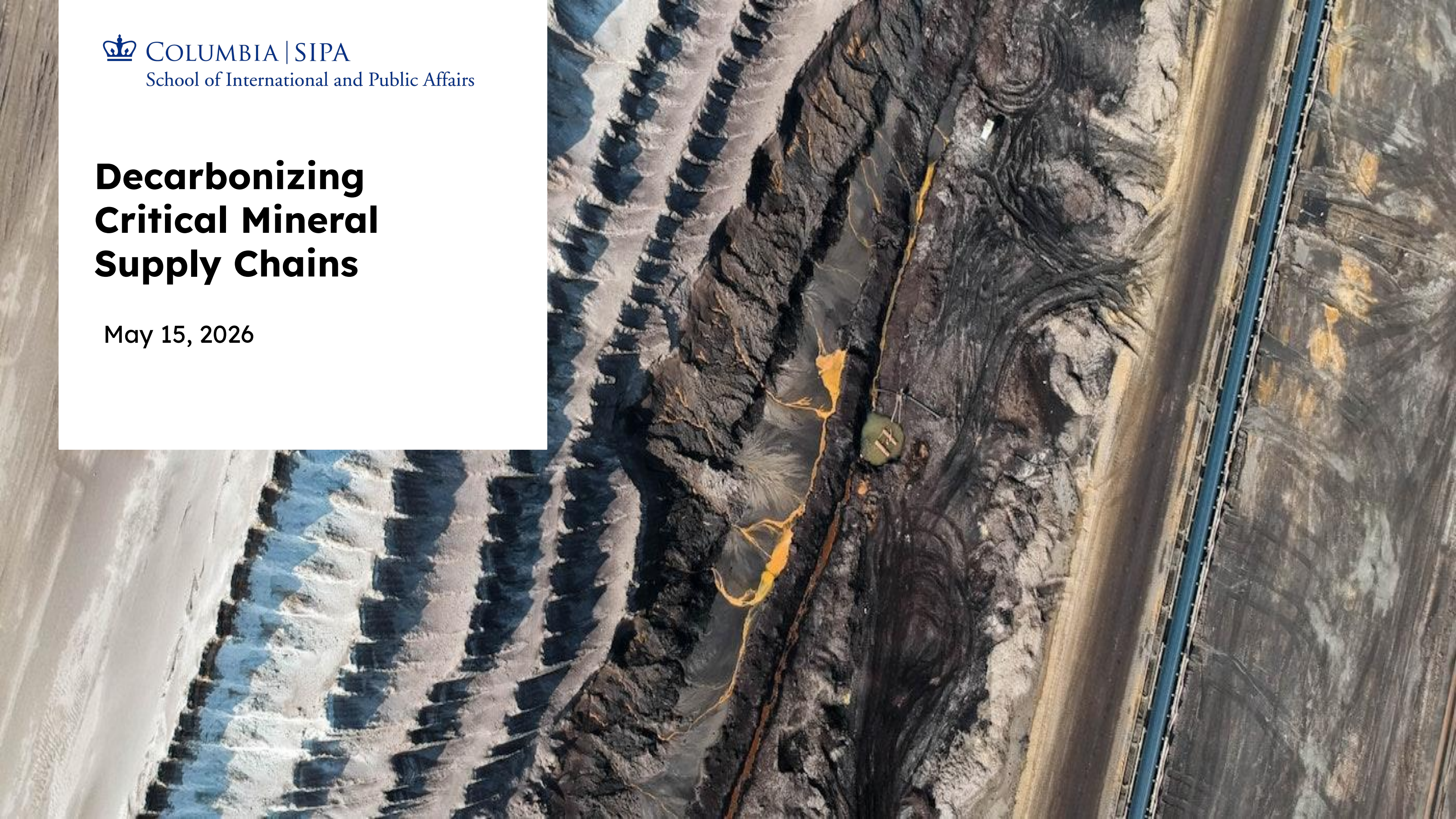

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Decarbonizing Critical Mineral Supply Chains

May 15, 2026

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Executive summary

The energy transition is accelerating demand for critical minerals, yet expanding production under business-as-usual conditions risks significant GHG emissions growth. This project complements the IEA's existing work by quantifying the emissions profile of four priority supply chains: copper, lithium, nickel, and synthetic graphite, across upstream and midstream stages, and mapping concrete decarbonization pathways.

Emission intensities vary dramatically by geography and processing route: nickel ranges from 6 to 93 tCO_2/tNi, and graphitization alone accounts for 65–80% of synthetic graphite emissions. Ore grade is a cross-cutting driver for copper and nickel, and industry reports tend to understate lithium emissions intensities due to incomplete grid and renewables accounting. Without intervention, demand growth could increase sectoral emissions by 76% for lithium, 95% for nickel, 108% for synthetic graphite, and 40% for copper by 2050.

Decarbonization requires deploying four cross-cutting levers across all minerals: grid electrification, low-emission fuels, energy efficiency, and carbon capture. However, these are not enough on their own. Process-level levers are equally critical: DLE for lithium brines and HPAL over RKEF for nickel laterites can reduce emissions by 30–50%. Enclosed induction furnaces are already at early commercial scale with up to 90% emissions reductions, while bio-based graphite feedstocks remain at pilot stage.

Closing the cost gap for low-carbon minerals requires coordinated action across miners, refiners, OEMs, and policymakers, as capital decisions made in the next five years will lock in emissions for over two decades.

About the client

The International Energy Agency (IEA) is the world's leading authority on energy data, policy analysis, and international cooperation. Created in 1974 by OECD member countries, its role has evolved from oil security to encompassing clean energy transitions, technology innovation, and climate solutions by engaging both member and partner governments globally.

This project is in consultation with IEA's Critical Minerals Division of the Directorate of Sustainability, Technology & Outlooks. The Critical Minerals Division drives IEA research on critical minerals markets, trends, and supply chains, including publishing its yearly flagship report — the Global Critical Minerals Outlook.

About the project team

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Acknowledgements

We thank the many individuals and organizations whose insights and guidance made this project possible.

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Research & Academia
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Industry
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Industry Associations & Nonprofits
Initiative for Responsible Mining Assurance (IRMA) · International Council on Mining and Metals (ICMM) · Nickel Institute · Cobalt Institute

Consulting
Trivium China

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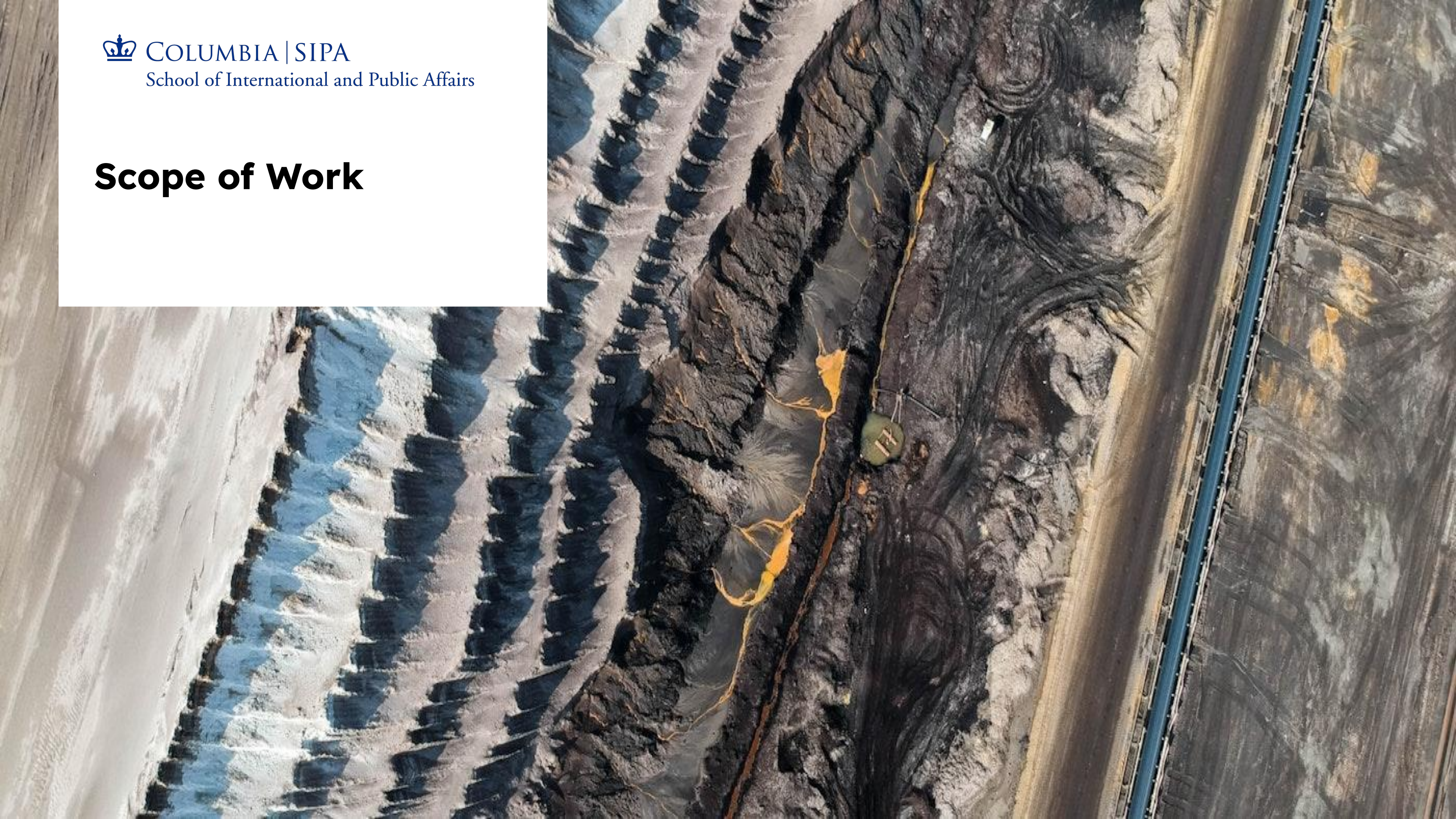
Scope of Work



This project seeks to complement IEA's work with actionable insights on emissions from critical minerals

IEA already covers:

Detailed assessment of the latest market and investment trends, along with their implications for critical minerals security

