Recycling of Critical Minerals

Strategies to scale up recycling and urban mining

A World Energy Outlook Special Report

International Energy Agency

INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 31 member countries, 13 association countries and beyond.

IEA member countries:

Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Japan
Korea
Lithuania
Luxembourg
Mexico
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Republic of Türkiye
United Kingdom
United States

The European Commission also participates in the work of the IEA

IEA association countries:

Argentina
Brazil
China
Egypt
India
Indonesia
Kenya
Morocco
Senegal
Singapore
South Africa
Thailand
Ukraine

Source: IEA.
International Energy Agency
Website: www.iea.org

Abstract

As the shift to a clean energy system accelerates, substantial investments in new mines and refining capacity, especially in geographically diverse regions, will be required to produce essential minerals such as copper, lithium, nickel, cobalt and rare earths. Recycling is indispensable to the security and sustainability of critical minerals supply for clean energy transitions. While recycling does not eliminate the need for mining investment, it creates a valuable secondary supply source that reduces reliance on new mines and enhances supply security for countries importing minerals. Moreover, scaling up recycling mitigates the environmental and social impacts related to mining and refining while preventing waste from end-use technologies ending up in landfills.

The importance of unlocking the potential of recycling has long been a theme of International Energy Agency (IEA) analysis, and this was one of the key takeaways from the first-ever IEA Critical Minerals and Clean Energy Summit in September 2023. This report, which responds to the request by Ministry of Foreign Affairs of Italy as part of its G7 agenda, aims to evaluate the current status of recycling of minerals critical to the energy transition, analyses the prospects for secondary supply under different scenarios, and outlines targeted policy recommendations to accelerate the uptake of recycling that can pave the way for more sustainable and secure future mineral supply chains.

Acknowledgements

This report was prepared by the Office of the Chief Energy Economist of the Directorate of Sustainability, Technology and Outlooks, in co-operation with other directorates of the International Energy Agency (IEA). **Tae-Yoon Kim**, Head of the Energy Minerals Analysis Unit, designed and directed the report together with **Tim Gould**, Chief Energy Economist. **Amrita Dasgupta** led the analysis for and the production of the report and was one of the principal authors.

The principal authors from across the agency were: **Eric Buisson** (rare earths and solar photovoltaic recycling), **Shobhan Dhir** (battery and copper recycling, economics), **Alexandra Hegarty** (state of play, mine waste, sustainability), **Gyubin Hwang** (economics, technology), **Yun Young Kim** (e-waste recycling, cross-border waste trade), **K.C. Michaels** (policies and regulations, sustainability), **Tomás de Oliveira Bredariol** (environmental issues), **Ryszard Pospiech** (data), and **Joyce Raboca** (policies and regulations, cross-border waste trade, sustainability).

Eleni Tsoukala provided essential support. Erin Crum edited the manuscript.

The report also benefited from valuable contributions and inputs provided by IEA colleagues, in particular, Laura Cozzi, Christophe McGlade, Oskaras Alsauskas, Simon Bennett, Jiayi Chen, Sadhika Gulati, Alexandre Gouy, Mathilde Huismans, Teo Lombardo, Kentaro Miwa, Tristyn Page, Apostolos Petropoulos, Jemima Storey and Biqing Yang.

Thanks also to Jethro Mullen, Curtis Brainard, Astrid Dumond, Zachary Egan, Lucile Wall, Isabelle Nonain-Semelin, Merve Erdil, Liv Gaunt, Grace Gordon and Rob Stone of the Communications and Digital Office.

This analysis has been supported by the Clean Energy Transitions Programme, the IEA's flagship initiative to transform the world's energy system to achieve a secure and sustainable future for all, particularly through the financial assistance of the Ministry of Foreign Affairs of Italy. Thanks also go to the IEA Working Party on Critical Minerals and the IEA Critical Minerals Expert Advisory Group who provided valuable input to the report.

Many experts from outside the IEA provided essential input and/or reviewed preliminary drafts of the report. Their comments and suggestions were of great value. They include: Stéphane Bassene (TotalEnergies); Peter Borkey (Organisation for Economic Co-operation and Development [OECD]); Stéphane Bourg (BRGM [French Geological Survey]); Andrew Brown (OECD); Peter

Buchholz (BGR [German Federal Institute for Geosciences and Natural Resources]); Aman Chitkara (independent expert); Vincenzo Conforti (Glencore); Grace Cook (Ramboll); Clint Cox (The Anchor House); Matteo Craglia (International Transport Forum); Alexandre Damiens (Orano); Martin Dietrich Brauch (Columbia Center on Sustainable Investment [CCSI]); Sylvain Eckert (Infravia); Rod Eggert (Colorado School of Mines); Steven Fecht (Ramboll); Colin Hamilton (BMO Capital Markets); Peter Handley (independent expert); Sara Hastings-Simon (University of Calgary); Daniel Hill (Natural Resources Canada); Kijune Kim (Korea Zinc); Paul Kolisnyk (Teck Metals); Luc Leboeuf (Natural Resources Canada); Courtney Lynn (EroCopper); Julien Masson (Eramet); Tom Moerenhout (Columbia Center on Global Energy Policy); Shinsuke Murakami (The University of Tokyo); Jane Nakano (Center for Strategic and International Studies [CSIS]); Junhyeok Park (Korea Institute of Geoscience and Mineral Resources [KIGAM]); Brian Parkey (Freeport-McMoRan); Alicia Polo y La Borda (The Copper Mark); Mark Richards (Rio Tinto); Benoit Richebé (Orano); Katarina Svatikova (OECD); Perrine Toledano (CCSI); Lyle Trytten (Trytten Consulting); Constanze Veeh (European Commission) and Ke Wang (World Resources Institute).

Table of contents

Executive summary

Recycling can bring multiple benefits in ensuring reliable and sustainable critical mineral supplies

Recycling is indispensable to the security and sustainability of critical minerals supply for clean energy transitions. As the shift to a clean energy system accelerates, substantial investments in new mines and refining capacity, especially in geographically diverse regions, will be required to produce essential minerals such as copper, lithium, nickel, cobalt and rare earths. While recycling does not eliminate the need for mining investment (or the associated revenues for resource-rich countries), it creates a valuable secondary supply source that reduces reliance on new mines and enhances supply security for countries importing minerals. This sets critical minerals apart from fossil fuels that cannot be re-used (and whose use via combustion results in long-lived emissions in the atmosphere). Expanding recycling infrastructure can also help build reserves to buffer against future supply disruptions. Moreover, scaling up recycling mitigates the environmental and social impacts related to mining and refining while preventing waste from end-use technologies ending up in landfills.

This first-of-its-kind report on critical minerals recycling presents key policy recommendations to accelerate the uptake of recycling practices. Building on its landmark report in 2021, the International Energy Agency (IEA) has been deepening its analysis on the latest market trends and key policy issues around critical mineral supply chains through extensive data collection, modelling and close dialogue with industry stakeholders. At the IEA Critical Minerals and Clean Energy Summit in September 2023, participants highlighted the critical role of recycling in enhancing mineral security. Responding to this growing emphasis, the report assesses the current state of recycling, explores the potential for secondary supply, and presents policy recommendations to scale up recycling.

Despite growing policy ambitions, the use of recycled materials has so far failed to keep pace with rising material consumption. In the case of copper, which plays a central role in all electrical applications, the share of secondary supply (including direct use scrap) in total demand fell from 37% in 2015 to 33% in 2023. Similarly, the share for recycled nickel decreased from 33% to 26% over the same period. The main exception is aluminium, which benefits from well-established waste management programmes and supportive regulations, where the recycled share increased modestly from 32% to 35%.

Recycling of battery metals is an emerging commercial opportunity and is growing fast. Production of recycled battery metals, such as nickel, cobalt and lithium, has recently seen rapid growth, albeit from a low base. When assessing recovered metal volumes relative to available feedstock for recycling, rates surged to over 40% for nickel and cobalt and to 20% for lithium in 2023. The market value of recycled battery metals also experienced nearly 11-fold growth between 2015 and 2023, with more than half of this growth occurring in the last three years. Although electric vehicle (EV) batteries are not yet available for recycling at scale, these developments indicate vast potential for expanding recycling, if the right policy incentives are in place.

Policy momentum is gaining strength, with a surge in new policies and regulations. According to the IEA's Critical Minerals Policy Tracker, more than 30 new policy measures related to critical mineral recycling have been introduced since 2022. These policies generally fall into four categories: strategic plans, extended producer responsibility (EPR), financial incentives and cross-border trade regulations. Some also include regulatory mandates such as industry-specific targets for material recovery, collection rates and minimum recycled content. However, most strategies are not yet comprehensive. Among the 22 countries and regions surveyed, only 3 had a broad framework that includes clear targets, implementation mechanisms, monitoring systems and economic incentives.

Recycling reduces the need for new mines, enhancing security and sustainability

A successful scale-up of recycling can lower the need for new mining activity by 25-40% by 2050 in a scenario that meets national climate pledges. While accelerated clean energy deployment calls for a substantial expansion of new mines and refineries to meet material demand, it also creates an opportunity for secondary supply to play an increasingly valuable role. In the Announced Pledges Scenario (APS), which reflects national climate pledges, recycling reduces new mine development needs by 40% for copper and cobalt, and close to 25% for lithium and nickel by 2050. The market value of recycled energy transition minerals grows fivefold, reaching USD 200 billion by 2050. As a result, requirements for primary materials start to decline around mid-century. Nonetheless, investments in new mines remain essential as supply levels required by mid-century are still higher than today's production and existing mines face natural declines in output.

Enhancing critical minerals recycling offers substantial financial and sustainability benefits. In the APS, some USD 600 billion of mining investments is required through 2040, while achieving net-zero emissions by 2050 necessitates around USD 800 billion. Without an increase in recycling, these amounts would be 30% higher, increasing the burden of mobilising the necessary financing. Recycling can also mitigate the environmental and social impacts associated with mineral production. On average, recycled energy transition minerals such as nickel, cobalt and lithium incur 80% less greenhouse gas emissions than primary materials produced from mining. This translates into a 35% cumulative reduction in emissions from the production of lithium, nickel and cobalt required to meet their needs in climate-driven scenarios over the period to 2040.

The energy security benefits of recycling are greatest in regions with limited mineral resources and high clean energy technology deployment. In Europe, under the APS context, secondary supply from batteries meets about 30% of the region's lithium and nickel demand by 2050, notably higher than the global average below 25%. This could substantially reduce either import bills or investment needs for domestic supply.

There is a major gap in today's recycling rates between advanced and developing economies. In the case of electronic waste (e-waste), collection rates are notably higher in advanced economies than in emerging and developing economies. Collection rates in developing economies in Asia and Latin America are below 5%, and just 1% in Africa, with little improvement since 2010, whereas rates stand at 30% in Japan and Korea and 40-50% in Europe and North America. Support to strengthen collection and recycling infrastructure in developing economies, along with technology and skill transfer, can help prevent waste from ending up in landfills while fostering economic development in these regions.

Battery recycling is key to boosting overall mineral recycling rates

Manufacturing scrap currently dominates the feedstock for battery recycling, but this balance shifts rapidly towards end-of-life EV batteries. Scrap from manufacturing processes still accounts for two-thirds of available recycling feedstock in 2030. From 2035 onwards, however, end-of-life EV and storage batteries take over as the largest source and represent over 90% of available feedstock by 2050. Lithium-ion batteries are one of the key technologies pushing up demand for critical minerals, but they also promise to be a major source for metal recovery.

Developments in battery chemistries have major implications for recycling. In the past few years, lithium iron phosphate (LFP) cathodes have gained significant market share from nickel-based chemistries, making up around 40% of EV batteries deployed in 2023, with their share expected to remain high. This shift impacts recycling economics due to LFP's lower material value. This underscores the need for tailored business models, such as toll-based recycling, supported by regulation and strict mandates to prevent LFP batteries from ending up in landfills. Lessons from the 99% recycling rate of lead-acid batteries in the United States, achieved despite their low residual value, illustrate that well-designed policy measures can overcome economic hurdles in recycling.

Battery recycling capacity is expanding rapidly, led by the People's Republic of China (hereafter, "China"). In 2023, global capacity for pretreatment and material recovery grew by 50% year-on-year, with China accounting for 80% of capacity for both. Analysis of the project pipeline indicates that China is on track to retain 80% of global pretreatment capacity and 75% of material recovery capacity in 2030. China recently announced the formation of China Resources Recycling Group Ltd., a state-owned enterprise dedicated to recycling and reusing end-of-life batteries, scrap steel and e-waste.

Battery recycling capacity is outpacing available feedstock, although the picture varies by region. If all announced projects come online as scheduled, global recycling capacity in 2030 could be over six times the available feedstock, even with the rapid levels of battery deployment achieved in the APS. However, the picture changes rapidly after 2030 as EVs reach end-of-life and feedstock availability increases sharply, surpassing announced material recovery capacity by 20% in 2040. There are major regional differences. China continues to see excess capacity relative to domestic feedstock. In Europe and the United States, excess capacity dissipates after 2030, and announced recycling capacity covers only 30% of feedstock by 2040. This is higher than in India, where the coverage in 2040 is just 10%.

Battery recycling could meet 20-30% of lithium, nickel and cobalt demand by 2050, but this depends on improving collection rates. The recovered metal volumes from available feedstock are influenced by many factors, with collection rates being the most critical. Under the assumption of continued increases in collection rates, in the APS, recycled volumes from batteries could reach 20-30% of demand for lithium, nickel and cobalt by 2050. However, the range varies depending on plausible variations in collection rates, from 25-35% with higher collection rates and 15-20% with lower rates. The reuse of EV batteries in storage applications plays a modest role, meeting around 10% of global storage demand by 2050.

The export of used EVs can significantly affect the global volume of recycling feedstock. A significant number of used conventional cars are exported from advanced to developing economies, but it is uncertain if this trend will continue with EVs, with major implications for battery recycling. In the APS, if EV exports mirror patterns of conventional cars, available battery feedstock for recycling in advanced economies and China could drop by 25% (1 terawatt-hour [TWh]) by 2050, while developing economies see a 50% increase (0.5 TWh); this is less than the decrease in advanced economies and China due to delayed battery retirement. Additional recycling capacity will be needed in importing regions, particularly for pretreatment facilities, to avoid waste and loss of potential feedstock for recycling. Clarity on EV export rules and conditions is important to reduce uncertainties and encourage recycling investments in both exporting and importing regions.

Relatively slow development of midstream battery supply projects is a major uncertainty for recyclers. While battery cell production projects are expanding in regions such as Europe and the United States, plans for the midstream supply chain such as precursor cathode active material (pCAM) and cathode active material (CAM) remain limited. By 2030, nearly 90% of these capacities are expected to remain concentrated in China, reducing the security benefits of recycling as recyclers need to compete globally to supply CAM producers, and cell manufacturers continue to import CAM. Strategic support for midstream development and vertically integrated projects could create more reliable domestic off-takers for recyclers. Strategic partnerships with countries with expanding CAM production, such as Korea, could provide a supplementary solution and serve as a valuable off-taker for European and US recyclers.

Greater clarity on policies and regulations is essential to support the uptake of battery recycling. The absence of clear, long-term regulations including export rules for used batteries and EVs as well as the implementation and enforcement of EPR creates barriers to investment. Providing long-term visibility for policies and regulations is crucial for instilling confidence in investors and recycling companies.

Traditional metal recycling matters, especially for copper

Scaling up the recycling of end-of-life scrap from traditional industries is essential to alleviate pressure on critical mineral supplies, particularly for copper. Copper is an essential material used in a wide range of electrical applications, but a supply deficit is beginning to appear on the horizon. By 2035 announced projects are sufficient only to meet 70% of copper requirements in the APS. Increasing copper recycling is one of the most critical actions needed to ensure that the shift towards a more electrified and renewables-rich energy system is not held up by a bottleneck in supplies.

Opportunities to boost secondary copper supply are rising as scrap volumes surge from around 2030. Copper scrap availability is expected to grow alongside consumption until 2030, then outpace demand growth. In the APS, scrap volumes (before collection and processing losses) increase from 16 million tonnes (Mt) today to 19 Mt by 2030 and 28 Mt by 2050, equivalent to 70% of projected demand. Construction remains the largest source of end-of-life copper scrap, but scrap from EVs and storage is set to grow the fastest, expanding more than 35-fold between 2030 and 2050. Enhancing collection rates and investing in secondary processing capacity are key to fully leverage this potential and ease future supply pressures.

Strong policy actions can further raise the share of secondary copper supply. The historical share of secondary supply in total copper demand has stagnated since 2015, but the anticipated surge in end-of-life scrap post-2030 is set to reverse this trend. A combination of policies – raising collection rates for legacy applications such as construction and cables, mandating recycling, improving sorting systems, and investing in new secondary smelters – can further elevate secondary supply's contribution. Facilitating strategic partnerships between copper scrap supply chain actors such as scrap collectors, pre-processors and secondary smelters can also help optimise capacity utilisation and increase scrap trade efficiency. In the APS, the share of secondary copper supply in total demand (excluding direct use scrap) rises from 17% today to nearly 40% by 2050, underscoring the critical role of copper recycling in easing future supply pressures.

There is substantial untapped potential for metal recovery from e-waste, mine waste and magnets

Metal recovery from e-waste needs much more attention from industry and policymakers. Despite rising awareness, only a quarter of e-waste generated in 2022 was documented as properly collected and recycled. Since 2010, global e-waste generation has risen five times faster than collection and recycling efforts, resulting in a decreasing share of recycled e-waste. In 2022 alone, metals contained in e-waste valued at around USD 90 billion, with only USD 28 billion recovered and turned into valuable materials. Of the 193 countries assessed in our report, only 80 had e-waste regulations as of June 2023, suggesting ample scope for strengthening policy actions. Stricter regulations and penalties for illegal dumping, enhanced traceability, and improvement in pretreatment processes can significantly boost critical mineral recovery from e-waste.

Rare earth recycling from permanent magnets is limited today but the rise of EVs and wind power brings significant potential to step up efforts. Currently, most rare earth recycling feedstock originates from manufacturing losses, with end-of-life permanent magnet recycling constrained by low collection rates (below 5%) and challenging economics. However, the growing use of permanent magnets in EV motors and wind turbines could drive up collection rates. High collection rates alone, however, may not be enough, as recyclers often prioritise more accessible or higher-value materials such as copper or battery metals. Improving recycling rates in this area is likely to require additional measures such as targeted economic incentives, rare earth recycling mandates and consumer commitments to using recycled content in products. In the APS, secondary rare earth supply triples by 2050, contributing to more secure and diversified rare earth supplies.

Recovering minerals from mine waste offers an opportunity to turn environmental liabilities into valuable resources. Mining generates around 100 billion tonnes of waste every year, in addition to the sizeable amount already existing in active, inactive and closed tailings. The accumulated waste volume is set to increase by almost 90% over 2020 levels by 2030. Reprocessing mine waste, or tailings, can reduce waste generation and mitigate environmental impacts such as water contamination, safety risks and soil pollution. For closed or abandoned sites, it also presents an opportunity for environmental remediation. Previously, the minerals left in mine waste were considered economically unviable, but declining ore quality and future supply concerns are making reprocessing more appealing. For instance, in Chile, the copper content in mine waste with higher grades than primary sources is poised to rise from 1.6 Mt in 2005 to 5.6 Mt by 2050. Realising this potential will require comprehensive waste resource mapping, supporting research and development for new recovery technologies, providing economic incentives, and addressing liability barriers related to mine waste at closed sites.

Several cross-cutting issues remains to be addressed

Recycling businesses can be profitable, but innovative pricing schemes and business models are key to improving economic viability. Profits for recycling energy transition minerals may be lower than for bulk materials, but increased policy support and feedstock availability can strengthen the business case. Market-based battery metal recycling is particularly sensitive to material price fluctuations, requiring recyclers to have robust balance sheets and working capital to weather volatility and commodity cycles. New models such as toll-based recycling and revenue-sharing could offer recyclers better economic stability and encourage long-term investments, especially for LFP batteries.

New technologies hold promises for improving recycling efficiency. Current technologies often struggle with the complexity and diversity of products containing critical minerals, resulting in lower recovery rates and material loss. Emerging technologies such as advanced sorting, novel chemical and physical processes, and new quality control methods can help overcome these challenges. Positive trends are evident: lithium-ion battery recycling patents grew at an average annual rate of 56% from 2017 to 2022, and venture capital investment in battery and waste recycling surged between 2022 and 2023. Policy incentives and collaborations between research institutions and industry will be essential to bring these promising technologies to market.

Countries are taking action to regulate scrap trade to reduce unmanaged waste leakage and incentivise domestic recycling capacity. In addition to national regulations, international waste agreements such as the Basel Convention and the Organisation for Economic Co-operation and Development Decision on the Control of Transboundary Movements of Wastes continue to strengthen the control of transboundary waste trade. These measures will help ensure that exported scrap is properly recycled and sustainably treated in importing regions. However, effective and nimble implementation is essential to prevent these regulations from hindering the growth of the global recycling industry. For battery metals, a harmonised international classification of lithium-ion battery waste and black mass would provide much-needed clarity, reducing uncertainties around regulations concerning these emerging waste streams.

Recycling is not free from environmental and social impacts. Poorly managed battery recycling may result in pollution from waste residues, water contaminants and harmful emissions. In many countries, the waste collection stage often involves child labour or unsafe practices. While various voluntary standards are emerging, there are still significant gaps in social and governance aspects, requiring efforts to strengthen existing recycling standards. Traceability mechanisms can allow stakeholders to verify that materials are sourced and recycled according to best practices. Such mechanisms can also allow consumers to favour recyclers with higher environmental and social performance.

Policy makers need to look beyond recycling to integrate broader circular economy principles. Opportunities beyond recycling include circular product design, repair, refurbishing, reuse and repurposing. Circular design principles reflect the importance of improving products' lifetime and facilitating easier recycling at the end of life. Increasing repairability via modular designs that make disassembly easier is a strategy that can be used in EVs and electronics. Repurposing and reusing also offer significant waste reduction opportunities. By adopting a holistic approach that considers the entire product life cycle, policy makers, industry stakeholders, and consumers can create more sustainable pathways for the use of critical minerals.

Key actions for policy makers

This report distils a set of key actions for policy makers to scale up critical minerals recycling.

1. **Develop detailed long-term policy roadmaps:** set clear targets and intermediate milestones to provide clarity on policy directions and greater certainty for investors.

2. **Harmonise waste management and recycling policies to develop efficient secondary markets:** facilitate international co-operation to reduce trade barriers and minimise unmanaged leakages.

3. **Strengthen domestic infrastructure with incentives and mandates:** encourage investment in recycling capacity at national and regional levels with economic incentives.

4. **Encourage traceability, standards and certifications to boost the consumption of recycled materials:** the uptake of recycling industries is enabled by transparency and international best practices.

5. **Provide targeted financial support for technology innovation, R&D and workforce training:** ensure continued support for more efficient processes, scaling proven technologies and training a workforce ready for the new energy economy.

6. **Strengthen recycling systems in emerging and developing economies:** introduce new technical and financial instruments to support investment in regions most vulnerable to the effects of improper waste management.

7. **Tackle data and information gaps:** access to reliable and granular data is pivotal for efficient policy and investment choices.

8. **Embrace a holistic approach beyond recycling:** product design, reuse, repair and refurbishment can play a major role in ensuring sustainable mineral value chains.

9. **Tackle environmental, social and governance (ESG) issues for recyclers:** ESG impacts must be identified, minimised and mitigated to contribute to sustainable and responsible supply chains.

Introduction

Why recycling?

Today, the global energy system is in the midst of a major transition to clean energy. An energy system powered by clean energy technologies differs profoundly from one fuelled by traditional fossil fuel resources. From renewables to electric vehicles (EVs), clean energy technologies require more minerals than their fossil fuel-based counterparts. Lithium, nickel, cobalt, manganese and graphite are crucial to battery technologies. Rare earth elements are essential for permanent magnets that are vital for wind turbines and EV motors. Electricity networks need a huge amount of copper and aluminium, with copper being a cornerstone for all electricity-related technologies. The shift to a clean energy system is set to drive a huge increase in demand for critical minerals, potentially posing supply-side strains and raising security concerns that might differ from the ones we face today for fossil fuels. In rapid energy transitions, minerals are increasingly recognised as essential to the good functioning of an evolving energy system, moving into a realm where fossil fuels have traditionally occupied a central role.

However, there are important differences between fossil fuels and minerals and metals. Fossil fuels burn up when they are used, requiring continuous inputs to run assets. However, the mineral resources required to build or operate a clean energy system can be recovered and recycled at the end of the infrastructure lifetime. The potential and scientific feasibility for copper, lithium, nickel, cobalt, rare earth elements and other critical minerals to be reintroduced into the energy supply chain through recycling implies a paradigm shift towards circularity for modern clean energy systems. The importance of unlocking the potential of recycling has long been a theme of International Energy Agency analysis, and this was one of the key takeaways from the first-ever IEA Critical Minerals and Clean Energy Summit in September 2023.

For base metals such as steel and aluminium, recycling practices are well-established, but this is not yet the case for many energy transition minerals such as lithium, cobalt, nickel, rare earth elements and silicon. In the case of battery minerals, today's feedstock for recycling is dominated by electronic waste and scrap from manufacturing processes, but this is set to change after the end of the decade as the first generation of EVs reach the end of their lives. The multiple benefits of scaling up efforts for recycling include:

- **Creating a secondary source of supply that reduces the burden on primary supply from new mines**. Ramping up recycling will neither offset completely the growth in demand for energy transition minerals nor eliminate the need for continued investments in mining and refining (and the significant associated revenues that accrue to resource-rich countries). However, it will relieve some of the burden on the extraction of virgin minerals. Our analysis shows that without scaling up secondary supplies (from recycling and reuse), investments required in mining to reach net zero emissions by 2050 globally would be USD 240 billion or around 30% higher over the period to 2040.
- **Providing enhanced security for countries and regions with high clean energy technology deployment but limited mineral resource endowment**. Lessons learned from several decades of energy security demonstrate the need for importing countries to diversify their supply sources and enhance their resilience to disruptions triggered by geopolitical events. Recycling can provide a secure and diversified source of supply. Domestic infrastructure and investments in like-minded countries for recycling of critical minerals can also assist in building reserves to protect against the worst impacts of future supply disruptions.
- **Lowering the environmental footprint of clean energy technologies.** Recycling has emerged as a potential pathway to alleviate some of the environmental impacts associated with the primary production of energy transition minerals. On average, recycled minerals emit 80% less greenhouse gas (GHG) emissions than their primary counterparts. This is, in part, because recycling processes often use less energy than the mining and processing of virgin minerals. The production of recycled materials also consumes less water than primary minerals. A strong example of the environmental benefits comes from the aluminium industry, where recycling of post-consumer scrap has been shown to reduce emissions by 90% compared with primary aluminium. Furthermore, recent studies show that total GHG emissions for manufacturing a nickel-rich lithium-ion battery cell can be around 28% lower if made from recycled materials rather than virgin minerals. It is worth noting that the gap between the implied emissions of virgin versus recycled materials varies strongly depending on the energy mix of the region where these are mined and processed and the region where they are recycled.
- **Reducing the amount of waste generated from end-use technologies, mining and manufacturing**. The massive amounts of waste generated through the accumulation of end-of-life products such as consumer electronics, information technology equipment, household appliances, and clean energy technologies such as solar panels, wind turbines, EVs and storage batteries would pose challenges for global ecosystems. In the absence of adequate recycling efforts and stronger collaboration between manufacturers and recyclers, this waste might end up in landfills, polluting land and water resources and putting the health and safety of local populations at risk. Furthermore, recycling is not just limited to the management of end-of-life products; it must also include the volumes of waste generated in the form of manufacturing scrap as well as mine waste.

Using scrap from manufacturing processes and recovering minerals from mine waste, also known as tailings reprocessing, can help reduce the amount of waste generated.

Resource efficiency, circular economy and recycling

While this report primarily focuses on recycling and urban mining, recycling is not the golden solution to all concerns surrounding the rapidly mounting mineral demand for the energy transition. Circular economy principles consist of a wider suite of strategies, with recycling being one component. A comprehensive approach to security and sustainability of supply will require a suite of supply- and demand-side measures, which will play a crucial role in narrowing supply-demand gaps while simultaneously mitigating the potential environmental and social harms associated with resource extraction and use. These complementary actions encompass elements such as continued technology innovation to boost material efficiency and enable mineral substitution, behavioural changes to temper demand growth, and promoting practices of repair and reuse as well as rigorous sustainability standards. By adopting a holistic approach considering the entire product life cycle, policy makers, industry stakeholders and consumers can create more sustainable pathways for critical mineral use.

Objective of the report

This report aims to evaluate the current status of recycling and urban mining for materials containing minerals critical to the energy transition. It sheds light on the various recycling technologies in use today for different clean energy application segments, analyses the potential business models emerging in different regions, presents projection results for secondary supply by mineral and scenario, and outlines targeted policy recommendations to accelerate the uptake of recycling and urban mining that can pave the way for more sustainable and secure future mineral supply chains.

Scope

The report considers a wide range of “critical minerals” that play a vital role in clean energy applications. The main focus is on key “energy transition minerals” such as copper, lithium, nickel, cobalt, graphite and rare earth elements. This report does not cover the recycling of plastics, paper, steel or other bulk materials although specific lessons from these markets were taken into account.

Our assessment of mineral demand in the clean energy sector includes demand for low-emissions power generation (solar photovoltaic [PV], wind, hydro, nuclear and other renewables), electric vehicle batteries and battery storage, electric vehicle motors, grid networks (transmission, distribution and transformer), and hydrogen (fuel cells and electrolyser) technologies.

Scenarios

Introduction to World Energy Outlook (WEO) scenarios

This report employs three main scenarios to explore different energy pathways to 2050. Each scenario is fully updated to include the most recent available energy market and cost data. Each scenario responds in different ways to the fundamental economic and demographic drivers of rising demand for energy services. These differences largely reflect the various policy choices assumed to be made by governments, which, in turn, shape investment decisions and the ways in which households and companies satisfy their energy needs.

The projections are derived from the Global Energy and Climate (GEC) Model, which is a large-scale modelling framework developed at the IEA. The GEC Model is a simulation model that reflects the real-world interplay among policies, costs and investment choices and that provides insights into how changes in one area may affect others. None of the scenarios included in this report should be considered a forecast. The intention is not to guide the reader towards a single view of the future, but rather to promote a deeper understanding of the way that various levers produce diverse outcomes, and the implications of different courses of action for the security and sustainability of the energy system.

The three main scenarios are:

Net Zero Emissions by 2050 (NZE) Scenario: This normative scenario portrays a pathway for the energy sector to help limit the global temperature rise to 1.5 °C above pre-industrial levels in 2100 (with at least a 50% probability) with limited overshoot. The NZE Scenario also meets the key energy-related United Nations Sustainable Development Goals (SDGs): universal access to reliable modern energy services is reached by 2030, and major improvements in air quality are secured. Each passing year of high emissions and limited progress towards the SDGs makes achieving the goals of the NZE Scenario more difficult but, based on our analysis, the recent acceleration in clean energy transitions means that there is still a pathway open to achieving its goals.

Announced Pledges Scenario (APS): This scenario assumes that governments will meet, in full and on time, all of the climate-related commitments that they have announced, including longer-term net zero emissions targets and pledges in nationally determined contributions (NDCs), as well as commitments in related areas such as energy access. Pledges made by businesses and other stakeholders are also taken into account where they add to the ambition set out by governments. Since most governments are still very far from having policies announced or in place to deliver in full on their commitments and pledges, this scenario could be regarded as giving them the benefit of the doubt, and very considerable progress would have to be made for it to be achieved. Countries without ambitious long-term pledges are assumed to benefit in this scenario from the accelerated cost reductions that it produces for a range of clean energy technologies. The APS is associated with a temperature rise of 1.7 °C in 2100 (with a 50% probability).

Stated Policies Scenario (STEPS): This scenario is designed to provide a sense of the prevailing direction of energy system progression, based on a detailed review of the current policy landscape. Whereas the APS reflects what governments say they will achieve, the STEPS looks in detail at what they are actually doing to reach their targets and objectives across the energy economy. Outcomes in the STEPS reflect a detailed sector-by-sector review of the policies and measures that are actually in place or that have been announced; aspirational energy or climate targets are not automatically assumed to be met. The STEPS is now associated with a temperature rise of 2.4 °C in 2100 (with a 50% probability).

Modelling methodology for critical minerals recycling

The mineral recycling model is integrated into the broader model for the demand and supply of critical minerals that forms its own module within the GEC Model. For the non-energy sectors, secondary mineral supply projections are based on historical trends for secondary supply in the sector, assuming gradual improvement in collection rates and efficiency levels by scenario. For clean energy applications, there is an enhanced granularity by sector, assessing lifetime by technology (for example, solar PV, wind turbines and EVs), collection and yield rates by application and mineral, based on extensive literature review. The collection rates evolve in time and vary by scenario, with the most ambitious rates being achieved in a world that is on track for the NZE Scenario.

Lithium-ion battery recycling is modelled with the highest level of granularity among the suite of clean energy technology applications owing to the central role these batteries play in the surge of demand for energy transition minerals. Battery recycling is modelled based on EV scrappage curves for different modes (car, buses, two- and three-wheelers, and freight transport) and battery storage replacement rates in combination with collection rates, chemistry and recycling technology shares, and process yield rates by scenario. Reuse of EV batteries in second-life applications is also accounted for. Finally, lithium-ion battery manufacturing scrap is also modelled as the other secondary source of supply.

Chapter structure

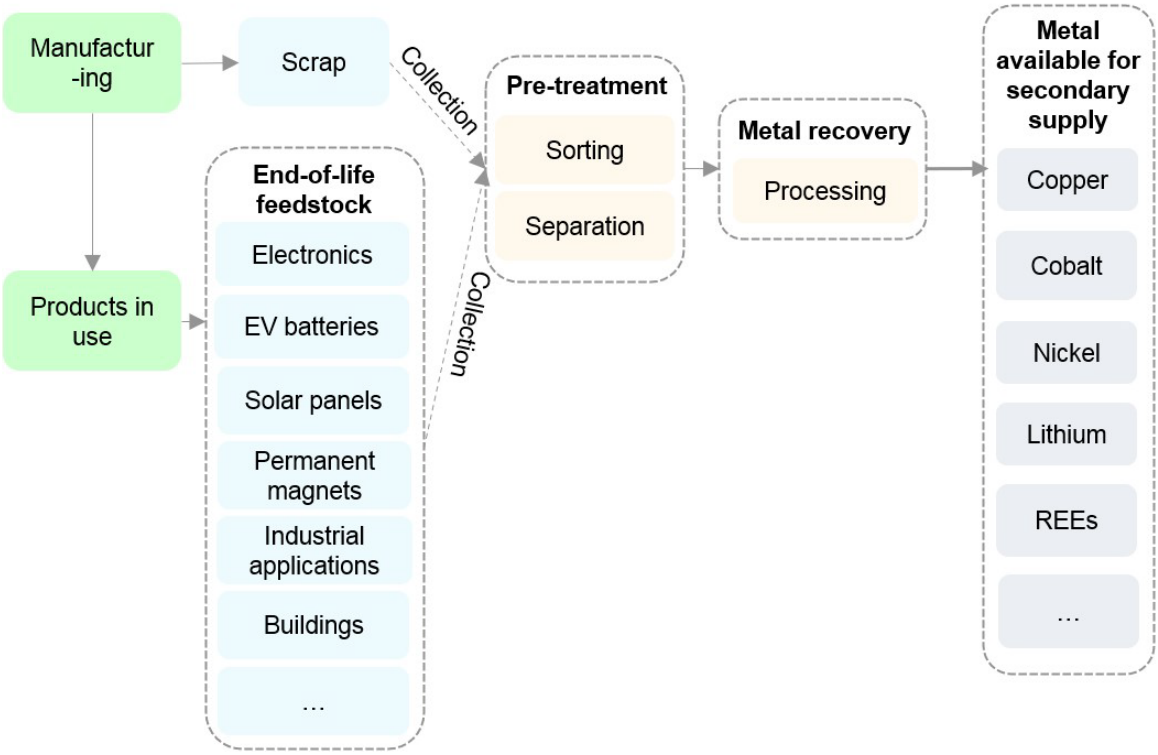
This report is structured into four chapters. Chapter 1 lays out the state of play, discussing the status for recycling and urban mining, various indicators used to assess recycling rates, progress by commodity and region, and recent policy developments. Chapter 2 presents the outlook for critical minerals recycling and looks deeper into some major segments such as lithium-ion batteries, copper scrap, rare earth elements from permanent magnets, mine waste and e-waste. Chapter 3 delves into various technological, trade and policy-related considerations that could enable an accelerated uptake of recycling globally. Chapter 4 presents the IEA's nine-point plan that includes key policy recommendations to scale up critical minerals recycling and urban mining.

Chapter 1. State of play

1.1. How recycling works

Recycling is the process of transforming materials containing recoverable metals into a usable product with varying levels of processing. One category of feedstock includes scrap produced during the manufacturing process; for example, when there are products or metals and alloys that did not meet the required quality standards for use (often referred to as "manufacturing scrap"). The other category is products that reached their end of life (referred to as "end-of-life scrap"). In the energy sector, these include batteries found in electric vehicles (EVs), solar panels, wind turbines and the permanent magnets within them, among others. The broader economy can also be seen as holding feedstock for recycling – this concept, referred to as "urban mining", views all human-made materials as potential sources of recoverable metals, including electronics, industrial parts, electrical wires, buildings and more.

Figure 1.1 Overview of the recycling process for energy transition minerals



Note: REE = Rare earth elements.

Recovering metals from materials requires as a first step significant efforts to collect and transport the feedstock for recycling. This stage is often the most challenging, as collection rates for many end-of-life products have historically been low, and there can be safety and regulatory issues with transporting the materials. Once materials have been collected, they typically go through a pretreatment and material recovery stage to recover the metals and minerals. These stages differ depending on the type of feedstock, but generally requires some level of sorting, separation and processing. The “material recovery” stage also differs depending on the feedstock, with processing for battery recycling, for example, happening through pyrometallurgy or hydrometallurgy. The material recovery stage can produce various products depending on the level of processing adopted, transforming the materials into a product suitable for use as secondary supply, either to be used in the same product it came from (closed-loop recycling) or in a different product (open-loop recycling). In some cases, scrap does not go through the processing stage and instead is used directly by fabricators (referred to as “direct-use scrap”).

Metals, apart from some specialty alloys, can be repeatedly recycled without loss of quality, with the specific metal available at the end of the recycling process depending on the feedstock. For EV batteries, the chemistry impacts the material available, with nickel, cobalt, manganese and lithium typically recoverable from lithium nickel manganese cobalt oxide (NMC) batteries for example. Solar panels, on the other hand, contain copper, aluminium, silver and silicon. Wind turbines include base metals such as nickel, aluminium and copper, and also contain rare earth elements from the permanent magnets. Currently, copper is more commonly recycled from industrial applications or buildings, but end-of-life batteries are emerging as a growing source of secondary copper supply.

There are also fewer conventional sources of recoverable minerals being explored in the context of the energy transition. These include re-mining and processing of waste (or tailings) from the primary production process. While this is not categorised as secondary supply in a strict sense, it provides a way to extract value from the waste stream. The mineral recovered in this process depends greatly on the initial mined commodity, the presence and volume of by-products, and the quality of those resources. In some cases, processing waste could lead to recovering more of the initial commodity. Additionally, there may be non-recovered metals within the waste that were not initially valuable but have gained value in the context of the energy transition. For example, historical tailings from copper mines could be rich in lower-grade copper ore – compared with the initially mined copper – which was not originally economically or technologically feasible to extract, or they may contain by-products of copper, such as cobalt.

1.2. Indicators to assess recycling performance

Before assessing the current levels of recycling and potential in the future, it is important to understand how different recycling indicators are calculated and what type of information they can give. Each can allow for consideration of different aspects, challenges and opportunities in the supply chain. While some indicators can assess the efficiency of the system at specific points, such as at the collection stage (end-of-life collection rate) or the separate stage (separation rate), some span across the entire supply chain (end-of-life recycling rate). Others evaluate recycling in the context of the broader mineral market, which can be useful for assessing the ways in which secondary supply can alleviate pressures on primary supplies.

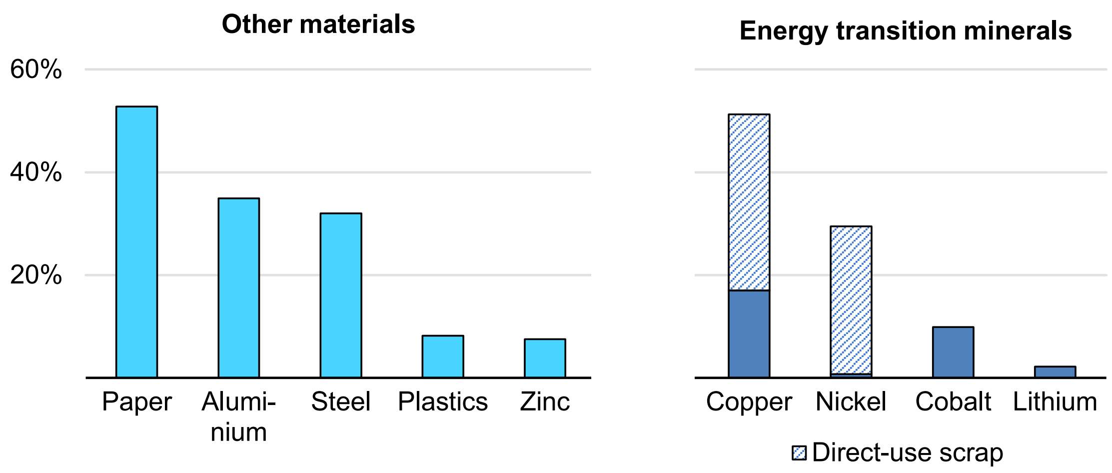
Table 1.1 Examples of common recycling indicators

Indicator	Definition (ratio)	Useful for assessing…
Efficiency rates		
End-of-life collection rate (EoL-CR)	EoL products collected for recycling / EoL products that are available for collection	The effectiveness of the material collection value chain for recycling
Separation rate (SR)	Metal in feedstock for metallurgical recovery / Metal in EoL products collected for recycling	How efficiently the pre-processing stage can turn end-of-life products into feedstock for metallurgical processes
End-of-life recycling rate (EoL-RR)	Metals recovered from EoL products / Metals contained in EoL products	The efficiency of the entire recycling supply chain (collection, separation, metallurgy)
Recycling rate (RR)	Metals recovered from secondary sources / Metals contained in feedstock	The efficiency of the entire recycling supply chain (collection, separation, metallurgy)
Relative to broader market		
End-of-life recycling input rate (EoL-RIR)	Metal produced from EoL feedstock / Total metal production	How much EoL products can contribute to total production
Recycled input rate (RIR)	Metal produced from secondary sources / Total metal production	How much secondary production from all sources can contribute to total production

Note: For indicators relative to the broader market, the indicators utilised in this report use "total demand" as an indicator of implied supply requirements (secondary projection + primary production).
Sources: Fraunhofer-ISI (2020), The promise and limit of Urban Mining, Joint Research Centre (2018), Towards Recycling Indicators based on EU flows and Raw Materials System Analysis data, and UNEP (2011), Recycling Rates of Metals A Status report.

A set of multiple indicators is needed when evaluating current and potential recycling rates. For example, the end-of-life collection rate may be useful when assessing the level of feedstock available for recycling, whereas the separation rate may be necessary for evaluating the technical capabilities of pre-processing. These can be particularly important for evaluating the efficacy of the recycling industry at different parts of the secondary supply chain. The segment of the market can also impact the indicators used or required. When considering only end-of-life feedstock (e.g. e-waste, EV batteries), the end-of-life recycling input rate could be the most useful indicator, whereas a combination of segments (e.g. end-of-life and manufacturing scrap) would require the broader recycled input rate.

Figure 1.2 Recycled input rate for selected materials, 2022



IEA. CC BY 4.0.

Notes: Recycled input rate is calculated as the metal produced from secondary sources over total implied supply. Excluding direct use of scrap for copper and nickel.
Sources: IEA analysis based on World Steel Association, International Aluminium Institute, FAO (2023), Forestry production and trade flows, accessed 22 July 2024, and USGS (2022), Zinc Statistics and Information, accessed 22 July 2024.

In this report, we mainly use indicators that place recycling rates within the broader market context. These measure the supply of minerals recovered from secondary sources (including through end-of-life products such as batteries, solar panels and permanent magnets, and through manufacturing scrap) relative to the total demand, or implied supply, of those minerals. These indicators can be useful for assessing the ways in which secondary supply can alleviate demand pressures on primary supplies, particularly in the context of the clean energy transition, which sees large increases in demand. Overall, the recycled input rate for energy transition minerals is much lower than that for other bulk materials.

Box 1.1 Data gaps in recycling

Despite the growing need to assess the status of recycling and the potential for metal recovery, there are still significant gaps in the availability and reliability of data on recycling. Standardised ways to calculate recycling indicators are often lacking, making it hard to compare data from different sources. Information for recycling input rates, which assess the share of secondary supply in total supply, are easier to obtain for many bulk materials, but for smaller energy transition minerals, reliable time series data on secondary supply are often not publicly available. Information on collection rates for various metals or recycling input rates is far harder to secure, particularly for minerals with less transparent markets. A study by the United Nations Environment Programme (UNEP) in 2011 took a comprehensive look at recycling rates of different metals, followed by the European Union's Material System Analysis and Raw Materials Information System, as well as several other studies such as Poncelet et al. (2022). However, the lack of up-to-date and comprehensive data makes it challenging to track historical performance in a systematic manner.

Moreover, across or within different studies, the availability of materials from recycling different sources of feedstock (e.g. end-of-life batteries, manufacturing scrap, e-waste, mine waste) is commonly assessed separately, making it difficult to assess how much secondary supply will truly be able to alleviate demand pressures from the energy transition.

Obtaining and estimating regional information also presents challenges. While some regions such as the United States and the European Union are tracking the flow of recycled materials to some extent, data gaps persist in other regions, particularly emerging market and developing economies that import large volumes of waste from advanced economies and where informal recycling is prevalent. Additionally, systematic data collection on recycling capacity and recovered metal volumes is often lacking in many regions. Efforts to enhance more data available in the public domain are essential to understand the status of material leakages and devise strategies to scale up recycling. Tackling data and information gaps is a priority area for follow-up action (see Chapter 4).

1.3. Business models

In the base metals sector, which includes materials such as copper, aluminium and zinc, business models tend to be well-established and relatively straightforward. The industry benefits from a mature infrastructure and a steady supply of post-consumer and post-industrial scrap. Companies in this sector often operate large-scale facilities that are well integrated into existing value chains and process flowsheets, processing large volumes of material that varies greatly in purity.

These companies typically fall into one of two broad business models: primary material producers with integrated recycling operations or toll recyclers that process materials on behalf of customers for a fee. However, many companies utilise a combination of these approaches to maximise efficiency and capture diverse market opportunities. Integrated recycling operators often accept material from other sources, and some toll-based "pure-play" recyclers harbour ambitions to move upstream and produce other goods.

