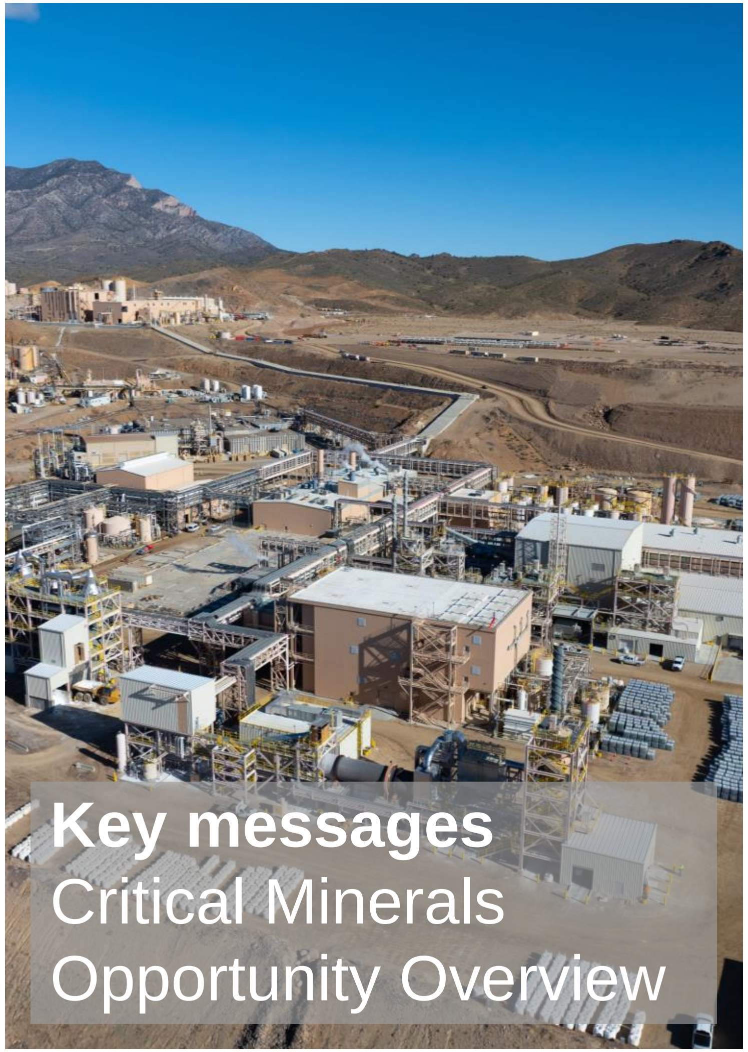
Columbia Business School
Climate Knowledge Initiative

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).



Key messages
Critical Minerals Opportunity Overview

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.

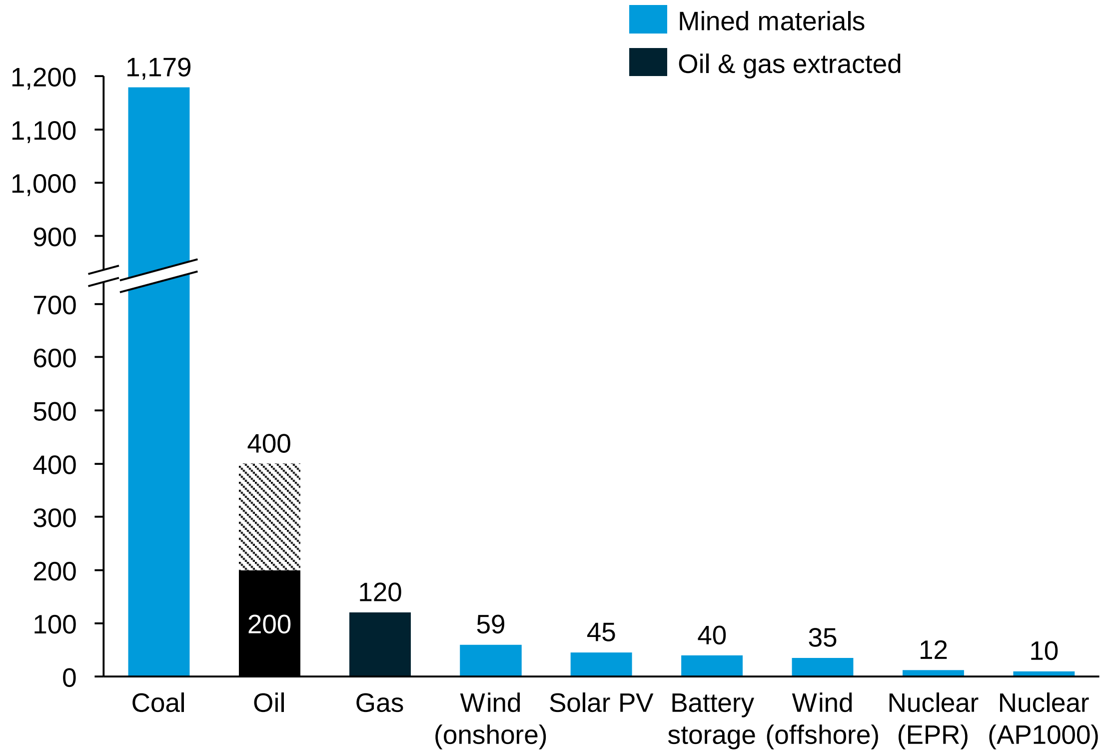
Technological advances in material recovery will enable projected recycled inputs to meet up to 40% of demand by 2050. Electrification and other advances in efficiency are also critical to decarbonize.

- 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.

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

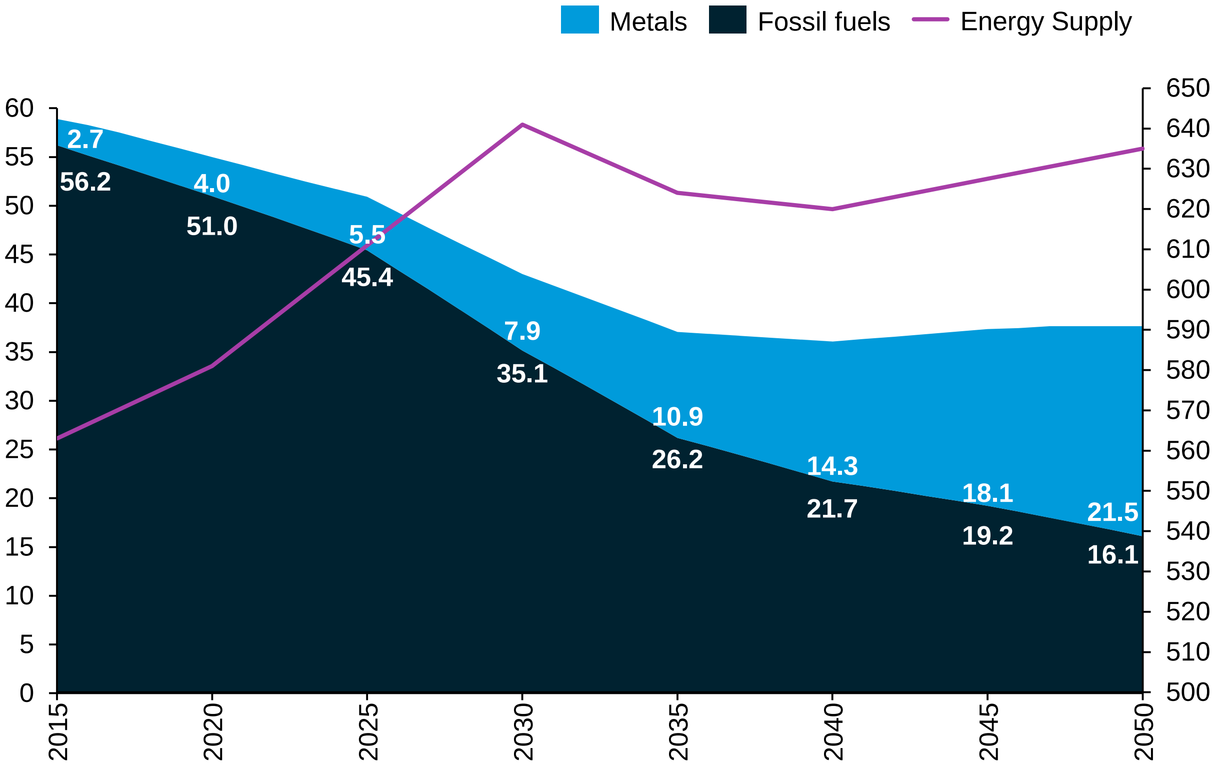
Fossil fuels have higher material intensity[1] and require consistent mining to produce the same energy as renewables

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. global energy supply[2], *2015-2050, Gt/year v. EJ/ year*



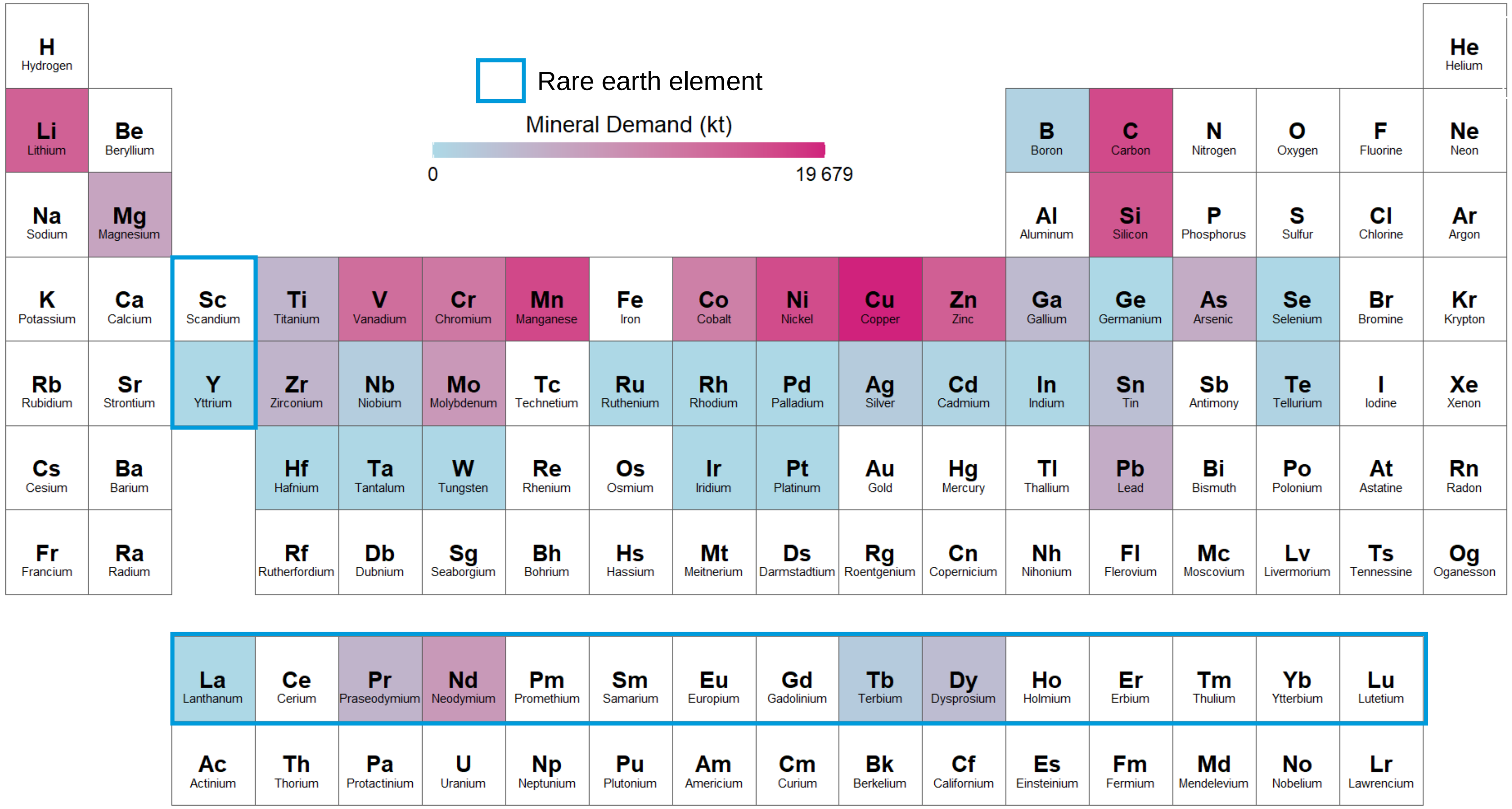
1) Refers to both direct material inputs and unused materials (waste rock, overburden, etc.) generated during extraction;
2) Based on the IEA scenario keeping temperature rise to 1.75°C by 2100.

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).

Minerals are 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

- Cu Copper
- Li Lithium
- Ni Nickle
- Co Cobalt
- C Carbon
- REE Rare Earths

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

Columbia Business School
Climate Knowledge Initiative

Columbia Business School
Climate Knowledge Initiative

Growing Demand

Global critical mineral demand is expected to see a 4 to 6x surge, driven in part by sectors central to the energy transition

Key sectors leading demand for critical minerals

Focus of deck: Electric Vehicles, Renewable Energy

Electric Vehicles	Renewable Energy	Digital Technology	Medical Equipment	Military Defense
~ 20-29% (CAGR to 2030) **2030 market value: $360B**	**~13-17%** (CAGR to 2030) **+5,500 GW capacity addition between 2024 and 2030**	**~7%** (CAGR to 2028) **$4.9T global tech spend in 2025**	**~5-6%** (CAGR to 2030) **2030 market value: $800B**	**~4%** (CAGR to 2030) **95% of critical minerals imported for U.S. defense tech**

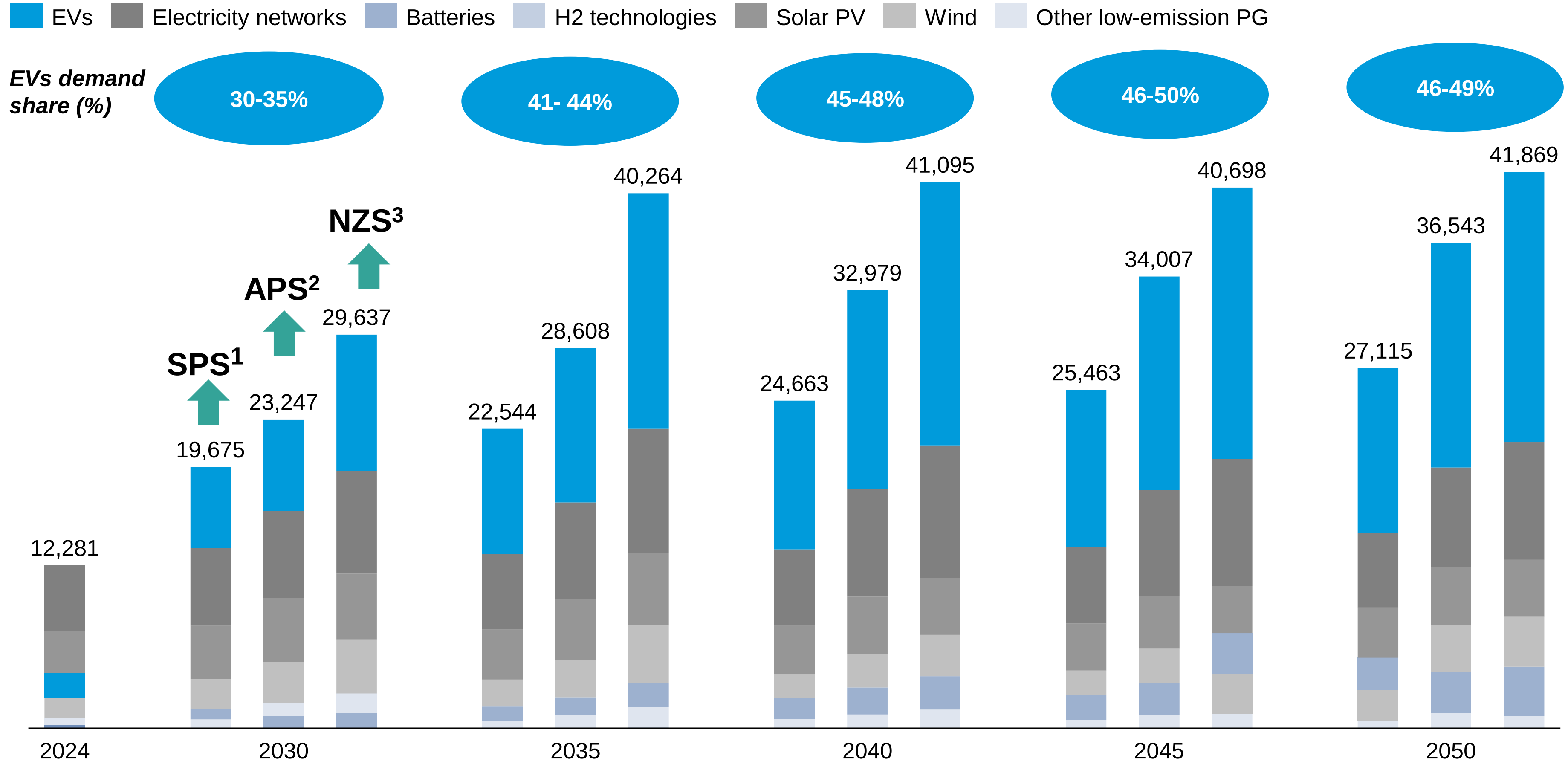
Minerals Required

Electric Vehicles	Renewable Energy	Digital Technology	Medical Equipment	Military Defense
Batteries: Lithium, Nickel, Cobalt, Manganese, Graphite, Phosphorus, Platinum, Dysprosium, Lanthanum, Neodymium, Praseodymium	**Wind turbines:** Copper, Aluminum, Zinc, Molybdenum **Solar:** Silver, Copper, Gallium, Tellurium	**Personal computers;** Silver, Aluminum, Copper, Gold **iPhones:** Dysprosium, Neodymium, Samarium, Terbium	**CAT scans:** Tungsten, Copper, Lead, Aluminum, Gold **X-rays:** Thullum, Yttrium, Gadolinium **Lasers:** Yttrium, Praseodymium, Neodymium, Samarium	**Jet engines:** Rhenium, Nickel **Night vision:** Lanthanum, Gadolinium, Yttrium **Military aircraft:** Aluminum, Copper

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).

Electric vehicles will represent ~50% of clean tech's critical mineral demand by 2050

Critical mineral demand by technology, *kt*



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).