Key policies related to critical minerals needed for the energy transition

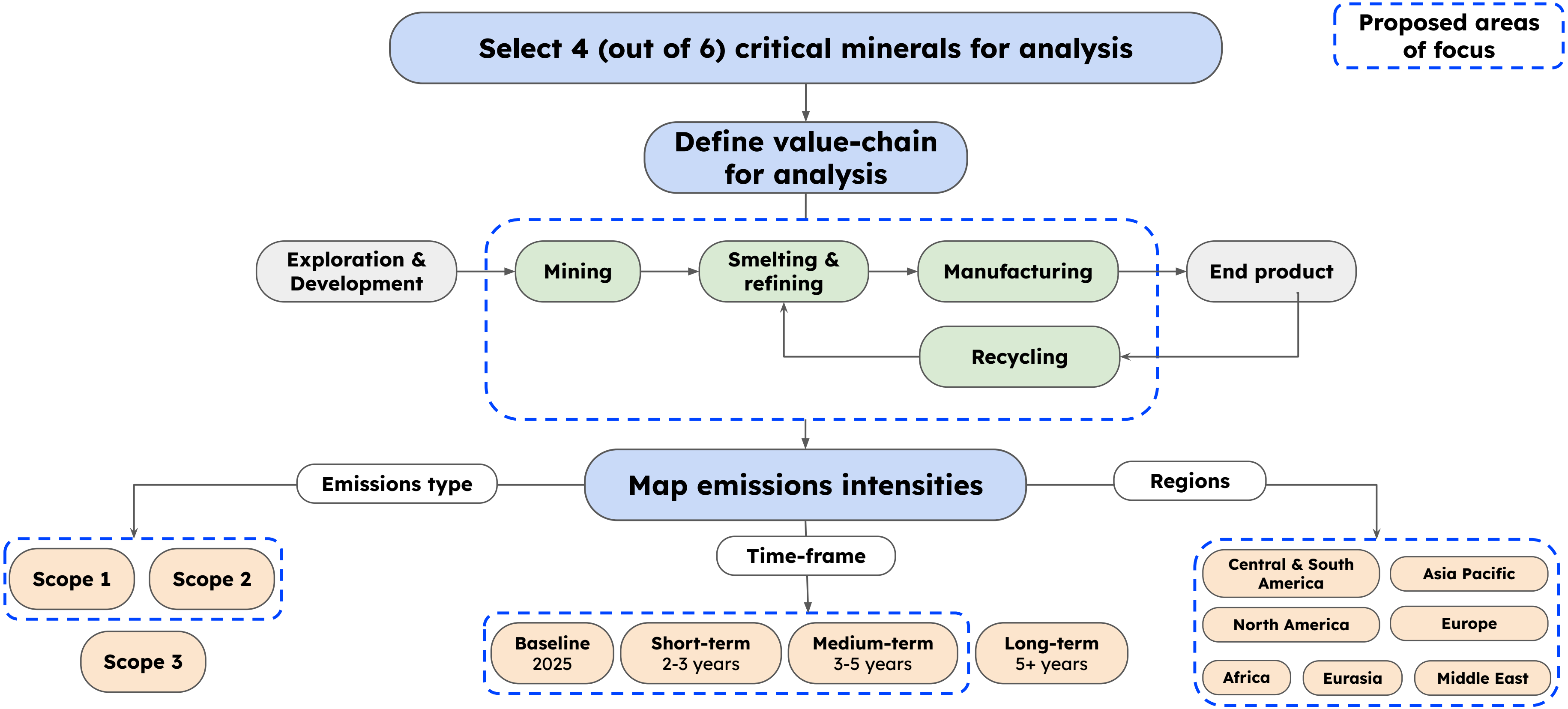
Supply and demand projections

How this project complements IEA's work:

Our project zooms in on the **emissions profile** of critical mineral supply chains and the concrete **levers to reduce them**

- **Quantifies emissions profiles** across upstream (mining) and midstream (refining) stages
- **Identifies key drivers of emissions intensity**, including technology, energy mix and geology
- **Maps best available and emerging decarbonization options**, by mineral and stage
- **Translates technical insights into actionable pathways**, distinguishing near-, mid- and long-term levers

We narrowed the scope to 4 priority minerals, focusing on upstream and midstream stages



Our mineral selection criteria reflect IEA priorities on demand growth, supply concentration and geopolitics

Criteria	Category Description	Weight	Copper	Lithium	Cobalt	Nickel	Graphite	Rare Earths
State of the art	*How advanced is the research about decarbonization?*	30%	5	4	3	4	2	2
Data availability	*Is there sufficient data on emissions across Scopes 1-3?*	30%	5	4	3	4	2	2
Criticality	*Is there a gap between current supply and future demand of this mineral? Can it be replaced?*	15%	3	5	3	4	5	4
Value added	*Is there a gap on research/analysis for decarbonization of this CM?*	20%	2	2	3	1	5	5
Geopolitical relevance	*Are the CMs concentrated geographically? Is the supply chain vulnerable to geopolitical tensions/export controls or conflict risks?*	5%	1	3	3	2	4	5
Score (weighted average)			**3.9**	**3.7**	**3.0**	**3.3**	**3.2**	**3.05**

Based on the matrix & discussion with IEA, we propose to cover:
Copper, Lithium, Nickel, and Synthetic Graphite.

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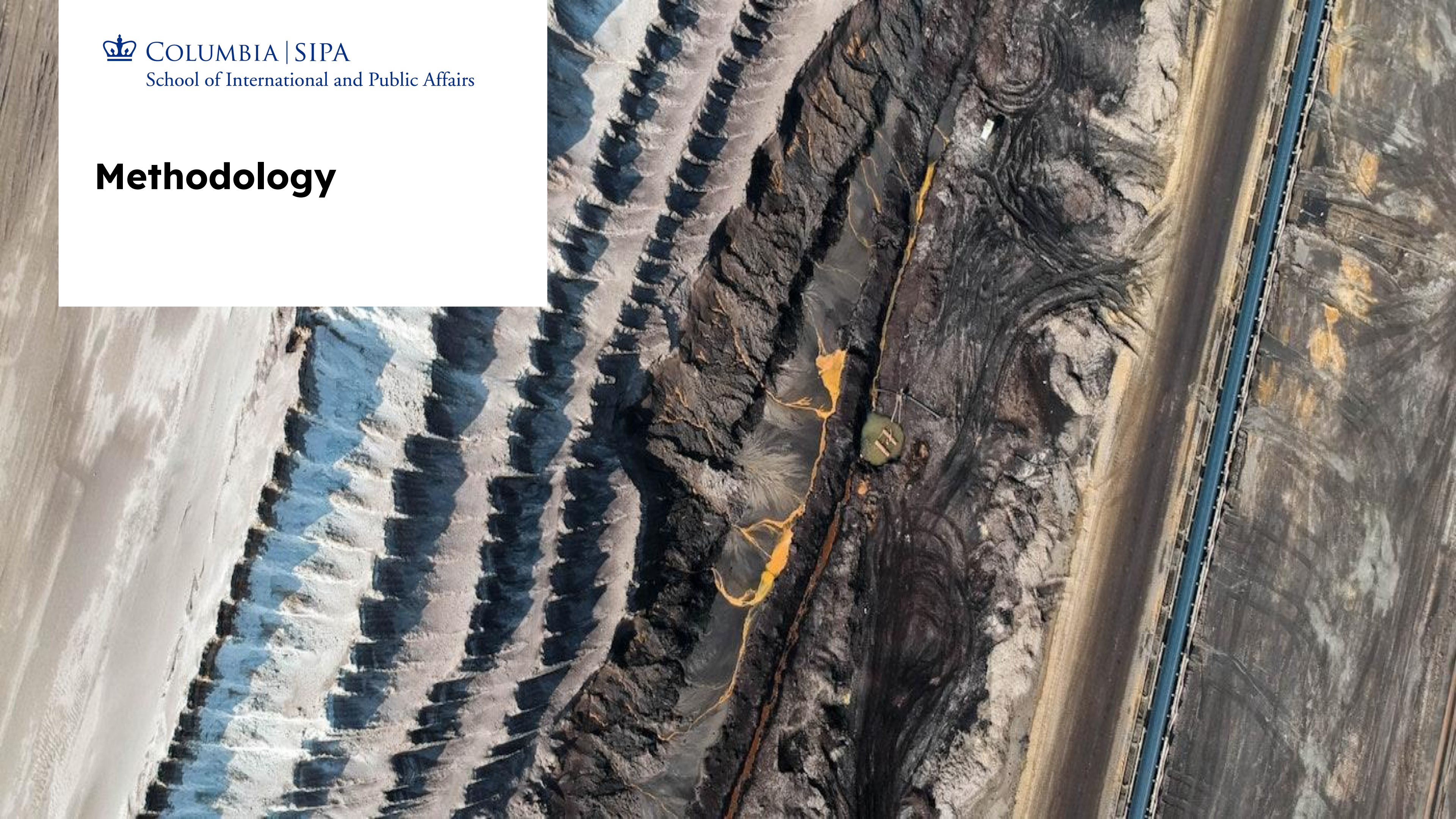
Methodology



We followed a structured, emissions-focused methodology to identify decarbonization opportunities

1. Map value chain

Map mine and processing sites worldwide

Understand value chain process and identify main source of emissions

High-level research to assess production levels and data availability

2. Build database

Deep research from:
- Academic papers
- Think tanks
- Company reports

Collect data:
- Volume produced
- Energy consumption
- Emissions

Define assumptions to fill data gaps

Build database: public data + assumptions

3. Identify levers

Interview experts

Identify and analyze decarbonization technologies

Build case studies for selected technologies

4. Build roadmap

Develop a decarbonization roadmap based on levers availability.

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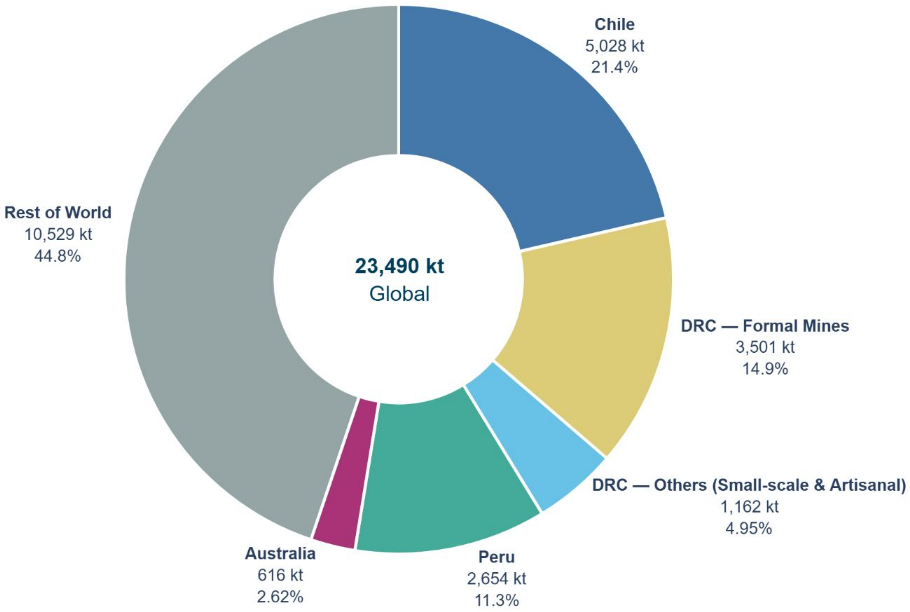
Database deep dive: Copper

Overview of the copper value-chain, scope of research and database coverage



Overview:

- Current Cu Production accounts for ~ 0.2 – 0.3% of global GHG emissions
- Future demand growth forecast upto +40% by 2050; driven by clean tech, AI & datacenters growth

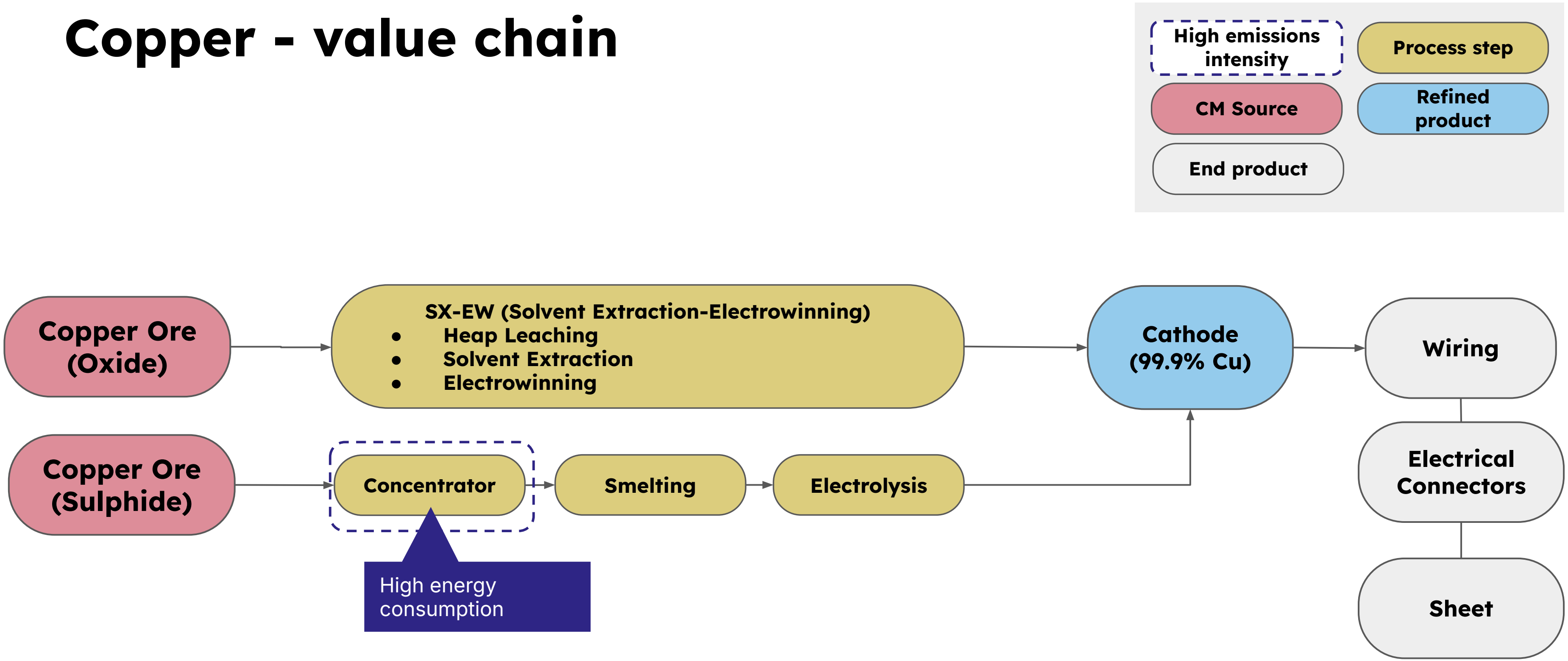
Key Risks:

