as the energy delivered throughout the lifetime of a product or to estimate the carbon footprint of a battery per unit of energy delivered. Incorporating such a metric would encourage battery design for longer lifetimes through first- and second-life applications.

On a similar note, requiring battery health information sharing, collection rate reporting, exports and imports, battery or materials flow tracking can facilitate reuse, repair and collection at EOL and reduce leakage. Studies indicate that data availability on battery composition, dismantling guidelines, battery performance, and remaining useful life can result in material savings for recyclers and second-life operators. Adding data attributes around recycled content in battery can also help original equipment manufacturers (OEMs) offer certified differentiated products to their customer.[65]

3.2 Design change and data standards

Set performance and data standards and finance R&D for design innovation that prioritizes disassembly and recyclability alongside safety, cost and range.

What is this change, and why is it needed?

A cascading hierarchy of LIB applications that prioritizes repurposing and reusing EOL batteries higher than recycling can yield substantial environmental and economic benefits. A recent study found that when choices are made at each stage of second life and recycling to provide the highest economic and environmental returns for the battery's chemistry and SOH, reusing or repurposing LFP batteries improved profits by 58% and reduced emissions by 18% compared to hydrometallurgical recycling without second life; NMC batteries saw profits boosted 19% and emissions reduced 18%.[66]

Non-standardized pack designs and varying bonding techniques such as fasteners, glues and adhesives used by manufacturers pose a challenge to repurposing, reusing and recycling batteries. The variety in components and design philosophies means that EOL batteries cannot be easily discharged and dismantled by automation, which adds significant effort, time and cost to preprocessing. Stakeholders in the EVB value chain need clarity on long-term regulations for battery recycling and targets for all commonly used battery chemistries, which must be agreed upon through consultation with industry. Incentives are essential for making the business case for recycling batteries with low material value.

Batteries need to be designed to allow for disassembly that grants easier access to battery modules and cells. This includes providing user manuals with part numbers; exploded-view diagrams; disassembly sequences; guidance on discharging a battery completely; safety measures; and information on fillings, casings, fixtures and reversibility triggers for adhesives. In addition to disassembly, batteries must be designed for recyclability, which requires certain design choices regarding materials and battery-cell form factors. For instance, cylindrical cells use fire-retardant plastic moulding that is not recyclable, whereas prismatic cells may use busbars and compression plates to perform the same safety function.

Several obstacles stand in the way of these design changes, including:

- *Potential for cost increases*: Redesigning batteries may increase costs of battery cells and packs. For instance, cell-to-pack configurations eliminate the module level in conventional battery design, resulting in cost savings of up to 40%.[67] Introduction of modular design features might require additional components and reduce these cost savings.

- *Conflict among design priorities*: Circular design priorities can conflict with one another; for example, increasing the durability of a battery can decrease the ease of disassembly because of the need to use permanent attachment mechanisms. Similarly, cell-to-pack configurations reduce ease of disassembly but help with lightweighting by providing some structural integrity to the EVB.

- *The need for research and development (R&D) funding*: Lastly, innovation that balances EOL management with performance and economic competitiveness will require R&D investment by both incumbents and start-ups. Smaller firms may not have the resources to build and operate the R&D-scale and pilot-scale production facilities required to fast-track the R&D process.[68] In such instances, funding is not always available at the necessary cost and R&D will compete with other organizational priorities, extending the R&D timelines.

In addition to design change, stakeholders need access to standardized BMS data to enable reuse and repurposing. Repurposing EVBs for optimal performance and safety in second life may involve disassembling battery packs to replace the BMS or degraded modules. A complete understanding of battery health, including SOH and degradation over time, helps diagnose faults and forecast remaining useful life. However, shared access to BMS data remains a challenge due to data privacy[69] and tampering concerns.[70] The resulting lack of information regarding the condition of the EVB, combined with certain attributes of battery design, exposes workers to safety risks.

While the rapidly evolving EVB industry is in its early stages, it presents a unique opportunity to reshape the thinking about battery design, but achieving this transformation requires collaborative action and technological innovation across industries. Collaboration among battery manufacturers and secondary material providers is needed to help drive design change, while multistakeholder organizations are essential to bridge the cooperation gap, raise collective ambition and guide manufacturers towards designs that prioritize ease of disassembly and recyclability. For example, the GBA's *Circular Design Rulebook* provides voluntary performance expectations on repairability, reusability and recyclability of a battery; the rulebook was developed in a pre-competitive multistakeholder environment and the associated score is being tested in a series of pilot projects.

What levers can be used to facilitate this change?

Establish international design standards that incorporate disassembly, recyclability and performance standards for second life.

The development of international standards for disassembly and recyclability of EVBs is crucial to ensuring a coordinated global approach to battery design. An existing regulation aimed at fulfilling this need in the EU is the End-of-Life Vehicle Directive, which requires "the design and production of new vehicles which take into full account and facilitate the dismantling, reuse and recovery, in particular the recycling, of EOL vehicles, their components and materials."[71] The directive is currently being revised to introduce updated regulations to improve vehicle circularity, including extended producer responsibility and improved measures for dismantling, reusing and recycling vehicle components.

Alternatively, the directive may soon be replaced by the European Commission's circular vehicles regulation proposal, the main objective of which "is to establish a closer link between the design requirements for vehicles and the provisions concerning ELV [end-of-life vehicle] management."[72] The proposal includes vehicle design requirements "formulated so that they are effectively prerequisites for proper execution of the provisions on ELV management". If this proposal is adopted, it could serve as a model for international design requirements that facilitate reuse, repurposing and recycling.

Create a standard definition and evaluation method for diagnosing battery health, along with secure data-sharing frameworks on battery health and performance among relevant value-chain stakeholders.

Accurate diagnosis of a battery's SOH is essential for evaluating retired EVBs for second-life applications and ensuring operational safety. When determined experimentally, SOH offers only a temporary snapshot of battery performance. Model-based SOH diagnostics can offer a comprehensive view of performance over time and allow predictions of ageing and remaining useful life. However, obtaining this data is challenging without SOH disclosure regulations due to privacy and tampering issues. Additionally, SOH may not be comparable between parties owing to proprietary evaluation methods and varying testing conditions.[73] Effective standards to enable sharing of BMS data must include uniform protocols for data collection, reporting and interpretation across manufacturers.

While regulations such as the EU's Battery Regulation 2023/1542 mandate access to standardized BMS data, they lack detailed technical guidelines for data collection and formatting.[74] Developing these guidelines would facilitate better decision-making around second-life uses and recycling. Public benefit partners should spearhead efforts to convene public and private stakeholders to develop a rulebook that defines acceptable methods for SOH diagnosis, data disclosure frameworks and contractual relationships between value chain players. Such guidelines could also facilitate regulations, similar to the Greenhouse Gas Rulebook[75] and Guidelines for Track & Trace Service Providers created by GBA[76] to ensure adherence to the EU Battery Regulation.

Expand and update standards to evaluate safety and performance of second-life batteries.