Observations

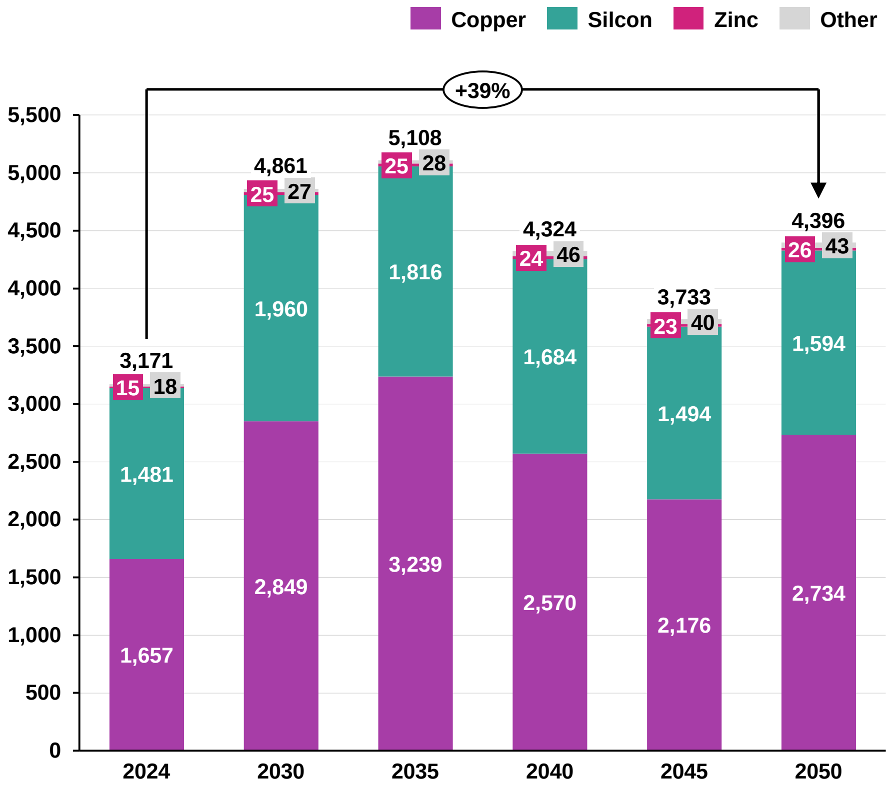
- **EVs surpassed 20%** of global share of clean tech in 2024, which is projected to **increase as much as ~82% by 2050**, led by increased competitiveness
- While clean tech's demand for critical minerals continues to increase, **digital tech and AI** will add more pressure to the global mineral supply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

Columbia Business School
Climate Knowledge Initiative

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

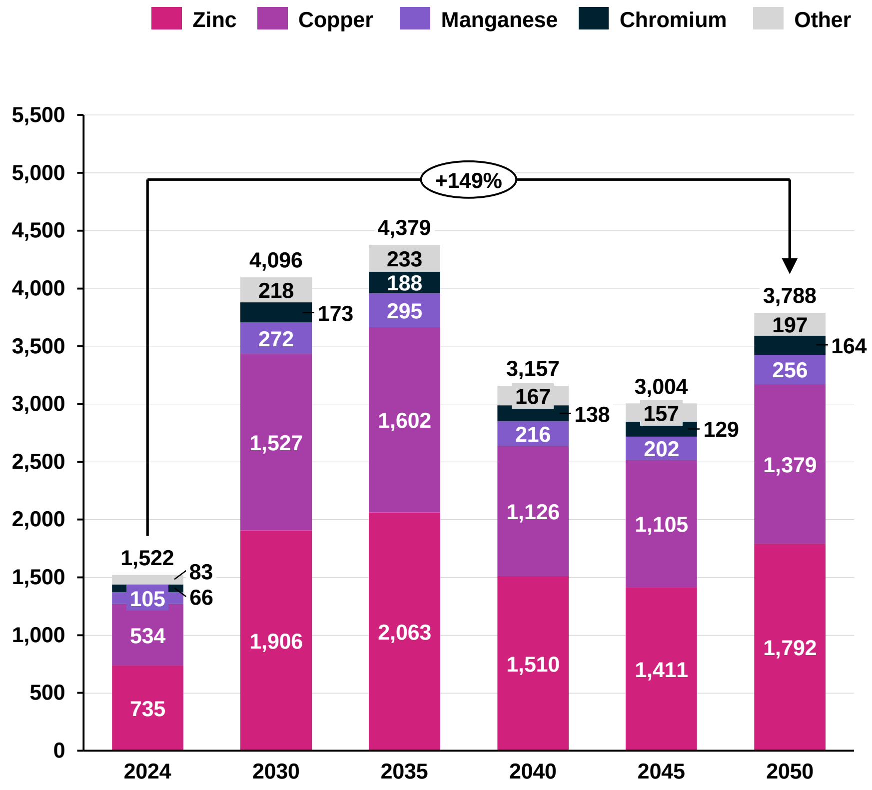
Solar's mineral demand[1] is expected to increase ~40% by 2050, primarily for Cu and Si

Mineral demand under NZE, *kt*



Wind's mineral demand[1] 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).

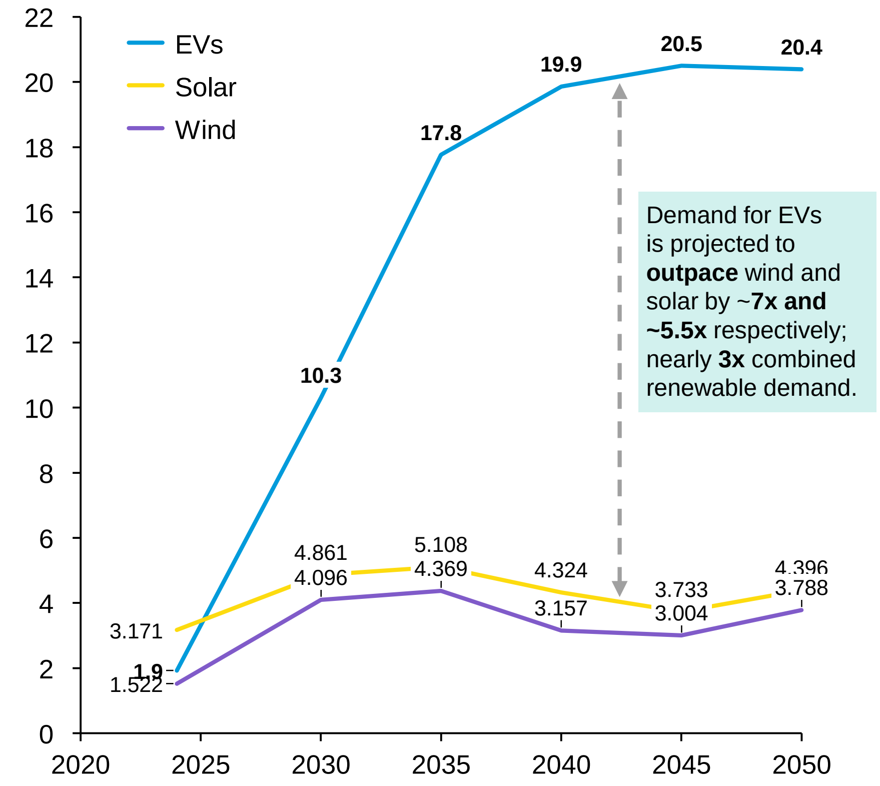
Credit: Khande-Jae Fisher, Isabel Hoyos, Ariela Farchi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Mining for the Energy Transition" (10 April 2026).

Columbia Business School
Climate Knowledge Initiative

Cu accounts for ~ 30-60% of cumulative mineral demand for renewables and EVs; demand from EV will outpace renewables by 3x

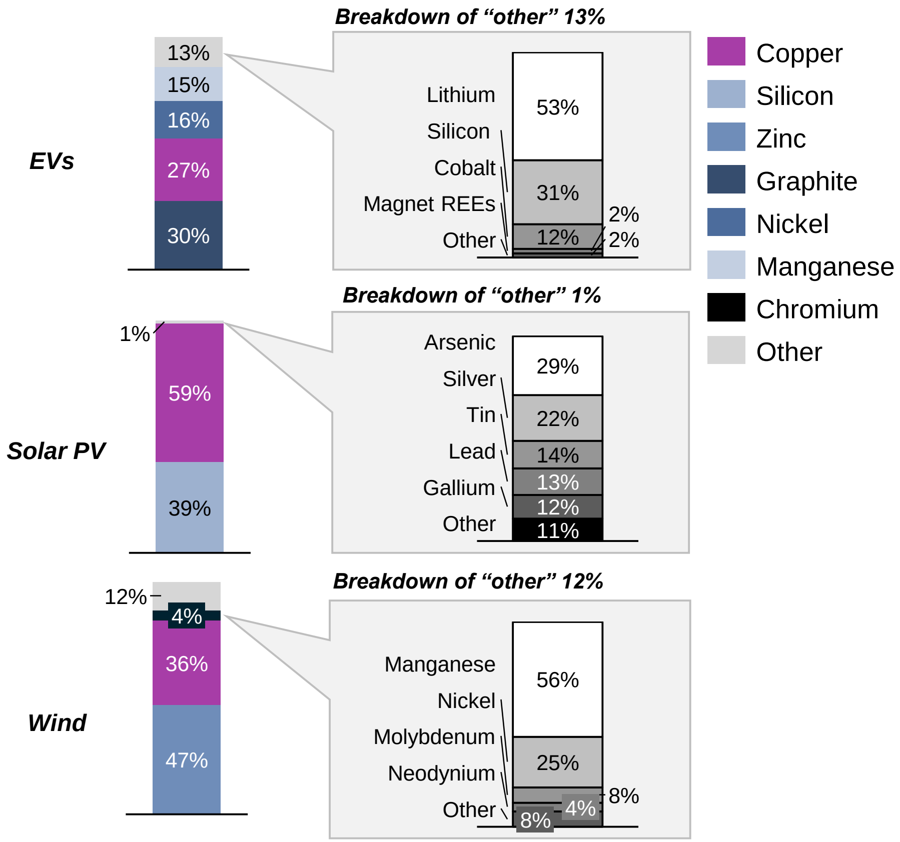
Demand[1] from EVs will grow 10x by 2050; solar and wind will increase by 40% and 150%

Annual critical mineral demand under NZE, *Mt*



>50% of EV demand[1] 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);

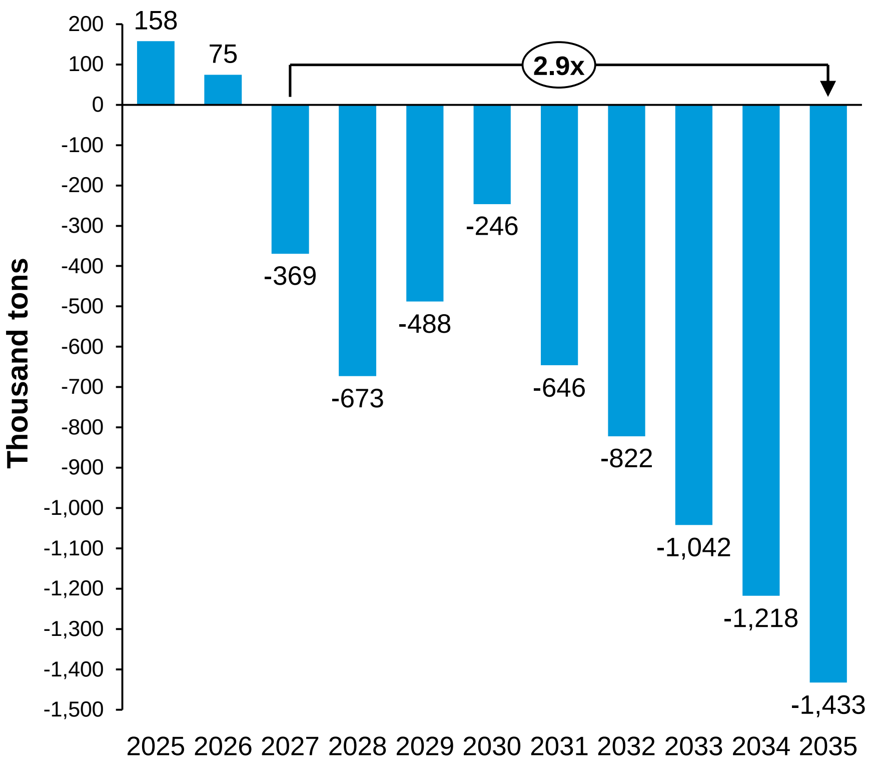
Credit: Khande-Jae Fisher, Isabel Hoyos, Ariela Farchi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Mining for the Energy Transition" (10 April 2026).

Columbia Business School
Climate Knowledge Initiative

Increasing demand expected to drive Cu deficit by 2035, with supply facing constraints and increased risk from floods and drought

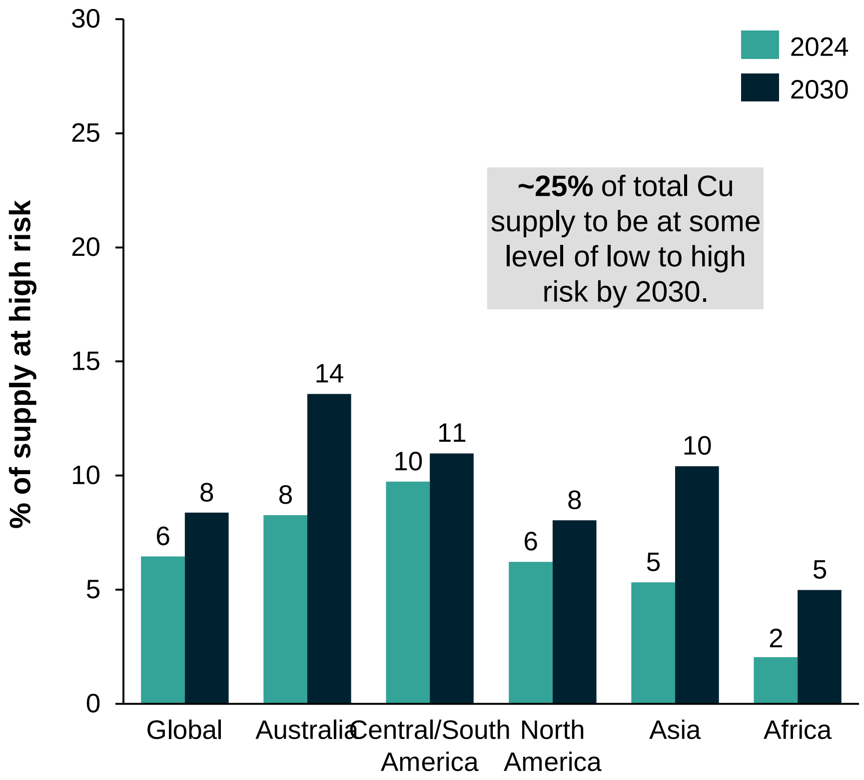
Cu deficit projected to reach ~7M metric tons by 2035, growing ~300% from 2027 to 2035

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 (Sprott, 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).

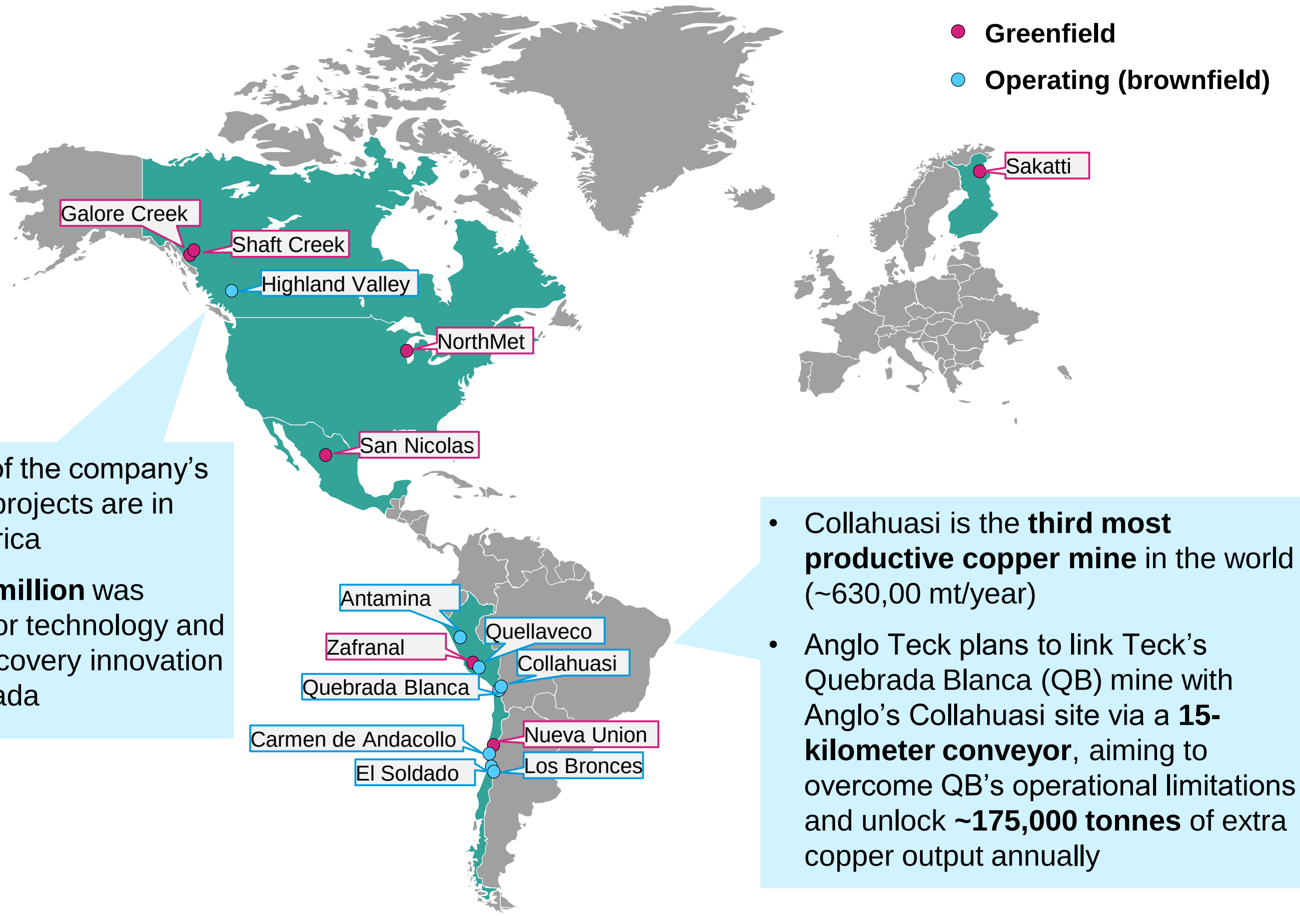
Columbia Business School
Climate Knowledge Initiative

In response to increasing Cu demand, Anglo American and Teck Resources merge in $53 billion deal, becoming a top global producer

Anglo Teck PLC formed from merger of Anglo American and Teck Resources, with an annual Cu output of 1.2 million mt/year

AngloAmerican Teck

- Anglo Teck's portfolio is **highly diversified** across North and South America, with seven greenfield and eight brownfield projects total; four of the greenfield projects are in North America, while seven of the brownfield projects are in South America
- The company is expected to produce **1.2 million mt** of copper output per year; equivalent to almost **half** of Peru's annual output
- Its target is **1.35 million mt/year by 2027**
- **Anglo Teck has major assets in Chile and Peru**, which account **for 24% and 12%** of global Cu production, respectively
- Copper will account for **>70%** of the company's production mix; other outputs are iron ore and zinc



- **Over half** of the company's greenfield projects are in North America
- **CAN$300 million** was budgeted for technology and mineral discovery innovation within Canada

- Collahuasi is the **third most productive copper mine** in the world (~630,00 mt/year)
- Anglo Teck plans to link Teck's Quebrada Blanca (QB) mine with Anglo's Collahuasi site via a **15-kilometer conveyor**, aiming to overcome QB's operational limitations and unlock **~175,000 tonnes** of extra copper output annually

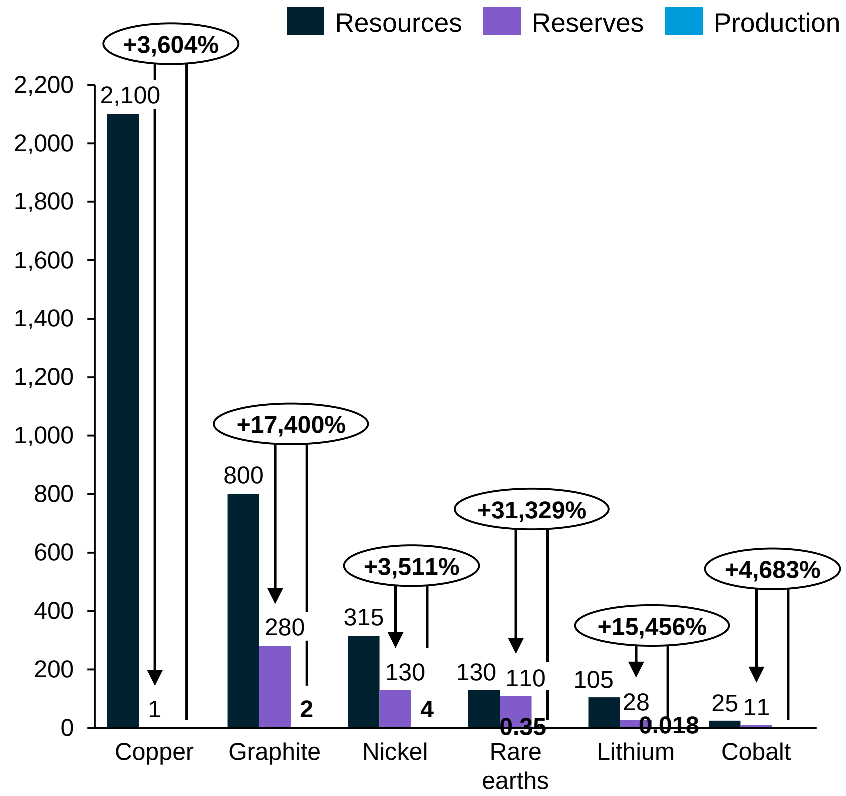
Sources: Mining megadeal shows the world is crazy for copper (WSJ, 2025); Anglo American, Teck to merge into $53 billion copper giant (WSJ, 2025); Anglo, Teck set to transform global copper mining landscape post merger (S&P Global, 2025); Anglo, Teck to merge, form global metals group (Argus, 2025); Anglo Teck deal hinges on troubled Chilean copper mine (Discovery Alert, 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).