- Falling ore-grades → emissions/tCu increases with rising throughput to meet demand
- Electrification without reliable low-carbon grids → fossil-fuel dependent backup continues

Dataset Summary:

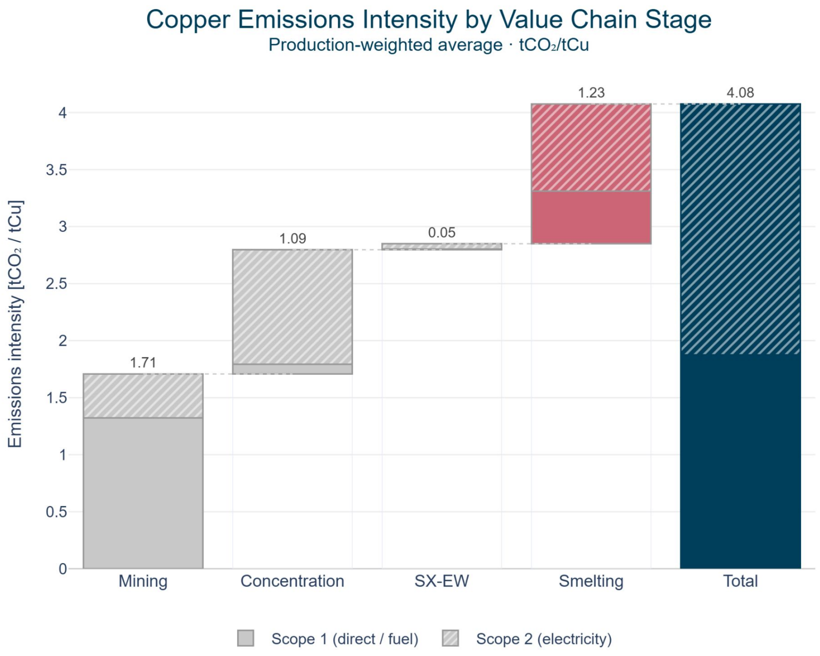
- Upstream & Midstream: 85% of emissions (Downstream: 15% of Emissions; out of scope)
- Dataset covers ~55% of global Cu production for CY2025 across Chile, DRC, Peru, Australia
- China dominates midstream; > 50% global smelting
- DRC smelts & refines >80% of own production (mine-to-cathode; based on DRC export records)

Copper - value chain



Sources: Super Fund Research Center, Copper Mining and Processing: Processing Copper Ores, 2015.

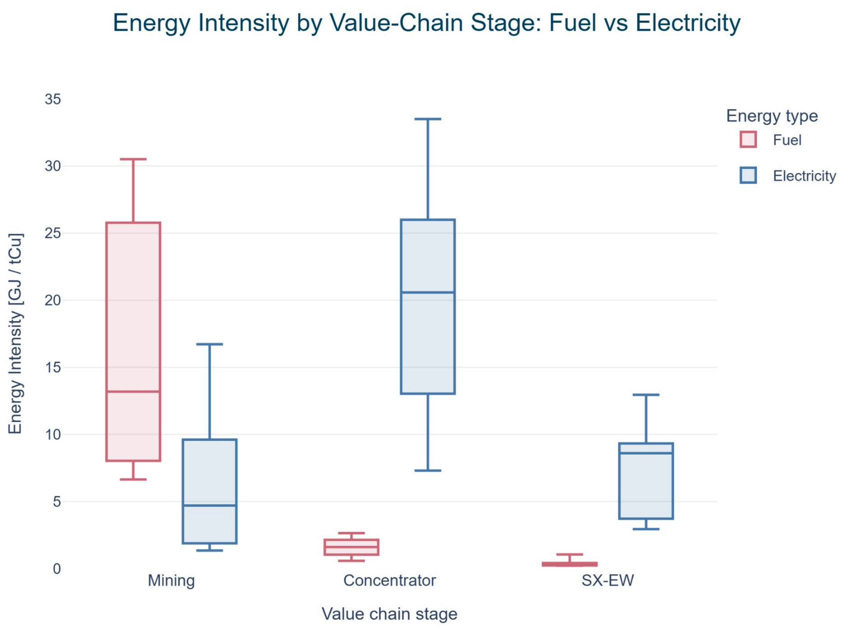
Mining and concentration are the main drivers of emissions for copper value chain



Key takeaways:

- **Upstream & Midstream:**
  ~85% of full-value chain Cu emissions
  (Downstream: 15% of Emissions; out of scope)
- **Upstream:** (mining/extraction, concentration & SX-EW) accounts for ~70% of database emissions
- **Midstream:** (smelting & refining) accounts for the remaining ~30% of database emissions
- **Scope 1/Scope 2 split:** 46% | 54%
- China dominates midstream: >50% of global smelting
- DRC smelts & refines >80% of own production
  (mine-to-cathode; based on DRC export records)
- Fuel-dependence is concentrated in extraction
  (haulage, trucks, trolleys, explosives etc.)
- Electricity use is concentrated outside extraction;
  (mined-ore-to-cathode; concentration, SX-EW, smelting)

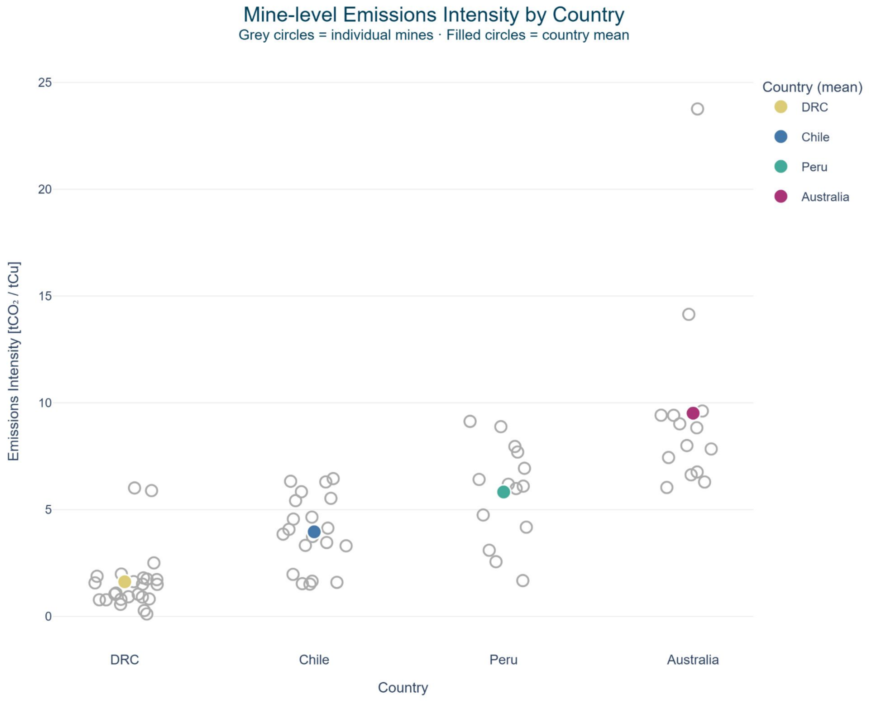
Electricity is consistently used across the value chain, highlighting the relevance of grid decarbonization



Key takeaways:

- Grid decarbonization + electrification efforts will be a key driver for mine-level abatement
- Mining energy-use → driven by mine-size (*length of trips*), ore grade (*# of trips*), depth (*ventilation + haulage*)
- Concentration energy-use spread → greatly impacted by grid EF and ore grade
- SX-EW spread is narrow; due to a fixed EW floor (~8 GJ/tCu) → anchors distribution regardless of ore grade

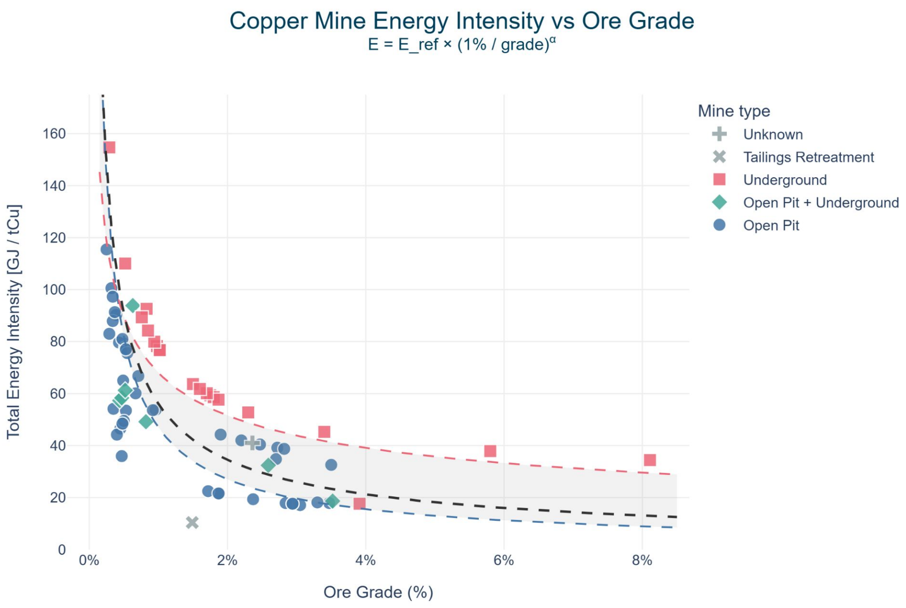
Lower emission intensity driven by low-carbon grids, electrification and higher ore-grades



Key takeaways:

- 100% RE PPAs can greatly drive down mine level emissions, especially when combined with electrification upgrades
- Electrification & Renewable PPA efforts
  - **Chile:** Escondida (BHP), Los Pelambres (Antofagasta)
  - **Peru:** Cerro Verde (Freeport-McMoRan)
  - **DRC:** Kamoa-Kakula Complex
- DRC has one of the lower EFs, driven by a combination of very-high ore grade + high RE-mix grid (hydro-dominant)
- Smaller-scale and ASM operations in DRC (almost entirely diesel)
- Grid inaccessibility / diesel reliance + very low ore grades can significantly increase mine emissions (see: Australian outliers)

Log-linear relationship between Ore Grade (% Cu) and Energy Intensity (GJ/tCu)



$$EI_{mine} = EI_{base} \times \left(\text{Ore Grade}_{base} / \text{Ore Grade}_{mine} \right)^{0.7}$$

Insights:

- As grade halves, energy requirement per tCu approximately doubles [1]
- Exponent chosen to be 0.7, fitted exponent in published datasets falls in the range 0.4–0.8 [2]
- Underground mines have higher baseline energy use due to additional ventilation, haulage needs (energy scales with depth)