Integrated recyclers, often large metal producers, incorporate recycled materials into their primary production processes. For instance, Aurubis, a leading integrated copper producer and recycler, operates a business model centred on processing both primary raw materials (copper concentrates) and recycled materials. While scrap utilisation helps stabilise production processes and improve asset productivity, its use of other feedstock materials such as electronic scrap allows it to benefit from existing copper production infrastructure and achieve economies of scale.

Closed-loop recyclers are a subset of integrated recyclers. These firms are typically manufacturers taking responsibility for recycling their own end-of-life products, driven by emerging extended producer responsibility (EPR) regulations. While less common in the base metals sector, this approach is gaining traction in industries using critical minerals to produce clean energy technology equipment. For example, PowerCo, Volkswagen Group's battery arm, aims to achieve vertical integration from raw materials through to recycling.

On the other hand, some recyclers exclusively process materials on behalf of clients. This may take a toll-based model, in which they return material to clients after receiving a processing fee. In this system, they do not have ownership of the material at any phase. This approach offers advantages that lower working capital requirements and reduce exposure to market price fluctuations. As a result of the fact that profit margins are built into the fee, toll recycling may remain profitable even for products with more challenging economics. Toll-based recyclers often specialise in specific processes or material types, allowing them to develop expertise and efficiencies in their segment. For example, a company might focus solely on the separation and sorting of complex electronic waste, returning the segregated materials to their clients for further processing or sale.

Alternatively, the buy-and-sell model, in which the recycler purchases scrap materials, processes them and sells them on to refiners, is also common. Commonly found in automotive recycling, these companies often have no direct involvement in metal production but serve as important intermediaries in the value chain. They often develop extensive networks of scrap suppliers and buyers, and may offer additional services such as collection, transportation and material grading. Given the volatility of critical mineral markets, the importance of economies of scale and the more specialised processing required compared with scrap cars, these companies seem unlikely to become a common feature in critical mineral recycling industries.

The capital expenditure for base metal recycling operations, while significant, may be lower in terms of marginal costs for expansions or upgrades. This is due to the established regulatory landscape for this industry as well as the well-understood processing technologies, which are often similar to primary production flows with adjustments for sorting and dismantling. The market for recycled base metals also provides a stable revenue stream for recyclers, albeit with regional differences in processing capabilities and enabling policies. Like other industrial investments, this is often heavily dependent on regional regulatory disparities that may accelerate or delay such projects.

Table 1.2 Comparison of business models between base metals and energy transition minerals

	Base metals	Energy transition minerals
Examples	Copper, aluminium, zinc	Lithium, cobalt, nickel (chemical)
Industry maturity	Well-established, mature infrastructure	Emerging industry with growing infrastructure
Feedstock	High material concentration but significant variance in alloy content	Lower concentration of materials due to complex, heterogenous chemical compounds
Regulatory landscape	Relatively well-established regulations and policies, especially for steel and copper	Evolving regulations and policies to support recycling development
Market dynamics	Stable and well-established markets for recycled materials	Emerging and growing markets for recycled materials
Process complexity	Complex but well-understood metallurgical processes	Often more complex, and customised given greater diversity of feedstock
Pretreatment requirements	Physical separation techniques, such as sorting, shredding, manual dismantling and magnetic separation, are all commonly employed	
Processing	Pyrometallurgical and hybrid processes, particularly smelting, are often used for base metal recycling	Hydrometallurgy enables the selective leaching, extraction and purification of the target metals from complex waste streams, but pyrometallurgy and hybrid processes are also used
Future processing methods	Recycling processes are often well-established and optimised	Growing focus on process intensification and efficiency improvements, including via the development of novel leaching agents, advanced separation techniques and automation

	Base metals	Energy transition minerals
Energy and environmental impacts	Recycling is generally less energy-intensive and has a lower environmental impact compared with primary production	In some cases, recycling these metals can be more energy-intensive and may generate complex waste streams due to the use of specialised chemicals and processes

In contrast, the business models in the recycling of energy transition minerals, which includes materials such as lithium, cobalt and chemical-grade nickel, are still evolving. This nascent sector faces multiple challenges in feedstock supply, including limited supply, inconsistent and dispersed availability, and technological variability. As battery technologies continue evolving, the end-product composition changes, leading to fluctuations in the types and quantities of recoverable materials. Given these challenges, effective business models in this sector must address not only the efficient collection of materials but also the strategic aggregation of feedstock. Aggregating, or blending, different sources to create a more consistent input stream is likely to help stabilise the recycling flowsheet against inherent variability of the source materials.

For energy transition minerals, there is a greater emphasis on closed-loop and specialised merchant recycling models. For example, a company recycling lithium-ion batteries such as Li-Cycle relies on partnerships with automotive original equipment manufacturers (OEMs), battery manufacturers and other industry stakeholders to ensure a steady supply of feedstock. While this does not necessary guarantee future supply of end-of-life batteries, such partnerships may contribute to a more reliable closed-loop ecosystem. These collaborations might also allow battery manufacturers or OEMs to better track their collections and recovery targets that are mandated through policies such as EPR mechanisms.

The processing part of the business model in energy transition minerals recycling can also be more complex, involving dismantling, sorting and often-proprietary processing techniques to extract the materials. As a result, the required capital expenditure is generally higher and carries more risk compared with base metals. This is due to the need for specialised equipment, ongoing research and development (R&D), and the challenges of scaling up novel processes. For instance, a company investing in a new hydrometallurgical plant for lithium recycling would face significant upfront costs required for the numerous stages involved in separating individual materials. In addition, ongoing R&D is required not just for process optimisation but also to remain adaptable to changing feedstock characteristics. As is discussed in Chapter 2, rapid changes in lithium-ion battery technologies towards low-cobalt cathodes or lithium iron phosphate (LFP) chemistries also pose risks for investments in facilities designed for NMC or lithium nickel cobalt aluminium oxide (NCA) batteries.

Despite these challenges, the business models in recycling energy transition minerals often benefit from growing market demand and evolving supportive regulations. There is a possibility that companies in this sector may be able to command premium prices for their recycled materials, especially as manufacturers seek more sustainable and secure supply chains for these components. This, however, would require a strong regulatory push given that most metal markets have not seen any premiums emerge for recycled material. Indeed, recycled lithium has traded for a discount in Chinese markets.

As the industry matures, it may see a convergence of business models with those in the base metals sector. This could involve larger-scale operations, more standardised processes and potentially lower marginal capital costs for expansion. However, for the time being, business models in energy transition minerals recycling will likely continue to be characterised by higher technological complexity, greater emphasis on R&D, and complex supply chain management.

In both sectors, successful business models will need to adapt to changing regulations, particularly around environmental standards, responsible sourcing and human rights, and circular economy principles. They will also need to continuously innovate to improve process efficiency and reduce environmental impacts. At the same time, these firms' profitability will remain largely dependent on commodity market prices, necessitating tools such as financial hedges to manage price risks.

Importantly, companies in both base metals and energy transition minerals recycling are increasingly adopting hybrid approaches, combining elements of integrated, merchant and closed-loop recycling. This flexibility allows them to adapt to changing market conditions, capture value at multiple points in the recycling value chain and build more resilient supply chains. For example, an integrated aluminium recycler might also operate scrap collection networks (merchant recycling) and partner with manufacturers for product take-back programmes (closed-loop recycling). Similarly, an energy transition minerals recycler might maintain closed-loop partnerships with key customers while also offering toll recycling services in the market. As the industry continues to evolve, even more creative combinations of these business models may emerge.

Box 1.2 Closed-loop recycling of industrial catalysts

Many industrial processes use chemical catalysts that contain critical minerals such as cobalt, platinum and nickel. These catalysts often play a key role in industries that require processes such as desulphurisation and hydrogenation. Like many other catalysts, they need to be changed after years of continuous operation due to poisoning or carbon deposition, which can cause inactivation.

Companies that employ these catalysts often have long-term agreements with the manufacturers, which are large chemical firms such as UOP or Axens. These long-term agreements often include provisions for the regeneration and/or recycling of spent catalysts. This arrangement ensures that the industrial users have a steady supply of catalysts with minimal process downtime while providing the manufacturers with a stream of material that can be regenerated or recycled.

The precise economic arrangement depends on the stakeholders, but the critical mineral content of the catalyst might be owned by either the manufacturer or the industrial user. In the first case, the user pays a leasing fee to the manufacturer for the use and maintenance of the catalysts without paying an upfront cost for the contained value. In the latter scenario, which is particularly common with large-scale refiners, the users own the material outright and contract manufacturers to refresh or recycle the material at the end of life.

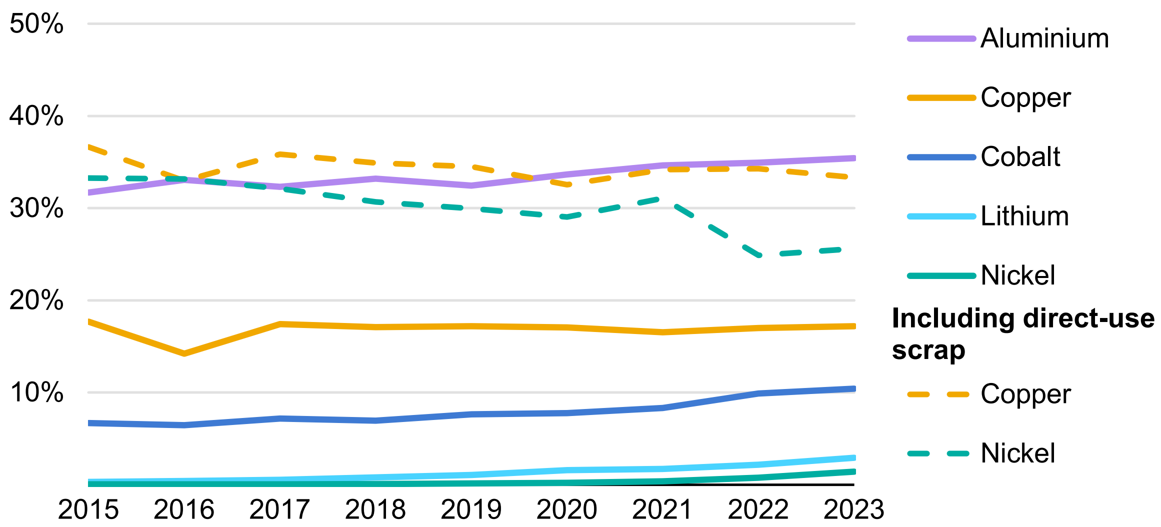
As a result of the close collaboration between the manufacturer/recycler and the end user, collection and recycling rates can be over 90%, with all parties benefiting from maximising the amount of recovered material. While not all the lessons from this business model are transferable to other recycling sectors, it highlights that stakeholder collaboration to align interests can lead to positive economic and environmental outcomes.

At the same time, due to the bilateral transactions that are at the core of this recycling model, there is little publicly available information about material volumes and costs. Furthermore, the high recovery rates in stable industries mean that total annual demand for new material (also known as net demand) is not a significant figure. For example, petrochemical catalysts account for only about 3% of annual cobalt demand. This belies a significant stock of in-use material, which can be freed up into the market in times of price volatility or technological substitution, warranting attention from policy makers.

1.4. Historical performance by commodity and region

The historical shares of secondary supply as a percentage of total supply (the recycled input rate) have varied significantly depending on the metal, with well-established base metal markets such as aluminium seeing notably higher rates as compared with other energy transition minerals. Regardless of the metal, the current source of feedstock for recycling is mainly end-of-life scrap (from either consumer products or infrastructure-related end users such as transport, construction and buildings) and manufacturing scrap from industries. EV and storage batteries currently do not make up a large share of feedstock for recycling, as they have not yet reached end-of-life in large scales.

Figure 1.3 Historical recycled input rate for selected materials



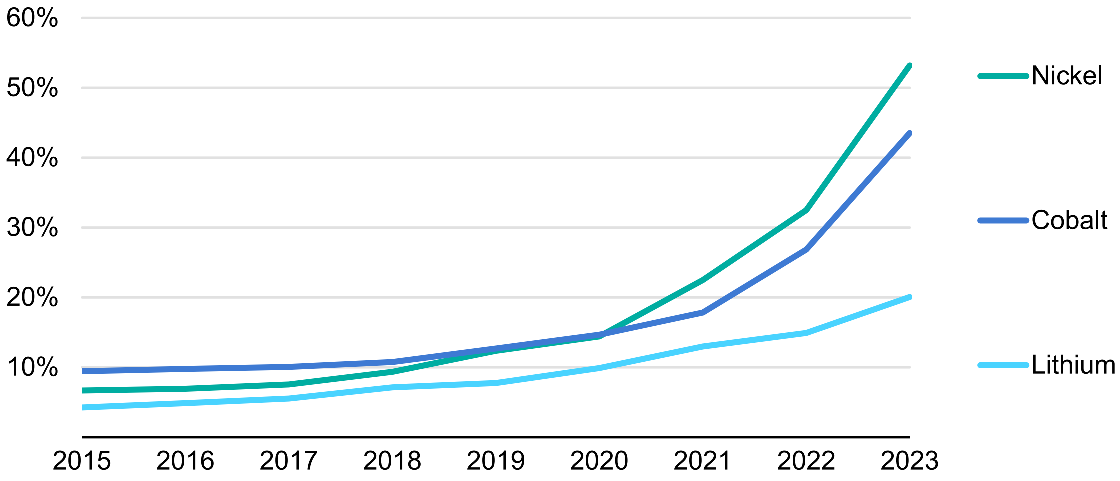
Notes: Recycled input rate is calculated as the metal produced from all secondary sources over total metal demand (where implied supply = demand). In the case of copper and nickel, the share with direct-use scrap is presented separately. In the case of nickel, direct-use scrap refers to scrap from the stainless-steel sector.
Sources: IEA analysis based on data from International Aluminium Institute, World Steel Association, Wood Mackenzie, Benchmark Mineral Intelligence and Project Blue.

Aluminium has had the largest recycled input rate over the last ten years at an average of about 35%, primarily driven by well-aligned economic incentives resulting from the high value of the material, low energy consumption of recycling compared with primary production, good access to scrap feedstock, the relatively short average lifetime of feedstock for recycling, and high end-of-life collection rates for aluminium-heavy end-of-life products such as cans (see Box 1.3). Well-established waste management programmes and regulatory schemes have also supported high rates of collection for consumer feedstock. While there have been increasing levels of metal production since 2015, the amount of secondary production has grown by almost double the rate over the same period, leading to a higher recycled input rate.

Aluminium is not representative of the wider trends among energy transition minerals, which have seen lower recycling input rates, albeit with variations between different minerals. Copper has seen the highest rate, maintaining around a 17% recycled input rate for the last decade (excluding direct-use scrap), due to the relatively easy access to scrap and its ability to be recycled repeatedly without loss of performance. However, compared with aluminium, copper recycling faces some challenges, such as its feedstock having a generally longer lifetime than some other base metals – for example, many aluminium-rich products such as packaging have a life cycle of only a few weeks, compared with the 5-10 years for consumer electrical products such as small appliances and electronic goods or the 20-50 years for industrial electrical or building products such as power cables. Copper included in waste such as cables or wires is also relatively more complex to recover due to high waste recovery and processing costs (e.g. contained copper in wire and cables that are buried underground in uneconomical quantities). Including direct use of scrap, the historical share has averaged around 35% for the last decade as copper can be easily reintroduced to the processing supply chain. Similar to aluminium, secondary production of copper has increased steadily alongside volume growth of total production, both increasing by approximately 15% from 2015 to 2023.

Other energy transition minerals, such as cobalt, lithium and nickel, have started to see upticks in the share of secondary supply in the last few years as EV and storage battery manufacturing and deployment has rapidly grown, with the major growth expected to continue. This has led to more investment into recycling facilities to recover these metals from manufacturing scrap and in anticipation of EV and storage batteries reaching end of life. Historically, secondary supply volumes have been limited due to the smaller quantities of feedstock such as those from consumer goods (e.g. rechargeable batteries) and therefore secondary supply volumes have been low due to issues with e-waste recycling (see Chapter 2 on e-waste). Out of these energy transition minerals, cobalt has had a relatively higher share due to its more common use in consumer products and its relatively high value. Lithium has also been recovered from consumer applications, though at a lower rate as there is less material available for recovery as it is found in relatively lower quantities within these feedstocks. Nickel has also had low historical secondary shares, but the direct-use nickel scrap has been significant, maintaining a share of around 30% over the last decade.

Figure 1.4 Recycling rates of battery lithium, nickel and cobalt from available battery recycling feedstock

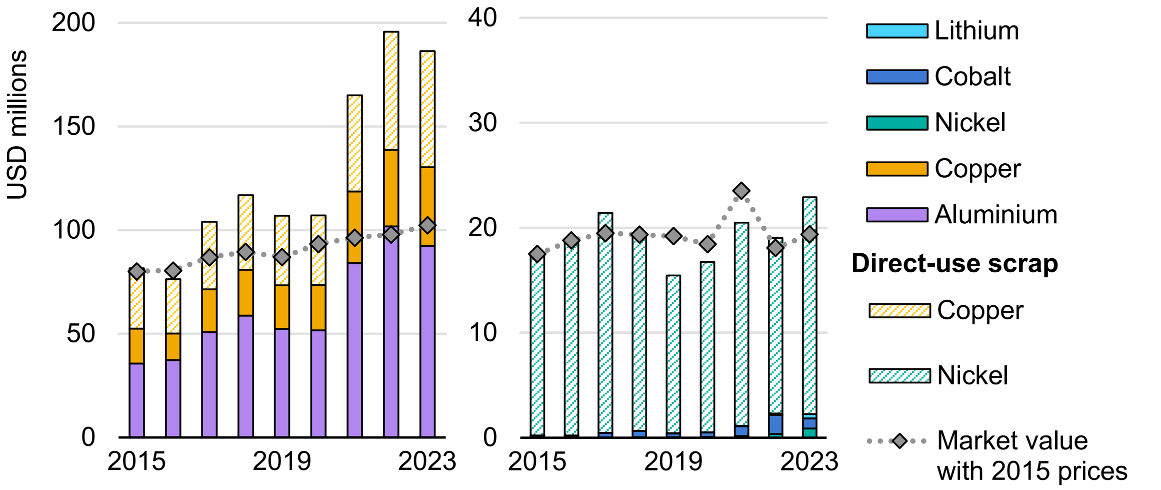


Notes: These recycling rates refer to the recovered metals from all battery secondary sources over the metals contained in the available recycling feedstock from all battery secondary sources (including manufacturing scrap and end-of-life batteries). Includes manufacturing scrap and end-of-life batteries from portable electronics, e-bikes, EVs, and maritime and storage applications.
Sources: IEA analysis based on data from Circular Energy Storage, Benchmark Minerals Intelligence and Project Blue.

EV and storage batteries are in the earlier stages of their deployment and have not reached end of life at scale, so there is limited recycling feedstock compared with established metals such as copper and aluminium. Therefore, it is more meaningful to look at the recycling rates of the critical battery metals – lithium, nickel and cobalt – compared with the available feedstock. This picture shows that the recycling rate of these battery metals has risen rapidly since 2020, particularly for nickel and cobalt, with the recycling rate of nickel over 50% and cobalt over 40%. The lithium recycling rate has also been rising steadily, reaching 20% in 2023. The higher recycling rates for nickel and cobalt make sense as nickel is primarily from EV battery manufacturing scrap, which is high grade, and techniques to recycle nickel are more established from pyrometallurgy and hydrometallurgy. Since nickel-rich chemistries have been the dominant EV cathode chemistries historically, and nickel is the most intensive metal in these batteries, there is more nickel in battery manufacturing scrap than for the other metals. Cobalt benefits from being the most valuable metal per tonne in the battery, and also from having established recycling techniques. Portable electronics have also utilised lithium cobalt oxide (LCO) cathodes for a long time, providing a larger source of end-of-life feedstock material for cobalt than for the other metals. Lithium, however, has not been historically recycled and therefore, the techniques to recover it have been implemented more recently, explaining its slower recycling uptake. For instance, lithium was not recovered through traditional pyrometallurgy where lithium ends up in the slag, but for modern pyrometallurgy and hydrometallurgy combined, lithium can be recovered.

Despite the recent uptick in secondary volumes for battery metals, the base metals recycling market – such as copper and aluminium – remains much larger at USD 100 million in 2023 compared with the USD 2.3 million recycled battery metals market. However, recycled battery metals have experienced significantly higher growth rates, increasing almost 11-fold between 2015 to 2023, with more than half of this growth occurring in the last three years. The rapid rise in prices of nickel, lithium and cobalt over the past few years contributed to the growth, but even when the price impact is excluded, growth has been nearly sevenfold.

Figure 1.5 Historical market value of secondary supply for selected materials

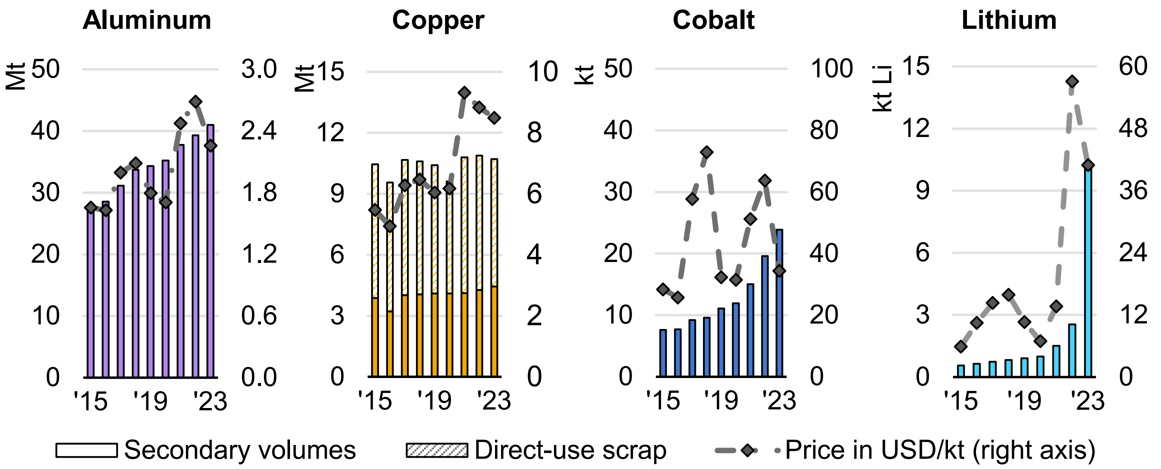


IEA. CC BY 4.0.

Note: Columns are based on the market value of real prices, line is based on 2015 real prices.
Sources: IEA analysis based on data from International Aluminium Institute, World Steel Association, Wood Mackenzie, Benchmark Mineral Intelligence, Project Blue, and S&P Global.

Historically, well-established recycling industries such as aluminium and copper have seen only relatively modest impacts of price on supply volumes, with scrap markets largely inelastic. Secondary supply has sometimes acted as a market balancing mechanism during tight supply periods. In contrast, battery metals have shown more correlation between prices and volumes; however, it is difficult to draw a direct connection between material prices and secondary supply volumes, as in recent years the driver for both has largely been related to growing policy attention and concerns over future supply strains. The rapid growth of battery metals recycling demonstrates that secondary supply can scale quickly when supported by the right incentives, such as regulatory frameworks, technology improvements and availability of feedstock.

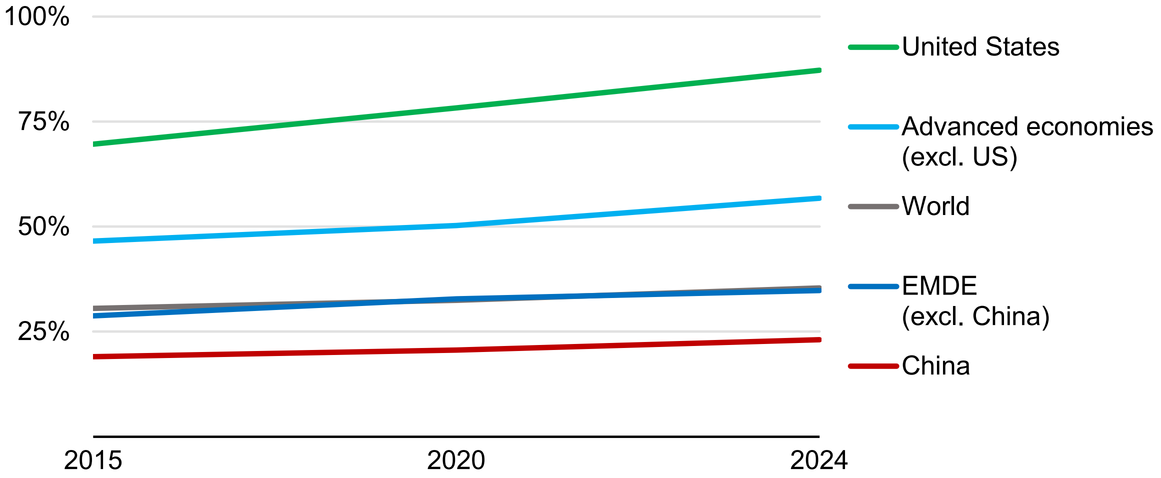
Figure 1.6 Price and volume of secondary supply for selected materials



Notes: Mt = million tonnes; kt = kilotonnes. Using real prices.
Sources: IEA analysis based on data from International Aluminium Institute, World Steel Association, Wood Mackenzie, Benchmark Mineral Intelligence, Project Blue, and S&P Global.

Although it is difficult to assess exact regional differences in historic secondary supply for all minerals, there are certain regions that have more well-established recycling industries than others. Broadly, China, Europe and North America have the highest levels of secondary production and recycled input rate across minerals as they have further developed refining and recycling industries. In metals where the direct-use scrap has historically been the largest contributor to secondary supply – aluminium, copper and nickel – the sources of secondary supply are necessarily in regions with strong refining footprints. For metals where end-of-life feedstock plays a more important role, the trade of materials between countries will influence the recycling input rate as it impacts the levels of feedstock available – large importers of products will have higher levels of feedstock, whereas large exporters will not (see discussion on EV import and exports in Chapter 2 on battery recycling). For less-established minerals where feedstock is largely starting to come from end-of-life batteries – cobalt and lithium – much of the current capacity for recycling exists in China. This is expected to continue in the near future as China continues to position itself as the dominant player in recycling for many key materials through actions such as the creation of China Resources Recycling Group Ltd., a newly established state-owned enterprise which will engage in recycling and reuse of end-of-life batteries, scrap steel and e-waste.

Figure 1.7 Recycled input rate of secondary aluminium supply by region

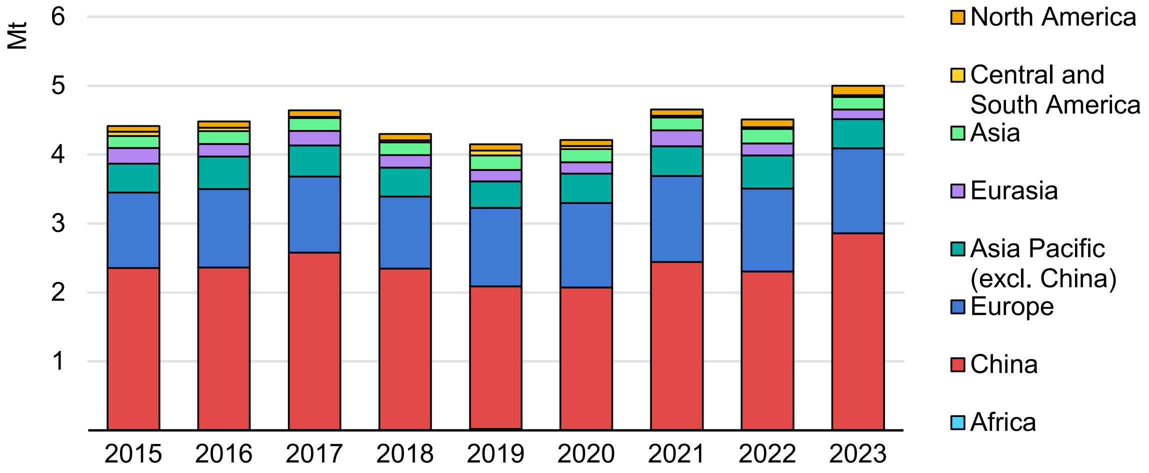


Note: EMDE = Emerging market and developing economies.
Source: IEA analysis based on data from International Aluminium Institute.

For aluminium, China has had the highest supply of secondary production, averaging around 10 Mt per year since 2015. However, due to its high levels of primary production, the share of secondary supply as a percentage of total supply has been around only 20% over the same period. The United States, on the other hand, has a significantly higher share of secondary supply as a percentage of total supply, although it historically ranked second for absolute secondary production volumes, 60% less than China's yearly average. More broadly, advanced economies see higher secondary shares than emerging markets and developing economies, where their supply of secondary production has been relatively subdued due to lower levels of collected feedstock.

China is also the largest supplier of secondary copper, accounting for approximately half of the average global supply since 2015. The country has seen a growth in its output of secondary copper over recent years, growing by about 1.5 times from 2 Mt in 2020 to 3 Mt in 2023. Germany is the second-largest secondary copper producer, maintaining a steady 0.4 Mt of production annually since 2015. By region, Europe holds the second-largest share of total secondary copper, accounting for about a quarter of the market and producing about 1.2 Mt annually since 2015. After Germany, the bulk of production within Europe comes from Belgium, Poland and Spain. After China, the United States has seen the highest volume increase in secondary production, from about 40 kt of production in 2020 to 100 kt in 2023.

Figure 1.8 Historical secondary copper supply by region

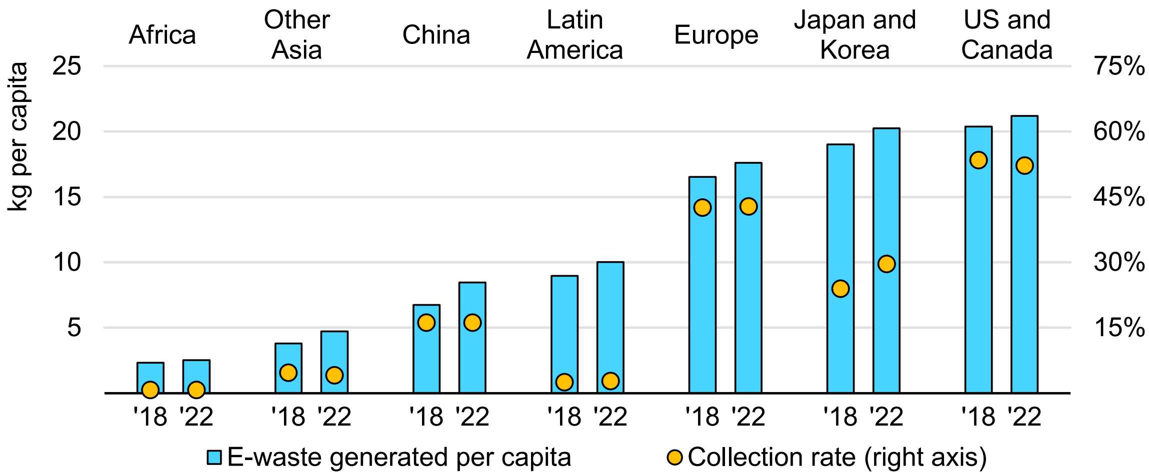


Notes: Includes both refined and smelted copper. Excludes direct use scrap.
Source: IEA analysis based on data from Wood Mackenzie.

Historical collection rates have also varied significantly by recycling segment and region. In the case of e-waste, levels generated and collected are higher in advanced economies, whereas rates in emerging and developing economies are significantly lower. Africa, in particular, has seen the lowest collection rates in part due to the lowest e-waste generation, which have not significantly improved over the past decade. However, other emerging and developing economies have seen improvements in collection rates since 2010. South America in particular saw an increase in collection rates, rising from 0% to 3% from 2010 to 2022. Brazil, in particular, had a 3% collection rate in 2022 as the country has introduced various laws to manage their e-waste, including the National Solid Waste Policy (Law 12.305/2010), which provides a framework for waste management, and Law No. 2539 promulgated in Acre, which introduced EPR, requiring companies that manufacture electronic equipment to create and maintain and collection and recycling programme.

Despite most current capacity for secondary production of cobalt, nickel and lithium being seen in China, there have been concerted efforts in the past few years to develop the industry in other parts of the world. Large-scale miners and processors are investing in the European and North American battery recycling industry, such as Glencore, which announced a partnership and USD 75 million investment into Canadian battery recycling company Li-Cycle, and SQM, which invested USD 9.4 million into a United Kingdom battery recycling firm. Companies working in the midstream battery value chain (e.g. cathode) are also positioning themselves as players in the battery recycling supply chain, with leading largest cathode producers BASF and Umicore investing in battery recycling plants in Europe. There has also been a plethora of battery recycling start-ups that have emerged in these regions. Thus far, much of the ex-China growth has largely been focused on the dismantling and shredding stages of the battery recycling industry, whereas the material recovery process is largely at the pilot or demonstration stage. The growth in the industry has been supported not only by market developments and expected future supply pressures, but also by policy developments within these regions.

Figure 1.9 E-waste generated per capita and end-of-life collection rate by region



Notes: kg = kilogrammes. Collection rate in the legend refers to e-waste documented as formally collected and recycled. "Other Asia" refers to Asia excluding Korea, Japan and China.
Source: IEA analysis based on Baldé, Kuehr, Yamamoto et al., International Telecommunication Union and United Nations Institute for Training and Research (2024), Global E-waste Monitor 2024.

Box 1.3 Lessons learned from the history of aluminium recycling

The aluminium recycling industry has a long history influenced by concerns over primary supply shortages, policies aimed at boosting collection rates and environmental concerns. Large-scale aluminium recycling began in the late 19th century with the first plant opening in the United States in 1904. Organised recycling efforts did not emerge until the Second World War, when supply shortages drove increased attention to recycling consumer products.

After the war, the use of recycling in industries such as the automotive industry, aerospace and packaging increased, but recycling primarily focused on industrial scrap. This remained steady due to its economic value, as it saves energy and reduces material costs.

The real global expansion in aluminium recycling occurred in the 1970s, driven by post-consumer recycling, especially of aluminium beverage cans. Policy programmes focused on increasing collection rates were introduced around the world, with deposit-return schemes emerging in the late 1970s and kerbside programmes in the early 1980s. By the late 1980s, many countries around the world had such programmes. Increased attention on the environmental impacts of consuming products also emerged as an important contributor to an uptick in recycling of post-consumer products, with recycled aluminium using 95% less energy than primary aluminium production.

While there are important differences between aluminium recycling and recycling energy transition metals such as cobalt, lithium and nickel, there are notable parallels. The recent rise in recycling for these metals stems from supply pressures, similar to aluminium, and growing concerns about the environmental impacts of primary production. Policy makers can accelerate the growth of these nascent recycling industries by creating regulatory and financial incentives – such as collection programmes that establish monetary incentives or remove the difficulty in returning end-of-life products and policies that leverage the environmental benefits of recycling – which take key learnings from established sectors such as aluminium, to ensure recycled sources become key contributors to the energy transition.

1.5. Recent policy developments

The International Energy Agency Critical Minerals Policy Tracker reveals that from 2022 to 2024, there have been over 30 policy developments related to mineral recycling. These policies and measures predominantly fall into four categories: strategic plans, EPR, financial incentives and cross-border trade regulations. Some policies fall under multiple categories or use alternative approaches. Mineral recycling policies also include regulatory mandates such as industry-specific targets for material recovery, collection rates and minimum recycled content with progressive targets.

Strategic plans. Several countries, including many advanced economies, have announced high-level strategies on the circular economy and economy-wide targets for secondary materials sourcing. These strategic plans act as roadmaps, with regulations to follow the objectives announced.

The European Union (EU) Circular Economy Action Plan, for example, sets out specific measures for vehicles and batteries in key value chains, including actions to support a market for secondary raw materials such as developing EU-wide end-of-waste criteria that specify when certain waste ceases to be waste and becomes a product, or a secondary raw material. The EU Critical Raw Materials Act (CRMA) aims to ensure that by 2030 the European Union's recycling capacity can produce at least 25% of its annual consumption of strategic raw materials. The Act also includes provisions to promote the recycling and circularity of critical raw materials in various sectors, including in applications like wind turbines. Germany's draft National Circular Economy Strategy and Italy's National Strategy for Circular Economy are also recent examples that show the development of recycling strategies in the European Union.

Many other countries and regions are working on this. China recently issued a waste recycling policy to achieve ambitious targets by 2025, aiming for 450 million tonnes in annual utilisation of major renewable resources and a resource recycling industry output value of CNY 5 trillion (Yuan renminbi)[1] per year. Australia outlines its general targets and actions to develop a recycling industry in its National Waste Policy Action Plan. Korea set the objective of increasing the recycling rate of critical minerals from 2% today to 20% by 2030. Kenya's National E-Waste Management Strategy lists high-level government interventions for recycling of waste from electrical and electronic equipment (WEEE) including lithium-ion batteries. Besides describing the set-up for infrastructure on WEEE, it includes actions for enhanced public awareness, education, research and capacity building.

Financial Incentives. Many advanced economies have introduced financial incentives to encourage the implementation of recycling technology and expand their domestic capacity. These incentives address two distinct aspects of the recycling process: the capacity to generate and collect scrap, and the domestic processing capacity. For well-established industries, the focus tends to be on enhancing processing capacity to compete globally. However, for emerging sectors such as battery recycling, incentives often target both collection and processing. Financial support may include grants and preferential loans or guarantees aimed at fostering the growth of recycling infrastructure. Additionally, some governments are implementing targeted support for the collection of emergent feedstocks such as batteries, recognising that processing capacity is valuable only when sufficient feedstock is available.

Examples supporting recycling infrastructure include the United Kingdom's CLIMATES programme, which invested GBP 5 million[2] to boost the country's supply chain capabilities through mid- and late-stage R&D projects. These projects focus on rare earth elements (REEs) used in high-performance magnets, improving circular design and finding sustainable routes for processing recovered REE materials. In Canada, the government set aside CAD 1.5 billion (Canadian dollars)[3] through the Strategic Innovation Fund to support critical minerals

[1] Exchange rate: 1 Chinese yuan (CNY) = EUR 0.13 = USD 0.14 (as of 13 November 2024).
[2] Exchange rate: 1 British pounds (GBP) = EUR 1.20 = USD 1.27 (as of 14 November 2024).
[3] Exchange rate: 1 Canadian dollar (CAD) = EUR 0.67 = USD 0.71 (as of 13 November 2024).

projects, with priority given to advanced manufacturing, processing and recycling applications. Canada also set aside more than CAD 190 million under the Critical Minerals Research, Development and Demonstration Program for pilot recycling plants and demonstration projects, under which three grants for recycling projects have already been approved. Japan subsidised two recycling projects above JPY 1 billion[4] under its critical minerals subsidy programme. The US Inflation Reduction Act provides tax incentives to facilities recycling critical minerals or clean energy technology equipment that contains critical minerals. The France 2030 investment plan supports recycling projects, with a EUR 54 billion budget over five years. China's waste recycling policy also outlines specific financial support mechanisms for recycling infrastructure, including tax benefits (VAT and corporate income tax), existing funding channels for key projects, and green financial instruments such as green credit, green bonds, and green trust. China also established a state-owned enterprise for resources recycling and reuse in October 2024 with a capital of CNY 10 billion.

Policy examples to fund the collection of feedstocks include the US Department of Energy's USD 15 million funding to drive recovery of spent consumer batteries at retailers that can be sent to recyclers and the AUD 2.23 million (Australian dollars)[5] Australian government grant under the Critical Minerals Development Program supporting cobalt retrieval from mine waste.

Extended producer responsibility (EPR). Many countries have adopted regulations or requirements to mandate or encourage EPR, which holds manufacturers accountable for the treatment of products at their end of life. A few have applied them specifically to the recovery of materials, usually in the e-waste sector. EPR as a policy approach can raise revenue and set incentives for the collection and recovery of material at the post-consumer stage of a product's life cycle. Unlike policies that target a single point in the chain, EPR can integrate environmental considerations through the product chain. This approach has significantly impacted the treatment of electronics and electrical waste since the 1990s, improving transparency in material and financial flows, shifting end-of-life management costs from local governments to producers, and increasing material recovery rates. These policies can also encourage modular designs for easier recycling.

In the European Union, the WEEE Directive mandates separate collection and proper treatment of WEEE, encourages eco-design, and harmonises national electrical and electronic equipment registers. The EU Batteries Regulation sets

[4] Exchange rate: 1 Japanese yen (JPY) = EUR 0.006 = USD 0.006 (as of 14 November 2024).
[5] Exchange rate: 1 Australian dollar (AUD) = EUR 0.61 = USD 0.65 (as of 13 November 2024).

requirements throughout a battery's life cycle, including responsible sourcing of primary material inputs, recovery targets for waste batteries and minimum recycled content levels, and establishes recycling efficiency goals. While not an EPR policy, the EU Battery Passport found in the Batteries Regulation can complement EPR schemes. It provides crucial data on battery composition, performance and sustainability, enhancing transparency and facilitating recycling. This information supports EPR goals by making it easier for producers to fulfil their obligations and for recyclers to process batteries efficiently.

In the United States, 25 states have enacted e-waste recycling laws, including California. In Korea, the EPR scheme includes producer accountability and financial incentives, requiring manufacturers to collect and recycle a specific percentage of their sold products, which encourages eco-friendly design, while offering rewards for meeting or exceeding recycling targets and imposing penalties for falling short. Colombia mandates the collection and long-term management of WEEE based on EPR. Starting in 2024, the government requires the mandatory collection of used lithium-ion batteries from electric vehicles, with collection rates increasing from 0.5% in 2024 to 65% by 2044. India, in 2022 issued Battery Waste Management Rules and E-Waste Management Rules, which require the collection and recycling of EV batteries and e-waste as well as increasing recovery targets and minimum use of domestically recycled materials. South Africa's Second-Hand Goods Act and EPR Regulations also fall under this typology.

Cross-border trade. Regulations under this category affect the transboundary trade of recyclable minerals. This can relate to the implementation of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention) or the Organisation for Economic Co-operation and Development (OECD) Council Decision on the Control of Transboundary Movements of Wastes Destined for Recovery Operations. Such regulations classify waste as hazardous or non-hazardous and define by-products, recyclable products, process of disposal and end of life – and other elements that influence cross-border trade of minerals or mineral products destined for recycling.

There are many approaches to managing critical minerals recovered from waste streams, and these varying approaches significantly impact cross-border trade. Some jurisdictions, particularly advanced economies, have specified in their waste legislation how to handle critical minerals that are considered valuable products. This clarity in legislation facilitates international trade by providing clear guidelines for exporters and importers. Other jurisdictions consider materials (e.g. those recovered from batteries) under general waste laws and treat them as hazardous waste. These differing classifications can create barriers to cross-border trade, as what one country considers a valuable resource might be treated as hazardous material by another, leading to complex regulatory hurdles and potential trade disputes. Cross-border trade of recyclable minerals may also be regulated by technical guidelines, such as those from the United Kingdom environment agency.

The EU Waste Framework Directive defines when waste ceases to be waste and becomes a secondary raw material, and how to distinguish between waste and by-products. In 2023, the Batteries Regulation amended the Waste Framework Directive to enhance the management of waste batteries, particularly emphasising the importance of recovering critical raw materials from battery waste through improved collection, treatment and recycling requirements and to adapt the waste management rules to waste batteries. The European Union has also developed specialised regulations for specific mineral waste streams such as those for copper scrap and batteries and accumulators. Other waste directives include those for WEEE, mine waste and end-of-life vehicles.

In Latin America, recent policy developments affect the trade of recycled mineral products such as laws in Mexico and Chile. Mexico's General Law for the Prevention and Integral Management of Wastes, amended in 2023, establishes comprehensive controls on transboundary movements including: prior consent requirements for exports, restriction of imports to recycling purposes only, mandatory tracking systems for waste transfers, and authority for the Ministry to restrict imports that could discourage domestic recycling. Similarly, Chile's Law 20.920 links trade provisions to the Basel Convention, prohibiting hazardous waste imports for disposal while permitting them for recycling under strict conditions requiring Ministry authorisation and environmental guarantees.

Import and export restrictions on minerals and metals and anti-dumping laws – used by countries to protect their domestic industries from unfair competition – also fall under this category. Many emerging market and developing economies have issued trade restrictions for WEEEs because low-quality, non-recyclable materials are often illegally shipped into these countries – many of which lack sufficient recycling and waste management capacity to handle such waste effectively. This is so despite the control of hazardous waste trade under the Basel Convention, which allows the transboundary movement of hazardous waste in certain regulated circumstances, including if "the wastes in question are required as raw material for recycling or recovery industries in the State of import".

India's Hazardous and Other Wastes Rules prohibits the import of e-waste for disposal, and Nigeria's National Environmental (Electrical/Electronic Sector) Regulations banned the importation of WEEE and near-end-of-life electric or electronic equipment and has strict regulations to manage e-waste. Numerous countries have also restricted exports of critical mineral scrap, such as Argentina and Viet Nam for copper and nickel waste and scrap, Burundi and the Democratic Republic of the Congo for cobalt, manganese and REEs, and many more.

The European Waste Shipment Regulation amended in 2024 and applicable starting in 2026 sets out rules on the export of waste to non-EU countries. The regulation places stricter burdens on EU scrap exporters, but allows easier intra-EU shipment and recycling of waste. Advanced economies have also issued policies that indirectly affect the trade of recycled critical minerals, such as the US Foreign Entity of Concern provisions and forced labour prevention acts in the United States, Canada and the European Union. Given the special implications of this topic, the international trade in waste is further discussed in Chapter 3 ("Cross-border waste and scrap trade").

Table 1.3 Policies and measures for the recycling of critical minerals

	Strategic plans	Financial incentives	EPR	Cross-border trade
Australia*	●	●	●	●
Brazil		●	●	
Canada*	●	●	●	●
Chile		●	●	●
China	●	●	●	●
Colombia			●	
European Union	●	●	●	●
France		●	●	
Germany	●	●	●	
Ghana			●	●
India	●		●	●
Indonesia				●
Italy	●	●	●	●
Japan		●	●	●
Kenya	●			
Korea	●		●	●
Nigeria			●	●
Pakistan				●
South Africa			●	●
United Kingdom	●	●		●

	Strategic plans	Financial incentives	EPR	Cross-border trade
United States*		●	●	●
Viet Nam			●	●

* In countries with federal systems, mineral recycling policies are typically managed at the subnational level rather than the national level. In the table, a circle is placed if the Policy Tracker includes policies from states that have implemented a policy related to the category. For detailed information on specific states and regulations, please consult the Critical Minerals Policy Tracker.

Note: We welcome feedback from jurisdictions regarding any updates to existing policies or on additional policies that are missing from the database. Further details can be found here.

Sources: IEA Policies Database (October 2024) with data from Columbia Center on Sustainable Investment (2023).