Supply Outlook

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

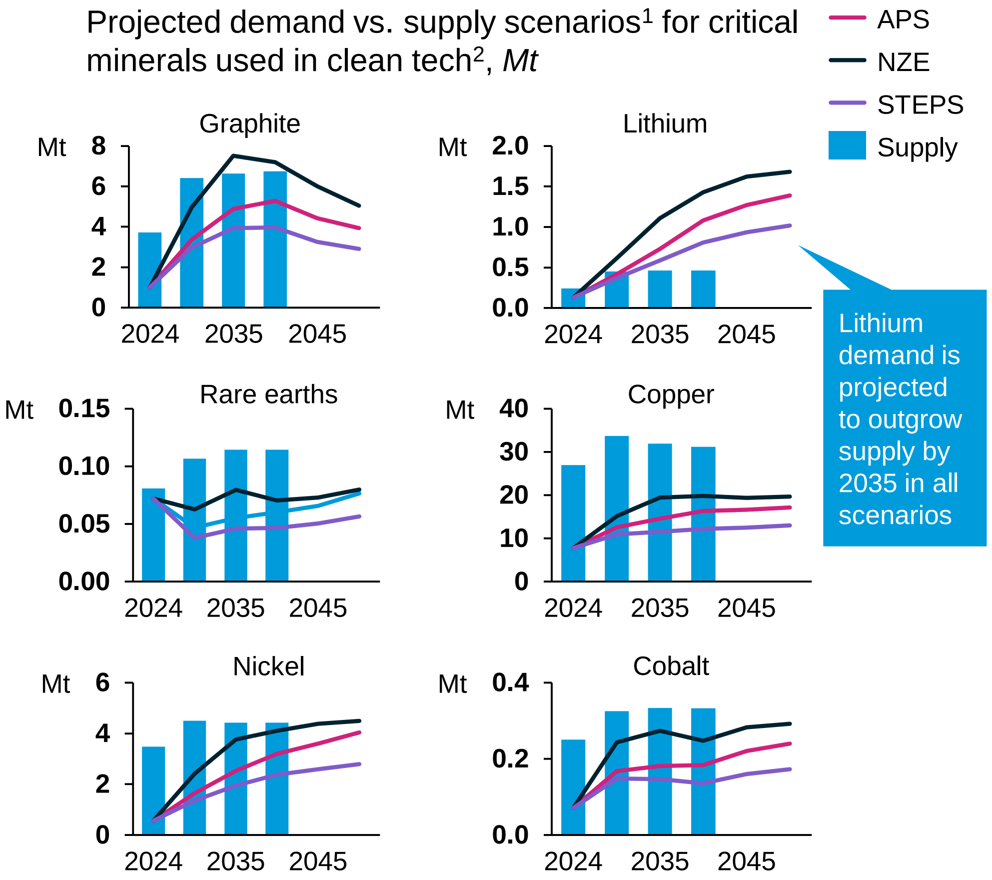
Current reserves and resources far outnumber production, particularly for CU

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



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

Projected demand vs. supply scenarios[1] for critical minerals used in clean tech[2], *Mt*



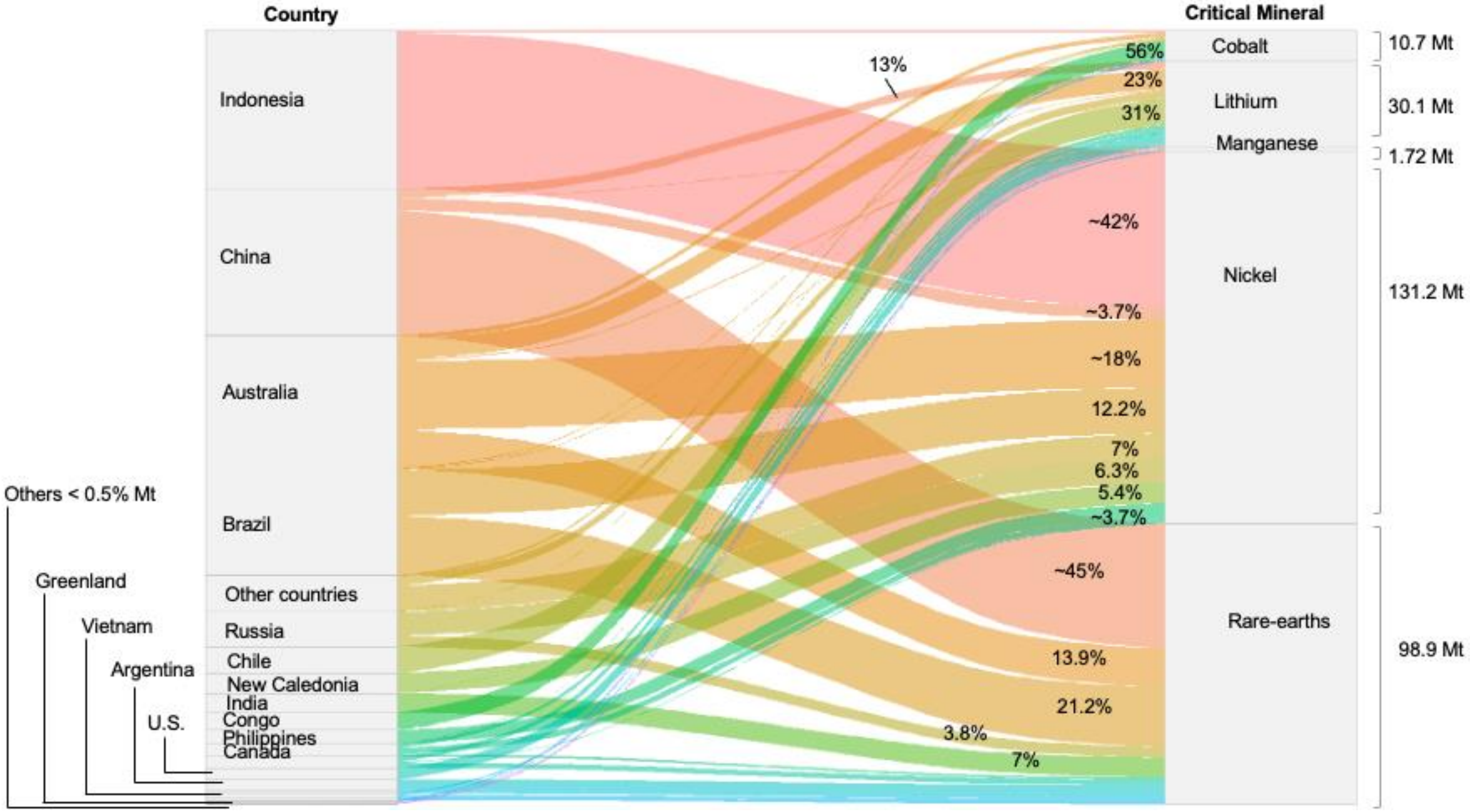
Observations

- 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 is more diversified

Global reserves[1] 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..

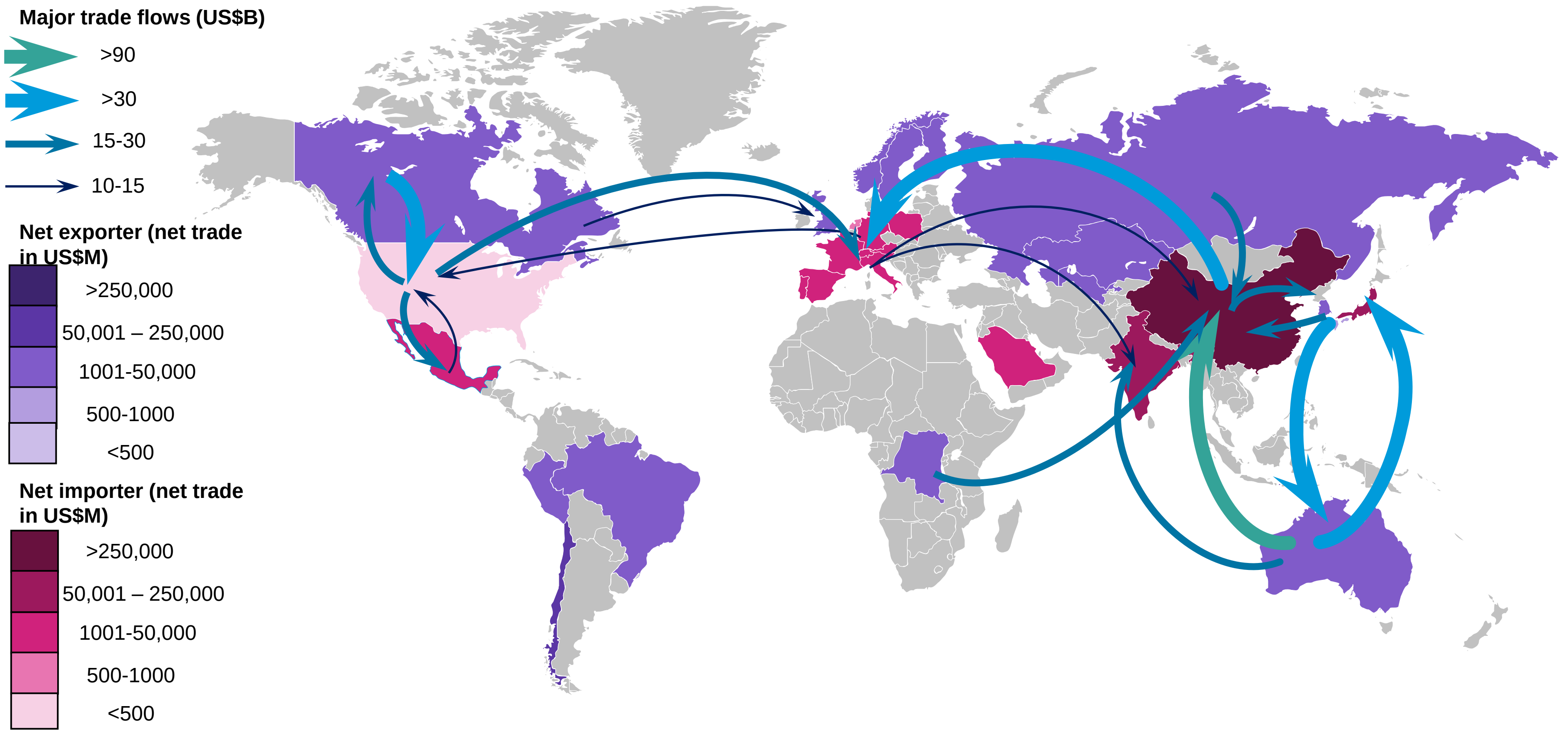
Source: Mineral commodity summaries (USGS, 2024).

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

Columbia Business School Climate Knowledge Initiative

China is the largest critical mineral importer of semi processed and raw materials; Australia and Chile are key trading partners

Global trade flows[1] 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).

Columbia Business School
Climate Knowledge Initiative

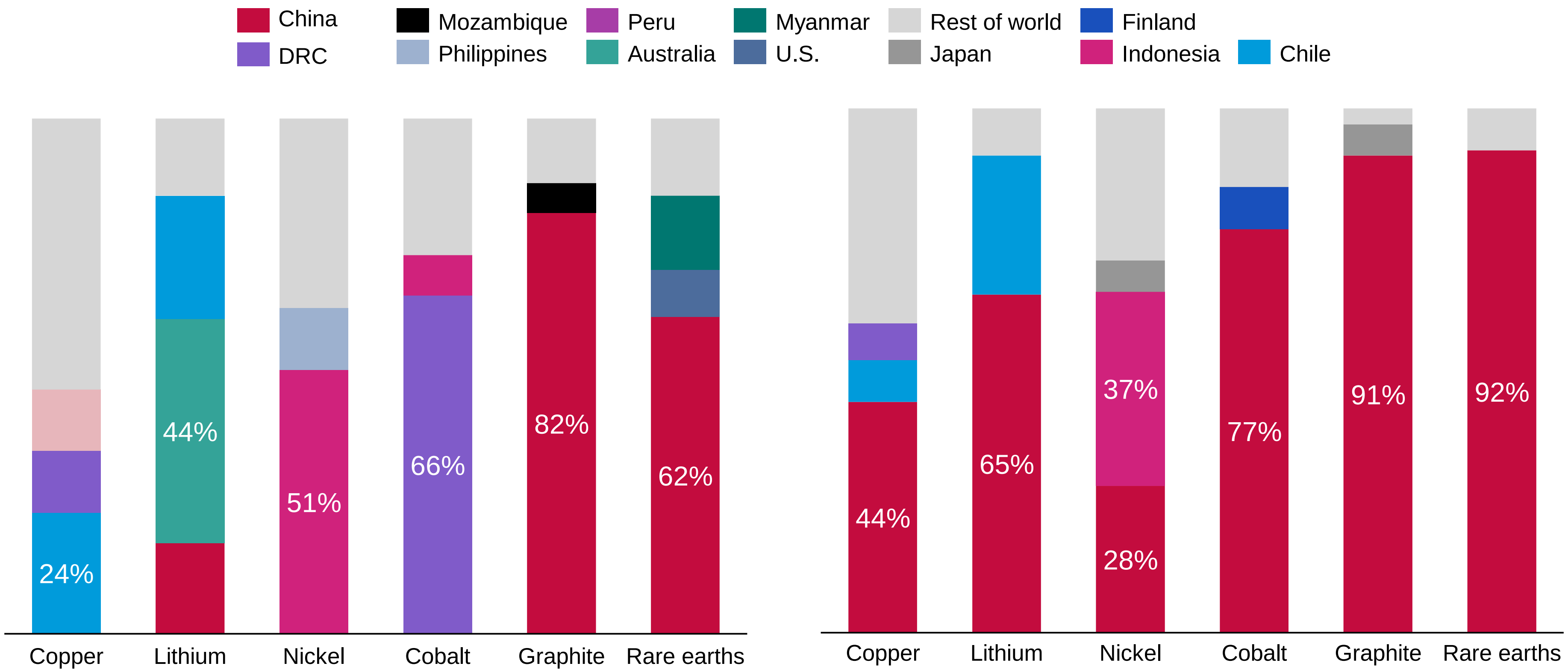
Upstream critical mineral production is dominated by a few key players; midstream capabilities are concentrated in China

Upstream: DRC, Indonesia, and Australia lead Co, Ni, and Li; China leads graphite and REE[1]

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.

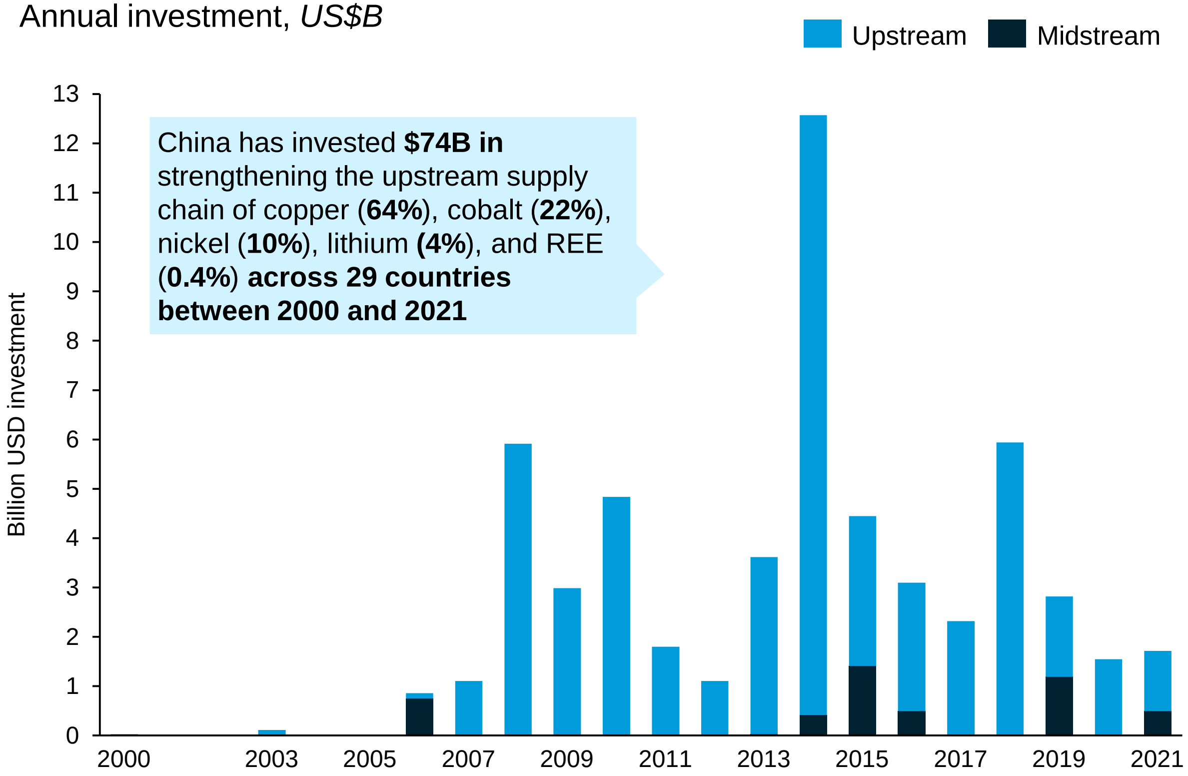
Sources: Global Critical Minerals Outlook (IEA, 2024); Global Critical Minerals Outlook (IEA, 2025); Japan's Responses to China's Supply Chain Dominance (RUSI, 2024); Namibia bans exports of unprocessed critical minerals (Reuters, 2023); Zimbabwe bans raw lithium exports to curb artisanal mining (Reuters,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

Global powers take different investment approaches; China focuses on upstream capabilities while U.S. explores 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 REE supply chain through public-private collaboration from mining to magnet production

Upstream

- **US$600 million** conditional funding from U.S. Export-Import Bank to Australia **Dubbo "mine to metals" project** under U.S.-Australia collaboration.
- **MOU** between U.S.-based **MP Materials** and Saudi Arabia-based **Maaden** to build a mine-magnet supply chain; mine production expected to begin in 2028.

