

10 April 2026

# Mining for the Energy Transition

**Gernot Wagner, Ariela Farchi, Isabel Hoyos, Pia Doris Morrow, Khande Jae Fisher, Leo Gordon, Hyae Ryung Kim, Brenda Rain, and Zacharia Thurston**

Cite as: Wagner et al. “Mining for the Energy Transition,” Columbia Business School Climate Knowledge Initiative (10 April 2026).



# The Opportunity



## Key messages

### Critical Minerals: The Opportunity

**Demand for critical minerals is growing as the world shifts toward renewables and other innovations in the energy transition. Even with higher emissions per ton according to lifecycle assessments, this shift could offset emissions from coal and gas by 89% and 83%, respectively.**

- Demand for critical minerals and rare earth elements is expected to increase significantly as demand for frontier technologies and products — EVs, renewables, medical equipment, military defense, and digital devices — continues to rise. Copper is the mineral in highest demand for EVs and renewables.
- Investment in the sector showed signs of slowdown in 2024, and startup funding declined, likely due to supply chain uncertainty. Meanwhile, exploration continued to increase.

**Reserves are diversified across the globe, but China maintains a near global monopoly on critical mineral refining, renewable tech, and rare earth element procurement.**

- China has a large market footprint, controlling >90% of graphite and rare earth refining and dominating downstream solar, battery, and EV manufacturing. It is expected to maintain a high market share until 2040.
- >40% of nickel and rare earth reserves are located in Indonesia and China, respectively, while Congo has 56% of cobalt reserves. Lithium is more diversified, though most reserves are concentrated in Chile, Australia, and Argentina. The U.S., Indonesia, and others are working to reduce dependence on China.

**Heightened environmental and social issues related to mining will require stronger policy and a regulatory push to alleviate water stress, land impact, and community tensions.**

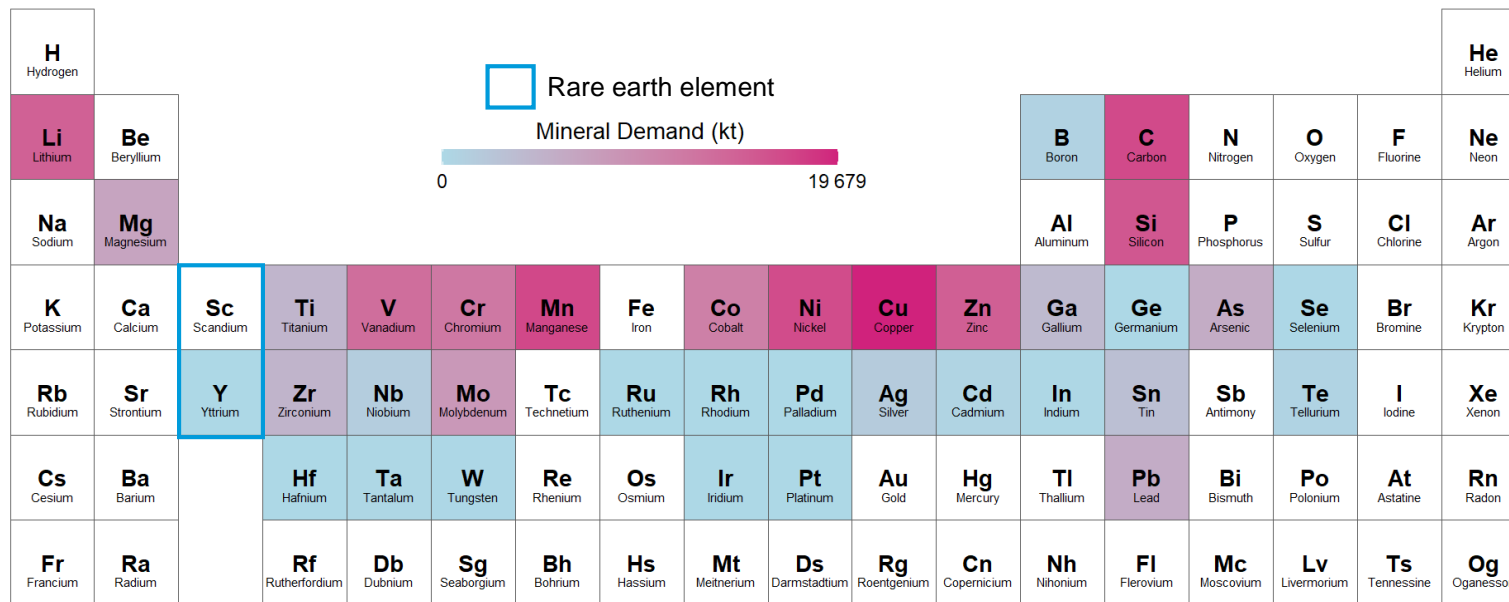
- Declining ore grades and high material throughput in mining require enhanced management practices and improved recovery techniques from tailings.
- A significant share of mining occurs in water-stressed locations, heightening risks to local communities and underscoring the need for less water-intensive extraction methods.

**Technological advances in material recovery will enable projected recycled inputs to meet up to 40% of demand by 2050. Electrification and other advances in efficiency are also critical to decarbonize.**

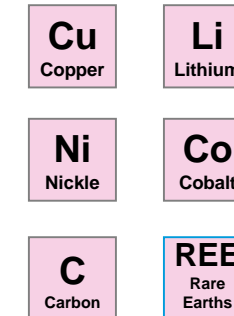
- The private sector is innovating for a circular economy, improving the recovery of minerals and the reuse and repurposing of products to maximize mineral utility in the supply chain.
- Policy remains fragmented globally, though state-level recovery incentives and targets are being implemented to encourage recycling of key minerals.

# Minerals designated as 'critical' based on their importance to national economies and security

## Critical minerals demanded for clean technologies, under Net Zero by 2050 scenario



### IEA key transition minerals



### Observations

- **Mineral criticality is country and context specific.** Minerals are designated 'critical' depending on economic, supply-chain, technology, geopolitical, and geological factors.
- While some countries adopt an **approach based on control supply and national security** (U.S., Europe, Japan), **others focus on capturing value** given the mineral's abundance in their territory (Indonesia, Nigeria), and some follow a **mixed pattern** (China).
- **The U.S. defined 50 key critical minerals**, whereas the **European Union defined 17.**
- **Critical minerals are scarce but essential for modern technologies**, economies, and national security, **with supply chains vulnerable to disruption.**

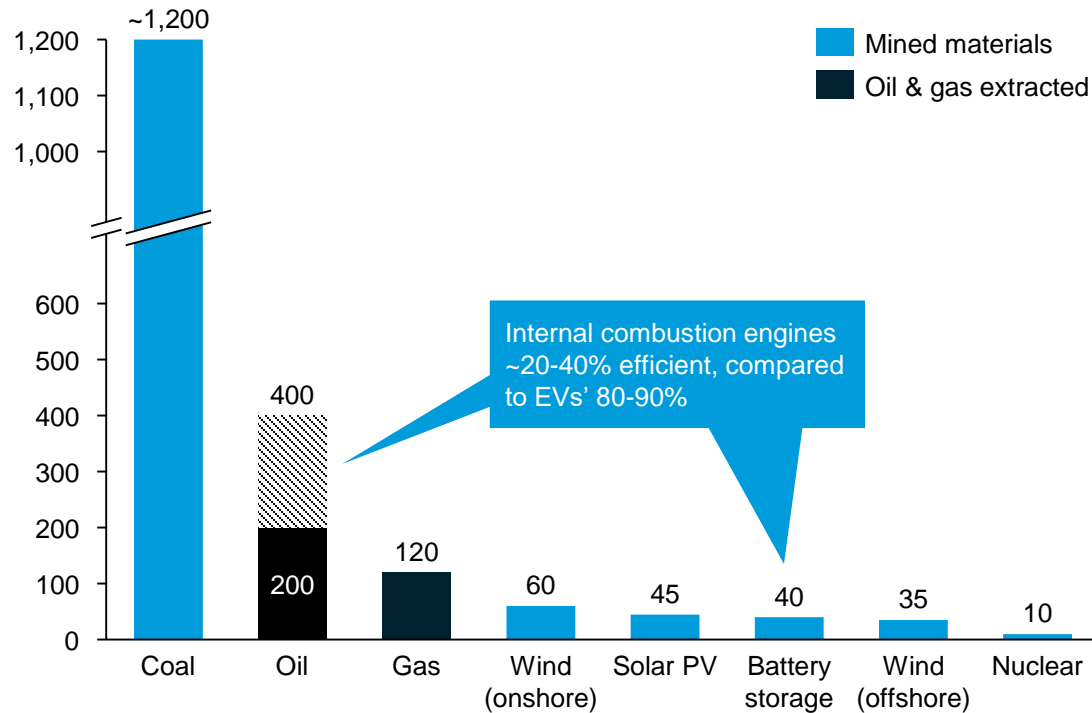
Sources: [Critical Minerals: A Primer](#) (International Institute for Sustainable Development, 2023); [2022 Final List of Critical Minerals](#) (Federal Register, 2022); [An EU critical raw materials act for the future of EU supply chains](#) (European Council and the Council of the European Union, 2024).

Credit: Brenda Rain, Zacharia Thurston, Ariela Farchi, Hya Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Despite its dependence on critical minerals, energy transition's material footprint lower than that of the fossil-fuel economy

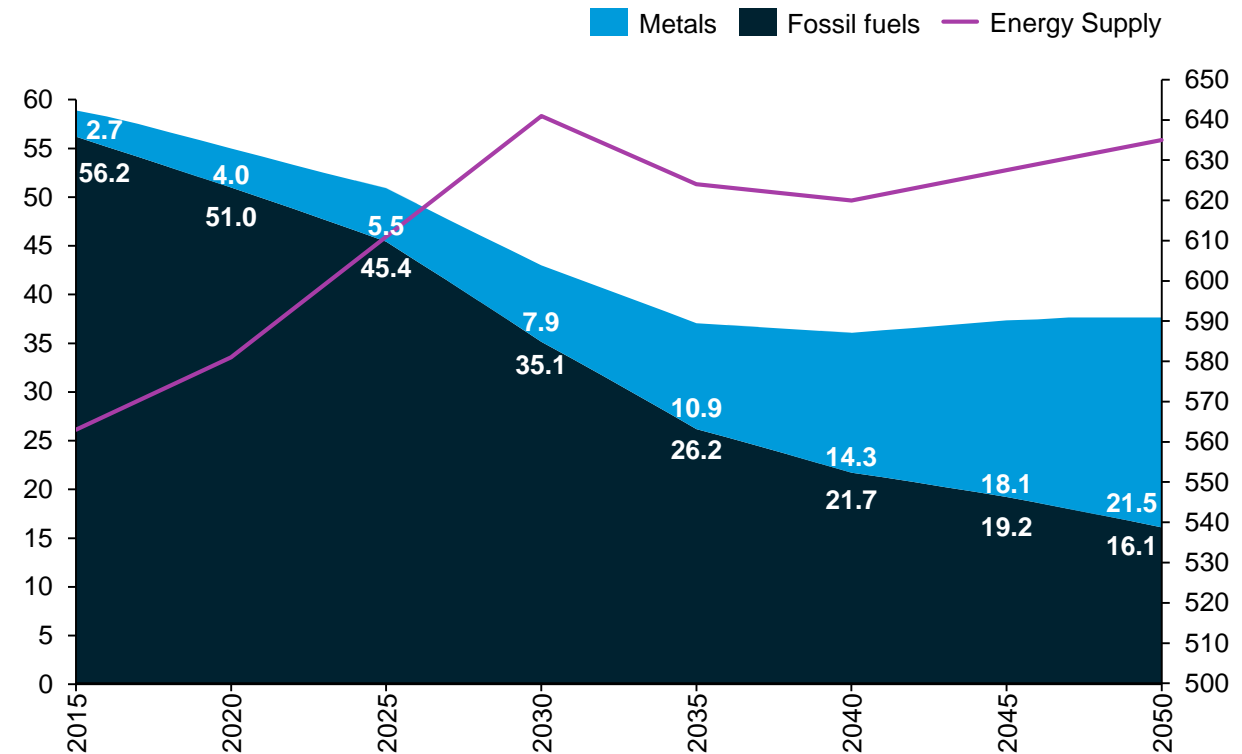
**Fossil fuels have higher material intensity and, unlike renewables, require continuous mining & extraction**

Mining requirements for energy sources, *tonnes of material/GWh*



**The energy transition will increase mineral demand, but decrease total material footprint, despite growing energy supply**

Material requirements of the energy transition (electricity and transport) v. growing global energy supply<sup>1</sup>, 2015-2050, *Gt/year v. EJ/year*



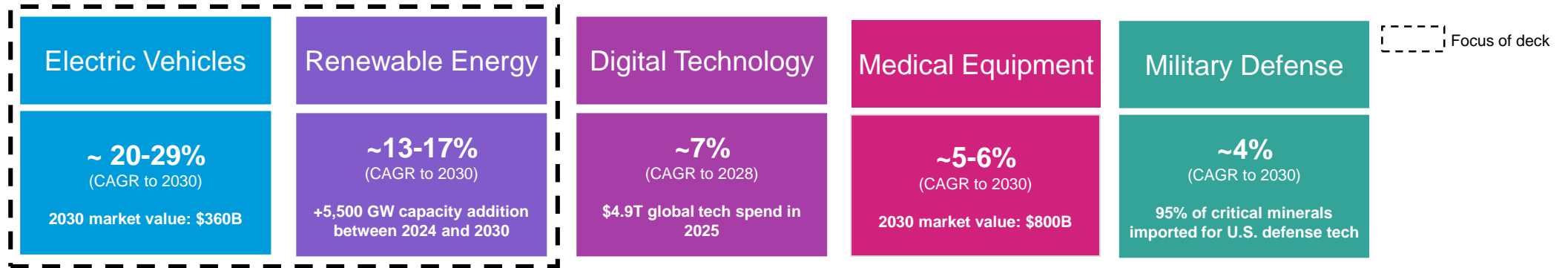
<sup>1</sup> Based on the IEA scenario keeping temperature rise to 1.75°C by 2100.

Sources: Wurmsdobler, [Mineral Resource Usage for the Energy Transition](#) (2025); [Sustainable Energy Transitions Require Enhanced Resource Governance](#) (Journal of Cleaner Production, 2021); [Energy Outlook 2025](#) (IEA, 2024).; Mining for Electricity (Our World in Data, 2022).

Credit: Leo Gordon, Isabel Hoyos, Ariela Farchi, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Global critical minerals demand expected to see 4-6x surge, driven energy transition

## Key sectors leading demand for critical minerals



### Minerals Required

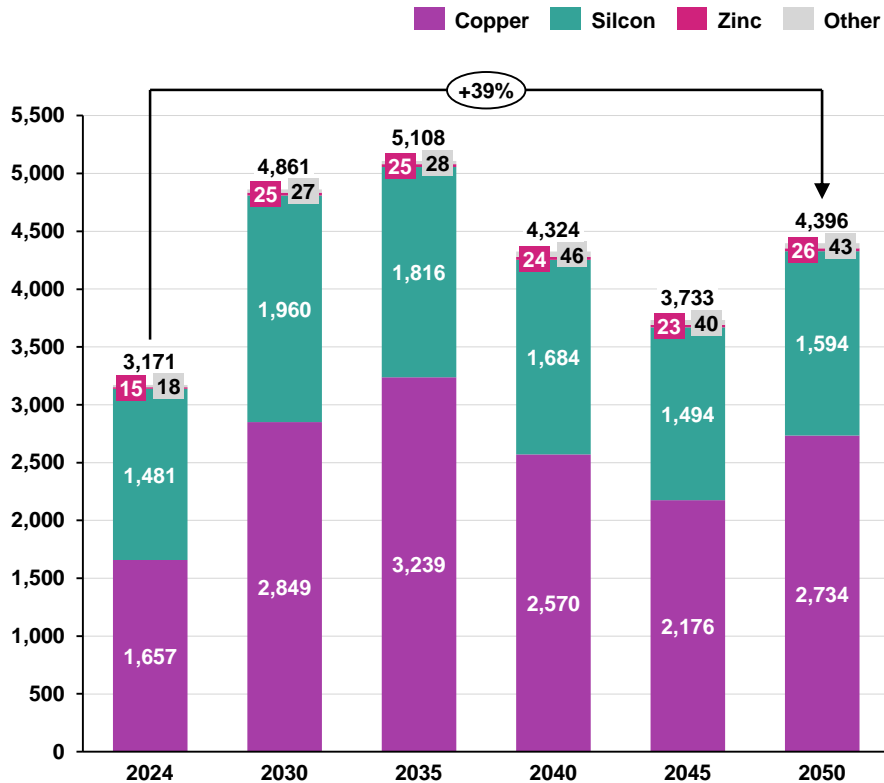
<p><b>Batteries:</b> Lithium, Nickel, Cobalt, Manganese, Graphite, Phosphorus, Platinum, Dysprosium, Lanthanum, Neodymium, Praseodymium</p>	<p><b>Wind turbines:</b> Copper, Aluminum, Zinc, Molybdenum</p> <p><b>Solar:</b> Silver, Copper, Gallium, Tellurium</p>	<p><b>Personal computers:</b> Silver, Aluminum, Copper, Gold</p> <p><b>iPhones:</b> Dysprosium, Neodymium, Samarium, Terbium</p>	<p><b>CAT scans:</b> Tungsten, Copper, Lead, Aluminum, Gold</p> <p><b>X-rays:</b> Thullum, Yttrium, Gadolinium</p> <p><b>Lasers:</b> Yttrium, Praseodymium, Neodymium, Samarium</p>	<p><b>Jet engines:</b> Rhenium, Nickel</p> <p><b>Night vision:</b> Lanthanum, Gadolinium, Yttrium</p> <p><b>Military aircraft:</b> Aluminum, Copper</p>
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Sources: [What is an EV?](#) (McKinsey, 2025); [Massive global growth of renewables to 2030 is set to match entire power capacity of major economies today](#) (IEA, 2024); [Medical Devices 2030](#) (KPMG); [DOE Invests Over \\$32 Million to Increase Efficiency of US Critical Minerals Production](#) (DOE, 2025); [Global tech spend to surpass \\$4.9 trillion in 2025](#) (Business Reporter, 2025); [Electric Vehicles](#) (Deloitte, 2020); [New silicon carbide prospects emerge as market adapts to EV expansion](#) (McKinsey, 2023); [BioSpace, Medical Devices Market Size](#) (2024); GMI Research, [Renewable Energy Forecast Report 2023-2030](#) (2023); Transparency Market Research, [Renewable Energy Market](#); [Defense Global Market Report](#) (The Business Research Company, 2025).  
 Credit: Zacharia Thurston, Khande-Jae Fisher, Ariela Farchi, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Mineral demand for solar and wind expected to grow ~40% and ~150% by 2050, respectively, driving demand for Cu, Zn, and Si

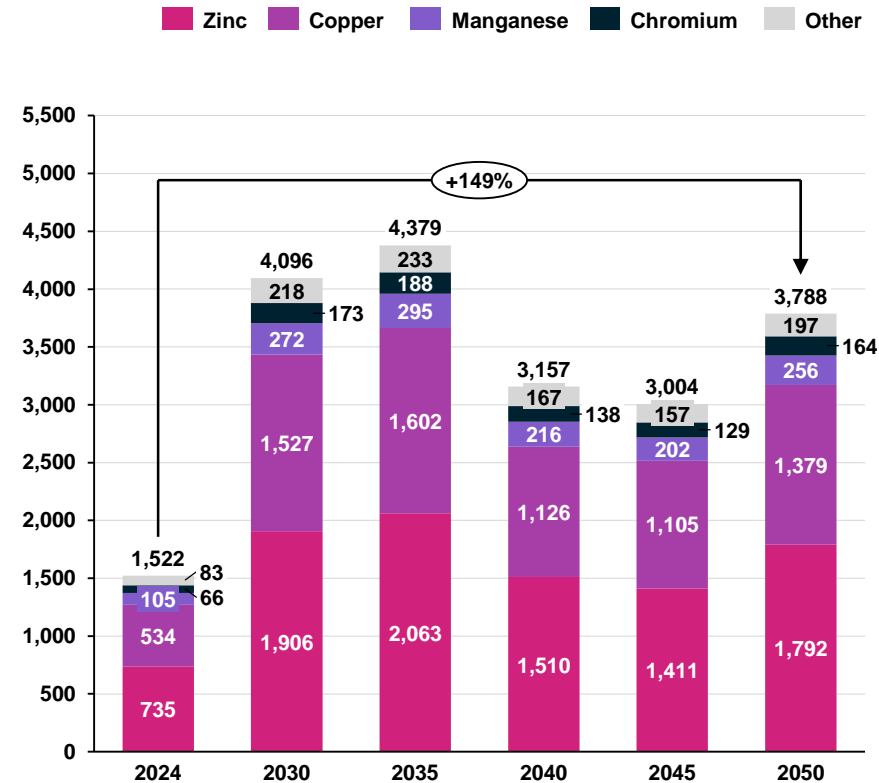
Solar's mineral demand<sup>1</sup> is expected to increase ~40% by 2050, primarily for Cu and Si

Mineral demand under NZE, kt



Wind's mineral demand<sup>1</sup> is expected to increase ~150% by 2050, primarily for Zn and Cu