Chapter 2. Outlook for critical minerals recycling

This chapter provides an outlook for secondary supply of key energy transition minerals and explores how recycling impacts the requirements for primary supply (mining and refining) and associated investments. Following the overview, the chapter delves deeper into key segments of recycling and urban mining, notably i) electric vehicle (EV) and storage batteries; ii) copper scrap; iii) rare earth elements from permanent magnets; iv) metal recovery from mine waste/tailings; and v) electronic waste (e-waste). The discussion focuses on the key challenges and opportunities for scaling up recycling in each segment.

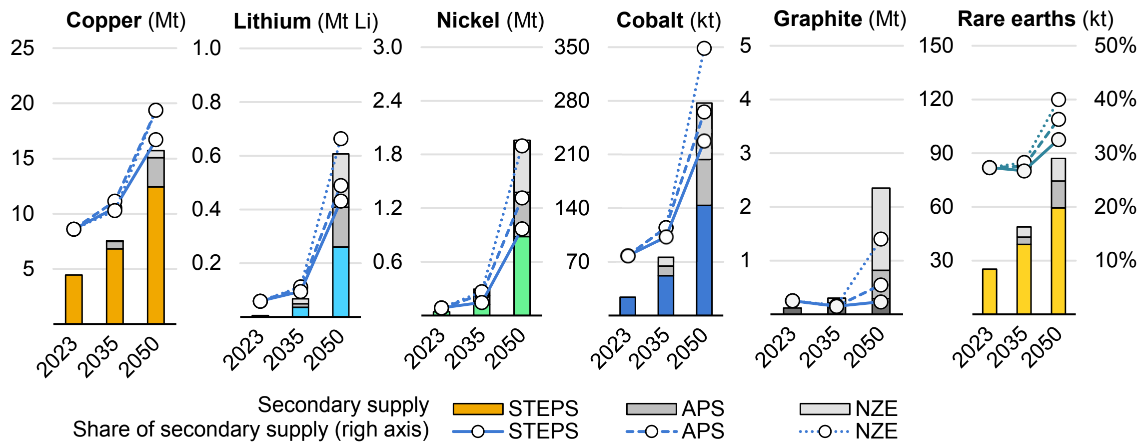
2.1. Overview of the impacts of recycling and implications for primary supply

Outlook for secondary mineral supplies

As discussed in Chapter 1 ("State of play"), historical shares of secondary supply in total mineral supply have varied significantly depending on the mineral, with well-established base metal markets such as aluminium seeing notably higher rates than energy transition minerals. Irrespective of the mineral in question, presently feedstock for recycling mainly comes from end-of-life scrap and manufacturing scrap. While the clean energy sector such as EV and storage batteries does not currently make up a large share of feedstock for recycling, this picture is set to rapidly change as a growing amount of deployed batteries, solar panels and wind turbines reaches their end of life.

In the Stated Policies Scenario (STEPS), a scenario that incorporates today's policy settings, the share of secondary supply in total demand grows consistently, from 17% today to 33% in 2050 in the case of copper (excluding direct use of scrap), with cobalt displaying a similar trajectory. Lithium and nickel also see notable growth in secondary supply thanks to growing deployment of batteries. In the Announced Pledges Scenario (APS), a scenario that reflects countries' climate ambitions, collection rates are higher than in the STEPS (see box on modelling methodologies in the Introduction). The share of secondary supply in this scenario crosses 20% of total demand in 2035 and 40% in 2050 for copper. This growth is driven by strong policy actions to increase collection rates. In the Net Zero Emissions by 2050 (NZE) Scenario, a stronger emphasis on sustainability and circularity translates into the most ambitious collection rates and efficiency levels: secondary supply volumes in 2050 are about 15% higher for rare earth elements, and over 35% higher for lithium, nickel and cobalt than in the APS. Despite additional demand in the NZE Scenario, the share of secondary supply remains higher than in the APS for most minerals. For graphite, while some recycling and reutilisation may exist for other applications, this has yet to emerge for clean energy applications such as batteries. Typically, for lithium, nickel, cobalt and graphite, an additional 9-12% of demand can be sourced from secondary supplies in the NZE Scenario compared with the APS in 2050. Nevertheless, recycling rates today vary widely by region, product and current deployment levels, and reaching the volumes of secondary mineral supply implied in the NZE Scenario will require significant efforts to improve collection rates and ramp up investment to build necessary infrastructure.

Figure 2.1 Secondary supply volumes and share of total demand for key energy transition minerals in the APS and NZE Scenario, 2023-2050



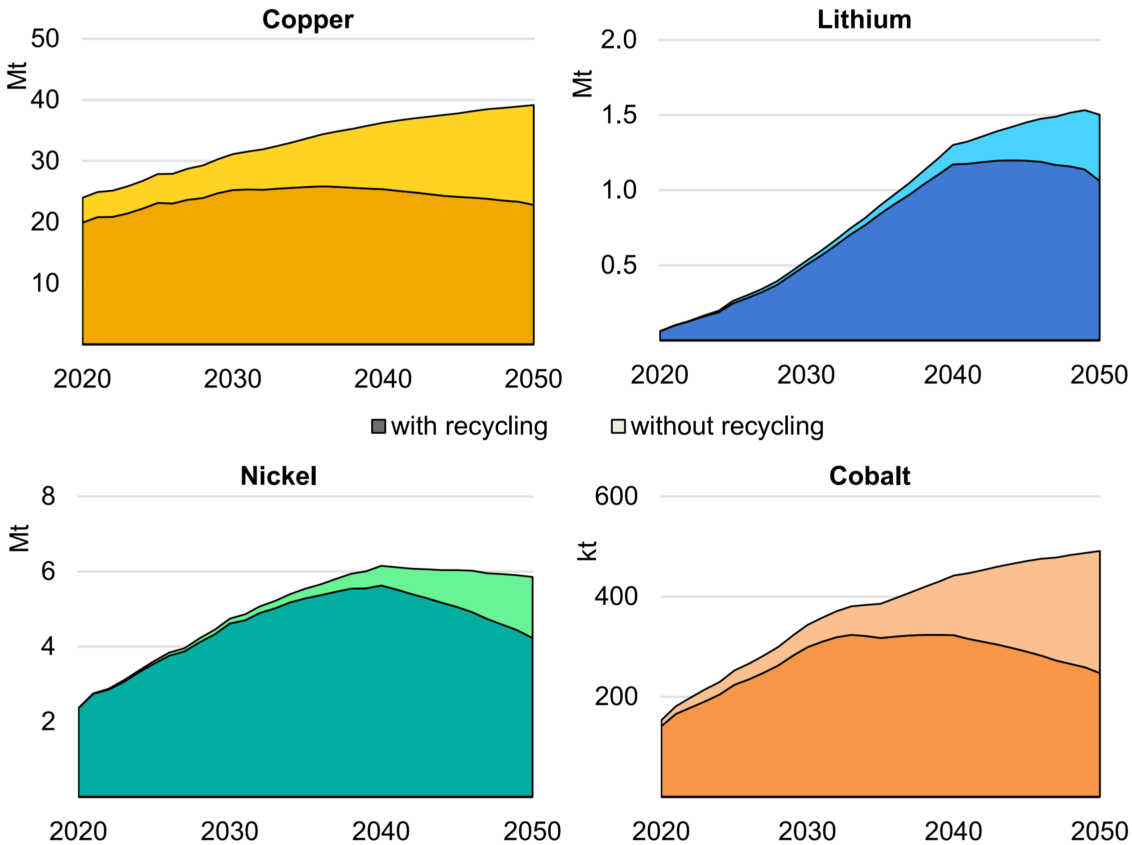
Notes: Mt = million tonnes; kt = kilotonnes. Includes recycled volumes from end-of-life equipment and manufacturing scrap. For copper, direct use scrap is excluded. For nickel, scrap from the steel sector is excluded. For rare earth elements, the figures are for magnet rare earth elements only (neodymium, praseodymium, dysprosium and terbium).

Significant differences exist across minerals, depending on how much they were used in the past in recyclable applications, the lifetimes of the products containing them, and how much of their future demand is driven by fast-growing clean energy applications. For minerals where most of the secondary supply comes from EV batteries – such as for lithium and nickel – the share of secondary supply in total demand is currently quite low (when recycling of nickel-containing alloys is excluded), but they grow quickly after 2030, both reaching around 30% of demand by 2050 in the NZE Scenario. The situation is similar for magnet rare earths – while the current secondary supply is dominated by industrial scrap, new opportunities arise from end-of-life EV motor and wind turbines. On the other hand, for copper and cobalt, which have many uses beyond the clean energy sector, their shares of secondary supply in total demand, which includes manufacturing scrap, are already above 10% today and they increase further to around 40-50% in 2050.

Implications for primary mineral supply

For all energy transition minerals, a faster ramp-up of clean energy deployment requires higher levels of primary supply, but also unlocks the potential for significant contributions from secondary supply volumes in the longer term. For example, primary copper demand in the APS grows by 3% annually to reach 26 Mt by 2030, while demand for nickel and cobalt grows more rapidly at around 6.5% per year due to their key role in the production of lithium-ion batteries. The steepest relative increase is for lithium, whose lithium demand grows 18% per year between today and 2030 in the APS. But as demand grows, so do the feedstock volumes for recycling after 2030. Thanks to burgeoning secondary supplies, required primary supply to meet growing demand starts to reduce by mid-century in the APS. Compared with the case without recycling, primary supply requirements are around 40% lower for copper and cobalt, and around 25% for lithium and nickel in 2050. Investments in new supplies would still be needed given that these levels are still higher than today's production levels and that there are natural declines from existing mines. Nonetheless, these reductions in required primary supply volumes highlight the benefits of higher recycling for mineral security, waste management and environmental footprint.

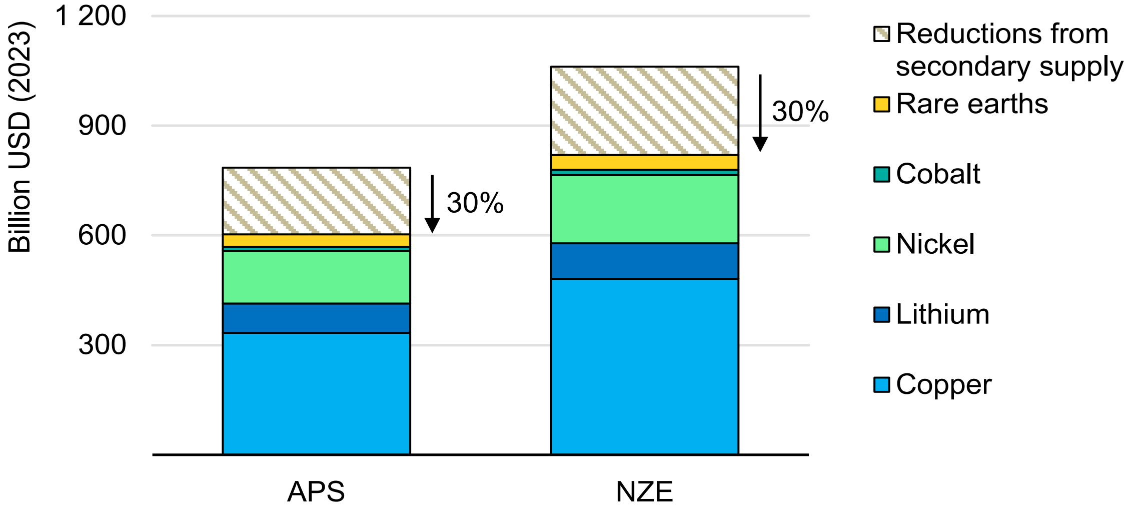
Figure 2.2 Reductions in primary supply requirements from recycling in the APS



Notes: The figures for lithium are on a lithium content basis. Includes total demand and secondary production from all sectors except for nickel, where secondary production from steel is excluded. Direct use scrap is excluded for copper.

Along with the security and environmental benefits (see Chapter 3), scaling up infrastructure to build a reliable source of secondary supply also brings financial benefits for global economies. The capital requirements for new mines to meet the mineral demand implied in the NZE Scenario through to 2040 is around USD 800 billion (excluding sustaining capital expenditure) but in the absence of efforts to ramp up the share of secondary supplies from today's levels, this amount would be over USD 1 trillion or 30% higher.

Figure 2.3 Reduced mining capital requirements to 2040 due to higher share of secondary supply in the APS and NZE Scenario



Notes: Capital requirements for the APS and NZE Scenario are calculated based on compiled capital intensity by region and production route. The values also assume an increased average capital intensity over today due to declining ore grades.
Source: IEA analysis based on data from S&P Global and company reports.

2.2. EV and storage batteries

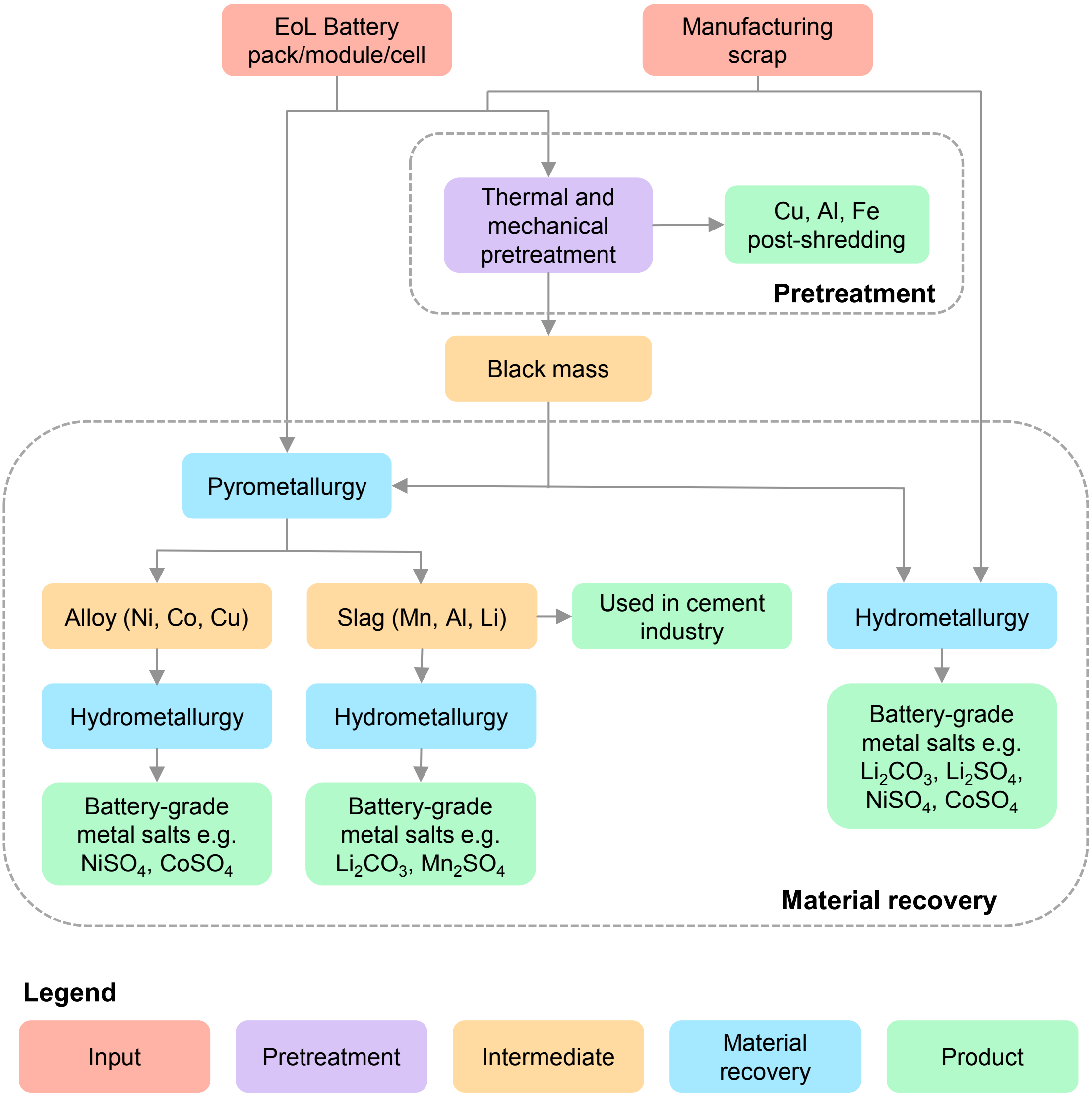
Lithium-ion (Li-ion) batteries are one of the most critical clean energy technologies for the energy transition, enabling decarbonisation of the road transport sector as well as the power sector. However, Li-ion batteries require substantial amounts of critical minerals, in particular lithium, nickel, cobalt, copper and graphite. Therefore, scaling up EV and storage deployment to achieve global climate goals necessitates a dramatic growth in the supply of these key battery materials, raising concerns around their security of supply. However, the rapid growth in battery deployment means that there will also be a significant growth in batteries reaching end of life and battery manufacturing scrap generated from the production processes. Battery recycling can therefore play a major role to recover the key critical minerals from these sources of battery waste and thus alleviate the pressure on their primary supply, reducing the mining requirement. Moreover, given that the supply of battery critical minerals is highly concentrated in a few producer countries, recycling can provide consumer countries their own source of battery materials, forming a key measure of diversification, reduced dependencies and mineral security.

Moreover, the major volumes of batteries that will reach end of life in the future also poses a significant challenge from a waste perspective. With some toxic compounds contained, improper disposal can pose environmental risks. Battery recycling can also minimise environmental impacts through a circular approach, preventing battery landfilling and reducing emissions from mining and refining operations. Battery recycling is one of the most important secondary sources of energy transition critical minerals in the future, particularly lithium, nickel and cobalt.

Recycling processes and pathways

There are a variety of Li-ion battery recycling feedstocks and recycling pathways that may be used to recover a range of battery metals. The Li-ion battery recycling process typically involves two major stages known as “pretreatment” and “material recovery”. Prior to this the end-of-life batteries must be prepared for recycling, first through discharge to minimise thermoelectrical hazards and ensure the battery is safe for further handling. The battery may be discharged before transportation for safety. Next the battery is dismantled, removing pack and module housing, battery management systems, and cooling systems as well as other electronic components to reach cell level.

Figure 2.4 Battery recycling processes and pathways



Note: EoL = end of life; Cu = copper; Al = aluminium; Fe = iron; Ni = nickel; Co = cobalt; Mn = manganese; Li = lithium; $NiSO_4$ = nickel sulphate; $CoSO_4$ = cobalt sulphate; Li_2CO_3 = lithium carbonate; Mn_2SO_4 = manganese sulphate; Li_2SO_4 = lithium sulphate.

Pretreatment

Pretreatment typically involves both thermal and mechanical processes. The mechanical processes physically break down the battery packs, modules or cells through shredding and sorting stages. Various sorting steps including sieving, sifting and flotation are utilised to separate components based on properties such as size, density, magnetism, shape and conductivity. The copper and aluminium current collectors are often separated and recovered during the pretreatment stage. The thermal processes, applied before or after mechanical processes, are used to remove the organic elements such as the binder components of the electrolyte, reducing the impurities for the material recovery stage. The complete process then yields the primary battery material recovery feedstock "black mass" – a powder containing the cathode and anode materials and thus the valuable battery metals such as nickel, cobalt, lithium and graphite. Black mass may still contain impurities including copper and aluminium current collector particles and residual electrolyte. Therefore, some recyclers put black mass through an additional thermal treatment to remove any remaining organic components. The pretreatment stage is typically less technically complex than the material recovery stage, with lower capital requirements.

Material recovery

Material recovery is the step where the battery metals are recycled and recovered, typically from black mass. This is the more technical and complex recycling stage. There are two primary battery recycling methods of material recovery: pyrometallurgy and hydrometallurgy.

Pyrometallurgy

Pyrometallurgy is an established technique for metal extraction and purification, which involves smelting the battery or material in a high-temperature oven, recovering a fraction of the metals as a metal alloy and the remainder of the metals as oxides (slag). The primary recoverable metals are in the form of an alloy (for a lithium nickel manganese cobalt oxide [NMC] chemistry including cobalt, nickel and copper) while others are contained in a slag (such as aluminium, lithium and silicon). Therefore, further hydrometallurgy processing is required to recover the individual metals or battery-grade salts. The removal of several key impurities during the pyrometallurgical smelting process, however, can enable simpler and shorter hydrometallurgy processing. Recovering lithium from the slag is possible using hydrometallurgical processes; however, the yield is typically lower than the nickel and cobalt from the alloy. In pyrometallurgy all the carbon from the graphite is burnt and thus cannot be recovered. Pyrometallurgy requires minimal pretreatment, so battery cells, modules and black mass may be used directly as inputs.

Hydrometallurgy

Hydrometallurgy involves chemical leaching and purification processes to precipitate out individual metal products. Hydrometallurgy can be used to produce battery-grade materials, for instance battery-grade lithium carbonate or nickel sulphates, or it can be used to produce intermediate products depending on the reagents used and the level of processing implemented. Advanced hydrometallurgical routes are being developed in industry which can recover the graphite; however, these processes are in their infancy compared with recovering lithium, nickel and cobalt. The primary inputs for hydrometallurgy are black mass or the intermediate products formed from pyrometallurgy; battery cells or modules cannot be used directly. The black mass feedstock typically has restrictions on the impurity level to be used as an input, for instance copper and aluminium.

Comparing pyrometallurgy and hydrometallurgy

Both methods have flexibility to deal with the feedstock of cells and variety of chemistries. However, pyrometallurgy is more flexible and requires less pretreatment, as hydrometallurgy processes require black mass or intermediate products and are typically designed for a certain range of grades to be economical. Though, to fully recover battery-grade materials from the products, pyrometallurgy still requires the application of additional hydrometallurgical techniques; therefore, pyrometallurgy is often used in combination with hydrometallurgy with a potentially simpler and shorter hydrometallurgical process required. Both methods can recover the valuable metals, specifically nickel and cobalt, and if not recovered during the pretreatment stage, the hydrometallurgy process can be engineered to recover the copper and aluminium. Conventionally, lithium yields from the pyrometallurgy combined with hydrometallurgy were typically lower than hydrometallurgy alone. However, recent developments in pyrometallurgy have enabled high lithium recoveries through recovery of lithium from the flue dust. Pyrometallurgy is a simpler process requiring only the high-temperature smelting, and not even requiring major dismantling, in comparison to the more complex chemistry involved with hydrometallurgy. There are material losses during pretreatment, therefore, using a combination of state-of-the-art pyrometallurgy and hydrometallurgy, requiring minimal pretreatment, can achieve competitive yields.

Direct recycling

Direct recycling is an emerging recycling process with very high recovery rates as it does not break down the cathode material into its constituent metals, but instead retains the material crystal structure and regenerates the cathode material through re-lithiation. This retains the embodied energy and economic value in cathode processing, avoiding the need to resynthesise from raw materials. It is therefore well suited to cathodes containing little valuable metals such as lithium iron phosphate (LFP). However, it is limited by its inflexibility as it must be tailored to each cathode chemistry, and recovered cathodes can be input only into production of the same battery type, which can be an issue as by the time of recovery, the cathode chemistry may be outdated. Nevertheless, new processing methods are under development to convert recycled chemistries into current chemistries e.g. NMC333 to NMC811. Other technical challenges include direct recycling's requirement for complete separation of anode and cathode materials. Therefore, it is well suited to manufacturing scrap where these materials are often available separately. Several companies are working on direct recycling including Farasis

Energy, Kyburz and Brunp (subsidiary of CATL). In 2024, an agreement was signed between Toyota and Argonne National Laboratory where researchers at Argonne will apply their direct recycling process to Toyota cells.

Feedstocks

End-of-life EV and storage Li-ion batteries. This is the primary source for battery recycling in the medium to long term. Batteries from end-of-life EVs and storage must be collected, discharged and dismantled prior to pretreatment and material recovery processes.

Manufacturing scrap. As gigafactories and cathode/anode production facilities start production and ramp up, there is typically significant scrap produced which does not meet quality requirements. This can be full cells or simply components, active material and precursors. Nevertheless, this is a highly important source of recyclable material, being a higher-grade feedstock source for recyclers as the scrap contains fewer impurities or requires less pretreatment and separation. Manufacturing scrap typically contains higher cathode material content and thus more valuable material than end-of-life black mass for instance. It can also be treated by both pyrometallurgical and hydrometallurgical processing routes. Higher-grade scrap is often batched together and separate from lower-grade or end-of-life batteries. Manufacturing scrap is particularly important this decade while EVs have not yet reached end of life and many gigafactories and midstream facilities are ramping up.

Black mass is the primary battery recycling feedstock for hydrometallurgy, being a fine powder containing the cathode and anode materials. Once end-of-life batteries have undergone shredding and separation during the pretreatment stage, the remaining active material mixture is known as black mass, which serves as the critical feedstock for hydrometallurgical recycling processes that recover the metal salts and battery-grade materials. Black mass has varying compositions depending on the chemistries used in the batteries, and has various grades which are again separated as different products.

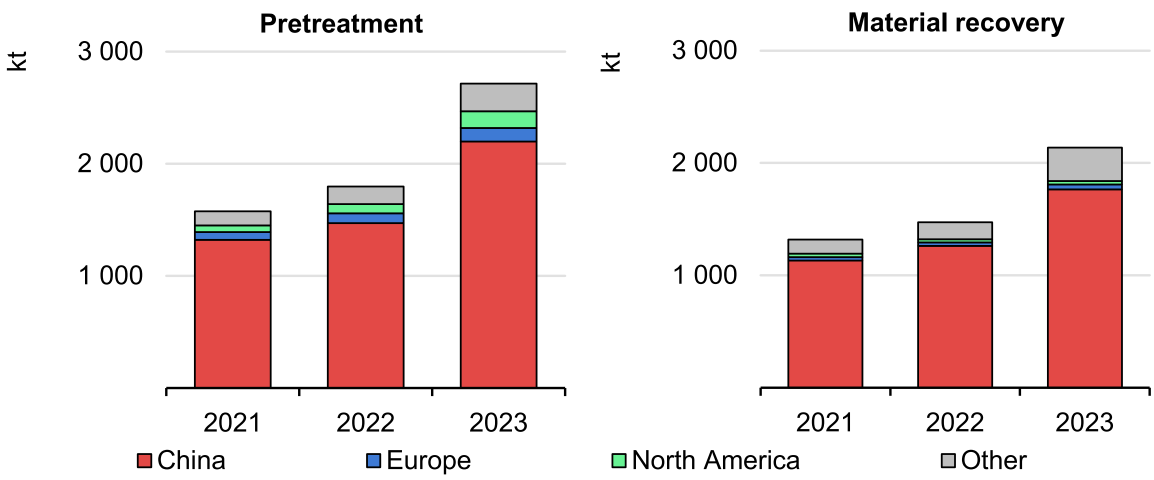
Current status

Capacity today

In 2023, global pretreatment capacity reached over 2 700 kt of cell-equivalent, and material recovery capacity reached 2 100 kt, with both stages experiencing almost 50% growth, notably larger than previous 10% year-on-year growth. Current pretreatment and material recovery capacity is dominated by China, with over 80% of global capacity for both. Europe and North America have a small share of current pretreatment capacity together with around 10%, but they have only 4%

share of material recovery capacity. This means that, despite domestic pretreatment capacity being developed in the United States and Europe, currently the majority of the black mass produced needs to be shipped elsewhere for battery-grade materials to be recovered, thus providing little domestic supply security benefit. Today the world's top 20 companies by capacity for both pretreatment and material recovery are all Chinese companies. The top three Chinese companies – GEM, Brunp (subsidiary of CATL) and Hunan Hongjie New Material – are the leading market players for both pretreatment and material recovery, holding around 15% of the global pretreatment market and almost 20% of the global material recovery market.

Figure 2.5 Historical battery recycling capacity for pretreatment and material recovery



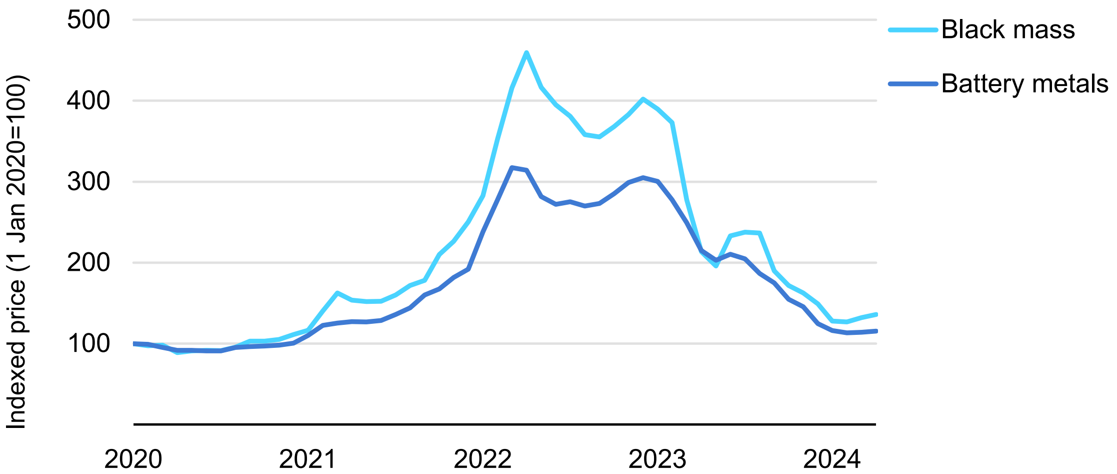
Note: Capacity in kilotonnes of cell-equivalent mass of total recyclable material.
Source: IEA analysis based on Circular Energy Storage.

Due to high yields, capability to produce battery-grade materials and flexibility in handling varying chemistries, hydrometallurgy is already emerging as the dominant Li-ion battery recycling process utilised globally, with over 90% of global capacity in 2023. A combination of pyrometallurgy and hydrometallurgy is the second-most-utilised pathway by capacity, though with only around 5% of global capacity. The additional use of hydrometallurgy enables battery-grade salts to be ascertained from the alloys and products of pyrometallurgy, crucial to be used as inputs.

Black mass price developments

Black mass in China, the world's most developed battery recycling market, is typically priced using payables to the virgin battery-grade mineral spot prices. Therefore, black mass prices are highly correlated to battery-grade metal prices. The payables account for the recycling costs and margins and are typically set to allow a discount to virgin materials due to higher impurities. As of September 2024, the payables for nickel and cobalt black mass in the United States are estimated to be trading at around 65-70%. In the future there may even be a premium for virgin materials given the policy priorities of domestic production in the United States and Europe. LFP black mass is priced differently, as lithium is the only valuable component; therefore, black mass is priced using fixed values based on the lithium content. Black mass from manufacturing scrap has higher cathode material content and is thus priced higher. Since 2020, black mass prices have closely matched battery metal price movements. However, this may change in the future as regulations on recycling become more stringent and demand for black mass increases. Recently in Korea recyclers have been increasing utilisation rates, but black mass supply has not increased to match. This has led to increased competition for black mass to maintain high operating rates during commissioning, driving payables to very high levels.

Figure 2.6 Black mass prices, 2020-2024



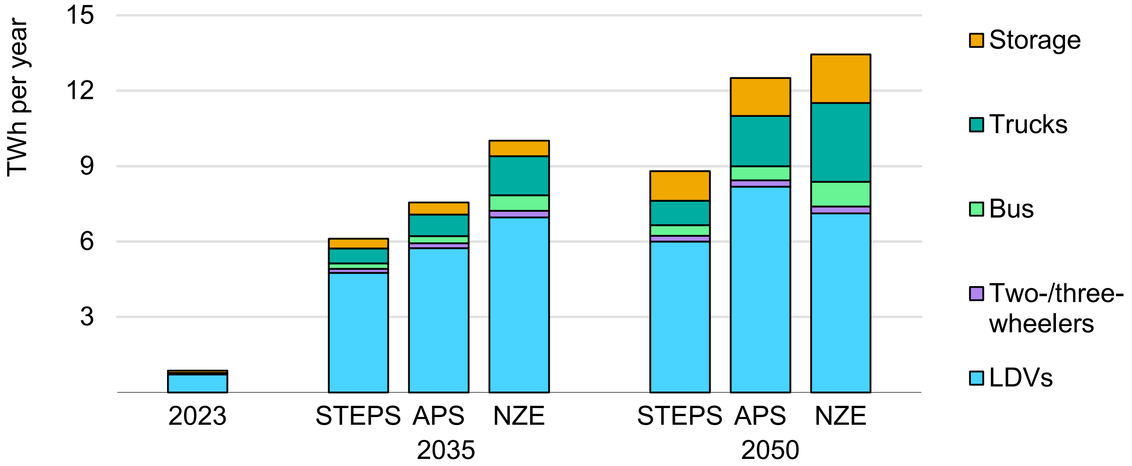
Note: Black mass price including lithium.
Sources: IEA analysis based on Circular Energy Storage, Bloomberg and S&P Global.

Outlook

Battery deployment projections

The exceptional growth in global EV sales is the primary driver for the dramatic growth in battery demand going forward. From almost 1 terawatt-hour (TWh) in 2023, demand increases sevenfold by 2035 to reach over 7.5 TWh in the APS, while increasing over elevenfold to reach 10 TWh by 2035 in the NZE Scenario. The growth in battery demand outpace growth in EV sales due to additional demand growth of battery storage, which surpasses the rates of demand growth for light-duty vehicles in both the STEPS and APS. There is also particularly fast growth in battery demand for electric trucks, which are deployed at scale later this decade, which increases 50-fold in the APS by 2035. In all scenarios, demand from electric trucks becomes larger than global storage demand in 2035. By 2050 global battery demand reaches 12.5 TWh in the APS. In the NZE Scenario, global battery demand reaches 13.5 TWh in 2050, a 16-fold increase from 2023.

Figure 2.7 Battery demand outlook, 2023-2050



Notes: LDVs = light-duty vehicles. EV battery demand in the NZE Scenario includes all modes.

Battery chemistry development and implications for recycling

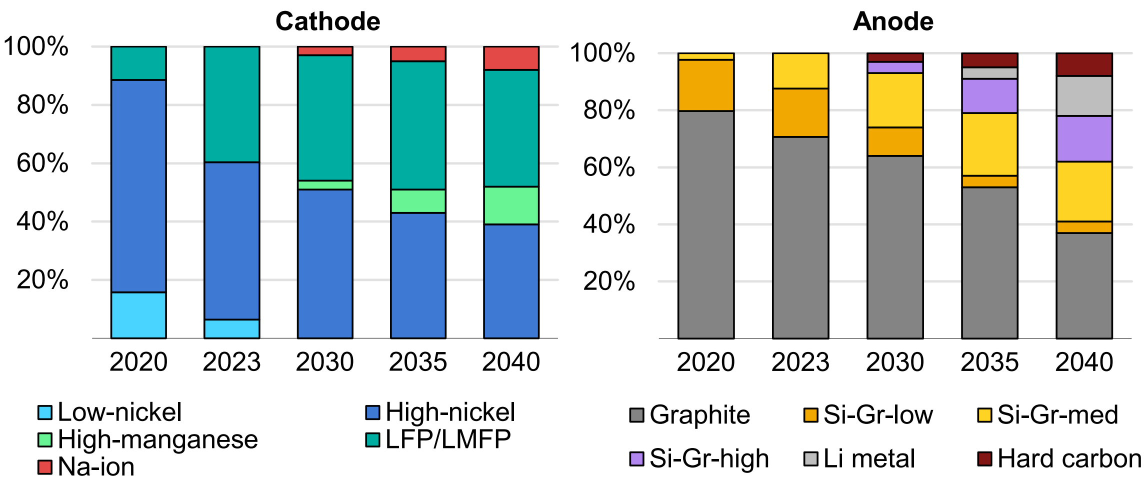
A crucial consideration for battery recycling is the rapidly evolving battery chemistries for electric cars, in particular the development of cathode chemistries where most of the recycling value is contained. A highly consequential development for the recycling industry is the major resurgence of LFP cathodes, which now supply around 40% of the global electric car market up from just 10% in 2020. LFP is a lower energy density and lower-cost chemistry, with greater thermal stability and longer cycle life than the nickel-rich chemistries such as NMC. The cell-to-pack innovation increased the energy density of LFP batteries, and hence their competitiveness, by removing dead pack weight in modules. During the years of high battery metal prices in 2022-2023, LFP batteries became more attractive to reduce exposure to the high nickel and cobalt prices compared with the nickel-rich chemistries. LFP and lithium manganese iron phosphate (LMFP) chemistries combined are set to become the leading chemistries from 2035, taking further share from the nickel-based chemistries. This is a critical development for the battery recycling industry as the recycling economics of LFP are more challenging than nickel-based chemistries (See Section 3.1 in Chapter 3). Lithium is the only valuable recoverable metal from LFP, whereas nickel and cobalt are also recoverable from NMC chemistries, providing significant additional value for recyclers. Therefore, recycled LFP batteries have greater challenges to compete with new LFP batteries, compared to the case with the NMC chemistry, suggesting toll-based recycling business models rather than market-based may be better suited to LFP recycling. This also highlights the importance of regulation and strict recycling mandates, as they guarantee LFP batteries will be recycled despite the more challenging economics for recyclers.

There are reports of Chinese recyclers also recovering battery-grade iron phosphate from hydrometallurgical processes; however, it is unclear whether this can be economically competitive with virgin material. Lessons from the very high recycling rate of lead-acid batteries, despite their low residual value, demonstrate that challenging economics can be overcome with the right policy mandates. Lead-acid batteries, used in internal combustion engine cars, are one of the most highly recycled products with a 99% recycling rate in the United States despite their low residual value. This was achieved through a range of policy measures including banning landfilling, mandating collection and recycling from producers, and incentivising consumer returns.

There are key regional differences in LFP deployment. China is by far the leading region for LFP deployment with two-thirds of all EV batteries sold by capacity in 2023 being LFP. The share of LFP was only 7% for the United States (US) and 6% for Europe in 2023. The lower European and US shares of LFP suggest the LFP recycling economics may be less immediately concerning; however, LFP deployment in both regions is growing rapidly with this trend anticipated to continue. With the scale of deployment increasing each year, LFP batteries are set to be a major source of material to recycle for all regions in the future.

The increasing share of manganese-rich cathode chemistries and sodium-ion in the longer term also pose challenges for the future battery recycling industry. Manganese is a lower-cost metal, helping to reduce battery costs for consumers but again being less valuable for recyclers to recover. Sodium-ion batteries contain few critical minerals, with hard carbon anodes used instead of graphite anodes. The current leading cathode chemistry for sodium-ion are metal oxide cathodes which typically contain nickel. Prussian white cathodes, which contain no critical minerals – only sodium, iron, carbon and nitrogen – are another material anticipated for use in some sodium-ion batteries. The lack of valuable metals again makes the economics of recycling sodium-ion batteries more challenging, again suggesting a toll-based model may be suited for this technology.

Figure 2.8 Electric car battery cathode and anode chemistry development projections, base case, 2020-2050



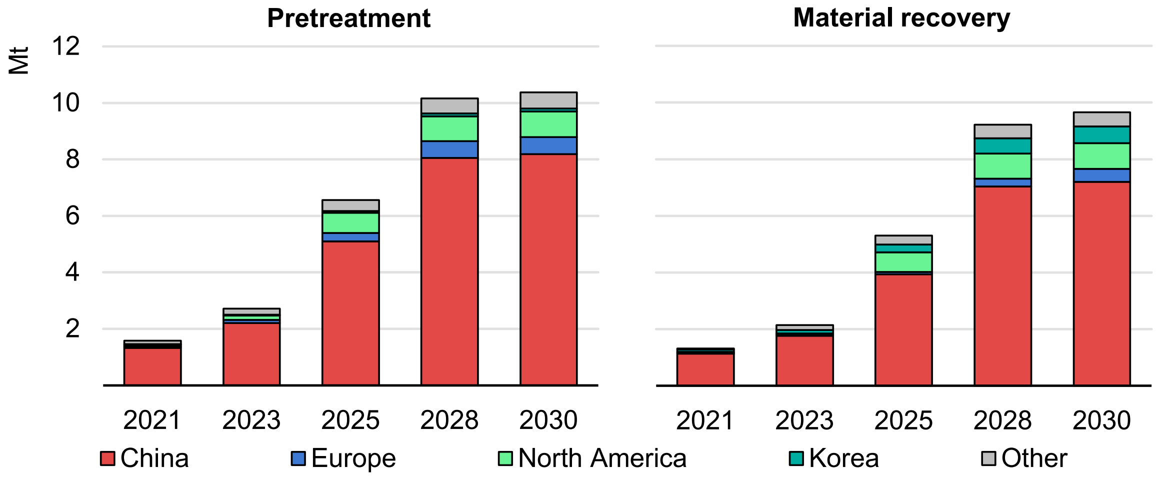
Notes: Base case electric car cathode and anode chemistry share projections. LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate; Na-ion = sodium-ion; NMC = lithium nickel manganese cobalt oxide. NCA = lithium nickel cobalt aluminium oxide. NMCA = lithium nickel manganese cobalt aluminium oxide. LNO = lithium nickel oxide. Low-nickel includes: NMC333 and NMC532. High-nickel includes: NMC622, NMC721, NMC811, NCA, NMCA, LNO. High-manganese includes lithium nickel manganese oxide (LNMO) and lithium-manganese rich NMC (LMR-NMC). Si-Gr = silicon-doped graphite. Si-Gr-low refers to 5% silicon content, Si-Gr-med = 5-50% and Si-Gr-high > 50%.

In terms of anode chemistries, there is a continually growing share of silicon-doped graphite anodes with increasing silicon contents. The trend is expected to continue to displace conventional graphite anodes with potentially full silicon anodes for all-solid-state batteries in the longer term. Silicon, while technically possible to recycle and with novel recycling methods being researched, is a low-value element and thus has very challenging recycling economics. The potentially eventual use of lithium metal anodes in all-solid-state batteries will increase the recoverable value of battery recycling due to its significantly greater value than both silicon and graphite.

Graphite recycling is also currently economically challenging due to its lower value, making it challenging to compete with virgin graphite material for batteries although it may be utilised in other sectors with lower purity requirements. Nevertheless, there has been recent progress developing low-cost recycling methods. Ascend Elements and Koura developed a hydrometallurgical process to produce 99.9% pure graphite exceeding battery-grade requirements and are planning to build a graphite recycling facility in the United States. Graphite processed in the United States can also qualify for the 45X tax credit, which will significantly improve the economics of graphite recycling in the region. Scientists recently developed a low-cost method of graphite recycling that has been shown to produce battery performance comparable with cells using virgin material, offering a potentially promising solution. With the graphite export controls introduced by China in December 2023, there is now greater incentive to develop graphite recycling capability to increase security of supply. Policy support could therefore support the economics of graphite recycling.

Recycling capacity development

Figure 2.9 Expected battery recycling capacity based on announced projects

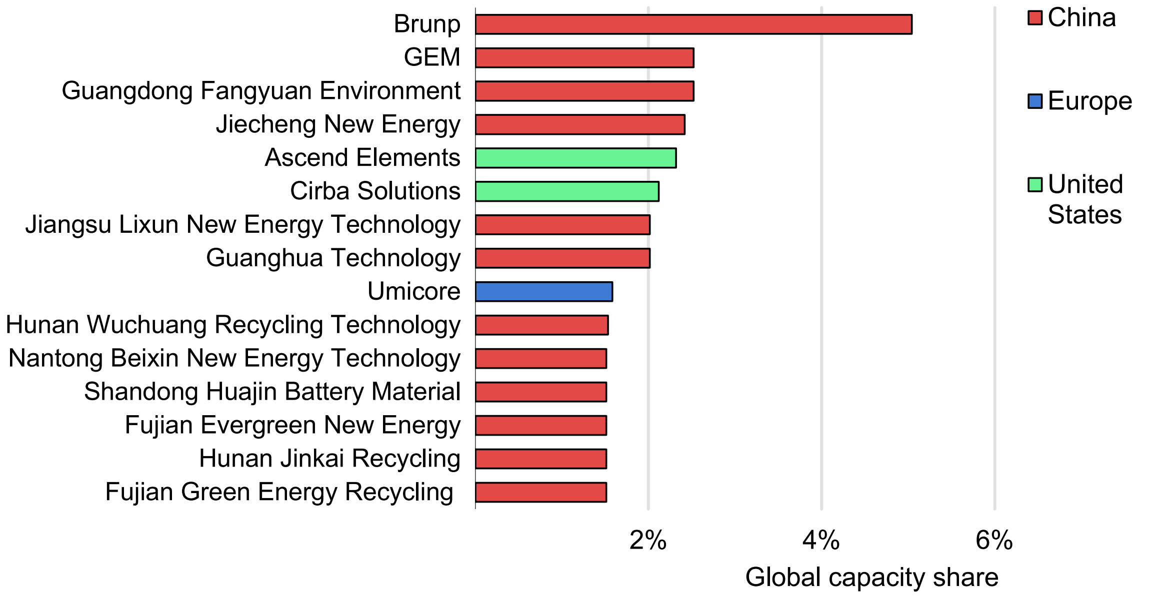


Note: Capacity in kilotonnes of cell-equivalent mass of total recyclable material.
Source: IEA analysis based on Circular Energy Storage.

Battery recycling capacity this decade, like all mid- and downstream stages of the battery supply chain, is dominated by China for both pretreatment and material recovery. Analysis of announced projects indicate that both capacities increase significantly, reaching around 10 Mt of cell-equivalent capacity by 2030. Some diversification occurs with North America holding 10% of preprocessing and material recovery capacity by 2030, while Europe holds around half of this with 5% of each. Korea also plays a major role going forward in material recovery capacity, reaching almost 600 kt in 2030, around 5% global share. Nevertheless, China is poised to retain over 80% of global pretreatment share and 75% of global material recovery capacity in 2030. Battery recycling facilities tend to be planned next to battery manufacturing facilities to minimise any transportation costs of manufacturing scrap. For example, Redwood Materials in Nevada which has a partnership with the Tesla-Panasonic gigafactory in Nevada, recycling its manufacturing scrap. After 2035, when it is anticipated EVs will reach end of life at major scale, there may be a case for more distributed recycling facilities depending on the costs of transporting end-of-life batteries compared with transporting recycled product.

Looking at the top battery recycling companies' capacity announcements also shows some levels of diversification from 2023 when all of the top 20 companies were Chinese. By 2030, US companies Ascend Elements and Cirba Solutions become the fifth- and sixth-largest pretreatment companies and the sixth- and seventh-largest companies for material recovery. Umicore is Europe's largest recycler, with a 2% market share for both the pretreatment and metal recovery stages. The battery recycling subsidiary of Northvolt, Revolt, may become a major player with 2% of the material recovery market if capacity announcements are realised. Nevertheless, both markets appear set to remain dominated by China, with CATL subsidiary Brunp having the largest market share of both stages, with around 5% of pretreatment and recovery market, double the share of the second-largest companies. However, this is based on announced project capacities, some of which may not come to fruition as scheduled or, if there is excess capacity, may be underutilised.