Standards to evaluate the safety and performance of second-life batteries – such as UL 1974[77] and IEC 62933-5-378 – should be expanded and updated in collaboration with second-life stakeholders. Ongoing updates will be needed to keep pace with evolving battery chemistries and to design and develop new second-life applications.

Collaborate across the second-life industry to develop a framework outlining acceptable conditions for reuse and repurposing within regions.

A framework is needed to establish acceptable use cases and evaluate the proposition for second life in different regions. For example, it is generally recognized that dismantling a battery pack down to the cell level is dangerous, and therefore repurposing is only viable at the pack or module level. Smaller modules or packs with compatible performance characteristics may instead be combined for second-life applications in energy storage; pilot projects are currently testing this.[79]

Given the small scale of battery reuse and repurposing today, and the corresponding lack of data, collaboration from second-life stakeholders – including scientific organizations, battery manufacturers, automakers and reuse/repurposing providers – is needed to consolidate knowledge and real-world data and outline these acceptable use cases. Since reuse and repurposing are restricted or not allowed in some countries, geographic context must be factored into this framework.

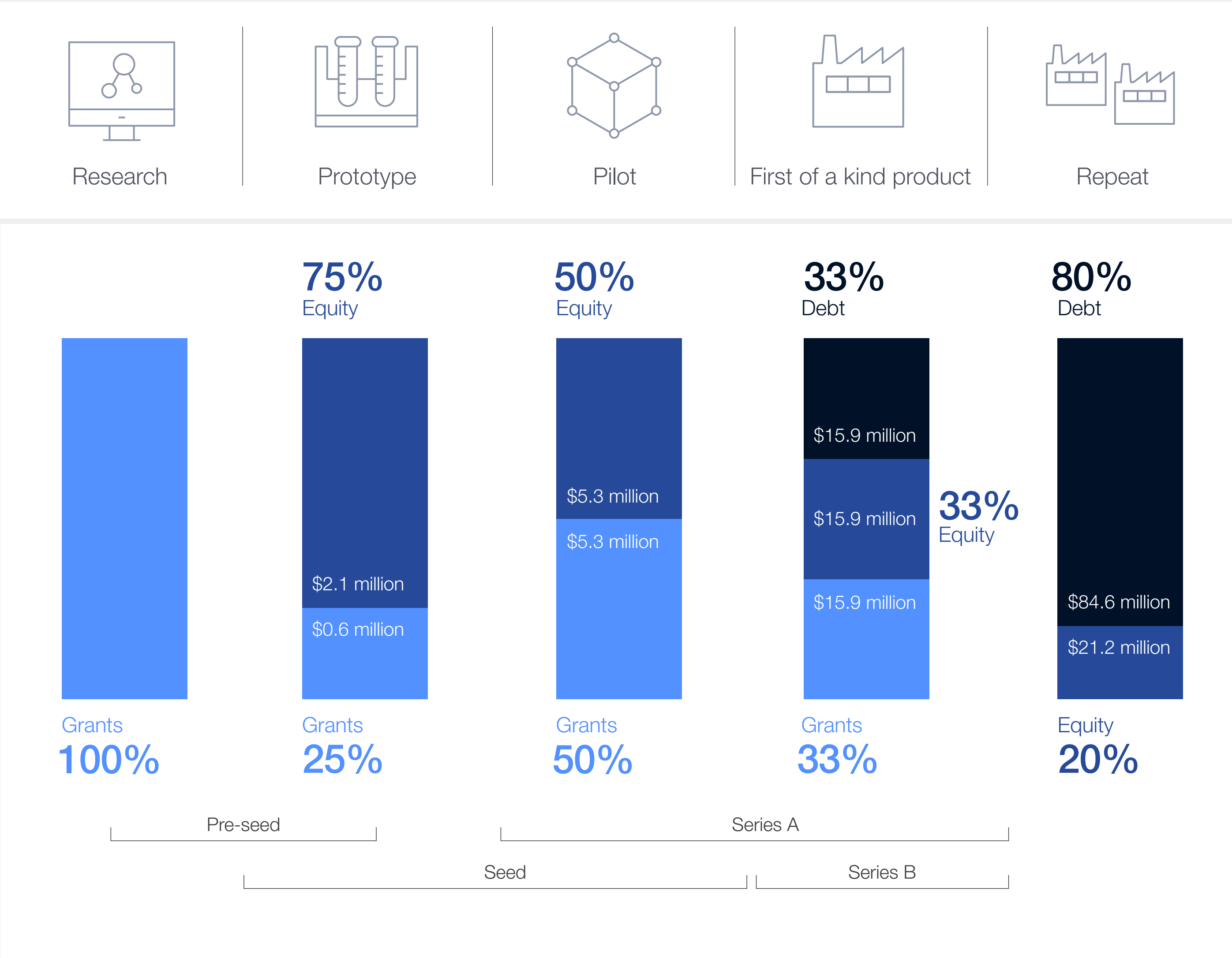
Encourage both governmental and private investment support for R&D for battery design innovation.

Design innovation that enables disassembly and recyclability requires both significant funding and ecosystem-wide collaboration. Governments play a key role in providing the large-scale funding needed for R&D. Government investment can support technology innovation by funding fundamental science and engineering research and supporting these technologies as they scale out of the lab and progress towards commercial maturity. This can take the form of grants for early-stage innovation as well as loan guarantees, concessional financing and other investment modes which seek a return in support of later-stage technology. Providing lower-cost funding to battery manufacturers to support R&D for design innovation can incentivize manufacturers to address the necessary design changes discussed above without sacrificing performance.

Government funding can most feasibly be combined with three other funding sources:

- *Philanthropic grants* to fund early-stage research conducted by universities or other academic or non-profit entities.
- *Venture capital* (including sustainability-focused investors) for seed funding to scale prototypes and pilots.
- *Corporate investment* by companies to finance R&D from prototyping onwards. Tax incentives can encourage additional investment.

FIGURE 8 **Climate tech capital stack**



Source: Extantia[80]

BOX 3 **Examples of government funding for EVB design innovation**

– *The United States CIRCULAR programme*: Supported by the Advanced Research Project Agency - Energy (ARPA-E) of the US Department of Energy with funding of up to $30 million, the programme focuses on R&D projects to promote a circular economy for EV batteries by extending battery life, improving recycling and advancing reversible manufacturing. It also emphasizes innovations in battery chemistries, battery design and tools for assessing environmental and economic impacts.[81]

– *The European Union Horizon Europe Batteries Partnership*: This partnership offers €925 million ($979 million) to fund projects that enhance battery design, manufacturing and recycling, in line with Europe's sustainability goals. It supports technological innovations such as safe and sustainable battery design and improved recycling flexibility.[82]

– *The United Kingdom (UK) Faraday Battery Challenge*: This challenge will invest £610 million ($774 million) to strengthen the UK's battery industry by developing high-performance, cost-effective and sustainable battery technologies. It supports research, manufacturing and recycling processes, focusing on commercializing battery tech for zero-emission vehicles.[83]

Governments can further support innovation by facilitating knowledge-sharing collaborations, such as those between academic research institutions and businesses. For example, Li-Bridge – a public-private partnership in the US – brings together the LIB industry and the US Department of Energy's national laboratory system to accelerate the development of a robust and secure domestic supply chain for LIBs.[84]

3.3 Policy to address economic and technical challenges

Use targeted policy interventions to help overcome economic and technical barriers faced by recycling and second life.