Mineral demand under NZE, kt



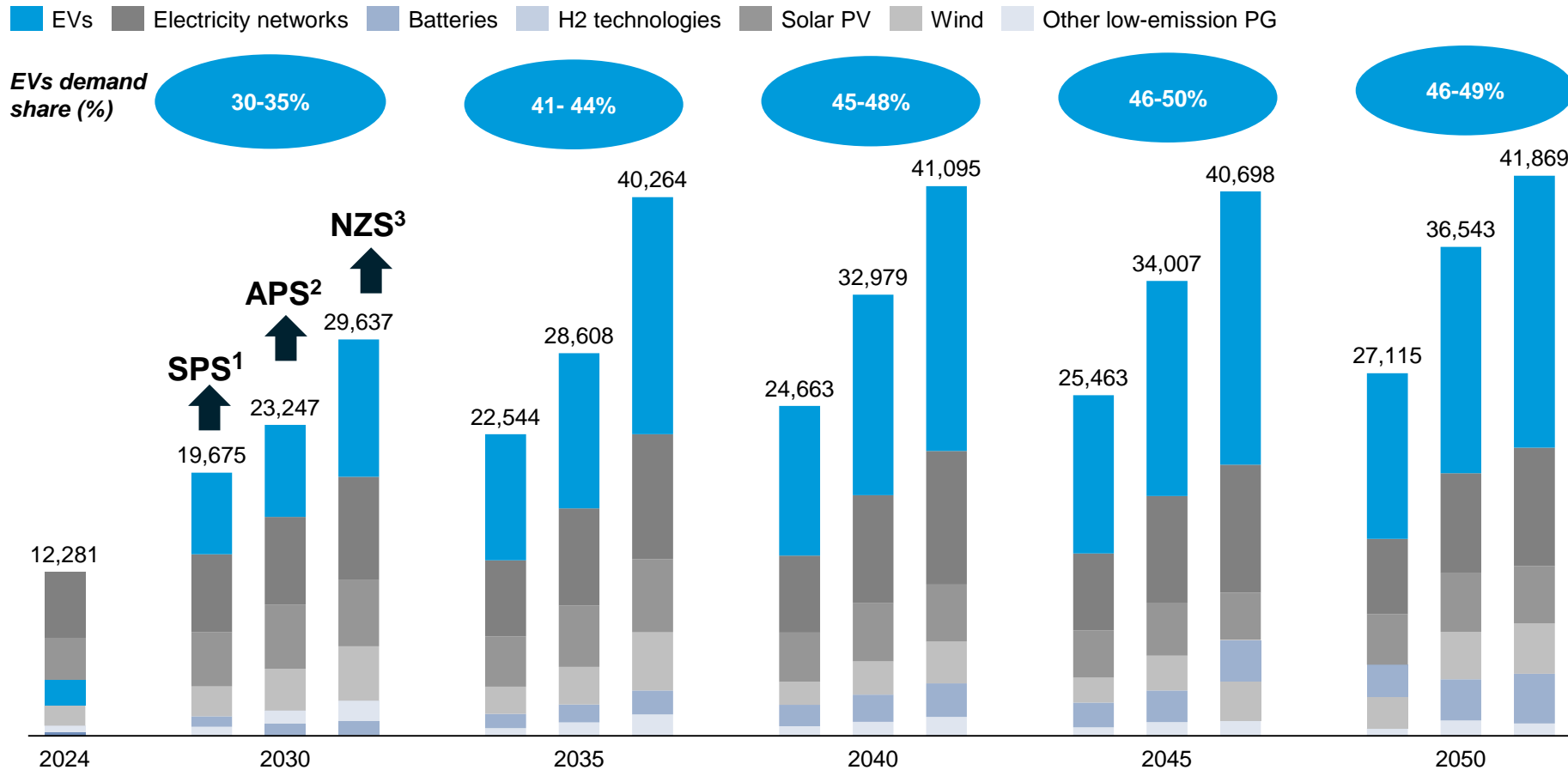
## Observations

- Cu, Zn, and Si will account for 49%, 21%, and 22% of cumulative wind and solar demand until 2050, respectively.
- Solar will comprise ~7% of cumulative Cu demand until 2050 under NZE; wind will comprise ~4%.
- Chromium, manganese, and nickel are essential for offshore wind as key elements for steel alloy manufacturing.
- “Other” key minerals for solar are arsenic, silver, and tin; “other” key minerals for wind are nickel and molybdenum.
- For solar, gallium demand will increase ~385x, while demand for cadmium, germanium silver, and tellurium will decrease.
  - Silver per kW of PV to decline due to design and efficiency improvements; recycling to supply two-thirds of silver demand between 2040 and 2050

1) Demand projections based on analysis pre-OBBBA; U.S. downstream solar and wind manufacturing capacity accounts for <3% and <9%, respectively, so overall impact is limited. Sources: [Critical Minerals Data Explorer](#) (IEA, 2025); [Global Copper Demand in Net Zero Scenario](#) (IEA, 2024); [Special Report on Solar PV Global Supply Chains](#) (IEA, 2025); [Materials used in U.S. Wind Energy Technologies](#) (NREL, 2023). Credit: Khande-Jae Fisher, Isabel Hoyos, Ariela Farchi, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Electric vehicles ~50% of clean tech's critical mineral demand

## Critical mineral demand by technology, kt



### Observations

- EVs surpassed 20% of global share of clean tech in 2024, which is projected to **increase as much as ~82% by 2050**, led by increased competitiveness.
- While clean tech's demand for critical minerals continues to increase, **digital tech and AI** will add more pressure to the global mineral supply.
- This will lead to global demand increases of 2% for copper and silicon, 3% for REEs, and 11% for gallium between 2024 and 2030.

1) Stated Policies Scenarios: Based on the current state of the policies. 2) Announced Pledges Scenario: Assumes government meets all climate commitments made.

3) Net Zero Emissions: Outlines a pathway to limit emissions by 2050, aligned with the goal of 1.5 degrees Celsius.

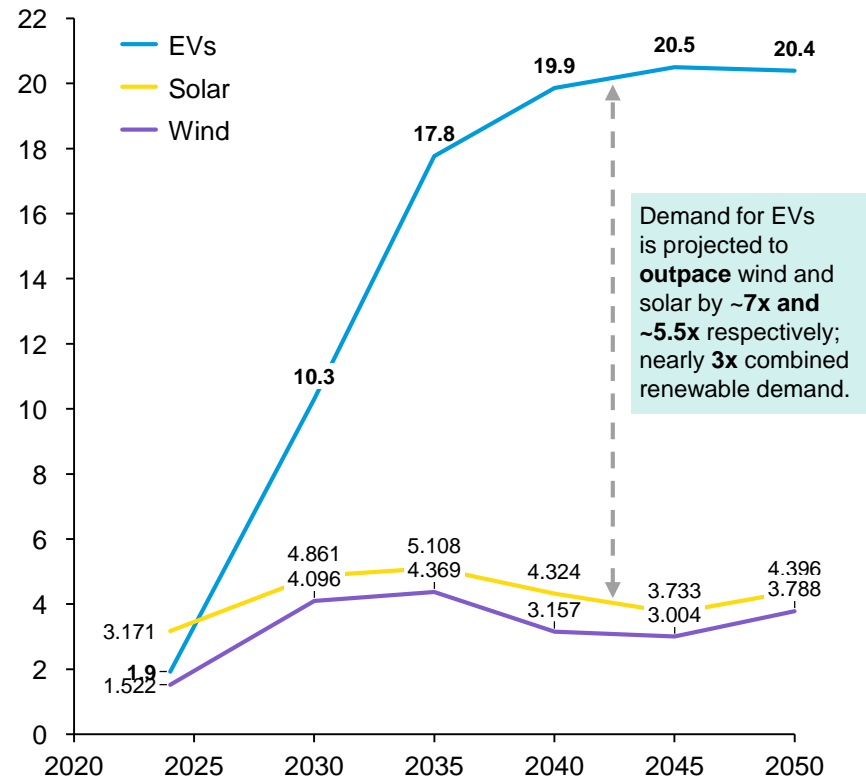
Sources: [Projected electric vehicle sales worldwide between 2030 and 2050](#) (Statista, 2025); [Critical Minerals Outlook 2025](#) (IEA, 2025).

Credit: Brenda Rain, Ariela Farchi, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Copper accounts for ~ 30-60% of cumulative mineral demand for renewables and EVs; demand from EV to outpace renewables 3x

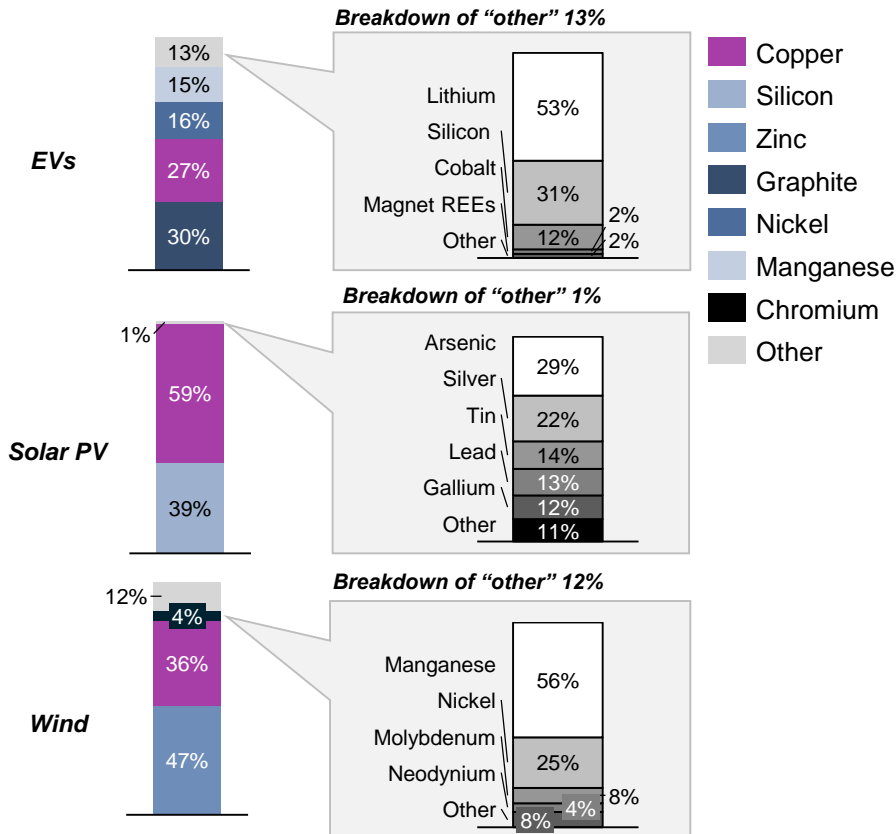
**Demand<sup>1</sup> from EVs will grow 10x by 2050; solar and wind will increase by 40% and 150%**

Annual critical mineral demand under NZE, Mt



**>50% of EV demand<sup>1</sup> is for Cu and graphite; renewables demand driven by Cu, Si, and Zn**

Distribution of cumulative mineral demand to 2050, %



## Observations

- Copper is essential for all sectors; it covers the greatest mineral share of solar PV demand.
- Cu is widely used for its conductive properties in cables, wiring, and electrical components for tech.
- Cu, Zn, and Si - the most crucial minerals for renewables - will account for **49%, 21%, and 22%** of cumulative wind and solar demand through 2050, respectively.
- EVs are expected to drive demand for lithium; they accounted for **85% of lithium demand** in 2023.

1) Demand projections are based on analysis pre-OBBBA.

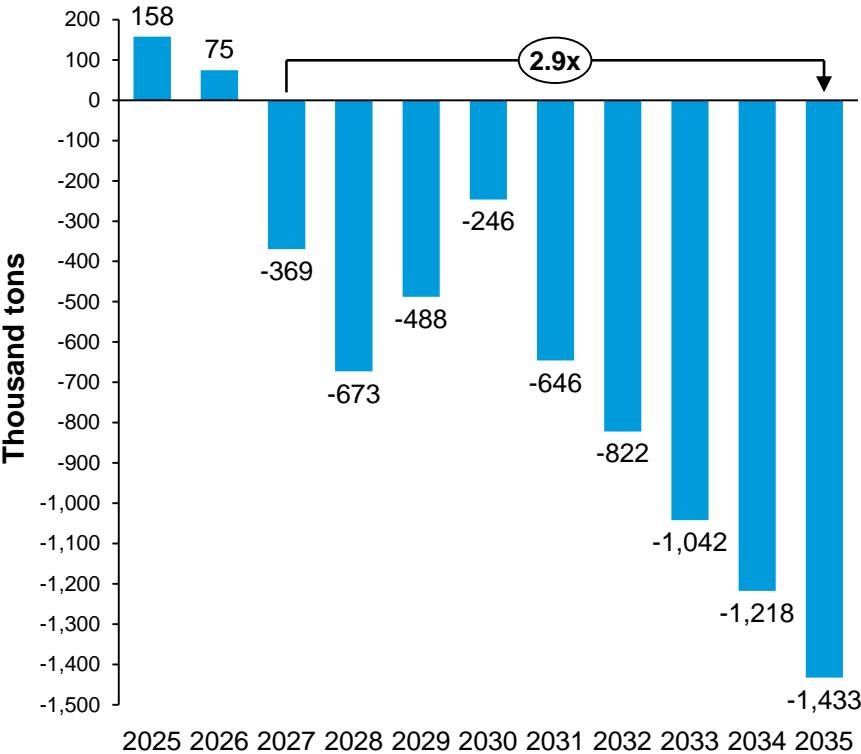
Sources: [Critical Minerals Data Explorer](#) (IEA, 2025); [Global Copper Demand in Net Zero Scenario](#) (IEA, 2024); [Special Report on Solar PV Global Supply Chains](#) (IEA, 2025);

Credit: Khande-Jae Fisher, Isabel Hoyos, Ariela Farchi, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Increasing demand expected to drive Cu deficit by 2035, with supply facing increased climate risks

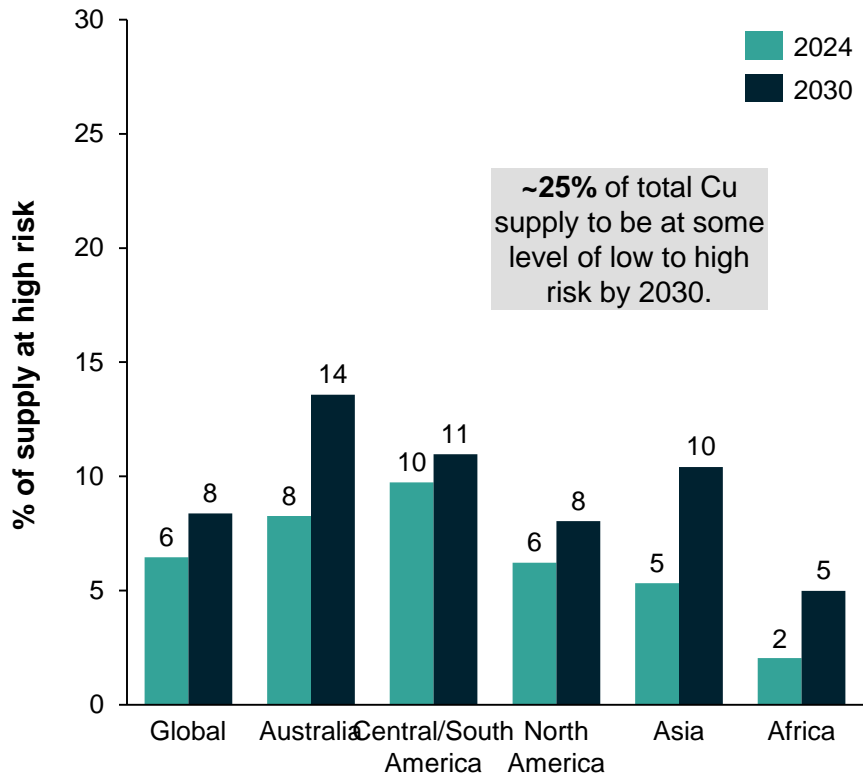
**Cu deficit projected to reach ~7M metric tons by 2035, growing ~300% from 2027 to 2035**

Annual Cu surplus and deficit to 2035, *thousand tons*



**Global Cu supply will grow only 2% by 2030 in face of high flood and drought risks**

Share of supply at high risk, %



**Observations**

- Cu demand for electricity networks, electricity generation, and electric vehicles is set to rise by 49%, 51%, and 555%, respectively; data centers will require more than 4.3 million metric tons by 2035.
- Fewer mine discoveries, declining ore grades, and disaster risks limit Cu supply production.
  - Cu ore grade has drastically declined by ~40% since 1991
  - Average lead times from discovery to production increased from 12.7 to 17.9 years; only four new sites were discovered between 2019 and 2023
  - Over 50% of current Cu production occurs in areas with high water stress
- Recycling of copper will be necessary: In 2023, secondary sources supplied nearly 20% of copper.

Sources: [Mining megadeal shows the world is crazy for copper](#) (The Wall Street Journal, 2025); [Global Critical Minerals Outlook](#) (IEA, 2025); [Copper Market Outlook](#) (Crux Investor, 2024); [US Electricity Grid Remakes Itself to Meet Surging AI-Led Power Demand](#) (Spratt, 2024).  
 Credit: Khande-Jae Fisher, Isabel Hoyos, Ariela Farchi, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

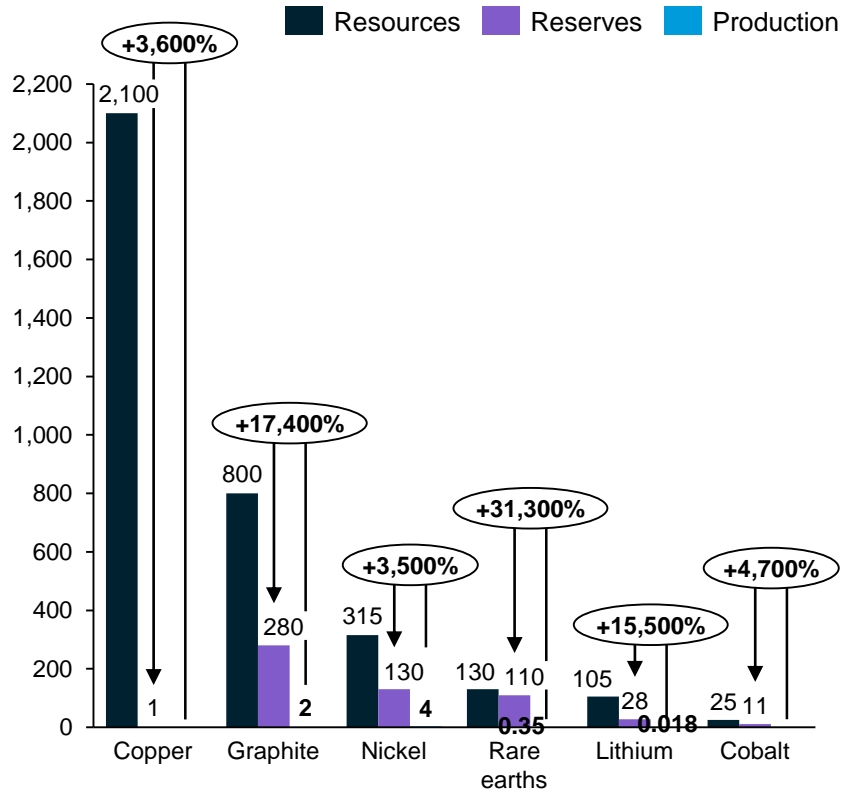


# Supply Outlook

# Existing reserves of all critical minerals fulfill projected clean tech needs through 2050, despite growing pressure on lithium supply

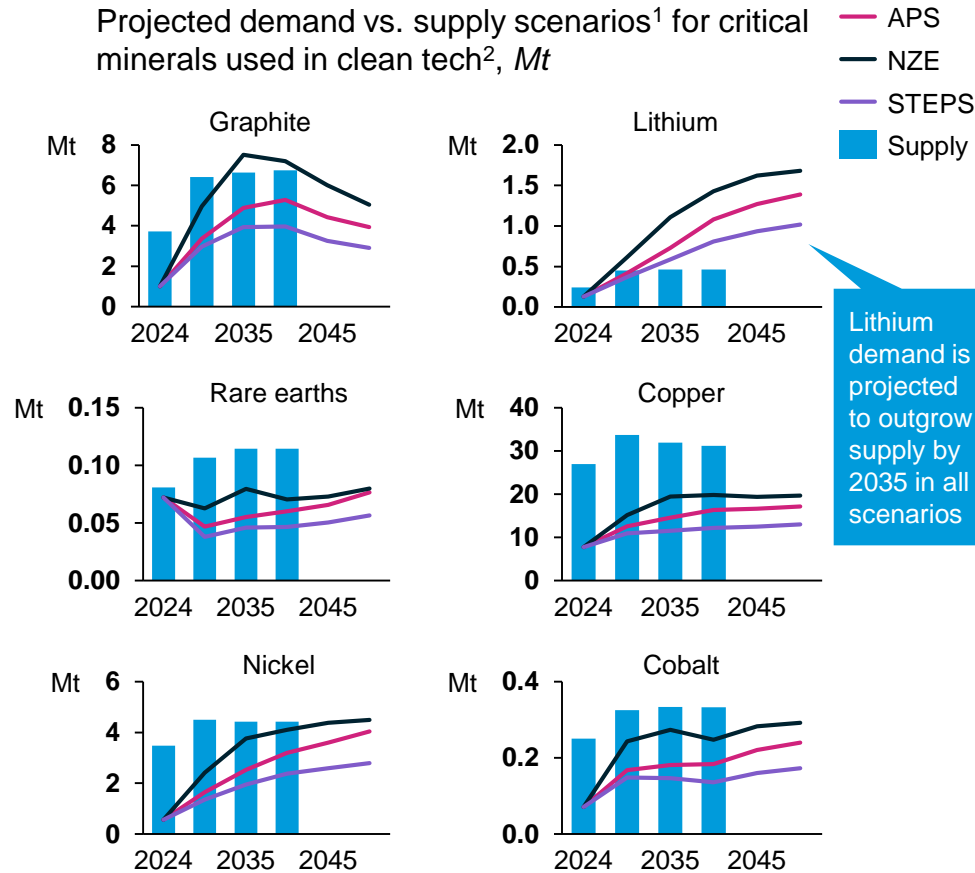
## Current reserves and resources far outnumber production, particularly for copper

Resources and reserves vs. global production of critical minerals, Mt 2023



## Across scenarios, production is projected to meet demand for minerals, except for lithium

Projected demand vs. supply scenarios<sup>1</sup> for critical minerals used in clean tech<sup>2</sup>, Mt



## Observations

- Overall, critical minerals **market gaps are the result of long lead times and permitting issues** around opening new mines and extending current capacity.
- **For lithium, beyond production increased 35% from 2023 to 2024**, driven by the growing demand of EVs.
- The gap between base case supply of lithium and climate-aligned demand calls attention to the **need for refining capacity additions**.