Key Risks:

- Falling ore-grades → emissions/tCu increases with rising throughput to meet demand
- Electrification without reliable low-carbon grids → fossil-fuel dependent backup continues

Sources: 1 Norgate & Haque (2010); Rankin (2016) | 2 Rankin (2016) | 3 Coursol et al. (2015)

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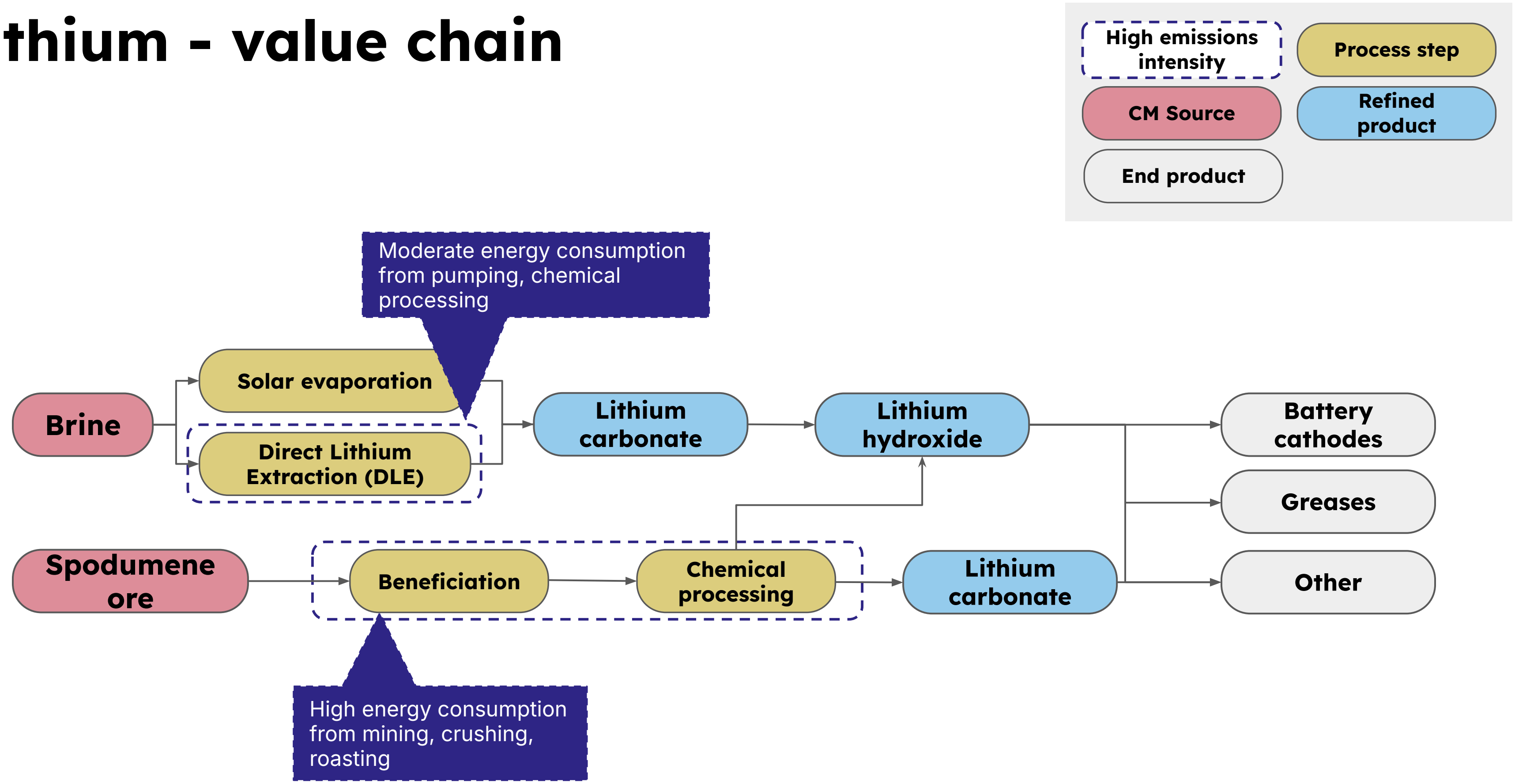
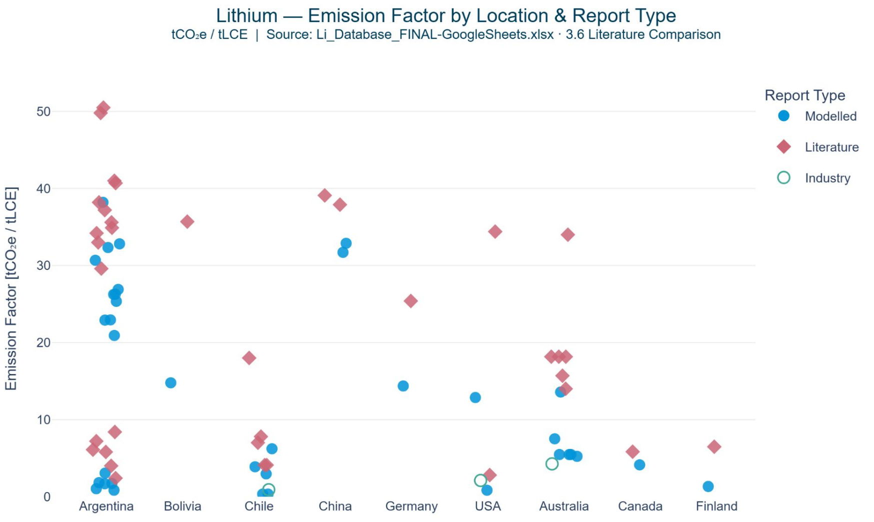
Database deep dive: Lithium

Lithium - value chain



Sources: Wu et. al, *Lithium resources and novel strategies for their extraction and purification*, 2025

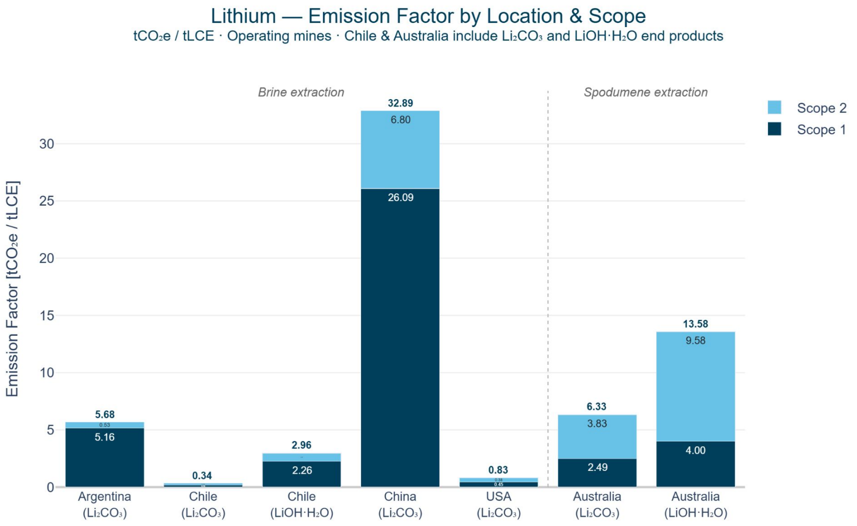
Total emissions intensity for lithium varies drastically for production from brine and spodumene ore



Key takeaways:

- Industry reports tend to **understate emissions intensities**, likely driven by use of renewable energy credits or behind-the-meter energy renewables generation.
- Literature includes Scope 3 emissions, while modeled data does not.
- Literature also utilizes **average grid emissions factors**, which may not account for localized grid conditions.

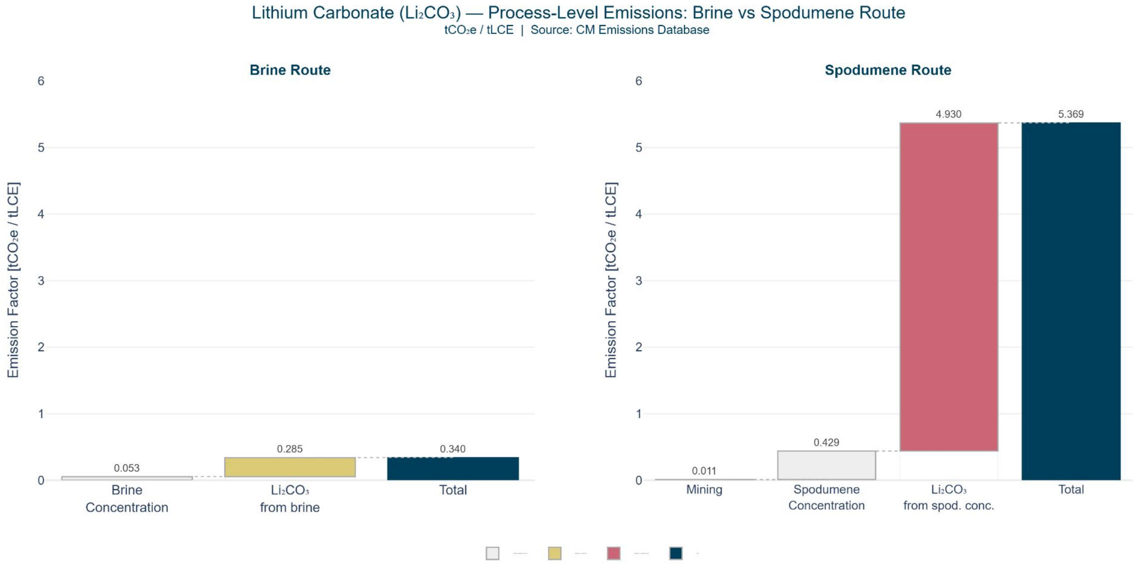
Scope 1 and Scope 2 emissions contribute nearly equally to overall emissions from Li processing



Key takeaways:

- Data accounts for over 50% of global lithium production in 2024.
- Scope 1 emissions from fuel use comprise **55% of total lithium Scope 1 & 2 emissions (4.9 MtCO_2e/yr).**
- Emissions factors can vary dramatically for the same process route (e.g. brine extraction from Chile vs. China) due to grid composition, use of diesel instead of natural gas for heating, and differing energy intensity of the extraction process. *(Schenker et. al, 2025)*

Midstream steps contribute the greatest share to emissions from Li_2CO_3 production

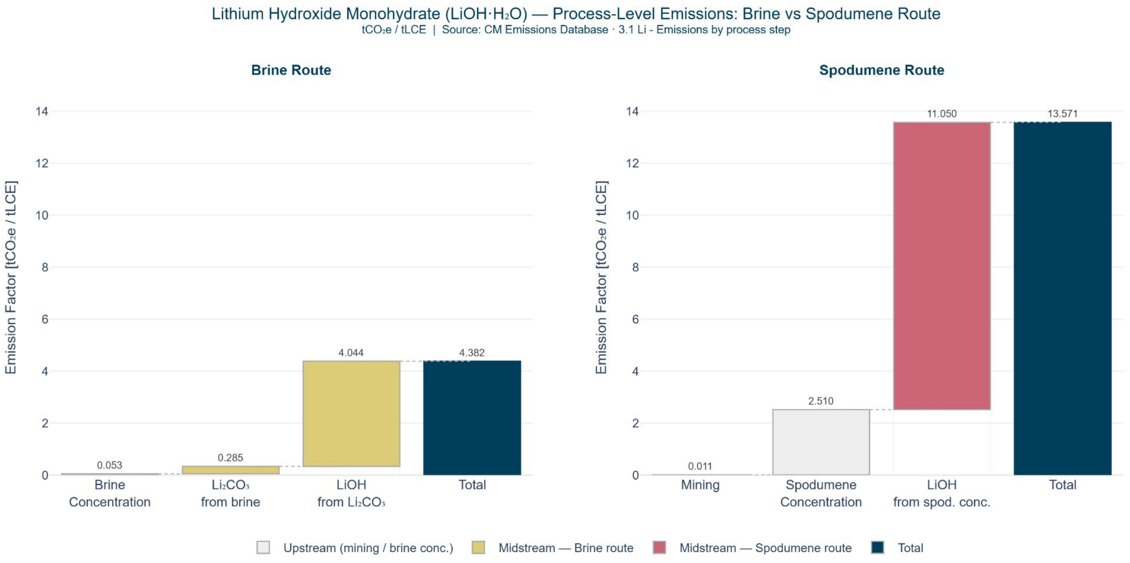


Sources: Schenker et. al, *Current and Future Impacts of Lithium Carbonate from Brines: A Globalized Regional LCA Model*, 2025 (Salar de Atacama, Chile); Khakmardan et. al, *LCA of Lithium Mining, Extraction, and Refining Technologies*, 2023 (Greenbushes, Australia); Jiang et. al, *Environmental impacts of lithium production showing the importance of primary data of upstream process in life-cycle assessment*, 2020 (Li_2CO_3 from spodumene in China).