Midstream

- Since 2020, DOD has awarded over **$439 million** to companies to develop **separating and processing capabilities** for permanent magnets, aiming to increase **U.S. production by 10,000 mt by 2028** (~1% of China's capacity and ~3% of global demand).
- **$400 million equity investment by DOD in MP Materials.**

Downstream

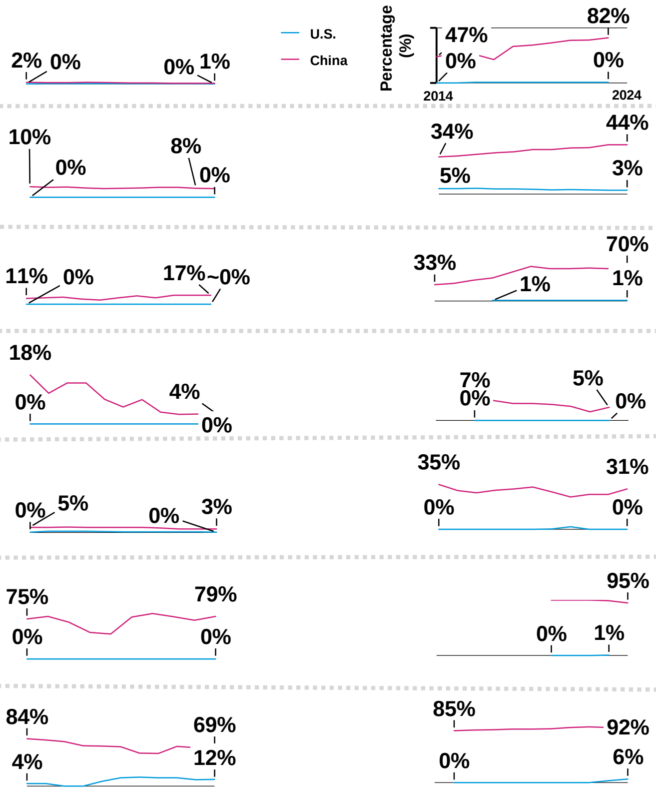
- **10-year offtake agreement between DOD and MP Material** to purchase 100% of magnets.
- **10-year price protection agreement with DOD** guarantees price floor of **$110/kg for** MP Material **NdPr products** (2x market price).

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,

Columbia Business School Climate Knowledge Initiative

China's refining dominance over the U.S. has been persistent across all critical minerals in the past decade

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

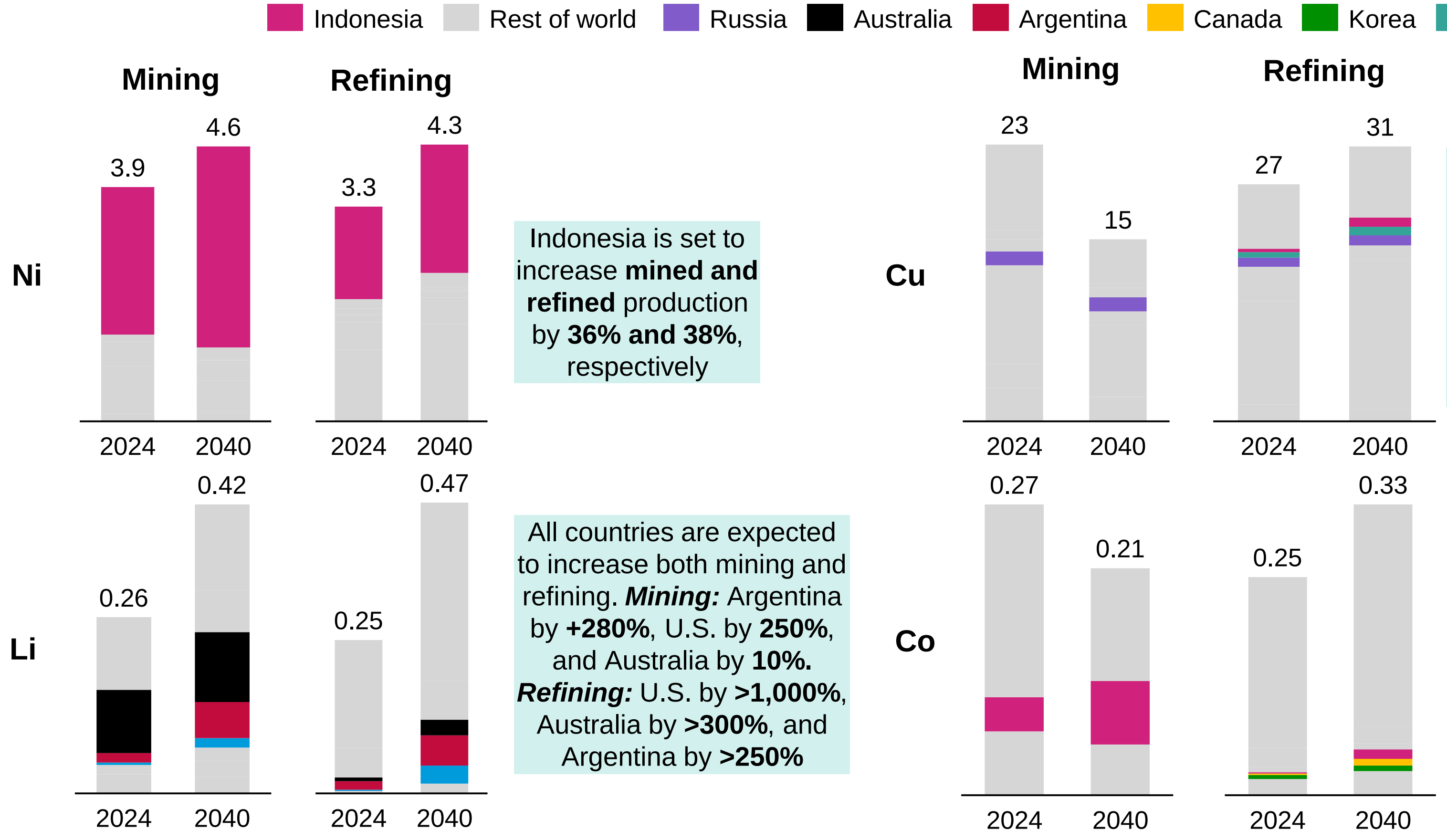


Mineral	Strategies: U.S.	Strategies: China
Cobalt (Co)	Attempts to increase **its influence in Central Africa Copperbelt through Lobito Corridor Railway**	**Continues to invest in TAZARA** (Tanzania Zambia Railway Authority)
Copper (Cu)	Refining capacity continues to decline	**Companies** continue to accelerate their **joint ventures to build smelter plants** near mines in **Africa and Latin America**
Lithium (Li)	**Continues to invest in lithium triangle ABC** but faces pushback from local governments and indigenous communities	**Continues to invest in lithium triangle ABC** but faces pushback from local governments and indigenous communities
Manganese (Mn)	Includes manganese in broader critical mineral strategies; in April 2025, released an Executive Order to **develop subsea mineral deposits**	Strengthening policies to support manganese processing within broader critical mineral strategies
Nickel (Ni)	Attempting to increase its production, providing **$20.6M funding to Talon Nickel mine**	**Expanded its production to Indonesia**, which owns 75% of its mining production and ~65% of its refined production
Graphite (Gr)	While facing supply chain risks, domestic investment and tariff strategies have been implemented to close the gap	Continues employing export control to the U.S
Rare earths (REEs)	**Stopped production in 2022**, and currently **80% of its consumption comes from China**; the remaining comes from second exporters	**Faces minor risk in using REEs as a trade dispute**, apart from issues related to illegal mining

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 countries, including Indonesia and the U.S., are increasing mineral refining capacity to reduce their dependence on China

Global planned mining and refining mineral production (non-China), *2024-2040*, *Mt*[1]



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

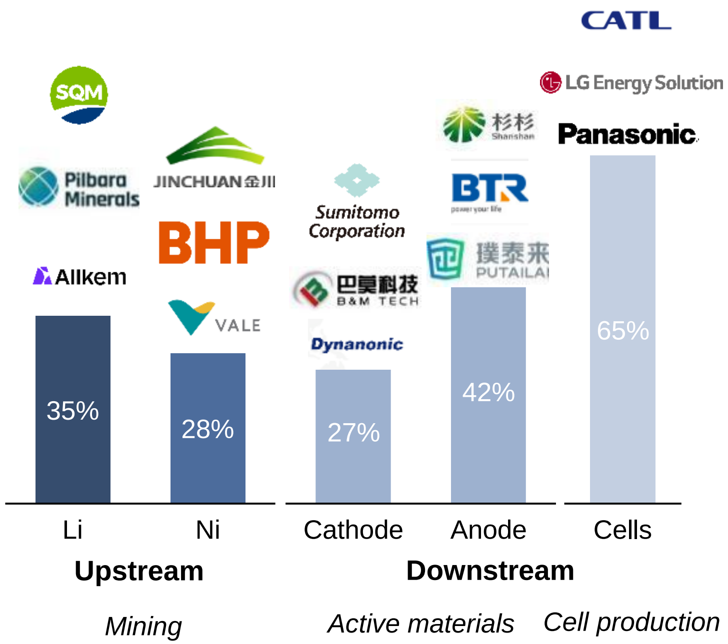
- Diversification is useful to **cushion countries against external shocks, derive more mineral benefits, and prevent resource-rich developing countries from becoming dependent** on external economies
- Global FDI greenfield mineral projects numbered 117 in 2023; approximately **75% of those were in 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).

A select number of companies and China dominate the EV battery supply chain, having reached hard-to-achieve economies of scale

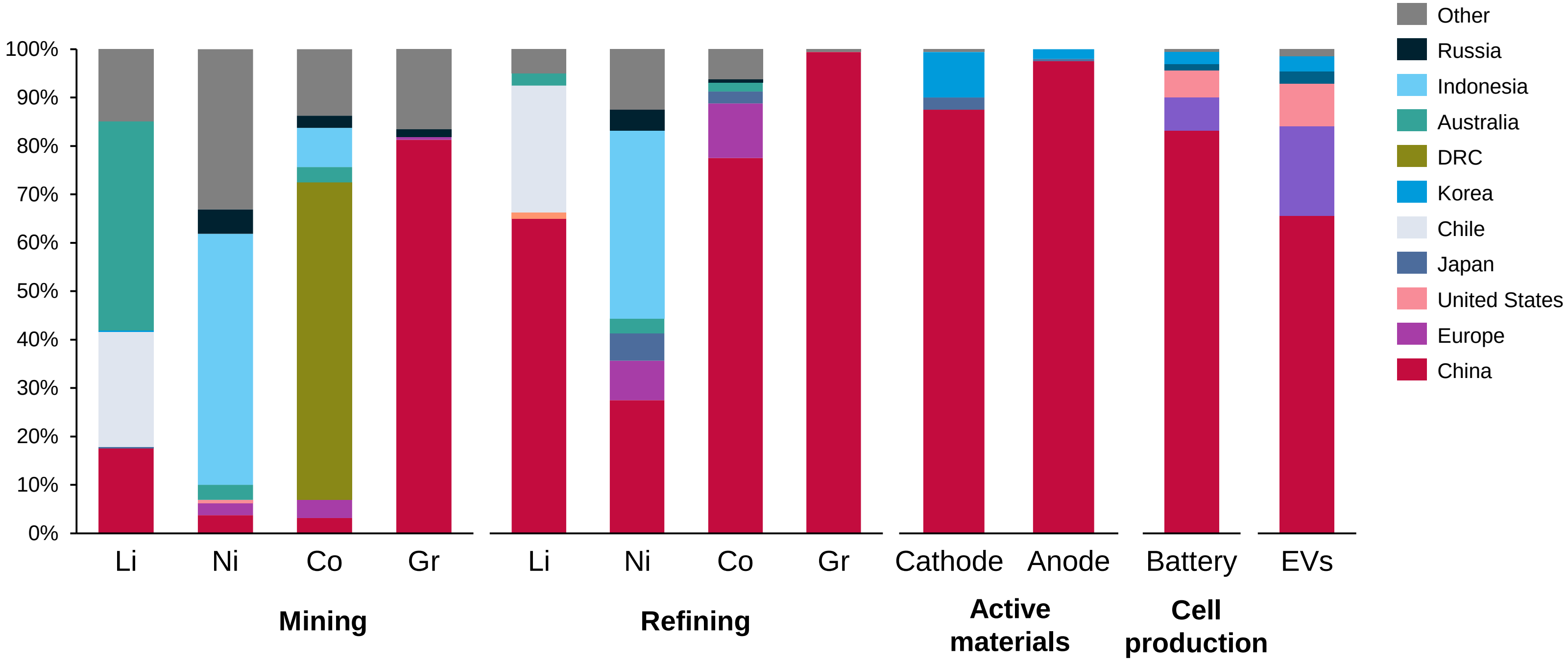
Upstream is mostly managed by LATAM and Australia, downstream is led by Asia

Share of total production of top three companies across supply chain,[1] *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,[2] *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.

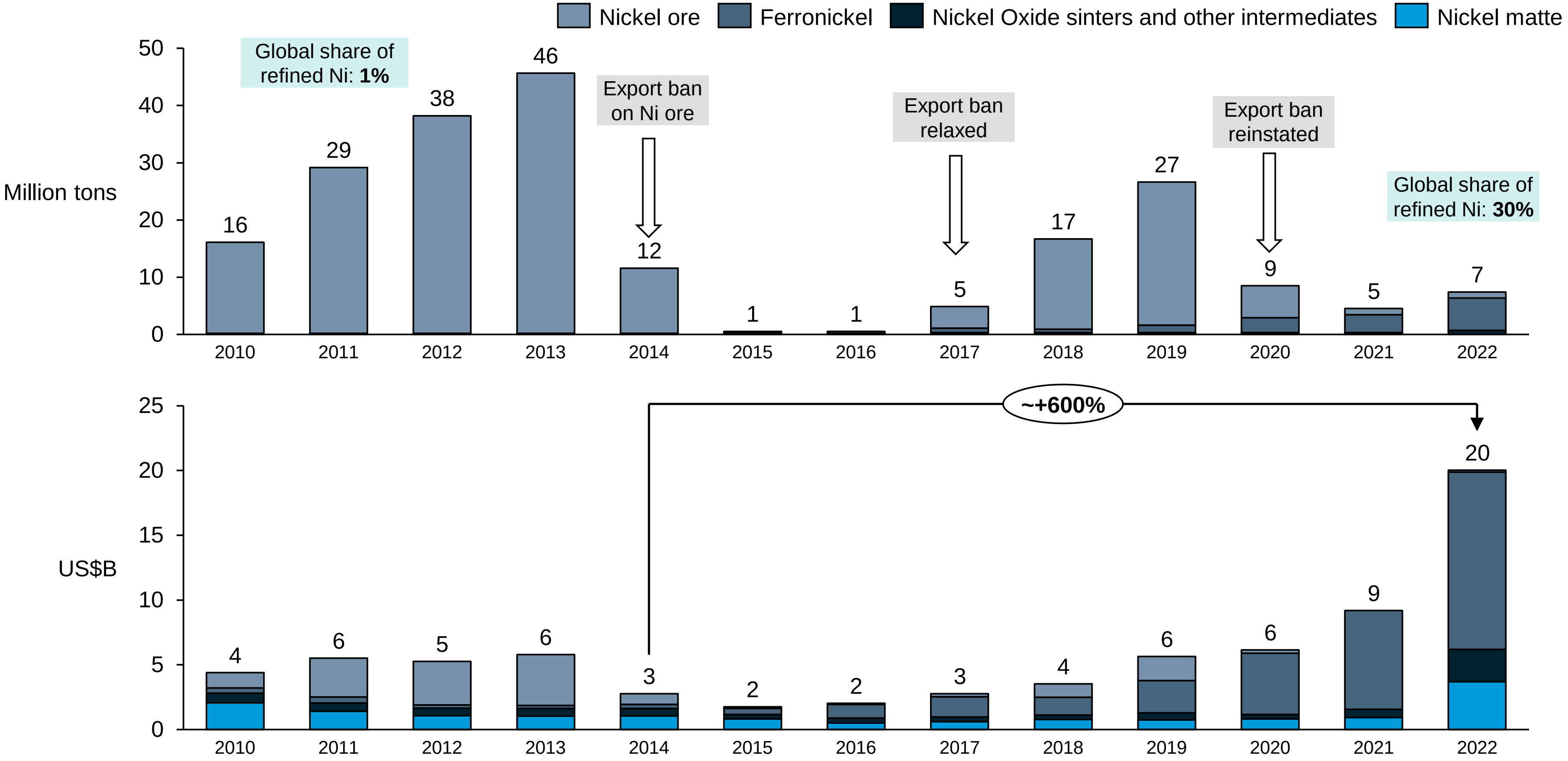
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Khande-Jae Fisher, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Mining for the Energy Transition" (10 April 2026).