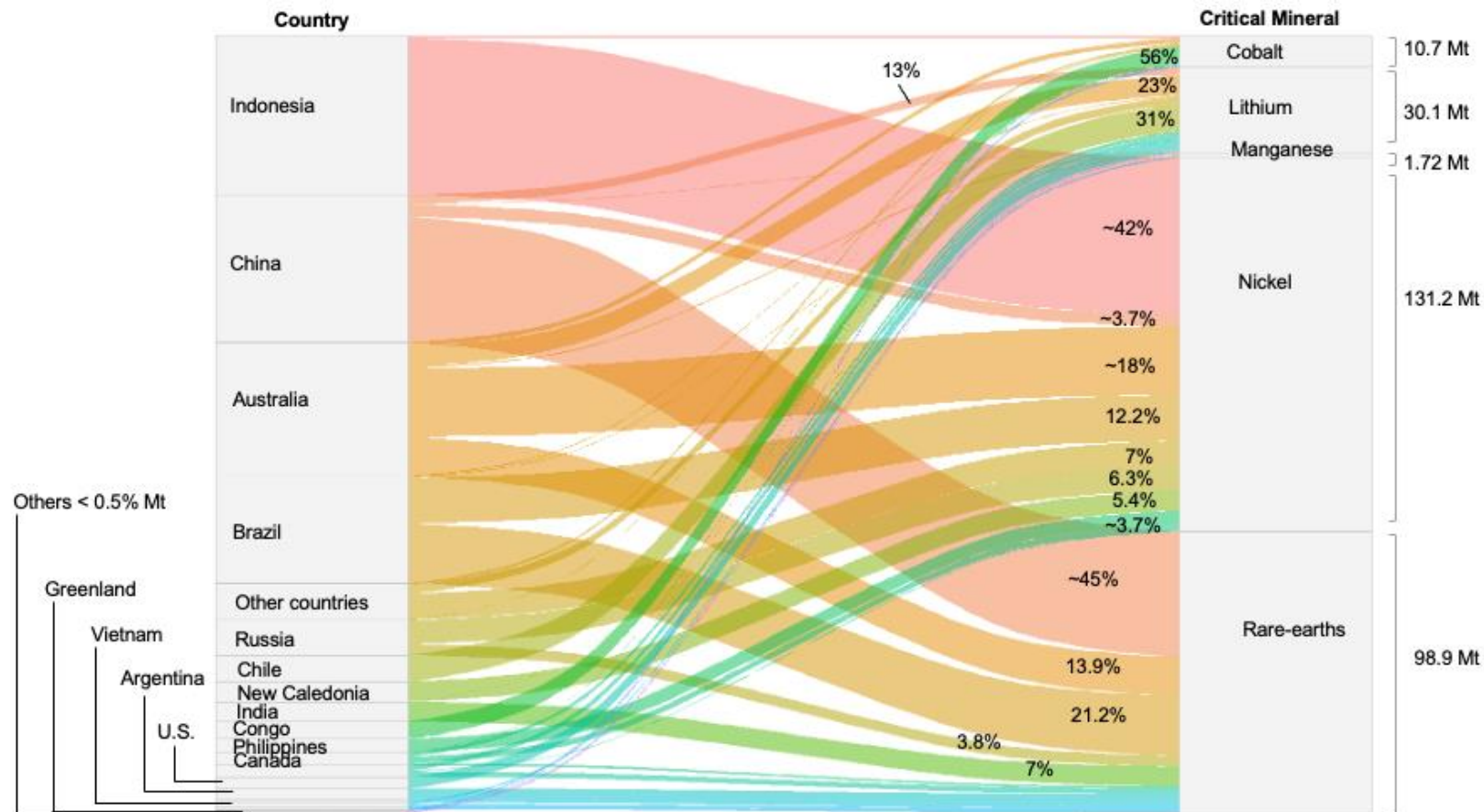
1) Scenarios refer to Announced Pledges Scenario (APS), Stated Policies Scenario (STEPS), and Net Zero Emissions by 2050 Scenario (NZE); 2) Clean technologies include renewable generation from wind and solar PV and other sources of low-emissions power generation, electricity networks, electric vehicles; battery storage.

Sources: [Mineral commodity summaries 2025](#) (USGS, 2025); [Global critical minerals outlook 2025](#) (IEA, 2025).

Credit: Brenda Rain, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Among minerals for batteries, reserves of nickel and rare earths are the most regionally concentrated; lithium more diversified

## Global reserves<sup>1</sup> distribution of battery's critical minerals in 2024



### Observations

- 97% of global lithium reserves can be found in seven countries; **Chile (31%)** and **Australia (23%)** have the largest reserves.
- **Rare earth reserves are 3.2x more abundant than lithium**, but **45% of reserves are in China**; **42% of nickel reserves are in Indonesia** and **56% of cobalt reserves are in DRC**.
- These countries have **significant influence** in the **NCX battery market**. The concentration influences **strategic investment decisions by major EV producers** in China looking to diversify their supply chain by investing in **mining assets across Africa and Latin America**, and even **overseas facilities for refining and downstream processing**.

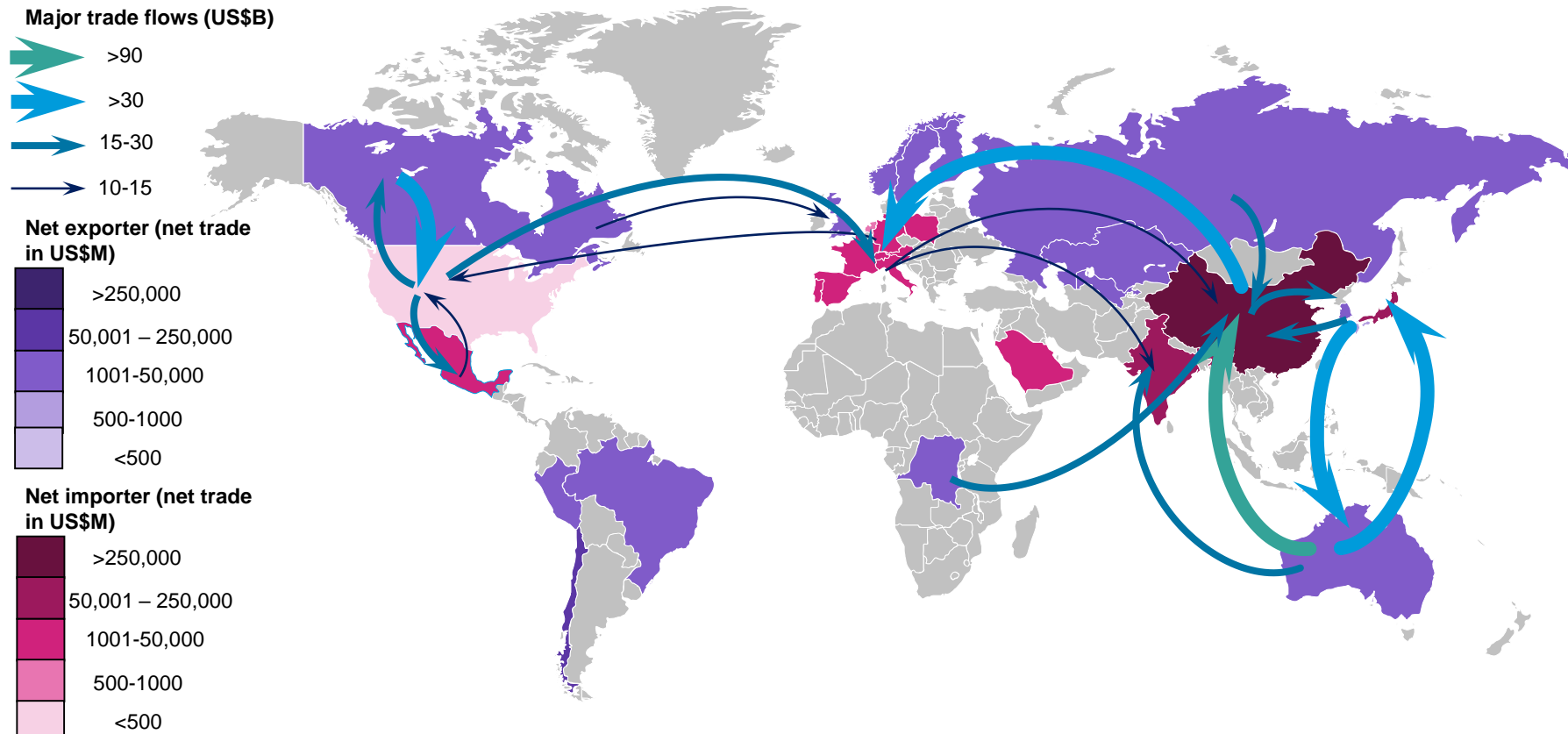
1) Part of the reserve base that could be economically extracted or produced at the time of determination. The term *reserves* need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials.

Source: [Mineral commodity summaries](#) (USGS, 2024).

Credit: Brenda Rain, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# China largest critical mineral importer of semi-processed and raw materials, Australia and Chile key trading partners

## Global trade flows<sup>1</sup> of material in 2023



### Observations

- China imports ~4x as much as it exports, sourcing US\$500 billion+ from several major exporters.
- Africa, South America, and Australia are net exporters, while Asia and Europe are heavily reliant on imported minerals.
- The largest global trade flow is Australia-China, valued at **US\$95 billion**.
- The **South China Sea** transported 24% of global trade in 2023; disruptions in this region may **significantly impact** critical mineral supply chains.
- The U.S. and Canada are each other's primary critical mineral trading partners.

1) Analysis excludes regional flows within Europe; based on UNCTAD's classification standards of 60 critical minerals.  
 Sources: [Trade in critical mineral shapes energy transition](#) (UNCTAD, 2025); [How South China Sea Tensions are rewriting global trade rules](#) (Atlas Institute, 2025).  
 Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

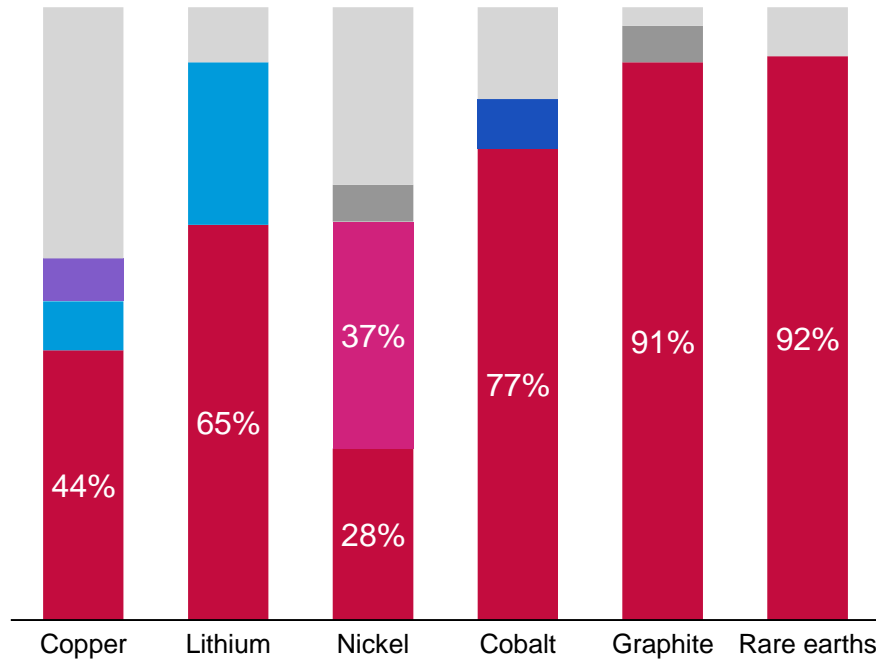
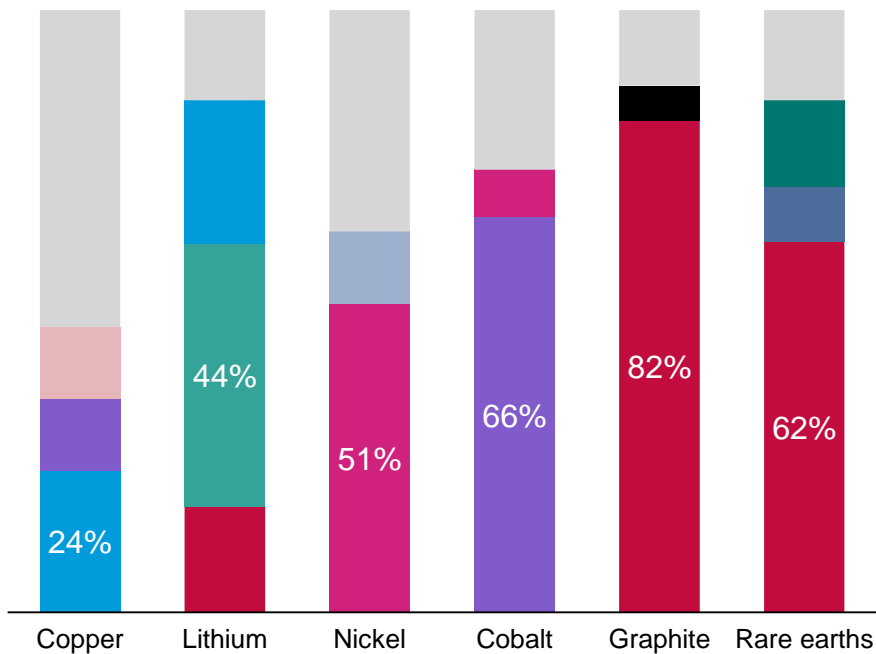
# Upstream critical mineral production dominated by few key players, midstream capabilities concentrated in China

## Upstream: DRC, Indonesia, and Australia lead Co, Ni, and Li; China leads graphite and REE<sup>1</sup>

Geographical distribution of mined/raw material production, 2023 %

## Midstream: China dominates global refining with ~90%+ of rare earth and graphite capacity

Geographical distribution of refined material production, 2023 %



### Observations

- Average market share of the top three refining nations grew from 82% in 2020 to 86% in 2024.
- Supply chain imbalances have triggered countries to employ market restrictions; levers include export bans, export licensing, stockpiling, and tax incentives for domestic companies.
  - Market restrictions may stimulate more domestic value addition, boosting fiscal revenues
- Zimbabwe and Namibia banned lithium ore exports as of 2022 and 2023, respectively; Indonesia banned nickel ore exports in 2014 and 2020.
- China is the dominant supplier of refined materials both by geography and ownership; it owns 65% of global nickel refining production.

1) Graphite extraction is based on natural flake graphite; rare earth elements are for magnet rare earth elements only.

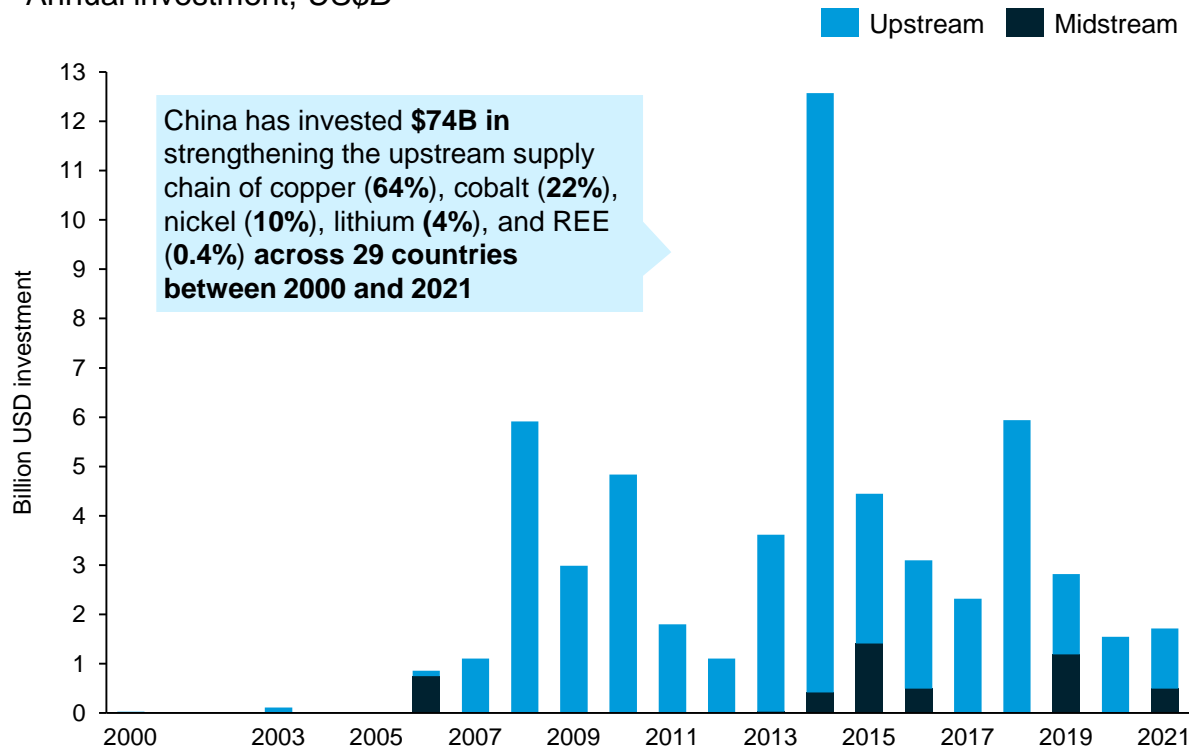
Sources: [Global Critical Minerals Outlook](#) (IEA, 2024); [Global Critical Minerals Outlook](#) (IEA, 2025); [Japan's Responses to China's Supply Chain Dominance](#) (RUSI, 2024); [Namibia bans exports of unprocessed critical minerals](#) (Reuters, 2023); [Zimbabwe bans raw lithium exports to curb artisanal mining](#) (Reuters, 2022)

Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

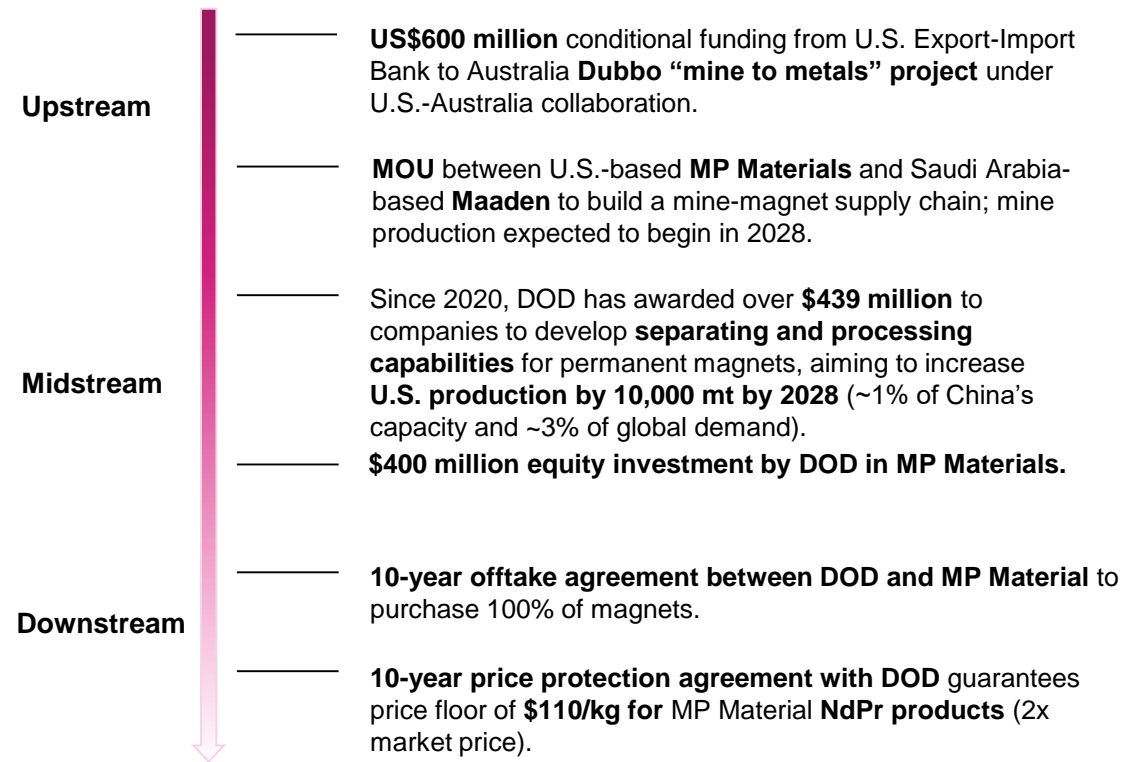
# China focuses on upstream capabilities while U.S. investments spread across rare earths value chain

China has invested \$74B in upstream capacity since 2000s to diminish earlier vulnerabilities

Annual investment, US\$B



The U.S. is developing the rare earths supply chain through public-private collaboration from mining to magnet production



Sources: [Mineral industry surveys by commodity](#) (USGS, 2025); [Mineral commodity summaries 2025](#) (USGS, 2025); [2022 Minerals yearbook China](#) (USGS, 2025); [2017-2018 Minerals yearbook China](#) (USGS, 2020); [World mineral statistic data](#) (BGS, 2025); [Which countries have the critical minerals needed for the energy transition](#) (2024); [Annual review 2024](#) (IMnI, 2024); [Mapping the evolution of manganese flows](#) (Resources, Environment and Sustainability2024); [Beijing’s bid to secure overseas transition minerals](#) (Aidata, 2025); [Global critical minerals outlook 2025](#) (IEA, 2025); [Global critical minerals outlook](#) (IEA, 2024); [Mineral security](#) (Resources for the Future, 2025); [Interactive Critical Minerals Prospectus](#) (ASM, 2024); [DOD Bets big on Rare Earth Elements](#) (Bipartisan Policy Center, 2025); [Developing Rare Earth Processing Hubs](#) (CSIS, 2025); [Trump strikes deal to restore rare earth access](#) (CSIS, 2025).