What is this change, and why is it needed?

The challenging economics of EV battery recycling can make it difficult for recycling businesses to operate profitably, in turn hindering the development and continued operation of EVB recycling infrastructure at scale. These challenges include:

– *High capital requirements*: Building recycling facilities requires significant investment in technology, equipment and operations. This is especially difficult in developing markets, where financial resources may be limited.

– *Insufficient feedstock volumes*: Recycling facilities require large volumes of feedstock to be profitable.[85] Because a small number of batteries have reached EOL to date, current recycling feedstock, which comes mainly from production scrap and damaged, defective or recalled batteries, is not always sufficient for profitability.[86]

– *Volatile mineral markets*: The value of recycled materials like lithium, cobalt and nickel is subject to market fluctuations. When mineral prices are low, recycling becomes less economically viable.[87] This volatility creates uncertainty for recyclers, as they may face negative profit margins, further discouraging investment. The United Nations Industrial Development Organization has observed that "the recycling sector consists to a large extent of small companies that are not resilient to market shocks";[88] this highlights the vulnerability of the industry, especially in the face of market volatility.

– *Downstream industry demand*: Recyclers need nearby industries, such as battery manufacturers, that can use their output in new products. If there is no local market for these materials, recyclers face additional transport costs, reducing profitability.

For the second-life industry, technological and safety challenges result in high costs of collection, diagnostics, disassembly and repurposing. A study by the University of California, Davis, found that the "levelized" cost of second-life battery energy storage systems (BESS) may be higher than that of new BESS, depending on the battery's condition and other factors – challenging the economic viability of repurposing.[89] Other challenges include occupational safety risks, potential risks during the use phase of second life, and questions around liability.

Policy interventions can help overcome these challenges to prevent them from impeding the growth of the second-life industry and the development of sufficient, long-term recycling infrastructure. Policy details must vary by region, influenced by the dominant battery chemistry, projected feedstock volumes and other region-specific factors. An international organization could provide a toolkit of policy options that regional and national governments can adapt to their specific needs.

Policies supporting recycling should prioritize second-life applications for batteries, where feasible, to prevent premature recycling. Given the fast-changing landscape of battery chemistries, policies must be adaptable enough to manage a variety of battery types and future developments in both battery chemistry and recycling technologies, such as direct recycling. This balance is essential to support sustainable growth in EVB recycling without causing industry uncertainty.

What levers can be used to facilitate this change?

Enact extended producer responsibility (EPR) provisions to address the economic barriers to recycling.

EPR requires producers to take responsibility for EOL management of their products – though definitions of "producer" may vary. In the EU Battery Regulation, for instance, the producer is defined as "any person in a Member State that… places batteries or accumulators, including those incorporated into appliances or vehicles, on the market for the first time within the territory of that Member State on a professional basis";[90] this could apply to a battery manufacturer, automaker, dealership, importer or other entity.

EPR has become the central policy for LIB management in the EU and will be the central policy in China.[91] While EPR is an effective tool for redistributing costs and managing EOL processes, it requires careful fee design to be effective. To raise the level of ambition and potentially deepen the impact of EPR, policy-makers may consider a modulated fee, in which producers pay for EOL management for their specific battery design rather than an industry average.

Modulated fees require a high level of traceability and are more challenging to implement than traditional EPR. Yet they can affect design (in addition to covering the costs of EOL management) by providing an economic incentive to battery OEMs to design for extended life and responsible EOL management, or an incentive to automotive OEMs to prioritize this in their purchase decisions. However, it is worth noting that eco-modulated fees have not been found to have any direct impact on battery design for consumer electronics, at least in the short term; as a relatively new concept, more study is needed.[92]

Another consideration for EPR is that the policy could require producers to have adequate EOL investment and capacity to handle the EVBs they sell *in the countries in which they are sold*. This would avoid producers shifting the EOL management responsibilities to countries without adequate EOL management resources. This EOL management capacity may include authorized third parties, with direct technical support from producers.

BOX 4

Examples of EPR for EVBs

– *EU*: The EU Battery Regulation requires producers to "have extended producer responsibility for the management of their batteries at the end-of-life stage. Accordingly, they should finance the costs of collecting, treating and recycling all collected batteries; carrying out compositional surveys of mixed collected municipal waste; reporting on batteries and waste batteries; and providing information to end-users and waste operators about batteries and appropriate reuse and management of waste batteries."[93]

– *China*: As explained by the International Council on Clean Transportation (ICCT), "vehicle manufacturers are required to provide technical support to [battery dismantling and recycling enterprises] and are responsible for selling batteries to a qualified handler for reuse or recycling. A unique code is attached to every battery produced in or imported into China for use in electric vehicles to allow for tracking and proper processing at the end of the battery's first life."[94]

– *India*: The country's Battery Waste Management Rules state that producers "have the obligation of Extended Producer Responsibility for the Battery that they introduce in the market to ensure the attainment of the recycling or refurbishing obligations", which includes collecting and refurbishing or recycling a certain percentage of batteries the producer puts on the market, and explicitly precludes the producer from landfilling or incinerating any batteries. Compliance is tracked through an online registry maintained by the Central Pollution Control Board.[95]

Implement regulations and incentives to address technical and financial barriers to second life.

Conflicting priorities among value-chain players and the uncertain economics of second-life applications can hinder the realization of their social and environmental benefits. EV OEMs lack financial motivation to collaborate with second-life battery providers and are additionally deterred by liability concerns and reputational risks associated with the safety of second-life usage. To encourage cooperation among stakeholders with varying interests, national policy-makers can implement measures such as right-to-repair regulations, frameworks for transferring liability across value-chain participants and regions, take-back mechanisms and incentives designed to unlock system-level benefits.

- *Right-to-repair regulations*: Their primary purpose is to allow independent technicians to repair EVBs by guaranteeing them access to the information, tools and parts needed to safely complete repairs; this access is also critical to enabling reuse and repurposing, making the right to repair a useful policy lever for enabling second life. Right to repair could also guarantee access to data on SOH and remaining useful life to enable reuse and repurposing. Right to repair should be accompanied by established guidelines for acceptable second-life uses, battery health diagnosis and data sharing as outlined above.