Columbia Business School
Climate Knowledge Initiative

Geopolitical Landscape

Value-adding policies increased Indonesia's global processed Ni share by 29% from 2014 to 2022 and increased 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

- **Military assistance** (weapons, technology, training)

Half public royalties

- **50%** of public royalties, license fees, and similar payments from natural resource projects in Ukraine

Benefits

Prioritization

- The U.S. International Development Finance Corp. is prioritized in offtake agreements plus has **right of first refusal.**

Asset ownership

- Agreement pertains only to net new assets, with **100% ownership being maintained for assets currently generating revenue.**

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

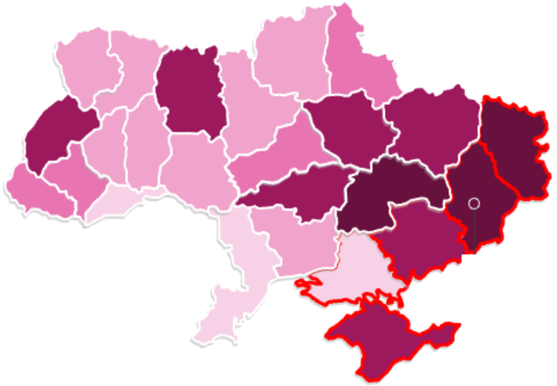
Ukrainian mineral deposits

Li Lithium | Cu Copper | Zn Zinc | REEs Rare Earths

Ti Titanium | Co Cobalt | Mn Manganese | Be Beryllium

Ni Nickle

Ukrainian mineral deposits $ reserve value



Estimated reserve value

- $3,000B-$4,000B
- $2,000B-$800B
- $50B-$200B
- $10B-$50B
- Up to $10B
- Russian occupied

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 unknowns

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)

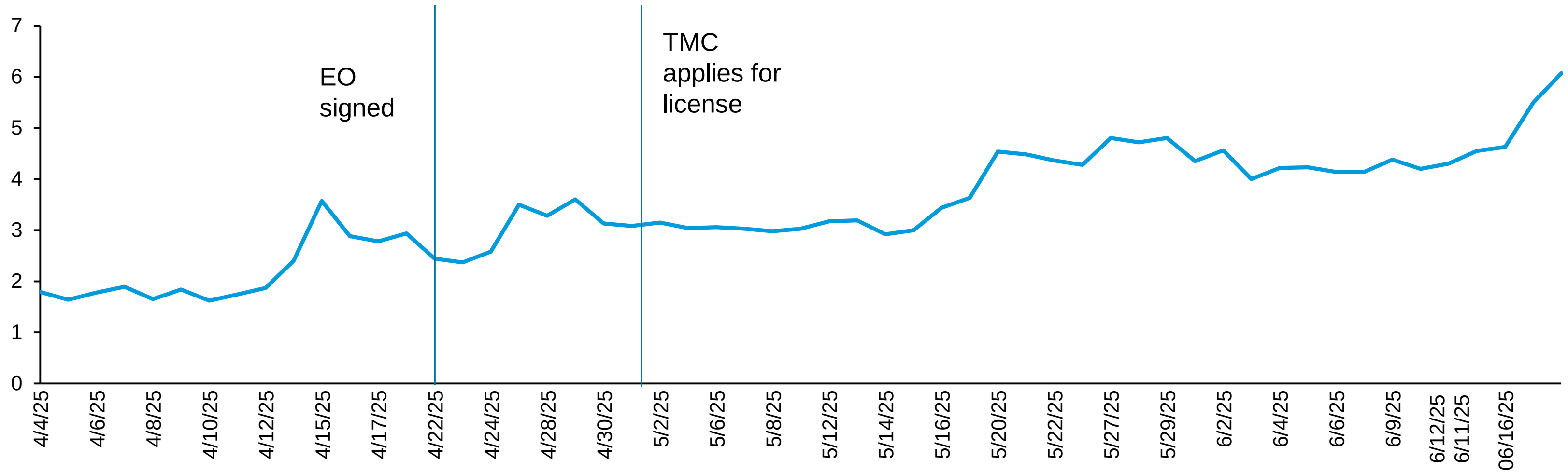
Cost

- 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 Naura 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.

Sources: Unleashing Americas Offshore Critical Minerals and Resources (The White House, 2025); TMC The Metals Company Inc. (MarketWatch.com, 2025).
Credit: Leo Gordon, Zacharia Thurston, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim et al., "Mining for the Energy Transition" (31 October 2025)

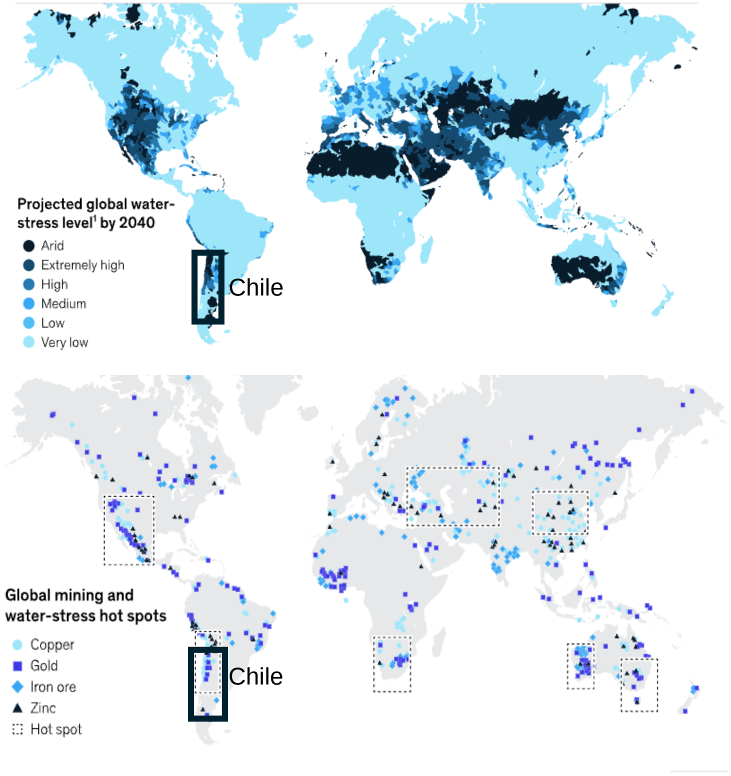
Columbia Business School
Climate Knowledge Initiative

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

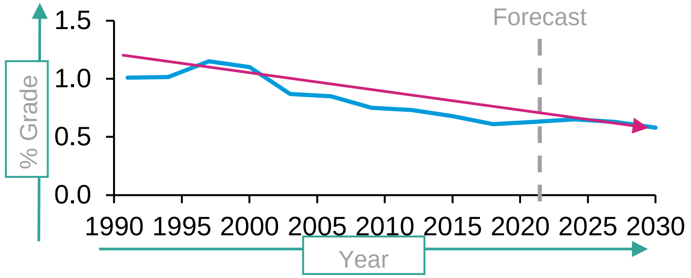
Observations

- **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).

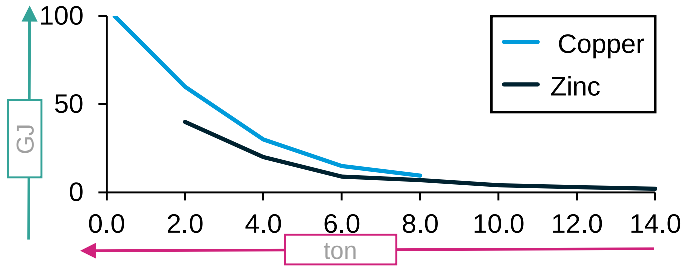
Aging mines and decreasing ore grade quality means exponentially more energy is required for optimal mineral production

Mined head grade, *% copper*



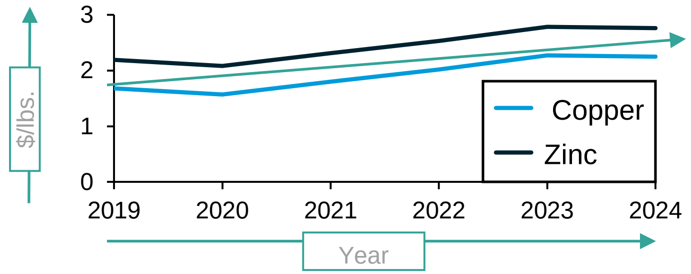
The percent of recoverable copper per unit of ore is declining

Energy consumption, *GJ/ton*



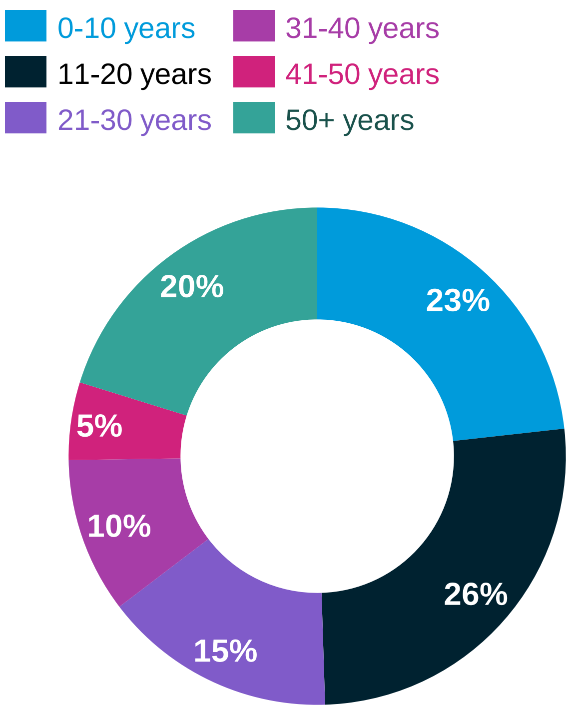
Exponentially more energy is required to extract copper, zinc, and other minerals as ore grades decline and recovery rates fall

Copper & zinc unit costs, *$/lbs.*



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

Age of copper mines operating in 2023



Observations

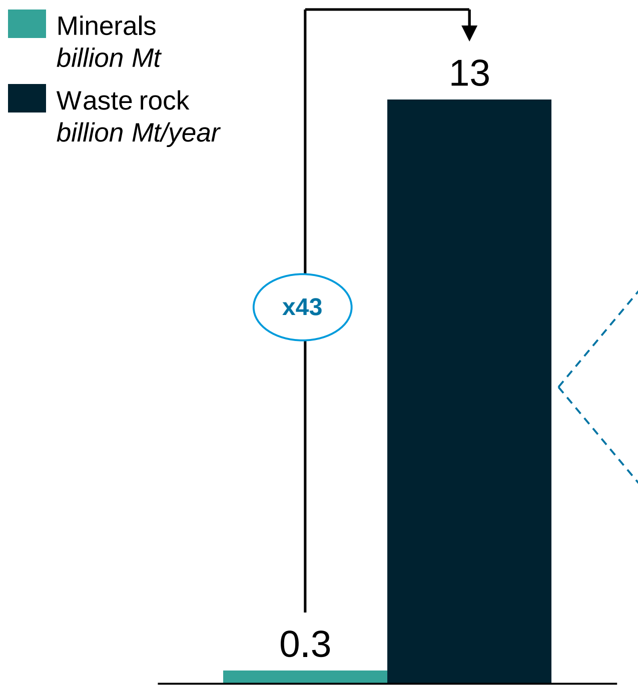
- As mines age, ore grades typically decline, leading to lower recovery rates and **the need to use significantly more energy to extract and refine each unit of metal**
- This not only increases operating costs but also heightens the environmental footprint of production
- **The same trend is evident 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

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).

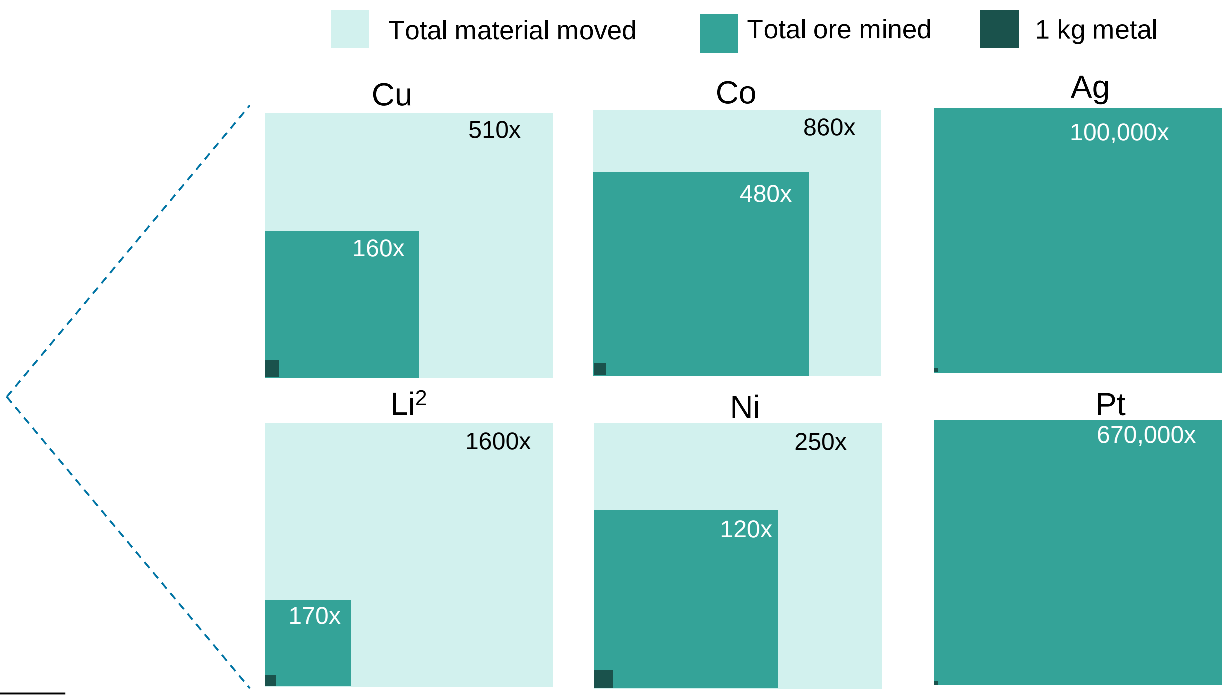
Columbia Business School
Climate Knowledge Initiative

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[2]



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).

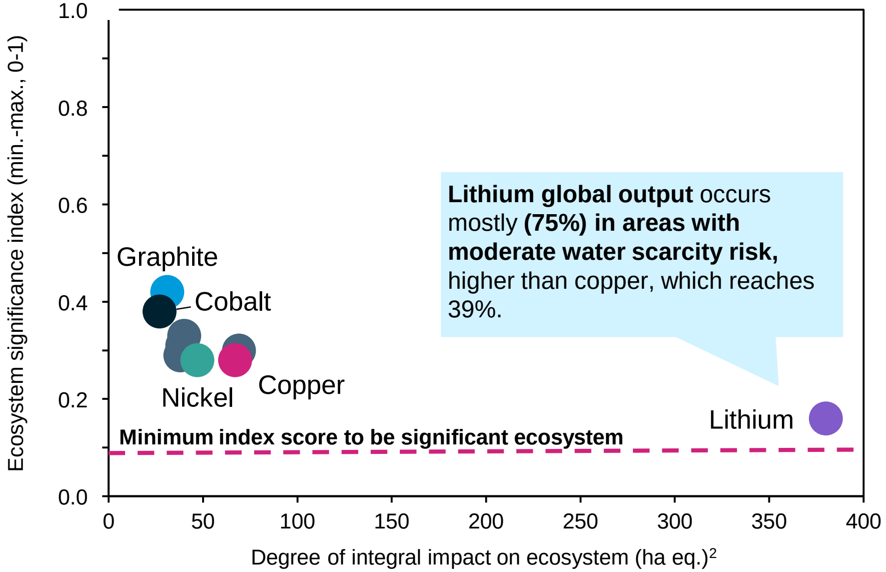
Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Mining for the Energy Transition" (10 April 2026).

Columbia Business School
Climate Knowledge Initiative

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

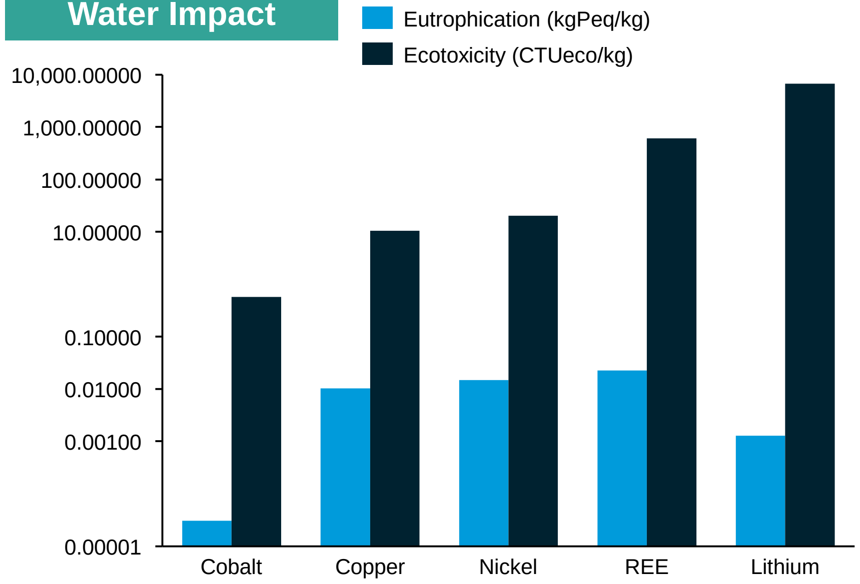
71% of transition mines impact ecosystems[1]; lithium and graphite have the largest footprint

Land Impact



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

Water Impact



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, **adaptative 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

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**

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_2 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)

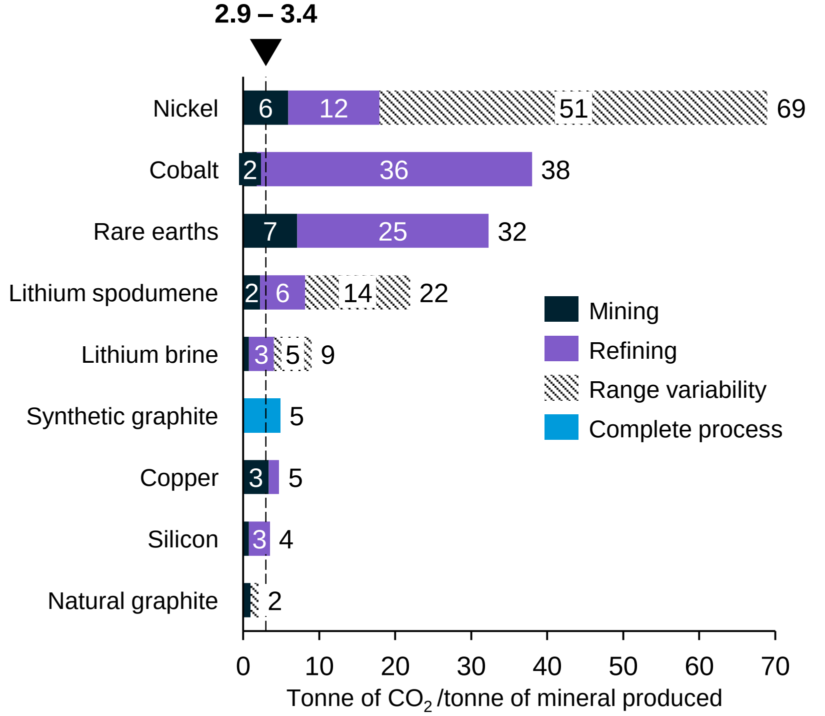
Sources: Climate risk and decarbonization (McKinsey, 2020); The journey of the electric submersible dewatering pump (Atlas Copco, 2023); Mining & Minerals (Sigma Thermal, 2025); Energy Technology Perspectives 2023 (IEA, 2023); 11 lithium stocks betting on direct lithium extraction (Investing News Network, 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_2 (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).