Credit: Brenda Rain, Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026). Our World in Data,

# China with persistent refining dominance over U.S. across critical minerals

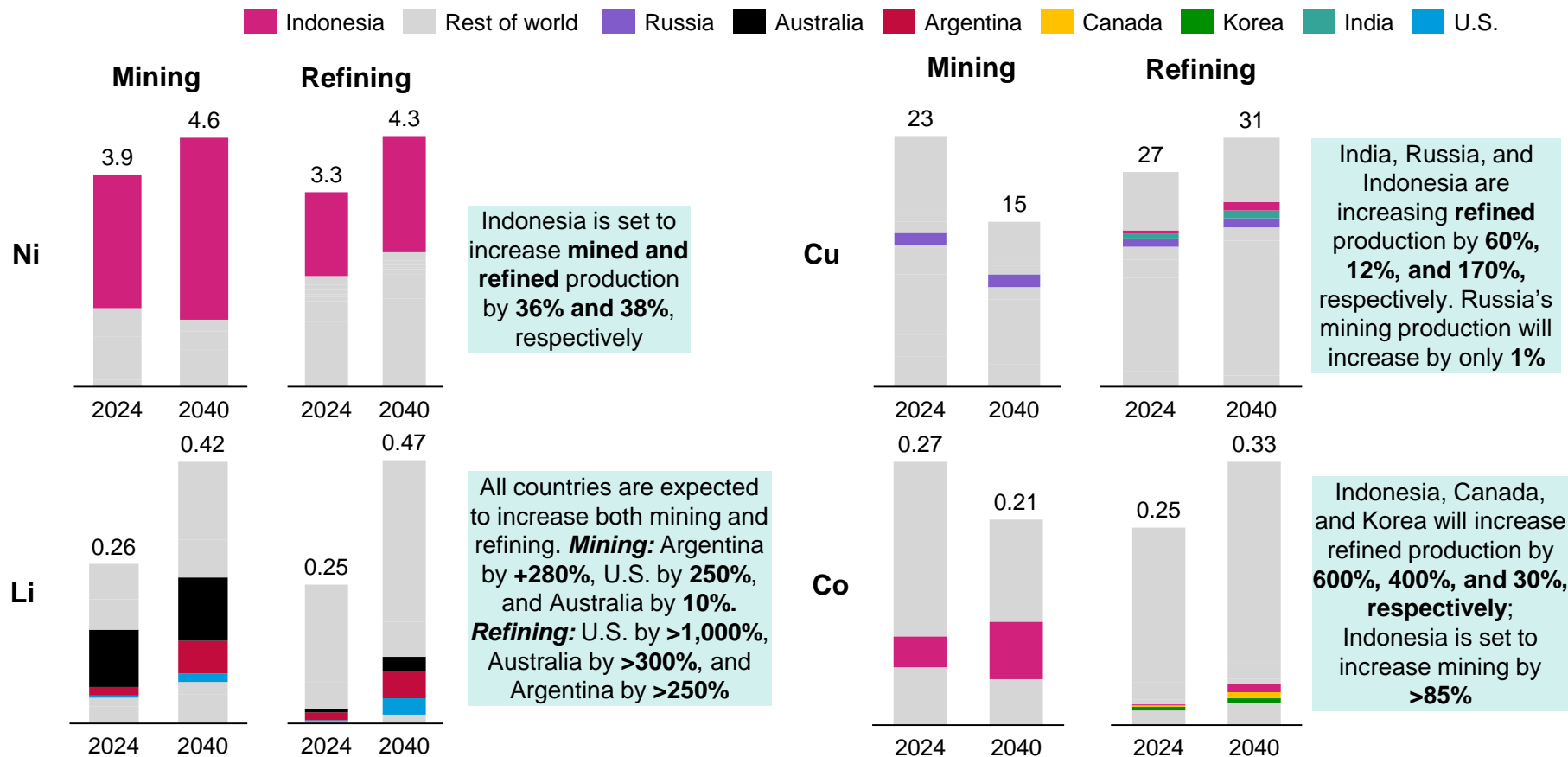
## Share of global mine and refined production of the U.S. and China, ~2014-2024

Mineral	Mine	Refine	U.S. 🇺🇸	Strategies	China 🇨🇳
<b>Cobalt (Co)</b>			<ul style="list-style-type: none"> <li>Attempts to increase its influence in <b>Central Africa Copperbelt through Lobito Corridor Railway</b></li> </ul>	<ul style="list-style-type: none"> <li><b>Continues to invest in TAZARA</b> (Tanzania Zambia Railway Authority)</li> </ul>	
<b>Copper (Cu)</b>			<ul style="list-style-type: none"> <li>Refining capacity continues to decline</li> </ul>	<ul style="list-style-type: none"> <li><b>Companies</b> continue to accelerate their <b>joint ventures to build smelter plants</b> near mines in <b>Africa and Latin America</b></li> </ul>	
<b>Lithium (Li)</b>			<ul style="list-style-type: none"> <li><b>Continues to invest in lithium triangle ABC</b> but faces pushback from local governments and indigenous communities</li> </ul>	<ul style="list-style-type: none"> <li><b>Continues to invest in lithium triangle ABC</b> but faces pushback from local governments and indigenous communities</li> </ul>	
<b>Manganese (Mn)</b>			<ul style="list-style-type: none"> <li>Includes manganese in broader critical mineral strategies; in April 2025, released an Executive Order to <b>develop subsea mineral deposits</b></li> </ul>	<ul style="list-style-type: none"> <li>Strengthening policies to support manganese processing within broader critical mineral strategies</li> </ul>	
<b>Nickel (Ni)</b>			<ul style="list-style-type: none"> <li>Attempting to increase its production, providing <b>\$20.6M funding to Talon Nickel mine</b></li> </ul>	<ul style="list-style-type: none"> <li><b>Expanded its production to Indonesia</b>, which owns 75% of its mining production and ~65% of its refined production</li> </ul>	
<b>Graphite (Gr)</b>			<ul style="list-style-type: none"> <li>While facing supply chain risks, domestic investment and tariff strategies have been implemented to close the gap</li> </ul>	<ul style="list-style-type: none"> <li>Continues employing export control to the U.S</li> </ul>	
<b>Rare earths (REEs)</b>			<ul style="list-style-type: none"> <li><b>Stopped production in 2022</b>, and currently <b>80% of its consumption comes from China</b>; the remaining comes from second exporters</li> </ul>	<ul style="list-style-type: none"> <li><b>Faces minor risk in using REEs as a trade dispute</b>, apart from issues related to illegal mining</li> </ul>	

Sources: [Mineral industry surveys by commodity](#) (USGS, 2025); [Mineral commodity summaries](#) (USGS, 2025); [2022 Minerals Yearbook China](#) (USGS, 2025); [2017-2018 Minerals Yearbook China](#) (USGS, 2020); [World mineral statistic data](#) (BGS, 2025); [Which countries have minerals needed for the energy transition](#) (Our World in Data, 2024); [Annual review](#) (IMnI, 2024); [Mapping manganese flows](#) (Resources, Environment and Sustainability, 2024); [Cobalt Market Report](#) (Cobalt Institute, 2024); [China's expanding copper influences](#) (China Global South, 2025); [Nickel mining in North America](#) (Investor News, 2025); [Can the West loosen China's grip on the global graphite market](#) (Mining Technology, 2025); [REEs in the trade dispute between US and China](#) (Intereconomics, 2019).  
 Credit: Brenda Rain, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Many including Indonesia and U.S., increasing mineral refining capacity to reduce their dependence on China

Global planned mining and refining mineral production (non-China), 2024-2040, Mt<sup>1</sup>



Indonesia is set to increase **mined and refined** production by **36% and 38%**, respectively

All countries are expected to increase both mining and refining. **Mining:** Argentina by **+280%**, U.S. by **250%**, and Australia by **10%**. **Refining:** U.S. by **>1,000%**, Australia by **>300%**, and Argentina by **>250%**

India, Russia, and Indonesia are increasing **refined** production by **60%, 12%, and 170%**, respectively. Russia's mining production will increase by only **1%**

Indonesia, Canada, and Korea will increase refined production by **600%, 400%, and 30%**, respectively; Indonesia is set to increase mining by **>85%**

## Observations

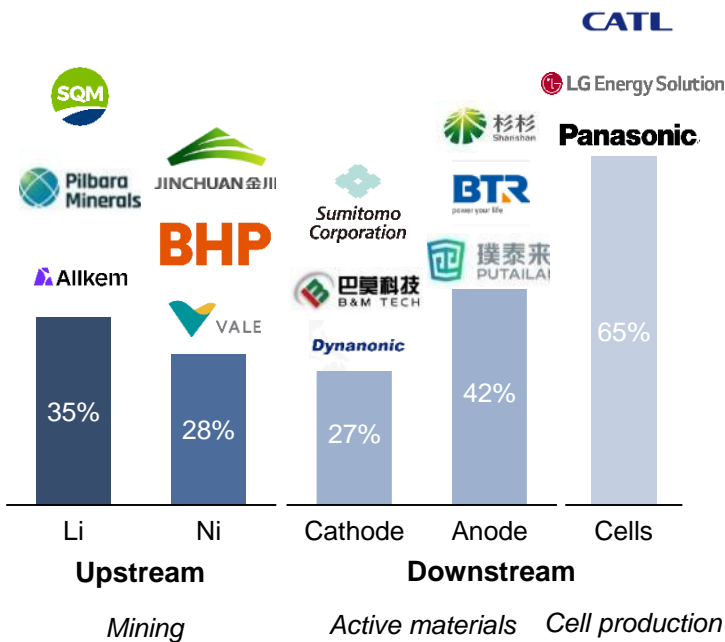
- Diversification is useful to **cushion countries against external shocks, derive more mineral benefits, and prevent resource-rich developing countries from becoming dependent** on external economies.
- Global FDI greenfield mineral projects numbered 117 in 2023; approximately **75% of those were in developing economies and half were dedicated to mineral processing.**
- Between 2024 to 2035, the average share of the top three refining nations is set to decline by 4%.

1) Projections based on IEA base case scenario with existing assets, those under construction, and projects that acquired all necessary permits, secured financing, or established offtake contracts. Sources: [Global Critical Minerals Outlook](#) (IEA, 2025); [Critical minerals boom: Global energy shift brings opportunities and risks](#) (UNCTAD, 2024); [Harnessing the Potential of Critical Minerals for Sustainable Development](#) (UN, 2025). Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Small number of companies, many in China, dominate EV battery supply chain by locking in economies of scale

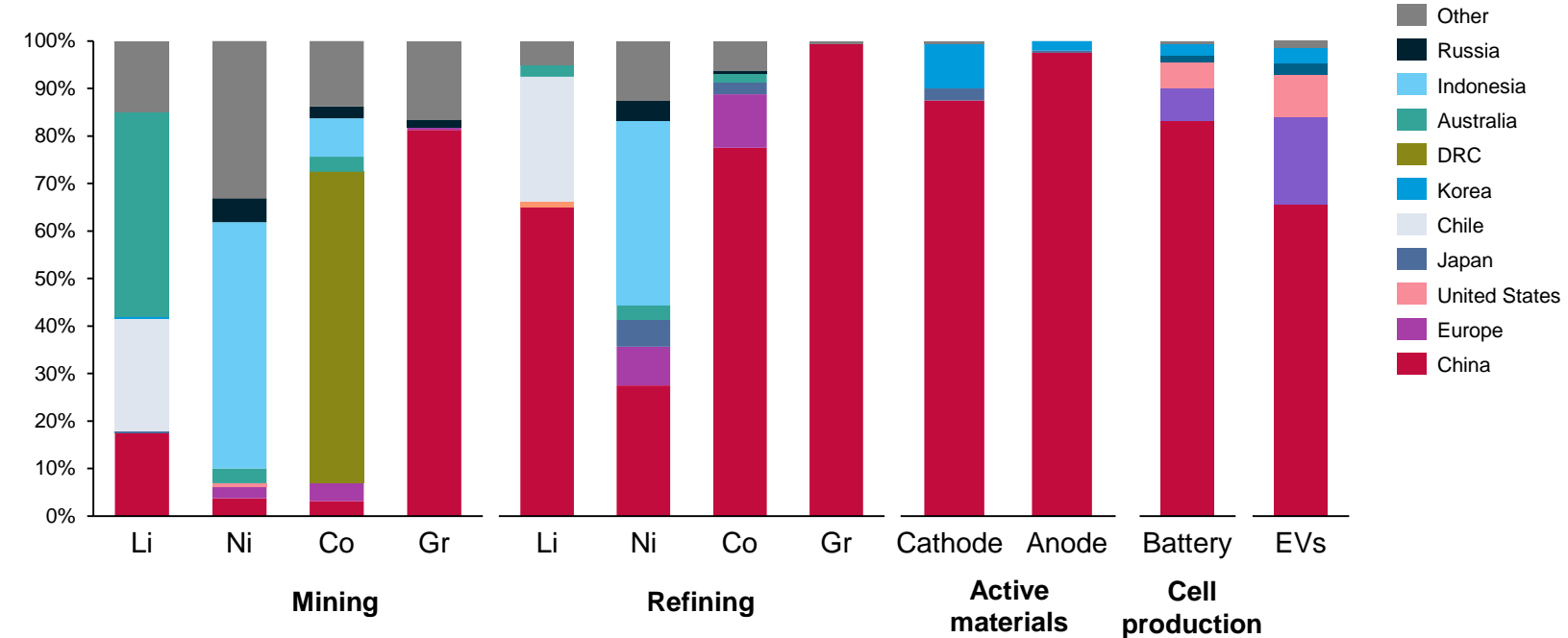
Upstream is mostly managed by LATAM and Australia, downstream is led by Asia

Share of total production of top three companies across supply chain,<sup>1</sup> 2021



While mining for battery and EV materials is more geographically diversified, most of the refining and production happens in China

Geographical distribution of the global EV battery supply chain,<sup>2</sup> 2023



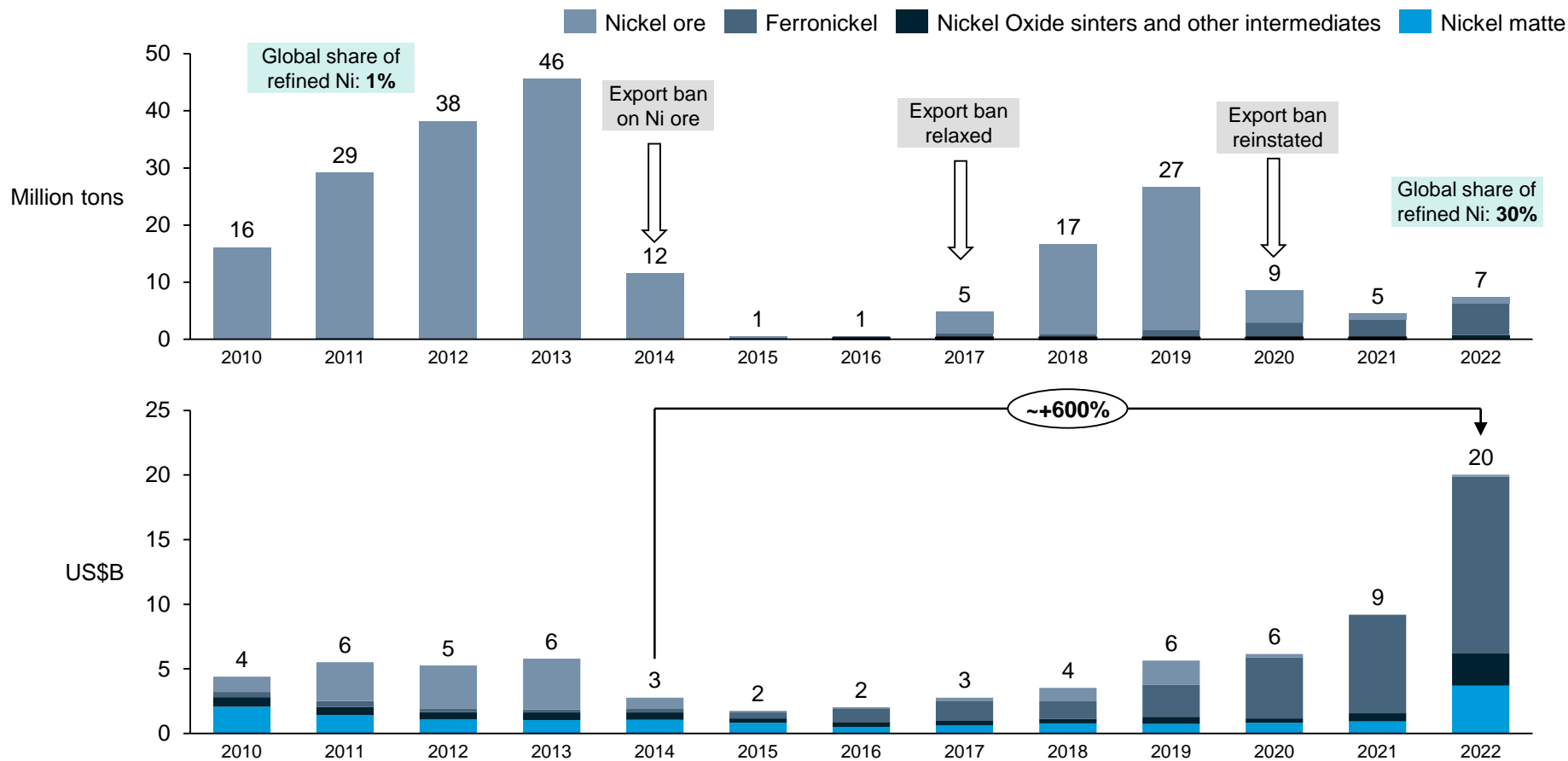
1) Mining by production capacity; cathode and anode by production capacity; cell production by MWh produced. 2) Geographical breakdown refers to the location of the production. Mining is based on production data. Material processing is based on refining production capacity data. Active material production is based on cathode and anode material production capacity data. Battery cell production is based on battery cell production capacity data. EVs based on electric cars production data.

Sources: [Global Critical Minerals Outlook](#) (IEA, 2024); [Mineral Commodity Summaries](#) (U.S. Geological Survey, 2022); [Benchmark Mineral Intelligence](#); [BloombergNEF](#); [S&P Global](#).

Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Khande-Jae Fisher, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Value-adding policies increased Indonesia's global processed Ni share by 29% from 2014 to 2022, increasing trade revenue ~7x

Traded quantity and traded value, 2010-2022, million tons/US\$B



### Observations





- In addition to the export ban in 2014, Indonesia introduced a local content clause for firms investing in domestic smelters.
- In 2017, the export ban was **relaxed due to falling Ni revenues**; instead, miners were required to allocate at least **30%** of smelter capacity to processing and the remainder was allowed for exporting.
- Value addition in Indonesia increased from **\$1.1 billion in 2015 to \$20.8 billion in 2021**.
- Indonesia's strategy has significantly expanded hydrometallurgy and pyrometallurgy smelting capacity, leading to an increase in stainless steel exports (**\$4 billion in 2022**).

Sources: [Prohibition of the export of nickel](#) (IEA, 2024); [Structural transformation through domestic value addition in commodity developing countries](#) (UN, 2024); [Harnessing the Potential of Critical minerals for sustainable development](#) (UN, 2025); [Critical minerals boom: Global energy shift brings opportunities and risk](#) (UNCTAD, 2024); [New mining rules in Indonesia relax ban on mineral exports](#) (SME, 2017); [Using trade policy to drive value addition: Lessons from Indonesia's ban on nickel exports](#) (UNCTAD, 2017).

Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# U.S.-Ukraine critical mineral deal strengthens future partnerships and supports U.S. strategy to reduce reliance on China

### Deal breakdown: U.S. vs. Ukraine

Contribution	Military 	Half public royalties 
<ul style="list-style-type: none"> <li><b>Military assistance</b> (weapons, technology, training)</li> </ul>	<ul style="list-style-type: none"> <li><b>50%</b> of public royalties, license fees, and similar payments from natural resource projects in Ukraine</li> </ul>	
Benefits	Prioritization 	Asset ownership 
<ul style="list-style-type: none"> <li>The U.S. International Development Finance Corp. is prioritized in offtake agreements plus has <b>right of first refusal.</b></li> </ul>	<ul style="list-style-type: none"> <li>Agreement pertains only to net new assets, with <b>100% ownership being maintained for assets currently generating revenue.</b></li> </ul>	

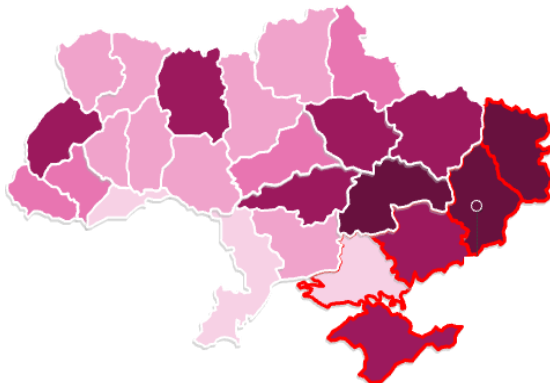
### Observations

- The **U.S.-Ukraine Reconstruction Investment Fund** (50/50 co-managed by the U.S. and Ukraine) was designed to funnel investment into Ukraine's postwar rebuilding for priority sectors like mining, energy, and infrastructure.
- Investments, payments, and incomes associated with the deal will **benefit from tariff waivers and tax exemptions** for both countries if transparency is upheld.
- Russian offensive has created a high-risk environment for deal security.