- *Liability transfer and disposal regulations*: Automakers and battery manufacturers are concerned about liability and EOL disposal responsibilities for second-life applications, especially in regions with EPR. Some start-ups may address these safety and liability issues by offering warranties for second-life products. It is also critical to ensure that all second-life batteries are eventually recycled at EOL. Each region should establish its own liability framework and disposal strategy based on its overall EOL management policy and available recycling infrastructure. For example, the EU battery regulation mandates a sales contract between the seller of second-life batteries and the consumer and places liability and EPR requirements on the seller.[96]

- *Incentives*: Second-life BESS are often viewed as ideal candidates for repurposing EVBs. As noted above, a recent study has indicated that the levelized cost of energy storage in second-life BESS can reach up to $278 per megawatt-hour (MWh) over a 15-year project period, more than a new BESS's at $211/MWh.[97] The repurposing costs can range from $28 to $36/kWh, compared to recycling costs of $9-$17/kWh.[98] Well-designed incentives, informed by the social and environmental benefits, could help align stakeholders and lower overall costs, especially as new battery prices continue to decline with technological advancements and economies of scale,[99] while second life usage is nascent.

Use material recovery targets and recycled content mandates to encourage recycling.

Material recovery targets require certain amounts of the materials in batteries to be recovered through recycling at EOL, which the International Council on Clean Transportation notes is "particularly important to ensure a high recovery of materials for which recycling is not necessarily profitable."[100] Material recovery targets are often accompanied by recycled content mandates, which require batteries to contain a certain percentage of recycled critical minerals.

Material recovery targets and recycled content mandates can be effective tools for supporting recycling, but they must be carefully designed to avoid unintended consequences. Policies (such as those pertaining to recovery rates) designed to increase recycling of one metal could inadvertently disadvantage recycling of another metal, which may reduce positive outcomes in the future as battery chemistry, demand and markets evolve.

Additionally, recycled content mandates could lead to premature recycling. Outcomes must be consistently evaluated to obviate undesirable market and environmental impacts, especially considering the complexity and evolving nature of the recycling industry. Finally, a focus on critical minerals recycling should not preclude the recovery of other battery materials such as electrolytes and rare earths.

BOX 5

Examples of recycled content and recovery targets

- **In the EU**, the Battery Regulation requires lithium-ion EVBs to contain at least 16% recycled cobalt, 85% recycled lead, 6% recycled lithium and 6% recycled nickel by the beginning of 2031. To achieve this, by the end of 2030 all waste batteries must enter a recycling process with a minimum efficiency of 70% in order to recover at least 80% of lithium, 95% of nickel, 95% of cobalt and 95% of copper.[101]

  Civil society organizations and recyclers have expressed concern that the latest draft EU legislation, which explains the methodology for calculating recycling efficiency and recovery rates, creates a loophole that excludes LFP batteries. Considering that 15% of all EVs sold in Europe in 2023 contained LFP batteries, and that this number is expected to increase to 57% of sales by 2030, the exclusion of LFP batteries from the mandatory calculation of recycling efficiency could undercut the impact of this regulation and disrupt the LFP recycling industry.[102]

- **In China**, recovery rates are not mandatory, but meeting the targets (98% for nickel, cobalt and manganese, and 85% for lithium) allows companies to qualify for a voluntary certification.[103] (An update drafted in 2024 will increase the lithium recovery rate to 90%.)[104]

Provide financial incentives to recyclers and second-life providers during scale-up.

Incentives to recyclers and repurposing companies provide additional revenue streams for these nascent industry players and can help EVB recycling scale up to meet demand. Incentives can go a long way towards derisking business models, especially at the onset when retired batteries or recycling feedstock volumes are low but high upfront investments are needed to build infrastructure at scale. Incentives provided to recyclers can level the playing field and help recycling remain profitable even in the face of volatile minerals markets, as the industry scales up. As the recycling market matures, these incentives should be phased out.

In the US, for example, the Inflation Reduction Act (IRA) 30D EV tax credit provides up to $3,750 per battery in incentives if the battery materials are sourced domestically or from a free trade agreement country. Since “domestic content” includes recycled content, batteries made with recycled content are eligible for the tax credit; and since automakers have an interest in producing cars that are eligible for the consumer tax credit, battery recycling is indirectly incentivized through the 30D provision.

To further utilize this provision to support recycling, policy-makers could consider directing a portion of this tax credit as a direct financial incentive to recyclers.

CASE STUDY 1

Triple-bottom-line accounting for EVB recycling

Overview

To understand the true return on investment of EVB recycling, RMI used a triple-bottom-line accounting approach: one that assesses financial, environmental and social performance. The assessment assigned a monetary value to the impacts of EVB recycling, using three metrics:

- *Financial metrics*, including profit pools from a typical recycling facility that uses hydrometallurgical processing and performs both shredding and refining.
- *Environmental metrics*, measured through reductions in emissions, land use and water use.
- *Social metrics*, measured using the income from the average number of jobs created per ton of recycling capacity and the resulting economic growth.

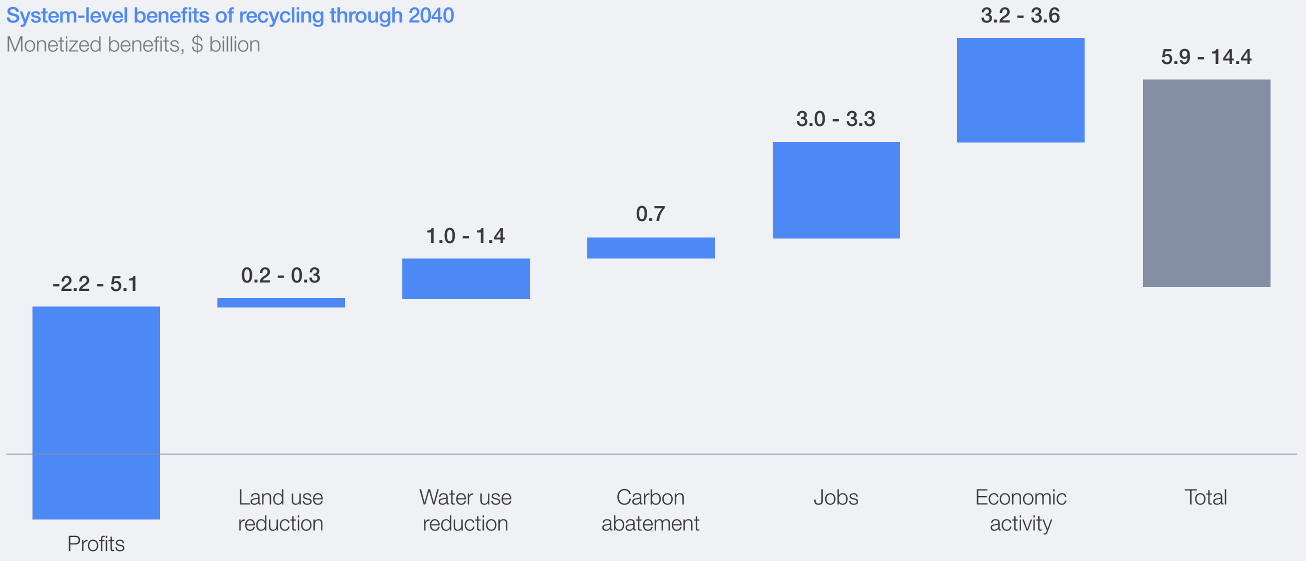
The results

The assessment found that EV battery recycling has a net positive impact on society even when metal prices are low.