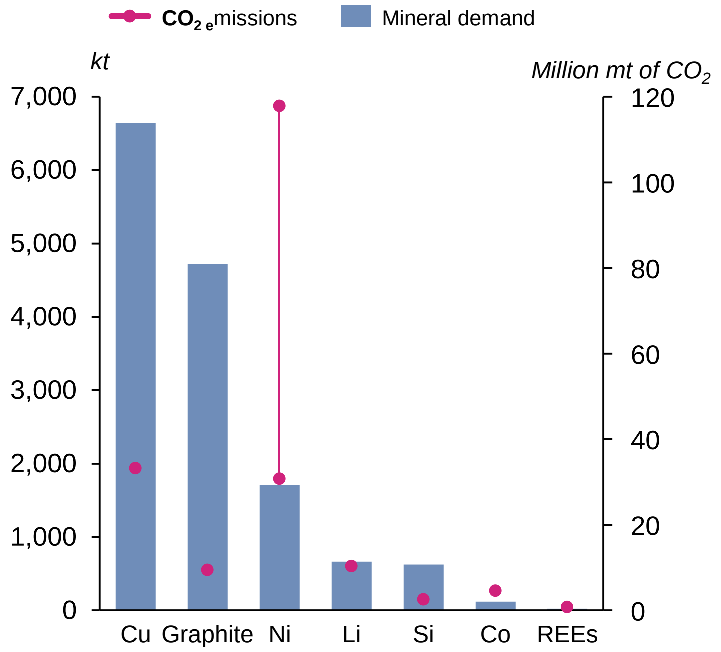
The impact of transitioning to a clean economy remains net positive, despite emissions from carbon-intensive minerals

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

Carbon intensity from mining and refining, *CO_2 tonnes/tonne of crude oil*

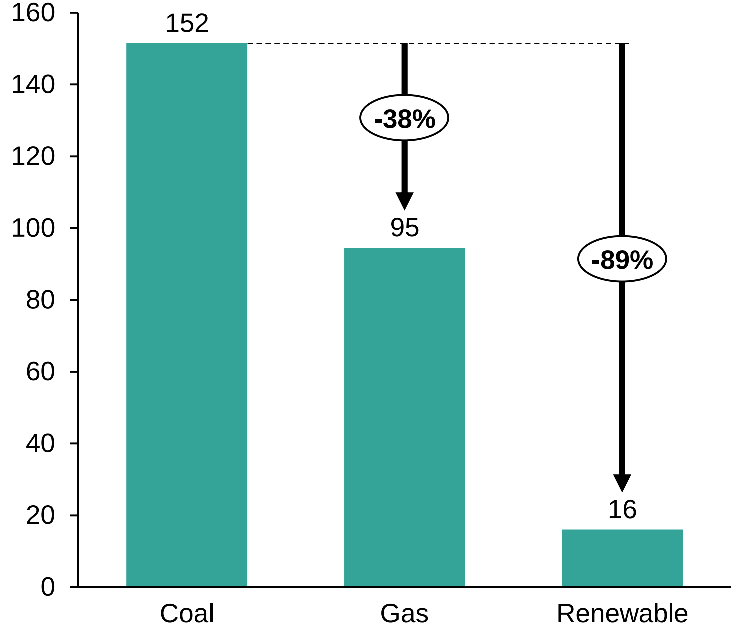


Additional mineral requirements and emissions under Net Zero Scenario by 2050



~135 $GtCO_2$ can be avoided by replacing process coal with renewable power

Cumulative GWP under 2DS[1] Scenario by 2050 through C-t-G methodology, *$GtCO_2e$*



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).

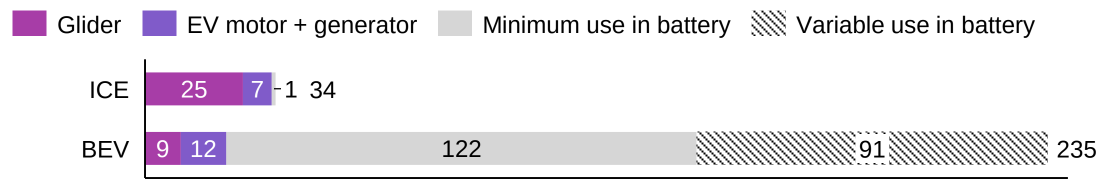
Credit: Brenda Rain, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Mining for the Energy Transition" (10 April 2026).

Columbia Business School
Climate Knowledge Initiative

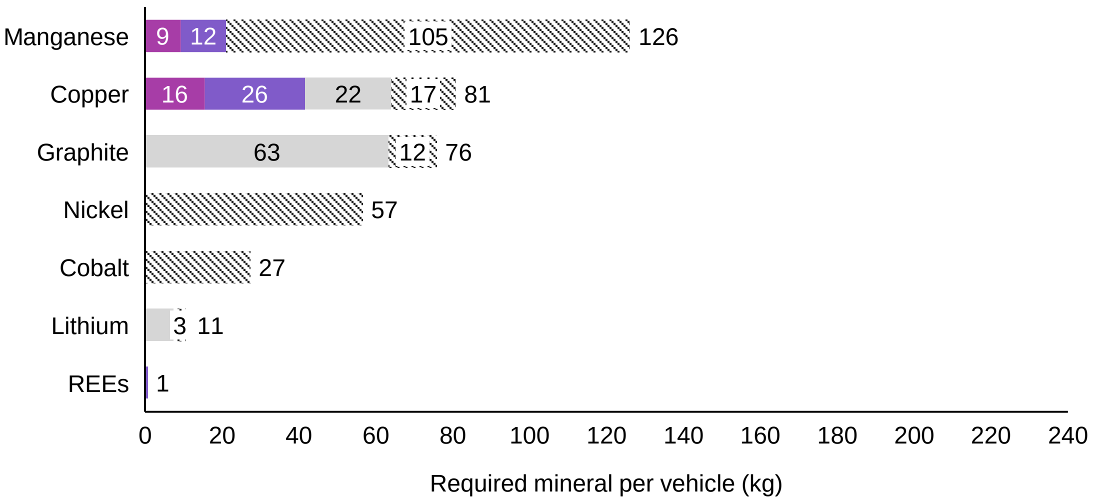
Emissions reductions achieved by EVs, enabled by critical minerals, far exceed emissions from their mining and processing

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

Critical mineral used in EV[1] compared to ICE by car components, *kg*

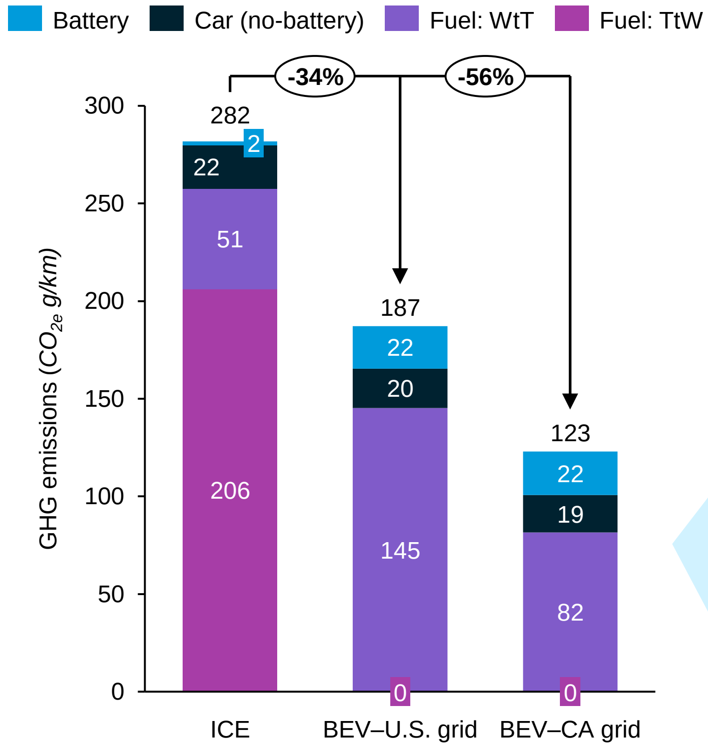


Critical mineral used in BEVs by type of mineral[2] and car components, *kg*



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_2e emissions** from BEVs at **50 g CO_2e/km** in **Belgium,** others set it at **~ 290 CO_2e/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).

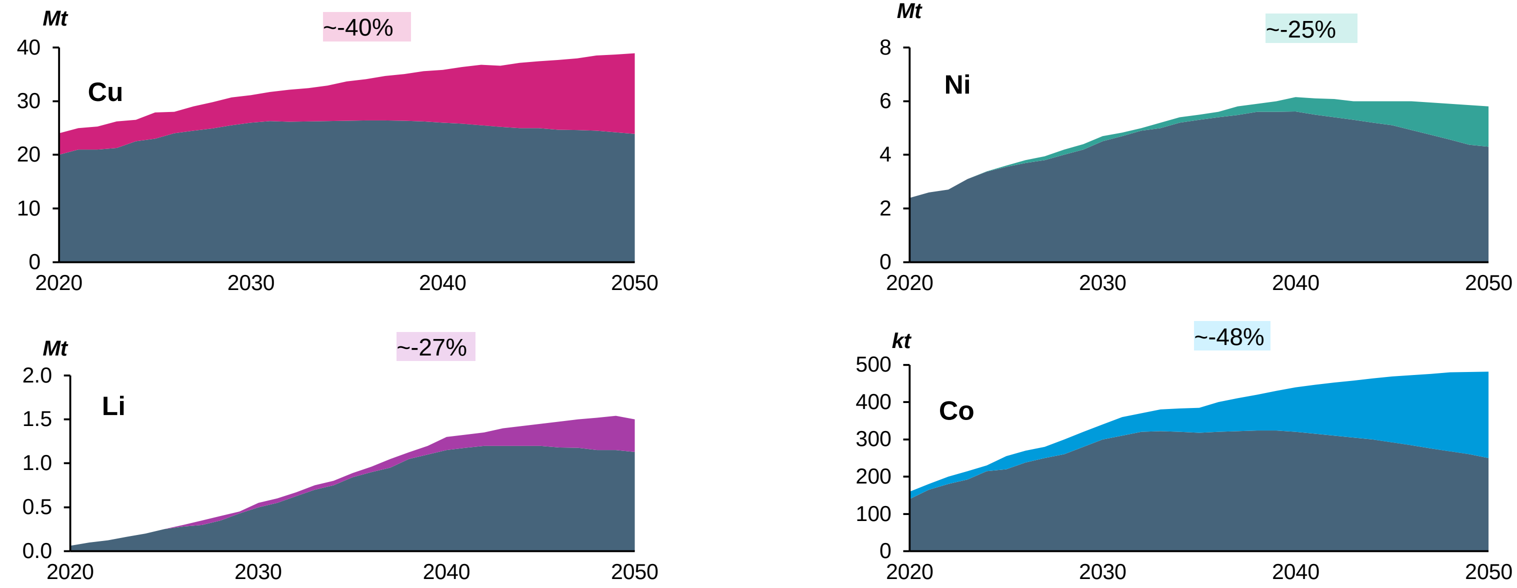
Columbia Business School
Climate Knowledge Initiative

Decarbonization Solutions & Innovations

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

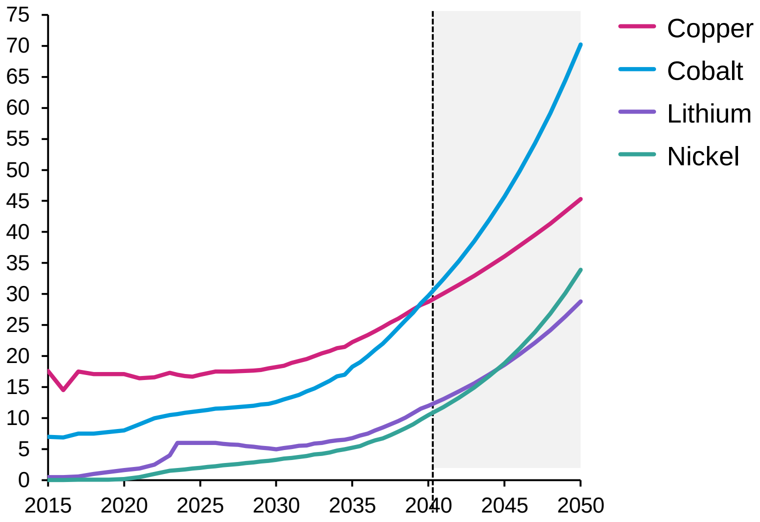
As share of recycled mineral input increases, demand for mined material is projected to decrease by 40% for Cu, 25% for Ni, 27% for Li and 48% for Co

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).

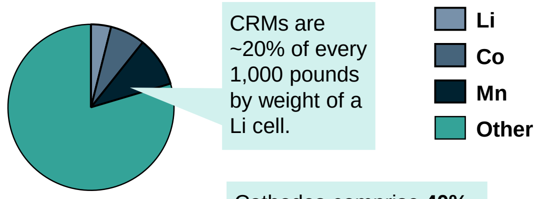
Columbia Business School
Climate Knowledge Initiative

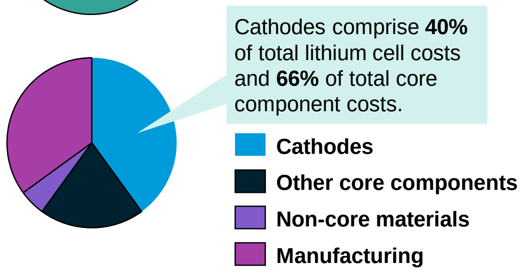
Circular models are essential to help fragmented supply chains, as poor design for recovery limits recycling scalability and profitability

Barriers to Critical Mineral Recovery

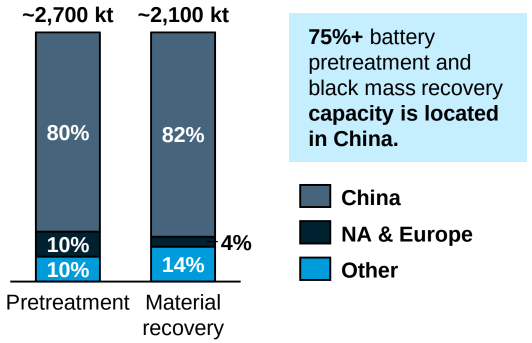
Heterogenous waste streams	• Diverse chemistries, hazardous materials, and inconsistent product quality in black mass limit process optimization for recyclers • Compositional and price variability of shredded batteries within black mass makes value unpredictable (e.g., LFPs are less profitable), leading to discounted payables, lower margins, and revenue uncertainty
High dispersion, low concentration of CRMs	• CRMs exist as trace amounts in many products, increasing processing needs • Extraction techniques vary in selectivity and cost; variability in waste streams reduce recovery performance
Fragmented supply chain and infrastructure	• Recycling facilities and underdeveloped collection infrastructure require high CapEx • Supply chains are geographically concentrated; nations export feedstocks for further processing • Low waste feedstock and manufacturing scrap dominate the waste stream: EVs and storage are only one-third of recyclable feedstock
Lack of design for disassembly	• Products are not designed for EOL recovery; disassembly is time consuming and expensive • Battery designs are not standardized; products often do not disclose compositional profiles, making identification and recovery of critical minerals difficult

Cathode costs vs. weight per cell



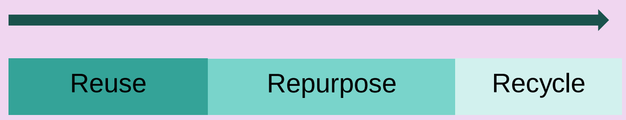


Pretreatment and material recovery distribution by country in 2023



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); Globa 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
Description	**Chemical dissolution** using aqueous materials to extract metals	Extraction of metals by **smelting at elevated temperatures** >1000 °C	**Reconditioning** of active materials **without breaking them down into elemental metals**
Recovery rate	Up to 99% (H)	<50% for Li; ~98% for Co, Cu, and Ni; *up to 97% for Li when combined with hydro (M)	Up to 98% in lab (H)
Energy consumption[1] (MJ/kg LFP)	30.6	18.4	3.5
Advantages	• Lower emission than pyro • High recovery rates for most metals	• Batteries require minimal pretreatment • High Ni, Co, and Cu recovery rates	• Lower emissions and energy than hydro/pyro • High Li recovery rates
Disadvantages	• Liquid waste; extensive water use • Battery requires pretreatment – primary inputs are black mass • Slow processing times	• High hazardous gas and liquid waste emissions • Battery requires additional processing (usually hydrometallurgy) for higher recovery rates • Lower recovery rate than hydrometallurgy for Li	• Requires customization based on cathode type • Recovered material may display lower level of performance • Only demonstrated in pilots; high operational and equipment costs

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

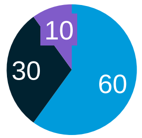
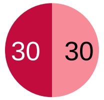
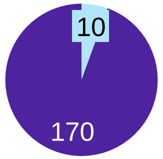
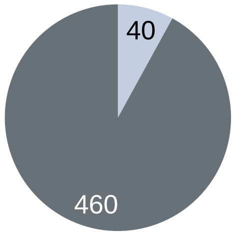
1) Energy based on lifecycle analysis; for pyrometallurgy, ~55% of energy consumption is due to smelting; for hydrometallurgy, 80%+ is due to upstream contributions.

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

	Collection, logistics, and sorting	Discharge and dismantle	Pretreatment	Battery materials recovery
Business Model	• Collection point • Transport and charging • Sorting and warehousing	• Discharging and dismantling • Material sorting	• Pack disassembly • Shredding and sorting	• Pyro- and hydrometallurgy • Hydrometallurgy • Refining
EBITDA estimate by 2030 in Europe, *$M*	***100***  Collection point; Transport & discharging; Others	***60***  Discharging & dismantling; Material sorting	***180***  Pack disassembly; Shredding & sorting	***500***  Pyro- & hydrometallurgy; Hydrometallurgy
Profit potential	• Smaller margin potential • Lower commodity price risk and requires fewer skills	• Smaller margin potential • Lower commodity price risk • Requires specialized safety protocols for battery handling	• Activities with low entry barriers, such as shredding face overcapacity • Lack of scrap for recycling, resulting in lower margin.	• Highest upside potential, if given large enough scale and additional value • Steepest entry barriers due to high CapEx and intellectual capital requirements

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

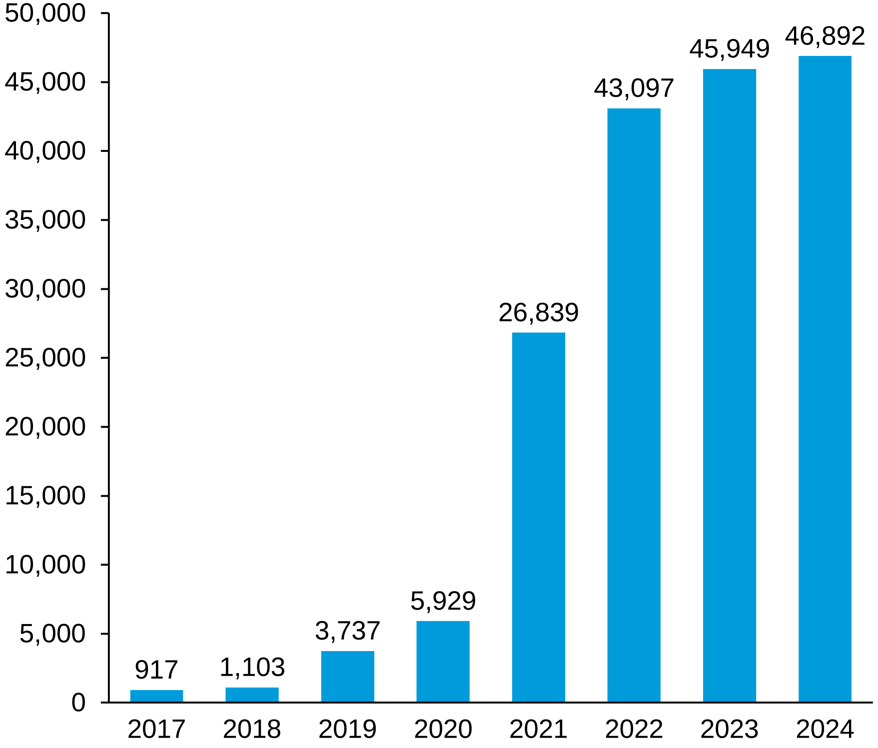
Sources: Striking Gold with EV Battery Recycling (BCG, 2023); Battery recycling (McKinsey, 2023); World of battery recycling (Catalyst podcast, 2024).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Mining for the Energy Transition"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

Columbia Business School
Climate Knowledge Initiative

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

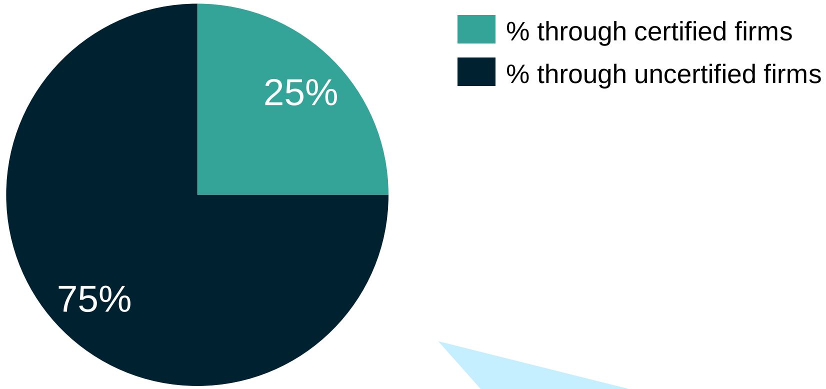
The number of companies registered for battery recycling rose 5,000%+ since 2017

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)

Sources: China EV battery recycling (Dialogue Earth, 2023); China's new used EV power batteries rules (S&P Global, 2024); Forecast Analysis of the Current Status of China's Power Battery Recycling Industry in 2024 (Shenzhen Electronic Chamber of Commerce, 2024); Waste battery recycling ecosystem: Why regular forces can't beat small workshops (STCN, 2023).
Credit: Hassan Riaz, Brenda Rain, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Mining for the Energy Transition" (10 April 2026).