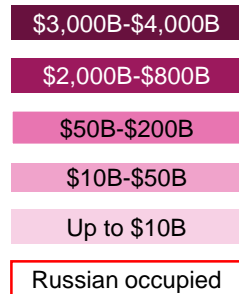
Ukrainian mineral deposits



Ukrainian mineral deposits \$ reserve value



Estimated reserve value



Estimated recoverable value of critical mineral deposits in Ukraine:  
**\$350B**  
 Higher value deposits located in Eastern Ukraine are at risk of loss due to Russian military offensive.

*Russia Seizes Key Lithium Field in Challenge to U.S.-Ukraine Mineral Deal*  
 June 2025 The New York Times

Sources: [How the US-Ukraine Critical Minerals Deal Will Shape Future Partnerships](#) (Carnegie Endowment for International Peace, 2025); [What we know about the US-Ukraine Critical Minerals Deal](#) (BBC, 2025); [Russia Seizes Key Lithium Field in Challenge to U.S.-Ukraine Minerals Deal](#) (The New York Times, 2025); [Mapping Ukraine's rare earth and critical minerals](#) (Aljazeera, 2025); [What minerals does Ukraine have and what are they for?](#) (BBC, 2025).

Credit: Zacharia Thurston, Brenda Rain, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Trump administration sees deep sea mining as an alternative to China’s market dominance, despite environmental concerns

## Deep sea mining has many unknowns

### Environmental impacts

- Deep sea ecosystems under-researched, risk of irreversible damage
- Downstream consequences for fragile ecosystems
- Uncertain environmental trade-offs vs. terrestrial mining (deforestation, local water pollution)

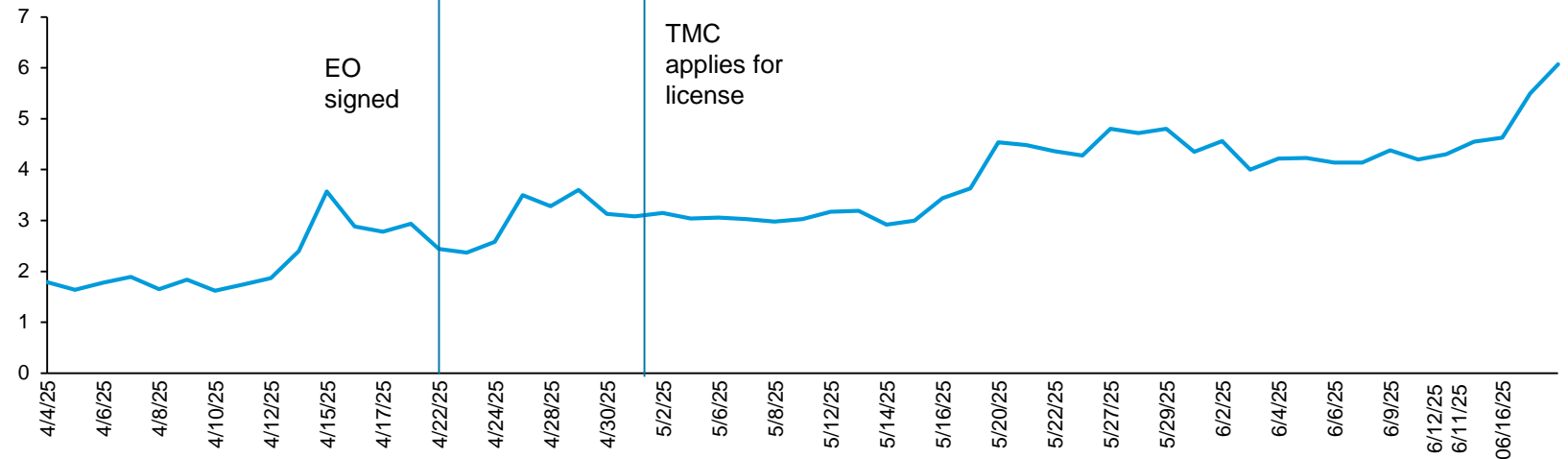
### Cost

- Uncertain economic viability compared with terrestrial sources, e.g., Indonesian nickel
- High OpEx due to the extreme depth and technological challenges of deep sea environments
- Tech unproven and costly

### Geopolitics

- U.S. securing supply chains for critical minerals
- U.S. unilateralism undermines the global governance of the ISA; China supportive of ISA’s multilateralism
- Increased risk of resource conflict in international waters

The Metals Company share price, US\$



## Trump’s executive order opens the backdoor to deep sea mining

On April 24, 2025, the Trump administration issued an Executive Order (EO) to **speed up permitting for deep sea mining operations**. Following the EO, **The Metals Company (TMC) applied for a U.S. license to extract minerals from the Clarion-Clipperton Zone (CCZ)**, a region of the Pacific stretching from Hawaii to Mexico.

The CCZ and the rest of the ocean floor in international waters falls under the jurisdiction of the International Seabed Authority (ISA), a body with 170 members including the EU but excluding the U.S. The ISA’s mandate regulates mineral-related activities in the “Area” (the seabed and ocean floor beyond national jurisdiction, which is ~50% of the earth’s seabed); it has granted over 30 exploration contracts but no exploitation contracts. TMC has partnerships with Tonga and Nauru to work through the ISA, but the EO obviates the need to work through the organization to exploit deep seabed. TMC could start exploitation as early as 2026.

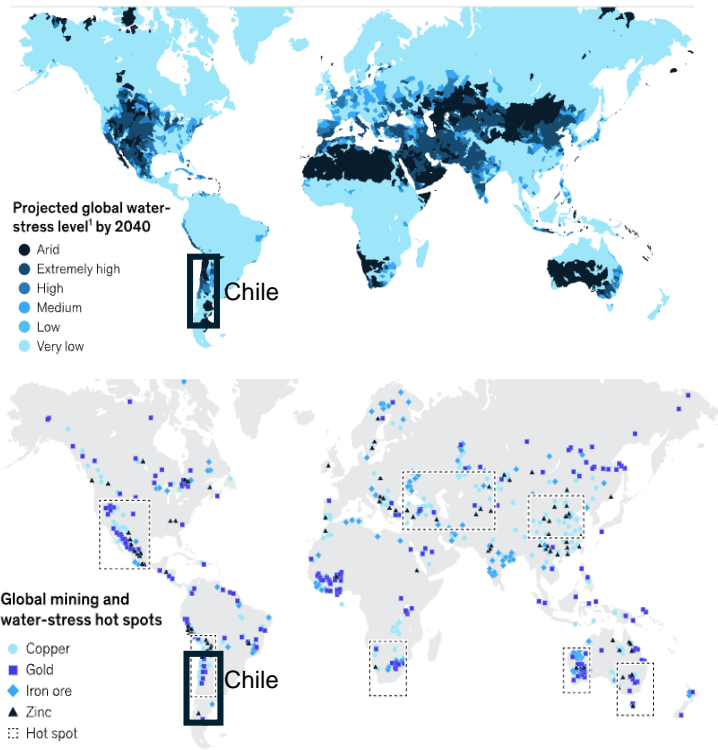
# Environmental & Social Impact



# Water stress in key mining regions poses operational and reputational risks for companies sourcing critical minerals

## Projected water stress and mining sites

By 2040, key mining regions could be increasingly vulnerable to water stress.



Map Credit: [McKinsey & Co.](#)

## Case Study: Chile 🇨🇱

*Innovations and investments in desalination and water technologies have reduced climate risk amid worsening drought, but sustaining gains will require urgent action as megadrought impacts intensify.*

2019 <u>Los Bronces Copper Mine</u>	2025 <u>Escondida Copper Mine</u>
2019 marked <b>one of the driest years on record</b>	Chile remains in <b>megadrought (15 years)</b>
Mine closed after significant production loss, leading Anglo to sign a deal with <b>Codelco's Andina division</b> to share water	Profound effects on Chile's water resources, agriculture, and ecosystems, <b>forcing mining operations to stop</b>
↓ <b>28%</b> Quarterly loss in copper production	↓ <b>\$47M</b> Fine imposed on BHP for depleting freshwater resources
↓ <b>44%</b> Decline in processing capacity	↑ <b>\$4B</b> Investment in desalination and water recycling infrastructure
↓ <b>9%</b> Annual production	↑ <b>16%</b> Production increase

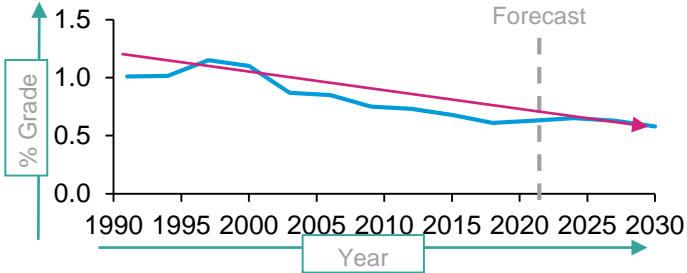
## Observations

- **Climate change is intensifying the physical risks** of heat, drought, floods, and extreme rainfall, **threatening mining operations and local communities.**
- Chile, the No. 1 global exporter of copper, with one-third of all supply, is in a megadrought.
  - Nearly **half of global copper, gold, iron ore, and zinc** production occurs in **high water-stress regions**
- Flooding, heat, and sea-level rise **jeopardize safety, infrastructure, and productivity**, while worsening drought restricts freshwater access.
- Even as companies like BHP invest in resilience, escalating climate pressures pose **growing operational challenges.**

Sources: [Climate risk and decarbonization: What every mining CEO needs to know](#) (McKinsey, 2020); [Worst drought in years pushes Anglo to sign water deal with Codelco](#) (Mining.com, 2020); [Mining companies are pumping sea water into the driest places on Earth. But has the damage been done?](#) (The Guardian, 2025).  
 Credit: Zacharia Thurston, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

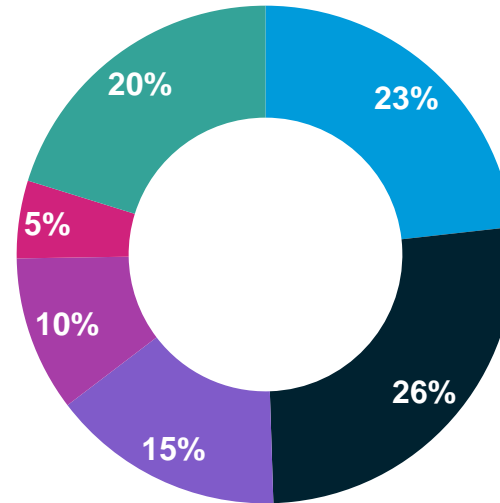
# Aging mines and decreasing ore grade quality means exponentially more energy is required for optimal mineral production

Mined head grade, % copper



The percent of recoverable copper per unit of ore is declining

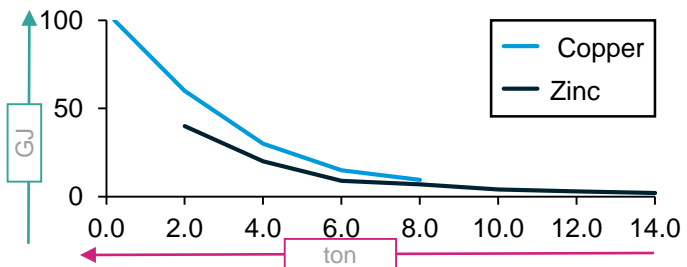
Age of copper mines operating in 2023



Observations

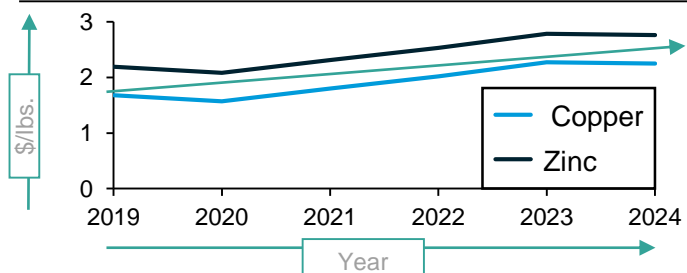
- As mines age, ore grades typically decline, leading to lower recovery rates and **the need to use significantly more energy to extract and refine each unit of metal.**
- This not only increases operating costs but also heightens the environmental footprint of production.
- The same trend is evident across other critical minerals, such as zinc, nickel, and rare earth elements,** posing serious implications for supply chain stability, national security, and long-term resource resilience — especially as demand accelerates in the clean energy and technology sectors.

Energy consumption, GJ/ton



Exponentially more energy is required to extract copper, zinc, and other minerals as ore grades decline and recovery rates fall

Copper & zinc unit costs, \$/lbs.



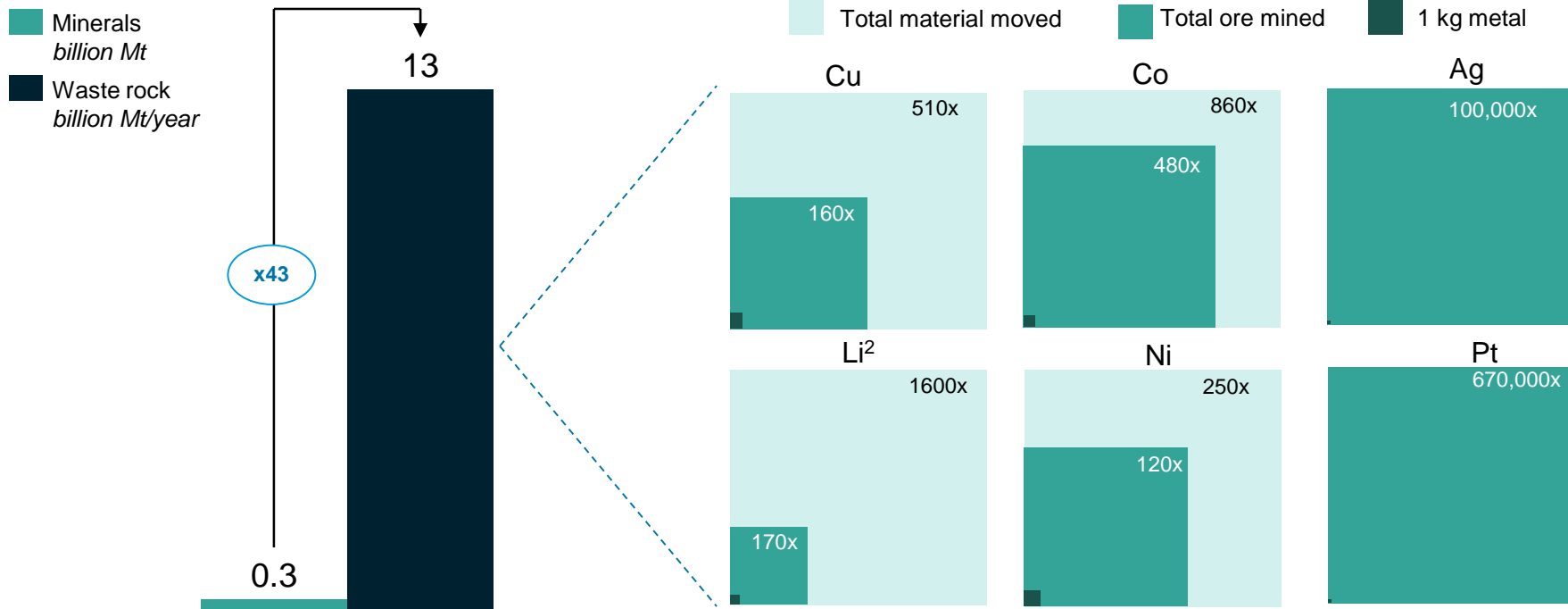
Declining ore grades as well as higher input costs are pushing up production costs

Sources: [Decreasing ore grades in global metallic mining: A theoretical issue or a global reality?](#) (MDPI, 2016); [How copper will shape our future](#) (BHP, 2023); [Base metals miners continue to fight against inflationary pressures](#) (Fastmarkets, 2024).  
 Credit: Zacharia Thurston, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Mining critical minerals removes much more material than when extracted as metals; regulation of environmental impacts required

13B mt of waste rock is generated per year from mining metals for energy transition<sup>2</sup>

Material moved per unit of metal



## Observations

- Clean up at large mine sites may cost up to billions of dollars over long remediation timelines; reprocessing tailings can offset site remediation costs; tailings often containing millions of dollars in recoverable materials.
  - Co, Li, and REEs are commonly found in tailings
- The EU’s Mining Waste Directive requires operators to have effective waste management. The U.S. has shown interest in recovering minerals from tailings.
- Mitigating material impacts requires effective governance and best practices: land use planning and zoning, strict impact assessments, land rehabilitation, and consistent reporting for transparency.

1) Based on ETC 100% decarbonization by 2050 scenario. 0.3B estimate is a maximum one-off scale-up that will decrease over time with recycling and circular economy. Total material moved refers to total rock that needs to be shifted to retrieve ore, including waste rock, overburden, and other material moved during mining process. Ag is typically mined as a byproduct for other metals; quantification of environmental impacts is limited, as waste is distributed with other metals. 2) Hard rock mining for lithium.

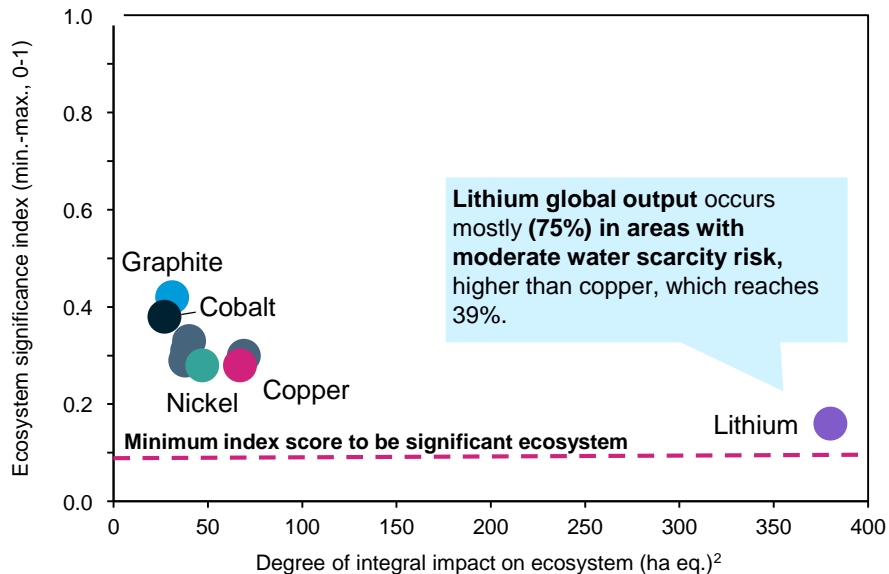
Sources: [Material and Resource Requirements for the Energy Transition](#) (ETC, 2023); [Geopolitics of the Energy Transition](#) (IRENA, 2023); [EU directive on the management of waste](#) (IEA, 2025); [Department of the Interior launches effort to unlock critical minerals from mine waste](#) (U.S. Department of the Interior, 2025); [Reuse of Solid Mining Waste](#) (ITRC, 2024).

Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Mining is vulnerable to environmental and social impacts that can overshadow clean energy's promise

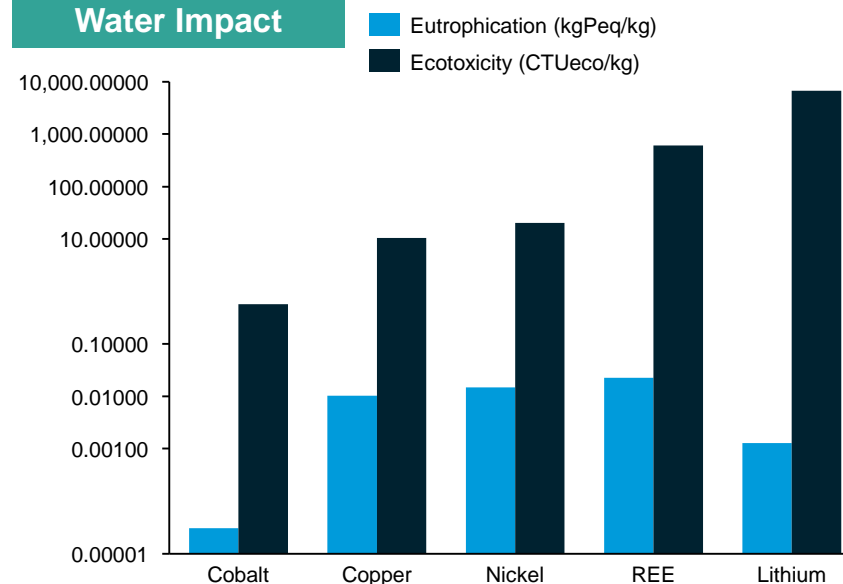
71% of transition mines impact ecosystems<sup>1</sup>;  
lithium and graphite have the largest footprint

## Land Impact



Tailings and acid create lasting damage on  
water systems; lithium and REEs lead impact

## Water Impact



## Social

- 10-20% of global cobalt production comes from artisanal small-scale mines, associated with poor working conditions and child labor
- Copper is also associated with the release of toxic chemicals (mercury, sulfuric acid, lead, PCBs), causing major harm to local ecosystems and communities

## Observations

- Compliance related to land, water, and social impacts are critical to mining companies maintaining a **license to operate**. Failure to comply implies legal, capital-raising, and reputational risks.
- Such challenges are addressed through **Environmental and Social Impact Assessments (ESIAs)**, which are **mandatory** for almost all **mining companies**. ESIAs address mitigation and eventual compensation events, **adaptive measures, and closure plans**.
- Beyond that, companies follow **country-specific initiatives related to water and waste management**, such as the Directive on the Management of Waste from Extractive Industries in the EU.