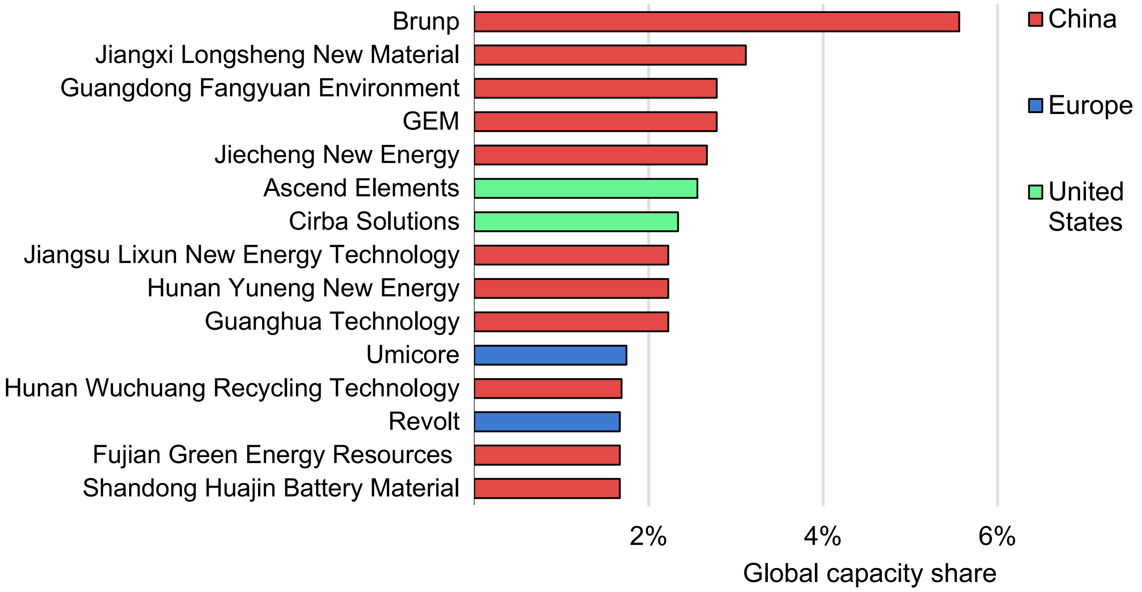
Figure 2.10 Top global battery pretreatment recycling companies by capacity based on announced projects, 2030



Notes: Colour refers to ownership region based on company headquarters location. Companies ordered by global capacity share based on announcements in 2030.

Source: IEA analysis based on Circular Energy Storage.

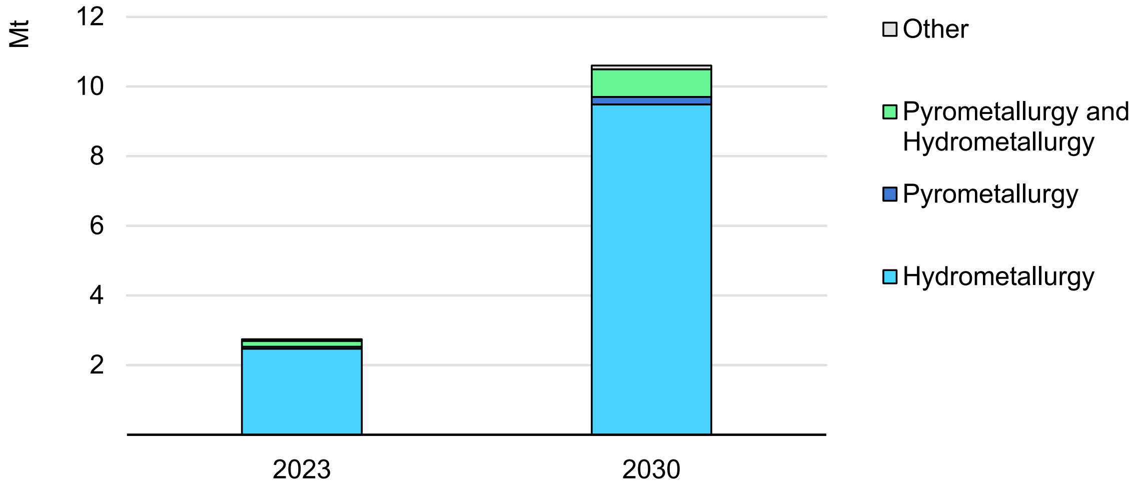
Figure 2.11 Top global battery material recovery recycling companies by capacity based on announced projects, 2030



Notes: Colour refers to ownership region based on company headquarters location. Companies ordered by global capacity share based on announcements in 2030.
Source: IEA analysis based on Circular Energy Storage.

Based on the current recycling project pipeline, with 90% of global capacity in 2030, hydrometallurgy is set to maintain its dominant position over other recycling processes for material recovery, again due to its high yields, competitive economics and flexibility to handle different chemistries. The combination of pyrometallurgy and hydrometallurgy is also set to grow its share modestly with novel processes being implemented with high yields, and simpler hydrometallurgical processes. Other methods including electrochemical techniques utilised by companies such as Nth Cycle are also anticipated to take global capacity share by 2030. Direct recycling is anticipated to make an impact in the next decade.

Figure 2.12 Recycling capacity by process, 2023 and 2030



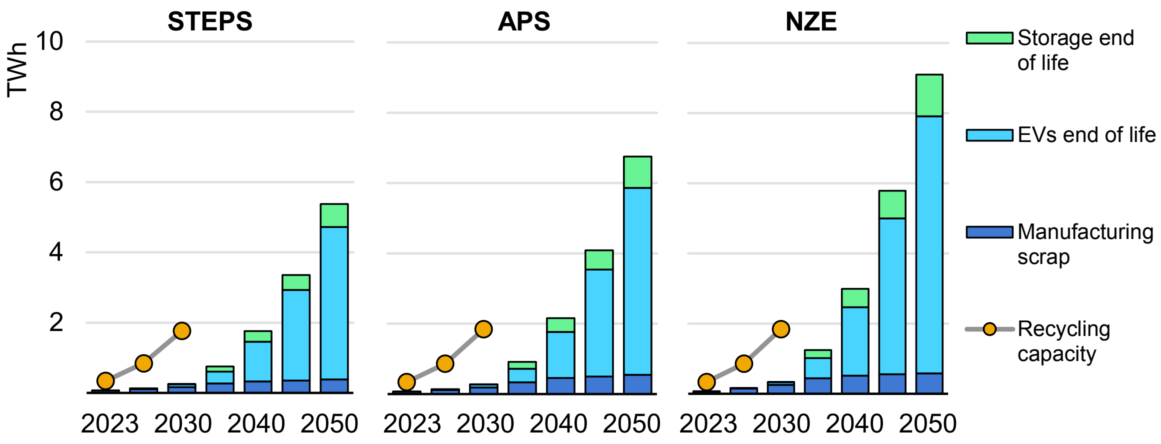
Sources: IEA analysis based on company announcements, BloombergNEF and Baum et al. (2022), Lithium-Ion Battery Recycling – Overview of Techniques and Trends.

Available battery material feedstock for recycling

One of the most critical questions for battery recyclers is when there will be the surge in available end-of-life EV batteries. There is considerable uncertainty regarding EV lifetimes, whether there will be EV exports to other markets and how this will affect available feedstock. Until 2035 the available material feedstocks to recycle are dominated by manufacturing scrap as EVs are anticipated to reach end-of-life at major scale only around then. In 2030 the global total battery material feedstock available to recycle is around 250 gigawatt-hours (GWh) in the STEPS and almost 300 GWh in the APS, of which two-thirds is manufacturing scrap in both scenarios. In the NZE Scenario, 350 GWh of material is available, of which 75% is manufacturing scrap. From 2035 however, end-of-life EV batteries become the largest source of battery recycling feedstock, responsible for around 45% of available material in all three scenarios.

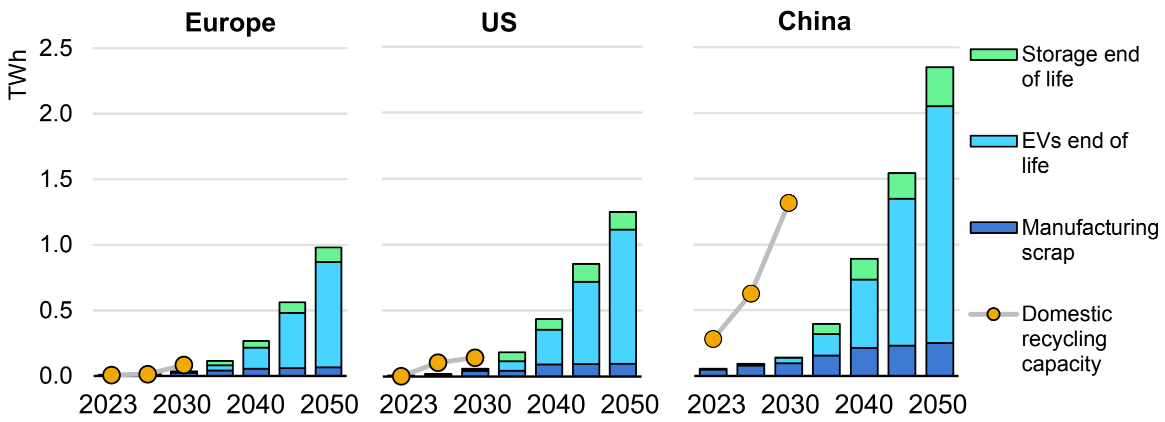
If all announced projects come online as scheduled, global recycling capacity in 2030 could be more than five times larger than total available material feedstock in that year in the NZE Scenario, indicating significant excess capacity. However, from 2040 global recyclable battery material supply increases dramatically driven by end-of-life EVs reaching 5.5 TWh in the STEPS, almost 7 TWh in the APS and over 9 TWh in the NZE Scenario in 2050.

Figure 2.13 Global available battery recycling feedstock and recycling capacity, 2023-2050



Notes: Global available feedstock shows maximum possible feedstock volumes for recycling before any collection rates or recycling process yield losses. Projected capacity is based on announced projects. 85% maximum utilisation rate for production capacity is assumed. Recycling capacity refers to material recovery capacity. Excludes batteries from portable electronics and e-bikes.

Figure 2.14 Regional available battery recycling feedstock and recycling capacity in the APS, 2023-2050



Notes: Available feedstock shows maximum possible feedstock volumes for recycling before any collection rates or recycling process yield losses. 85% maximum utilisation rate for production capacity is assumed. Recycling capacity refers to material recovery capacity. Excludes batteries from portable electronics and e-bikes.

Looking at the available material and capacity regionally, however, shows a very different picture. In China there is considerable overcapacity, with domestic capacity five times larger than domestic material availability in 2023, equating to a utilisation rate of only 20% if all available material is collected. In Europe current domestic material recovery capacity is around the same as domestic feedstock supply. However, the United States has a significant material recovery capacity deficit to process the available recyclable material with domestic capacity meeting only 25% of feedstock supply. In India domestic capacity meets only 5% of available feedstock, showing a major capacity deficit. This is one of the key reasons why significant black mass exports to east Asia are occurring from these regions due to the current lack of material recovery capacity. Despite China’s de facto black mass import ban via its hazardous waste classification, black mass still enters via other Southeast Asian countries such as Malaysia, the Philippines and Thailand, which provide some level of processing removing elements such as lead before shipping it to China for recycling under mixed hydroxide precipitate (MHP) classification. Nevertheless, there is a possibility that China removes this black mass import ban in the near future. Meanwhile the European Commission is reviewing the reclassification of black mass and battery scrap as hazardous waste, which intends to prevent unmanaged export to non-member countries of the Organisation for Economic Co-operation and Development (OECD) via the EU Waste Shipment Regulation to limit material leakage.

Looking ahead in China, there continues to have significant excess capacity compared with domestic feedstock availability. Chinese recycling capacity in 2030 is 9 times larger than domestic material available in the APS in 2030 and is even 1.5 times larger than the material available in 2040 in the APS. This exceptional surplus of recycling capacity demonstrates a similar picture to Chinese battery cell and solar module production where there is considerable excess capacity, which has led to fierce price competition and market consolidation. Therefore, there can also be an expected push from Chinese recyclers to access battery recycling feedstock from the rest of the world going forward.

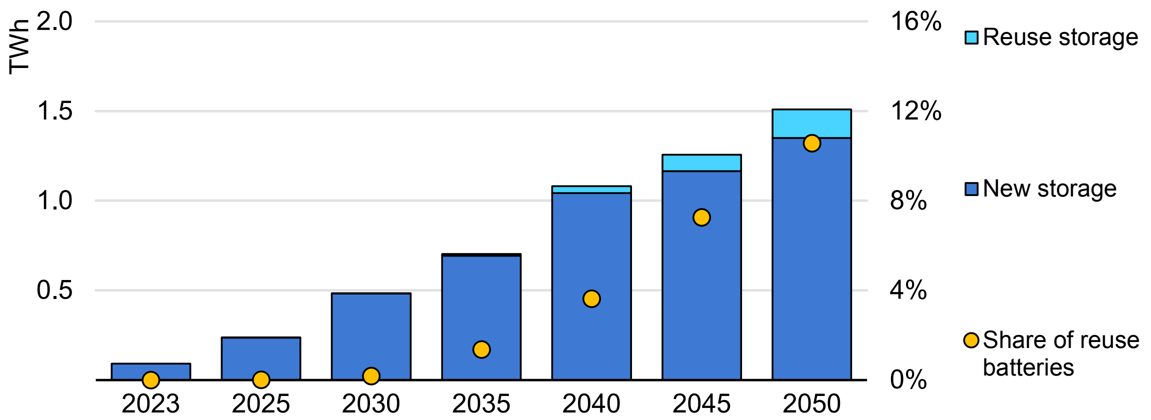
For the United States and Europe, it is a different picture compared with today, with more than sufficient capacity to process available material feedstock but considerably less surplus capacity than China in 2030. For Europe and the United States, domestic capacity in 2030 is 2.5 times larger than domestic feedstock in the APS in 2030. However, as feedstock grows rapidly thereafter, it is only 40% greater than available feedstock material in 2035. For the United States, domestic capacity in 2030 is 2.5 times larger than 2030 supply in the APS but meets only 75% of feedstock supply in 2035. In India, only a quarter of 2030 feedstock can be met by domestic capacity. Whether battery recycling markets become regional or global is a key determining factor in how this plays out. The growth in capacity in European and US markets appears on track to satisfy domestic feedstock supply with little excess, whereas China has a considerable domestic excess capacity. Securing sufficient supply of recyclable battery material before the later surge in end-of-life batteries will be the key challenge for recyclers, particularly in China.

Projected reuse

Reuse or second-life applications of EV batteries in storage applications has long been discussed and anticipated. However, reuse accounts for only a small share in total grid storage deployment due to challenging economics. The costs of disassembly, grading, testing, quality control and the additional liability regarding reuse are challenging to compete with the continually decreasing costs of new batteries. This is particularly true as LFP is the primary chemistry used for storage applications and is the lowest-cost chemistry. Reuse volumes grow to only 40 GWh in 2040 and 160 GWh in 2050 in the APS and 220 GWh in 2050 in the NZE Scenario. In both scenarios this results in only 10% of the global storage demand being met by reuse in 2050. Though a small market, batteries used in reuse applications reduce available recycling volumes with the material becoming available for recycling after its application in the grid.

There are also instances where EV battery packs are being dismantled illegally at end of life with the cells being reused in e-bikes due to higher value than being recycled. This has led to some safety incidents including e-bike fires and challenges for some of the largest Chinese battery recyclers in collecting batteries for recycling. It is anticipated that regulations in China will tighten to restrict this practice, but it demonstrates an issue of illegal reuse which may become prevalent in some areas without proper regulation.

Figure 2.15 Batteries reused in storage applications in the APS, 2023-2050

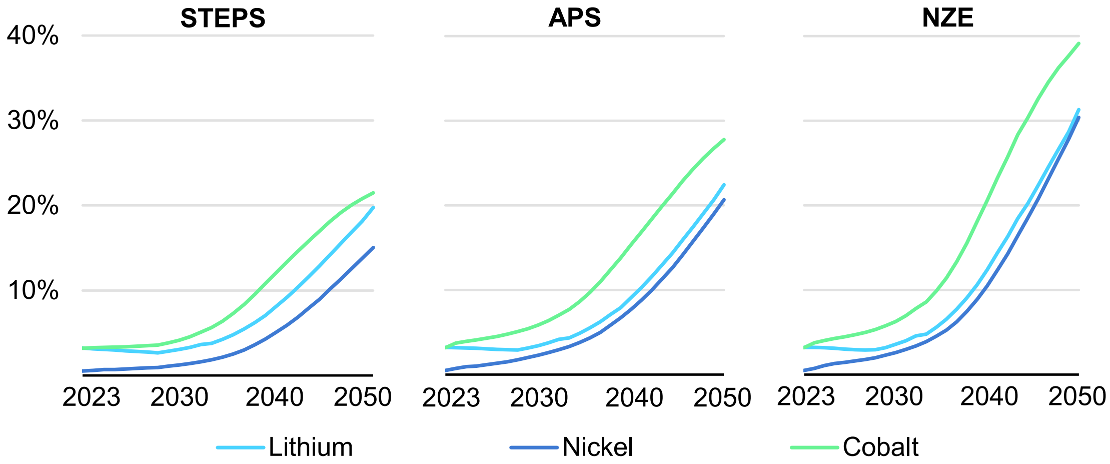


Notes: Reuse batteries refer to EV batteries that have been repurposed after reaching end of life for a second life in storage applications.

Projected metal recovery from battery recycling

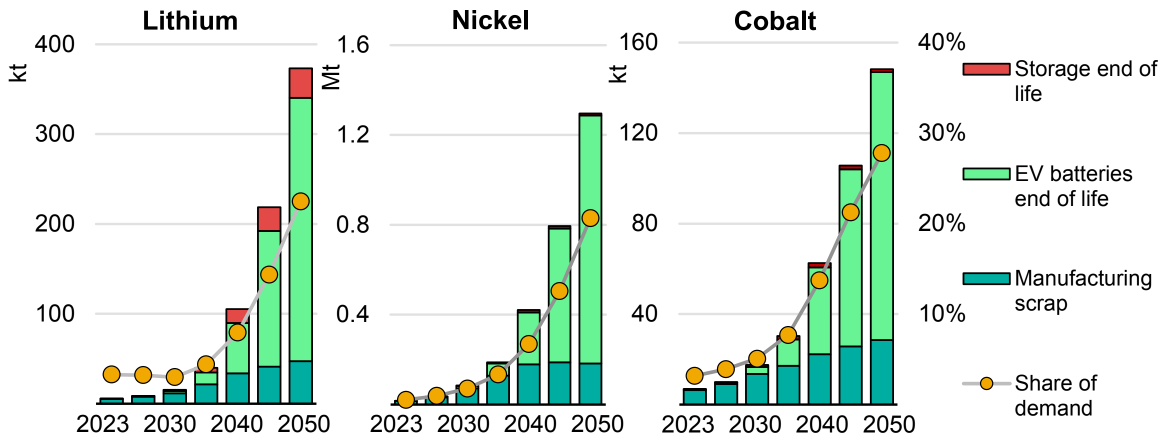
How the available battery material for recycling translates into secondary supply battery metals and minerals depends on factors including collection rates, recycling process shares and recycling process yields. Due to the particularly rapid growth in lithium demand outpacing the growth in lithium recycling volumes, the share of secondary supply of lithium from EV and storage batteries manufacturing scrap and end-of-life recycling falls 0.5% from 2024 to 2030. Cobalt and nickel secondary supply shares grow continually going forward in all scenarios. Cobalt has the highest share of secondary supply, reaching around 12% of global demand in both the STEPS and APS in 2040. The higher share is due to the decreasing cobalt content in current and future battery chemistries coupled with its higher value. Lithium and nickel reach only half the share of global demand, with around 7% in the same scenarios in 2040. By 2050 this increases to almost 30% for cobalt and just over 20% for lithium and nickel in the APS, increasing to 40% for cobalt and 30% for lithium and nickel in the NZE Scenario. In 2050, in the APS, secondary lithium from EV and storage batteries reaches over 370 kt, nickel almost 1.3 Mt and cobalt 150 kt in 2050.

Figure 2.16 Secondary battery metals supply as share of global demand, 2023-2050



Notes: Secondary supply based on recycled metal volumes which refer to the metal volumes recovered from recycling, accounting for collection and recycling process yield losses. Secondary supply includes EV and storage batteries manufacturing scrap and end-of-life recycling. Other sources excluded. Demand includes all sources.

Figure 2.17 Recycled battery metal volumes in the APS



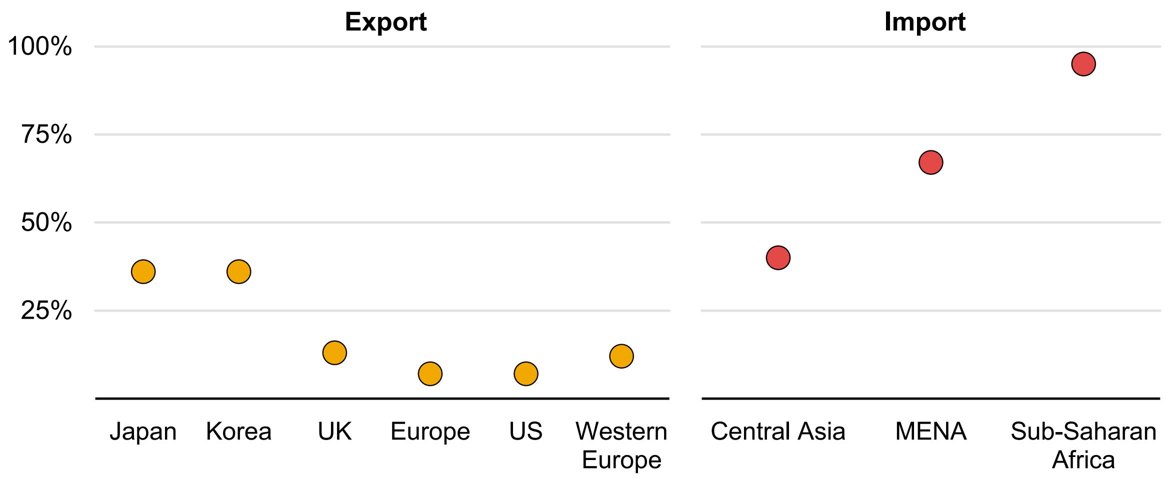
Notes: Recycled metal volumes detail the metal volumes recovered from recycling, accounting for collection and recycling process yield losses. Recycled volumes from EV and storage batteries manufacturing scrap and end-of-life recycling. Other sources excluded for share of demand. Demand includes all sources.

Spotlight: Implications of second-hand EV and battery export

Around a quarter of the world's population lives in countries where at least half of the cars on the road are imported used vehicles. This trade is predominantly from advanced economies to emerging market and developing economies because used vehicles are lower cost for consumers. There is considerable uncertainty as to whether this trend will continue with EVs, with significant implications for the battery recycling industry. Around a quarter of total vehicles imported by emerging economies have poor emissions standards and are highly polluting. Therefore, the export of used EVs to developing countries provides clean vehicles through more affordable EV options thus likely increasing their adoption, improving air quality and also supporting the decarbonisation efforts of these countries. However, when there is a lack of capacity to process and recycle the batteries in importing countries, it means a reduction of recycled volumes globally, potentially necessitating greater primary supply. For exporting regions, there are implications for domestic security of supply as the batteries, and critical minerals contained within, leave the original end-of-life country and region, reducing the feedstock available for domestic recycling.

There are several trends which make it likely that EV exports will not reach the levels seen with internal combustion vehicles. First, the lack of charging infrastructure in importing countries; second, the policy priorities to retain end-of-life batteries and critical minerals domestically for recycling in regions such the United States and EU; third, the greater logistical and safety challenges in transporting used EVs and batteries; and fourth, the possible influx of low-cost internal combustion engine (ICE) cars toward emerging markets as they become less popular in developed markets. Nevertheless, there is considerable uncertainty as to how this plays out.

Figure 2.18 Share of used internal combustion engine vehicles exported and imported in selected regions, average 2015-2020



IEA. CC BY 4.0.

Source: ITF (2023), New but Used: The Electric Vehicle Transition and the Global Second-hand Car Trade.

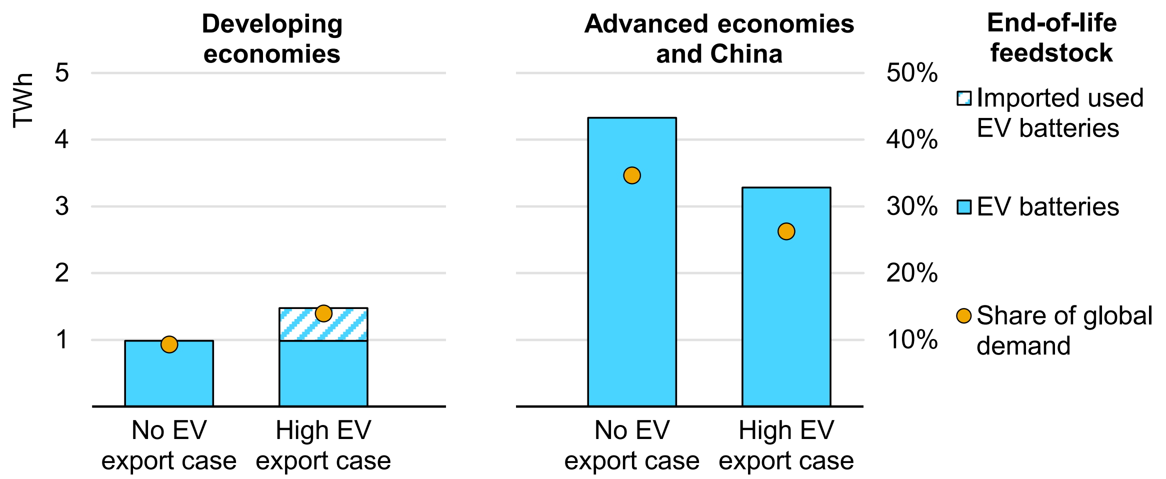
Between 2015 and 2020 both Japan and Korea exported over 35% of vehicle deregistrations, the United Kingdom almost 15%, and the United States and Europe 7%. Though the majority of used vehicles in Europe are exported within Europe from Western to Eastern European countries. Meanwhile, 40% of vehicles sold in Central Asia are imported, increasing to 67% in the Middle East and North Africa, and 95% in Sub-Saharan Africa. However, a critical qualification is that used vehicle exports are significantly under-reported for several reasons, for instance in particular for land borders, therefore the export shares for United States and Europe are likely underestimated whereas the shares for Japan and Korea are likely more accurate. Exports of new vehicles from China have grown consistently over recent years and it is expected the same may happen for used vehicles with the major wave of vehicles reaching end of life in coming years.

To illustrate the potential impact of EV exports on the battery recycling market, we present the *High EV Export Case* where export of EVs is assumed to follow the same trends for ICE vehicles, against the *No EV Export Case*. For China it is assumed that the export share will match that of Japan and Korea due to its rapid growth in exports, and this is a critical determinant of the exported volumes.

In the APS context, the results show that in the High EV Export Case that global available battery material feedstock for recycling in advanced economies and

China decreases by a quarter in 2050 from 4.3 TWh in the No EV Export Case to 3.3 TWh. Yet, in developing economies, as imported EVs reach their end of life, the available battery material to recycle increases by 50% to 1.5 TWh by 2050. Therefore, though there will be a significant reduction in available material to recycle in advanced economies, there is also eventually a corresponding increase in developing economies. However, given the new lifetime of the imported EVs, the timing of the batteries becoming available for recycling will be delayed. Moreover, further recycling capacity would be needed in these regions to properly recycle battery materials as used EVs are retired. Battery recycling pretreatment facilities producing black mass could be particularly well suited to developing countries, since they are less technically complex and specialised with lower capital requirements, and thus could provide an economic development opportunity for these regions.

Figure 2.19 Impacts of used EV export on end-of-life batteries feedstock for recycling, 2050



Notes: High export case assumes export of EVs is the same as for ICE vehicles based on regional and country export share data. No export case assumes there is no EV export. Imported EV vehicles are assumed to have a different lifetime to the first life of EVs.
Source: IEA analysis based on ITF (2023), New but Used: The Electric Vehicle Transition and the Global Second-hand Car Trade.

One of the most critical determinants of the extent of EV export is the regulations in place, particularly for EV batteries. According to the European Union battery regulation, batteries cannot be exported from the European Union without evidence that they will be treated by the recipient according to human health and environmental protection standards equivalent to those required in the European Union. How this will be enforced is a key question, and there are similar learnings from the European Union Waste from Electrical and Electronic Equipment (WEEE) directive, which restricted material export of WEEE to countries that did not meet equivalent requirements for disposal.

Policy implications

Key barriers

There are several barriers to development of a successful global battery recycling industry.

The mismatch of waste codes for black mass and end-of-life batteries within regions, including their interpretation and application, such as across the European Union and North America. This creates frictions and inefficiencies which hinder the development of an efficient, competitive, regional battery recycling supply chain. Today, lithium-ion batteries are typically categorised under code 16 06 05 of the European Waste Code. However, rules surrounding the transportation of end-of-life EV batteries vary according to the batteries' conditions, their mode of transport and how they are labelled. Moreover, the classification of black mass under the European Waste Code is not straightforward, as the material is made up of multiple materials considered hazardous under EU Classification, Labelling, and Packaging (CLP) Regulation. Administrative procedures for shipping black mass can vary between countries, making its transportation more inefficient, challenging and costly.

The lack of clear long-term battery recycling regulations including battery waste export restrictions and how extended producer responsibility (EPR) will be implemented and enforced. Without clarity on these rules, there is significant uncertainty about the environment recyclers will be operating within, which deters long-term investment. Material recovery facilities are large and capital-intensive; therefore, as much clarity as possible is needed on the long-term regulatory environment to provide confidence for strategic decisions and project investments. The rules will even shape the most appropriate recycling business model, for instance toll or market-based.

Lack of financial and permitting support for strategic recycling projects. In lower battery metal price environments, the economics of recycling in regions such as Europe and North America can be more challenging. Global market conditions could make it more difficult for European and US recyclers to compete with Chinese recyclers on cost due to their vertical integration, scale advantages and low labour costs, with Chinese recyclers likely to be able to pay higher prices for black mass and battery waste and still make a profit margin. To build domestic recycling capacity in such environments may require initial financial support and project de-risking measures.

The lack of simultaneous development of the midstream battery supply chain. In recent years, a growing number of projects to build battery cells have been announced in various regions such as Europe and the United States. However, announced projects for the midstream value chain such as precursor cathode active material (pCAM) and cathode active material (CAM) are still lacking. Based on announced projects, almost 90% of these midstream capacities are set to remain concentrated in China by 2030. European or US recyclers would have to compete with Chinese recyclers to sell their refined products to these CAM producers. Again, due to the lower costs of Chinese recyclers, their products could be sold at discounts to Western recycled products, which also would need to include shipping costs, making it more challenging to compete. Moreover, any domestic security advantages of developing a domestic recycling industry are lost at this stage as there remains a dependency on Chinese CAM producers since CAM is the actual product required by the European battery cell producers.

The lack of clarity on rules for EV export reduces confidence where recyclable material will become available and in future feedstock supplies, deterring investment in recycling projects in both exporter and importer regions.

The uncertainty regarding future battery chemistry development means that many valuable metals and minerals to recover now may be less relevant in the future. Also, the future recycling economics can change if chemistries such as sodium-ion penetrate highly where there are fewer valuable metals to recover.

Sector-specific recommendations

Waste legislation and enforcement

Improve harmonisation of regional black mass and battery waste codes. This is critical to ensure the development of an efficient and competitive regional battery recycling supply chain, reducing costs and increasing margins. Given that the hub-and-spoke business model is particularly suitable for battery recycling, it is important that waste flows can be transported efficiently between smaller pretreatment facilities and material recovery hubs. The alignment of waste codes must also involve harmonisation with freight and shipping regulations.

Minimise unmanaged leakage of recyclable battery waste. Critical to the development of a successful domestic and regional battery recycling industry is the supply of recyclable waste and feedstock. Before around 2035, when EVs reach end of life at scale, there will be high global competition for feedstock, particularly with the significant excess capacity in China. Moreover, the black market for trade of used vehicles is substantial for ICE vehicles, and similar patterns could be anticipated for used EVs and their batteries, albeit at a smaller scale. Therefore, taking measures to minimise untraced EV batteries and battery recyclable waste leakage is key. Traceability measures such as those planned for the EU battery passport could be adapted to minimise black market EV export and control waste flows to ensure they are properly recycled. Measures such as the

EU End-of-Life Vehicle Directive (ELV Directive) and Waste Shipments Regulation can help to curb leakage by setting stricter controls on the export of waste to non-EU countries.

Provide long-term visibility for battery waste and EV export rules and enforcement measures with increasing ambition to ensure eventual recycling. In addition to measures to regulate material leakage without assurance of effective recycling measures, clear, strict rules set on battery waste and EV export and import conditions requirements are critical to provide as early as possible. This again enables the location that end-of-life batteries and recyclable feedstock will become available to be forecast more accurately and helps businesses plan ahead and make the necessary project investments. The Waste Shipments Regulation for the European Union is a good example in this regard.

Clearly define and progressively increase EPR requirements, recycled content regulations and enforcement measures. Clear definitions of EPR rules and enforcement measures are critical to provide confidence to investors and recycling companies. Progressively increasing, and clear, EPR and recycled content requirements – for instance the increasing recycled content requirements in the EU battery regulation – reduce risk for recycling projects, providing a guaranteed market, thus stimulating necessary investment. This also supports recycling of battery chemistries with more challenging recycling economics such as LFP.

Project and infrastructure development

Support strategic recycling projects and incentivise developments of the midstream value chains such as pCAM and CAM. Refined battery chemicals such as lithium carbonate or nickel sulphates, which are typical main recycling outputs, are processed into CAM to be used as inputs for battery cell manufacturing. Providing financial, de-risking and permitting support could prioritise integrated strategic projects extending to pCAM and CAM production. These integrated projects reduce dependencies for CAM production, resulting in an increasing closed-loop system, as well as positively impacting the recycling economics. Given the significantly greater battery cell production capacity in Europe and the United States than CAM production, developing the CAM value chain could provide more guaranteed domestic off-takers for recyclers. For example, Northvolt is aiming to produce CAM from the battery metals it recycles through its recycling programme Revolt. These projects could receive support similar to that for the strategic projects for the EU Critical Raw Materials Act (CRMA), including improved access to financing and permitting fast-tracking.

Support and incentivise graphite recycling projects and those projects with greater flexibility to deal with various battery chemistries and cell formats. There will be a wide variety of battery chemistries utilised going forward and recyclers need to be able to be adaptable to recover materials from them. Therefore, providing support to those recycling facilities preparing chemistry flexibility is important. Despite novel graphite recovery processes being developed, graphite recycling is currently economically challenging. Supporting and incentivising these projects is important to provide a domestic source of graphite supply as well as reducing its waste. The same applies with cell formats; however, with the market consolidation occurring in the battery manufacturing sector, cell formats may become more standardised, which may simplify this area of recycling, as was the case for lead-acid batteries. Nevertheless, chemistries and cell formats are a source of competitive advantage for battery manufacturers, therefore recyclers are likely to benefit from flexibility to these. Support such as that offered by the EU CRMA for strategic projects could be beneficial.

Facilitate battery recycling capacity-building investment in developing countries. Providing technical assistance for recycling capacity building in developing countries, where it is possible a significant volume of EV batteries will reach end of life after used EV exports, will be crucial to ensure that EV batteries do not reach landfill, and critical minerals are recovered. This can also support a new industry and area of economic development in developing and emerging economies. Foreign direct investments and policy development banks can strategically support these projects. The development of pretreatment capacity in these regions, which is less capital-intensive and technically complex, is particularly well suited. While domestic capacity is being built, countries could support these countries with collection activities and in the logistics to transport their waste batteries to countries with recycling capacity.

Facilitate the development of comprehensive collection and take-back infrastructure. Support in developing schemes that streamline and incentivise collection of end-of-life batteries and EVs plays an important role, together with information and communication campaigns for consumers, and incentives to increase battery collection rates. Policies for the collection of used electronics already exist: the EU WEEE and Restriction of Hazardous Substances (RoHS) Directives, which together entered EU law in 2003, increased WEEE collection rates to 11 kilogrammes (kg) per inhabitant in 2021, accounting for over half of the WEEE generated in the same year (19.6 kg/inhabitant). A combination of progressive collection rate targets, consumer information campaigns, EPR mandates requiring electronics distributors to facilitate collection and recycling, and improved collection infrastructure have enabled the region to redirect electrical waste flows towards recycling. China, on the other hand, has mandated that battery and EV manufacturers bear the responsibility of facilitating EV battery recycling by standardising battery assemblies, building collection networks and tracing new batteries throughout their lifetimes. The EU battery regulation specifies measures to increase EV battery collection rates including progressively increasing collection targets and ensuring producers of batteries collect waste batteries in the member state where they make the batteries available on the market, through measures such as establishing a take-back and collection system, setting up collection points, and offering the collection free of charge. The EU CRMA also requires member states to increase the collection rates of products containing critical minerals. Experience of lead-acid batteries can provide valuable lessons, where landfilling is prohibited all over the world, collection activities are mandated by producers, and recycling points are widely available.

Collaboration and partnerships

Strategic partnerships between recycler and CAM producing countries as well as pretreatment and material recovery countries. For instance, Korea is developing considerable domestic CAM production capacity and therefore could provide off-takers for European or US recycled refined products. Korea is also developing significant material recovery capacity, which may lead to some vertical integration of CAM production. Partnerships and offtake agreements de-risk key recycling projects and provide the guaranteed market needed for investment. This can form a supplementary solution to building domestic CAM production with recycling. Moreover, this could support the development of a recycling industry in emerging markets where pretreatment facilities could produce black mass that is exported to countries with material recovery capacity.

2.3. Copper recycling

Scaling up the recycling of end-of-life scrap from traditional industries is also essential to reduce pressure on critical mineral supply. Here, we explore this using copper as an example.

Copper has a unique and unmatched combination of characteristics: high electronic conductivity, longevity, ductility and corrosion resistance at a reasonable price. This combination but particularly the superior conductivity is the critical reason for it being present in all of the most important clean energy technologies – EVs, batteries, solar photovoltaic (PV), wind and electricity networks. However, copper faces one of the most concerning supply gaps of all critical minerals. Based on anticipated secondary supply and the current mining project pipeline, there is a copper supply deficit emerging to develop as early as later this decade. By 2035 announced projects are only sufficient to meet 70% of copper requirements in a scenario on track to meet countries' climate pledges. Given the challenges from declining ore quality, coupled with the rapid growth in demand from clean energy technologies, this supply gap poses major risks for the rapid deployment of clean energy. The substantial supply deficit requires a wide range of supply- and demand-side measures to close the gap, including investment in new mines, substitution, material efficiency and secondary supply. Scaling up copper recycling is therefore one of the most critical actions to help close this gap and ensure the energy transition progresses unhindered. Copper is also a unique material that has an infinite recyclable life, being able to be reused indefinitely independently or in alloys without quality losses, presenting even greater potential.

How it works

Types of copper scrap

Copper scrap falls under two broad categories: manufacturing scrap and end-of-life scrap.

Manufacturing scrap

Copper manufacturing scrap is scrap produced during the production processes. Manufacturing scrap is known as "new scrap" and can be split into "home scrap" or "prompt scrap". Home scrap material typically includes off-specification products from refineries, smelters and semi-fabricators, including off-spec cathodes, anodes, rods and bars. Prompt scrap refers to scrap that has been further processed downstream, including alloys or coatings. Manufacturing scrap is currently well recycled with many closed loops for both home and prompt scrap.

End-of-life scrap

End-of-life copper scrap is from products that have finished their useful life, often known as "old scrap". This is typically more complex to process given the wide array of multi-material products copper is contained in, providing challenges in extracting the copper and with increased possibility of generating hazardous waste. This is the area of greatest potential to scale up copper recycling. Table 2.1 details the primary end-of-life products and their typical copper grade.

Table 2.1 End-of-life copper products

Region	Construction	Electricity networks	Transport	Industrial machinery	Appliances
% of 2023 demand	30	16	15	12	17
Key products	Building wiring, plumbing	Power cables, transformers	Vehicle wiring, EV motors	Industrial transformers and motors	Computers, refrigerators, consumer electronics
Copper form	Wire, pipes, alloy	Wire, cable	Wire, motors, sensors,	Wire, cable, motors, alloy	Wire, cable, alloy, tubes
Copper grade %	<2	5-80	<2	<2	5-20

Note: Not covering all of copper demand.
Sources: IEA analysis based on International Copper Association, Wood Mackenzie

Copper scrap recycling processes and pathways

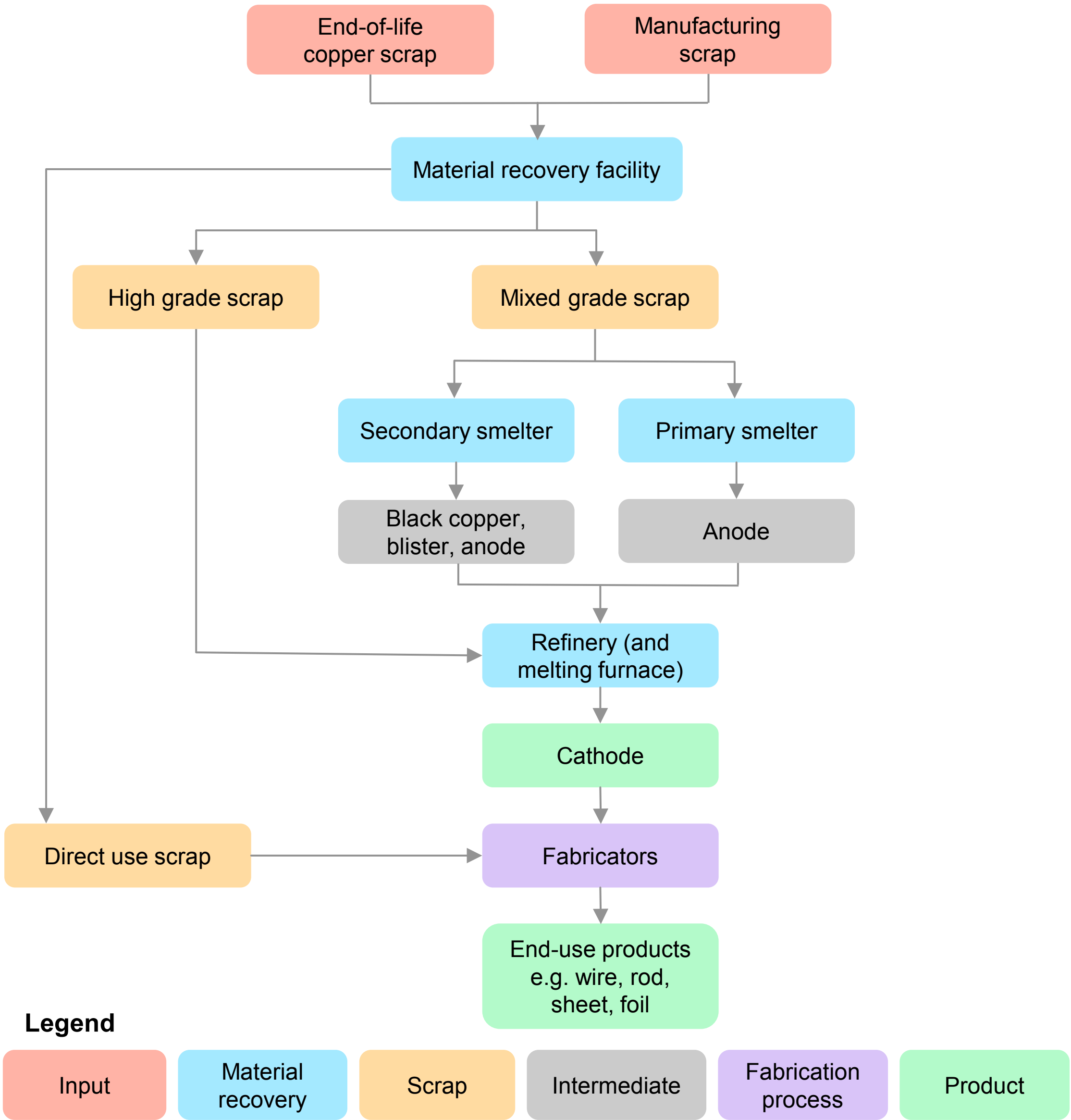
Copper scrap is used in the supply chain at different stages depending on quality, type and where it is generated. The scrap is then recycled in two major pathways: as direct-use scrap, or secondary production.

End-of-life scrap must first be mechanically processed and sorted in material recovery facilities where various mechanical processes are used to separate the copper, such as pressing, crushing, shredding, and magnetic or current separation, depending on the product. The majority of scrap is then recycled using pyrometallurgical processes.

Direct-use scrap

The majority of copper scrap recycled is referred to as direct-use scrap. Fabricators of semis utilise high-grade scrap (typically >99%), often known as No. 1 scrap, to supplement their cathode supply requirements or to be the sole feedstock for semi production, and this is known as direct-use scrap. High-quality copper alloy scrap is typically recycled as direct-use scrap in a closed loop to produce the same alloy. The direct-use process is simpler, and much more energy- and cost-efficient than smelting and refining, typically requiring only a melting furnace. High-grade manufacturing scrap forms the majority of sources for direct-use scrap, though some end-of-life wire and cable scrap can be used, if meeting the minimal impurity requirements. No. 1 scrap is the most valuable, high-price copper scrap. There is also significant growth potential for the electrodeposition of thin copper foils from high-grade copper scrap, given the rapid growth in EV battery demand as it is used for the anode current collector.

Figure 2.20 Copper scrap recycling processes and pathways



IEA. CC BY 4.0.