Key takeaways:

- Lithium carbonate production from **spodumene** is **15x** more emissions-intensive than from **brine extraction.**
- China's **coal-heavy grid** contributes to the high emissions factor from spodumene conversion to lithium carbonate.

Emissions intensity for LiOH-H_2O is greater than for Li_2CO_3 end products

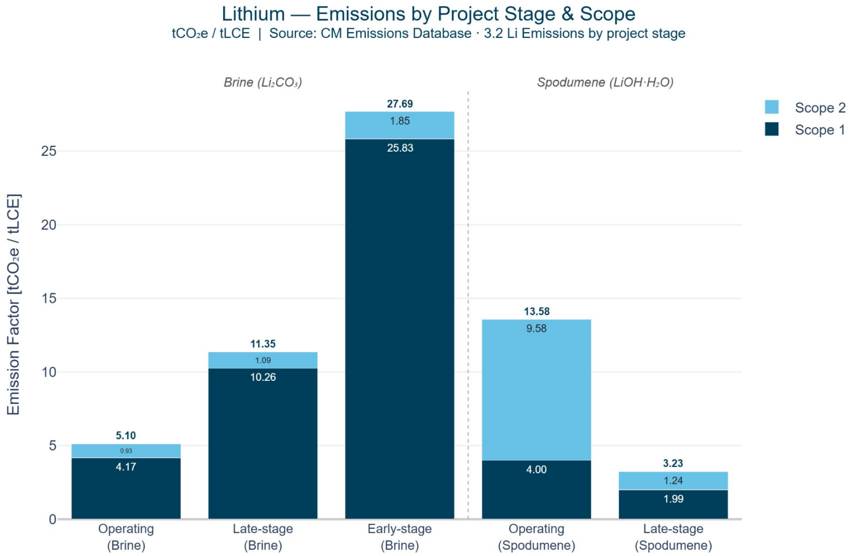


Key takeaways:

- Lithium hydroxide production is more emissions-intensive than lithium carbonate: **over 11x** from brine, and **over 2x** from spodumene
- Emissions projections will depend on evolution of battery chemistries: LiOH-H_2O used in NCM and NCA batteries, while Li_2CO_3 used in LFP battery chemistries.

Sources: Kelly et. al, *Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries*, 2021. (Salar de Atacama, Chile; Greenbushes, Australia)

Emissions for lithium end-products will change with feedstock composition and processing pathways



Sources: Schenker et. al, 2025 (Li_2CO_3 from brine extraction); Chordia et. al, *Life cycle environmental impacts of current and future battery-grade lithium supply from brine and spodumene*, 2022. ($LiOH\text{-}H_2O$ from spodumene extraction)

Key takeaways:

- Emissions factor of lithium carbonate via brine extraction is **over 5x greater for early-stage projects than operating mines.**
    - Lower lithium purity in brine and more energy-intensive processes increase emissions factors.
- Emissions factor of lithium hydroxide via spodumene extraction is **4x less for late-stage projects than operating mines.**
    - More efficient processing and grid composition decreases emission factors.

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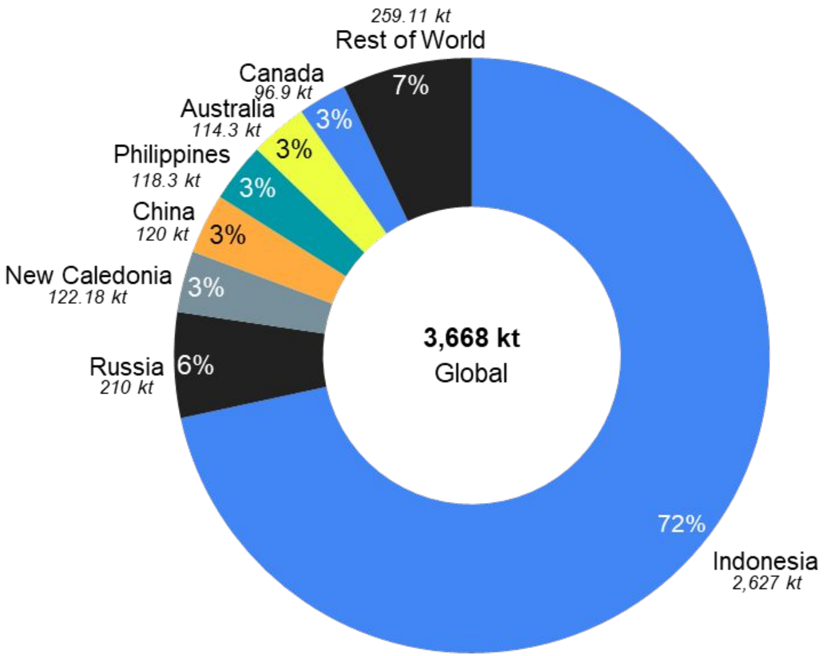
Database deep dive: Nickel

Overview of the Nickel value-chain, scope of research and database coverage

Global Nickel Production by Countries in 2025



Overview:

- Current Ni Production **accounts for ~ 0.33%** of global GHG emissions
- Dataset **covers 63 facilities across 12 countries,** representing ~3,668 kt

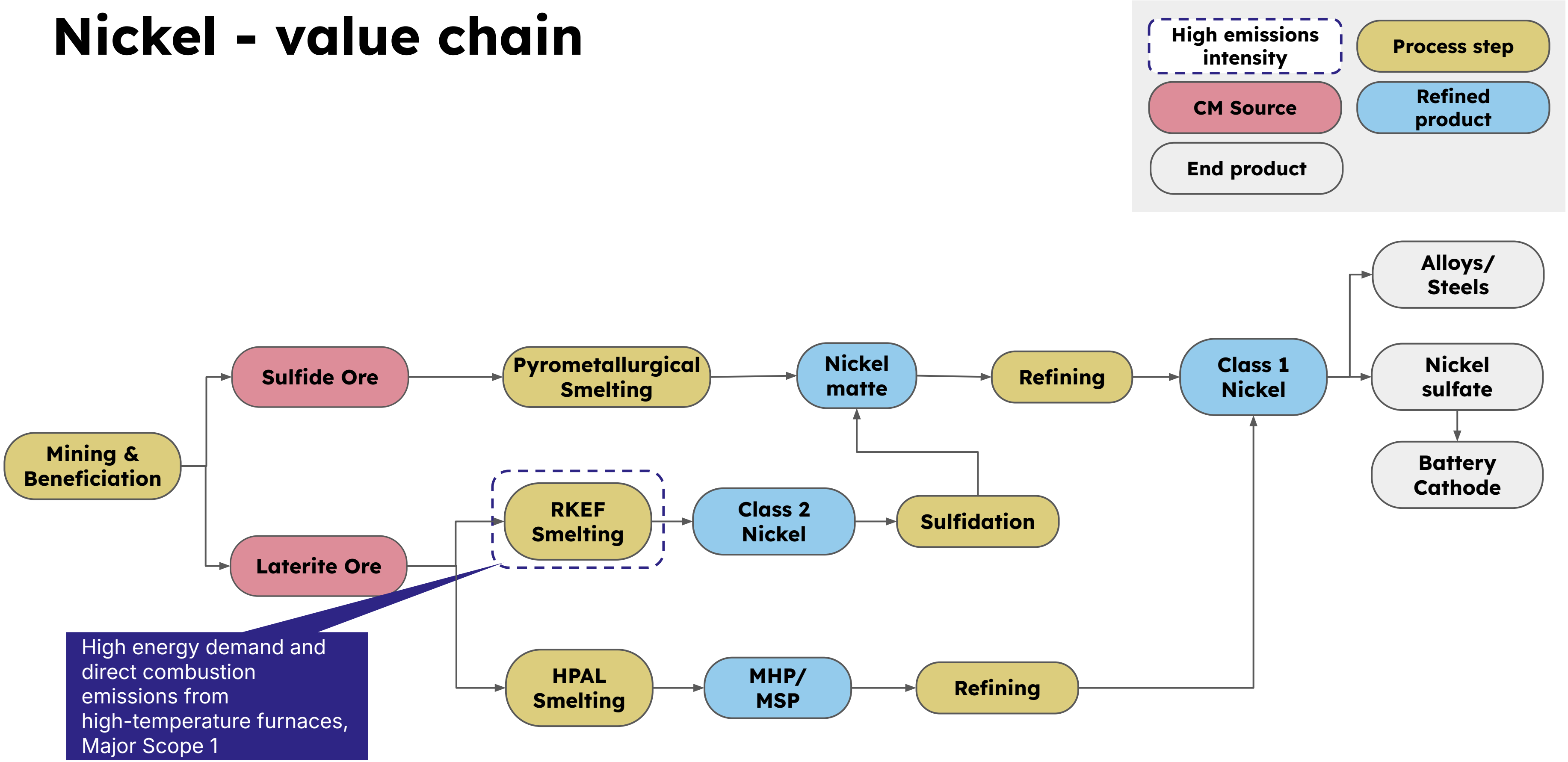
Key Risks:

- **Captive coal-powered Rotary Kiln Electric Furnace (RKEF) dominance.** 68% of Ni production runs on coal grids
- Scope 2 electricity **accounts for 59% of total modelled emissions**

Dataset Summary:

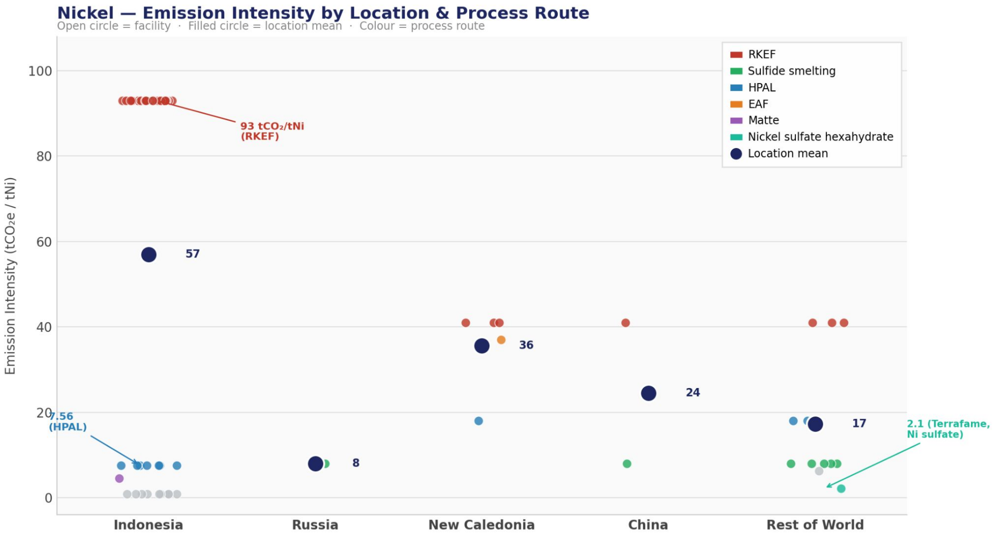
- Midstream accounts for >99.8% of modelled Scope 1 & 2 emissions
- Emission intensity ranges from **2.1 tCO_2/tNi** to **93 tCO_2/tNi**
- RKEF **accounts for 55% of nickel production** but **contributes 93% of total Scope 1 + Scope 2 emissions**