The analysis showed that with triple-bottom-line accounting, the social and environmental benefits of recycling can be worth as much as $164 more per ton of lithium carbonate equivalent than direct lithium extraction (DLE) and as much as $700 more per ton than conventional mining. (DLE is a process that extracts lithium from brine and is less emissions-intensive than mining.)

These social and environmental benefits, combined with recycling profit pools, can collectively create a net present value of $5.9 billion to $14.4 billion of global benefits by 2040. This estimate is based solely on US feedstock volumes and would increase substantially using global volumes.

The holistic value of recycling



Source: RMI[105]

Today, mined minerals have much higher profit margins than recycled minerals, but when currently unaccounted-for environmental and social externalities are factored in, the return on investment of EVB recycling can be far greater than that of mining.

Using levers such as policy and innovative finance mechanisms, these externalities can be accounted for and used to strengthen the business case for EVB recycling, even in the face of low mineral prices and an unpredictable market.

Investors and policy-makers have an assortment of tools available to demonstrate the true value of recycling, even in the face of a fluctuating market. A comprehensive analysis and set of recommendations for investors and policy-makers are available from RMI.[106] Used wisely, these tools can reduce uncertainty, unlock further investment and fully realize recycling's potential financial, environmental and social benefits.

3.4 Regional value chains and cross-border movement

Develop regional, circular value chains within a global circular economy, and facilitate responsible cross-border movement of battery materials.

What is this change, and why is it needed?

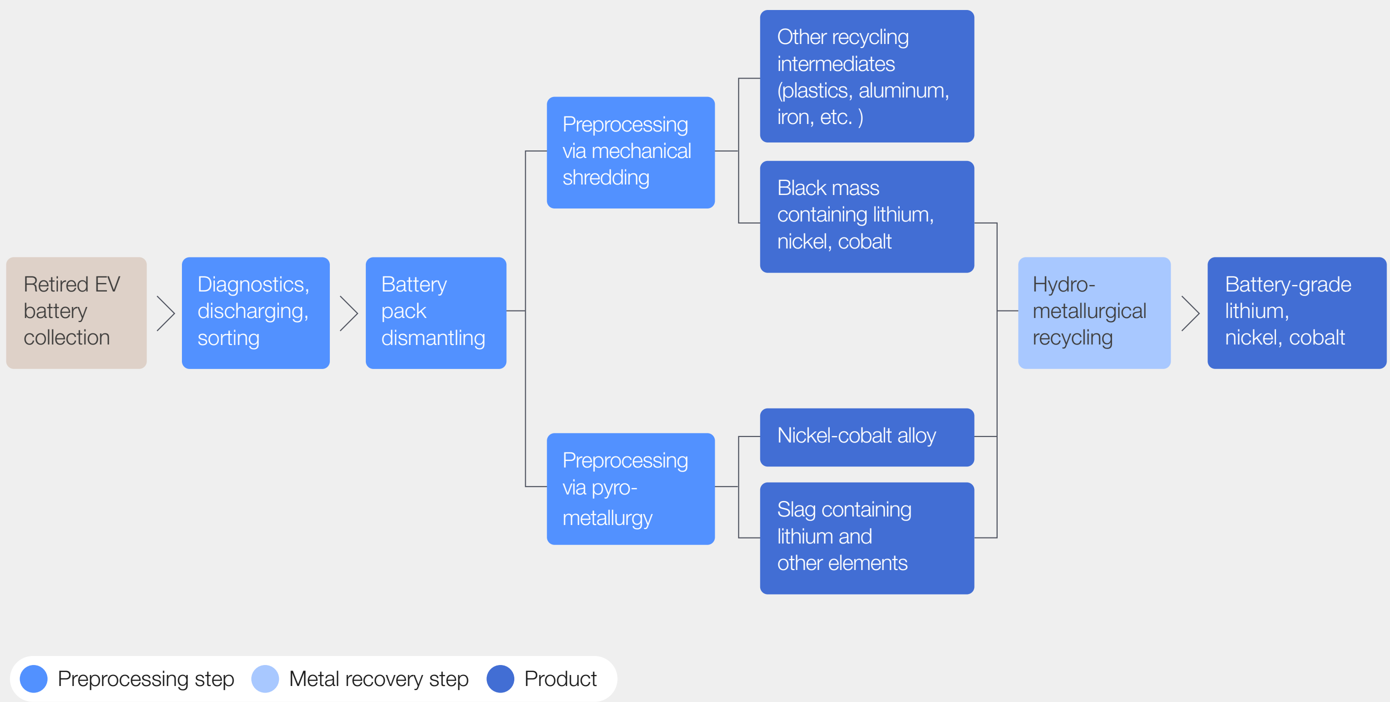
A responsible circular battery supply chain should ensure that everyone shares in the benefits of both first- and second-life EVBs while also sharing the costs of EOL management. Expanding participation in the EVB value chain by creating regional circular loops can allow raw materials – whether sourced from mining or recycled batteries – to be utilized in the regions where they are produced in addition to being exported to benefit other parts of the world. This approach would also enhance the resilience of the EVB supply chain by reducing dependence on a few countries, decreasing the need for trade alliances and restrictions, and reducing emissions, costs and safety challenges associated with transporting battery materials.

However, these regional loops must function within a global circular economy that promotes the sharing of technology, knowledge and resources. The goal is not to restrict or close borders but to create a more inclusive system for the benefit of people, the environment and the supply chain.

To support this system, infrastructure for battery collection, preprocessing and metal recovery will be essential in regions with growing EV adoption. At a minimum, regions expecting EV uptake should develop networks for battery collection, disassembly, diagnostics and preprocessing to ensure easier handling and transport of battery materials to recovery centres. In certain cases, such as small island nations, it may be more cost-effective to ship EOL batteries to recyclers rather than establish local preprocessing facilities.

It is also important to recognize the need for some consolidation of value-chain segments to achieve economies of scale, to make these operations economically viable and minimize their environmental footprint. While regionalization of recycling can be beneficial, the optimal scale is essential to achieve the lowest possible environmental footprint.

FIGURE 9 **The battery recycling process**



Source: RMI

Since individual countries will probably not have complete value chains, batteries and battery materials will still need to cross borders. Countries will want to control the EOL movement of batteries to mitigate social and environmental harms due to improper disposal. These guardrails would need to be balanced to ensure non-hazardous material, like shredded batteries, is not subject to the same level of trade controls as EOL batteries, which are more hazardous.

Additionally, considering EV import/export trends, used batteries (in the form of used EVs) will continue to move across borders. Precautions must be taken to ensure that the batteries being exported have sufficient remaining useful life to avoid an influx of battery waste in the guise of secondary use.

What levers can be used to facilitate this change?

Capitalize on synergies among current and future processes, infrastructure and skillsets when building regional value chains.