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

NIO

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

User

EV sale without battery component:
~$11,000 less

Customer enrolls in a battery subscription for **~$1,760 per year, with a battery swap fee of ~$11 to $14.**

NIO has also expanded globally, having launched its **first swap station in Abu Dhabi** in early 2025 and **surpassed 30 swap stations in Europe.**

NIO

Second-Life Usage

Batteries at **60-80%** performance level are **repurposed** for renewable energy storage.

Batteries with **<60%** performance level are **recycled.**

Laddering model

- NIO has constructed **over 2,000 swapping stations**, allowing for a robust infrastructure and resilient supply chain
- **80% of drivers in China** have access to a swapping station **within 3 kilometers**
- When depleted, **batteries can be swapped in ~3 to 4 minutes**, faster than the average time it takes to charge EVs (4 to 10 hours for 80% of Level 2 vehicles and 5 to 6 hours for Level 1 PHEV)

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

Recycling capacity of **3,100 mt per year**

Technology	Supply Chain
• Nth Cycle's **electroextraction** produces **44% less emissions** than current recycling methods • Avoids environmentally harmful smelting and waste generation of traditional recovery methods • Modular design allows multiple units to be installed in **parallel to scale production** or **in series to extract multiple metals** from the same feedstock • Extracts **Li, Ni, Mn, and Co** (Cu, Dy, Pr in development)	• System improves upon logistics issues within the CRM supply chain: modular, collocated, and **compatible with multiple industries, mines, recyclers, and metals** • **Integrates** with consumers' physical facilities and equipment; fully customizable • Rapid deployment**: Six-month permitting time and 12-month installation time**, reducing the long and costly approval times with traditional refineries

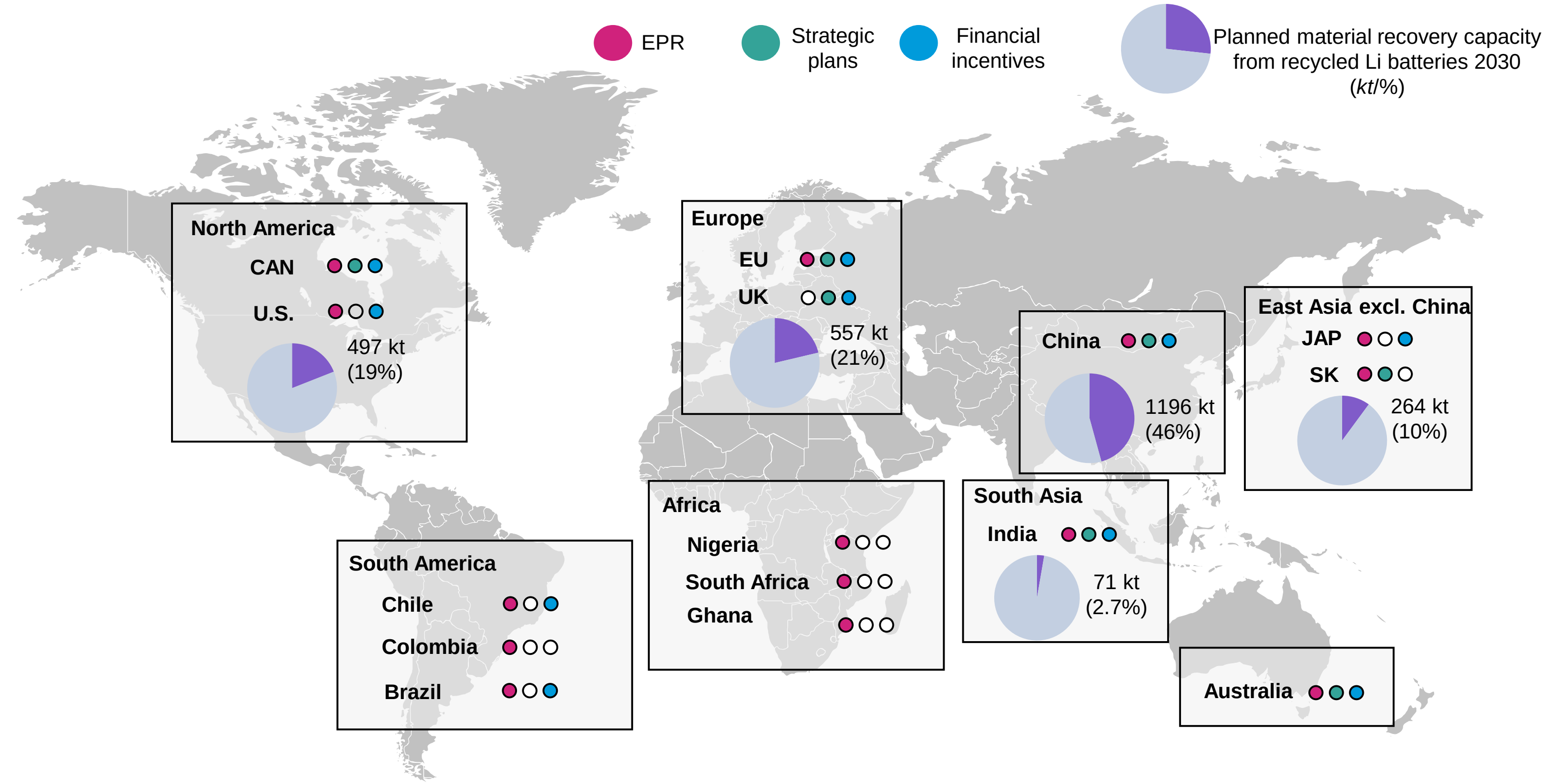
Observations

- 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

Sources: Technology (Nth Cycle); Operations Begin of First Domestic Commercial-Scale Scrap Refining System (Nth Cycle, 2024); Nth cycle receives $7.2 million 48c tax credit (Nth Cycle, 2024); Nth Cycle closes $44 million financing (Nth Cycle, 2023); Nth Cycle secured $2.3 million seed funding (Nth Cycle, 2021); Nth cycle secures $12.5 million in Series A (Nth Cycle, 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).

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.

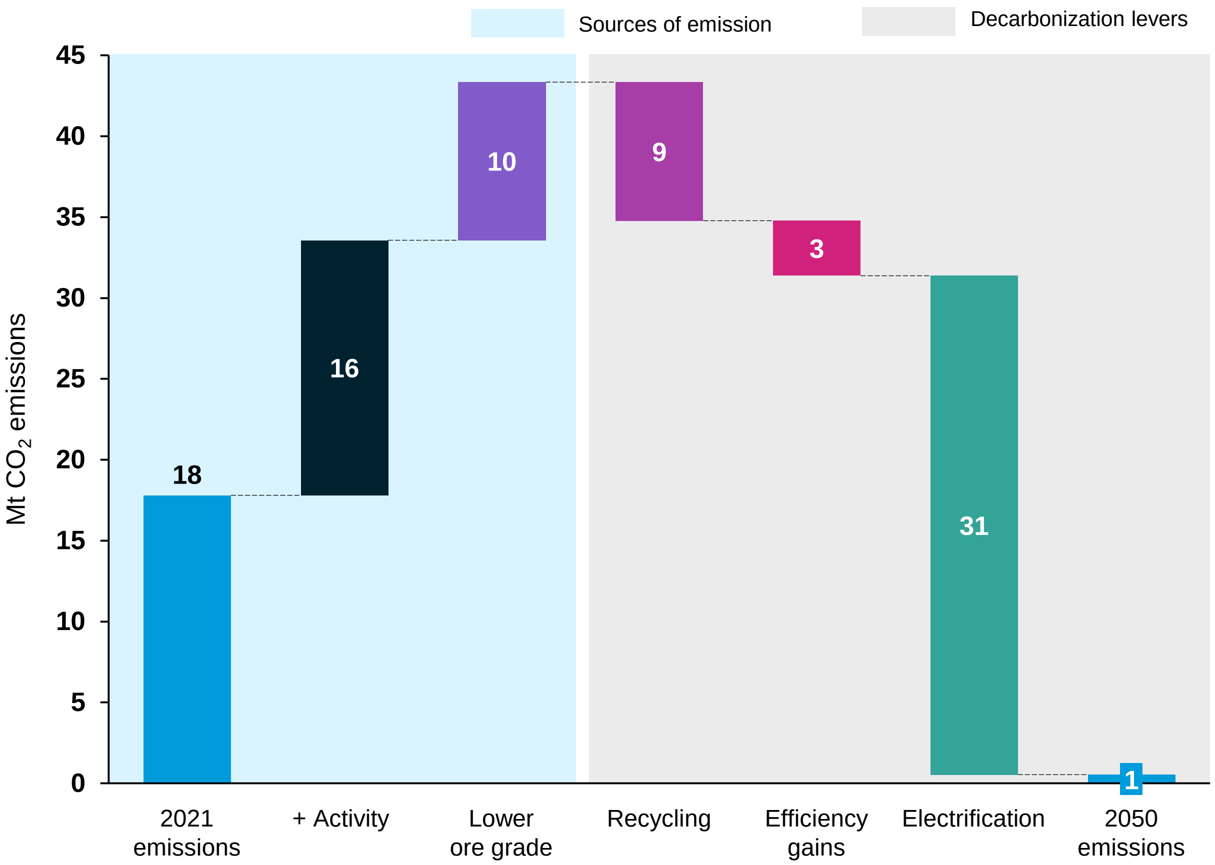
Sources: Recycling of critical minerals (IEA, 2024); Extended producer responsibility system (IEA, 2024); Battery & critical mineral recycling (DOE, 2024); Battery manufacturing & recycling grants (DOE, 2024); EU critical raw materials act (UNECE, 2024); One big beautiful bill (Fastmarkets, 2025); Battery 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).

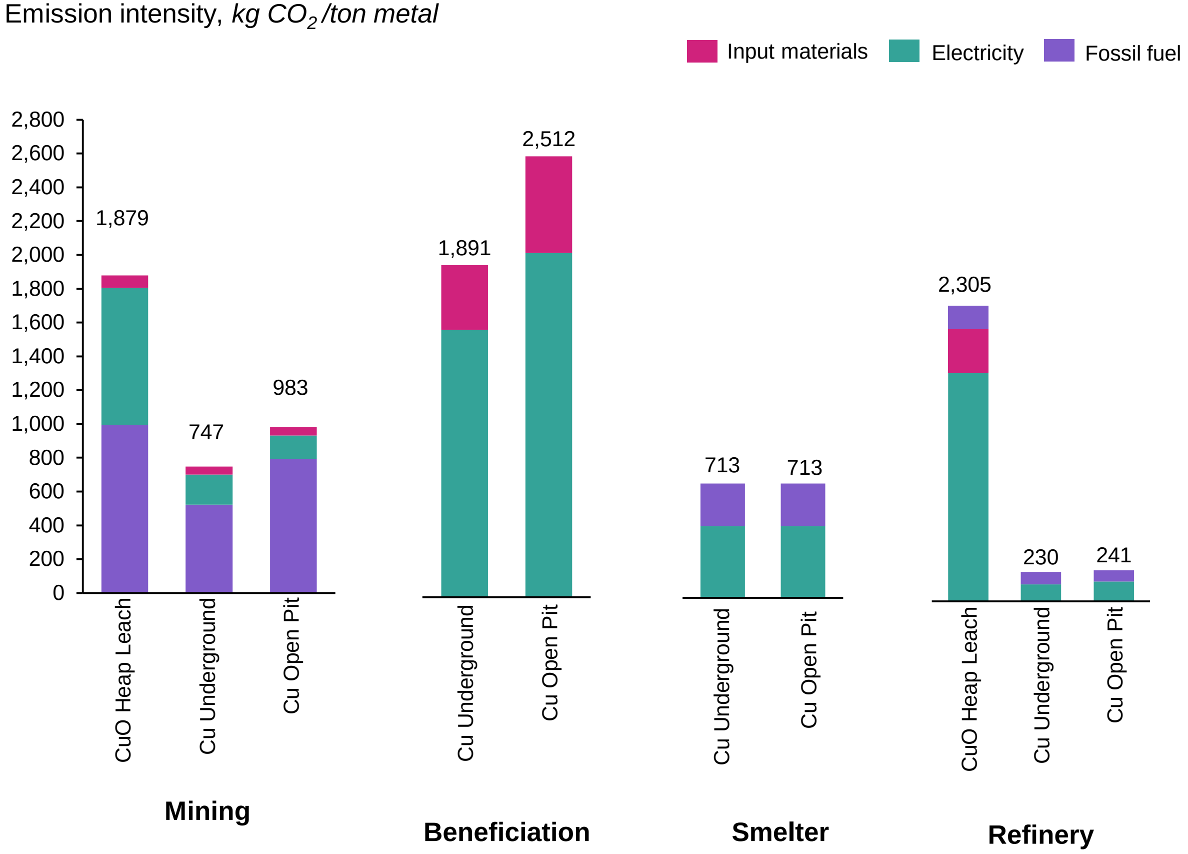
Columbia Business School
Climate Knowledge Initiative

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).

Columbia Business School Climate Knowledge Initiative

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

	Electrify gas appliances	Favor low-carbon electricity sources	Electrify trucks
Technology readiness	●●●	●●●	●●○
Capital requirement	●●○	●●●	●●○
Emission reduction potential, %	-100% (to 0)	-100% (to 0)	-100% (to 0)
Note:	Emission reduction potential depends on emission intensity of the local grid's electricity mix.		
Leading companies	WATTCO (Manufacturer of Electric Heating Elements and Controls), Atlas Copco, SIGMA THERMAL	CODELCO, PRONY Resources, BHP, VULCAN ENERGY	KOMATSU, CATERPILLAR, LIEBHERR

Sources: Climate risk and decarbonization: What every CEO mining needs to know (McKnsey, 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[1]	Founded + total raised	Investors	Activity
KoBold Metals	Mineral exploration company **using AI and an "efficacy of information"** approach to **reduce uncertainty and accelerate discovery** 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)	• Backed by Bill Gates and Jeff Bezos • Valued at **$2.96B** • Operational internationally and scaling
VERAI	Developer of an AI-powered platform that analyzes complex data to **detect hidden mineral deposits in underexplored terrain**, 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	• Capable of locating REE at 9.1% to as high as **20% purity**
EARTH AI	Vertically integrated mineral exploration company **that uses AI to predict ore locations for metals** 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)	• Successful operations — **discovered 117 ppm of indium**, typically found at 1 ppm
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	• **Building U.S. supply chain** for rare earth elements • Building second magnet manufacturing facility in the U.S.
minesense	A platform that **boosts mine productivity and recovery** through real-time, sensor-based **sorting to detect low-grade ore and subtle mineral differences**, 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	• **JPMorgan made $42M investment in 2022** • Named Deloitte Technology Fast 50 winner.
the metals company	**Explores and processes polymetallic nodules from the Clarion Clipperton Zone**, rich in nickel, copper, cobalt, and manganese, which are critical metals for energy and manufacturing. It **focuses exclusively on deep sea** 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	• **U.S. backed subsidiary**, waiting for approval to begin mining per U.S. Executive Order; Korea Zinc recently invested **$85 million**

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).