1) Significant ecosystems are those relevant areas for preserving biodiversity and nature and that contribute to people's lives through ecosystem services, locally or globally. 2) Hectare equivalent.  
Sources: [Metals for Clean Energy: Pathways to solving Europe's raw materials challenge](#) (KU Leuven, 2022); [Natural and synthetic graphite production emissions worldwide as of 2021](#) (Statista, 2025); [How copper mines pollute](#) (Environment America, 2025); [Rocks and hard places: The ecosystem risks of mining for energy transition minerals](#) (S&P, 2024).  
Credit: Brenda Rain, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# System-based water management and reuse/reprocessing tailings innovations lead efforts to reduce water and waste impact

## Water consumption

### Direct lithium extraction (DLE)

- Selective extraction of lithium through adsorbents, ion exchange, solvent extraction membrane separation, or electrochemistry; **currently experimental**
- Albemarle piloted a DLE plant in Mongolia in 2024
- YLB is building a semi-industrial DLE plant to **produce 14,000 mt of lithium carbonate per year**



### Dry processing techniques

- Techniques include air classification as well as electrostatic, magnetic, and gravity separation
- DryFlow's stacked magnetic technique is **effective in moisture levels >10%**



### Real monitoring & water recycling

- Closed-loop water circuits and real-time monitoring systems
- Freeport's advanced bioreactor **reduced freshwater requirements by 65%** and improved discharge quality
- ABB's AI-powered copilot displays **30% faster troubleshooting times** vs. traditional methods



## Waste reduction

### Tailings for CO<sub>2</sub> capture

- Reduces tailings production and emissions by **repurposing tailings for direct capture**. Tailings can then be stored underground or used to produce carbon-negative concrete for infrastructure projects
- Newmont's partnership with NREL to research tailings for capture received **\$4.38M** in research funding from DOE



### Tailings reprocessing

- Implementing new metallurgic processes to recover minerals from existing tailings
- Antofagasta uses chloride salts and sulfuric acid for leaching copper with a **recovery rate of 70%**
- Cerro de Pasco offers **mineral extraction from tailings at \$1 to \$2 per ton** (~2-15x cheaper than open-pit and ~30-200x than underground mining)



Sources: [Climate risk and decarbonization](#) (McKinsey, 2020); [The journey of the electric submersible dewatering pump](#) (Atlas Copco, 2023); [Mining & Minerals](#) (Sigma Thermal, 2025); [Energy Technology Perspectives 2023](#) (IEA, 2023); [11 lithium stocks betting on direct lithium extraction](#) (Investing News Network, 2024); [Lithium mining](#) (McKinsey, 2022); [Innovative water management strategies transforming the mining industry](#) (Discovery Alert, 2025); [Research the Use of Mine Tailings in Conducting Direct Air Capture of CO<sub>2</sub>](#) (Newmont, 2023); [Cuprochlor-T](#) (Antofagasta Minerals, Cuprochlor-T 2023); [Production & Extraction in Magnolia](#) (Albemarle, 2025); [YLB and the Russian company Uranium One Group](#) (Bicentennial of Bolivia, 2023); [Seven Ways ICMM members are exploring innovative technologies](#) (ICMM, 2024); [ABB launches AI-powered GMD Copilot](#) (Discovery Alert, 2025); [Extracting Critical Minerals from Historic Tailings](#) (Crux Investor, 2025).

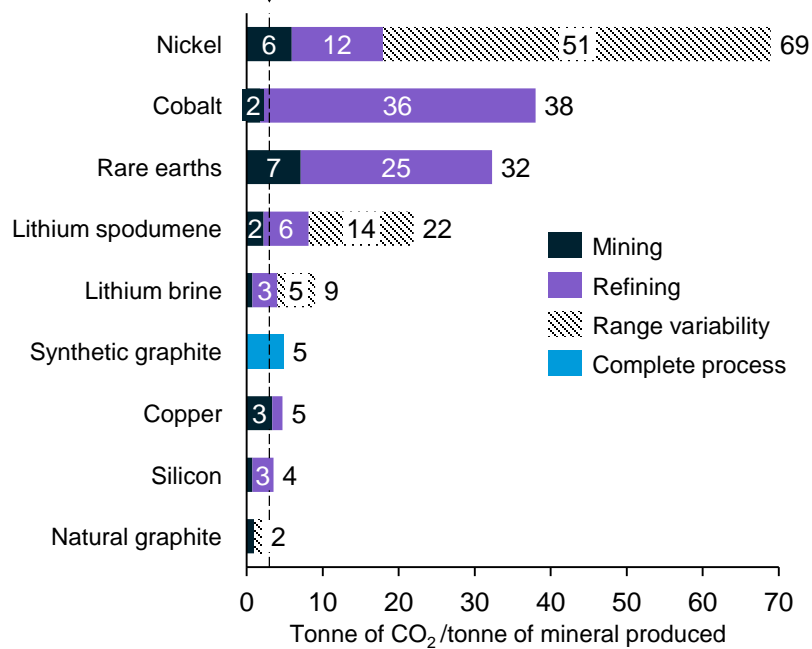
Credit: Brenda Rain, Khande-Jaé Fisher, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# The impact of transitioning to a clean economy remains net positive, despite emissions from carbon-intensive minerals

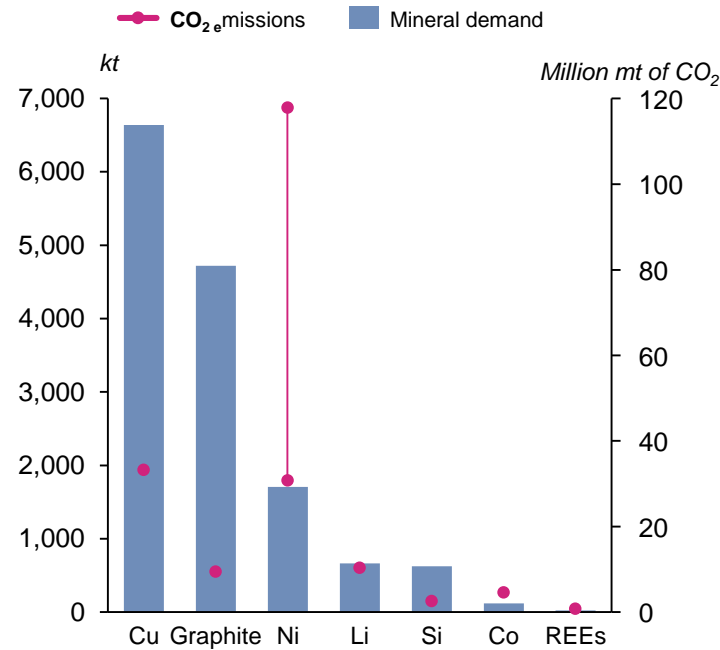
The high carbon intensity of critical mineral supply chains remains a key challenge for a clean energy future, as demand rises; with nickel being the toughest obstacle

~135 GtCO<sub>2</sub> can be avoided by replacing process coal with renewable power

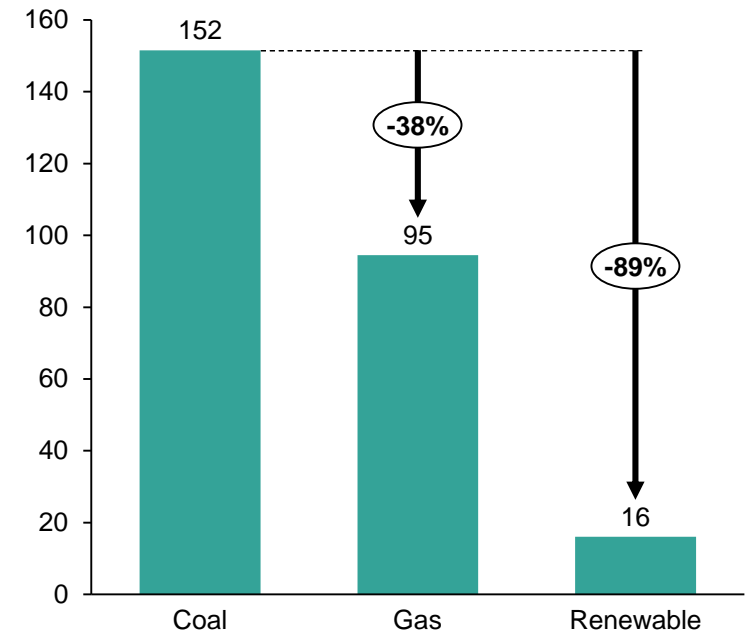
Carbon intensity from mining and refining, CO<sub>2</sub> tonnes/tonne of crude oil 2.9 – 3.4



Additional mineral requirements and emissions under Net Zero Scenario by 2050



Cumulative GWP under 2DS<sup>1</sup> Scenario by 2050 through C-t-G methodology, GtCO<sub>2</sub>e



1) 2DS is an IEA's scenario that considers at least a 50% chance of limiting the average global temperature to 2°C by 2100.

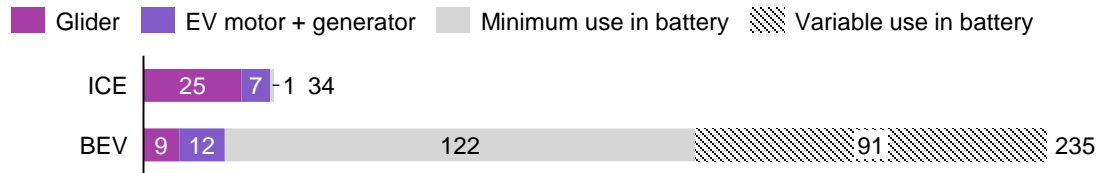
Sources: [Metals for Clean Energy: Pathways to solving Europe's raw materials challenge](#) (KU Leuven, 2022); [Natural and synthetic graphite production emissions worldwide as of 2021](#) (Statista, 2025); [How copper mines pollute](#) (Environment America, 2025); [Rocks and hard places: The ecosystem risks of mining for energy transition minerals](#) (S&P, 2024); [Sustainable recovery](#) (IEA, 2020); [Minerals for climate action](#) (World Bank Group, 2020); [Material and resource requirements for the energy transition](#) (Energy Transitions Commission, 2023); [An updated LCA of utility scale solar PV systems installed in the United States](#) (NREL, 2024).

Credit: Brenda Rain, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

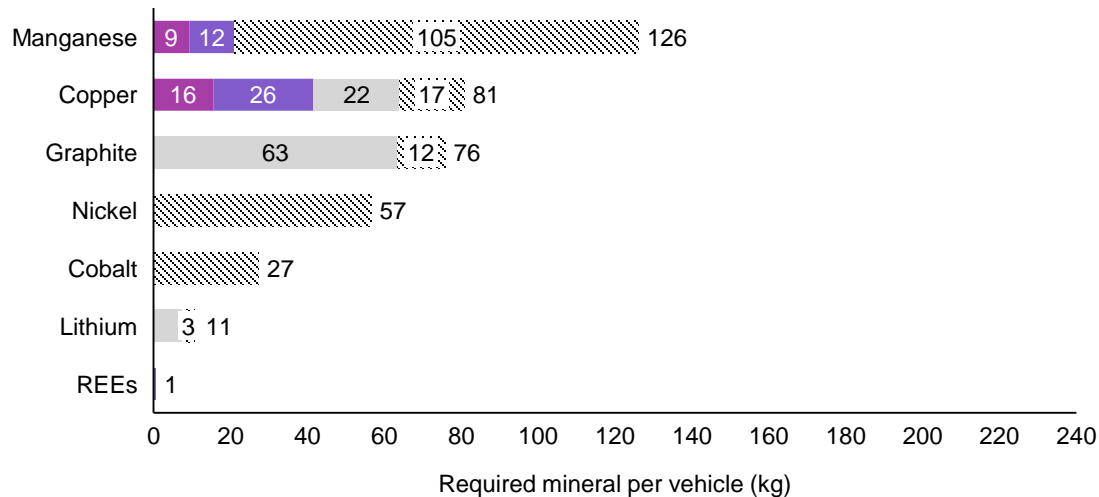
# Emissions reductions achieved by EVs, enabled by critical minerals, far exceed emissions from their mining and processing

Passenger EVs require 6x more minerals than ICEs, raising upstream emissions from mining and refining

Critical mineral used in EV<sup>1</sup> compared to ICE by car components, kg

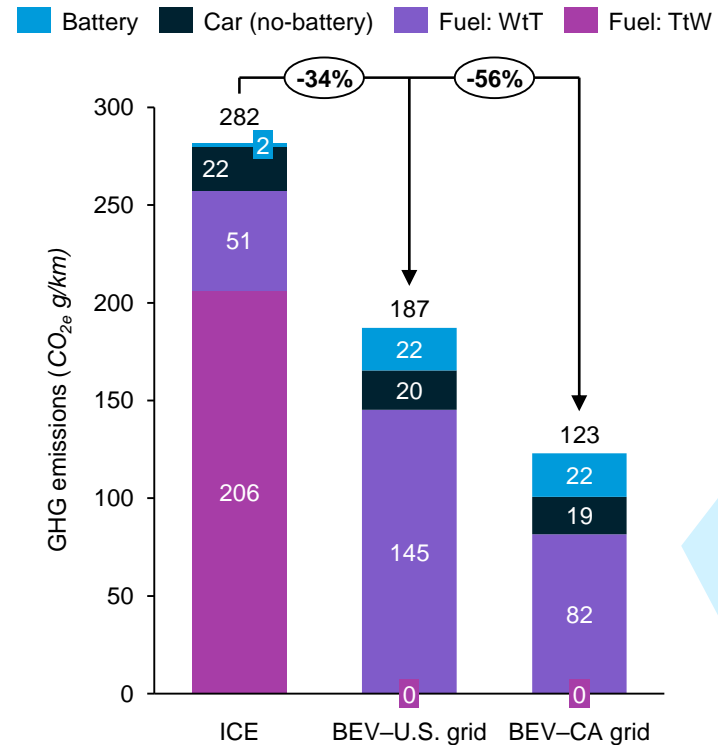


Critical mineral used in BEVs by type of mineral<sup>2</sup> and car components, kg



Increased emissions from EVs mineral needs (91% compared to ICEs) are far outweighed by reductions during vehicle use phase

LCA (WTW) GHG emissions comparison of ICE vs. BEV in the U.S.



The size of emission reduction is highly local for EVs. For example, while some evidence set CO<sub>2</sub>e emissions from BEVs at 50 g CO<sub>2</sub>e/km in Belgium, others set it at ~ 290 CO<sub>2</sub>e/km in Denmark.

The level of BEVs emissions depends on several factors, including the electricity generation mix that is available to power the grid and technical characteristics such as:

- Engine efficiency
- Vehicle size and weight
- Auxiliary systems (heating, air conditioning)

It also depends on behavioral and contextual patterns, such as driving style and weather.

1) Considers an EV motor NdFeB and a 75-kWh battery with graphite anodes. 2) Variability in each type of mineral is associated to the different models of batteries considered (NCA, NCA+, NMC (333, 532, 622, 811), LFP, LMO).

Sources: [Environmental effects of battery electric and ICE vehicles](#) (Congressional Research Service, 2020); [The role of critical minerals in clean energy transitions](#) (IEA, 2021).

Credit: Brenda Rain, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

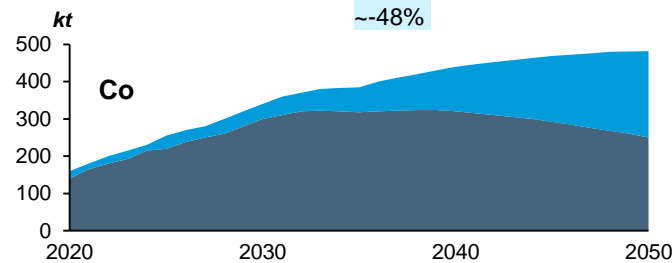
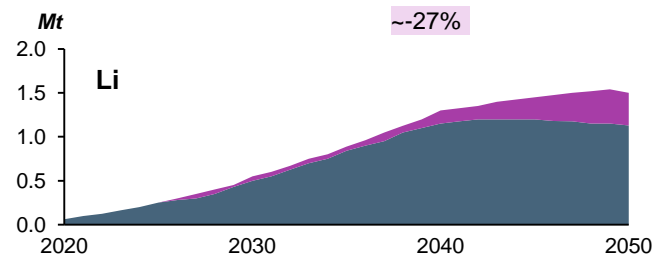
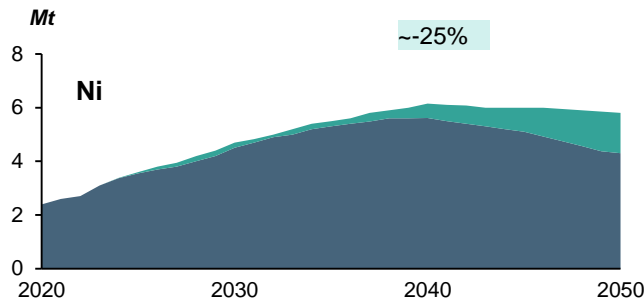
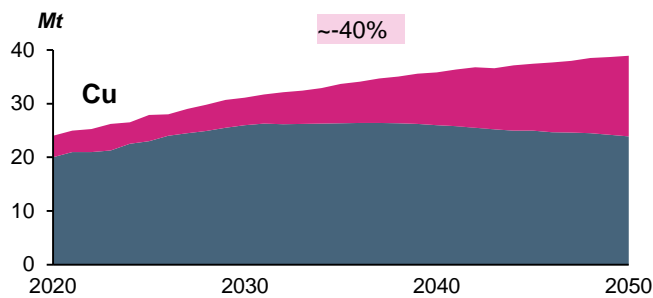


**Decarbonization Solutions**

# Recycling emerges as a key solution; rates are set to significantly increase for Co, Li, Ni, and Cu and alleviate primary demand

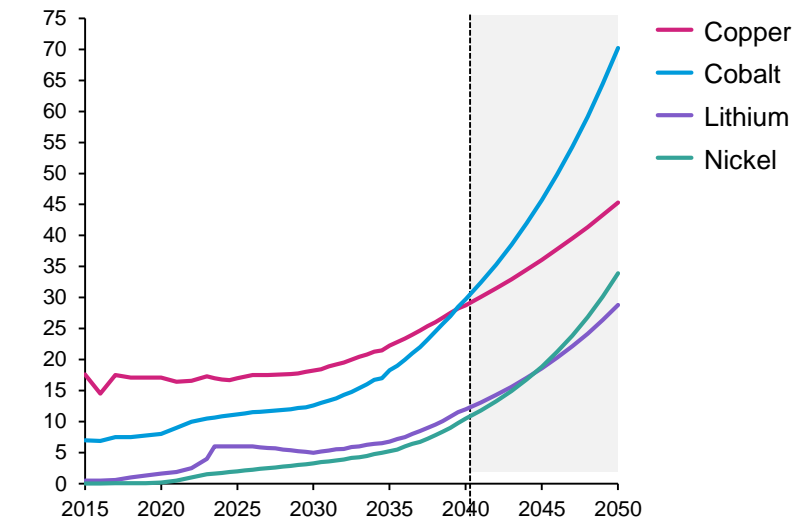
As share of recycled mineral input increases, demand for mined material is projected to decrease by 40% for Cu, 25% for Ni, 27% for Li and 48% for Co

Percentage market share of recycling for specific CRMS, %



Recycled input rates are expected to grow +25%

Historical and projected recycled input rates for critical metals in Net Zero Scenarios, 2024, %



## Observations

- Recycled metals produce **80% less emissions** than mined metals.
- Less than 1% of battery metals are currently from recycled inputs, but **recycling is projected to lower total new mining demand for critical metals by 25-40%** by 2050.
- If all announced projects come online, global recycling capacity could rise to **6x more than available feedstock by 2030**.
- Recycling is projected to **reduce mining investment needs by 30%** by 2040.

1) 2040-2050 recycled input rates extrapolated using CAGR from 2030-2040, assuming constant annual growth.

Sources: [Recycling of Critical Minerals](#) (IEA, 2024); [Global Critical Minerals Outlook](#) (IEA, 2025); [Circularity of critical minerals in the energy transition](#) (World Economic Forum, 2024).