All regions expecting EV uptake will need to build out collection networks and preprocessing infrastructure to process EOL EVBs into black mass, the powder created when batteries are shredded before hydrometallurgical recycling. Identifying synergies between a region's existing role in the EVB value chain and its future needs in a circular battery economy, and capitalizing on overlapping processes, infrastructure and skillsets, can help do so efficiently. For example, in regions with a regulated lead-acid battery recycling framework like Brazil, the US and the EU, auto OEMs, dealers, dismantlers and salvage entities are well-positioned to manage the collection and reverse logistics of batteries.[107]

In addition to building collection networks and preprocessing infrastructure, developing battery recycling hubs that recover battery minerals from black mass is critical for expanding a region's role in a circular battery economy and creating regional, circular value chains. At the same time, since metal recovery facilities are capital-intensive, require high utilization to be profitable, and demand specialized expertise, investments must be allocated efficiently. Locating these battery recycling hubs in or near the following markets can support efficiency while diversifying the value chain:

– *Raw metal refining markets*: New facilities can be designed to handle both ore and recycling feedstocks, as the processes, infrastructure and skillsets required are similar.[108] This approach helps future-proof the facilities and workforce development, as both current and future feedstocks can be managed with the same processes. It also addresses challenges related to underutilization of recycling infrastructure during the scaling period by enabling recyclers to supplement recycling feedstocks with mined materials, thereby scaling essential refining capacity while improving the economics. Although current recycling investments are geographically concentrated in China, this approach can be adopted by mineral-rich countries with planned refining capacity projects, such as Chile, Argentina, Australia and Indonesia.[109]

– *Midstream manufacturing markets*: Regions with existing midstream manufacturing capabilities can utilize recovered battery materials and therefore are well-suited to reintegrate recycled materials back into the production process. This is an advantage that exists in Asian markets today.[110] This strategy will be useful in regions with plans to expand into cathode manufacturing, such as the US, Europe,[111] India[112] and Morocco.[113] Close synergies between recycling and cathode manufacturing can also help reduce steps in the process and improve recycling economics, a strategy adopted by some recyclers.[114]

– *Used EV markets*: During 2015-2018, 40% of used light-duty vehicles exported by the three main exporting countries were imported by African countries.[115] If current trends continue, Africa will see significant numbers of used EVs in the years ahead – and therefore, eventually, EOL EVBs. There is an opportunity to locate battery recycling hubs in these markets, as they are likely to have the feedstock volumes needed for these facilities to operate efficiently. Furthermore, co-locating EVB manufacturing in these regions can capitalize on the amount of raw material that will be returned to the value chain, while diversifying the value chain and allowing former raw material extraction markets to transition into a new role in the value chain.

Direct international development investment towards building recycling and manufacturing capacity in emerging economies.

Existing international development partnerships and capacity-building initiatives should prioritize developing battery recycling and manufacturing capacities in developing countries. For example, the EU Global Gateway – a plan for EU member states to invest up to €300 billion between 2021 and 2027 in sustainable, high-quality projects that have lasting community impacts[116] – could dedicate a portion of its climate and energy or transportation portfolio to focus on build-out of battery value-chain infrastructure in the Global South.

Multilateral development banks (MDBs) can also contribute to supporting investment and growth of local value chains in developing countries.[117] The World Economic Forum previously examined the role of MDBs and development finance institutions (DFIs) in advancing battery energy-storage systems in developing countries and found that, by virtue of their climate and development mandate and better credit ratings than companies in developing countries, MDIs and DFIs can create an impact-multiplier effect on two fronts: generating a "pull factor" for substantially increasing the scale of funding; and ensuring judicious capital allocation across the clean energy value chain and geographic areas. The same logic can be applied to the development of battery value-chain infrastructure, indicating the potential role of MDBs and DFIs in financing infrastructure build-out in the Global South.[118]

Form multinational partnerships to support regional value chain growth through technology transfer and knowledge sharing.

In 2023, the EU and the Republic of Zambia signed a memorandum of understanding to establish a partnership on sustainable raw materials value chains. This partnership includes promoting and investing in the recycling, reuse and remanufacturing of critical raw materials, such as through technology transfer between the two countries, and cooperating on skills, capacity-building and competencies necessary to develop a circular economy.[119] While some other countries have also formed strategic partnerships to strengthen critical minerals supply chains, they have largely focused on reducing supply gaps and increasing resilience of the supply chain. The EU-Zambia partnership could serve as a model for how to build circularity into critical minerals partnerships, especially in the Global South.

Deepen public-private dialogue and regulatory coordination to facilitate responsible movement of EVBs and materials across borders.

Even within regions, trade barriers need to be addressed to make possible the regional business models suggested above. An analysis by the National Board of Trade Sweden found two sets of rules that are most applicable to the trade of used LIBs, which could pose challenges:

– Rules governing *trade* in waste – specifically, the Basel Convention on the Control of Trans-boundary Movements of Hazardous Wastes and their Disposal ("Basel Convention").

– Rules governing the *transport* of waste, including the Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) that applies in Europe; the Convention concerning International Carriage by Rail (COTIF) that is applicable in Europe, the Maghreb and the Middle East; and related agreements covering transport by sea and air.[120]

The Basel Convention is an inter-governmental agreement on hazardous and hazardous-equivalent waste trade controls. Lithium-ion batteries may be covered by the Basel Convention, but heterogeneity in country-level interpretation creates trade compliance complexities. Further, the Basel Convention's trade controls are not well understood or implemented consistently at borders. Countries need clearer standards, consistent implementation and transparency through T&T tools like DPPs. In addition, the Basel Convention's Prior Informed Consent process must be digitalized and streamlined.

As the study by the National Board of Trade Sweden notes, the ADR and COTIF "have been implemented differently in the signatory states and in some cases complemented with additional requirements, resulting in businesses having to adjust to several different sets of rules and requirements."[121] While ADR and COTIF provide more certainty than the Basel Convention when it comes to LIBs, adhering to their rules is similarly burdensome and expensive. Much deeper public-private dialogue is required to pinpoint the barriers and commit to policy reform, which in turn will need a strong investment signal from companies; otherwise, policy appetite will be limited. Regulatory cooperation between countries within regions and dialogue with the private sector will be vital for ensuring that policy signals complement the private sector strategies suggested above.

Revise and harmonize import/export regulations of used EVs to prevent overburdening importers with EOL management.

There are several regulatory tools that can be implemented to prevent importing countries from receiving used EVs (and therefore EVBs) with limited remaining useful life, which could overburden their recycling infrastructure while providing limited benefits:

– *Requirements for data-sharing on battery SOH*: Before used EVs are exported, data on the battery's SOH and associated information should be reported. (This again emphasizes the need for globally coordinated T&T platforms and DPPs to provide visibility into critical data about battery health.)