Columbia Business School
Climate Knowledge Initiative

CKI Team

Research Fellows

Leo Gordon
Master of Public Administration
CKI Fellow
lmg2257@columbia.edu

Khande-Jae Fisher
MS in Sustainability Science
CKI Fellow
kjf2153@columbia.edu

Brenda Rain
MS in Sustainability Management
CKI Fellow
brr2135@columbia.edu

Zacharia Thurston
MS in Sustainability Management
CKI Fellow
zt2326@columbia.edu

CKI Staff and Faculty

Staff

Isabel Hoyos
M.S. in Sustainability Management
Senior Staff Associate
ih2428@columbia.edu

Ariela Farchi Behar
M.S. in Sustainability Management
Staff Associate
af3487@columbia.edu

Pia Doris Morrow
M.S. in Sustainability Management
Staff Associate
pm3346@columbia.edu

Hyae Ryung (Helen) Kim
PhD in Sustainable Development
Senior Research Fellow
hk2901@columbia.edu

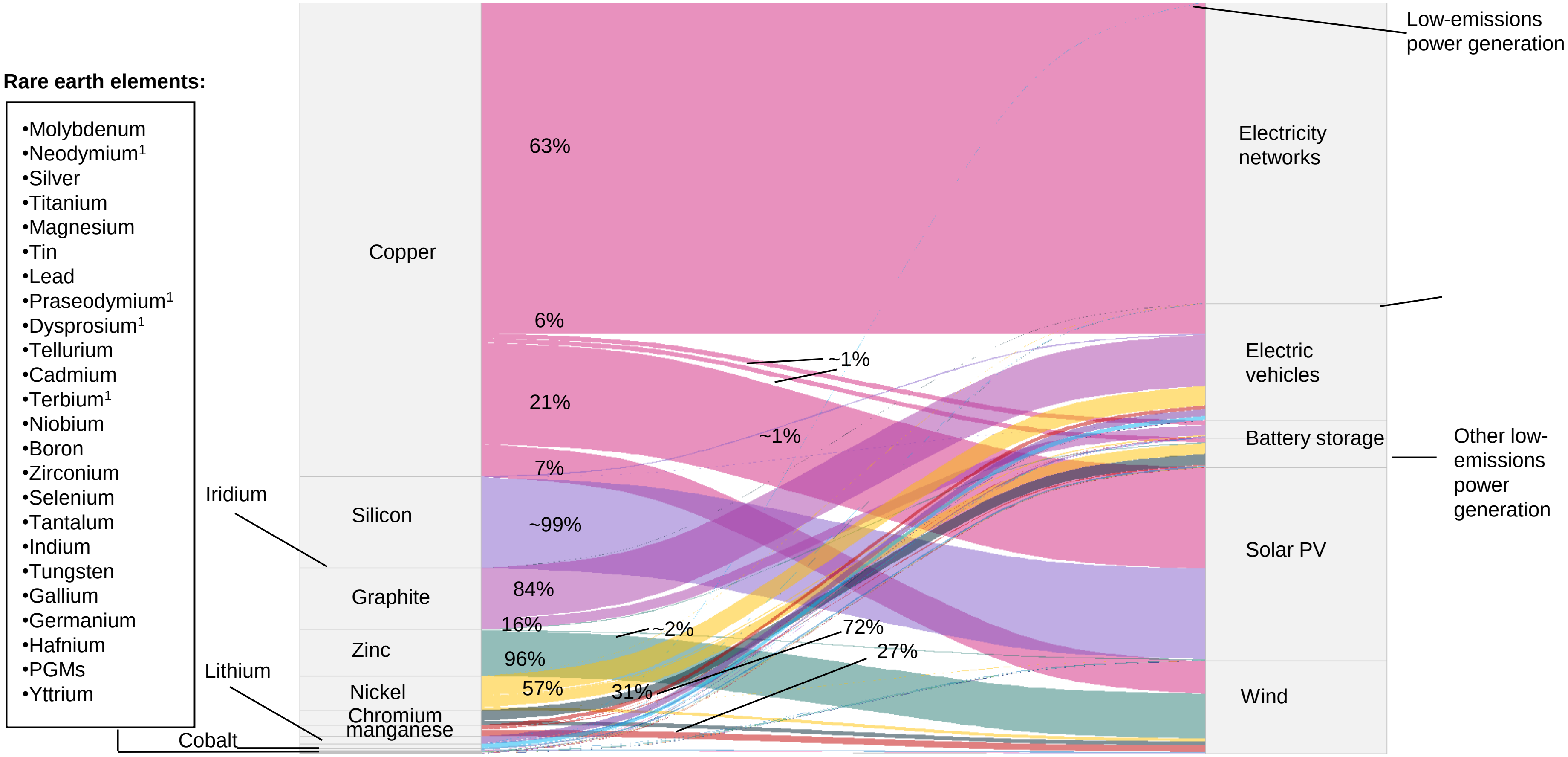
Faculty and Advisors

Gernot Wagner
Senior Lecturer, Columbia Business School
Faculty Director, Climate Knowledge Initiative
gwagner@columbia.edu

Columbia Business School
Climate Knowledge Initiative

The clean energy transition requires a variety of minerals, with copper (Cu) critical across all technologies

Critical minerals demand by key clean technologies, 2024



Observations

- Renewable power generation (solar PV and wind) requires between **11 to 15 different critical minerals**
- Developing **electricity networks** relies heavily on **copper** supply
- **Rare earth elements (REE)** are employed in developing wind technologies (~55% total kt) related to permanent magnets and EV motors (~45%)
- Although proportionally some elements are less required in terms of volume, they are pivotal to produce clean tech like **EVs, which require 50-100 kg of graphite in their battery packs**

1) Refers to magnet rare earth elements, which typically are stronger and more resistant to demagnetize in comparison to regular REEs.

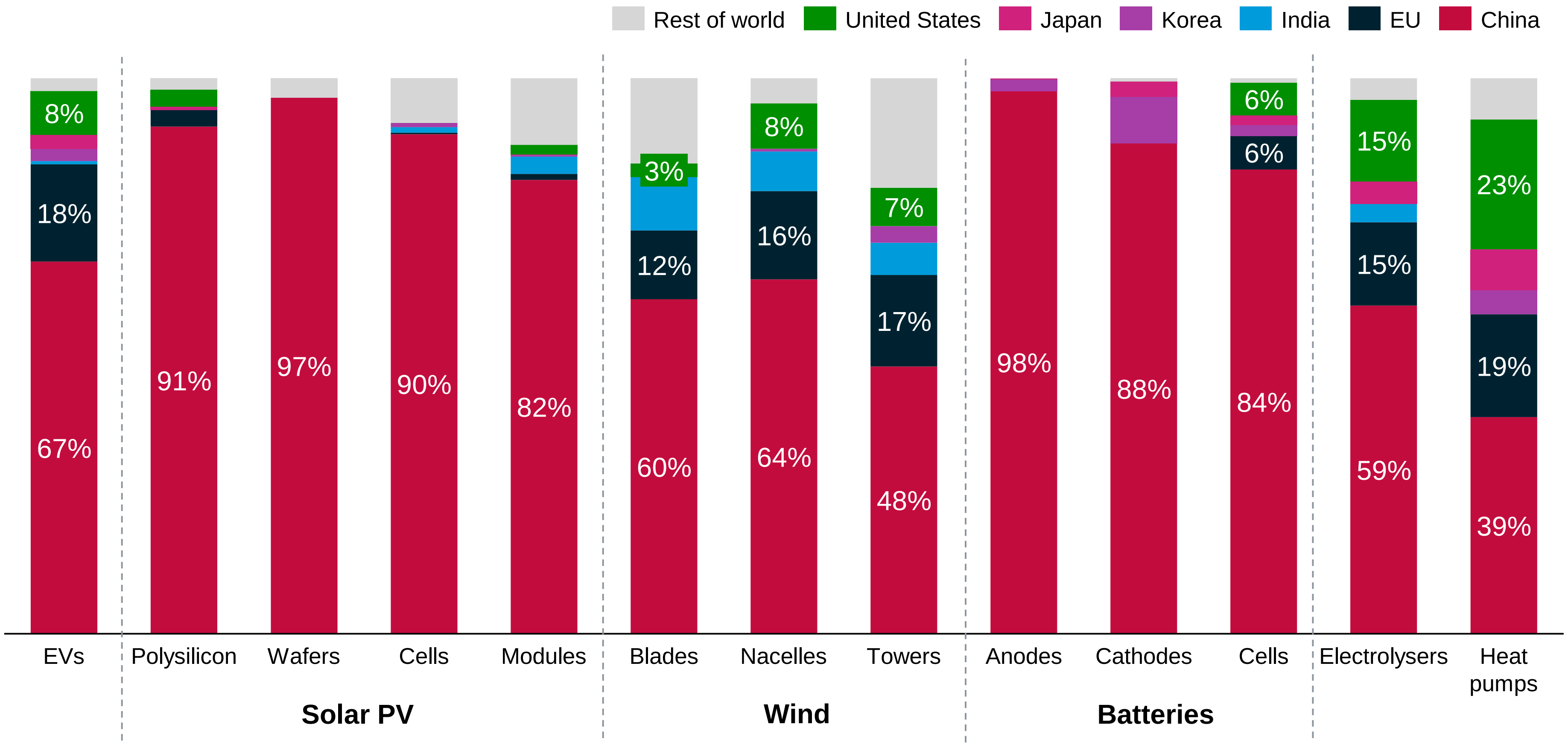
Sources: The 6 Major Applications of Rare Earth Elements in Renewable Energy (Stanford Advanced Materials, 2025); Critical Minerals Outlook 2025 (IEA, 2025); Synthetic graphite for EV batteries (Reuters, 2023).

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

Columbia Business School
Climate Knowledge Initiative

Solar PV, battery, and EV manufacturing are highly concentrated in China; other energy tech sectors are more globally distributed

Geographical distribution of energy tech manufacturing capacity, *2023 %*

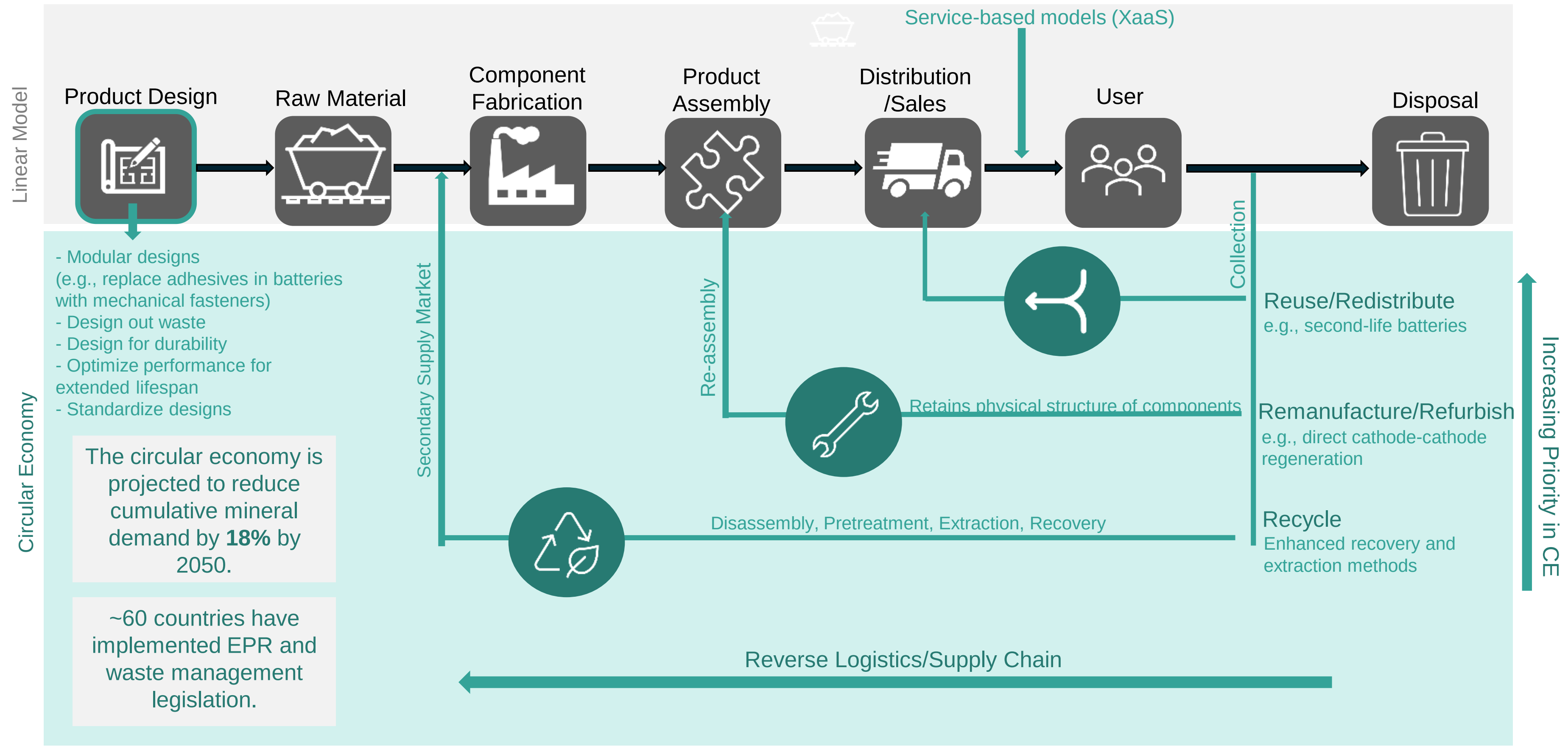


Observations

- Though countries in Asia Pacific are developing manufacturing capacity, many facilities are Chinese-owned rather than domestic
- Governments are mobilizing support to domestic manufacturers to increase capacity: In 2025, **Chile and the EU signed an agreement to invest up to 216.5 million** euros in Chile's renewable hydrogen industry
- Under the Stated Polices Scenario[1], China is projected to lead average annual investment in solar PV, wind, and batteries until 2030; post-2030, North America is expected to surpass China in annual investments across batteries, solar PV, wind, and heat pumps

Note: 1) EA STEPS/Stated Policies considers existing policies and those under development.
Sources: Energy Technology Perspectives (IEA, 2024); EU, EIB, and KfW to finance renewable hydrogen projects in Chile with up to €216.5 million (Delegation of the EU to Chile, 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).

CE strategies extend value creation of CRMs, emphasizing better design, reuse, and remanufacturing



Observations

- Closing critical mineral loops requires shifting consumption and production toward longer product life and stronger end-of-life collection
- Circularity creates significant producer value for discarded minerals (e.g., up to US$297 million in Cu alone)
- Linear supply chains are highly vulnerable to climate and geopolitical disruptions
- The circular supply chain localizes resource loops, minimizing waste and prioritizing resilient networks to withstand shocks and stresses
- For critical minerals, extending product life through reuse and remanufacturing is preferred over recycling due to process inefficiencies and costs in recovery

Regional flows in the EU.
Sources: Circular transitions (UNEP, 2025); Tools for Circularity (ICMM, 2024); A circular economy for critical minerals is fundamental for our future (Deloitte, 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).

Unlocking key critical mineral solutions will require supply chain diversification, closed loops, and strong international partnerships

Key Problems

Environment

- **Water stress in mining locations**
  - Drought limits the water needed for mining and processing; water stress fuels conflict and creates tighter regulations
- **Poor waste management**
  - High waste volumes intensify impacts on land, water, and communities

Industry

- **Reduced ore qualities**
  - Lower ore grades increase energy, water, and chemical use, raising production costs
  - Reduced output per ton of ore constrains supply and drives market volatility
- **Fragmented supply chain**
  - Refining and downstream capacity is concentrated in China, creating supply chain vulnerabilities

Policy

- **Nationalism**
  - Export bans, royalty hikes, and state intervention disrupt supply security
- **Fragmented supply chain**
  - Concentrations of reserves in a few countries expose markets to conflict and trade disputes
- **Investment uncertainty**
  - Shifting policies and unstable governance deter capital and slow project development

• Potential Solutions

Environment

- **Water efficiency and recycling**
  - Deploy closed-loop systems and low-water processing to reduce reliance on scarce water
- **Climate resilient infrastructure**
  - Invest in backup power and water supplies
- **Responsible waste management**
  - Expand waste valorization and tailings management to reduce impacts

Industry

- **Improved extraction techniques**
  - Invest in advanced extraction and processing tech to improve efficiency
- **Improved supply chain resilience**
  - Diversify supply sources and pursue value addition
  - Develop secondary/recycled mineral markets and employ circular economy principles to reduce demand on volatile primary markets

Policy

- **Partnerships**
  - Negotiate long-term offtake agreements and strengthen local partnerships
- **Diversified supply chains**
  - Develop supply routes across regions and invest in friendly and reliable jurisdictions
  - Implement nationwide strategic plans and incentives for recycling
- **Mixed financing tools**
  - Use risk-sharing tools (insurance, blended finance) to attract capital despite instability

Sources: 10 ways the world can improve access to minerals for the energy transition (World Economic Forum, 2024); Shoring Up the Critical Mineral Supply (The Regulatory Review, 2025); Global Critical Minerals Outlook (IEA, 2025).
Credit: Khande-Jae Fisher, Zacharia Thurston, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Mining for the Energy Transition" (10 April 2026).

Columbia Business School
Climate Knowledge Initiative

Variations in mining tech can meet demand and hedge climate risk

TRL: 1= industrial use, 5 = conceptual

Technology Type	TRL	Description	Company Highlight
Traditional Mining	1	Open-pit/underground mining, then crushing and grinding	RioTinto, VALE
Heap Leaching	1	Leaching metals from ore heaps via acid or alkaline	Metso:Outotec, BARRICK
Froth Flotation	1	Use of chemicals and air bubbles to separate minerals	ERIEZ, Metso:Outotec, BHP
Solvent Extraction & Electrowinning	1	Electrochemical separation of metals in leachate	Freeport-McMoRan Copper & Gold, KGHM, Metso:Outotec
Pyrometallurgy	1	High-temperature smelting to separate metal	AngloAmerican, BARRICK, tmc
Hydrometallurgy	2	Leaching ores with aqueous solutions	ENEOS, metso minerals
Bioleaching (Biohydrometallurgy) and Biosorption	1 / 4	Use of bacteria to leach metals from ore (only for select minerals)	CODELCO, BHP, AngloAmerican, BARRICK
Direct Lithium Extraction (DLE)	3	Selective adsorption or solvent extraction from brines	Livent, SQM
Ion Exchange	2	Separation of metal ions using resins or membranes	Purolite, LANXESS, SUNRESIN
Plasma Separation	5	High-energy plasma used to separate elements	pi7 Technologies
Electrochemical Separation	4	Uses electric currents to isolate specific ions	Mangrove Lithium, Lithios
Nanofiltration/Membrane Separation	4	Filters ions using selective membranes	nanostone water, DUPONT
Magnetic Separation	2	Uses magnetic properties to isolate minerals	BUNTING, MULTOTEC
Phytomining	5	Hyperaccumulator plants to absorb metals from soil	Metalplant
Urban Mining (Recycling)	3	Extraction of critical minerals from e-waste	NOVEON

Sources: Heap Leaching in Mining (Euromines, 2012); Mining – Flotation (Hycontrol); Solvent Extraction for Hydrometallurgy (Syensquo, 2025); Electrowinning techniques in recovery of critical minerals (20 Years, 2025); Pyrometallurgy in the Recovery of Niobium and Tantalum (20 Years, 2022); Efficiently recovering critical materials and rare earth elements (Koch Modular Process Systems); Producing Copper Nature's way, Bioleaching (Copper Development Association, 2004); Selective biosorption (iScience, 2025); Sustainable lithium production (SLB); Ion exchange resins for mining and metallurgy) Lanxess); Cleaning up critical minerals and materials production (MIT News, 2025); Advancing Electrochemistry in Critical Resource Recovery (Argonne National Laboratory); Critical Mineral Separations (Annual Reviews, 2024); Magnetic separation in mining (2023); Phtomining bolsters U.S. mineral supply chains (ARPA-E, 2024); Recyling Critical Minerals (IEA, 2024).

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

Columbia Business School
Climate Knowledge Initiative

Glossary

AD/CVD	Antidumping and countervailing duties
APAC	Asia Pacific
APS	Announced Pledges Scenario
ASEAN	Association of Southeast Asian Nations
BaaS	Battery as a service
BIPV	Building integrated PV
BoS	Balance of system
BSF	Back surface field
c-Si	Crystalline silicon
C&I	Commercial & industrial
CAGR	Compound annual growth rate
CapEx	Capital expenditures
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CPV	Concentrator PV
CRM	Critical mineral
CSP	Concentrated solar power
EMEA	Europe, Middle East, and Africa
EPC	Engineering, procurement, and construction
EPR	Extended Producer Responsibility
ESP	Energy service provider
EVA	Ethylene vinyl acetate
FiT	Feed-in tariff
FBR	Fluidized bed reactor
FPV	Floating PV
HJT	Silicon heterojunction cells
IRA	Inflation Reduction Act
IRR	Internal rate of return
ITC	Investment tax credit
LID	Light-induced degradation
LFP	Lithium iron phosphate battery
MOIC	Multiple on invested capital
Mono-Si	Monocrystalline silicon
NPV	Net present value
NZE	Net Zero Scenario
OBBBA	One Big Beautiful Bill Act
OEMs	Original equipment manufacturers
OpEx	Operating expenses
O&M	Operating and maintenance
PAYG	Pay as you go
PERC	Passivated emitter and rear cell
Poly-Si	Polycrystalline silicon
PPA	Power purchase agreement
PTC	Production tax credit
PV	Photovoltaic
REC	Renewable energy credit
REE	Rare earth elements
R&D	Research and development

Glossary

RPS	Renewable portfolio standard
SG&A	Selling, general, and admin. expenses
SiO_2	Quartzite
SPV	Special-purpose vehicle
SPS	Stated Policies Scenario
TCO	Transparent conductive oxide
VIPV	Vehicle integrated PV
VOST	Value of solar tariffs
XaaS	X as a service