Secondary production

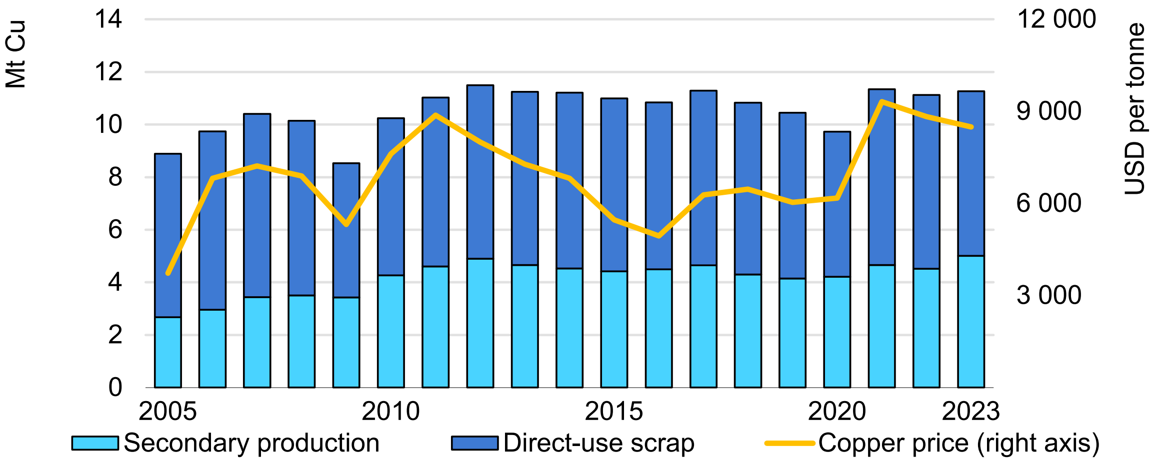
If the copper scrap is lower grade and requires processing by smelters and refiners, this is known as secondary production. Here the lower-grade scrap is processed by either primary smelters or separate secondary smelters. Primary smelters often have a limit of how much scrap they can process as they are designed for treating concentrate, though scrap addition is an important method of controlling heat. The optimal ratio of scrap and concentrate is around 15% for primary smelters, limiting the scrap they can process. Modern secondary smelters are instead designed for treating scrap only or have flexibility to vary the ratio of scrap and concentrates. After smelting, the scrap is refined to produce copper cathode. This lower-grade scrap is often referred to as No. 2 scrap and is typically end-of-life scrap, containing greater impurities, preventing its use at the direct-use stage, thus requiring the smelting and refining. This lower-grade scrap trades at a significant discount to prices of primary copper. The greater impurities provide a sufficient margin for smelters to upgrade the material.

Current status

Copper scrap drivers

Copper scrap generation and collection are primarily driven by two factors – copper price and the economic cycle. As global industrial production and economic activity rise, copper scrap generation and the availability of recyclable material typically increase. Higher industrial output leads to more new building construction and the simultaneous demolition of older buildings, which increases both manufacturing and end-of-life copper scrap. The same pattern applies to passenger vehicles and consumer electronics. Increased demand drives copper prices higher, incentivising scrap traders to release more scrap, which in turn boosts copper scrap collection and draws down from critical scrap pools. The inverse takes place during an economic downturn, where scrap generation is reduced with less investment in new buildings and projects, and fewer end-of-life consumer products are scrapped for new products. Falling demand leads to lower prices, prompting scrap traders to hoard material until prices recover. These trends are particularly prevalent in the United States and Europe. The historical relationship between secondary copper supply and copper price shows that they are correlated with little lag, highlighting the role of prices in determining secondary production levels, acting as a market balancing mechanism.

Figure 2.21 Relationship between copper recycling volume and price



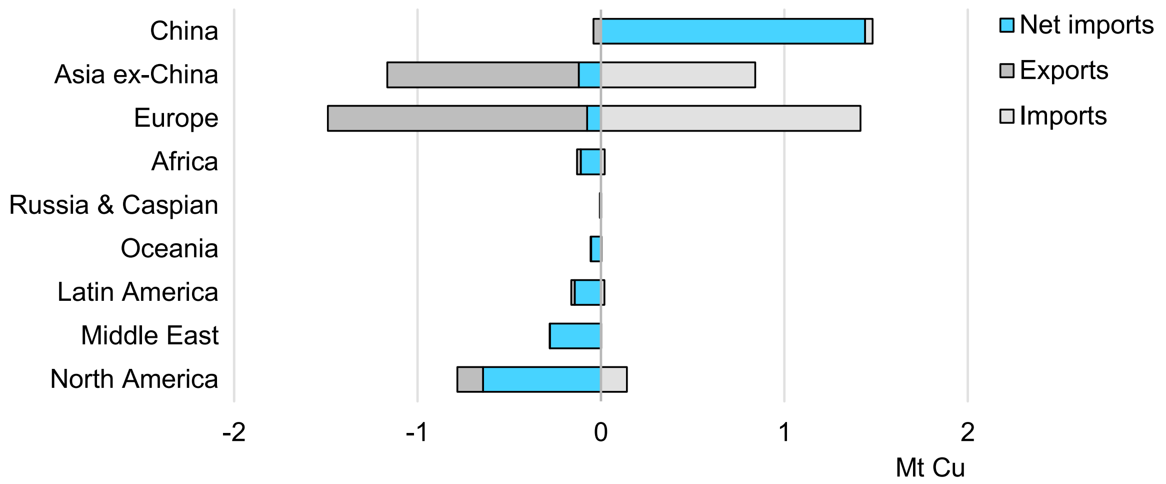
Note: Cu = copper. Prices based on the London Metal Exchange (LME) Copper Grade A Cash prices. Nominal prices.
Source: IEA analysis based on Wood Mackenzie, London Metal Exchange (LME) and S&P Global.

There are other recent trends which affected scrap usage. First, process automation in semis fabrication has led to higher efficiencies, resulting in less scrap generation. There has also been the strong growth in Chinese smelting and refining capacity. This excess capacity has driven lower treatment and refining charges (TC/RCs), thus squeezing margins for smelters. In response, smelters have increasingly turned to scrap, which offers greater discounts compared with concentrate. Consequently, there has been a rise in dedicated secondary smelting capacity to realise better margins in this challenging smelting market environment.

Copper scrap trade

Copper scrap is traded widely globally. The largest net importer is China, importing almost 1.5 Mt of copper scrap in 2022, and the world's largest net exporter is the United States, with North America exporting 0.8 Mt in the same year. Less than 30% of North America's copper consumption is from scrap (including direct-use scrap), lower than the global average, with 60% of the exports going to Asia and half of this to China. Chinese import restrictions on low-grade waste enacted in 2017 have reduced gross scrap imports from the United States, but imports of high-grade scrap have remained high. Some exported scrap is upgraded in Malaysia and Thailand for consumption in China. The United States has been a major exporter of low-grade scrap due to the lack of treatment capacity, though it is taking steps to increase domestic secondary smelting and processing capacity.

Figure 2.22 Copper scrap trade balance 2022



Note: Positive values mean import volumes.
Source: IEA analysis based on Wood Mackenzie.

Currently, only 20% of China's copper consumption comes from scrap, down from 40% a decade ago. The surge of domestic copper consumption has been met increasingly by imports of concentrate and cathode, with the share of domestic consumption from concentrate imports rising from 15% to more than 40% over the same period. The import restrictions implemented in 2017, driven by environmental concerns related to low-grade scrap processing, have led to an increase in the grade of imports – scrap imports by gross mass have declined by 60% since 2013 while imports based on copper content have fallen by only 20%. Nevertheless, domestic scrap collection has not increased. With the surge in Chinese smelter capacity pushing down TC/RCs and a tight supply of concentrate, there are concerns about a potential shortage of copper scrap. The recent change in tax policy could exacerbate this issue, placing further pressure on some scrap processors who rely on tax rebates, forcing them to reduce production.

Despite having relatively balanced copper scrap trade, Europe imported and exported significant volumes of scrap in 2022, with around 1.5 Mt of copper scrap traded both within Europe and across external borders. Over half of Europe's total copper consumption comes from scrap (much higher than the global average). The majority of this trade is intra-European, with only a quarter of traded scrap being with countries outside Europe. As with the United States, the largest share of exports from Europe are flowing to China (around half in 2022) but also to India.

EU policy making is prioritising domestic scrap recycling, with moves to drive up the recovery of critical minerals and control scrap exports. The European Union's CRMA provides recycling targets and designates strategic recycling projects for support to increase recycling rates. In the European Union, scrap metal trade is classified as waste trade, which creates challenges for exporting to China. With the approval of the Waste Shipment Regulation Act, which entered into force in 2024, exporting scrap to non-OECD countries will be more difficult, as this requires evidence and permits that the waste is being sent to facilities capable of handling the material sustainably. These restrictions will support European scrap processors, though if domestic capacity is not developed quickly enough this could reduce global scrap usage. There is major European investment focused on expanding secondary production and direct use over primary smelters. Secondary smelter costs are also more sensitive to energy prices compared with primary smelters as they usually require natural gas as fuel. This implies that policy makers and companies need to deal with pressures from high energy costs when expanding secondary smelters, in view of stricter environmental, social and governance regulations.

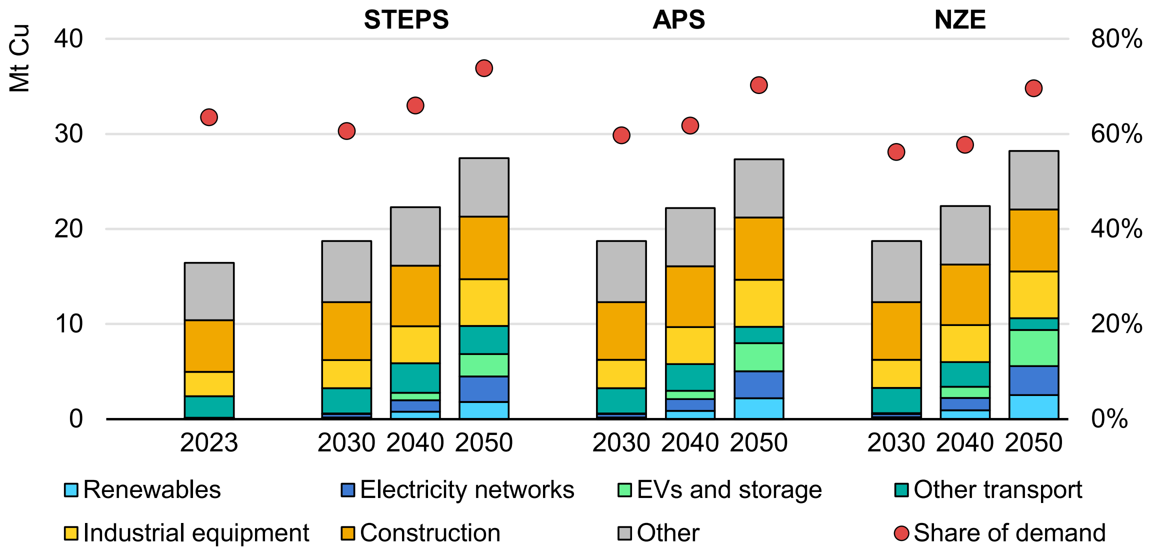
Finally, Asia (excluding China) is a key region for copper scrap trade with 45% of the region's consumption being met by scrap, driven by high scrap demand in Japan and Korea, where there is significant scrap processing capacity. Despite being relatively balanced in net trade, around 1 Mt of copper in scrap is imported and exported throughout the region. Japan, Korea and India are key importers of scrap from the United States and Europe, while Malaysia, Viet Nam, India and Thailand were also in recent years taking the low-grade scrap that was previously going to China before the import restrictions on low-grade scrap were enacted. However, all four regions have also recently implemented restrictions on low-grade scrap, highlighting the need to develop low-grade copper scrap capacity in Europe and the United States.

Outlook

Available end-of-life scrap

A significant end-of-life copper scrap pool is expected to become available in the coming years, with the volume of available scrap growing in line with demand until 2030 and then outpacing demand growth until 2050. By 2030, available scrap volumes are projected to reach nearly 19 Mt, equivalent to 60% of global demand in the APS for that year. By 2050, this figure is expected to rise to 27 Mt, which would represent 70% of demand in the APS. There are inevitable yield losses that must be accounted for, but this demonstrates massive opportunities to increase future secondary supply. Increasing collection rates and investing in secondary processing capacity are key to unlocking this potential and reducing pressure on primary supply. Construction remains the largest source of end-of-life copper scrap across all scenarios to 2050. However, copper from EVs and storage is the fastest growing source of end-of-life scrap, growing more than 35-fold from 2030 to 2050 in the APS. The higher copper intensity of EVs compared to ICE vehicles, from the batteries and motors, results in greater copper volumes becoming available when EVs reach end of life, compared to the displaced copper from conventional ICE vehicles. There is significantly more electricity networks deployment over the next decades in the APS and NZE Scenario than in the STEPS but given the very long lifetimes of network infrastructure, there is only slightly more copper available from end-of-life electricity networks scrap by 2050, with the vast majority reaching end of life after 2050.

Figure 2.23 Available end-of-life copper scrap feedstock available for recycling outlook, 2023-2050

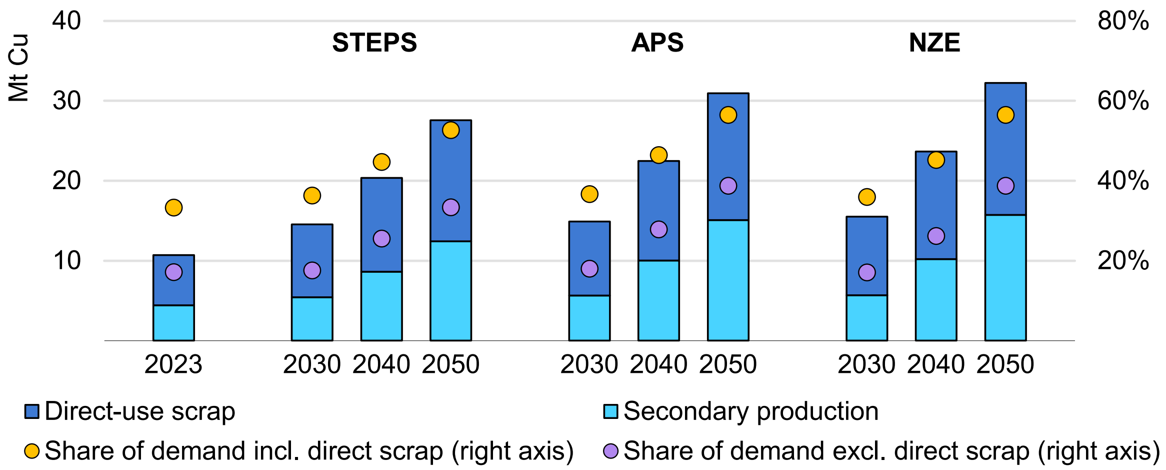


Notes: Available end-of-life scrap refers to maximum possible feedstock volumes reaching end of life before any collection rates or recycling process yield losses. Excluding direct-use scrap.

Projected metal recovery

Similar to batteries, the actual recycled volumes of copper from the available scrap depend on two critical rates, the collection rate and the processing yield. With copper recycling processes relatively well established, the scope for yield rate improvements is marginal, whereas collection rates have substantial room for improvement. However, the historical share of secondary supply in total copper demand has not improved since 2015 (including direct-use scrap, the share declined from 37% in 2015 to 33% in 2023). This is due to the combination of lower prices, scrap trade restrictions from China, higher energy and shipping costs reducing recycling profitability, the impact of Covid-19, and the fact that EU and US policies promoting domestic scrap collection have yet to take effect.

Figure 2.24 Recycled copper volumes outlook, 2023-2050



Notes: Recycled copper volumes detail the volumes recovered from recycling from secondary production and direct-use scrap, accounting for collection and recycling process yield losses.

However, to meet climate pledges, both copper scrap recycling and primary copper production need to increase significantly. In the APS, total secondary supply reaches 15 Mt in 2030 and 31 Mt in 2050, with direct-use scrap being the dominant source in 2030, responsible for around 60% of secondary supply. By 2050, the share of recycled volumes from secondary production grows, responsible for around half of secondary supply. This shift reflects the growth in clean energy technology reaching end of life including EV batteries and motors, electricity networks, and solar PV. The share of secondary supply in total demand rises to almost 20% by 2030 and 30% in 2040, and almost 40% in 2050, excluding direct-use scrap in the APS. This growth is driven by strong policy actions to increase collection rates, implement recycling mandates, improve sorting systems, and encourage investment in new secondary smelters and processing facilities.

Policy implications

Key barriers

The challenge in economically extracting and collecting legacy end-of-life copper. The long life cycle of copper products, particularly in buildings and infrastructure, means that much of the copper – such as old cabling in unused but not demolished buildings – may remain inaccessible for more than 30 years. This is in stark contrast to the relatively short lifetimes and easier accessibility of certain aluminium products. These legacy copper volumes are often challenging to access, extract and collect economically. Also, some legacy copper that is no longer needed may not be replaced quickly, delaying its entry to the scrap pool. Furthermore, copper scrap collection and sorting is traditionally a low-margin business compared with mining and smelting, which disincentivises investment in the scrap collection sector.

The difficulty economically sorting and separating copper and its alloy types from complex electronic end-of-life scrap coupled with the insufficient scrap pre-processing capacity. The value of the copper extracted is often not high enough to justify the separation and sorting cost from complex waste, for example electronic waste, which may also produce hazardous material, or from copper contaminated steel scrap. This results in substantial volumes of copper scrap being lost to landfill, as they are not recovered due to unfavourable economics. There is also insufficient scrap pre-processing material recovery capacity.

Insufficient secondary copper supply chain integration and co-operation. In many regions, copper collection infrastructure is insufficient with limited co-ordination between secondary supply chain actors, including collection operations, material recovery facilities and scrap upgrading facilities, increasing costs and inefficiencies with scrap processing.

The lack of low-grade copper recycling capacity in the United States and Europe. Given the tightening scrap quality import regulations or scrap import bans in China, Malaysia, India, Viet Nam and Thailand, there are few regions that will be able to accept low-grade scrap for processing. The lack of domestic capacity build-up to upgrade or process low-grade scrap in these regions, coupled with higher costs, will mean that more scrap may end up reaching landfill.

Lack of incentives for consumers to recycle copper scrap products. There are also insufficient incentives and information for consumers to bring back copper-containing products or to replace legacy copper products, such as old copper piping.

Lack of clear regulatory mandates for copper collection and recycling. There is a distinct lack of clear copper collection and recycled content mandates in current policy frameworks. This increases uncertainties for investment and thus reduces investor appetite for domestic secondary smelters and processing facilities, as well as in scrap collection and sorting infrastructure.

Cost and regulatory barriers to transporting scrap. For example, there are time implications to acquire certain permits for transporting certain copper waste products, such as e-waste, which is classified hazardous in some countries. This can sometimes introduce inefficiencies to scrap recycling.

There is insufficient reliable, accurate and up-to-date data on copper scrap and waste flows. The lack of reliable reported data on copper waste and scrap flows hinders effective policy making on copper recycling. Tracking copper contained in many waste products is challenging and requires improved data collection and reporting.

Sector-specific recommendations

Facilitate strategic partnerships between copper scrap supply chain actors across countries, maximising capacity utilisation and increasing the efficiency of scrap trade. There are copper scrap recycling hubs globally, with some countries with greater capacity for scrap sorting and mechanical processing or others for secondary smelting, for instance. Therefore, facilitating the formation of strategic partnerships and co-operation and potential offtake agreements between key scrap supply chain actors is critical. Increasing co-ordination between scrap collectors, pre-processors, secondary smelters and other supply chain actors across countries is important. This can also enable scrap processors to have a guaranteed, steady source of scrap supply matched to their capacity, reducing risk for investment and increasing recycling rates, while mitigating the risks of price volatility.

Support strategic copper recycling projects, prioritising vertical integration and supply chain co-ordination. Primary smelters are limited in the fraction of scrap they can use to around 15% and there is a current global overcapacity of primary smelters. Therefore, it is crucial to provide financial, permitting and de-risking support for secondary smelters that solely target scrap, as well as for collection, sorting and material recovery facilities, and projects that upgrade low-grade scrap. Prioritising integrated facilities or a collection of co-ordinated secondary supply chain projects is also key to improve the recycling economics and tackle the current copper scrap market fragmentation. This also extends to support for copper semi-fabricators with greater input grade flexibility.

Scale up effective collection infrastructure and systems, including incentives for consumers. Providing support to scale up collection systems and infrastructure is crucial, as increasing collection rates offers the greatest potential for enhancing copper recycling. Developing cost-effective collection mechanisms tailored to the local area and ensuring that scrap reaches high-standard processors is essential. It is also important to strengthen information and communication campaigns for consumers and provide consumer incentives to bring back copper-containing products.

Implementation of comprehensive long-term progressive copper scrap regulations and EPR mandates is pivotal including collection rates, defined producer responsibility schemes, potential recycled content mandates, potential bans on copper scrap in landfills, and enforcement of design for recycling standards for new products to ensure a larger pool of end-of-life products that are economically recyclable. Long-term, progressive regulations are also crucial to provide market and investor confidence to stimulate the investment needed in scrap collection, sorting and processing required. This can also support higher scrap utilisation in lower price environments. Regulations should also focus on improved copper scrap and waste flow data collection and reporting.

Prioritise research and development support and capital expenditure investment for novel emerging recycling technologies that can efficiently sort and separate copper and its alloys, increase scrap ratios of conventional smelters, or enhance recovery from complex waste. There are new technologies emerging with great promise for improving the economics of sorting copper and copper alloy scrap, for instance sensor-based scrap sorting such as X-ray fluorescence and laser-induced breakdown spectroscopy. There are also novel hydrometallurgical processes that can recover copper from complex electronic waste, such as printed circuit boards. Pretreatment and temperature-controlling technology can also be used to increase the scrap ratio of conventional smelters. Targeting financial support and grants for further R&D and commercialisation projects can help increase the volume of scrap which can be recycled economically. These technologies can also facilitate the economical recycling of low-grade scrap. Supporting projects such as the US Aurubis recycling project in Virginia, which focuses on low-grade copper recycling and the capability to handle complex electronic waste, is essential. Additionally, promoting the adoption of new technologies that enhance sorting and separation processes is important.

Facilitate copper recycling capacity building in developing economies, prioritising health and safety. Providing technical assistance alongside equipment and technology support for copper scrap recycling capacity building in developing economies is crucial. There can be significant volumes of copper containing waste being imported to in these regions, providing considerable untapped resources. Strengthening infrastructure to adequately recycle these resources can provide opportunities for economic development in developing economies. However, some informal processing operations including cable burning or manual crushing can be dangerous for the health and safety of workers. It is therefore important to ensure that safe, high-standard, formal operations are supported. Development finance institutions and foreign direct investment can strategically support collection infrastructure, high-standard projects to upgrade scrap, and secondary smelter and refining projects in these regions.

2.4. Rare earth elements from permanent magnets

Some elements of the rare earth group, particularly neodymium (Nd), praseodymium (Pr), dysprosium (Dy) and terbium (Tb), can be alloyed with iron and boron to make permanent magnets, then used as key components of several clean energy technologies, particularly EV motors and wind turbines (hereafter referred to as "magnet rare earths"). Other rare earth elements, such as cerium and lanthanum, are used in applications such as consumer batteries, fluorescent lamps and polishing powders. There are existing capacities to recycle these rare earth elements, notably from fluorescent lamps, but the recycling of magnet rare earths from end-of-life products has historically been limited. However, the energy transition is making magnet rare earths recycling more feasible than before, due to their rising use in larger applications such as wind turbines compared with previous uses.

In the STEPS, secondary supply has the potential to reduce primary supply requirements for magnet rare earths by over 25% in 2035, and over 30% in 2050. In the APS and NZE Scenario, these figures are higher due to greater collection efforts and efficiency, reaching 35% and 40% in 2050, respectively.

How it works

Feedstock

From the perspective of end-of-life collection, EV motors and wind turbines are likely to be among the most accessible sources of end-of-life magnet rare earths. An EV motor typically contains about 1 kg of magnets, and wind turbines can contain up to 2 tonnes, when a magnet in an electronic speaker can be as light as a few milligrammes. Another secondary supply source for magnet rare earths could be those found in medical imaging machines. However, rare earth elements are mostly used in low-field machines (from 0.25 tesla to 0.5 tesla), while higher-field machines (1.5 tesla or 3 tesla) use superconductors that do not contain rare earth elements.

There is also potential to recycle permanent magnets from electric or electronic waste, where they are often used to produce sound or haptic feedback, in robotic and drone motors, and historically in hard drives. However, sourcing rare earth elements from electronic waste faces significant challenges: the magnets are generally small and embedded in complex objects. Automation and artificial intelligence-based technologies are, however, well positioned to facilitate sorting, presenting new opportunities.

Collection, disassembly and sorting capacities are key to the economic viability of magnet recycling. Innovations have focused on robotic systems, such as Apple's robot, Dave, and on recycling processes without disassembly, such as the pyrometallurgical process developed by Nissan and Waseda University for EV motors.

Raw materials can also come from waste generated during magnet manufacturing processes (often referred to as "swarfs"), which is produced during shaping and cutting, which is the currently the main supply source for secondary raw materials.

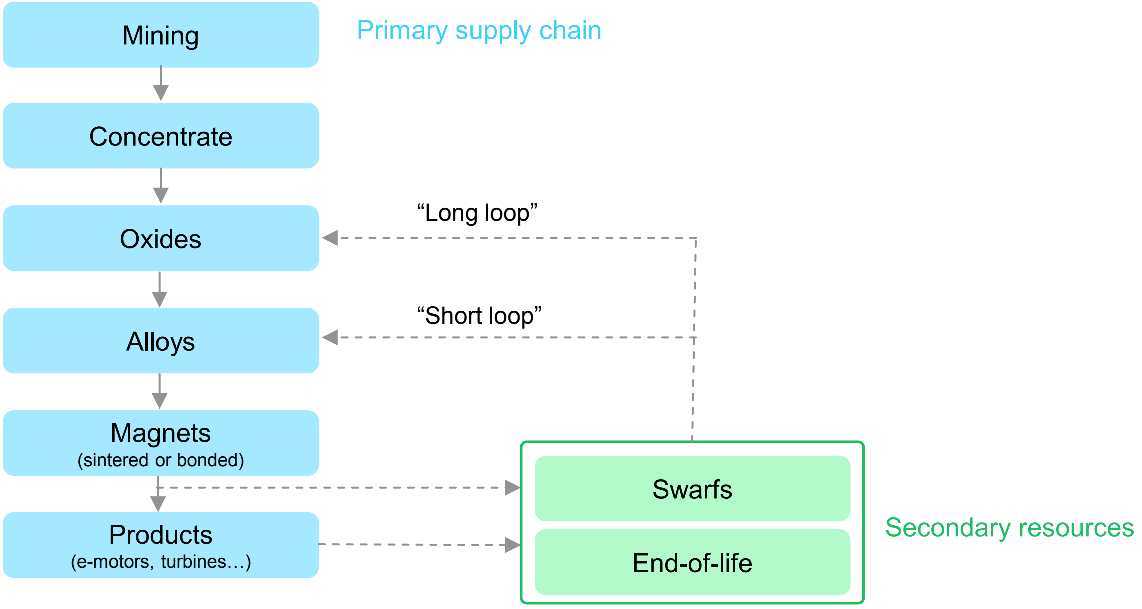
Technological pathway: "Short loop" versus "long loop"

Rare earth recycling has historically focused on the latter: production of rare earth oxides from waste, or "long loop". This approach requires similar processing capacities to those required to refine mine concentrate into oxides, allowing for higher flexibility with regard to input composition and possible impurities. Manufacturing scrap – swarf – is often contaminated during the cutting process and can be oxidised, making it a candidate for long loop reprocessing into oxides.

Rare earth recycling has historically focused on the latter: production of rare earth oxides from waste, or "long loop". This approach requires similar processing capacities to those required to refine mine concentrate into oxides, allowing for higher flexibility with regard to input composition and possible impurities. Manufacturing scrap – swarfs – is often contaminated during the cutting process and can be oxidised, making it a candidate for long loop reprocessing into oxides.

Recycling of permanent magnets into reusable alloys is sometimes referred to as "short loop" or "magnet to magnet" recycling, enabled by new technologies, such as hydrogen-based processing of magnet scrap. Depending on the type of recycling, the ability to track the composition of magnets and enhance sorting capacities can lead to increased efficiency. Short loop recycling also requires monitoring the grades and chemical compositions of the magnets.

Figure 2.25 Magnet rare earth recycling pathways



Current status

Business models for rare earth magnet recycling

A small rare earth magnet recycling industry is already operating, producing about 25 kt in China, mostly from swarfs, and a promising number of rare earth recycling start-ups and projects are emerging.

New rare earth recycling businesses may face three challenges. First, they may need to compete with mined primary supply, potentially reducing revenue while also vying for limited feedstock sources. The existing volumes of mined supply and the capacities of the magnet industry suggest that significant price spikes for new alloys and magnets are unlikely, emphasising the need for substantial cost reductions to remain competitive against primary supply. Second, the evolving compositions of magnets may diminish interest in their collection and recycling. Earlier generations of magnets contained up to 10% of heavy elements, such as dysprosium and terbium, which are more challenging to source; however, this proportion is expected to decrease in future waste streams. Third, the growing demand for secondary supply presents business opportunities, but higher scrap prices could undermine the competitiveness of recycled materials compared with virgin materials, adding another layer of business risk. For instance, in July 2024, the value of 50% grade NdPr from NdFeB scrap on the Shanghai Metals Market was USD 48/kg, about 10% more than the refined 99% NdPr oxide itself.

Another area of uncertainty is whether consumers will place additional value on the environmental benefits of using recycled products, with some recycling projects claiming an 80% emissions reduction compared with primary supply. If this is the case, downstream consumers may also accelerate their demand for recycled products, similar to Apple's recent pledge to use 100% recycled rare earth elements in new products by 2025.

A wide range of policies can positively support recycling economics. These include lowering the cost of accessing scrap through standardised labelling, implementing EPR schemes to support collection efforts, setting material-specific recycling targets and encouraging the purchase of recycled materials.

Successful rare earth recycling capabilities will hinge on synergies with either rare earth magnet producers or primary miners and refiners:

- Long loop recycling requires similar know-how to the separation of rare earth oxides when refining mine concentrate. Some recycling plant projects are designed to refine both mine concentrates as well as magnets, and some mine projects are considering integrating secondary supply into their primary processing capacities.
- Due to the importance of scrap in secondary supply, most recycling capacities will likely be located near rare earth magnet manufacturing facilities, serving as both suppliers and potential clients.

Rare earth refining companies seeking to diversify their supply sources may therefore be well suited to expand into rare earth magnet recycling businesses. An alternative business model could be "toll-based" recycling, in which the recycling plant provides the service while the raw material remains the property of the waste producer or a client looking to source recycled rare earths.

Outlook

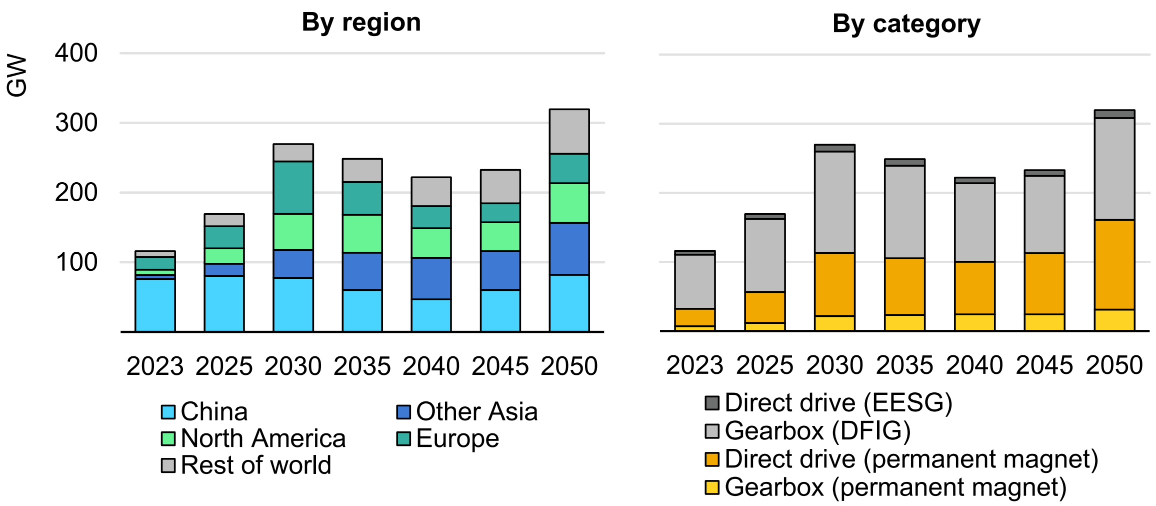
The availability of secondary rare earth elements varies depending on scenarios. In the NZE Scenario, demand for permanent magnets increases rapidly, raising pressures on primary supply. This provides incentives to tap the potential of secondary supply sources, first from manufacturing scrap and then end-of-life scrap. For the latter, two applications – wind turbines and EV motors – are particularly important as they consume large amounts of rare earth elements. Depending on policy and economic incentives, businesses' ability to collect end-of-life equipment for these applications will shape the outlook for secondary supply.

Wind turbine deployment outlook

In the APS, installed wind capacity grows at an annual 9% rate between now and 2040, with offshore wind experiencing faster growth, close to 17%. Capacity additions would require around 24 kt of magnet rare earth elements per year at their peak, or about 80 kt of permanent magnets. In the NZE Scenario, the faster pace of wind capacity additions raises the peak annual requirements for rare earth elements to around 30 kt, up to 60% of those requirements coming from offshore wind.

Wind turbines can be either direct-drive or equipped with gearboxes. Direct-drive wind turbines dominantly use rare earth-based permanent magnet synchronous generators, but some use electrically excited synchronous generators. Wind turbines with gearboxes, mainly used in onshore, were generally double-fed induction generators free of rare earth elements, but the use of permanent-magnet synchronous generator, which uses magnet rare earths, is growing recently. Overall, as turbines become more powerful and taller, the market share of permanent magnet-based technologies is likely to increase, due to their greater efficiency and reduced weight.

Figure 2.26 Wind capacity additions by region and category in the APS



Note: GW = gigawatt; EESG = electrically excited synchronous generator; DFIG = double-fed induction generator.

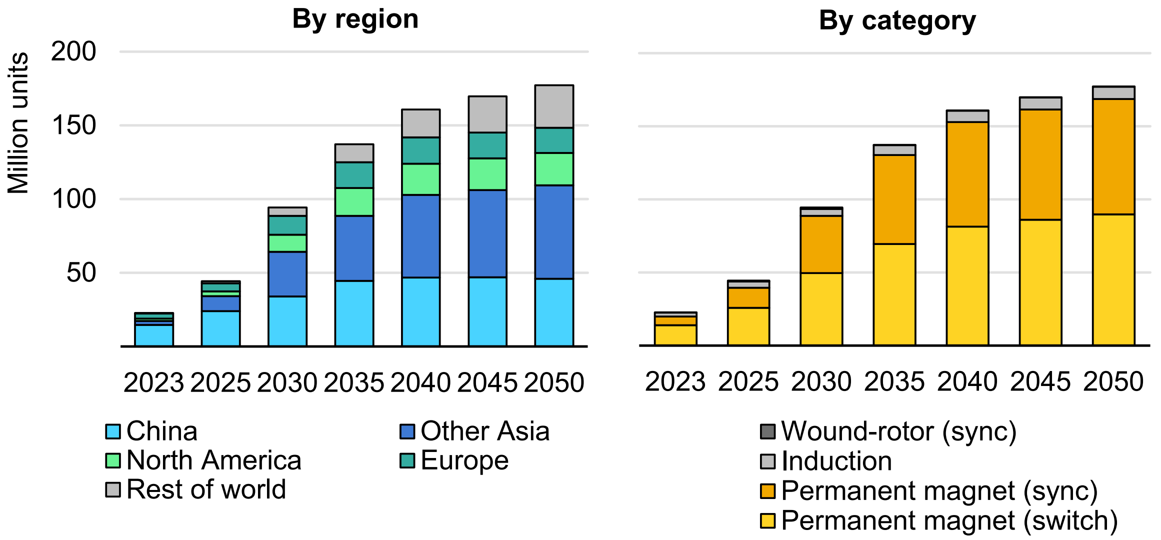
The relative long life of wind turbines – which can reach up to 25-30 years – means that it will take time for retired wind turbines to be available in the market. In the APS, a feedstock of about 48 kt of end-of-life rare earth permanent magnets used for wind power generation are available in 2050, and above 50 kt in the NZE Scenario – but these will need to be collected and recycled. End-of-life permanent magnets from wind turbines are likely to benefit from higher collection rates than magnets available in most applications such as consumer electronics. In the STEPS, collection rates ramp up to 50% by 2050. These rates are slightly higher in the APS (55%) and in the NZE Scenario (60%).

EV motor deployment outlook

Permanent magnet motors – generally using rare earth alloys such as neodymium-iron-boron – are currently dominant in electric vehicles. Among EV motors containing rare earth-based permanent magnets, synchronous motors are the most widely used today, but innovation and technology trends are exploring the use of switched reluctance motors, for their improved performance and reduced rare earth requirements per vehicle.

However, some EV motors use rare earth-free technologies, typically with wound or induction motors. Several pledges have been made by vehicle manufacturers to remove rare earths from EV motors, but this often comes with a series of disadvantages: loss of efficiency and heavy weight, as well as larger copper requirements.

Figure 2.27 EV motor sales by region and category in the APS

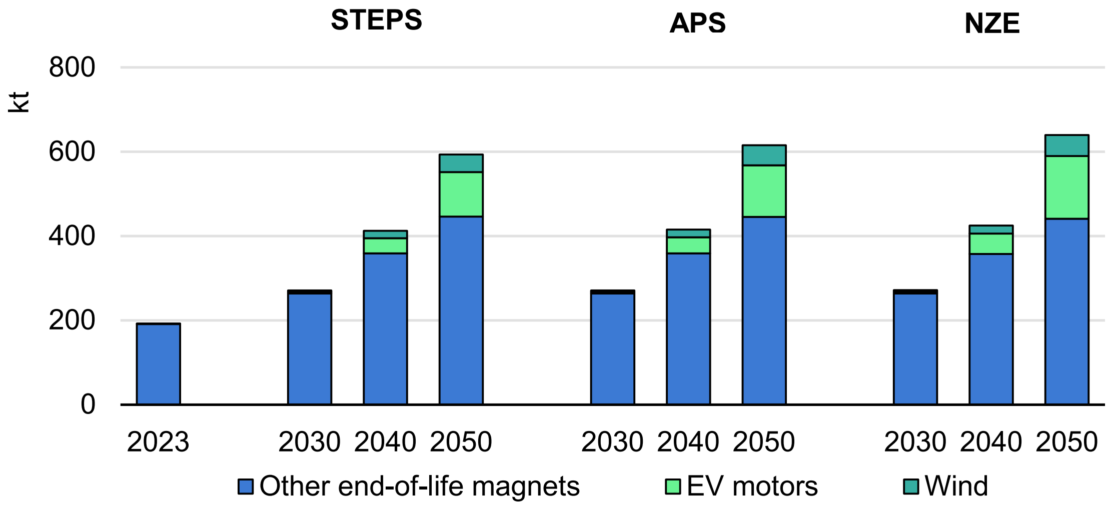


Note: sync = synchronous motor; switch = switched reluctance motor

Projected end-of-life permanent magnets

The current feedstock of end-of-life permanent magnets mostly comes from electric and electronic waste, including personal devices, but also robotics and industrial machinery – but suffers from generally lower collection rates than those achievable for clean energy technologies. Current collection rates for these rare earth-based permanent magnets can be estimated at around 5% or lower, with the potential of rising up to 10% or 15% depending on policies.

Figure 2.28 End-of-life magnet rare earth elements feedstock by scenario

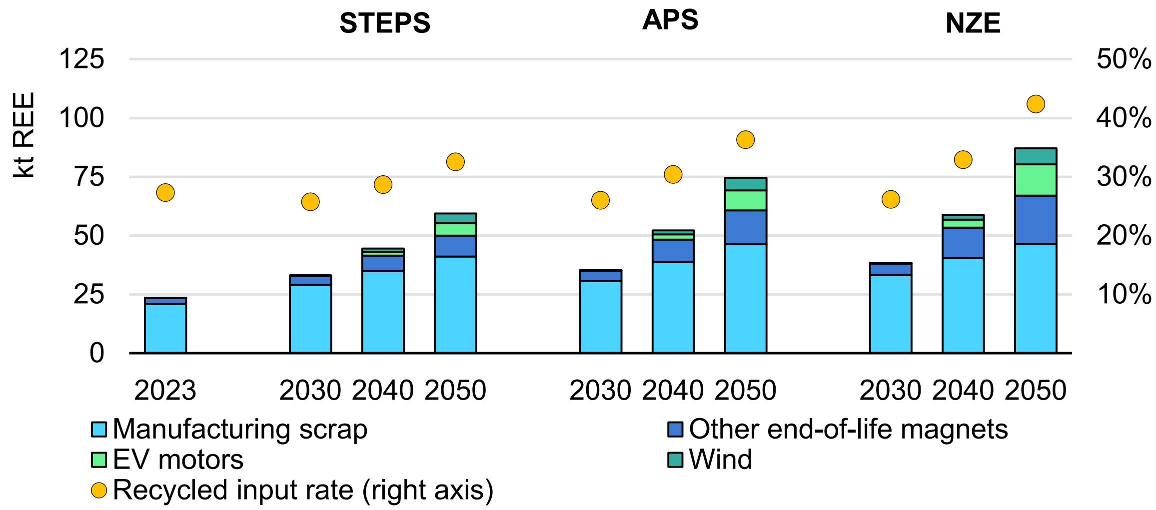


The flow of end-of-life magnets from clean energy technologies emerges by 2030 and becomes significant by 2040, reaching about 15% of total end-of-life magnet feedstock in the APS and NZE Scenario. These magnets benefit from significantly higher collection rates, growing to 25% in the STEPS in 2050 for those in EV motors, and reaching 50% for wind turbine magnets. Policy incentives allow for higher collection rates, reaching up to 40% for EVs and 60% for wind turbines in the NZE.

Projected metal recovery

Swarf, about 90% of today's secondary supply, are expected to remain the dominant source of secondary raw materials throughout 2050 in all three scenarios. As total demand for magnet rare earth increases, volumes of swarf grow proportionally, while the wave of end-of-life materials from clean energy technologies will only emerge in the medium term.

Figure 2.29 Secondary supply of magnet rare earth elements by scenario



Notes: REE = rare earth elements content. Recycled input rate is calculated as the metal produced from secondary sources over total implied supply.

A significant number of rare earth recycling projects have been announced, whether short or long loop, including in Canada, China, France, Germany, the United Kingdom and the United States. These aim to recycle both swarfs and end-of-life permanent magnets, and some developers also plan to find synergies with primary supply. Publicly announced projects already amount to 30 kt of waste processing capacity per year, containing about 8 kt of rare earths, and corresponding to about 7% of demand in 2026.

Table 2.2 Selected rare earth recycling projects

Project	Planned capacity	Ramp-up	Recycling activity	Notes
Apple robotic disassembly (United States, Netherlands)	1.2 million devices per year	Existing pilot	Sorting	Robot "Dave" focuses on collecting permanent magnets from haptic components
Caremag (France)	2 000 tonnes waste per year		Long loop	1 000 tonnes of EoL magnet per year and 1 000 tonnes of swarfs
Cyclic Materials (Canada)	100 tonnes waste per year (pilot)	Pilot launched in 2024	Long loop	Further refining of the oxides will be done with developments with Solvay projects (France)
GeoMega (Canada)	1.5 tonnes waste per day (pilot)			

Project	Planned capacity	Ramp-up	Recycling activity	Notes
Hypromag (UK, US, Germany)	700 to 1 150 tonnes of alloy output per year	2024	Short loop (hydrogen processing)	Synergies with primary supply projects
Ionic Rare Earths (UK)	30 tonnes of waste per year (pilot)	2024	Long loop	Partnership with Ford and downstream alloy manufacturer LCM
MagREEsource (France)	1 000 tonnes waste magnets per year	50 tonne pilot launched in 2024	Short loop (hydrogen processing)	
Neo Performance Materials (Estonia)	2 000 tonnes magnet output, with a share sourced from secondary feedstocks	2025	Magnet production	
Noveon (US)	10 000 tonnes magnet output per year		Magnet production, short loop	
Orano (France)	7 tonnes waste per year	2024	Short loop (hydrogen processing)	4 tonnes in 2024, 7 in 2026
ReElement (US)	3 000 tonnes waste per year	2025	Long loop	56 tonne pilot
Shenghe Resources (China)	10 000 tonnes of waste per year	2024		Existing capacities, plus two additional projects (3 kt and 5 kt)

Policy implications

Key barriers

Two key barriers may hinder the recycling of magnet rare earths:

- **Collecting and recycling e-waste does not always lead to recycling the rare earth elements they contain.** While several policies exist to ensure collection and recycling of e-waste (see section 2.6), there is a risk that recyclers may focus only on the most easily recyclable or valuable raw materials, such as copper or precious metals.
- **Economic uncertainties may deter necessary investment in recycling facilities**, due to the relatively low price of magnets produced from virgin materials. This competition with primary sources means that the economics of a recycling facility will most likely be determined by the cost of inputs. Early entrants

may also need to compete to source the limited swarf volumes and first wave of end-of-life materials, putting pressure on feedstock cost. Downstream supply chain concentration adds an additional risk to recycling projects.

Sector-specific recommendations

Enhance economic incentives to recycle rare earth elements. Policies can aim to lower the costs associated with collecting and procuring waste and scrap or increase the value of recycled materials. Existing EPR mechanisms can significantly incentivise collection, particularly for electronic devices by holding producers or importers accountable for the collection and recycling of end-use products. Mineral-specific recycling targets, focusing on elements such as neodymium or praseodymium, can further incentivise resource efficiency. Long-term policy planning is essential to encourage businesses to integrate recycling into their operations and to support investment in recycling infrastructure.

Encourage pledges to use recycled rare earths. While recycling small permanent magnets from consumer electronics presents significant challenges, their small mass means that favouring recycled materials can be done at a very small additional cost. While recycled rare earths cannot supply 100% of volumes required for wind turbines or EVs, the smaller volumes required in portable electronics make these pledges easier. Pledges to use 100% recycled rare earths in the electronic goods sector have already been made by key consumer electronic companies. The European Union's CRMA mandates that, starting from 2027, manufacturers of goods containing permanent magnets should disclose the share of key minerals, including magnet rare earths, recovered from end-of-life magnets. Mandatory shares of recycled rare earth materials are then to be adopted before 2031.

Embrace eco-design and efficient labelling to identify the presence and composition of permanent magnets that can facilitate the work of recyclers. Similarly, an evolution of waste identification codes could be a possible option to facilitate the collection of EoL magnets. Legislation adopted in 2022 in France already mandates that e-waste and EV manufacturers disclose whether products contain "at least X milligrammes [mg] of rare earth elements" – but with varying success: while some manufacturers provide useful estimates of rare earth elements content, others simply mention a minimal content of "1 mg" even for products such as EVs, which contain much larger volumes in practice. Similarly, the European Union's CRMA plans to mandate that product manufacturers disclose the presence, type, weight and removal instructions for the magnets contained in the products. These measures are set to enter into force two years after the adoption of detailed legislation, which is expected by the end of 2026.

Capture synergies when collecting critical minerals from end-of-life vehicle streams to simplify waste management. Policies can incentivise operators that collect end-of-life batteries from scrap vehicles to also collect motors during vehicle dismantling, ensuring that both can be properly treated and recycled in subsequent processes.

Address the high level of geographical concentration in the downstream magnet value chain. While the recycling of rare earth-based permanent magnets is an encouraging step towards supply diversification, the rare earth oxides need to be refined into rare earth metal alloys ("metallisation"), then manufactured into permanent magnets to be used in final applications such as wind turbines or EV motors. However, these downstream supply chains remain highly concentrated, requiring continued efforts to diversify the entire permanent magnet value chain to realise the security benefits of recycling.