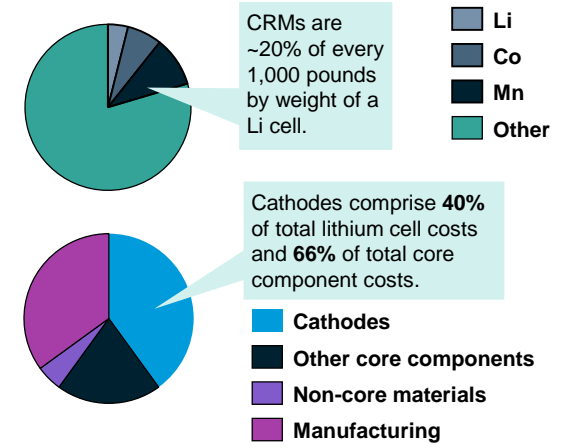
Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Circular models are essential to help fragmented supply chains, as poor design for recovery limits recycling scalability and profitability

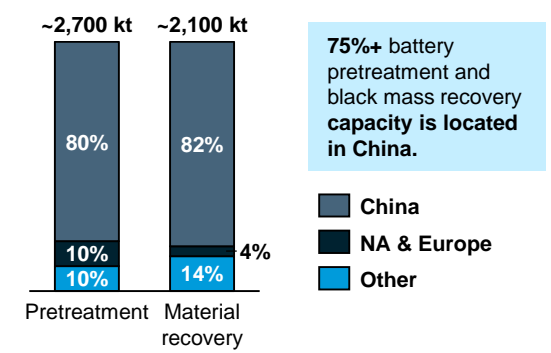
## Barriers to Critical Mineral Recovery

<b>Heterogenous waste streams</b>	<ul style="list-style-type: none"> <li>Diverse chemistries, hazardous materials, and inconsistent product quality in black mass limit process optimization for recyclers</li> <li>Compositional and price variability of shredded batteries within black mass makes value unpredictable (e.g., LFPs are less profitable), leading to discounted payables, lower margins, and revenue uncertainty</li> </ul>
<b>High dispersion, low concentration of CRMs</b>	<ul style="list-style-type: none"> <li>CRMs exist as trace amounts in many products, increasing processing needs</li> <li>Extraction techniques vary in selectivity and cost; variability in waste streams reduce recovery performance</li> </ul>
<b>Fragmented supply chain and infrastructure</b>	<ul style="list-style-type: none"> <li>Recycling facilities and underdeveloped collection infrastructure require high CapEx</li> <li>Supply chains are geographically concentrated; nations export feedstocks for further processing</li> <li>Low waste feedstock and manufacturing scrap dominate the waste stream: EVs and storage are only one-third of recyclable feedstock</li> </ul>
<b>Lack of design for disassembly</b>	<ul style="list-style-type: none"> <li>Products are not designed for EOL recovery; disassembly is time consuming and expensive</li> <li>Battery designs are not standardized; products often do not disclose compositional profiles, making identification and recovery of critical minerals difficult</li> </ul>

Cathode costs vs. weight per cell

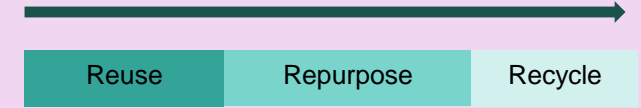


Pretreatment and material recovery distribution by country in 2023



### Circular economy principles may address recycling gaps and complexities

CRM circular economy (CE) ideal lifecycle



- CE principles prioritize **reuse (extended life) and repurposing (second-life applications) over recycling** to minimize waste and maximize value, keeping CRMs in use longer
- Replacing product-oriented with **service-oriented business models shifts lifecycle responsibility** to producers, promoting Extended Producer Responsibility and incentivizing recovery
- Strategies like track-and-trace programs, automation of disassembly, and optimized product transport and collection routes **promote streamlined recovery at EOL and more uniform waste streams**
- CE is projected to **reduce cumulative mineral demand by 18% by 2050**

Sources: [Recycling of Critical minerals](#) (IEA, 2024); [Globo EV Outlook](#) (IEA, 2025); [The battery cell component opportunity in Europe and North America](#) (McKinsey, 2024); [Critical Transitions Report](#) (UNEP, 2025); [Lithium-Ion Battery Recycling](#) (Deloitte, 2025); [Developing a Global Standard for EV Battery Tracking](#) (SAE, 2024); [Powering the Future](#) (World Economic Forum, 2025); [Advancing Sustainable Battery Recycling](#) (Systemiq, 2023).  
 Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Hydrometallurgy is projected to dominate recovery capacity as a mature, flexible, selective, and low-energy process

	Hydrometallurgy	Pyrometallurgy	Direct Recycling
<b>Description</b>	<b>Chemical dissolution</b> using aqueous materials to extract metals	Extraction of metals by <b>smelting at elevated temperatures</b> >1000 °C	<b>Reconditioning</b> of active materials <b>without breaking them down into elemental metals</b>
<b>Recovery rate</b>	Up to 99% <b>H</b>	<50% for Li; ~98% for Co, Cu, and Ni; *up to 97% for Li when combined with hydro <b>M</b>	Up to 98% in lab <b>H</b>
<b>Energy consumption<sup>1</sup> (MJ/kg LFP)</b>	30.6	18.4	3.5
<b>Advantages</b>	<ul style="list-style-type: none"> <li>Lower emission than pyro</li> <li>High recovery rates for most metals</li> </ul>	<ul style="list-style-type: none"> <li>Batteries require minimal pretreatment</li> <li>High Ni, Co, and Cu recovery rates</li> </ul>	<ul style="list-style-type: none"> <li>Lower emissions and energy than hydro/pyro</li> <li>High Li recovery rates</li> </ul>
<b>Disadvantages</b>	<ul style="list-style-type: none"> <li>Liquid waste; extensive water use</li> <li>Battery requires pretreatment – primary inputs are black mass</li> <li>Slow processing times</li> </ul>	<ul style="list-style-type: none"> <li>High hazardous gas and liquid waste emissions</li> <li>Battery requires additional processing (usually hydrometallurgy) for higher recovery rates</li> <li>Lower recovery rate than hydrometallurgy for Li</li> </ul>	<ul style="list-style-type: none"> <li>Requires customization based on cathode type</li> <li>Recovered material may display lower level of performance</li> <li>Only demonstrated in pilots; high operational and equipment costs</li> </ul>

**Hydrometallurgy will dominate** recovery processes by ~90% in 2030 due to **high yields, mature economics,** and **flexibility** with various chemistries.

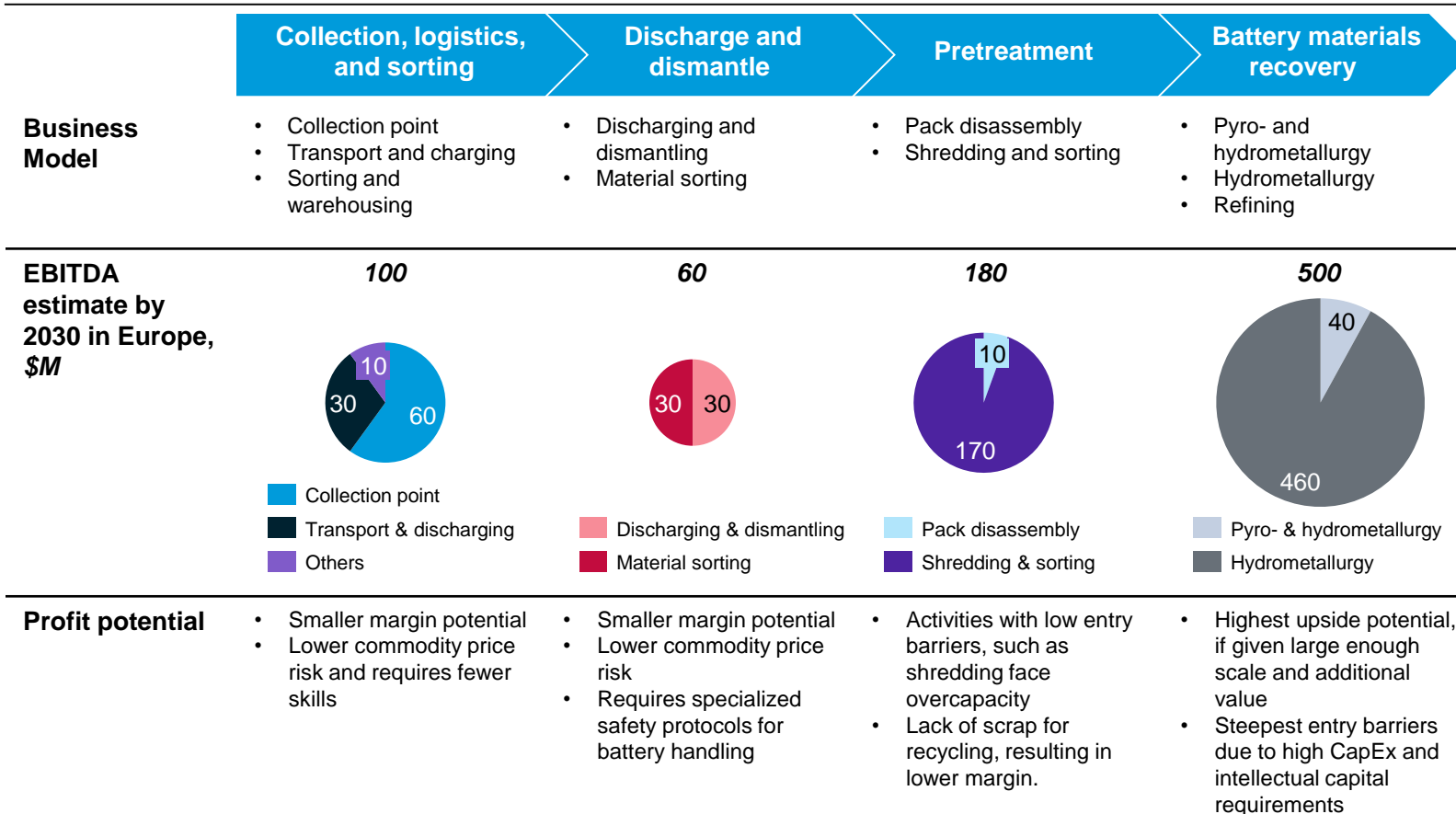
1) Energy based on lifecycle analysis; for pyrometallurgy, ~55% of energy consumption is due to smelting; for hydrometallurgy, 80%+ is due to upstream contributions.

Sources: [Recycling of Critical Minerals](#) (IEA, 2024); [Lithium-Ion Battery Recycling](#) (Deloitte, 2025); [High Volume Battery Recycling: Technical Review](#) (Batteries, 2025); [Environmental Impacts of Pyro- and Hydrometallurgical Recycling for Lithium-Ion Batteries](#) (Journal of Business Chemistry, 2025); [Direct recycling of Li-ion batteries from cell to pack level](#) (Carbon Energy, 2024); [Critical Review of Lithium Recovery Methods: Advancements, Challenges, and Future Directions](#) (Processes, 2024); [Efficient Direct Recycling of Lithium-Ion battery cathodes by targeted healing](#) (Joule, 2020); [Recycling and Reuse of Spent LIBs](#) (Molecules, 2024); [Comparison of different process for recycling lithium-ion batteries](#) (Duesenfeld, 2021).

Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Achieving profitability in battery recycling is challenging due to feedstock shortages and mining's competitive advantages

## Profit opportunities across the value chain



## Key challenges

### Feedstock shortages

- Due to extended battery life, recyclers supplement their supply with waste material from battery cell manufacturing. However, **scrap rates are expected to fall** as battery manufacturers improve production efficiency
- Having battery manufacturers as both key suppliers and primary customers, recycling companies are facing **massive margin pressure from both sides of the market**

### Lack of scale

- Current lack of scale** makes it **difficult for recyclers to compete with incumbent raw material producers**, given that the core recycling technologies are not fundamentally different from primary material processing

### Limited profit pool

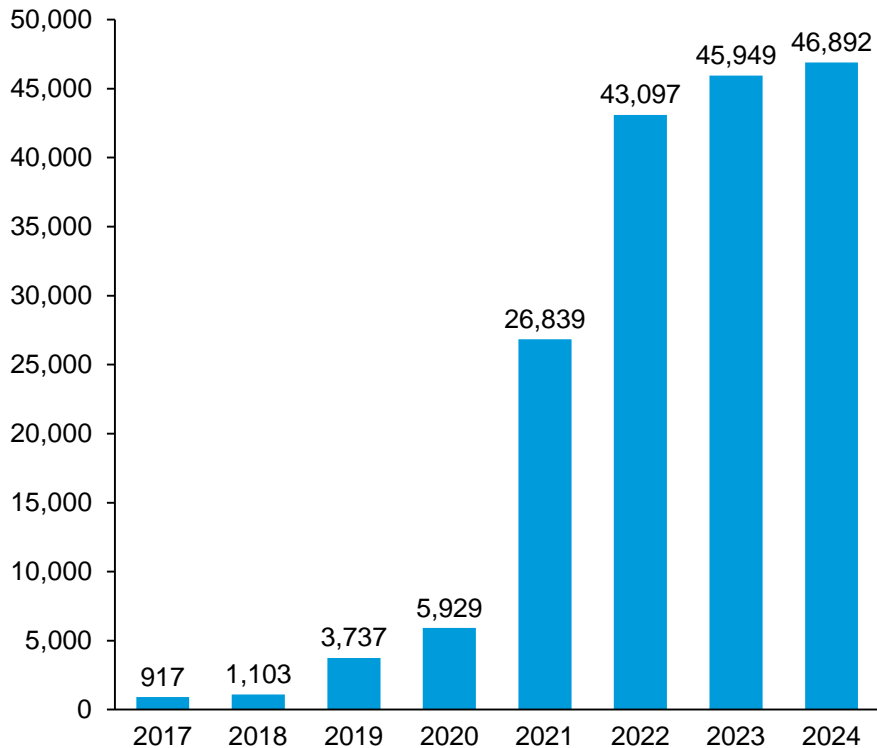
- Traditional recycling players are advised to compete for the **overall materials recovery** profit pool, not just the front end
  - Building a **cross-value-chain ecosystem through partnerships** may be an option
  - Investing in **technologies** that bring **better material recovery rates, product quality, and process efficiency** is essential to be chosen by OEMs

Sources: [Striking Gold with EV Battery Recycling](#) (BCG, 2023); [Battery recycling](#) (McKinsey, 2023); [World of battery recycling](#) (Catalyst podcast, 2024).  
 Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Policies that assign recycling responsibilities to OEMs strengthen the battery recycling supply chain

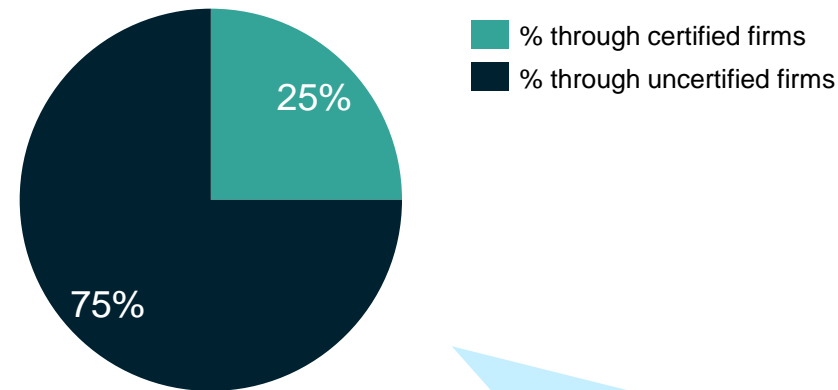
## The number of companies registered for battery recycling rose 5,000%+ since 2017

Number of yearly registrations of companies related to power battery recycling in China



## The majority of retired batteries are processed through uncertified companies

Share of retired batteries flow throughout certified companies, 2023, %



In China, **uncertified companies** are **cheaper, faster, and better networked** at the **sourcing of batteries**.

But they face a **challenge**: They pose **environmental and safety risks** and lack recycling, safety, and hazardous waste management licenses, **creating a paradox for the battery recycling industry: Bad drives out good.**

## Observations

- Since 2018, **China has enshrined end-of-life recycling responsibilities to original equipment manufacturers (OEMs)**.
- Although **156 companies have been certified as battery recyclers**, most batteries are recycled by uncertified and illegal small firms.
- Policy actions to address this concern include:
  - **Subsidies for compliant recyclers** to increase recycled volumes, and a **crackdown on unregulated recyclers**
  - **A battery leasing model** (e.g., NIO) where batteries are leased by OEMs to consumers, increasing the recycling network
  - **Battery traceability standards** to serialize all produced batteries for government third-party agencies to track (e.g., **EU Battery Passport policy** announced by the EU in 2023)

# NIO's battery swapping and BaaS model promotes extended battery lifespan and streamlines collection for easier recycling

NIO leases EV batteries to consumers, enabling easier reuse, repurposing, and recycling

## About



**Founded:**  
2014

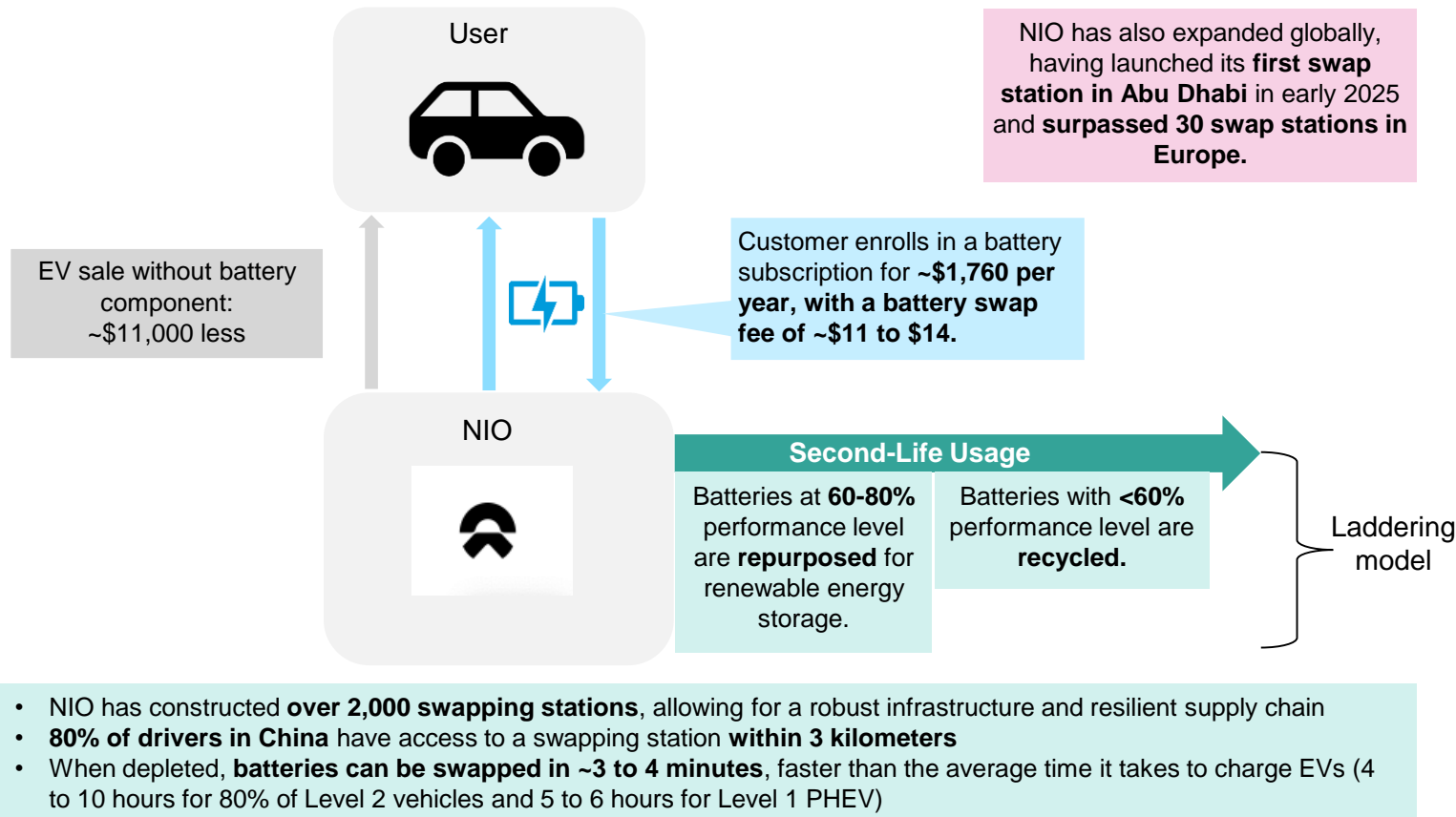
**Headquarters:**  
Shanghai, China

**~785,714 delivered**  
as of July 2025

**Offerings:**  
BaaS with battery subscription, charging

**2316 Power swap stations**

**3594 Power charger stations**



## Observations

- NIO has streamlined battery management while simultaneously developing infrastructure and supply chains for scalable deployment.
- Batteries are approximately one-third of total upfront costs of EVs; NIO's subscription model improves affordability for consumers.
- NIO's laddering model aligns with circular economy principles and assigns batteries to different use cases based on their state of health.
- NIO has achieved a >90% recovery rate for lithium.
- By 2021, NIO completed more than 2 million swaps and converted ~40% of its consumer base to battery swapping.

Sources: [EV Charging Redefined](#) (NIO, 2025); [What's new with NIO in 2025](#) (NIO, 2025); [NIO's BaaS Strategy](#) (SMU, 2022); [Charger Types and Speeds](#) (U.S. Department of Transportation, 2025); [NIO's Big play: How battery swapping stations can drive growth](#) (MarketBeat, 2024); [The Chinese Company that made battery swapping work](#) (INSEAD, 2024).  
Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Nth Cycle tackles critical mineral waste variability, recovery efficiency, and supply chain gaps in one integrated system

Nth Cycle’s electroextraction process reduces emissions and enhances recovery logistics

## About



Founded: 2017

Headquarters: Massachusetts

40+ employees

Patents 3

15+ years of R&D, with ~\$60 million raised in seed to Series B and non-dilutive funding

Oyster refining system for metal extraction



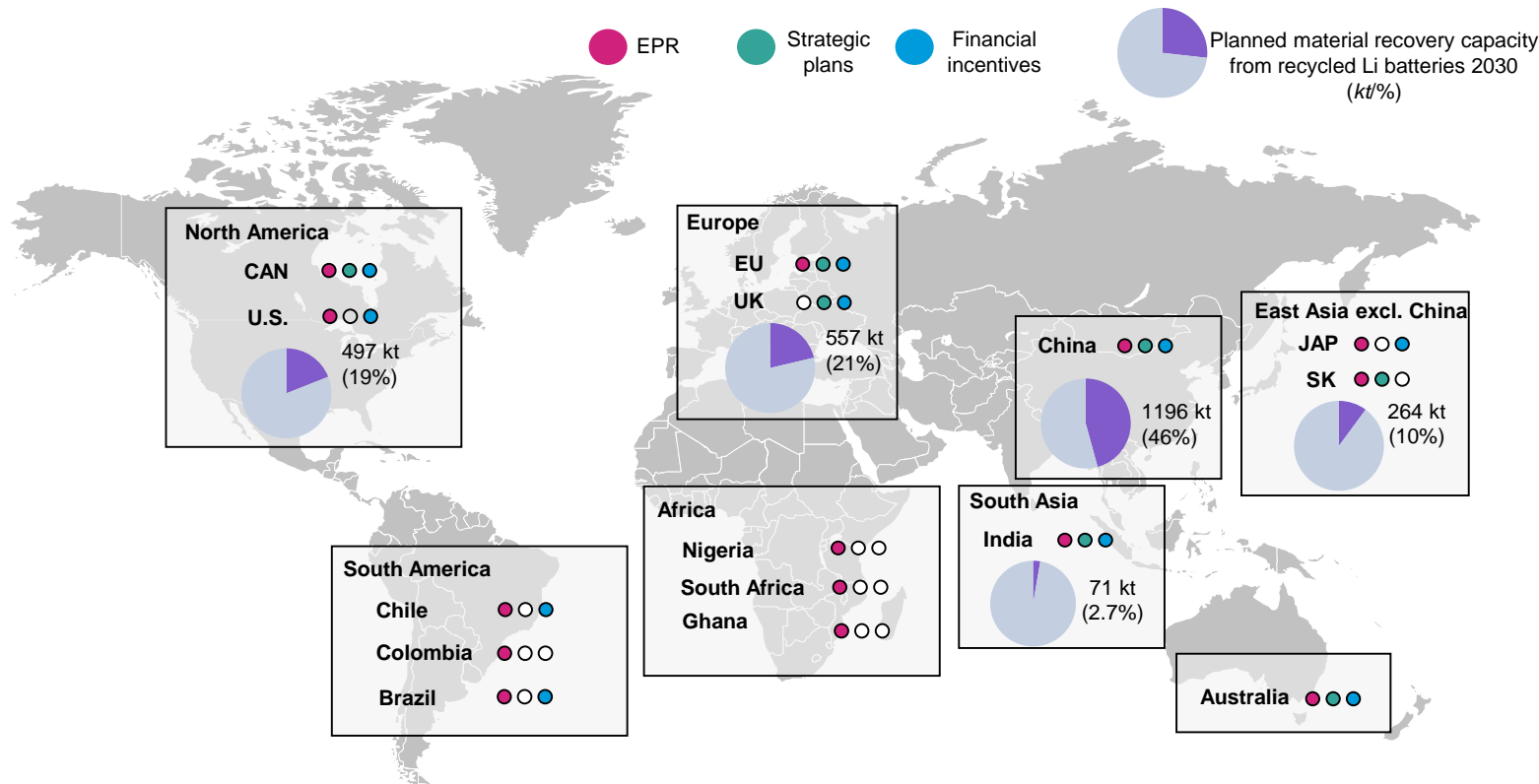
Technology	Supply Chain
<ul style="list-style-type: none"> <li>Nth Cycle’s <b>electroextraction</b> produces <b>44% less emissions</b> than current recycling methods</li> <li>Avoids environmentally harmful smelting and waste generation of traditional recovery methods</li> <li>Modular design allows multiple units to be installed in <b>parallel to scale production</b> or <b>in series to extract multiple metals</b> from the same feedstock</li> <li>Extracts <b>Li, Ni, Mn, and Co</b> (Cu, Dy, Pr in development)</li> </ul>	<ul style="list-style-type: none"> <li>System improves upon logistics issues within the CRM supply chain: modular, collocated, and <b>compatible with multiple industries, mines, recyclers, and metals</b></li> <li><b>Integrates</b> with consumers’ physical facilities and equipment; fully customizable</li> <li>Rapid deployment: <b>Six-month permitting time and 12-month installation time</b>, reducing the long and costly approval times with traditional refineries</li> </ul>

## Observations

- Oyster refining system, replaced fossil fuels with electricity, followed by precipitation and filtration for highly efficient recovery of metals.
- Tech compatible with diverse inputs, including renewable energy, EVs, scrap metal, black mass, and mined ore.
- First commercial installation launched in Ohio in 2024; processes black mass and Ni scrap.
- Received \$7.2 million from the IRA Advanced Energy Project 48C Tax Credit allocation in 2024.
- Company’s business model supports the development of domestic refining capacity and strengthens supply chain resilience.