– *Import restrictions and financial incentives*: Importing countries should enact performance-based restrictions or fiscal disincentives to avoid receiving older vehicles, obsolete technologies or inferior products that have limited utility. Performance-based import restrictions are already seen to some extent with internal combustion engine (ICE) vehicles, with approximately 19% of countries adopting advanced emissions standards for used vehicles.[122] Performance-based standards for EV imports based on battery health are emerging, as seen in Kenya in 2024 when the country banned imports of used EVs with a battery SOH of less than 80%.[123] Beyond import restrictions, some of the fiscal instruments in place for used ICE vehicle imports may be adapted for EVs, including age-based taxation or progressive excise tax based on battery health.[124]

– *Demonstration of EOL management capacity*: Countries that import EVs should be able to demonstrate they have the capacity to treat EOL batteries. Capacity building and awareness campaigns should help developing countries to acquire knowledge and expertise in EOL EVBs.

Coordination between importing and exporting countries is needed to prevent inferior products from being imported, particularly by developing countries, while still meeting demand for used EVs. International coordinating bodies such as the UN's Informal Working Group on Safer and Cleaner Used and New Vehicles may prove useful in these efforts,[125] and projects such as the UN Road Safety Fund's Safer and Cleaner Used Vehicles for Africa may serve as a reproducible example of work to harmonize import-export regulations.[126]

CASE STUDY 2

Challenges faced by a small island nation

Overview

As a small, remote island in the Atlantic, Bermuda is taking impressive action on its vehicle electrification journey, as seen in its actions to electrify the government's vehicle fleet[127] and public buses.[128] As part of that effort, it is strategically asking the battery recycling question early. While its fleet is diverse, including public buses and fleet cars, private passenger vehicles and two-wheelers, the relatively small numbers of vehicles make it challenging to design a cost-effective EVB EOL strategy.

Bermuda's internal combustion engine vehicles are already being disposed of improperly by being dumped at a landfill site on newly reclaimed land on inshore waters. There is insufficient demand for aftermarket parts, no local infrastructure for recycling given the small population, and no cost-effective option to get the vehicles to the mainland for proper disposal.

As its vehicle stock transitions to EVs, Bermuda will need to find a way to deal not only with EOL vehicles, but also with EOL batteries, which carry their own risks if not disposed of properly. Fortunately, Bermuda is asking this question early in its EV transition in order to have a robust solution in place by the time meaningful numbers of EVBs reach EOL on the island.

Challenges

Bermuda faces several challenges on its road to responsible EOL EVB management:

- *Remote location*: Bermuda is approximately 650 miles from the nearest landmass, the US. Transportation of goods in and out of the island is already expensive, and products are normally significantly more expensive than in the US. Transporting used batteries off the island will incur significantly higher cost due to fire and safety considerations, which will be considerably greater than the possible revenue from the recoverable battery materials. Furthermore, there are very few shipping lines going through Bermuda and their willingness and competency to handle used battery products is unknown.

- *Small population*: With a population of around 60,000, Bermuda does not have the economies of scale that can help reduce cost and increase efficiency of EOL management.

- *Lack of manufacturing presence*: Bermuda does not have an EVB manufacturing sector to potentially remanufacture used batteries or utilize recycled content from EOL batteries.

Bermuda and its closest neighbour

Solutions needed

Because of the factors outlined above, the development of a full-fledged circular economy in Bermuda is not a feasible solution for managing EOL vehicles. Instead, the only viable options for proper battery disposal are exporting used batteries at the lowest cost possible or shredding batteries for export.

To transport retired batteries off the island, Bermuda will require safe, cost-effective shipping options to a region that has adequate infrastructure for reuse or recycling. To comply with the Basel Convention, the intended purpose of the exported lithium-ion batteries (i.e. repurposing or recycling) needs to be designated before leaving Bermuda and there must be an agreement with a certified agent in the destination country.

Any solution requires optimizing the residual value of the battery or battery materials and the logistics and handling costs. Exporting batteries for second-life use might yield higher returns but would also involve higher transport costs due to safety concerns. It would require battery testing and diagnostics to ascertain quality for reuse or repurposing.

By contrast, shredding batteries on the island helps mitigate the risk of fire during storage, reduces shipping costs and is viable if the batteries are designated to be recycled. This pathway will require a shredding facility on the island, and related workforce training and certification for disassembly and handling of retired EVBs.

The case of Bermuda highlights some of the risks and challenges faced by any market that lacks the infrastructure needed to safely and responsibly manage EOL batteries, especially if it faces additional challenges related to costs, logistics and viability of battery management options. Developing solutions early in the EV transition will be critical to mitigating the environmental and social risk inherent in improper disposal of EVBs.

3.5 Workforce development and transition

Invest in the workforce needed for a circular battery economy by training and reskilling for circular jobs, integrating and preventing development of informal markets, and prioritizing principles of just transition.

What is this change, and why is it needed?

The transition to a circular battery economy provides opportunities to build socio-economic value through workforce development and necessitates intentional planning with a focus on equity to ensure a just transition.

The circular economy's workforce needs will evolve. If a fully circular battery economy is established, the economies of raw material extraction markets will significantly change, with job needs shifting towards other parts of the value chain such as refining, manufacturing and EOL management. Intentional planning will be needed to ensure a just transition for these workers, enabling them to move into other segments of the EVB value chain or other industries. While it will be important to reskill and upskill workers to have flexibility and adaptability to move into roles outside of the EVB industry, the recommendations in this report focus on opportunities within the EVB industry.

In addition to the need to transition workers out of raw material extraction markets in the long term, in the short term, there is significant need to develop the workforce required to support a circular battery economy. For example, collecting, sorting, disassembling, repairing and repurposing are critical roles that will need to be filled. These will require reskilling, education, training and certification. Given the nascent nature of the EVB industry today, stakeholders throughout the value chain must continually evaluate the evolving needs of the industry and update their strategies to develop the workforce needed and support the transition of workers out of roles that are no longer needed.

It is estimated that there will be 10 million jobs across all segments of the global battery value chain by 2030, driven largely by EVs, with more than half of these in developing countries.[129] For some segments of the value chain, such as recycling, the impact of transitioning to a circular economy is well researched and understood; for example, it is estimated that every 1,000 tons of lithium-ion batteries collected at EOL create 15 jobs connected to collection, dismantling and recycling of those batteries.[130]

For other segments of the value chain, the impact of circularity on workforce needs is more challenging to quantify. For example, a circular economy can help reduce supply gaps and enable further production of EVBs, creating battery manufacturing jobs; but a truly circular economy will also extend the life of a battery, which will reduce manufacturing needs. To understand the economic development opportunities that battery circularity presents within the refining market, more research is needed to disaggregate the refining and manufacturing market skills and workforce.

If managed responsibly, workforce transition in raw material extraction markets can present opportunities for socio-economic growth, including the chance to develop new industries and transition workers to higher-skilled, higher-paying jobs. Raw material extraction markets, and their workforce, must be enabled to benefit from a circular battery economy in a way that has not occurred in the current battery value chain – namely, capturing the returns of their labour and the value of their natural resources within their economies. This pattern can change with an equitable approach to developing a circular economy – one that includes more countries in more segments of the value chain, as discussed in Section 3.4, and that consistently evaluates who benefits from, and who bears the cost of, change.