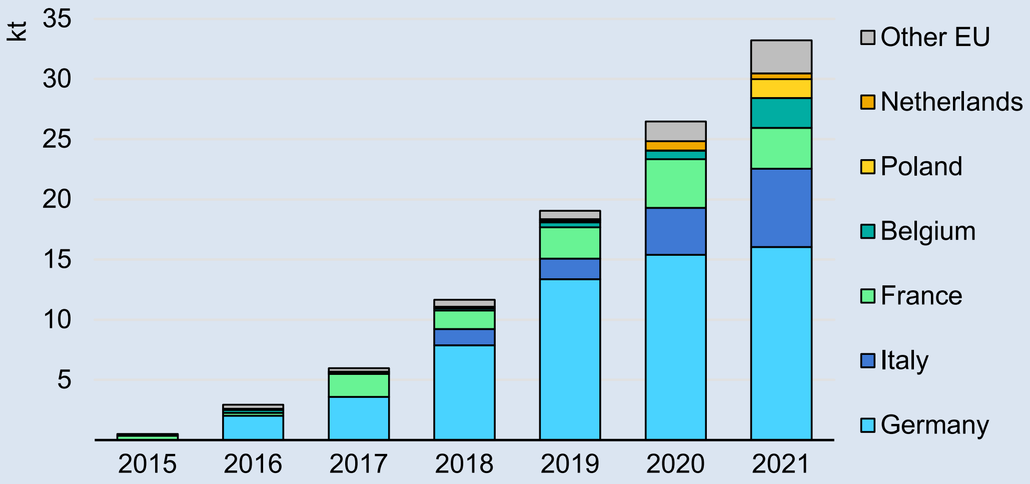
Develop robust collection frameworks in emerging market and developing economies. In regions where two-/three-wheelers are particularly prevalent, there could be a significant resource of permanent magnets available, if adequate collection infrastructure is put in place. A scenario with high levels of second-life EV exports (see Section 2.2) could further increase the availability of secondary rare earth elements feedstock in developing economies. Strengthening collection systems will help prevent these materials from being lost in the supply chain.

Box 2.1 Recovering critical minerals from end-of-life solar cells

Solar PV waste is projected to increase exponentially, starting from around 2030, as the first generation of installed capacities reach the end of their life cycle. In the APS, waste from end-of-life solar panels reaches 13 Mt by 2050. The majority of this waste is made of concrete, steel, aluminium and glass, but there are also considerable amounts of copper, silver, silicon and other materials in the waste. Regulations already aim to incentivise proper waste management, such as EPR schemes in Europe, where the cost of management and waste disposal is borne by domestic manufacturers or importers. In the European Union, solar panels are covered by the same regulation as applicable to electrical and electronic waste.

Under these schemes, frameworks were created to track data on solar PV waste collection, which reached nearly 35 kt of collected waste in the European Union and the United Kingdom combined. For example, in France, the producer organisation Soren receives a contribution of about EUR 10 million per year from 460 companies (including about 430 importers) to collect about 5 kt of end-of-life panels per year. About 91% of the processed waste is recycled.

Figure 2.30 Waste solar PV collected in the European Union



Source: IEA analysis based on Eurostat (2024), Waste electrical and electronic equipment (WEEE) by waste management operations (env_waseleeos), accessed 15 October 2024.

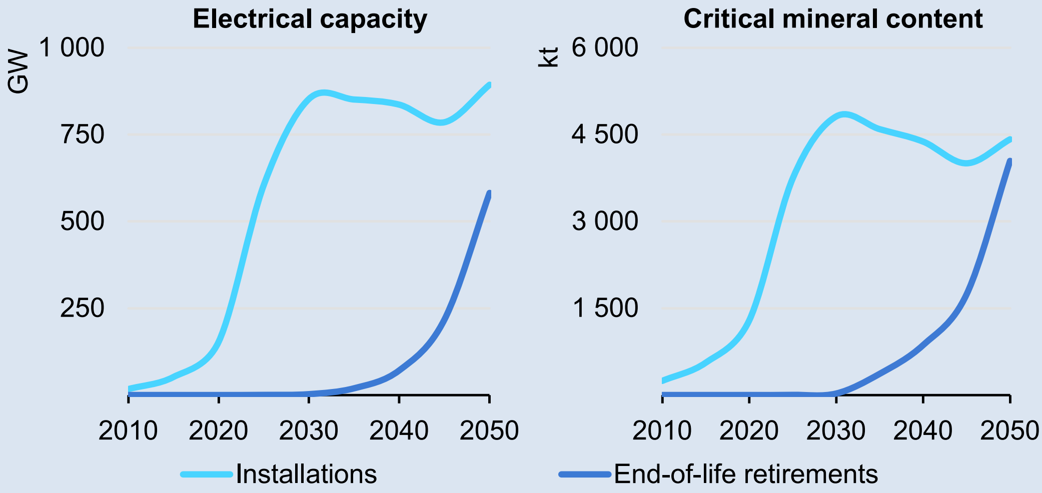
Some critical minerals are already being recycled from end-of-life solar PV cells, such as copper and silver. Silver is about 0.02% of the weight of a typical crystalline silicon solar panel but represents 7% percent of the raw material value. However, among various critical minerals, the high-purity silicon is not widely recycled, due to high costs and weaker economic incentives. Silicon can also be recycled from solar PV manufacturing waste, but this faces similar economic challenges as recycling from end-of-life panels.

Global solar PV capacity additions for electricity generation continued to set new records in recent years. Solar PV alone accounted for three-quarters of renewable capacity additions worldwide in 2023. Going forward, solar PV installation far outstrips any other power generation source in all scenarios. The rapid deployment of solar panels implies burgeoning amounts of retired solar panels after 2030. Recent technological improvements may have varying impacts on the volume of critical minerals in solar PV waste. While solar panels have long expected lifetimes, increased performance in next-generation solar cells could lead to the early retirement of some installed capacities, increasing the availability of critical minerals for recovery. However, this growth is partially offset by the declining raw material requirements in solar cells, particularly silver.

Today, a large part of retired panels risk ending up in landfills because of lower costs and the lack of regulatory enforcement. If unchecked, the environmental impacts of these landfills could increase exponentially after 2030, making a strong case to enforce a better collection of decommissioned panels and recycle them – however, this volume needs to be compared with the total amount of electronic waste to be produced (section 2.6), of which solar PV is only but a relatively small share.

After 2030, inherent mineral contents in waste are set to grow quicker than critical mineral requirements for new panel installation. This provides significant opportunities to reduce primary material requirements through recycling.

Figure 2.31 Solar PV additions and retirements in the APS, by electrical capacity and critical mineral content



Notes: Mineral content covers copper and silicon as well as metals found in smaller volumes, including silver. End-of-life retirements do not consider collection rates and yield losses, which would reduce actual recovered metal volumes.

2.5. Mine waste

How it works

Mining waste includes all materials generated during the extraction and processing of ore into a commercially viable concentrate. It can come in many forms, such as waste rock produced during the stage of accessing the ore deposit, tailings generated when separating valuable and unvaluable material, and mine drainage water, which consists of surface or groundwater draining from active or abandoned mines. Sometimes there are minerals left within mine waste that had low economic value at the time of extraction and therefore were not considered financially feasible to recover. It may have also been the case that the appropriate technology was not available at the time of original recovery. However, increasing demand for minerals in clean technologies coupled with concerns over supply gaps have prompted a re-evaluation of the financial feasibility of recovering these minerals, positioning mine waste as a potential resource.

Technological pathway

The technological pathway for recovering minerals from mine waste depends on the type and characteristics of the mine waste and the specific mineral being recovered. However, the process to extract minerals is generally similar to the original value chain and includes the following steps: crushing, milling, classification, separation (including flotation, gravity separation, magnetic separation), leaching or solvent extraction, metal extraction, and/or metal recovery. Additional challenges exist in recovering minerals from mine waste, such as secondary minerals created during the weathering and disposal process, the uneven size and texture of waste particles, and oxidation of minerals, which may require adaptations to primary production processes or the development of new technologies.

Materials that can be recovered

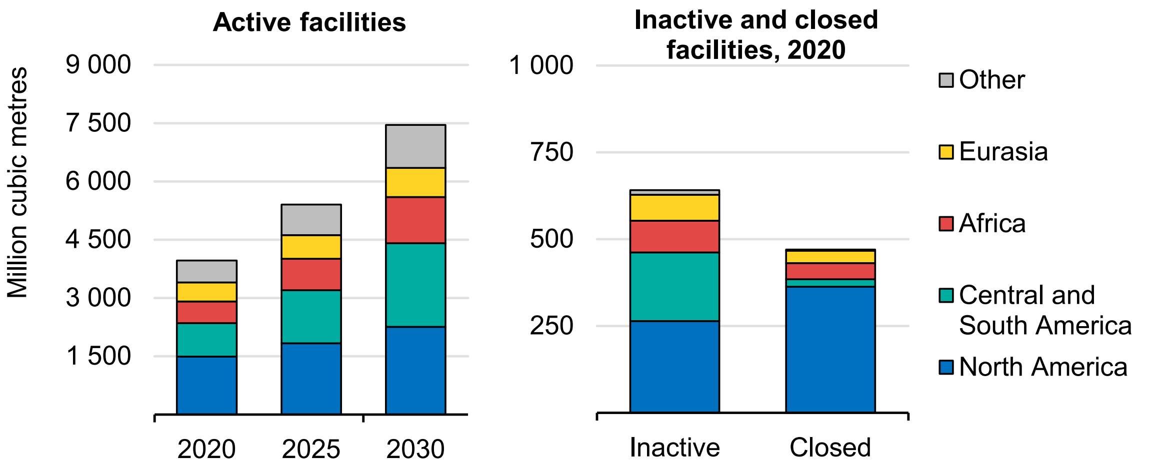
The minerals that can be recovered from mine waste depend on the geology and the extraction or processing that was originally applied when the waste was generated. For example, commonly found minerals within gold and iron tailings could include copper, zinc and some rare earth elements. For copper tailings, metals such as cobalt, zinc and rare earth elements may be found. Rare earth elements can also be found in tailings from tin, phosphate, bauxite, coal, titanium and uranium. Depending on the ore grade and recovery efficiency of the original process, varying levels of the originally targeted commodity may also be present.

Current status

Some companies are already recovering minerals from mine waste. For example, US Strategic Metals has been recovering cobalt from tailings at a former Superfund site since 2019. However, large-scale production from mines is still not common. Companies have started to actively evaluate the potential of recovering minerals from mine waste, including large mining companies. Rio Tinto invested USD 2 million in Regeneration to focus on re-mining and processing of waste from legacy mine sites, aiming to extract minerals from tailings, waste rock and water. Barrick Gold is also exploring the possibility of critical metals recovery at Nevada Gold Mines, targeting nickel, cobalt, scandium and zinc using an ion-exchange recovery system to extract materials from heap leach copper solutions. In Europe, examples include Euro Manganese, which is looking to recover and refine battery-grade manganese from tailings at a decommissioned mine site, and LKAB, which is looking to recover rare earth elements in phosphates from iron ore mine tailings. Similar initiatives are under way in countries such as the Democratic Republic of Congo and Zambia, among others.

Mining generates large amounts of waste, with around 3 500 large-scale mining operations estimated to produce over 100 billion tonnes of solid waste every year. In addition, there were an estimated 5.75 billion cubic metres of waste in active, inactive and closed tailings in 2020 for just over 100 of the world's largest mining companies, mainly located in the Americas. As new mines and associated tailings facilities open, the volume of active facilities is expected to grow by 1.7 billion cubic metres by 2025, increasing the amount of tailings worldwide by about 35% since the beginning of this decade. If current growth continues, this would mean that the amount of waste generated would reach almost 8.5 billion cubic metres by 2030, 87% higher than 2020 levels. This does not include tailings from abandoned sites, where there are an estimated 500 000 abandoned mining sites in the United States alone, as well as those from artisanal mine sites.

Figure 2.32 Volume of active, inactive and closed tailings facilities by region, 2020 to 2030



Note: Data are self-reported by over 100 of the world's largest mining companies and cover approximately 30% of global commodity production. 2030 values are estimated based on regional growth rates between 2020 and 2025.
Source: IEA analysis based on data from Global Tailings Portal (2020), Tailings storage facility table, accessed 12 July 2024.

The amount of waste and tailings is likely to increase further due to several factors. For more developed markets, like copper, much of the economically recoverable higher-quality ore has already been exploited, necessitating the extraction of lower-quality ore in the future, which generates more waste for the same amount of material. For less developed markets, the quantity of waste will increase as new mines are opened to ramp up supply for the energy transition. Although future waste does not contain large amounts of originally targeted ore, it could still contain co- or by-products that have traditionally not been the focus of the specific miners.

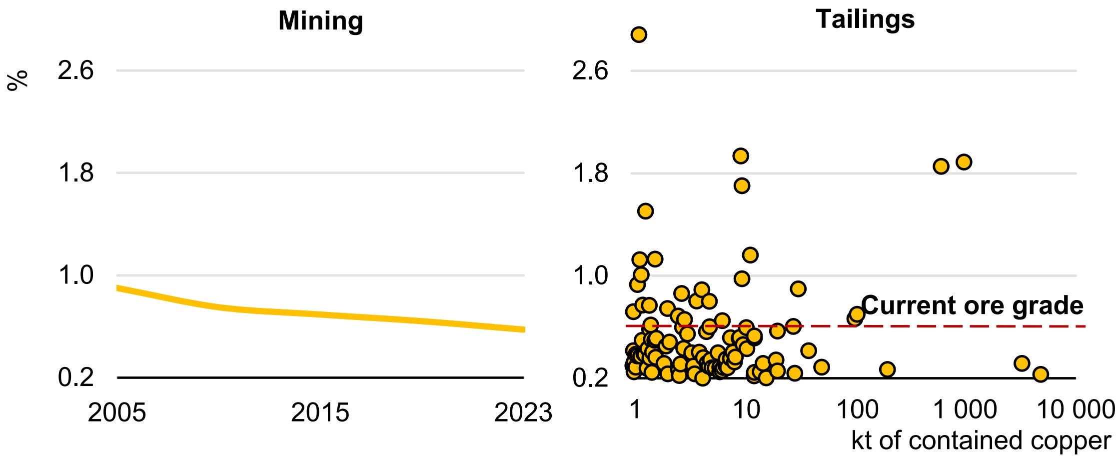
Economics and business models

Several factors influence the economics of using mine waste as a source of material recovery. Prices of metals and minerals play a significant role, with higher prices creating more financial incentive to extract the relatively smaller quantities of minerals within waste. Market price volatility often seen in the mining sector, on the other hand, can work to deter investors from committing the substantial upfront costs involved in evaluating and extracting minerals from mine waste. Recovery efficiency also impacts the financial viability, as a smaller quantity of potentially recoverable minerals means lower rates of return.

Historically, minerals remaining in mine waste were deemed economically and technologically unviable for extraction and further processing due to their low quality or quantities. However, elevated prices in recent years, coupled with declining ore grades and increasing supply pressures, have made reprocessing mine waste a more attractive option. The driving factor behind this re-evaluation depends on the mineral. A key factor in more mature markets is the expectation of continually declining resource quality, which could cause ore grades to decline past the level of contained metal within historical tailings. In this case, it could be the case that the cost of recovering resources from mine waste is lower than that of opening a new mine.

Chile provides an example of this. Over the last almost 20 years, the average ore grade for copper in Chile has declined by a third from 0.9% to 0.6%. In 2005, there was only 1.6 Mt of contained copper that was higher than primary ore grades. In contrast, today there are 100 tailings sites with ore grades that exceed primary production, totalling 2 Mt of contained copper, suggesting extracting copper from these tailings could be economically attractive. If this trend continues, by 2050 there could be 5.6 Mt of contained copper that exceeds the ore grade found in primary mining operations, almost 3 times higher than today.

Figure 2.33 Average contained copper found in tailings versus ore grade in Chile



Note: Tonnes of contained copper cuts off values less than 1 kt of contained copper.
Sources: IEA analysis based on data from Ministerio de Minería (2022), Ley Promedio de Mineral de Cobre en las Operaciones Mineras en Chile por tipo de proceso, accessed 2 October 2024 and Servicio Nacional de Geología y Minería (2023), Programa de Caracterización de Depósitos de Relaves de Chile, accessed 12 July 2024.

For other minerals found in smaller quantities, such as nickel, cobalt, lithium or rare earth elements, heightened prices and the outlook for future supply gaps are key factors that have made mine waste reprocessing more appealing than in the past. These minerals were often left unexploited as they were only found as by-products in small quantities. However, the context of the energy transition may make recovering these minerals financially more viable. Some of these minerals may also face declining ore quality issues: for example, nickel has been shown to have a long-term declining ore quality trend. Recent technological developments have made the recovery of these lower ore grades or the small quantities found as by-products more feasible.

The optimal business model for re-mining and reprocessing mine waste depends on the specific characteristics and ownership of the waste. Mine waste can be found in active sites, where it may be easier to recover minerals in-house due to clearly defined ownership. It can also be found in closed or abandoned facilities where legal ownership and liability is less clear, which may necessitate a different approach. The business model is also influenced by whether companies operate purely upstream or are vertically integrated. Vertically integrated companies may face lower upfront capital costs if they already have the necessary infrastructure for waste recovery. On the other hand, smaller companies may struggle with the significant capital investments required. Additionally, a company's focus – whether it is a diversified major or a specialist in specific minerals – affects its ability to re-mine waste. Diversified majors may have broader technical expertise, while specialised companies may need to acquire new technical know-how and capacity to deal with minerals outside their core expertise.

Environmental risks associated with mine waste also impact the business models. The liability and costs of safely storing and managing mine waste are significant, particularly in jurisdictions with stringent regulations for mine site closure and rehabilitation. By reassessing mine waste as a potential resource, companies could offset these costs. Reprocessing mine waste can not only reduce financial burdens associated with mine and tailings closure, but also mitigates environmental risks, such as acid mine drainage and tailings failures (see below section on "Environmental implications"). Reprocessing waste could also help avoid escalating compliance costs resulting from increasingly stringent environmental standards.

Environmental implications

Processing of waste can bring environmental benefits by mitigating impacts and risks from mine waste such as water contamination from acid mine drainage, safety hazards related to tailings facilities and soil pollution from leaching waste piles. For active mining operations, re-mining waste reduces waste volume and may mitigate environmental impacts, while at closed or abandoned sites, it offers an opportunity to remediate contamination and pollution, potentially transforming environmental liabilities into assets. Sustainable waste management throughout the recovery process is essential to ensure that mining waste is properly repurposed as valuable resources instead of contributing to environmental harm.

Tailings pose an environmental risk as they contain large quantities of dangerous and toxic substances, such as heavy metals and sulphide minerals. They are often stored near the mine site in heaps or large ponds called tailings storage facilities (TSFs). Inadequate tailings management or uncontrollable factors, such as earthquakes, can result in the collapse of TSFs and the release of pollutants through hundreds of kilometres. Over the period of 2010 to 2019, there were 45 instances of mine tailing failures that resulted in over 100 million cubic metres of tailings being released and almost 500 deaths. One of the largest was Vale's 2019 failure at Brumadinho tailings dam mine in Brazil, which released around 10 million cubic metres of tailings, killing 270 people in nearby settlements, destroying local infrastructure and polluting nearby water bodies. In 2020, the UN Environment Programme, the International Council on Mining and Metals, and the Principles for Responsible Investment released a Global Industry Standard on Tailings Management, the first global standard with an integrated approach to tailings management, aimed at preventing failures and enhancing the safety of mine tailings facilities. When reprocessing tailings to recover resources, it is also essential to properly manage the reopening and handling of tailings to minimise environmental hazards.

Soil contamination arising from the leaching of hazardous substances from waste piles is another significant environmental concern. These waste piles, potentially containing heavy metals such as lead and mercury, can release contaminants into the soil and groundwater. Rainfall water or surface water run-off can work as a solvent and lead to a leaching process that spreads these pollutants, contaminating the site and more distant ecosystems. The potential for large-scale heap-leach pad and waste rock stockpile failures further increases environmental risks. Remediation is often required and can demand long-term and costly efforts, such as the removal of contaminated soil, stabilisation of waste piles, and soil treatment (e.g. through thermal processes or phytoremediation that uses plants to absorb toxins).

Sulphide minerals often mined for nickel and cobalt have high contents of potentially harmful metals such as zinc, lead and cadmium. Acid mine drainage (AMD) happens when mining activities expose waste rock high in sulphide contents to air and water, creating a chemical reaction that forms sulphuric acid. Without proper management to prevent or clean up AMD, the acid can cause environmental damage such as water pollution. In total, an estimated 20 000 to 50 000 mines worldwide release acidic drainage, causing around 4 500 kilometres of streams to turn acidic.

Policy implications

Key barriers

Recovering minerals from mine waste and treating it as a source of secondary supply presents several challenges. One key challenge is economic viability, as the value or quantity of the minerals may not be sufficient to justify or incentivise recovery. High investment costs, including those for resource evaluation, capital expenditures, and the handling and transportation of materials, can further complicate the business case for recovery.

Another barrier is the lack of knowledge and technical expertise. Often, there is insufficient mapping or understanding of the potential scale of resources, especially at closed or abandoned sites with no active owner or where the state has assumed ownership. Even at active sites with existing owners, knowledge or technical gaps may exist within companies whose expertise lies in specific segments of the value chain, such as extraction, or in particular minerals, which may differ from those contained within the waste. Additionally, the uncertainty of identifying significant or viable resources can often deter investment and limits the identification of promising opportunities.

Current regulatory frameworks, along with the non-uniformity or ambiguity of relevant legislation for mine waste, present multiple challenges. In many countries, the management of mine waste can be regulated through various combinations of mining, environmental and land-use legislation. In some cases, mine waste is governed by a patchwork of regulations, making compliance difficult. The complexity increases when it comes to recovering resources from mine waste. While many jurisdictions require environmental assessments for mining activities, including mine waste management and closure plans, these regulations often lack specific provisions to facilitate the recovery of minerals from mine waste. Separate permits for recovering resources may be required, but companies are often reluctant to apply due to the already lengthy and complex permitting processes for primary mining. In some regions, there are no specific permitting systems for the recovery of minerals from mine waste. Furthermore, a lack of standardised methods for classifying mine waste as potential resources complicates efforts to identify viable recovery opportunities.

The complex issue of environmental and legal liability, especially for closed or abandoned sites, poses a major challenge. In many jurisdictions, operators are legally responsible for preventing and remedying any environmental damage caused by their activities, including taking preventative measures and providing financial guarantees. If operators were to take ownership of mine waste at closed or abandoned sites to recover minerals, they would inherit the associated legal and environmental liabilities, which could significantly deter them from pursuing recovery efforts at such sites.

Sector-specific recommendations

Establish economic incentives for companies to recover minerals from mine waste. Some countries impose fees or taxes per unit of mine waste or tailings produced, such as the Philippines, which could be reduced if minerals are recovered from these waste materials at existing sites. Additionally, incentives could include reduced royalties on primary commodities based on resource evaluation or R&D efforts aimed at improving recovery efficiency at mine waste sites. These incentives could apply to both active and closed sites. Discounts in royalties could be similarly applied to recovered materials, particularly those recovered from closed or abandoned facilities. If countries already provide exploration tax credits, such as Canada's Critical Mineral Exploration Tax Credit, these could be extended to include exploration expenditures targeted at recovering critical minerals from mine waste, or countries could consider implementing them.

Provide funding through grants or loans for technological R&D to re-mine waste and tailings. Policy makers could incorporate provisions within their domestic strategic plans on developing technologies for more efficient mineral recovery from waste. For example, these include funding for R&D for innovative processing technologies, including from recovering value from waste. The state of Queensland in Australia similarly provides AUD 5 million (Australian dollars) in funding for companies seeking to recover value from mining and processing as part of the Queensland Critical Minerals Strategy. Other countries provide funding through industrial policies. The United States provides funding through the Infrastructure Investment and Jobs Act for pilot projects focused on processing, recycling and developing critical minerals, with at least 30% dedicated to secondary recovery from mine waste and related sources. USD 140 million was earmarked for a rare earth demonstration facility to extract, separate and refine rare earth elements from mine waste and other materials.

Develop or fund mapping and resource estimation systems to provide a comprehensive overview of available mine waste sources, facilitating easier identification of potential resources. Already some efforts exist where geological agencies have attempted to make information on mine waste publicly available. Examples include Geoscience Australia's Atlas of Australian Mine Waste, which has recorded more than 1 000 sites across the country to help identify and utilise large tailings. The US Geological Survey has invested USD 2 million from the Bipartisan Infrastructure Law into co-operative agreements with 14 states to study the potential for critical mineral resources in mine waste.

Streamline or clarify the regulatory framework where legislation regarding mine waste resource recovery is patchy or unclear. In jurisdictions lacking specific legislation, policy makers should update existing laws or introduce new ones to add provisions for mine waste resource recovery. This should take into account the interconnected nature of waste legislation, environmental permitting and environmental impact assessment requirements, aiming to reduce the complexities associated with a fragmented legislation landscape. Some jurisdictions are already working towards this goal; for example, the Ontario government in Canada has proposed amendments to the Mining Act that would allow applicants to submit a recovery permit application detailing the proposed mine waste recovery activity and remediation plan, thereby eliminating the need for a full mine site closure plan.

Update or create regulations that address the liability barriers associated with mine waste at abandoned or closed sites. Policies such as the proposed United States' Good Samaritan Act, which allows non-liable parties such as volunteers and non-profits to clean up sites without being held responsible for past pollution, could serve as a model. Amending or extending similar legislation to companies reclaiming mine waste for mineral recovery could be beneficial, provided incentives are properly aligned to prevent original companies from exploiting the law. Policy makers should also consider revising the classification of mine waste to ensure consistency across jurisdictions, with consideration of the different types of mine waste. Any new or revised policies aiming to incentivise the re-mining of waste need to adequately consider environmental, social and governance impacts. This includes developing robust plans to identify and minimise environmental impacts, consulting local communities and Indigenous Peoples, and ensuring a clear and inclusive multi-stakeholder approach to the development of any new legislation.

2.6. E-waste

How it works

Current status and potential

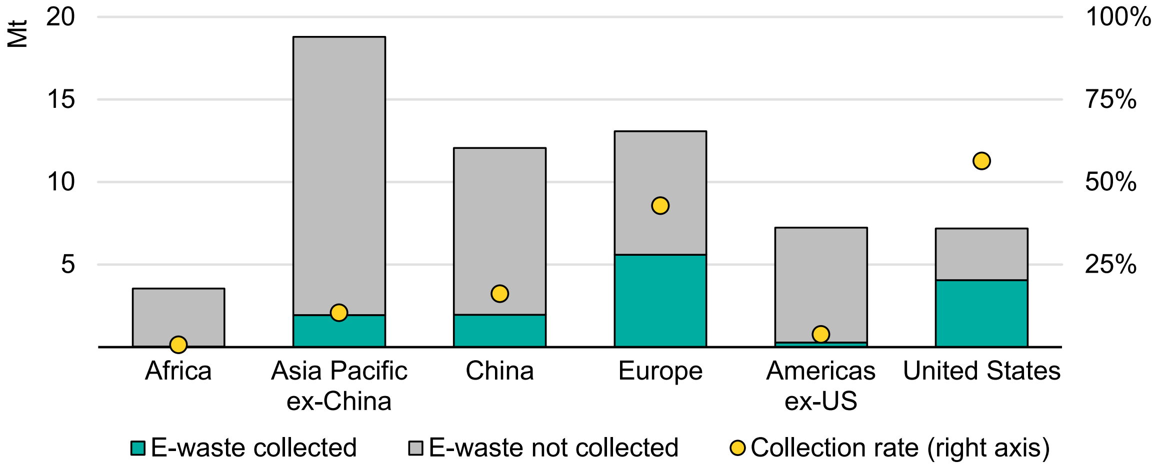
Electronic waste, commonly known as “e-waste” or waste from electrical and electronic equipment (WEEE), is a term used to describe discarded electrical or electronic devices. This type of waste can include large household appliances – including cooling and freezing appliances, small household appliances, information technology (IT) equipment, consumer electronics such as televisions, lamps and lighting devices, medical equipment, electronic toys and tools, etc. The United States Environmental Protection Agency (US EPA) considers e-waste to be a subset of used electronics and recognises the inherent value of these materials that can be reused, refurbished or recycled to minimise the actual waste that might end up in a landfill or improperly disposed in an unprotected dumpsite.

The e-waste recycling industry has developed due to concerns surrounding the environmental and health impacts of irresponsible e-waste dumping. For example, there are problems with open-air burning and acid baths being used to recover valuable materials from electronic components, which expose workers to harmful substances. There are also issues with toxic materials leaching into the environment. These practices can expose workers to high levels of contaminants such as lead, mercury, cadmium and arsenic, which can lead to irreversible health effects. The waste is very often shipped to emerging and developing economies that lack the capacity to handle these materials appropriately.

These concerns have led to domestic laws, regulations and policies being developed – as of June 2023, 81 countries are covered by some form of e-waste legislations, policies and regulations. International treaties such as the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (hereafter, "Basel Convention"), which entered into force in 1992, were established to regulate e-waste being shipped from advanced economies with high consumption levels to developing economies. Furthermore, the extended producer responsibility (EPR) policy approach, a set of economic instruments designed to generate revenue and create incentives for the collection and recovery of materials at the post-consumer stage of the product life cycle, has significantly impacted the volumes of waste treated globally, with many countries adopting the policy since the 1990s. EPR strategies have led to improved transparency regarding material and financial flows, shifted end-of-life management costs from local governments to producers, and increased material recovery rates. Nevertheless, illegal e-waste exports remain a major issue today.

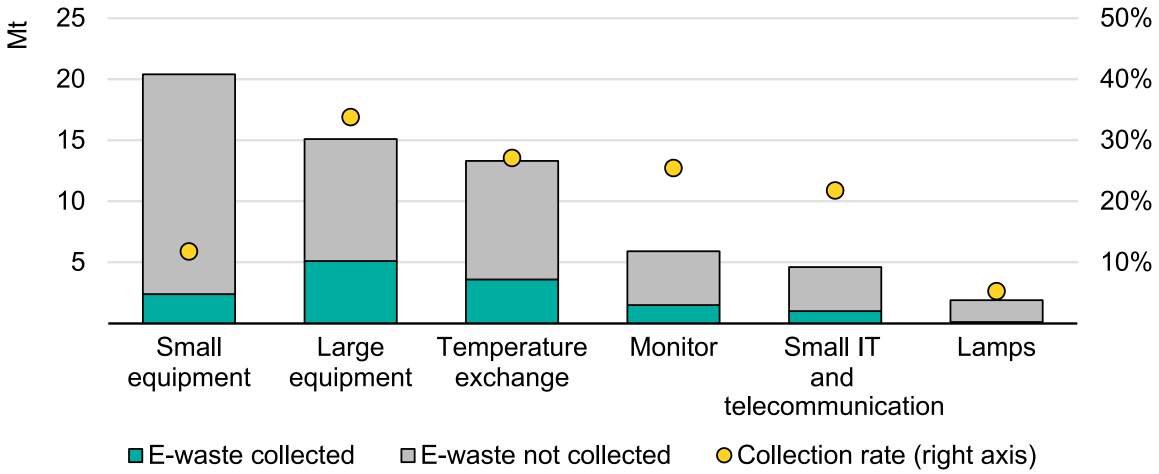
An estimated 62 Mt of e-waste was produced in 2022, an 82% increase from 2010. Despite rising awareness about the issue, less than a quarter of this waste generated in 2022 was documented as having been properly collected and recycled – there are, though, sizeable volumes being recycling outside of formal systems. Furthermore, the UN's Global E-waste Monitor 2024 projects that the amount of e-waste is set to expand by 33% to 82 Mt by 2030. The report also highlights that since 2010, global e-waste generation is rising five times faster than collection and recycling efforts. Consequently, recycling rates are projected to decline from 22% in 2022 to 20% by 2030 as current efforts fail to keep pace with the staggering growth of e-waste.

Figure 2.34 Amount of e-waste generated and collected by region, 2022



Note: US = United States.
Source: IEA analysis based on Baldé, Kuehr, Yamamoto et al., International Telecommunication Union and United Nations Institute for Training and Research (2024). Global E-waste Monitor 2024.

Figure 2.35 Amount of e-waste generated by types of appliances, 2022



Notes: Small equipment includes electrical and electronic toys such as vacuum cleaners, microwave ovens, video cameras and e-cigarettes. Large equipment includes washing machines, clothes dryers, dishwashers, electric stoves, large printers and PV panels. Temperature exchange equipment comprises items such as refrigerators, freezers, air conditioners and heat pumps. Monitors includes televisions, laptops and tablets. Small IT and communication equipment includes mobile and other phones, personal computers, GPS devices, and printers. Lamps includes fluorescent, high-intensity discharge and LED lamps.
Source: IEA analysis based on Baldé, Kuehr, Yamamoto et al., International Telecommunication Union and United Nations Institute for Training and Research (2024). Global E-waste Monitor 2024.

Technological pathway

While the specific technological pathways used for recycling and treating e-waste depends on the type of appliances or devices, a general flow of the process involves many or all of the following steps: sorting, physical dismantling, disassembly, physical pretreatment, thermal pretreatment and chemical pretreatment.

Physical pretreatment can include processes such electrostatic separation, which is a method that uses electrical charges to separate different types of materials based on their conductivity, i.e. a method to separate metals from non-metals in the waste stream. Thermal pretreatment can be pyrometallurgical processes that use high temperatures (smelting or incineration) to extract metals with different melting points. Chemical pretreatment is often a hydrometallurgical process that uses acids to extract metals through a difference in their chemical reactivities and is particularly effective in recovering precious metals from e-waste.

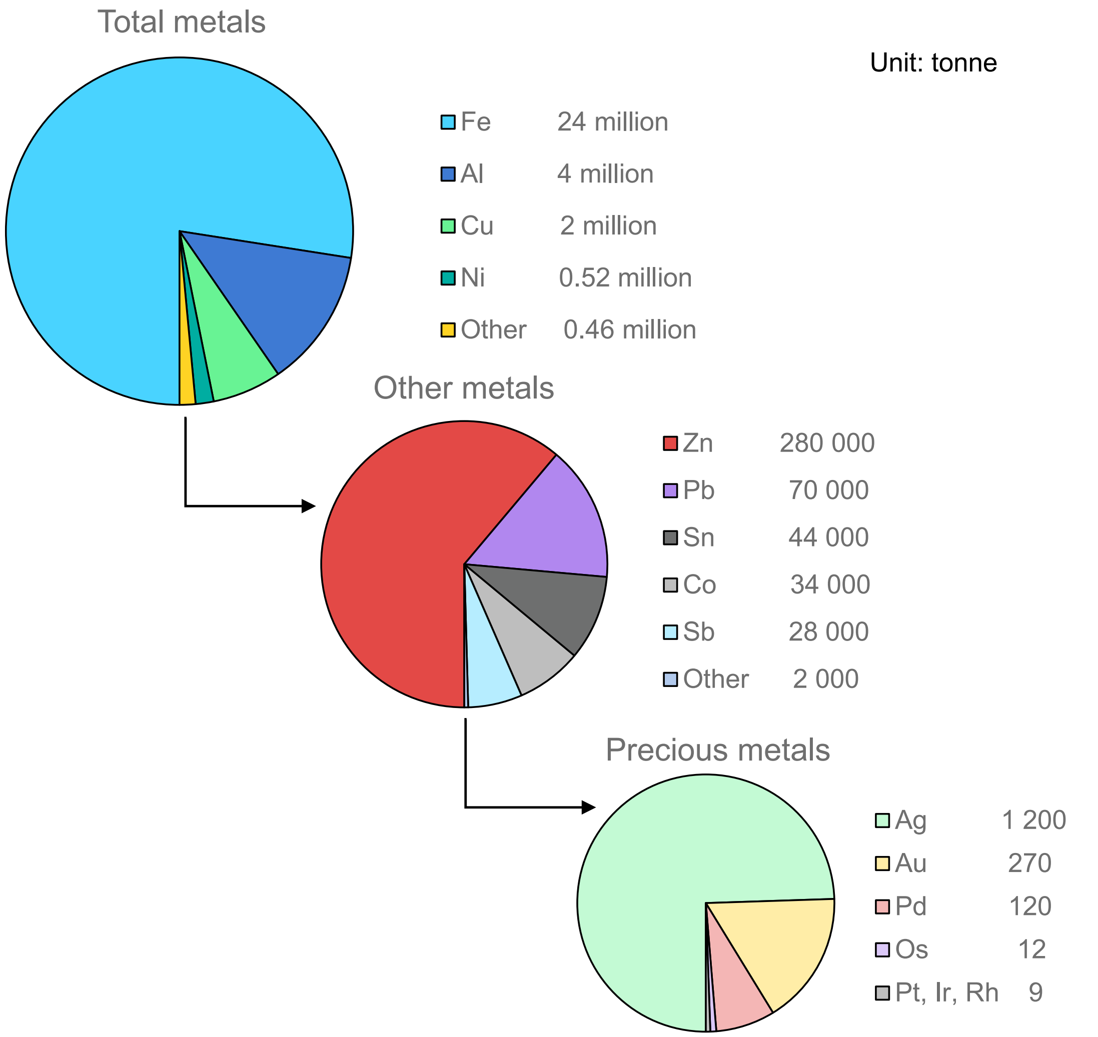
Several techniques can increase the potential efficiency of the recycling processes for e-waste. For example, automated sorting systems that use sensors, conveyor belts and artificial intelligence (AI) to categorise the different waste streams from a mixed pile of e-waste can help increase the efficiency of the identification and segregation steps and reduce the need for strenuous manual labour. Recent research shows the potential for combining material flow analysis (MFA) with geospatial analysis to optimise the yields and profits from e-waste recycling: MFA is used to estimate future e-waste flows, and geospatial analysis is used to estimate e-waste generation at the regional level.

Current status

Materials that can be recovered

The composition of e-waste varies by type of device or appliance, but it consists primarily of metals and plastics. In 2022, all e-waste worldwide contained 31 Mt of metals, which tend to have higher recycling rates than other materials. The most common materials recovered from e-waste treatment processes include bulk metals such as iron, aluminium and copper, and hazardous materials such as mercury, lead, arsenic and cadmium, but also valuable or critical minerals such as nickel, rare earth elements, indium, cobalt, platinum, palladium, silver and gold. Recent studies have shown that the latest electronic products entering the waste stream incorporate fewer toxic materials and more valuable metal content, presenting broader opportunities for material recovery.

Figure 2.36 Estimated volume of metals contained in e-waste, 2022



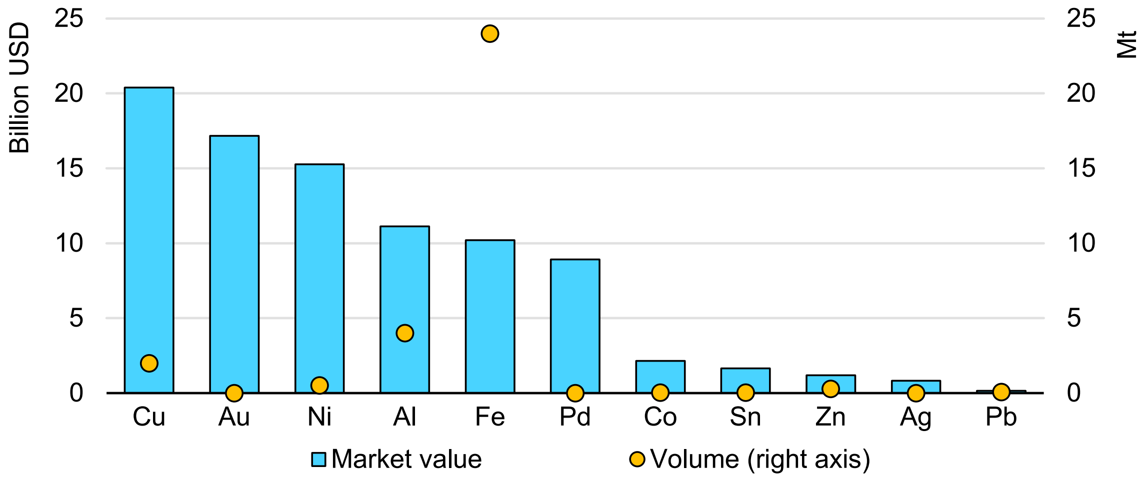
Notes: Fe = iron; Zn = zinc; Pb = lead; Sn = tin; Sb = antimony; Ag = silver; Au = gold; Pd = palladium; Os = osmium; Pt = platinum; Ir = iridium; Rh = rhodium; Ru = ruthenium.
Source: IEA analysis based on Baldé, Kuehr, Yamamoto et al., International Telecommunication Union and United Nations Institute for Training and Research (2024). Global E-waste Monitor 2024.

Economics and business models

The e-waste recycling industry began developing to mitigate the environmental and health impacts of large volumes of untreated waste, rather than to generate economic profit through the recovery of precious metals and/or critical minerals. This contrasts with the case of EV battery recycling, which tends to be focused on the economics of producing secondary critical mineral supplies.

The recycling infrastructure for e-waste developed over decades despite limited economic incentives and high process complexity. This progress was largely driven by national regulations and international treaties that encouraged waste collection, sorting and pretreatment methods. Initially, private sector investments in e-waste recycling were primarily a response to regulatory and policy initiatives. However, today the industry is transitioning towards a balance between policy-driven and profit-driven business models, as the value of critical minerals found in e-waste, even in small quantities, has become increasingly significant for various stakeholders. For example, in 2022, e-waste contained metals worth around USD 90 billion, with just USD 28 billion of that recovered and turned into secondary raw materials.

Figure 2.37 Implied market value for contained metal volumes in e-waste, 2022



Note: Market value is based on the 2022 average market price of each metal multiplied by the volume contained in e-waste.
Sources: IEA analysis based on Bloomberg, S&P Global and Baldé, Kuehr, Yamamoto et al., International Telecommunication Union and United Nations Institute for Training and Research (2024). Global E-waste Monitor 2024.

Policy implications

Key barriers

Challenges contributing to the widening gap between amount of waste generated and recycling rates include rapid technological advancements, increased consumption, limited repair and refurbishment options, shorter product life cycles driven by shrinking innovation cycles, growing electrification across various sectors, design inefficiencies, and inadequate e-waste management infrastructure.

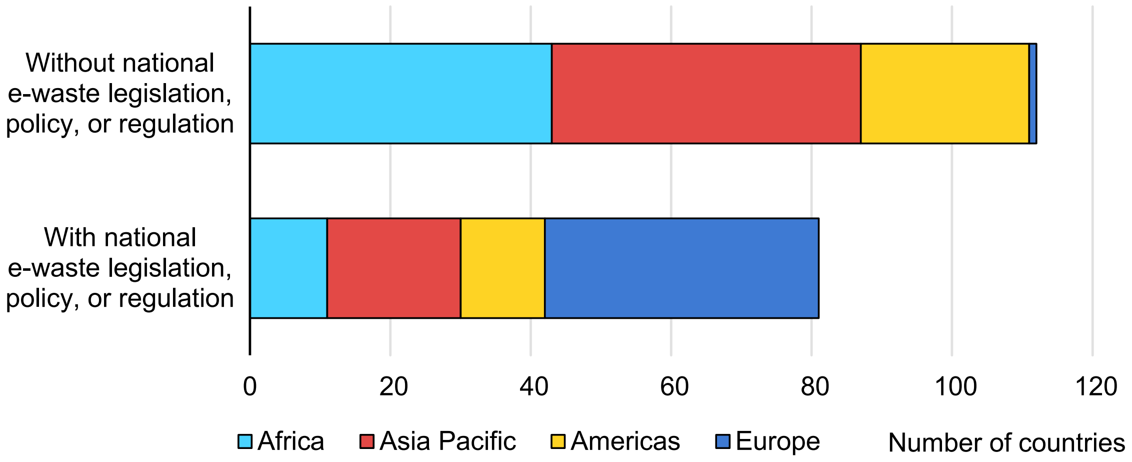
E-waste recycling is particularly challenging due to the difficulty in sorting, as e-waste comes in highly heterogeneous shapes, sizes and material compositions – even for similar appliances or devices. Scaling up e-waste recycling requires stronger policy support, as traditional market-based profit margins tend to be slim. The materials retrievable from e-waste lack consistency, and recycling processes typically focus on bulk materials that can be recovered in large quantities, rather than critical minerals, which are often present in smaller amounts.

Sector-specific recommendations

The Global E-waste Monitor 2024 highlights that if countries could bring the e-waste collection and recycling rates up to 60% by 2030, the implied benefits – including through minimising human health risks – would exceed the costs and amount to over USD 38 billion. This section aims to outline key recommendations that could enable the scaling up of e-waste recycling.

Harmonisation of e-waste regulations and collection targets. While collection rates in advanced economies are above the global average, there is still much room for improvement as these have remained more or less stagnant over the last decade. On the other hand, collection rates in emerging and developing economies is well below the global average, with the rates being the lowest in Africa. There is a need to harmonise regulations, mobilise the EPR wherever possible and leverage strategic partnerships with emerging economies. All policies should have clear targets for collection rates; for example, since 2019, the EU directive on WEEE requires the minimum annual collection rate to be 65% of the average weight of electrical and electronic equipment (EEE) placed on the market in the three preceding years in the member state concerned, or alternatively 85% of WEEE generated on the territory of that member state. Although the Union has not been successful in meeting its e-waste collection targets in full, its collection rate is considerably higher than other regions/countries without similar targets.

Figure 2.38 Countries with and without e-waste disposal legislations, policy or regulation as of June 2023



Note: Data cover 193 countries.
Source: IEA analysis based on Baldé, Kuehr, Yamamoto et al., International Telecommunication Union and United Nations Institute for Training and Research (2024). Global E-waste Monitor 2024.

Raising public awareness about the issue. A lack of information about the negative impacts of improper disposal means that very often smaller e-waste such as handheld electronics or lighting devices are discarded with common household waste, making it impossible to safely recover them. Measures such as public awareness campaigns on how to dispose of end-of-life electronics, incentivising companies or mandating local governments to operate pick-up services for larger appliances, and postal collection for smaller devices could vastly improve collection rates from households.

Stricter regulations and penalties for illegal e-waste dumping and the uncontrolled trade of untreated waste should be implemented, alongside enhanced support for building recycling infrastructure and capacity in developing economies. Often much smaller markets for the sale of EEE (for example due to a lack of universal access to electricity in sub-Saharan Africa), emerging and developing economies have long been faced with the challenges of importing untreated e-waste from advanced economies with minimal infrastructure to safely recycle it. Studies suggest that the total e-waste in Africa in 2019 was as high as 5.8 Mt, with up to half of them originating from illegal transboundary imports from developed countries in the Americas, Europe and China. The main recipients of e-waste in the continent were Egypt, Ghana, Kenya, Nigeria, Senegal and Tanzania. In 2019, Indonesia sent back around 250 waste-filled shipping containers to the United States, the United Kingdom, Germany, France, Hong Kong and Australia, citing the violation of rules on the import of hazardous materials. More recently, in 2020 Thailand passed a strict ban on the imports of e-waste, while India further tightened the regulations for their import in 2022. Measures to prevent or penalise illegal e-waste exports and imports are the first step towards dealing with this issue, but this must also be accompanied by stepping up investments for recycling infrastructure and skill and knowledge transfer to emerging economies.