# Most countries have implemented extended producer responsibility (EPR) measures for recycling for batteries

## Policies and incentives implemented in each region to date



### U.S.

- 25 states have passed legislation for electronics recycling
- Over **\$3B** in grant funding has been allocated to support demonstration projects and facilities for battery recycling
- **Section 45x** of the Inflation Reduction Act offers credits to manufacturers using recovered materials; set to **phase out in 2034** under **OBBBA**

### EU

- **Circular Economy Action Plan (2020)**: Introduces EPR for end-of-life management, mandates accessible product composition data, and sets guidelines to optimize waste streams and extend product lifespans
- **Critical Raw Minerals Act (2023)**: Sets minimum **recycled content targets for batteries by 2035** (20% Co, 10% Li, 12% Ni), aims for **15% of demand** to be met from recycled sources, and standardizes project classification

### China

- The Ministry of Industry and Information Technology **raised lithium recovery targets to 90%** (from 85%), and **98% for nickel, cobalt, & REEs**
- Under the **Plan for the Implementation of the Extended Producer Responsibility System**, battery producers must publish recovery data, adopt product coding, and implement full lifecycle tracking
- New EV recycling guidelines standardize recycling plants for electric vehicles with digital tools to trace and collect data

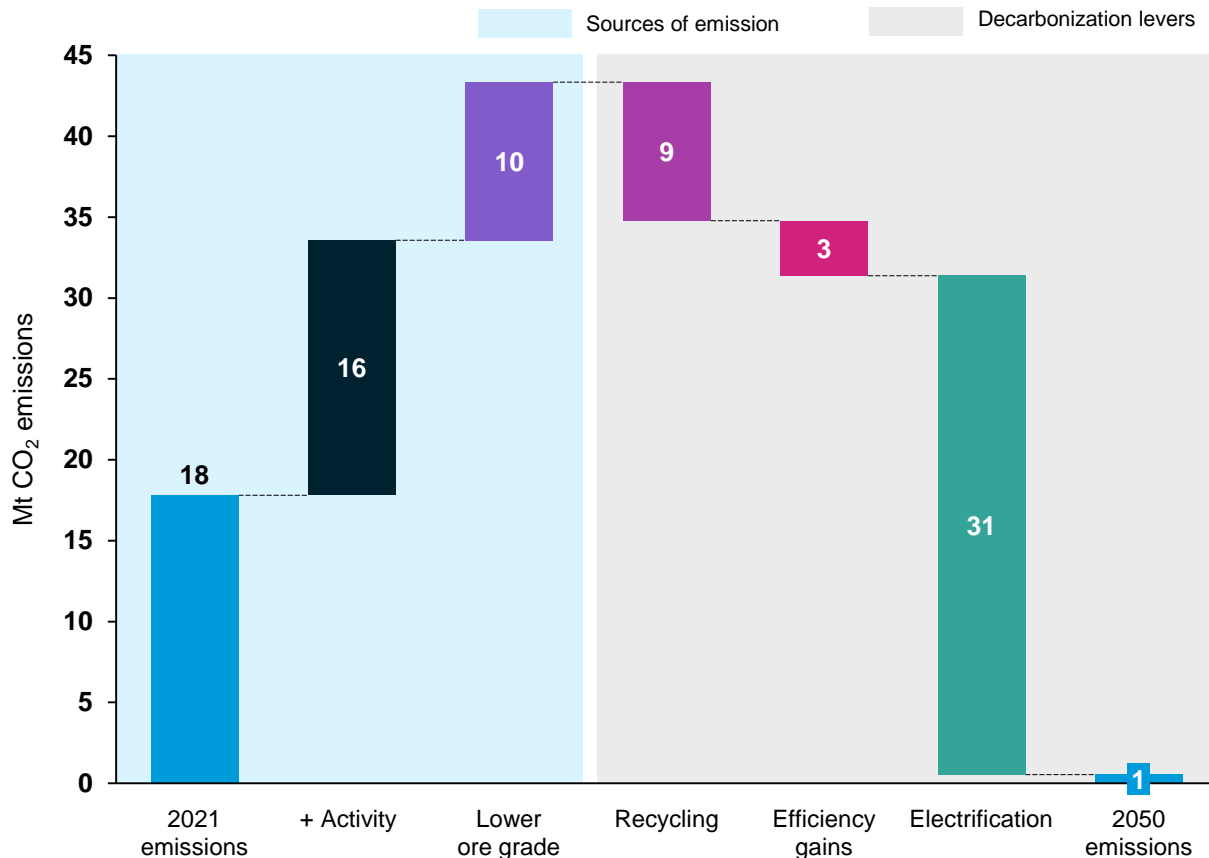
1) For federal systems, CRM recycling is typically managed at subnational level. 2) For the U.S., while some federal initiatives include CRM recycling, policies are typically integrated into broader supply chain strategies rather than issued as a dedicated strategic recycling plan. 3) EU member countries are highlighted as having all three measures due to comprehensive EU policy; however, not all member states have fully implemented them at the national level.

Sources: [Recycling of critical minerals](#) (IEA, 2024); [Extended producer responsibility system](#) (IEA, 2024); [Battery & critical mineral recycling](#) (DOE, 2024); [Battery manufacturing & recycling grants](#) (DOE, 2024); [EU critical raw materials act](#) (UNECE, 2024); [One big beautiful bill](#) (Fastmarkets, 2025); [Battery regulation](#) (EU, 2023); [China releases proposed standards for recycling](#) (Rho Motion, 2024); [State E-waste legislation in the U.S.](#) (ERI, 2025); [Treasury and IRS](#) (Mayer Brown, 2024); [Expected battery recycling](#) (IEA, 2024); [International outlook lithium battery recycling](#) (Circular Energy Storage, 2022).

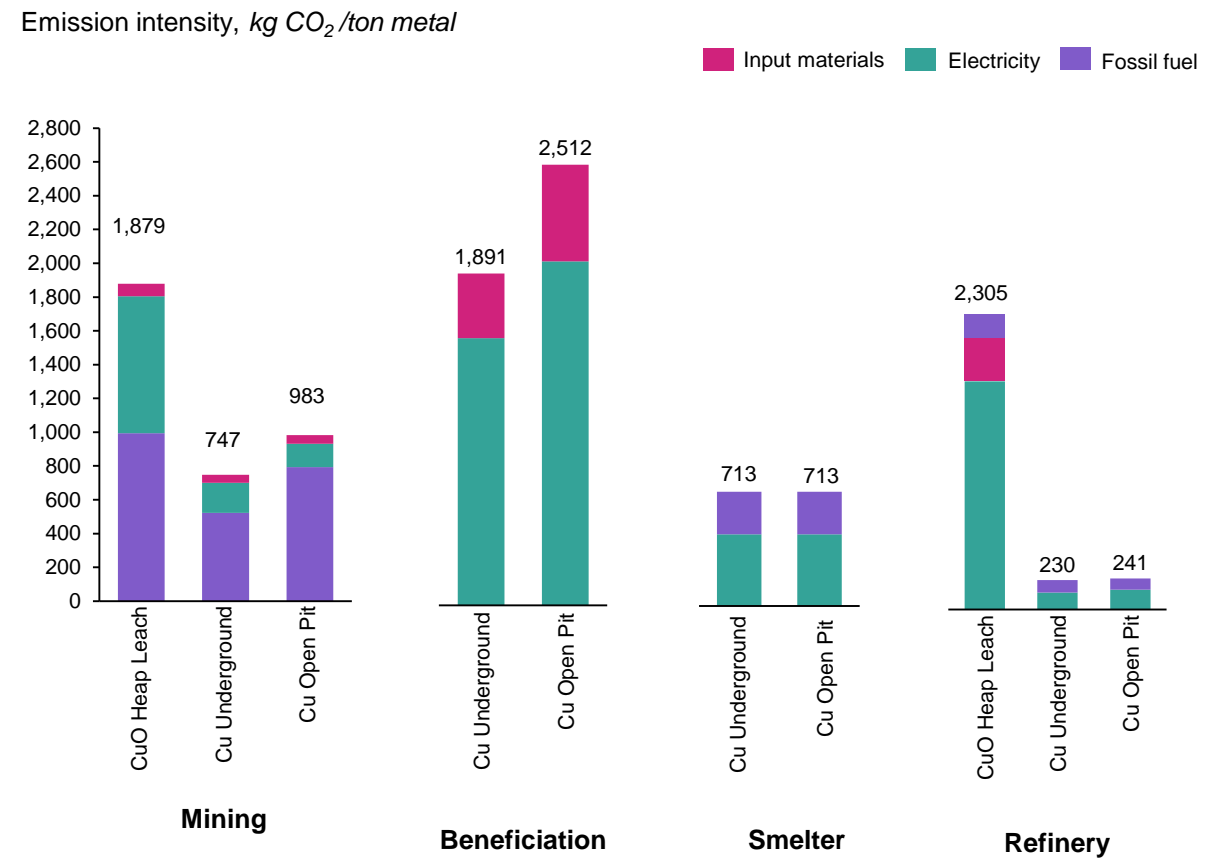
Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Electrification and renewable power can reduce mining and refining process emissions

## Mining: Electrification is the key to decarbonizing the critical minerals supply chain



## Refining: Though emission intensity varies by commodity and location, electricity is the main postmining emission source



Sources: [Climate risk and decarbonization: What every mining CEO needs to know](#) (McKinsey, 2020); [The journey of the electric submersible dewatering pump in mining applications](#) (Atlas Copco, 2023); [Mining & Minerals](#) (Sigma Thermal, 2025); [Energy Technology Perspectives 2023](#) (IEA, 2023); [11 lithium stocks betting on direct lithium extraction](#) (Investing News, 2024); [Lithium mining: How new production technologies could fuel the global EV revolution](#) (McKinsey, 2022); [Net zero road map copper and nickel](#) (IFC, 2023).







Credit: Brenda Rain, Hyae Ryung Kim, and Gernot Wagner. [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Most accessible ways to decarbonize include electrifying gas appliances, using low-carbon electricity sources, and electrifying trucks

	Electrify gas appliances	Favor low-carbon electricity sources	Electrify trucks
Technology readiness	● ● ●	● ● ●	● ● ○
Capital requirement	● ● ○	● ● ●	● ● ○
Emission reduction potential, %			
Note:	Emission reduction potential depends on emission intensity of the local grid's electricity mix.		
Leading companies			

Sources: [Climate risk and decarbonization: What every CEO mining needs to know](#) (McKnsy, 2020).  
 Credit: Brenda Rain, Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# Technological advances with proven impact are improving efficiency and adding value across the critical mineral pipeline

Company	Description	Series <sup>1</sup>	Founded + total raised	Investors	Activity
 KoBold Metals <sup>®</sup>	Mineral exploration company using AI and an “efficacy of information” approach to <b>reduce uncertainty and accelerate discovery</b> of critical materials for EVs and renewables. HQ: Berkeley, CA	C	Founded 2018 Raised \$941M	Bossa Invest, Climate First, Durable Capital Partners, Equinor, and Maple Capital (5/31 investors)	<ul style="list-style-type: none"> <li>Backed by Bill Gates and Jeff Bezos</li> <li>Valued at <b>\$2.96B</b></li> <li>Operational internationally and scaling</li> </ul>
 VERA I	Developer of an AI-powered platform that analyzes complex data to <b>detect hidden mineral deposits in underexplored terrain</b> , helping the industry uncover concealed resources. HQ: Boston, MA	B	Founded 2020 Raised \$39.6M	Insight Partners (New York), Orion Innovation, T. Rowe Price Group, Bloomberg Capital, and Chrysalix Venture Capital	<ul style="list-style-type: none"> <li>Capable of locating REE at 9.1% to as high as <b>20% purity</b></li> </ul>
 EARTH AI	Vertically integrated mineral exploration company that uses AI to <b>predict ore locations for metals</b> like copper, nickel, cobalt, and rare earths, boosting discovery rates while cutting risk and costs. HQ: San Mateo, CA	B	Founded 2017 Raised \$32.1M	Alpaca VC, Deep Acre, Intrepid Financial Partners, Overmatch (Austin), and Sparkwave Capital (5/35 investors)	<ul style="list-style-type: none"> <li>Successful operations — <b>discovered 117 ppm of indium</b>, typically found at 1 ppm</li> </ul>
 MP MATERIALS	Operates the Mountain Pass Mine, the only large-scale rare earth site in North America, and is developing a magnet manufacturing facility in Texas. Its operations span materials and magnetics. HQ: Las Vegas, NV	Public	Founded 2017	Pentagon, JPMorgan Chase, Goldman Sachs	<ul style="list-style-type: none"> <li><b>Building U.S. supply chain</b> for rare earth elements</li> <li>Building second magnet manufacturing facility in the U.S.</li> </ul>
 minesense	A platform that <b>boosts mine productivity and recovery</b> through real-time, sensor-based <b>sorting to detect low-grade ore and subtle mineral differences</b> , enabling more efficient sorting and resource planning. HQ: Vancouver, British Columbia	C	Founded 2008 Raised \$147M	Mining Innovation Commercialization Accelerator, Evok Innovations, JP Morgan Asset Management, North Sky Capital, and Aberdeen Group	<ul style="list-style-type: none"> <li><b>JPMorgan made \$42M investment in 2022</b></li> <li>Named Deloitte Technology Fast 50 winner.</li> </ul>
 the metals company	<b>Explores and processes polymetallic nodules from the Clarion Clipperton Zone</b> , rich in nickel, copper, cobalt, and manganese, which are critical metals for energy and manufacturing. It <b>focuses exclusively on deep sea</b> resource development and metallurgy. HQ: Vancouver, British Columbia	Public	Founded 2011	First Manhattan Co., Old West Investment Management, Baird Financial Group, UBS Group, and Korea Zinc	<ul style="list-style-type: none"> <li><b>U.S. backed subsidiary</b>, waiting for approval to begin mining per U.S. Executive Order; Korea Zinc recently invested <b>\$85 million</b></li> </ul>

1) Seed: \$50K-\$5M - idea-stage, developing product and team. Series A: \$5M-\$15M - product validated, building market fit. Series B: \$15M-\$50M - scaling users, revenue, and operations. Series C: \$50M-\$100M+ - expanding market reach or prepping exit.

Sources: Pitchbook (2025); [KoBold Metals raises \\$537 million in race for critical minerals](#) (Mining.com, 2025); [Rare, high-grade indium find validates Earth AI's exploration technology](#) (Global Mining Review, 2025); [VERAI exploration tech uncovers REE potential](#) (International Mining, 2025); [The Pentagon to become largest shareholder in Rare Earth Miner, MP Materials](#) (CNBC, 2025).

Credit: Zacharia Thurston, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

# CKI Team

## Research Fellows

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**Leo Gordon**  
Master of Public Administration  
CKI Fellow  
[img2257@columbia.edu](mailto:img2257@columbia.edu)



**Brenda Rain**  
MS in Sustainability Management  
CKI Fellow  
[brr2135@columbia.edu](mailto:brr2135@columbia.edu)



**Khande-Jae Fisher**  
MS in Sustainability Science  
CKI Fellow  
[kjf2153@columbia.edu](mailto:kjf2153@columbia.edu)



**Zacharia Thurston**  
MS in Sustainability Management  
CKI Fellow  
[zt2326@columbia.edu](mailto:zt2326@columbia.edu)

# CKI Staff and Faculty

## Staff

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**Isabel Hoyos**

M.S. in Sustainability Management  
Senior Staff Associate  
[ih2428@columbia.edu](mailto:ih2428@columbia.edu)



**Ariela Farchi Behar**

M.S. in Sustainability Management  
Staff Associate  
[af3487@columbia.edu](mailto:af3487@columbia.edu)



**Pia Doris Morrow**

M.S. in Sustainability Management  
Staff Associate  
[pm3346@columbia.edu](mailto:pm3346@columbia.edu)



**Hyae Ryung (Helen) Kim**

PhD in Sustainable Development  
Senior Research Fellow  
[hk2901@columbia.edu](mailto:hk2901@columbia.edu)

## Faculty

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**Gernot Wagner**

Senior Lecturer, Columbia Business School  
Faculty Director, Climate Knowledge Initiative  
[gwagner@columbia.edu](mailto:gwagner@columbia.edu)

# Glossary

<b>AD/CVD</b>	Antidumping and countervailing duties	<b>CSP</b>	Concentrated solar power	<b>Mono-Si</b>	Monocrystalline silicon
<b>APAC</b>	Asia Pacific	<b>EMEA</b>	Europe, Middle East, and Africa	<b>NPV</b>	Net present value
<b>APS</b>	Announced Pledges Scenario	<b>EPC</b>	Engineering, procurement, and construction	<b>NZE</b>	Net Zero Scenario
<b>ASEAN</b>	Association of Southeast Asian Nations	<b>EPR</b>	Extended Producer Responsibility	<b>OBBBA</b>	One Big Beautiful Bill Act
<b>BaaS</b>	Battery as a service	<b>ESP</b>	Energy service provider	<b>OEMs</b>	Original equipment manufacturers
<b>BIPV</b>	Building integrated PV	<b>EVA</b>	Ethylene vinyl acetate	<b>OpEx</b>	Operating expenses
<b>BoS</b>	Balance of system	<b>FiT</b>	Feed-in tariff	<b>O&amp;M</b>	Operating and maintenance
<b>BSF</b>	Back surface field	<b>FBR</b>	Fluidized bed reactor	<b>PAYG</b>	Pay as you go
<b>c-Si</b>	Crystalline silicon	<b>FPV</b>	Floating PV	<b>PERC</b>	Passivated emitter and rear cell
<b>C&amp;I</b>	Commercial & industrial	<b>HJT</b>	Silicon heterojunction cells	<b>Poly-Si</b>	Polycrystalline silicon
<b>CAGR</b>	Compound annual growth rate	<b>IRA</b>	Inflation Reduction Act	<b>PPA</b>	Power purchase agreement
<b>CapEx</b>	Capital expenditures	<b>IRR</b>	Internal rate of return	<b>PTC</b>	Production tax credit
<b>CCS</b>	Carbon capture and storage	<b>ITC</b>	Investment tax credit	<b>PV</b>	Photovoltaic
<b>CO<sub>2</sub></b>	Carbon dioxide	<b>LID</b>	Light-induced degradation	<b>REC</b>	Renewable energy credit
<b>CPV</b>	Concentrator PV	<b>LFP</b>	Lithium iron phosphate battery	<b>REE</b>	Rare earth elements
<b>CRM</b>	Critical mineral	<b>MOIC</b>	Multiple on invested capital	<b>R&amp;D</b>	Research and development

# Glossary

<b>RPS</b>	Renewable portfolio standard
<b>SG&amp;A</b>	Selling, general, and admin. expenses
<b>SiO<sub>2</sub></b>	Quartzite
<b>SPV</b>	Special-purpose vehicle
<b>SPS</b>	Stated Policies Scenario
<b>TCO</b>	Transparent conductive oxide
<b>VIPV</b>	Vehicle integrated PV
<b>VOST</b>	Value of solar tariffs
<b>XaaS</b>	X as a service