Nickel - value chain



Sources: IFC, 2023; Nickel Institute, 2024

Nickel emissions are route-driven, with laterite pyrometallurgy as the main hotspot



RKEF = Rotary Kiln Electric Furnace
HPAL = High Pressure Acid Leach
EAF = Electric Arc Furnace

Note:
Hydrometallurgical refers to HPAL process
Pyrometallurgical refers to RKEF, EAF, Matte, NPI, and FeNi processes

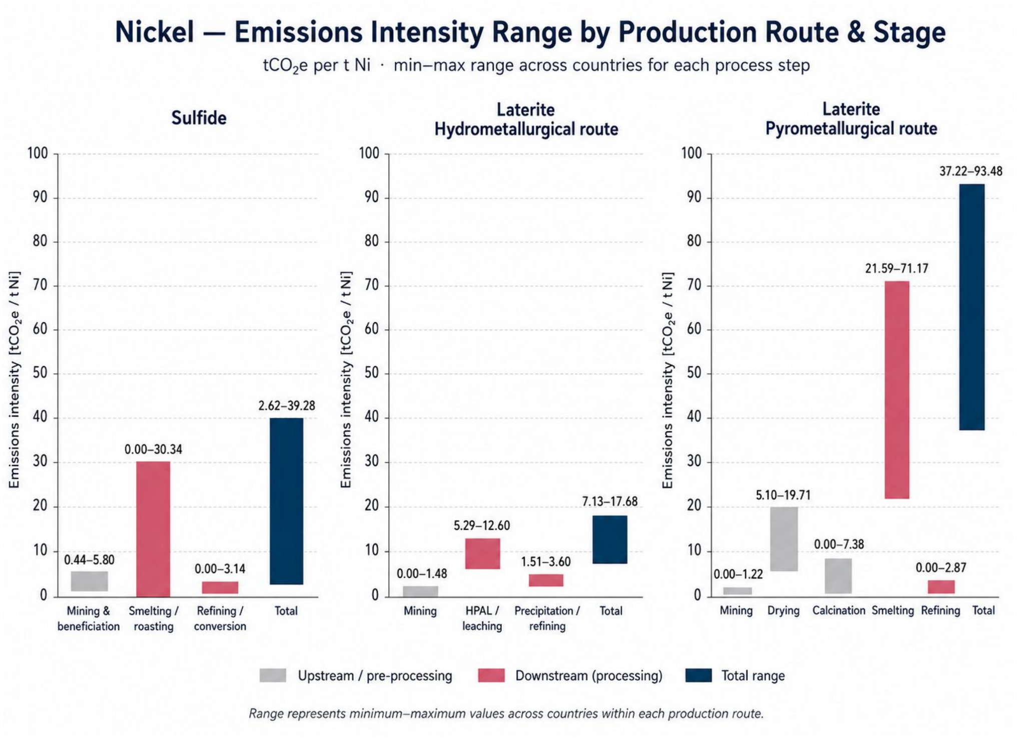
Key takeaways:

- **Mean Nickel emissions** range from around **8 tCO_2/tNi** to **57 tCO_2/tNi** across different geographies, mainly due to differences in processing technology and electricity sources
- Indonesian HPAL operations emit around **7.56 tCO_2/tNi**, while RKEF operations emit around **93 tCO_2/tNi** — a difference of more than 12× greater

Technology divide:

- **Sulfide:** 8 tCO_2/tNi → consistently the lowest-emission pathway
- **Hydrometallurgical-laterite:** 7–18 tCO_2/tNi → lower-emission option for laterite ores
- **Pyrometallurgical-laterite:** 41–93 tCO_2/tNi → highest-emission pathway from Scope 2 captive coal plants

High-temperature processing drives the bulk of nickel emissions, especially in RKEF routes

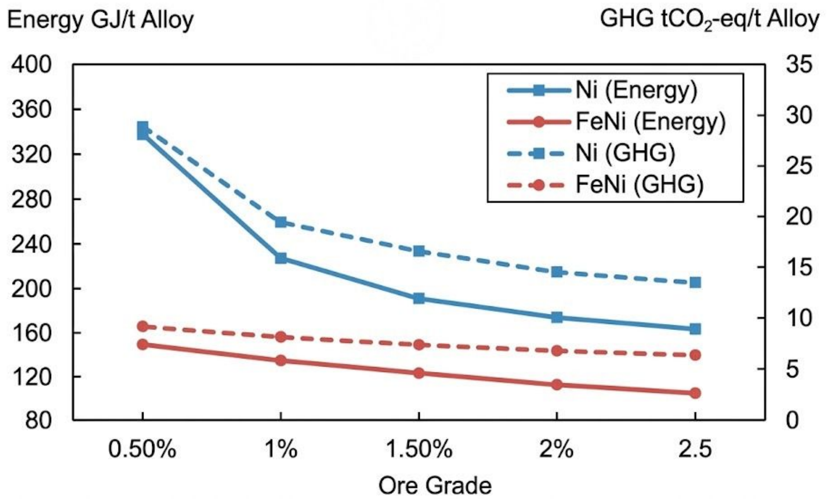


Key takeaways:

- **Pyrometallurgical-laterite (RKEF) dominates the decarbonization priority, mainly in Indonesia**. RKEF accounts for 2.03 Mt Ni, or 65% of modeled production
- Production-weighted emissions intensity are:
  - 86.3 tCO_2e/tNi for **Pyrometallurgical-laterite,**
  - 10.6 tCO_2e/tNi for **Hydrometallurgical-laterite,**
  - 8.0 tCO_2e/tNi for **sulfide smelting**
- **Hydrometallurgical-laterite (HPAL)** is a small share of modeled emissions despite meaningful production volume
- Sulfide smelting accounts for around 0.46 Mt Ni, or about 15% of production across the three routes shown

Higher emission of upstream Nickel processing is associated with lower ore grade

Effect of ore grade on total energy consumption and GHG emissions



Non-linear relationship between Nickel Ore grade and Emissions Intensity

$$E_i = EF_i \times Q_i$$

Where (*i* = contribution source e.g. fuel, coal, lime):

- E_i = GHG from emission source
- EF_i = Emission Factor
- Q_i = Amount of contribution source

Key takeaway:

A **+1 % increase in nickel ore grade** is associated with a **decline in GHG intensity, roughly 3.7–6.5 tCO_2e per tonne of contained Ni**, depending on whether the route is ferronickel or pure nickel production.

Sources: Wei et. al., Energy Consumption and Greenhouse Gas Emissions of Nickel Products (2020)

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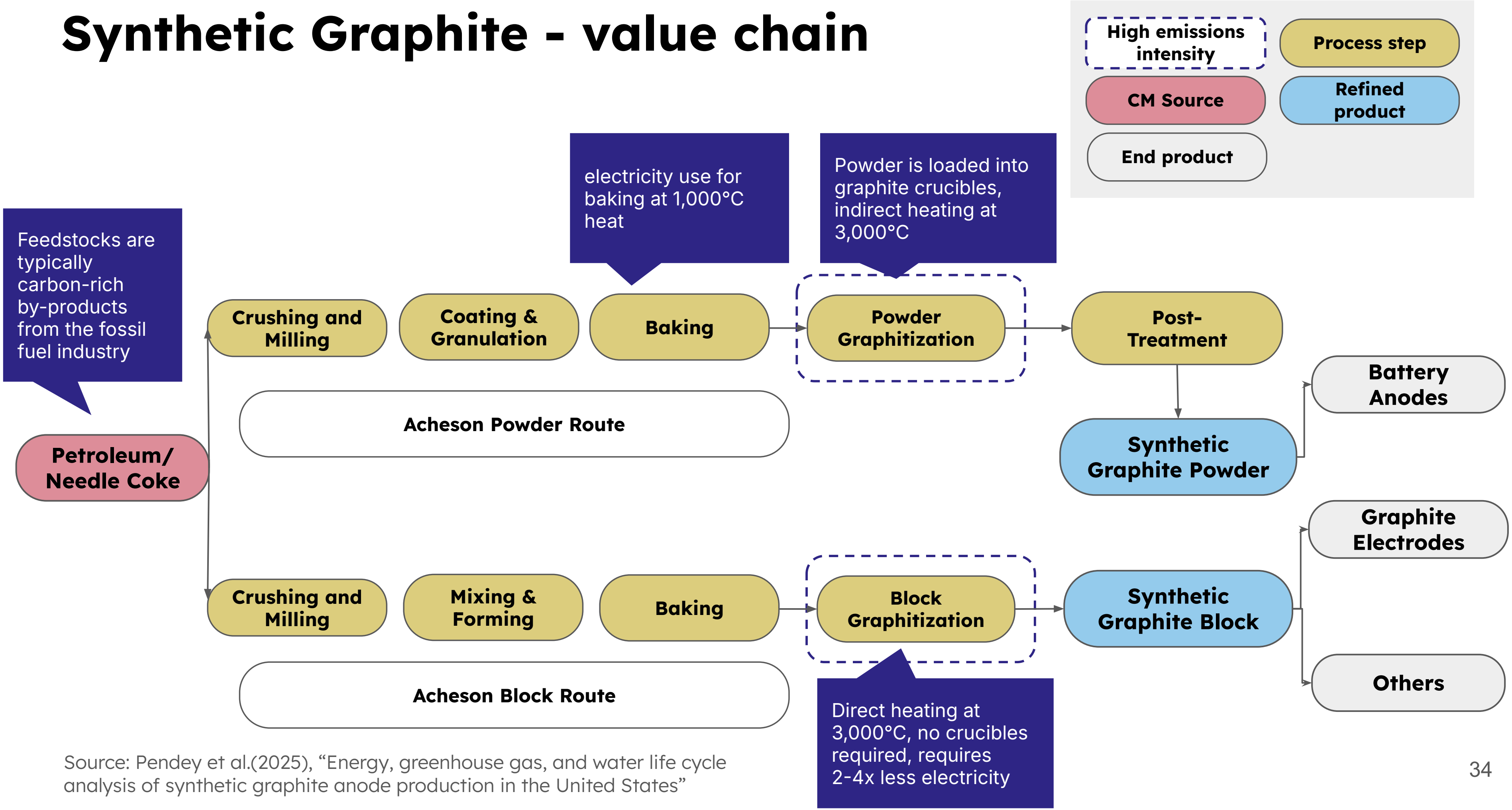
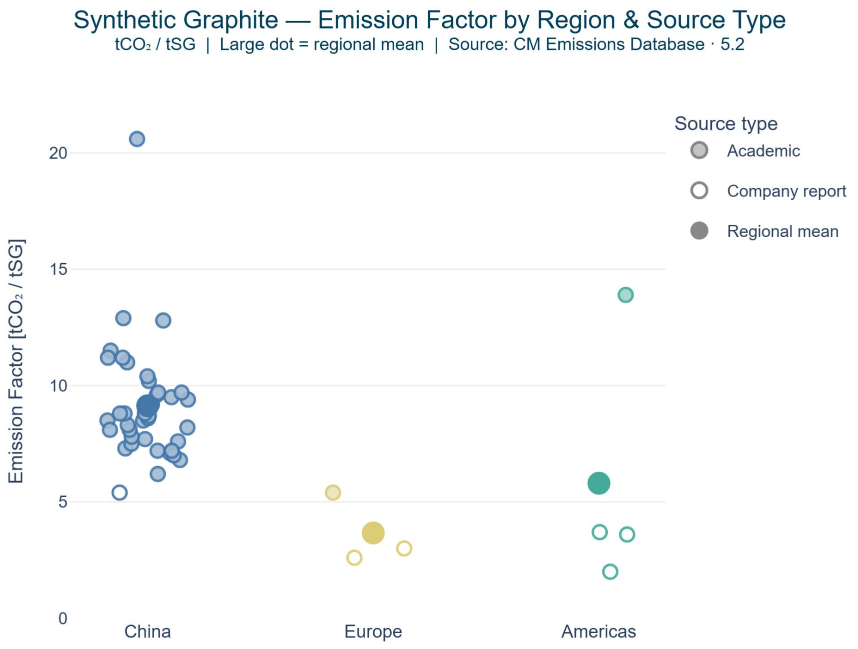
Database deep dive: Synthetic Graphite