In addition to the socio-economic opportunities associated with workforce development and transition, there is also an opportunity to reduce and integrate informal sectors of the EVB value chain, which are defined by the International Monetary Fund as economic activities that have market value but are not formally registered[131] and do not generate tax revenue.[132] For example, the Indian government estimates that 20% of LIBs in the country are recycled by informal recyclers and highlights the need to prevent the growth of informal battery recycling.[133] Transitioning to a circular economy creates opportunities for formalizing these markets, which enables upward economic growth for workers, offering a chance for them to earn higher wages[134] and experience better working conditions.[135]

What levers can be used to facilitate this change?

Advance public-private partnerships for reskilling and job placement.

It will be essential for governments and industry stakeholders to work together to make reskilling programmes accessible and to develop job placement programmes that help workers transition smoothly into other segments of the value chain. This will be critical for raw material extraction markets, where workers will need to shift out of the mining sector without losing their source of income. It will also be important in markets where significant workforce development is needed to fill roles in a circular battery economy.

Examples of public-private partnership for reskilling for the circular economy can be found in other sectors, such as the electronics scrap and remanufacturing industries. For example, the REMADE Institute was awarded $380,000 by the US Department of Energy to create bilingual online training programmes for the e-scrap and remanufacturing industries. The training is targeted towards jobs that do not require four-year degrees and allows entry-level employees to progress to mid-level roles while reducing onboarding costs for employers.[136] Examples of public-private partnership for reskilling and job placement can also be drawn from the transition from fossil-fuel energy to clean energy that is already underway.

Other lessons to be learned from the transition of fossil fuel workers to the clean energy sector include what needs exist, what has worked well, and what challenges have emerged. According to a statistical analysis conducted using occupational-skill profiles from the US Bureau of Labor Statistics, many fossil fuel industry workers already have many of the skills required to take on jobs in the clean energy sector,[137] which means job placement programmes that help recruit workers and match them to appropriate roles are as important as reskilling programmes.

A potential challenge to job placement is that workers in need of transition will often not be in the geography where new jobs are created even if they possess the skills required for the new jobs, as has been seen with the clean energy transition.[138] Proactive measures must be taken to ensure new jobs in the circular battery economy are in the same geography as where workforce transition is required from raw material extraction and refining roles. The creation of regional value chains, as discussed in Section 3.4, can help prevent this challenge by reducing the concentration of the EVB value chain and creating a more dispersed circular battery economy.

In addition to ensuring workers are matched to suitable jobs, it is important to plan for continued, long-term employment. It has been found that clean energy jobs often last only through the construction phase.[139] Similarly, due to high labour intensity and low efficiency of raw mineral extraction, recycling usually requires fewer workers.[140] According to an analysis by RMI, recycling is more labour-efficient on a combined basis when considering that the same unit of labour produces lithium, nickel and cobalt simultaneously, with a labour-to-output ratio of 0.02-0.03 workers per tonne. Mining, on the other hand, is less labour-efficient overall, with a labour-to-output ratio of 0.14-0.32 workers per tonne, since different mining processes must be run for each metal. To prevent employment loss due to a new circular EVB industry and ensure sustainable, stable employment, public-private partnerships for workforce development must take a long-term view and plan for multiple phases of the circular battery economy transition.

Develop curricula and training programmes with standardized certification, through a collaboration of industry and educational institutions.

Developing curricula and training programmes requires a collaborative effort between industry players and educational institutions. This includes education at every level, from elementary to graduate school: early introduction to EVBs and circular economy can plant interest to pursue careers in the field later in life, whereas programmes for older students can provide direct training to existing workers and new workers entering the workforce.[141] While universities can help fill the need for certain roles like engineers, institutes for technical and vocational education and training as well as community colleges can develop specialized courses and programmes for some jobs, especially those connected to EOL management. Battery manufacturers, automakers, recyclers, repurposing companies and other industry stakeholders throughout the value chain should collaborate on the development of these programmes to ensure that the training is up to date, is relevant to industry needs, and provides appropriate safety training.

For example, with the support of Honda, Mercedes-Benz, Nissan, UL Research Institutes and other private-sector players, the University of California San Diego's Materials Research Science and Engineering Center and Sustainable Power and Energy Center introduced a "battery boot camp" that focuses on design principles and operation mechanisms of LIBs.[142] In another instance, in response to LG Energy Solution announcing a $1.7 billion expansion in operations that will require 1,200 workers with a background in energy storage manufacturing, Grand Rapids Community College introduced a battery bootcamp focused on providing certificates in battery manufacturing and power storage.[143]

Government can also play a role in curriculum development by identifying common skills and training required across multiple employers and sectors within the circular battery economy.[144] For example, the US Department of Energy has established a panel of industry experts that will help build consensus on core training needs and implement standardized training guidance that can be used by companies and local training programmes.[145] Government support might also be needed to regulate standardized certification and education programmes to ensure all workers have the level of skill needed to safely handle batteries.

Educational programmes and certifications need to be standardized to ensure all workers have the skills they need to ensure quality, effectiveness, worker safety and consumer safety. Certification development and standardization might also require continuous professional development for some jobs, to ensure workers have the skills they need as battery chemistry, manufacturing processes and EOL management processes evolve.[146]

Conclusion

A resilient, responsible battery value chain that enables the EV transition, respects human rights and protects the environment is within reach.

The world is at an inflection point in the transition to electrified transport, and the decisions made today will affect the way people and goods move for decades to come. Now is the time to diverge from business as usual and accelerate efforts to build a battery value chain that minimizes environmental harm, capitalizes on the opportunities at hand, and centres around equity.

Now is the time to build a circular battery economy.

It is often said that necessity is the mother of invention. Pressing concerns surrounding today's battery value chain, particularly its social and environmental impacts, are spurring an increasing number of stakeholders to explore how they can address these challenges by advancing a circular battery economy. Through collaboration with an expert advisory panel and extensive research, this report proposes actionable recommendations that can help guide them.

By developing standardized, interoperable platforms for tracking and tracing battery materials, setting design and performance standards, and using targeted policy interventions, stakeholders can manage batteries more responsibly throughout their life cycle. Additionally, fostering regional circular value chains and facilitating responsible cross-border movement of materials will enhance value-chain resilience and reduce environmental impacts. Importantly, investments in workforce development will ensure a just transition for workers impacted by this shift.

Implementing these recommendations will unlock the full potential of a circular battery economy, benefiting businesses, the environment and communities globally.

As this report shows, the challenges in implementing a circular battery economy are not small, but they are surmountable.

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Endnotes

1. Throughout this report, "EVBs" refers to the batteries used to power EVs – currently lithium-ion batteries, and potentially sodium-ion or solid-state batteries in the future. While EVs also contain lead-acid batteries (LABs) used to start the vehicle, this report does not examine or make recommendations related to LABs.
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