Enhance efforts to improve traceability and data collection. At present, data and estimates for e-waste generation and collection are difficult to obtain at national or subregional levels and total waste volumes are often underestimated due to leakages. Access to reliable data is central to identifying the sectors and regions that require the maximum attention. Understanding which minerals are being retrieved, in what quantities and of what value would also contribute to increasing process efficiencies. Reinforcing government-industry collaborations to this end will yield more transparency.

Improve pretreatment processes to expand the potential for recovering critical minerals from e-waste. Current processes like pyrometallurgy often result in the loss of critical minerals found in small quantities due to the lack of proper sorting beforehand. because the focus of the industry so far has been on recycling bulk materials such as steel or treating toxic substances. To improve the recovery of precious metals and/or critical minerals, it is essential to first remove the components containing important raw materials such as printed circuit boards and batteries and feed these components separately to recycling facilities. Companies can create their business models with circularity in mind: for example, Apple not only has programmes to collect its used devices for recycling, but also has developed proprietary automated systems that efficiently disassemble lithium-ion batteries from the devices to recycle them separately and has pledged to use 100% recycled cobalt in all its devices by 2025.

Chapter 3. Cross-cutting issues to maximise the potential of recycling

3.1. Economics of recycling

As discussed in Chapter 1 (“State of Play”), recycling business models for traditional metals and critical minerals differ significantly. This is in large part due to the relative difficulty of recovering the valuable materials contained in the feedstock, which often necessitate more complex, customised processes than those found in traditional metal recycling.

Traditional metal recycling benefits from established markets, stable demand and well-understood processes, leading to more predictable returns on investment. However, while emerging recycling models for critical minerals have the potential for higher value creation, they also come with high levels of uncertainties and financial risks. Critical mineral recycling often needs to deal with fluctuating demand tied to evolving technologies and processes that may still be in the optimisation phase.

The economic viability of critical minerals recycling projects is influenced by a multitude of factors. Material prices play a crucial role; when prices of critical minerals are high, recycling becomes more attractive. However, these prices can be highly volatile, adding uncertainty to long-term project planning. Feedstock availability is another key factor; unlike base metals with well-established scrap collection systems, critical mineral recyclers often need to develop new collection networks or rely on partnerships with manufacturers for a steady supply of end-of-life products.

Regulatory support also significantly impacts the economics of critical minerals recycling. Supportive policies, such as extended producer responsibility (EPR) schemes, recycled content mandates or financial incentives for recycling, can improve the economics of these operations. Conversely, a lack of regulatory clarity or support can hinder investment and growth in this sector.

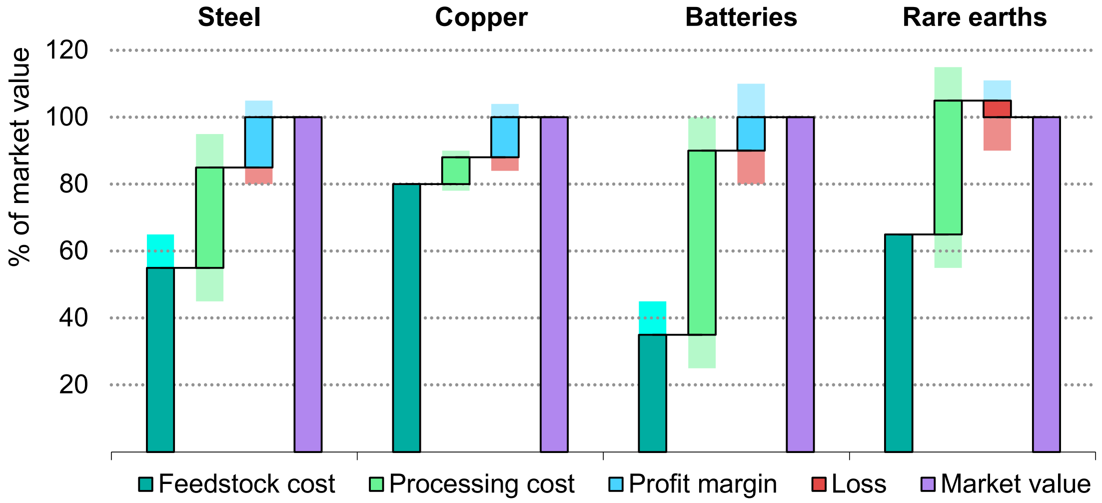
The development of innovative pricing and payment schemes is essential to enhance the economic viability of recycling. One key issue is the time lag between when recyclers purchase end-of-life products and when they can sell the recovered materials. This gap can lead to significant working capital requirements. Revenue-sharing models, where scrap suppliers receive an upfront payment followed by additional sums depending on the actual recovery and sale, are being introduced to address this issue.

In terms of the realised value of recycled material, most transactions are based on the market prices for the metal, often indexed to the London Metal Exchange (LME) price. The volatility of these prices means that the profitability of the recycling operation may vary day-to-day, necessitating a strong balance sheet to withstand fluctuations. Integrated recycling operations that are part of a large manufacturer such as BASF or Umicore may thus have an advantage in cash flow management.

Policy solutions implemented in other energy markets offer valuable insights into addressing these challenges and ensuring that market participants have confidence in the long-term business case for recycling. This could include contracts for differences, where governments guarantee the prices of recycled material sold on the market. Cap and floor mechanisms work in a similar fashion but with a greater degree of merchant risk, providing more economic incentives for the recycler. These mechanisms can mitigate price volatility for recyclers, supporting long-term investment planning.

However, administrative and practical complexities are likely to outweigh those in electricity markets. In addition, many major players derive their competitive advantage from their ability to mitigate market volatility. This means that such mechanisms may be limited to greenfield investments for specialised, more critical commodities rather than larger, existing operations for metals such as copper.

Figure 3.1 Indicative economics of recycling different materials



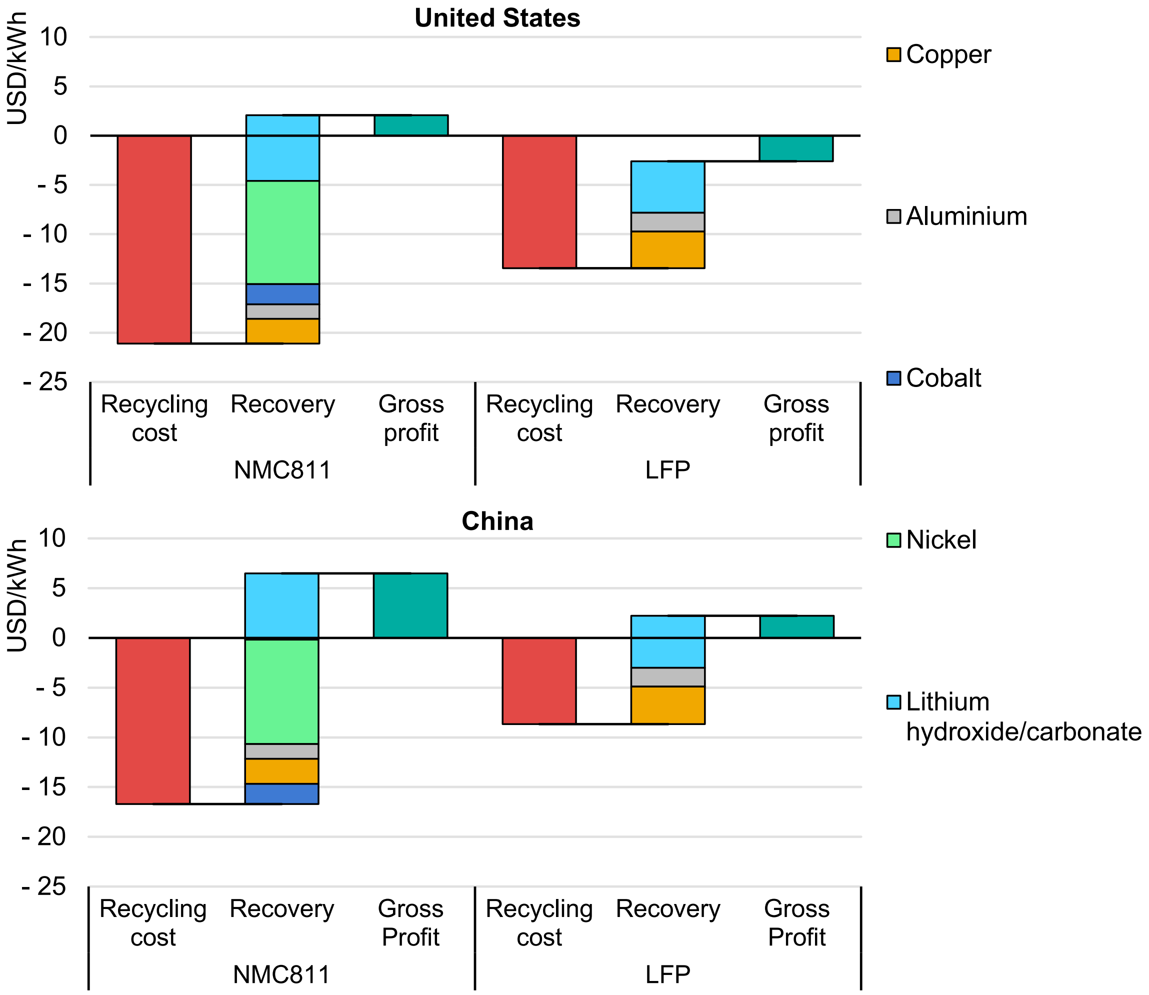
Notes: Light colours indicate the range of possible outcomes. Battery materials analysis is based on nickel-manganese-cobalt (NMC) 811 chemistry. Prices are as of August 2024, with recovered products assumed to have the same value as primary material.
Sources: IEA analysis based on BloombergNEF, International Copper Study Group and World Steel Association.

Diving deeper into the economics of recycling, in traditional metal markets, the value of scrap metal is typically between 50-80% of that of primary material. This is largely a result of the low marginal costs of recycling, especially where primary production circuits already exist. In contrast, critical mineral recycling feedstock such as batteries generally has a lower market value due to the high processing costs incurred during recycling. The profitability of recycling operations is further influenced by the market value of recovered materials. In general, prices of critical minerals used for the energy transition, such as lithium and cobalt, have been far more volatile, resulting in market participants facing potential difficulties in making long-term investment decisions.

Nonetheless, our analysis suggests that recycling businesses can be profitable based on today’s prices. For battery metals, the scale of profits may be much smaller than for steel and copper recycling, but strengthened policy support, technology development and the increasing availability of feedstock implies potential to enhance the business case for recycling. The economics of rare earth elements recycling face greater commercial challenges today, but this can also change with economic incentives, rare earth-specific recycling mandates and consumers’ growing commitments to use recycled materials in products.

Battery recycling economics

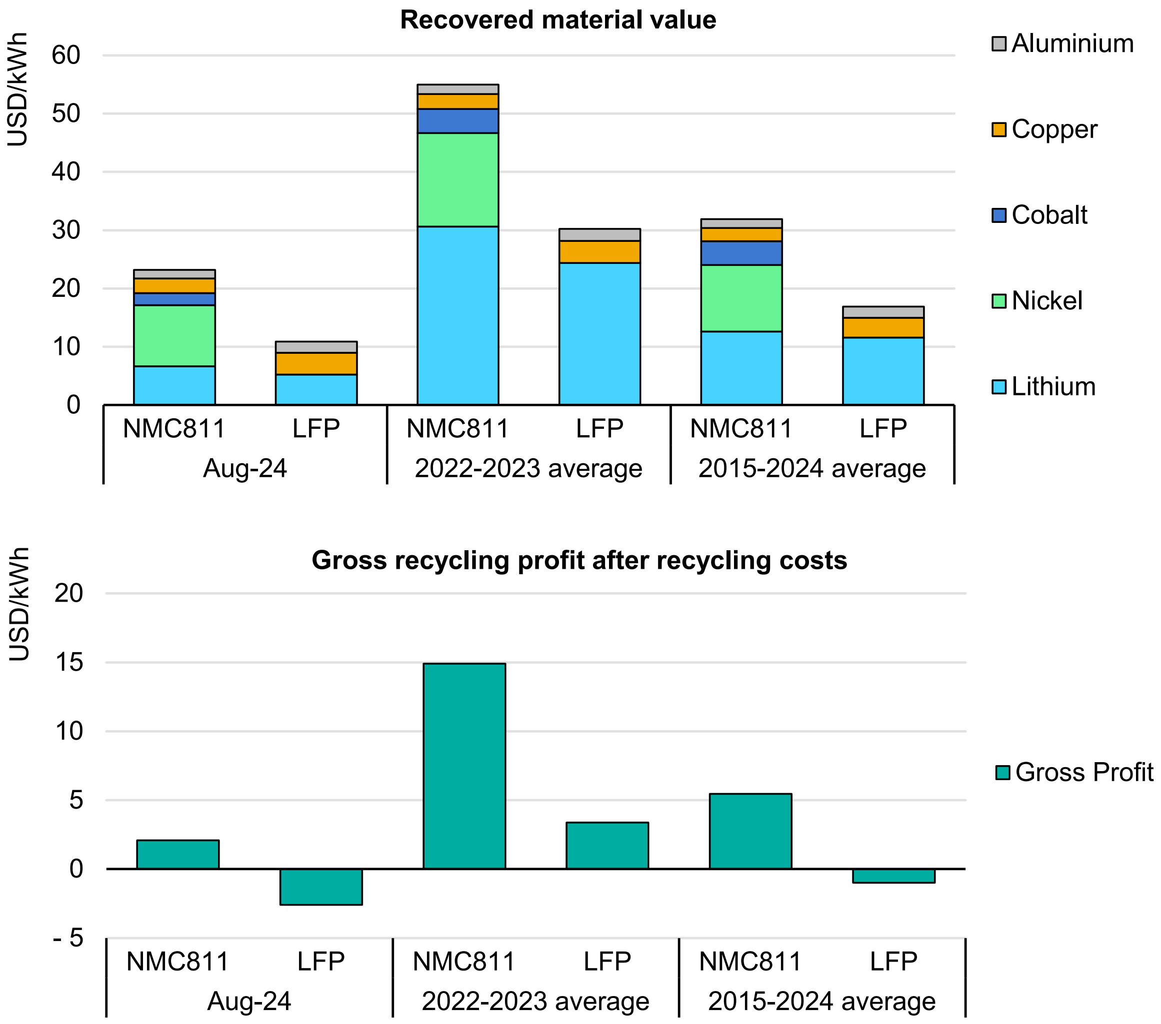
Figure 3.2 Indicative battery recycling economics in the United States and China at current battery metal prices



Notes: kWh = kilowatt-hour; LFP = lithium iron phosphate. Based on hydrometallurgy process. Average domestic material recovery facility capacity in 2023 used for each country – 10 kilotonnes (kt) for the United States and 50 kt for China of battery pack. Incorporates different energy and labour costs for each country. Includes black mass purchase cost for each chemistry. Material prices for lithium, nickel, cobalt, aluminium and copper from August 2024. Based on market-based recycling business model.
Sources: IEA analysis based on S&P Global, LME and BloombergNEF.

The economics of battery recycling is highly sensitive to three factors: the battery chemistry, battery metals prices, and the location of recycling. NMC811 batteries have superior economics to recycle than LFP due to the valuable nickel and cobalt that can be recovered in addition to lithium, contrasting with just lithium from the cathode material for LFP. In the United States, our analysis shows that NMC811 appears to be just profitable using a hydrometallurgical process with today's metal prices (August 2024) while LFP is loss-making due to the low lithium price compared with the costs of hydrometallurgical recycling. However, the picture varies by region. In China the labour costs are lower, and this is coupled with greater economies of scale of recycling and increased vertical integration, resulting in significantly lower recycling costs. Today, the average material recovery facility in China is around five times larger than in the United States. LFP can therefore be recycled profitably in China even at current low lithium prices, posing a significant advantage over other regions. The availability of collection and sorting infrastructure for recycling feedstock is a final significant factor that can influence the recycling economics.

Figure 3.3 Indicative gross profit of battery recycling in the United States under different material price cases



Notes: Analysis using lithium carbonate, lithium hydroxide, nickel, cobalt and copper prices from August 2024, the average prices from 2022-2023, and the average long-term prices from 2015 until August 2024. Based on hydrometallurgy process. Lithium hydroxide prices are used for NMC811 and lithium carbonate prices for LFP. Based on market-based recycling business model. Average domestic material recovery facility capacity in 2023 used – 10 kilotonnes (kt) of battery pack for the United States. Includes black mass purchase cost for each chemistry.
Sources: IEA analysis based on S&P Global, LME and BloombergNEF.

However, the economics can quickly change based on the battery metals prices. For instance, using the average battery metals prices from 2022-2023 when metals prices were high, LFP recycling becomes profitable in the United States due to the much greater value of recovering lithium. Since lithium prices are the primary determinant of LFP economics, the surge in lithium prices during this time (the lithium price increased more than sevenfold from the start of 2021 to May 2022) changes the economic picture, making LFP recycling profitable. Recycling of NMC811 using 2022-2023 average prices is also significantly more profitable than at recent price levels (August 2024). This demonstrates how sensitive the economics of market-based battery recycling are to battery metals prices, which have experienced high volatility in recent years. Despite the recycling recovery economics improving with higher metal prices, black mass prices are based on the battery metal prices so the price movements are highly correlated (See Figure 2.6). Therefore, in high metal price environments the purchase cost for black mass feedstock will also increase, countering some of the gains from metal recovery. Using long-term average prices (2015-August 2024) shows improved economics compared with current levels for both chemistries, though LFP remains marginally unprofitable to recycle in the United States.

3.2. Technology innovation

New technologies on the horizon to improve recycling efficiency

Innovations in the recycling value chain have the potential to boost metal recovery while minimising environmental impacts. Today's pyrometallurgical recycling methods consume significant amounts of energy to recover trace minerals, whereas hydrometallurgical processes often use less energy but incur environmental impacts from the supply chains for reagents. In addition, current recycling technologies often struggle with the complexity and diversity of modern products containing critical minerals, leading to suboptimal recovery rates and material leakage.

Emerging technologies across the entire recycling value chain can help address these challenges by improving efficiency, selectivity and environmental performance. From collection to final refining, these innovations can reshape how we approach the recycling of critical minerals. Advanced sorting technologies are enabling more precise identification and separation of materials, while novel chemical and physical processes are pushing the boundaries of what can be recovered economically. Automation and artificial intelligence are optimising processes and reducing human exposure to hazardous materials, while new tracking and quality control methods are enhancing the traceability and reliability of recycled materials.

These technological advancements are not only improving the recovery rates of known critical minerals, but also potentially enabling the recycling of elements that were previously considered uneconomical to recover. As these technologies mature and are integrated into recycling systems, they have the potential to significantly increase the circular use of critical minerals, reduce the environmental footprint of recycling operations, and contribute to a more sustainable and resilient supply chain.

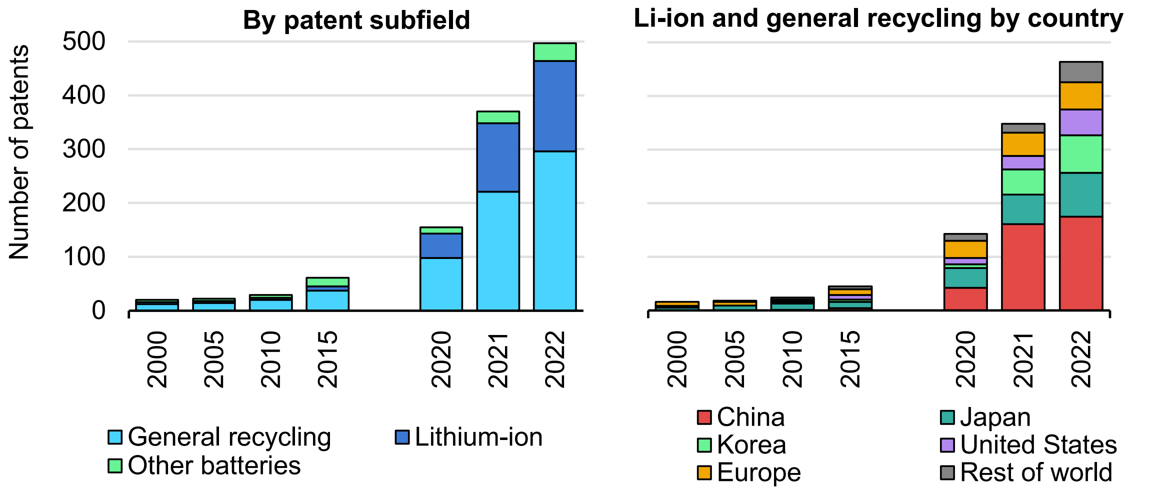
Table 3.1 Advanced recycling technologies to improve recovery rates

Stage	Technology	Description	Key benefits	Status
Collection and sorting	X-ray fluorescence sorting	High-speed scanners that identify elemental composition of materials on conveyor belts.	• Precise identification of critical minerals • High-throughput sorting • Adaptable to varying, heterogenous feedstocks • Can sort alloy types and even specific alloys – potentially high impact for copper alloy sorting	Commercially available
	Automated sorting	Robots equipped with computer vision to identify and sort different types of e-waste and components.	• High accuracy in sorting • Adaptability to new product types • Reduced labour costs	Commercially deployed
Sorting, quality control, sampling, assaying	Laser-induced breakdown spectroscopy (LIBS)	Rapid elemental analysis technique using laser ablation and spectroscopy. Can provide real-time composition analysis of recycled materials.	• Fast, accurate analysis and valuation of critical mineral content • Minimal sample preparation required • Potential for inline quality control	Commercially deployed
Preprocessing and disassembly	Automated disassembly	Robotic systems using machine vision to identify, classify and safely disassemble various product types such as batteries or phones.	• Increased processing speed • Enhanced worker safety • Adaptability to various battery designs	Commercially deployed, systems being tested for battery recycling
	Advanced shredding and separation	Multistage shredding systems combined with advanced separation technologies such as eddy current separators and optical sorters.	• Improved liberation of materials • Higher purity of output streams • Efficient processing of mixed e-waste	Commercially available, many companies developing proprietary systems

Stage	Technology	Description	Key benefits	Status
Chemical processing	Advanced hydrometallurgy	Next-generation leaching and solvent extraction techniques optimised for critical minerals. Includes selective leaching and advanced separation membranes.	• Higher selectivity for and improved recovery of target metals • Reduced chemical consumption	Companies developing proprietary systems
Thermal processing	Plasma arc recycling	Use of plasma technology to recover metals from complex electronic waste, particularly effective for precious metals.	• Can process mixed materials • High recovery rates for precious metals • Lower emissions compared with traditional smelting	Commercially available
Refining	Electrochemical recovery systems	Advanced electrowinning and electrorefining processes designed specifically for recovering high-purity metals from complex, low-concentration solutions.	• Lower energy consumption • Higher purity of recovered metals • Ability to treat complex, mixed-metal streams	Commercially available but not widely deployed
	Membrane electrolysis for metal recovery	Ion-selective membranes for high-purity metal recovery.	• High selectivity • Ability to treat dilute solutions	
Direct recycling	Cathode material regeneration	Regeneration of battery cathode materials through re-lithiation. Does not break down cathode material into constituent metals but retains material crystal structure. Requires highly specific separation of cathode and anode materials.	• Retains embedded economic and energy value in cathode processing so suited to low-value cathodes such as LFP • Well suited to cathode manufacturing scrap as already separated • Very high yields for battery recycling	Commercial research and development, industrial and academic research
Process optimisation	Digital twins	Virtual model of the entire recycling process for real-time optimisation and predictive maintenance.	• Enhanced process control • Improved material tracking • Optimised recovery rates	Commercially deployed but not widely

Data from the European Patent Office clearly highlight the rapid pace of innovation in battery recycling, with patent filings increasing sevenfold between 2012 and 2022. Chinese applicants accounted for a third of applications filed in 2022, equalling Japan and Korea combined. The majority of patents filed were for general recycling technologies such as sorting, opening, crushing or pre-reclamation processes. Lithium-ion battery recycling patents have been growing at the fastest pace, at an annual average of 56% between 2017 and 2022.

Figure 3.4 International patent families for battery recycling technologies



Notes: Li-ion = lithium-ion. Some international patent families may be labelled in more than one sub-field. Other batteries include lead acid, nickel metal hydride, nickel cadmium and disposable batteries.
Sources: IEA analysis based on European Patent Office.

Policies to support innovation efforts

Innovation efforts in critical minerals recycling can be supported through a mix of policies that drive technological development in addition to incentivising the adoption of these technologies. On the "push" side, many governments are already directly supporting research and development through grants and competitions such as the American-Made Challenges programme. These programmes could not just involve increased funding for academic institutions, laboratories and private companies, but also support tighter stakeholder collaboration to test, scale and commercialise advanced technologies. Effective administration of limited financial resources can be supported by identifying and clearly delineating priority sectors.

On the other side, "pull" policies could incentivise market uptake of innovative technologies. A key strategy entails recycling standards that become more stringent over time. For instance, the European Union (EU) Battery Regulation mandates lithium material recovery targets of 50% by 2027 and 80% by 2031. Given that EPR regulations mandate that manufacturers take responsibility for end-of-life products, increasingly strict recovery targets would incentivise product manufacturers to collaborate with recyclers to accelerate technological innovation.

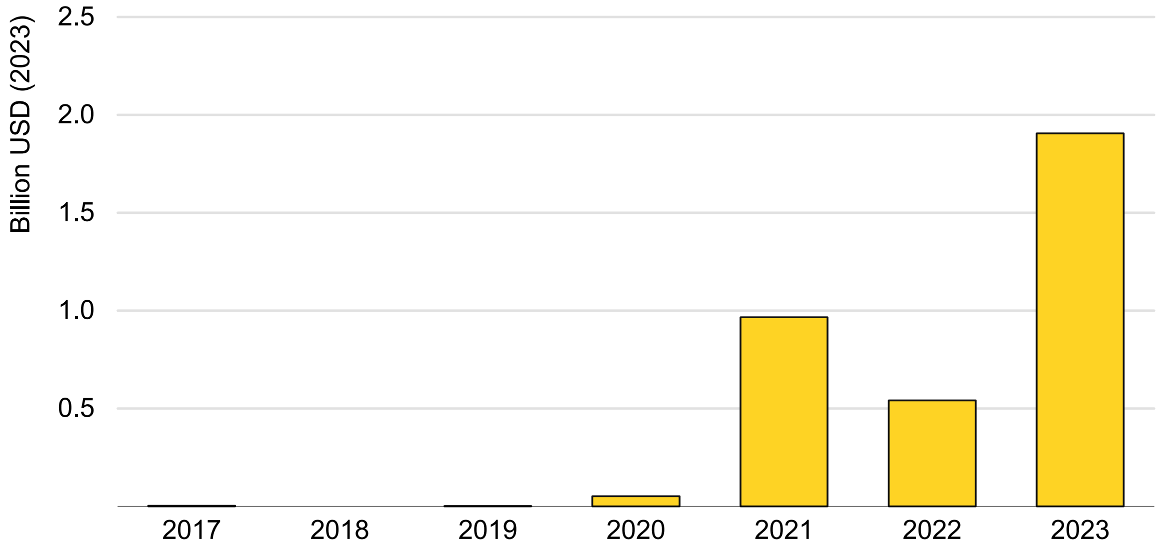
The synergy between push and pull policies is essential to commercially viable innovation in critical mineral recycling. While push policies ensure a steady stream of new ideas and technologies, pull policies create the necessary market conditions for these innovations to be adopted and scaled up. At the international level, collaborative research programmes and technology transfer initiatives can accelerate global progress in recycling innovations. Harmonised standards for the consumption and trade of recycled materials can create larger, more stable markets for these products. By integrating a diverse set of policies, governments can encourage innovation across the entire recycling value chain from collection to refining.

Venture capital investment in recycling

Venture capital investment in battery and waste recycling sectors increased significantly between 2022 and 2023. The bulk of this was driven by the USD 1 billion and USD 540 million in Series D equity funding raised by US-based companies Redwood Materials and Ascend Elements respectively. However, data on investment in other critical mineral recycling remain unclear. This discrepancy highlights a number of issues in the development of recycling technologies and markets.

The surge in investment for battery recycling reflects the growing importance of electric vehicle (EV) batteries, but it may be overshadowing other critical mineral recycling needs. This uneven focus creates an information gap, and the lack of clear investment data for non-battery minerals suggests a need for improved tracking and reporting mechanisms across the broader recycling sector. This untapped potential could present opportunities for investors willing to take on higher risks. However, it also underscores the need for targeted policies to support the deployment of recycling technologies for a wider range of critical minerals, not just those used in batteries.

Figure 3.5 Venture capital investment in battery and waste recycling



Source: IEA analysis based on Cleantech Group i3 database.

3.3. Cross-border waste and scrap trade

Benefits and challenges from the cross-border trade of scrap materials for recycling

On the positive side, exporting recyclable materials to countries with superior recycling infrastructure allows for greater recovery and reuse of valuable materials, particularly when domestic capacity in exporting regions is insufficient. This practice can also assist companies in building economies of scale and achieving recycling targets and efficiencies mandated by regulations.

On the other hand, if importing countries do not have adequate systems and infrastructure to process scrap, it could result in a loss of recycled volumes at a global level. Exporting scrap also means a loss of potential domestic sources of secondary supply, which reduces the security advantage of recycling. Scrap metals are often linked to hazardous waste that entails risks for transport, storage and final destination. Disparities in regulations and enforcement standards between countries, as well as at the sub-national level, can be exploited by irresponsible actors that may also undertake illegal dumping and inadequate waste treatment. Furthermore, the transportation of waste across borders involves significant energy use and emissions, which can potentially offset the environmental benefits of recycling.

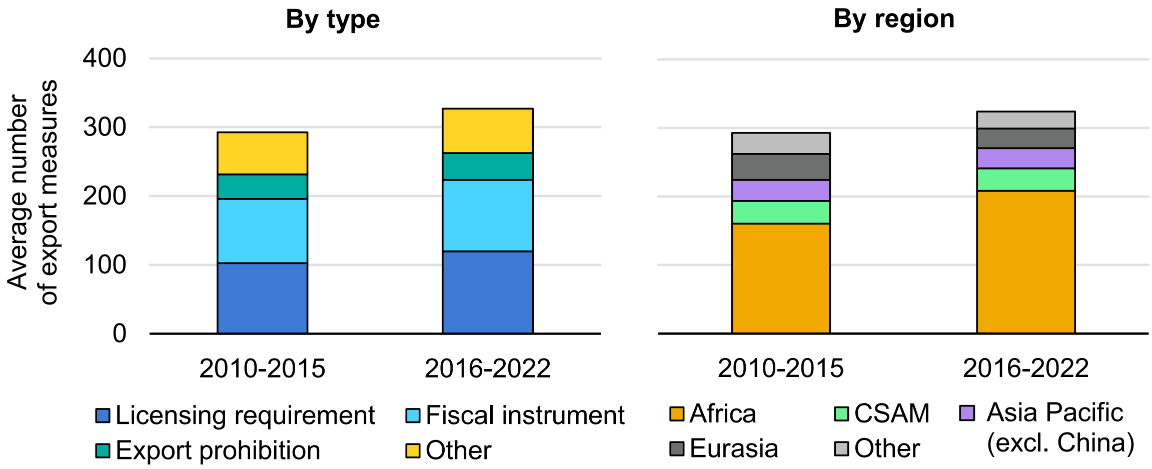
The laws regulating cross-border waste flows can be intricate, with varying management requirements and recovery targets across regions and countries. Regulations for cross-border shipments of waste specify which waste can be shipped where and under which conditions (essentially whether prior approval for the shipment is needed), and how to enforce these conditions. Transboundary movement of waste requires compliance with the waste legislations of both importing and exporting countries, as well as adherence to international agreements. This includes following verification procedures for scrap quality, meeting national recovery targets, fulfilling waste management requirements and ensuring all necessary permits and environmental standards are in place.

Countries are taking action to regulate scrap trade while incentivising domestic and regional recycling

Many countries have restricted or outright banned the import or export of waste scrap due to challenges in managing these materials. Regulatory gaps and loopholes are often exploited, leading to illicit waste trade. For example, waste may be misclassified or mislabelled as recyclable materials to circumvent legal restrictions. To address the difficulties in managing both permitted and illicit imports of e-waste, China has progressively restricted imports since 2018, while

India banned e-waste imports in 2016. Moreover, from 2009 to 2022, several countries implemented restrictions or bans on the export of critical minerals or metals waste and scrap. Various policy measures were employed, including permitting requirements, fiscal restrictions such as export taxes and tax rebate reductions, and export prohibitions or quotas. These measures were often coupled with goals of safeguarding domestic supply, health or environmental protection.

Figure 3.6 Export control measures for critical minerals and metals waste and scrap



Notes: CSAM = Central and South America. Other regions include Europe, China, the Middle East and North America. Covered minerals and metals include copper, nickel, aluminium, molybdenum, cobalt and manganese. Only includes measures that have not ended. Fiscal instruments include export taxes, fiscal tax on exports, value-added tax rebate reduction/withdrawal, and export surtax.
Source: IEA analysis based on data from OECD (2023), Inventory of export restrictions on industrial raw materials, accessed 18 October 2024.

Some economies have been adopting various export and import restriction measures, alongside other policy tools, to stimulate domestic recycling capacity. The United States, through Foreign Entities of Concern (FEOC) provisions in the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA), has limited the import of goods containing minerals from designated entities, including China, Iran, North Korea and the Russian Federation. For example, EV batteries containing minerals extracted, processed or recycled by an FEOC are excluded from tax credits under the Clean Vehicle Credit. As China is the world's leading recycler of scrap metals, this policy limits access of US companies to recycled materials from that source. Concurrently, the BIL and IRA offer incentives for manufacturing products with high recycled content. The IRA also amended Section 48C of the Internal Revenue Code to renew and expand tax credits for investments in projects that expand clean energy and critical materials recycling. Additionally, the US Department of Energy has announced over USD 3 billion in grants to boost domestic production of advanced batteries and battery materials, including through recycling. This combination of measures could lead to a significant increase in domestic recycling capacity.

The European Union has taken another approach to waste trade. As part of its Circular Economy Action Plan, it updated the Waste Shipment Regulation in May 2024. This regulation restricts scrap exports to countries that do not meet EU waste treatment standards and encourages intra-EU waste shipment for reuse and recycling. This can lead to increased scrap collection and recycling within the European Union, depending on various factors, including how these restrictions will be implemented, how they will be affected by other policies and regulations, the state of global and regional scrap markets, and how businesses and consumers adapt to these changes. These measures also aim to better tackle illegal waste shipments and ensure that export only takes place when there are guarantees that the waste is managed in an environmentally sound manner.

Recycling mandates and quotas are commonly used to encourage domestic recycling. In India, provisions on local content treat domestically recycled batteries preferentially compared with imported recycled batteries in the Battery Waste Management Rules. Through these rules, the government requires producers to incorporate minimum percentages of domestically recycled materials, starting at 5% in 2027-28 and increasing to 20% by 2030-31. It also sets ambitious targets for EV batteries, including a 90% recovery target by 2027. These requirements are based on the total dry weight of the battery and also applies to imported batteries.

In the United States, while not per se a recycling quota, the Clean Vehicle Credit incentivises recycling by including it as one of the ways manufacturers can meet critical mineral sourcing requirements for EV batteries. For critical minerals in EV batteries, manufacturers can meet requirements by using minerals recycled in North America or extracted or processed in the United States or sourced from countries with a US free trade agreement. By 2025, 60% of the value of these minerals must come from these combined sources, increasing annually to 80% by 2027 to be eligible for a USD 3 750 credit. An additional USD 3 750 credit is available when the value of the battery components meets the North American manufacturing or assembly requirements, starting at 60% in 2024 and 2025 and gradually increasing to 100% in 2029. There is also a battery funding programme with a budget of USD 125 million to boost battery collection and recycling nationwide.

With proper implementation, recent amendments to international waste agreements will increase control of transboundary waste trade

Recycling often requires collection in one jurisdiction and processing in another, often crossing multiple borders. International co-operation is a way to support better regulatory practices, particularly concerning e-waste and battery waste. Before export from one jurisdiction to another, there is a requirement of classifying the material for reuse or as waste: hazardous, non-hazardous and others. Current regulatory frameworks face several challenges in such classification, the commingling of obsolete e-waste with functional used electrical equipment and low collection rates. Moreover, the illegal trade of non-recyclable products remains a significant issue. Waste improperly tagged as reusable and recyclable often ends up in informal recycling sectors, where safety and environmental measures are limited, leading to pollution and health risks.

In addition to domestic regulations, this international flow is regulated and facilitated by mainly two international waste agreements: the Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal (hereafter, "Basel Convention") and the OECD Decision on the Control of Transboundary Movements of Wastes Destined for Recovery Operations (hereafter, "OECD Decision"). Both agreements have recently undergone amendments that will significantly impact the trade of e-waste from January 2025.

The Basel Convention

The Basel Convention is a global treaty designed to regulate the international movement and disposal of hazardous wastes to promote environmentally sound management of these wastes. It implements a Prior Informed Consent (PIC) procedure for transboundary movements of covered wastes and prohibits exports of hazardous waste from OECD countries to non-OECD countries. Trade of covered waste with non-parties is prohibited, except under specific agreements under Article 11, which allows parties to form bilateral, multilateral or regional agreements or arrangements regarding transboundary movement of hazardous or other wastes under certain conditions. As of 2024, 191 countries are parties to the Basel Convention, with notable non-parties such as Haiti and the United States, having signed but not ratified it. In accordance with Article 11, the United States has entered into bilateral agreements with Canada, Mexico, Costa Rica, Malaysia and the Philippines to allow transboundary movement of hazardous waste with the United States.

The OECD Decision

Functioning as an Article 11 agreement under the Basel Convention, the OECD Decision facilitates trade in certain types of waste destined for recovery operations. Applicable to all 38 member countries, the OECD Decision provides a simplified control system for intra-OECD waste movements, including certain e-wastes, without PIC controls. Notably, this system enables waste trade with the United States, a non-party to the Basel Convention.

The OECD Decision establishes two primary control procedures for transboundary waste movements: the Green procedure for low-risk wastes and the Amber procedure for those presenting sufficient risk to justify control. Under the Green procedure, wastes can move between OECD countries without prior consent, subject only to normal commercial controls. The Amber procedure requires written consent from competent authorities before shipment.

The system also offers flexibility to member countries. They retain the right to apply stricter controls on certain wastes for health and environmental protection. Countries may opt to treat Green-listed wastes as Amber-listed, applying more stringent procedures, or reclassify Amber-listed wastes as Green-listed if the wastes are determined to lack hazardous characteristics. Additionally, members can designate pre-consented recovery facilities pre-approved by the importing country's authorities to receive specific waste types. Such facilities benefit from simplified and accelerated notification procedures.

E-waste amendments in force from January 2025

Starting 1 January 2025, the Basel Convention e-waste amendments will become effective, expanding the control of transboundary movements of e-waste. These “Swiss-Ghana Amendments” aim to close the “reuse loophole” by establishing new classifications for hazardous and non-hazardous e-waste and requiring PIC for all e-waste shipments. The “reuse loophole” stemmed from a lack of clarity in characterising used electrical equipment as waste or reusable items. This ambiguity allowed the transboundary movement of e-waste under the guise of reuse or repair, often circumventing the Convention’s regulatory framework. Some waste operators and electronics manufacturers exploited this loophole, claiming equipment was destined for repair to export e-waste to countries ill-equipped to handle it safely.

Post-amendment, all e-waste, regardless of classification, will require PIC for transboundary movement. Non-hazardous e-waste will be reclassified and be subject to the same control procedures as hazardous wastes. This reclassification acknowledges that while not inherently hazardous, these wastes can still pose risks to human health and the environment if mismanaged. In June 2023, the Conference of the Parties adopted interim technical guidelines for transboundary movements of electrical and electronic waste and used equipment, providing clearer criteria for categorising used equipment and enhancing enforcement measures.

These amendments have significant implications for e-waste trade. Parties to the Basel Convention will be prohibited from receiving any e-waste from non-party countries unless they have an Article 11 agreement. Notably, while these amendments are usually automatically adopted to the OECD Decision, this was not the case due to a lack of consensus among OECD member countries. Consequently, each member country will now control e-waste in conformity with its domestic legislation and international law, informing the OECD by 15 January 2025.

While these new amendments and guidelines represent a significant step towards comprehensively addressing the reuse loophole, their effectiveness in practice remains to be seen and will depend heavily on how they are implemented.

Box 3.1 Challenges behind and improving the implementation of the Prior Informed Consent procedure

The Prior Informed Consent (PIC) procedure of the Basel Convention is a strict requirement for transboundary movement of hazardous wastes and other wastes. The procedure forms the heart of the Convention's control system and is based on four key stages: i) notification; ii) consent and issuance of movement document; iii) transboundary movement; and iv) confirmation of disposal. It enables importing and transit countries of waste cargoes to formally consent to the trade.

Even as the PIC procedure stands as the cornerstone of the Basel Convention, its expansion to cover all e-waste trade from 1 January 2025 highlights concerns from the recycling industry on effective implementation. Main challenges include long lead time coupled with high administration costs as preparation, submission and acknowledgement of numerous documents is required from not only governments of exporters and importers, but also from all governments of ports the cargo carrying the waste transits. Reports from industry note that it is not unusual to have to go through the PIC process in up to ten countries and that its notifications can take several weeks in countries where processes are well-established to several months or, in some cases, years.

To tackle such concern, the Small Intersessional Working Group on improving the PIC procedure was established by the 16th meeting of the Conference of the Parties to the Basel Convention. Recommendations provided by the working group focus on easing the inefficiency in the administrative interactions with "competent authorities" – often the environmental authorities or ministry of the states of import or transit. They include encouraging them to promptly communicate the receipt of notification, opting for electronic transmission of documents rather than hard copies and posts, and adopting shared or generic email addresses instead of individual emails that are often outdated and difficult for the successor to take over.

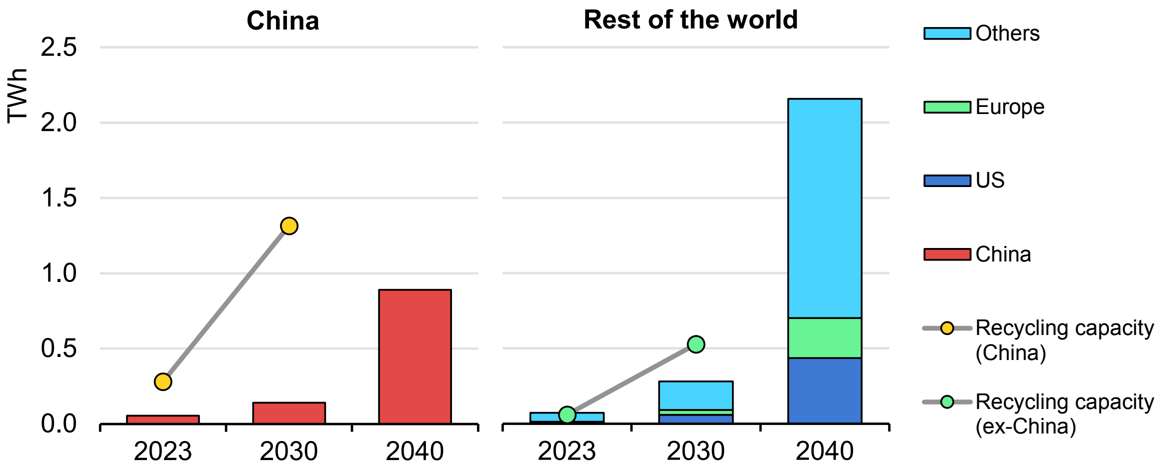
One recommendation notably references the OECD's use of pre-consented waste recovery facilities for Amber control procedures to incorporate a fast-track system. A pre-consent is a document granted for a recovery facility that allows it to receive certain waste for up to three years after the approval of the initial written notification – the OECD's version of the Basel Convention's PIC. Intra-OECD trade benefited from the system by reducing a repetition of administrative procedure for trades with reliable recycling facilities. Applying the pre-consented waste recovery facility concept to the Basel Convention would enable non-OECD countries to also benefit from the fast-tracked system.

Internationally harmonised classification of black mass can provide improved clarity to the recycling industry

Today, the geographic locations with large volumes of EV sales and pretreatment and refining facilities for recycling are unevenly spread across the world, creating a need for transboundary movements of spent batteries and black mass. Pretreatment facilities entail relatively straightforward and simpler technology of physical shredding, producing what is known as black mass. Refining facilities that extract valuable materials from black mass such as lithium, cobalt, nickel and manganese require more advanced technologies as well as significant investment and time to establish sufficient capacity. Countries may opt to export black mass when they have the infrastructure to collect and pretreat end-of-life batteries but lack refining capacity. Countries that already have well-established refining facilities but lack feedstock would actively seek to import them.

Today in many regions, the battery recycling capacity is currently higher than the available feedstock. Announced expansions in recycling capacity indicate that there may still be imbalances between capacity and feedstock availability, which may vary by region (see Chapter 2). International agreements and national regulations setting clear classifications on spent batteries and black mass trading are therefore critical with the intense global competition to secure feedstock. Depending on national strategies, countries may either facilitate trade or regulate them from exiting their borders.

Figure 3.7 Available battery recycling feedstock in the APS and domestic recycling capacity in China and the rest of the world



Notes: TWh = terawatt-hour. Available battery recycling feedstock includes end-of-life EV batteries, end-of-life storage batteries and manufacturing scrap. Projected capacity is based on announced projects. 85% maximum utilisation rate for production capacity is applied. Recycling capacity refers to material recovery capacity. Excludes portable electronics and e-bikes.

The global recycling industry will benefit from greater clarity when international agreements address the evolving needs of the shifting recycling landscape through a harmonised classification framework. Until then, national regulations may significantly influence its trade. The classification of lithium-ion battery wastes and black mass exemplifies the regulatory challenges that today remain opaque. They may be classified as hazardous or non-hazardous across different jurisdictions depending on their stages of treatment. Different compositions of black mass would render it one or the other, and cobalt, nickel, lithium and graphite are some of the highly desirable materials that could be extracted in volumes.

Today, the Basel Convention's annexes do not explicitly classify end-of-life lithium-ion batteries and black mass in their lists, leading to varying interpretations of their classification based on their usual components and characteristics. The case for classifying them as hazardous waste stems from two factors: first, their viewing conventional electrolytes falling under Annex VIII (which lists wastes characterised as hazardous), and second, their alignment with Annex III hazardous characteristics (including properties such as explosive, flammable liquids or solids, liable to spontaneous combustion, corrosive or eco-toxic). However, certain materials recovered through battery dismantling might fall under list B of Annex IX (which covers wastes not requiring control unless they contain Annex I – wastes to be controlled – materials to an extent causing them to exhibit Annex III – hazardous – characteristics), creating uncertainty about the classification of certain types of black mass.