Synthetic Graphite - value chain



Source: Pendey et al.(2025), "Energy, greenhouse gas, and water life cycle analysis of synthetic graphite anode production in the United States"

China dominates the SG supply chain with the highest production emission intensity

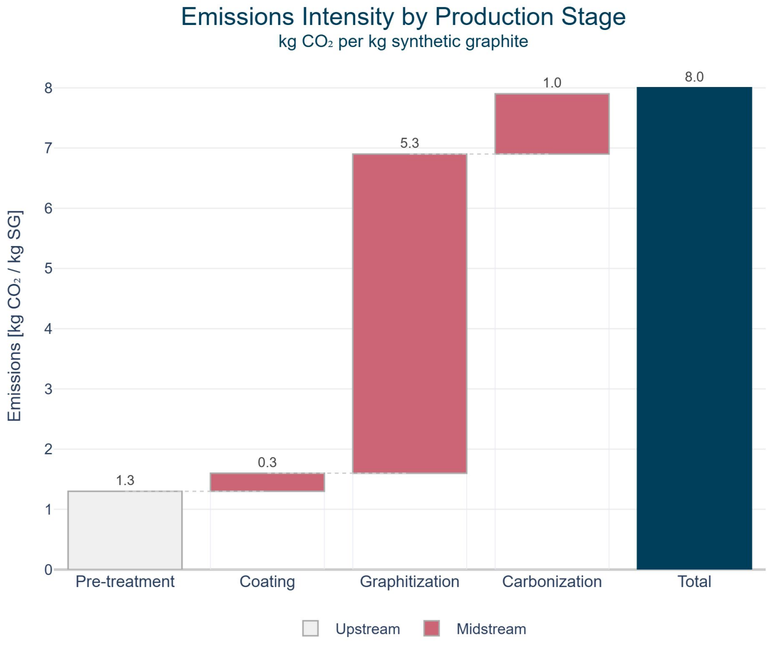


Data: 36 plants + 3 country estimates from academic paper, 6 LCA company reports + estimations -> around 40% of global synthetic graphite production

Key takeaways:

- China (production: 80%, avg EF: 9)
  - Scope 2 dominates (~80% of total EF)
  - Regional grid EF varies widely, currently clustered in Inner Mongolia (coal-heavy)
- Europe (production: 4%, avg EF: 2.8)
  - Very low scope 2 due to clean electricity & innovations, scope 3 becomes the constraint (>50%)
- Americas (production: 5%, avg EF: 5.3)
  - Mostly **electrodes production** (less energy-intensive)
- Company reports underestimate due to excluding crucible losses/ renewable credits

Graphitization alone accounts for 65%[1]-80%[2] of the total GHG emissions in SG production



Sources: 1. Wang et al. (2025), "Carbon Footprint and Decarbonization Potential of Battery-Grade Synthetic Graphite," 2. Pandey et al. (2025), 3. Interview with Tokai Cobex

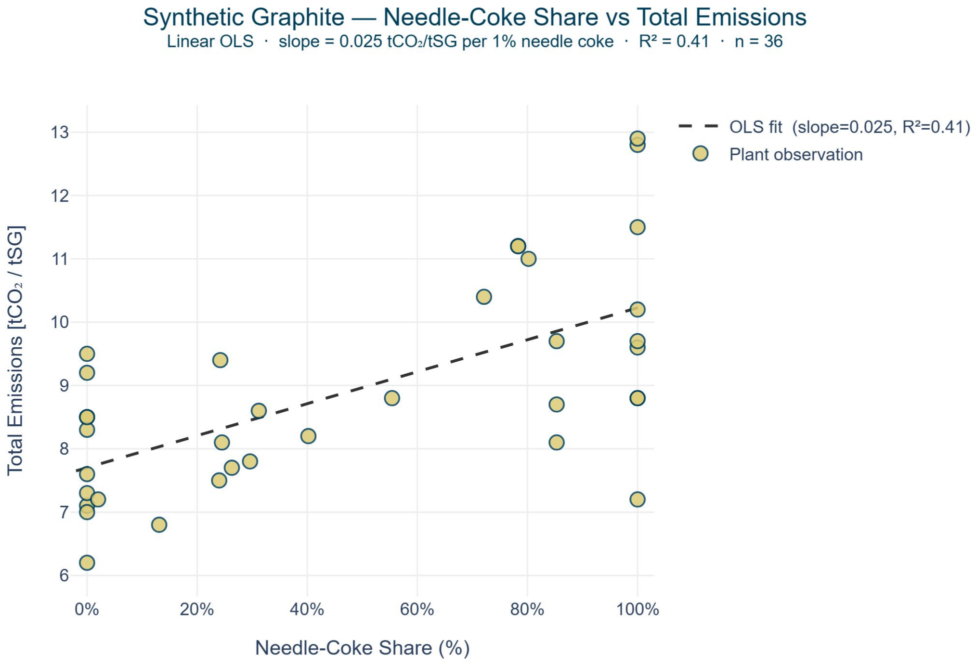
Key Takeaways:

- Graphitization is the most energy-intensive
  - uses enormous electricity -> emission **varies largely due to grid mix**

Ex: 36 Chinese plants (graphitization accounts for ~66% of total CF) vs. Vianode Norway (<13%)

  - the utilization of renewable electricity and green hydrogen could effectively reduce the CF by 41% to 70%[1]
- Production Route: Block vs. Powder
  - Block route requires 2-4x less electricity than powder route[3] due to direct heating and no crucibles use, but lower purity

A higher needle coke share in feedstock is associated with a higher carbon footprint



Linear relationship between Needle Coke Share (%) & Carbon Footprint (tCO_2/t)

$$CF_{plant} = 0.025 \times \text{NC Share} + 7.64$$

- As needle coke share rises 0→100%, plant CF increases by ~2.5 tCO_2/t, **a 34% uplift over a petroleum coke-only baseline**
- Needle coke has a more ordered carbon structure, leading to ~25% higher discharge capacity in the resulting anode compared to petroleum coke
- Needle coke is more expensive and demands more electricity for processing

Source: Wang et al. (2025)

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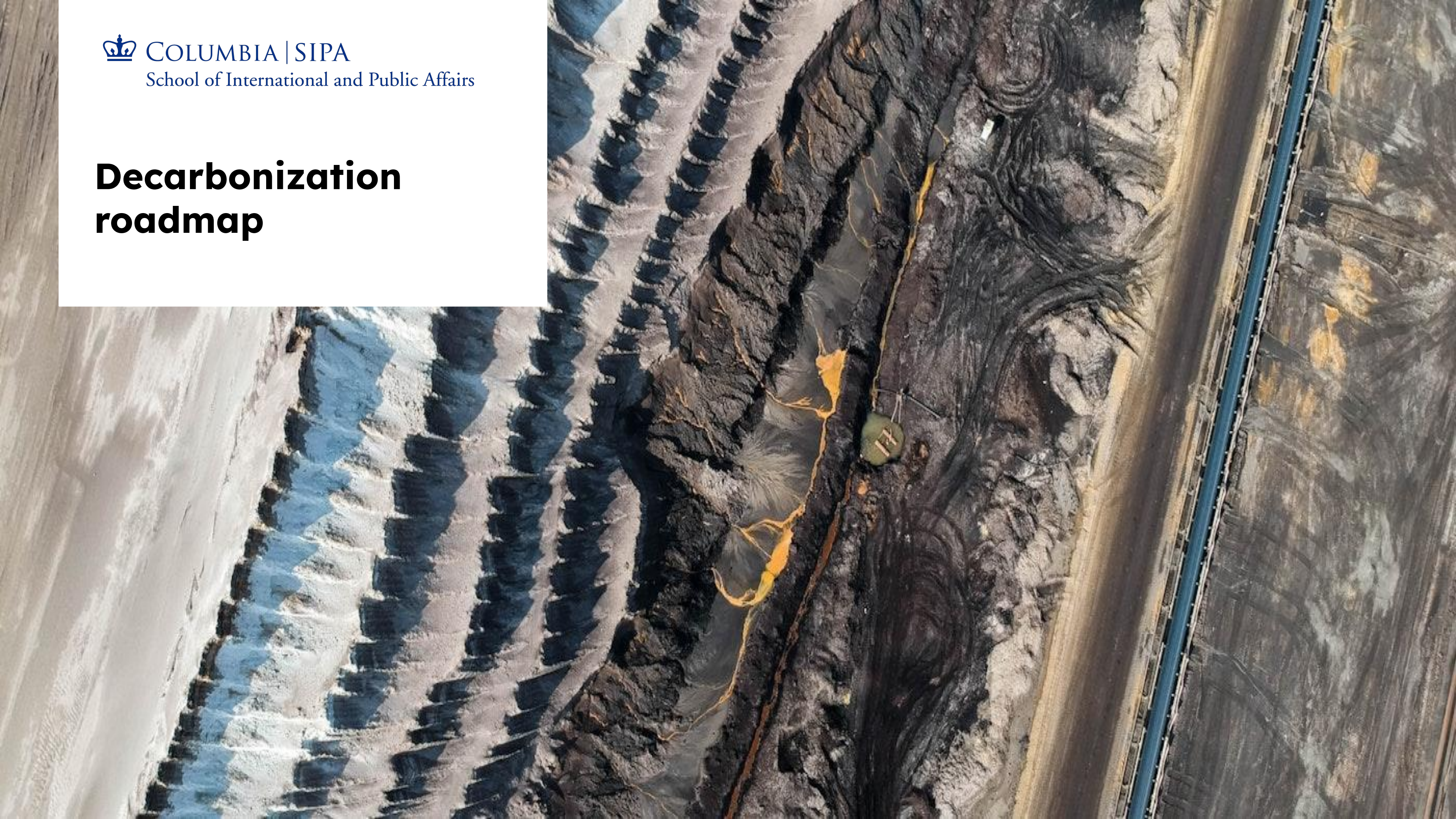
Decarbonization roadmap