While the Basel Convention's controls on transboundary movements apply to wastes in its specified lists and categories, wastes lacking definitive classification – such as lithium-ion battery waste and black mass – fall under the national legislation of individual importing and exporting countries. Under the OECD Decision, the classification would be similar. For example, hazardous lithium-ion batteries labelled for recycling or disposal are banned for export from OECD to non-OECD countries and subject to PIC, but when labelled for repurposing, they may be traded without PIC requirements. To address these ambiguities, technical guidelines on the environmentally sound management of waste batteries other than waste lead-acid batteries are currently under discussion. The latest draft, released in June 2024, defines black mass as "waste obtained from the mechanical crushing of batteries and is sent to another plant for recycling".

Until a more defined international classification is introduced, national regulations may play a large role in its trade. Some governments and regional unions are seeking national and regional regulations to prevent valuable feedstock from exiting their borders to create incentives for the growth of domestic recycling industry.

In the European Union, classification of black mass is dependent on member country regulations, which are not uniform. On the regional level, updates to the battery directive in 2023 support circularity of battery materials through recycling, but they do not classify or define black mass as a recyclable material. The Waste Shipments Regulation provides that in case of disagreements on the classification of a substance, the Commission is authorised to establish detailed criteria for classifying specific substances and to adopt acts to ensure uniform application. Dedicated waste codes to black mass are expected under the European List of Waste. Meanwhile, the industry has urged the European Union to classify black mass as hazardous waste, requiring recyclers to follow PIC procedures under the Basel Convention, making it difficult for export.

The United States recognises that black mass could exhibit one or more characteristics of hazardous waste, but considers them as non-hazardous "solid waste" once the recycling process is complete and no longer exhibits such characteristics. As a result, black mass falls under the jurisdiction of state and local solid waste regulations, rather than federal oversight. Recent committee proposals in the US Congress advocate for safeguards within the domestic battery recycling industry, suggesting that any facility benefiting from Department of Energy or Department of Defense funding for black mass processing should be prohibited from exporting this material outside the United States. Consequently, as it is not a party to the Basel Convention, US-based companies would be prohibited from exporting black mass. In conjunction with the IRA, these regulations aim to bolster domestic recycling efforts by retaining critical minerals within the national market.

China recently allowed black mass imports. Previously, battery scrap was characterised as "solid waste" and was under the List of Solid Wastes Prohibited from Import. In 2021, China banned all imports of solid waste. A clarification in 2022 categorised products made from lithium-ion battery scrap such as black mass as "crude nickel-cobalt hydroxide", imported as "nickel hydrometallurgical intermediate" or "cobalt hydrometallurgical intermediate". As of January 2024, black mass is officially imported as "crude nickel-cobalt hydroxide", with a tariff reduction from 6.5% to 3%, and reports mention that China may continue to ease its black mass restrictions.

On the other hand, countries that must rely on importing feedstock to boost their recycling industry are seeking to deregulate and support domestic management of end-of-life battery wastes and black mass. Korea's Ministry of Environment unveiled plans in 2023 to reclassify EV waste batteries alongside scrap metal as recyclable resources to be made exempt from its national Waste Control Act. EV waste batteries can receive recyclable classification once they have been approved for showing no signs of damage, immersion or hazardous risks. An announcement to amend the Waste Management Act also targeted incentivising EV battery recycling. For example, both the storage and treatment period have been expanded to 180 days in response to the recycling industry's struggle to secure raw materials from the previous standard of restricting storage capacity of recyclable waste to less than 30 days of capacity that can be handled per day.

It is encouraging to see increasing efforts to reduce unmanaged leakages and enhance traceability. A harmonised international categorisation of lithium-ion battery waste and black mass would provide much-needed clarity to the global recycling industry, addressing the varying interpretations of regulations for these emerging waste streams. Effective implementation remains crucial to ensure these regulations do not hinder the global growth and scale-up of the recycling industry.

3.4. Sustainability considerations

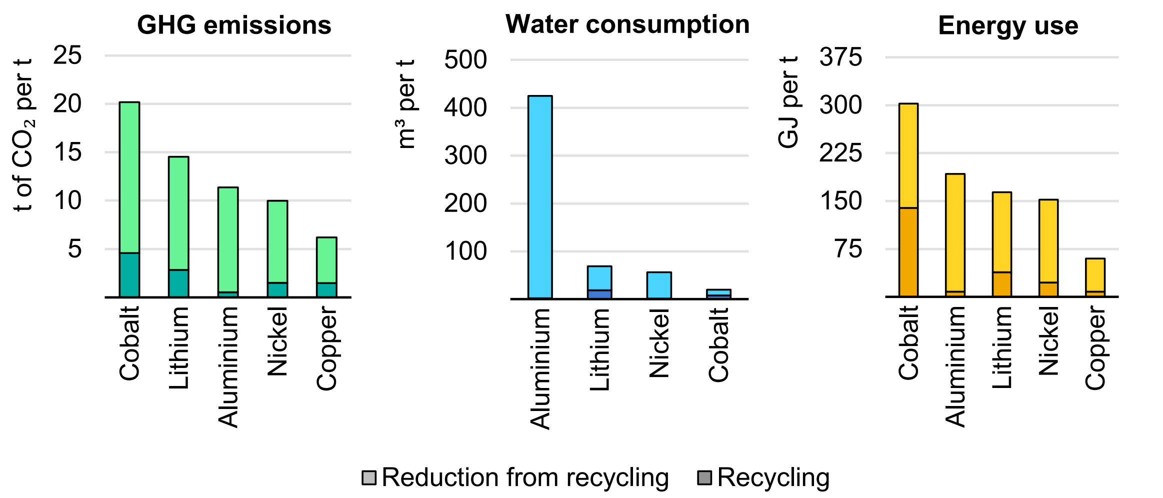
Recycling can help manage environmental, social and governance impacts of the mineral supply chain

In recent years, there has been growing focus on establishing and maintaining sustainable and responsible mineral supply chains. Recycling has emerged as a viable method to mitigate some of the environmental, social and governance (ESG) impacts associated with primary mineral production. This has important implications for the clean energy transition, as supply chains cannot be truly secure unless they are also sustainable and responsible.

Recycling critical minerals minimises waste disposal and mitigates land-use impacts by optimising the use of available resources. Through the recovery of minerals from end-of-life products, there is less need to develop new mining operations. This reduction in mining activities lessens the environmental degradation typically associated with resource extraction, including habitat destruction and soil erosion. Additionally, by decreasing the volumes stored in waste stacks, tailings facilities or landfills, recycling allows for land reclamation and rehabilitation. Thus, recycling of critical minerals can support more sustainable land use and minimise risks related to waste management.

Recycled minerals often bring other environmental benefits, including lower energy demand, emissions and water use. Although different between minerals, on average recycled energy transition minerals (including nickel, cobalt and lithium carbonate) incur 80% less greenhouse gas (GHG) emissions than primary ones, due to a combination of the elimination of the need for mining and lower energy use. For Class I nickel, recycled sources release 85% less GHG emissions than primary sources; for copper this number is 75%. In part this is because recycling processes use less energy than the mining and processing of virgin minerals; for example, the recycling of copper uses only 15% of the energy that is required for mining and processing of primary copper. For some minerals, the energy mix is also a contributing factor. For instance, for lithium carbonate recycling, coal makes up a share of around 30% globally, whereas in primary production it accounts for 70%. Some recycled minerals similarly utilise less water than primary minerals; on average, they use 80% less water. This also depends on the mineral and on the production route. On average, recycled Class I nickel uses 97% less water than primary sources, recycled lithium uses 75% less water and recycled aluminium nearly 99% less water.

Figure 3.8 Comparison of recycled versus primary production



Notes: t = tonne; CO_2 = carbon dioxide; m^3 = cubic metre; GJ = gigajoule. Nickel = Class I nickel; Lithium = lithium carbonate. Rates are industry averages.
Sources: IEA analysis based on GREET 2024, Copper Development Association, Van de Voet et al (2018), and Golroubary et al (2022).

Addressing the ESG impacts throughout the recycling value chain is also crucial

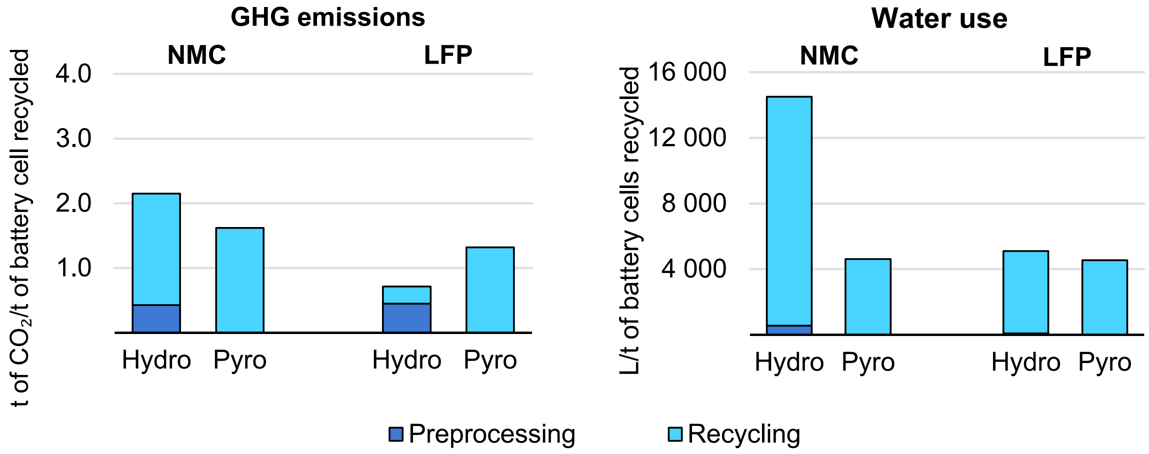
Recycling has lower impacts than primary mineral production processes in some ESG dimensions. However, it is not free from negative ESG impacts. While ESG impacts differ across projects, there are some common risks that must be mitigated for recycling activities to contribute to sustainable and responsible supply chains. Battery recycling, while beneficial, can potentially lead to other environmental challenges, including pollution from waste residues, water contaminants, deleterious emissions, auxiliary materials and transportation.

Energy transition minerals are often linked to hazardous waste, which can be toxic to human health. In many countries, the collection stage is characterised by informality and can involve child labour or unsafe practices. Mismanagement of hazardous mineral waste happens in the absence of regulatory frameworks or where these are not fully implemented and may be compounded by waste trade, especially when the importing country lacks the regulatory and governance capacity to manage these impacts. Furthermore, weak governance structures can exacerbate these problems, leading to corruption, lack of transparency, and inadequate enforcement of environmental and labour standards, which in turn perpetuate unsafe practices and environmental degradation.

Informal recycling facilities may handle hazardous mineral waste, such as e-waste, leading to metal contamination and potential blood poisoning, which is particularly risky for children exposed to surface dust and soil. In one study on formal and informal e-waste recycling facilities in the Philippines, authors identified a higher level of metal contamination in e-waste recycling sites than surface soil. Another study showed the vulnerability of communities that live near e-waste recycling sites (handling mostly imported waste). Communities near e-waste recycling sites face exposure to harmful chemicals such as brominated flame retardants and non-dioxin-like polychlorinated biphenyls, which are persistent organic pollutants that have dangerous effects on the environment and on health (e.g. cancer). In these contexts, burning and illegal dumping can contribute to the exposure of local populations to these pollutants.

The different stages of the lithium-ion battery recycling and the type of battery recycled present varying environmental and social impacts and therefore necessitate different mitigation strategies. During the pretreatment phase, there are issues such as gas emissions from secondary reactions, electrical safety concerns during discharging and dismantling, and the potential for significant water use and contamination from hazardous cathode materials such as nickel and cobalt. The pretreatment phase also presents risks related to the flammability of battery components, necessitating strict emissions control measures.

Figure 3.9 GHG emissions and water use for NMC and LFP recycling processes



Note: NMC = NMC 811; gal = gallon; Hydro = hydrometallurgy; Pyro = pyrometallurgy.
Source: IEA analysis based on GREET 2024.

The main treatment phase has two types of processing methods: pyrometallurgy and hydrometallurgy (see Chapter 2 for further details), which have varying environmental and social impacts. In the case of NMC battery recycling, pyrometallurgy has 5% lower GHG emissions and 70% lower water use than hydrometallurgical processes, but an almost 5 times higher GHG emissions for LFP battery recycling. However, it is important to note that pyrometallurgical processes require additional hydrometallurgical techniques to fully recover materials, meaning that the GHG emissions and water use could be higher. In both processes there are also environmental hazards from solid waste disposal. Some recyclers are looking at new techniques that can minimise the emissions and water consumption, such as through closed-loop systems.

Improving the environmental and social performance of battery recycling requires a holistic approach, addressing risks at each stage of the process while implementing best practices and innovative technologies. Recyclers should implement stringent safety protocols, using appropriate equipment and training, and aim for closed-loop water systems or high treatment standards. Additionally, analysing battery passports can ensure safe discharge methods. There should also be an appropriate balance of environmental protection, worker safety and operational efficiency throughout the recycling life cycle.

Above all, the application of a waste management hierarchy is a prerequisite to the efficient use of resources and can mitigate the environmental impact of all materials. Products should be used for their full technical lifetime to minimise unnecessary environmental impacts and life-cycle emissions. Studies have shown that batteries with 200 cycles of use or more have lower negative impacts on the environment. Designing products for longevity and retrofitting or reusing products to the fullest extent possible are also key components to minimising overall environmental impacts.

Regulations can incentivise recycling while ensuring sustainable supply of secondary minerals

Policies and their effective implementation can promote recycling operations and support the mitigation of related ESG impacts. This can be done through general policies, targeted regulations or voluntary frameworks. Regulatory frameworks can establish minimum requirements for waste battery management for generators, collectors, transporters and recyclers. EPR schemes can create incentives for producers to incorporate ESG considerations into product design and collection programmes, with governments monitoring performance. Where policies are not yet in place, companies can follow industry standards that outline best practice for mineral waste management. Some examples include the US Responsible Recycling (R2) Standard, which is a certification for electronics recyclers, and the e-Stewards Standard, an electronics waste recycling standard created by the Basel Action Network. Analysis by the Roundtable on the Responsible Recycling of Metals found that while key areas such as hazardous material management and health and safety are well-covered in recycling schemes, there are significant ESG-related gaps in labour and human rights, biodiversity, community engagement, grievance mechanisms, and anti-corruption measures, which are more comprehensively addressed in voluntary standards for primary metals.

There are also standards used in evaluating the repurposing of EV batteries for second-life applications. These standards certify repurposing facilities by assessing processes for sorting, grading and determining the continued viability of battery cells and aim to ensure safety, consistency and cost-effectiveness. As such, these initiatives aim to support manufacturers and developers in bringing safer second-life batteries to market and reducing environmental impact throughout the battery life cycle. For example, in North America, UL Solutions has established the UL 1974 Standard for Evaluation for Repurposing Batteries, while in Europe, CEN and CENELEC are developing standardised battery designs to facilitate second-life use as requested by the European Commission.

Table 3.2 Summary of selected voluntary sustainability schemes for metals recycling

Scheme	Focus	Value chain	Objective
US Responsible Recycling (R2) Standard	End-of-life electronic products	Collection, testing, repair, processing, materials recovery, final disposition	Quality, environmental, health and safety management
UL 1974 Standard for Safety for Evaluation for Repurposing or Remanufacturing Batteries	End-of-life batteries, batteries intended for repurposing	Testing, sorting and grading, repurposing, processing for secondary use	Quality, health and safety management
Institute of Scrap Recycling Industries (ISRI) Specifications	All metal scrap, electronic scrap and other recyclable products	Trading, processing specifications, grading, materials recovery	Quality, environmental, health and safety management and compliance
Recycling Industry Operating Standard (RIOS)	All recyclable products	Entire recycling value chain	Quality, environmental, health and safety management
Basel Action Network (BAN) e-Stewards Standard	End-of-life electronic products	Collection, testing, repair, processing, materials recovery, final disposition	Environmental, health and safety management
ISO 59014:2024 Sustainability and traceability of the recovery of secondary materials	Secondary materials	Collection, classification, sorting and non-destructive processes, materials recovery (excludes repurposing and repair)	Health, safety and human rights management
CEN and CENELEC Standard for Waste Electrical and Electronic Equipment	End-of-life electronic products including solar photovoltaic panels	Collection, transport, sorting, processing, materials recovery, final treatment	Waste and end-of-life products containing metals

Source: Adapted from The Roundtable on the Responsible Recycling of Metals Mapping Report – Analysis and Comparison of Standards, Guidelines and Selected Legislation to inform Responsible Metals Recycling Schemes (2024).

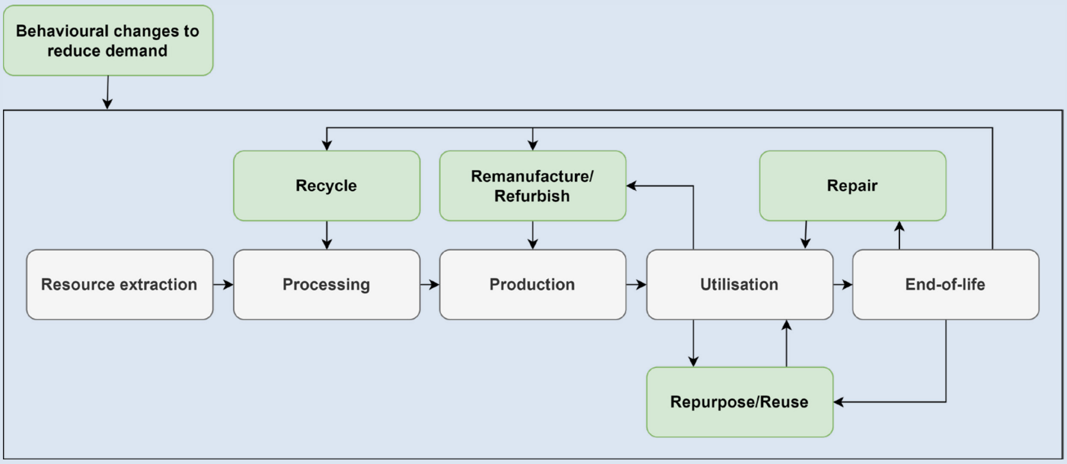
There are several regulations in place to improve recycling rates and ensure a sustainable and responsible supply chain. Recycling thresholds linked to ESG requirements are increasing, and circularity links are being strengthened, impacting brand owners and manufacturers. This presents an opportunity to link requirements to more responsible recycling. The EU Regulation on Batteries and Waste Batteries (Batteries Regulation), for example, sets recycling goals for 2025 to 2031, with an increasing trend towards stricter controls over metal recycling, including specific recovery rates and quality specifications and minimum recovered content requirements. It extends EPR schemes to all categories of batteries and includes waste collection targets. Along with the battery passport, a third-party verified carbon footprint declaration is required for the Batteries Regulation, while an environmental footprint declaration is required for the Critical Raw Materials Act. Furthermore, reporting requirements encompass access to information and public participation in decision-making as well as community life and Indigenous People as part of the social risks to be considered in due diligence policy and the risk assessment process. In general, regulations can further establish minimum quotas for products containing critical minerals and establish clear and practical classifications and terms around waste and non-waste for such products.

Finally, compliance for these regulations can be supported by traceability mechanisms. Such mechanisms would help manage the adverse impacts associated with waste trade and mineral recycling and allow key stakeholders to verify if materials are sourced, processed and recycled in compliance with best practices. They can also support an assessment of the differences in company performance along the various ESG dimensions, building on company-reported data, voluntary initiatives, certification schemes and other transparency initiatives.

Box 3.2 Beyond recycling: Opportunities for product design and waste reduction

While recycling plays a crucial role in addressing challenges for critical mineral supplies, it is not the first line of defence against resource depletion and waste generation. Circular economy principles emphasise a hierarchy of strategies, with recycling being one component. There are opportunities that go beyond recycling such as demand mitigation, product design, repair, refurbishing, reuse and repurposing.

Figure 3.10 Material flows and policy interventions in a circular economy ecosystem



IEA. CC BY 4.0.

Source: IEA analysis based on Helbig and Hillenbrand (2024), Principles of a Circular Economy for Batteries.

Behavioural changes – such as increased use of active and public modes of transport, right-sizing of personal cars, and keeping electronic devices in use for longer – are the first step in optimising resource consumption while meeting societal needs for services such as mobility and communication. These approaches aim to rethink how society can meet these needs in a manner while using resources (including critical minerals) more efficiently with reduced externalities of supply chains.

As a next step, circular design principles highlight the importance of improving products' lifetime and facilitating easier recycling at the end of life. This entails considering a product's entire life cycle at the design phase and making choices that facilitate value retention or recovery. Increasing repairability via modular designs that make disassembly easier is a common strategy used by products including EVs and electronics. This focus can be supported by "right to repair" regulations that increase the availability and affordability of keeping products in use.

Repurposing and reusing also offer significant waste reduction opportunities. These processes can reuse products directly, as is often the case with refurbished electronics that service their original functions with minor changes. Repurposing adapts products for similar or new purposes. For instance, EV batteries no longer suitable for vehicles can be used in stationary energy storage (see Chapter 2), extending their useful life in less intensive applications before recycling is necessary. These strategies not only conserve resources but also drive innovation and create new business opportunities. Companies specialising in refurbishment or repurposing are generating economic value while reducing the environmental impact of critical minerals value chains.

To realise these opportunities, supportive policies and consumer education are essential. Governments can incentivise design for circularity, set standards for repurposed products and encourage product longevity. Educating consumers about the benefits of repair, reuse and shared ownership models can help shift behaviour patterns and incentivise the consumption of fewer products or more sustainable alternatives.

While recycling remains of unquestionable importance, a broad suite of strategies offers significant opportunities to reduce reliance on primary and recycled materials alike and minimise waste. By adopting a holistic approach considering the entire product life cycle, policy makers, industry stakeholders and consumers can create more sustainable pathways for critical mineral use, paving the way for a truly circular and resource-efficient economy.

Chapter 4. Policy recommendations

In order to ensure secure and sustainable mineral supply chains for a clean energy transition that achieves global climate goals, a redoubling of efforts to scale up all forms of recycling (manufacturing scrap, e-waste, end-of-life clean technologies), urban mining and mine waste treatment is needed. This final chapter synthesises all key policy measures outlined in Chapters 2 and 3 in the form of a comprehensive nine-point action plan for policy makers, highlighting and summarising key areas of concern and recommendations for policies to tackle them. While all policy areas will be crucial in building a global circular economy for critical minerals, the specific set of policy actions to be adopted will vary by country or region, depending on their unique context.

Recommendation 1. Develop detailed long-term policy roadmaps

Set clear targets and intermediate milestones to provide clarity on policy directions and greater certainty for investors

In an environment with fluctuating feedstock and metal prices, recyclers may face uncertainties about the economic viability. This is particularly relevant for energy transition minerals where the market is at an early stage of development compared with base metals. Scaling up recycling also requires adequate collection, sorting and metal recovery infrastructure, all of which demand significant upfront investment.

Long-term policy visibility is therefore central to providing the confidence investors and recyclers need to commit to new projects. An essential step is for policy makers to provide clear, science-based targets for collection rates and minimum volumes of recycled materials that need to feed into the next generation of products and technologies. It is also important to indicate how these targets will be turned into action. Moreover, efforts to encourage investment should go hand in hand with broad strategies that encompass technology innovation and sustainability standards. For mine waste, revisiting current mining regulations or creating new ones with specific provisions and permitting requirements related to mine waste recovery will be vital.

The European Union's Critical Raw Materials Act addresses many of these aspects to some extent: setting a target for recycled materials to account for at least 25% of the Union's annual consumption of strategic raw materials by 2030; limiting the time taken for permit-granting processes for recycling projects to 15 months; improving co-operation along the critical raw materials value chain between the Union and partner countries, including capacity building and technology transfer programmes to promote circularity and responsible recycling of critical raw materials in producing countries; an Innovation Fund that could provide grants to enable the development of recycling capacity of raw materials related to clean energy technologies. It is worth highlighting that policies and roadmaps alone may not be sufficient unless they include strategies for tracking their implementation and progress. Among the 22 countries and regions surveyed in Chapter 1, only 3 offer a comprehensive roadmap with long-term strategies for recycling critical minerals. Examples of comprehensive roadmaps, such as those Korea's Rare Metals Supply Plan 2.0 and China's 14th Five Year Plan on Circular Economy, are strategies that exhaustively cover all policy aspects (clear targets, timelines, implementation mechanisms, monitoring systems, technical frameworks, economic measures and regulatory frameworks).

Recommendation 2. Harmonise waste management and recycling policies to develop efficient secondary markets

Facilitate international co-operation to reduce trade barriers and minimise unmanaged leakages

As with any other global challenge, no one country or region alone can find a perfect solution for waste management and recycling if it does not also consider its relationship with the rest of the world. International collaboration and partnerships are indispensable for harmonising rules across jurisdictions, especially for emerging waste streams. This includes developing common approaches for classifying waste, monitoring the trade of second-hand goods (especially for passenger cars and end-of-life batteries) and strictly penalising the illegal trade or export of untreated waste (such as e-waste) to emerging and developing economies (EMDEs). While it is critical to maintain consistent tracking of progress towards common goals through proper regulations, the effective implementation of these measures is crucial to avoid unintended consequences that could hamper the scale-up of the global recycling industry.

The unclear classification of lithium-ion battery waste and black mass in international agreements as well as in different jurisdictions is one area that could benefit from a harmonised approach. Without an internationally harmonised classification in their specified lists and categories, companies face the challenge of operating and trading under varying national regulations in exporting and importing countries. Establishing detailed yet practical criteria for classifying specific substances or developing dedicated codes for black mass could help reduce trade barriers and minimise unmanaged leakages, thereby helping create a larger market for recycling.

One example of international co-operation in this area is the Basel Convention, an international treaty designed to reduce the movements of hazardous waste between nations and restrict the movement of hazardous waste from advanced economies to EMDEs. Recent amendments effective from 1 January 2025 will subject all e-waste to Prior Informed Consent (PIC) procedures. While these changes aim to foster environmentally responsible management of e-waste and contribute to developing an accountable global e-waste system, industry concerns on costly and lengthy PIC procedures show the challenges in effective implementation of the Basel Convention objectives. Enhancing efficiency in the implementation of the PIC procedures as well as providing clearer classification of emerging wastes and tradeable recyclables such as end-of-life lithium-ion batteries and black mass can help accomplish the objectives and support the development of the recycling industry.

Recommendation 3. Strengthen domestic infrastructure with incentives and mandates

Encourage investment in recycling capacity at national and regional levels with economic incentives

While the export of recyclable materials to countries with better recycling infrastructure ensures that valuable materials are recovered and reused, especially when domestic capacity is lacking, efforts to build domestic collection and recycling infrastructure and investment in like-minded countries should go hand in hand to reap the security benefits of recycling.

Nearly every region in the world is underperforming when it comes to the actual achievable potential for the collection of e-waste and end-of-life technologies, due to the lack of adequate incentives and efficient collection and recycling infrastructure. For a traditional metal such as copper, a critical issue limiting recycling is the challenge of economically sorting and separating copper and its alloy types from complex electronic post-consumer scrap, where the value of the copper recovered is often not high enough to match the recycling cost. Moreover, collection infrastructure is often insufficient in many regions, with limited co-ordination among supply chain actors. This is compounded by insufficient incentives and information for consumers to recycle copper-containing products. Access to product dismantling guides from manufacturers, including safe handling procedures, could alleviate some of the challenges faced by recyclers. For a clean energy technology like solar panels, some regions such as the European Union have incorporated regulations mandating the collection and recycling of end-of-life panels as a part of their extended producer responsibility (EPR) strategies. However, while metals such as copper and silver in solar panels are recycled for profit, the collection of silicon is not mandated and in the absence of price incentives, the semiconductor is often discarded along with glass, concrete and other materials deemed as waste.

Formalising waste collection and sorting at national and even sub-national levels is a crucial first step to ensuring strong domestic recycling infrastructure, but the approach must be tailored to each country's existing waste management capabilities. In regions with established systems, optimising the use of the EPR schemes; introducing national deposit schemes for technologies like solar panels, wind turbines, electric vehicles; investing in public awareness campaigns; and incentivising companies or mandating local governments to operate pick-up services for large household appliances and postal collection for smaller devices could all boost collection rates. In other places, strengthening the waste management policy and infrastructure would be necessary.

Beyond collection, financial incentives such as grants for recyclers with high environmental and social performance and subsidies or tax benefits for companies ensuring proper end-of-life management for their products can help strengthen recycling infrastructure. Minimum recycled content mandates could also prove effective. More innovative pricing mechanisms such as contracts for differences (CfD) and cap-and-floor revenue models could be considered. These models would enable policy makers to provide targeted support to mitigate financial risks associated with price volatility. The cap-and-floor model, which would set upper and lower limits on the prices that recyclers receive for their materials, may be of particular relevance to this market. This would protect recyclers from extreme price drops while allowing them to benefit from price increases up to a certain point, balancing risk and reward.

There is also a need to invest across the value chain. Taking the example of battery recycling, incentivising developments of the midstream value chains such as precursor cathode active material (pCAM) and cathode active material (CAM) production, which serves the dual purpose of providing scrap feedstock for the recycling industry as well as becoming a consumer of the recycled materials, would help de-risk investment in recycling facilities. Recyclers can be incentivised to develop integrated projects that extend into pCAM or CAM manufacturing. Strategic partnerships between recycler and CAM-producing countries as well as pretreatment and material recovery countries can also form a supplementary solution to building domestic CAM production with recycling.

Recommendation 4. Encourage traceability, standards and certifications to boost the consumption of recycled materials

The uptake of recycling industries is enabled by transparency and international best practice

Employing traceability systems across the life cycle of end-use products that contain critical minerals can be a crucial enabler to incentivise the use of recycled materials and ensure compliance of recycling mandates. The battery industry has taken meaningful early steps towards traceability, but other sectors – such as those containing critical mineral-heavy products like solar panels, wind turbines and fuel cells – are further behind. To ensure effectiveness, robust third-party audit and assurance systems aligned with international due diligence frameworks play an important role, independently verifying claims related to recycling rates, material origins and adherence to standards. Additionally, standardised measurement, transparent reporting methodologies, regular monitoring protocols, product passports, proper labelling and independent verification processes enhance traceability efforts.

To ensure the credibility and effectiveness of traceability schemes, policy makers can support their adoption. They can also encourage harmonised approaches that ensure interoperability between standards and align with international frameworks and best practices, especially those requiring multi-stakeholder collaboration. Moreover, they can establish policies that require private companies to adopt responsible disposal practices and encourage traceability systems within EPR frameworks. Manufacturers may be required to incorporate unique identifiers or digital passports into their products, enabling tracking of critical minerals throughout the product life cycle and facilitating end-of-life management. By linking EPR schemes to data reporting systems, producers would report on the fate of their products and the critical mineral recovery rates. This integrated approach would enhance transparency, improve recycling rates and drive innovation in circular design and recycling technologies across a wide range of industries that rely on critical minerals.

Recommendation 5. Provide targeted financial support for technology innovation, R&D and workforce training

Ensure continued support for more efficient processes, scaling proven technologies and training a workforce ready for the new energy economy

Significant investments in recycling technologies, workforces and supply chains are required to improve the efficiency and economic viability of recycling industries.

Governments can play a key role in directing the flow of investment by providing grants, incentives and support for projects. Public and multilateral financial institutions can play various roles in scaling funding available for projects. The participation of development finance institutions can be particularly influential in ensuring that recycling projects deliver social and environmental co-benefits.

Research and development efforts should focus on addressing key challenges in critical minerals recycling. These include improving the recovery rates of low-concentration minerals, reducing the energy intensity and environmental impacts of recycling processes, developing new recycling methods for emerging technologies and promoting more effective recovery of minerals from mine waste. Collaborations between research institutions and industry can help ensure that novel, viable technologies have a clear pathway to commercialisation. The International Energy Agency's Technology Collaboration Programme could play a role in this regard by facilitating multilateral collaboration on metal refining and recycling technologies. At the same time, policy support can focus on highly innovative technologies that have the potential to meaningfully change the landscape, instead of taking a scattered approach to technological investment.

Investment in workforce development is crucial to support the growth of the recycling industry. This includes not only advanced degree programmes in engineering and basic science fields like materials science and chemical engineering, but also vocational training needs for roles such as collectors and technicians. Partnerships between educational institutions and industry can ensure that training programmes align with industry and local community needs.

Recommendation 6. Strengthen recycling systems in emerging market and developing economies

Introduce new technical and financial instruments to support investment in regions most vulnerable to the effects of improper waste management

Numerous global challenges have shown that the populations least responsible for crises often suffer the worst impacts, lacking the infrastructure and financial resources needed to address them effectively. As highlighted throughout this report, unregulated and untreated waste that might contain some critical or precious minerals, but also hazardous materials, have often found their way from advanced economies to EMDEs. But beyond waste, several second-hand appliances, devices and in particular, vehicles, are also shipped to EMDEs for reuse to extend their lifespan before they need to be recycled.

Measures to prevent illegal waste exports and imports is the first step towards dealing with this issue, but second-hand products will still need to be recycled in these regions. However, in Africa for example, collection and recycling rates remain the lowest in the world due to insufficient infrastructure and technical capacity to recover the value of waste. It is crucial to have support from advanced economies to direct investments not only towards scaling up recycling infrastructure and waste management systems, but also for skill and technology transfer to EMDEs and to ensure that these regions have fair representation in all global dialogues on issues that affect their future. Providing technical assistance for recycling can not only prevent equipment like solar panels and EV batteries from ending up in landfills, but also foster a new area of economic development in EMDEs. For instance, battery recycling pretreatment facilities that produce black mass could be well-suited, since they are less technically complex and specialised with lower capital requirements.

Recommendation 7. Tackle data and information gaps

Access to reliable and granular data is pivotal for efficient policy and investment choices

As things stand today, granular data and information on amount of waste generated, average product and vehicle lifetimes, collection rates, recycling capacities, and amount and value of recovered materials for most countries and regions is extremely rare to access through public channels. This information is essential for policy and investment decisions to be as effective and efficient as possible. Improved data can play a role in tracking and supporting the recovery of critical minerals by the recycling industry. Regulations can include data obligations – for example, EU legislation provides reporting obligations for reuse and recycling targets, including for specific products such as batteries. The EU Critical Raw Materials Act also aims to establish a database for closed extractive waste facilities to facilitate the recovery of minerals from these.

A noteworthy example comes from the US Environmental Protection Agency, which has been collecting and reporting data on the generation and disposal of waste in the United States for over 35 years. These data help measure the success of materials management programmes across the country and characterise the national waste stream. International organisations and bodies can play a key role in assisting national and regional governments to develop strategies for data collection, share best practices and provide platforms to make such data openly accessible. Material-specific recycling recovery rates could be incorporated into regulations requiring information disclosure by recyclers and entities subject to EPR schemes.

Recommendation 8. Embrace a holistic approach beyond recycling

Product design, reuse, repair and refurbishment can play a major role in ensuring sustainable mineral value chains

A truly sustainable approach to critical mineral value chains requires a broader perspective beyond recycling that starts with consumer demand management, resource efficiency and circular product design. Policies such as education programmes can play a crucial role in fostering a culture wherein consumers better understand the environmental impact of their choices and are able to meet service needs without necessarily increasing material demand or depleting natural capital.

For end-of-life products and technologies, reuse, repurposing and refurbishment should be the first line of defence over recycling. Manufacturers should be incentivised to design products for longevity, repairability and recyclability. This could include using standardised components, making products easy to disassemble or designing out hazardous materials that complicate recycling.

This may entail regulations such as eco-design regulations or tax incentives for circular design. The EU Ecodesign for Sustainable Products Regulation notably expanded the original directive's focus on energy efficiency to a broader framework on circularity, highlighting the importance of life-cycle thinking in resource management. Rules like the "right to repair" legislation can help make repurposing and refurbishment more affordable for certain products, extending the life of end-use equipment and reducing the need for virgin materials.

Recommendation 9. Tackle environmental, social and governance issues for recyclers

ESG impacts must be identified, minimised and mitigated to contribute to sustainable and responsible supply chains

While there may be lower greenhouse gas (GHG) emissions and water and energy use associated with the production of recycled minerals versus virgin minerals, recycling can still incur adverse environmental, social and governance (ESG) impacts. Recycling operations are not immune to environmental impacts such as air or water pollution and GHG emissions. There may also be negative impacts to soil or human health from improperly generated or managed waste. The emergence of the recycling industry could also cause land-use changes, local community impacts, human rights concerns or biodiversity changes.

All of these impacts need to be identified, minimised and mitigated for recycling to contribute to creating sustainable and responsible energy mineral supply chains.

Sustainable mine waste management can also ensure that instead of causing environmental harm, mining residues are used as valuable resources. Given the varying ESG performance among companies, policy makers could consider adding ESG considerations into their policy tools to incentivise and reward demonstrated high ESG performance among recyclers, similar to those incorporated in some jurisdictions for primary critical mineral supply chains. For instance, funding could be given to recyclers who have demonstrably good ESG performance or could be conditional on meeting certain ESG criteria. Strategic funding could be provided to companies that conduct research and development that improves the environmental performance of recycling processes. International partnerships supporting the development of the recycling industry should also include ESG performance considerations. Without forgetting the human cost of the minerals industry, these should be integrated with multi-stakeholder input and follow international best practices, such as the Organisation for Economic Co-operation and Development (OECD) Due Diligence Guidelines for Responsible Business Conduct and the principles of Free Prior and Informed Consent for Indigenous Peoples.

Annex

Policies

Table A.1 Policies and measures for the recycling of critical minerals

Region/Country	Title	Jurisdiction	Typology
Australia	National Battery Strategy	National	Strategic plans
	National Waste Policy Action Plan	National	Strategic plans
	Regulation for small electrical products and solar photovoltaic systems	National	Extended Producer Responsibility
	Critical Minerals Development Program	National	Extended Producer Responsibility; Financial incentives
	Hazardous Waste (Regulation of Exports and Imports) Act, 1989	National	Cross-border trade
	Recycling and Waste Reduction Act 2020	National	Extended Producer Responsibility
Brazil	(Acre) Lei 2.539	Sub-national	Extended Producer Responsibility
	Law No. 12305. Brazilian National Policy on Solid Waste	National	Extended Producer Responsibility
Canada	(Quebec) Plan for the Development of Critical and Strategic Minerals 2020-2025	Sub-national	Strategic plans
	(Ontario) Electrical and Electronic Equipment (EEE) Regulation	Sub-national	Extended Producer Responsibility
	Cross-border Movement of Hazardous Waste and Hazardous Recyclable Material Regulations	National	Cross-border trade
	Canada's Federal Budget 2022	National	Financial incentives
Chile	Law 20.920 Establishment of a framework for waste management, extended producer responsibility and recycling	National	Cross-border trade

Region/Country	Title	Jurisdiction	Typology
Colombia	Regulatory Decree of the Environment and Sustainable Development Sector addresses WEEE, batteries and accumulators	National	Extended producer responsibility
European Union	EU Sustainable Batteries Regulation	Regional	Extended producer responsibility
	EU Directive 2006/66/EC Battery Directive	Regional	Extended producer responsibility
	European Critical Raw Materials Act	Regional	Strategic plans
	EU Rules on End-of-Life Vehicles	Regional	Extended producer responsibility
	Waste Electrical and Electronic Equipment Directive	Regional	Cross-border trade
	EU Directive on the Management of Waste from Extractive Industries	Regional	Cross-border trade
	EU Strategic Action Plan on Batteries	Regional	Strategic plans
	EU Ecodesign Regulation	Regional	Extended producer responsibility
	Regulation (EU) 2024/1157 on shipments of waste	Regional	Cross-border trade
	EU Copper Scrap Criteria	Regional	Cross-border trade
	EU Waste Framework Directive	Regional	Extended producer responsibility
France	Anti-Waste Law 2020	National	Extended producer responsibility
	France Law implementing EU regulation relative to batteries and waste batteries	National	Extended producer responsibility
Germany	Electrical and Electronic Equipment Act	National	Extended producer responsibility
	Germany's Untied Loan Guarantees (UFK)	National	Financial Incentives
	National Circular Economy Strategy (NKWS)	National	Strategic plans

Region/Country	Title	Jurisdiction	Typology
Ghana	Hazardous and Electronic Waste Control and Management Act, 2016 (Act 917)	National	Cross-border trade; Extended producer responsibility
India	Hazardous and Other Wastes Rules	National	Cross-border trade
	E-Waste Management Rules, 2022	National	Extended producer responsibility
	Battery Waste Management Rules 2022	National	Extended producer responsibility
Italy	National Strategy for the Circular Economy	National	Strategic plans
	Legislative Decree No. 49 of 2014	National	Extended producer responsibility
	Organic provisions for the valorisation, promotion and protection of Made in Italy	National	Financial incentives
Japan	Critical Minerals Subsidy Program	National	Financial incentives
	Law for the Control of Export, Import and Others of Specified Hazardous Wastes and Other Wastes	National	Cross-border trade
	Law for the Promotion of Effective Utilization of Resources	National	Extended producer responsibility
Kenya	National E-Waste Management Strategy 2019-2024	National	Strategic plans
Korea	Wastes Control Act	National	Cross-border trade
	Act on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal	National	Cross-border trade
	Act on the Promotion of Saving and Recycling of Resources	National	Extended producer responsibility
Mexico	General Law for the Prevention and Integral Management of Wastes	National	Cross-border trade
Nigeria	National Environmental (Electrical/Electronic Sector) Regulations, 2022	National	Cross-border trade
	National Environmental (Battery Control) Regulations, 2024	National	Cross-border trade

Region/Country	Title	Jurisdiction	Typology
Pakistan	Pakistan Import Policy Order 2022	National	Cross-border trade
	National Hazardous Waste Management Policy, 2022	National	Cross-border trade
People's Republic of China	Announcement on Adjustment of Import Waste Management Catalogue Announcement No. 36 of 2009	National	Cross-border trade
	Crude Nickel Cobalt Hydroxide standard	National	Cross-border trade
	Opinions on Accelerating the Construction of a Waste Recycling System	National	Financial incentives
	Regulations for the Administration of the Recovery and Disposal of Waste Electric and Electronic Products	National	Extended producer responsibility
	Establishment of the China Resources Recycling Group	National	Financial Incentives; Extended producer responsibility
	Specifications for the Comprehensive Utilisation of Waste EV Batteries 2024	National	Extended producer responsibility
	14th Five Year Plan on circular economy	National	Strategic plans
	Plan for the Implementation of the Extended Producer Responsibility System	National	Strategic plans
South Africa	Export Control Regulations 2012	National	Cross-border trade
	Extended Producer Responsibility Regulations 2020	National	Extended producer responsibility
	Second-Hand Goods Act 2009	National	Extended producer responsibility
United Kingdom	National Planning Policy Framework	National	Strategic plans
	UK waste classification technical guidance	National	Cross-border trade
	Critical Materials for Magnets (Innovate UK) - Circular Critical Materials Supply Chains Programme	National	Financial incentives

Region/Country	Title	Jurisdiction	Typology
United States	(New Jersey) Senate Bill 601	Sub-national	Strategic plans
	(California) Electronic Waste Recycling Act of 2003	Sub-national	Extended producer responsibility
	Qualifying Advanced Energy Project Credit, Section 48C Inflation Reduction Act	National	Financial incentives
	Section 301, Trade Act 1974	National	Cross-border trade
	Battery and Critical Mineral Recycling Grant Program	National	Financial incentives
Viet Nam	Decree No. 08/2022/ND-CP	National	Extended producer responsibility
	Law No. 72/2020/QH14 on Environmental Protection	National	Cross-border trade

Note: We welcome feedback from jurisdictions regarding any updates to existing policies or on additional policies that are missing from the database. Further details can be found here.
Sources: IEA Policies Database (October 2024) with data from Columbia Center on Sustainable Investment (2023).

Abbreviations and acronyms

Al	aluminium
AMD	acid mine drainage
APS	Announced Pledges Scenario
AUD	Australian dollars
BAN	Basel Action Network
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BIL	Bipartisan Infrastructure Law
BRGM	Bureau de Recherches Géologiques et Minières
CAD	Canadian dollars
CAM	cathode active material
CCSI	Columbia Center on Sustainable Investment
CLP	Classification, Labelling, and Packaging Regulation
Co	cobalt
CO_2	carbon dioxide
CRMA	Critical Raw Materials Act
Cu	copper
DFIG	double-fed induction generators
EEE	electrical and electronic equipment
EESG	electrically excited synchronous generators
ELV Directive	End-of-Life Vehicle Directive
EoL	end of life
EPA	Environmental Protection Agency
EPR	extended producer responsibility
ESG	environmental, social and governance
EU	European Union
EV	electric vehicle
Fe	iron
FEOC	Foreign Entities of Concern
GEC	Global Energy and Climate Model
GHG	greenhouse gas
ICE	internal combustion engine
IEA	International Energy Agency
IRA	Inflation Reduction Act
ISRI	Institute of Scrap Recycling Industries
IT	information technology
KIGAM	Korea Institute of Geoscience and Mineral Resources
LCO	lithium cobalt oxide
LDV	light-duty vehicle
LFP	lithium iron phosphate
Li-ion	Lithium-ion
LME	London Metal Exchange
LMFP	lithium manganese iron phosphate
MENA	Middle East and North Africa
MFA	material flow analysis

NCA	lithium nickel cobalt aluminium oxide
Nd	neodymium
NDC	nationally determined contribution
Ni	nickel
NMC	lithium nickel manganese cobalt
NZE	Net Zero Emissions by 2050 Scenario
OECD	Organisation for Economic Co-operation and Development
OEM	original equipment manufacturer
pCAM	precursor cathode active material
PIC	Prior Informed Consent
Pr	praseodymium
PV	photovoltaic
R&D	research and development
REE	rare earth element
RIOS	Recycling Industry Operating Standard
RoHS	Restriction of Hazardous Substances
SDG	Sustainable Development Goal
STEPS	Stated Policies Scenario
TC/RCs	treatment and refining charges
TSF	tailings storage facility
UK	United Kingdom
UNEP	United Nations Environment Programme
US	United States
WEEE	waste from electrical and electronic equipment

Units

GJ	gigajoule
GW	gigawatt
GWh	gigawatt-hours
kg	kilogramme
kt	kilotonne
kWh	kilowatt-hours
m^3	cubic metre
mg	milligramme
Mt	million tonnes
t	tonne
TWh	terawatt-hour

International Energy Agency (IEA)

Unless otherwise indicated, all material presented in figures and tables is derived from IEA data and analysis.

IEA Publications
International Energy Agency
Website: www.iea.org
Contact information: www.iea.org/contact

Typeset in France by IEA - November 2024
Cover design: IEA
Photo credits: © Shutterstock