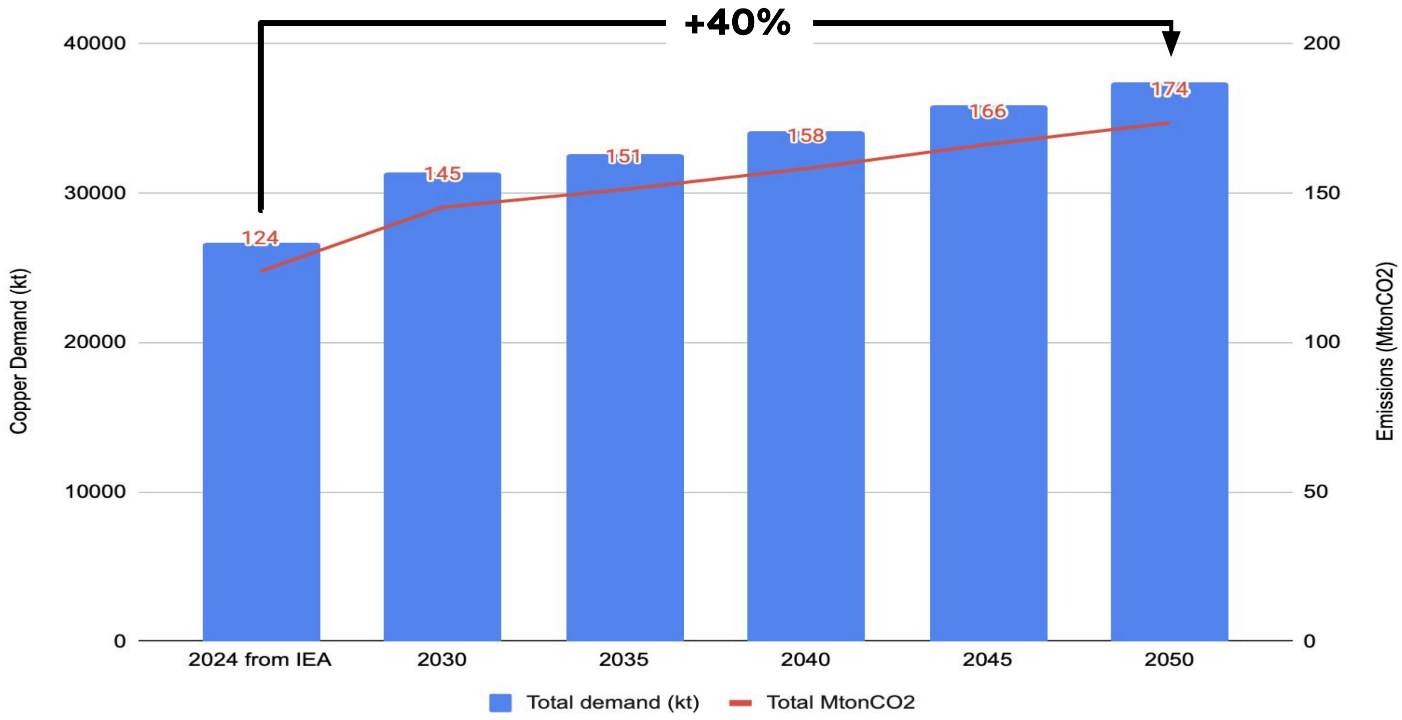


Decarbonizing critical minerals requires deploying four well-known levers, but they are not enough

Lever	Green electricity	Low emission fuels	Carbon capture	Energy efficiency
Abatement potential	**70-100%** of scope 2	**30-100%** of scope 1	**Up to 30%** of residual/hard to abate	**5-20%** transversal across value chain
Availability	**Available now** solar & wind cost-competitive in most regions	**Biofuels now** green H_2 at scale in 5–10 years	**Post-2040 for mining** technology exists but not yet cost-competitive	**Available now** best-in-class motors, automation,mine-to-mill optimization
Challenges	Intermittency and storage needs, remote mine locations, weak PPA frameworks in key producing countries	Green H_2 cost premium; distribution infrastructure; sustainable biomass availability at scale	High cost (\$50–300/tCO_2); best suited as last-resort offset for residual emissions, not a primary lever	Requires upfront capex for retrofit; modest impact relative to other levers; benefits eroded by declining ore grades

Sources: IFC Net Zero Roadmap for Copper & Nickel (2023); Istrate et al., Joule (2024); IEA Critical Minerals Outlook (2024)

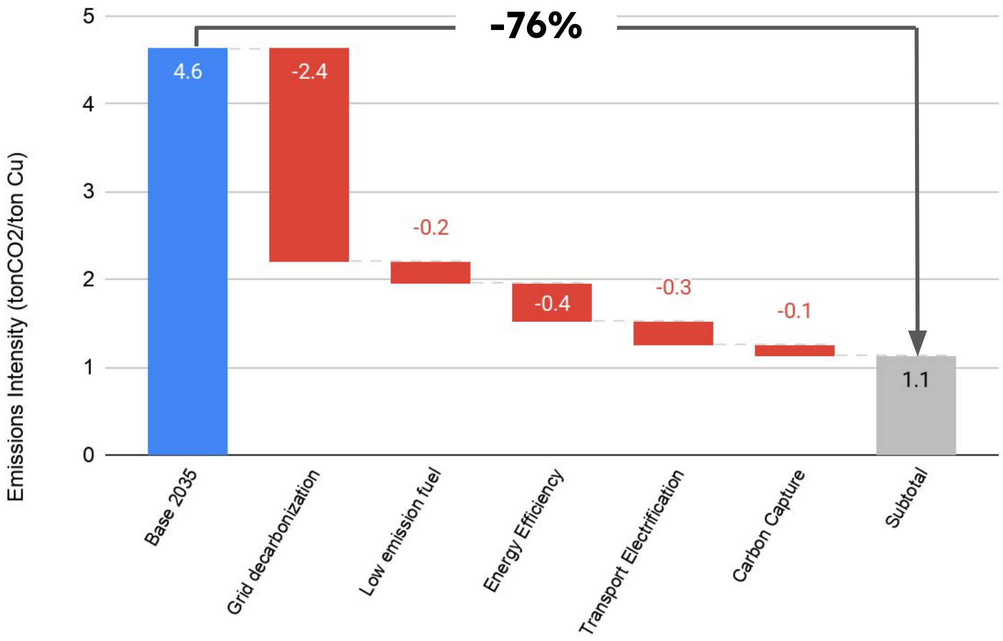
Copper demand growth could drive a 40% rise in Cu emissions under business as usual operations



Notes: (1) IEA Global Critical Mineral Outlook 2025 - Stated Policies Scenario. (2) Based on emission intensities from internally developed database, assuming a business-as-usual scenario—i.e., maintaining the same contribution shares to meet demand across producing countries.

Deploying available and emerging technologies could cut Cu emissions by 76% by 2035

Copper emissions abatement potential by lever in 2035



Key levers:

- **Low Carbon Electricity:** Accelerating adoption of low-carbon PPAs and on-site RE across key regions delivers largest abatement
- **Energy Mix & New Generation:** Diversification within a low carbon grid-mix with clean new capacity additions will be necessary to realise full decarbonization potential from electrification of operations
- **Energy Efficiency:** Mine-to-mill optimization, ore sorting, high pressure grinding rolls offer immediate, cost competitive emissions reductions
- **Hard-to-abate Residuals:** Open-pit diesel hauls and high-temperature smelting heat remain challenging sources

Novel heap leaching can bypass conventional smelting, reducing energy intensity

Heap Leaching | Upstream — Sulfide Ore Route

How it works:

Controls particle size, temperature, and chemistry in highly permeable heaps to activate natural microbes, enabling direct copper recovery from sulfide ores without conventional grinding, flotation, and smelting

Why it reduces emissions:

- Eliminates grinding and flotation, removing energy-intensive processing steps
- Cuts smelting, eliminating direct fossil fuel combustion from high-temperature furnaces

Examples:

Early commercial

Nuton (Rio Tinto) — USA

Bio-leaching technology producing copper without conventional smelting. Up to 85% recovery from primary sulfide ore. First industrial-scale copper production achieved 2025 in Johnson Camp Arizona, becoming lowest-carbon Cu producer in U.S. for Scope 1/2

Late Pilot

SandLix™ (Anglo American) — Chile, South Africa

Bio-oxidising heap leach targeting sustainable recovery of low-grade chalcopyrite ores. Early lab trials achieved 80-90% copper extraction rates within 250 days. In Q3 2025, 15,000 tonne prototype at El Soldado mine completed. Commercial-scale system demonstration now underway (2026).

Sources: Rio Tinto Nuton (January 2026), Anglo American FutureSmart Mining (March 2026)

Novel electrochemical technology could eliminate smelting emissions and enhance Cu recovery

Electrochemical Reduction | Midstream — Sulfide Ore Route

How it works:

Uses a vanadium-based solution to react with copper in sulfide concentrations and mine waste, isolating solid copper in minutes in a closed-loop system - replacing high-temperature smelting without combustion or toxic SO_2emissions. Runs at ambient temperature, recovering 90-99% Cu up to 90 minutes (vs high temperature for smelting)

Why it reduces emissions:

- Eliminates high-temperature smelting, removing direct fossil fuel combustion and toxic SO_2 emissions
- Closed-loop system produces zero harmful emissions - fully electric process

Examples:

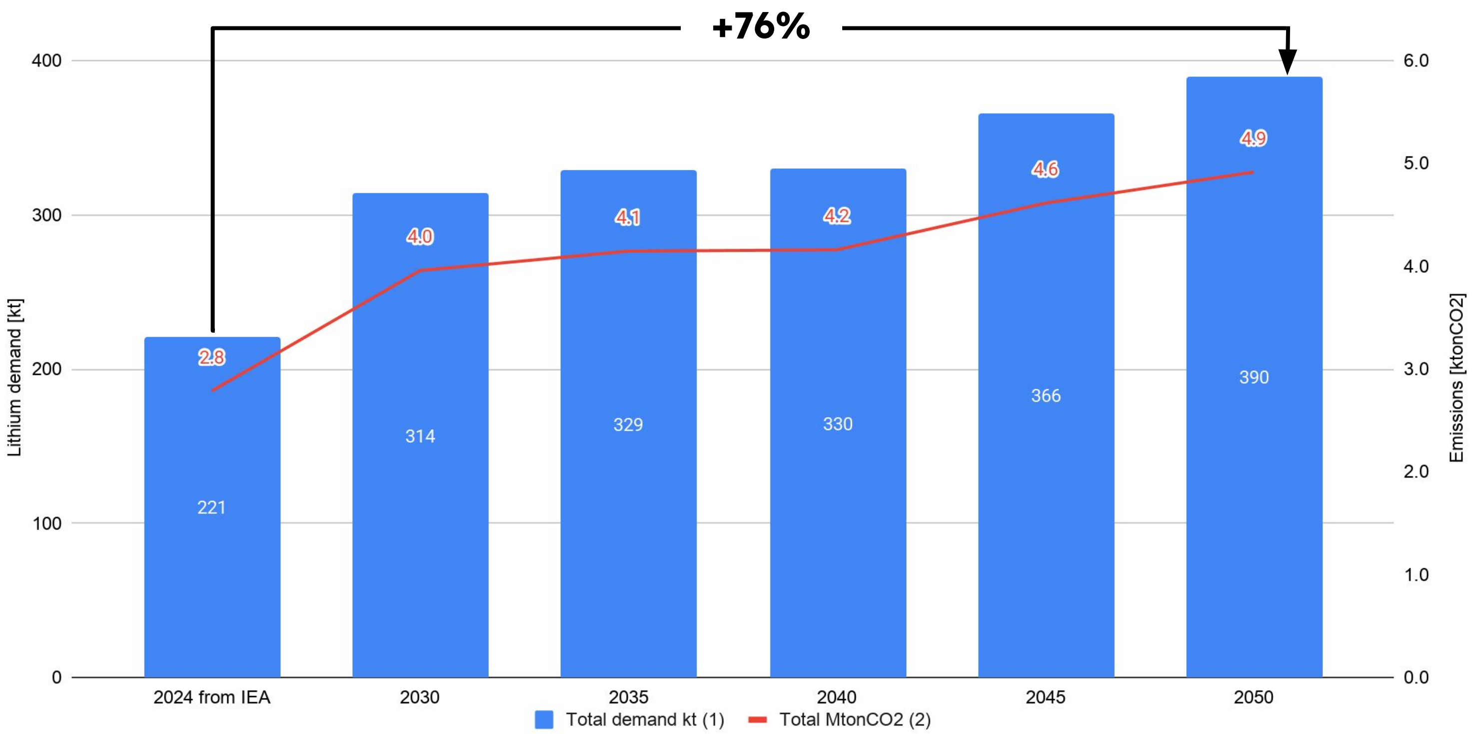
Lab / Pre-Pilot

RACER™ (Still Bright) — USA

- Colorado pilot facility designed for 2tCu/year capacity.
- Demonstration unit targeting 500tCu/year planned for 2027 or 2028. Modular design requiring ~80% lower upfront CapEx vs conventional smelter, with comparable OpEx (self-reported).
- Backed by Breakthrough Energy Ventures, featured in MIT Technology Review and World Economic Forum.

Sources: Still Bright (2025), MIT Technology Review (November 2025)

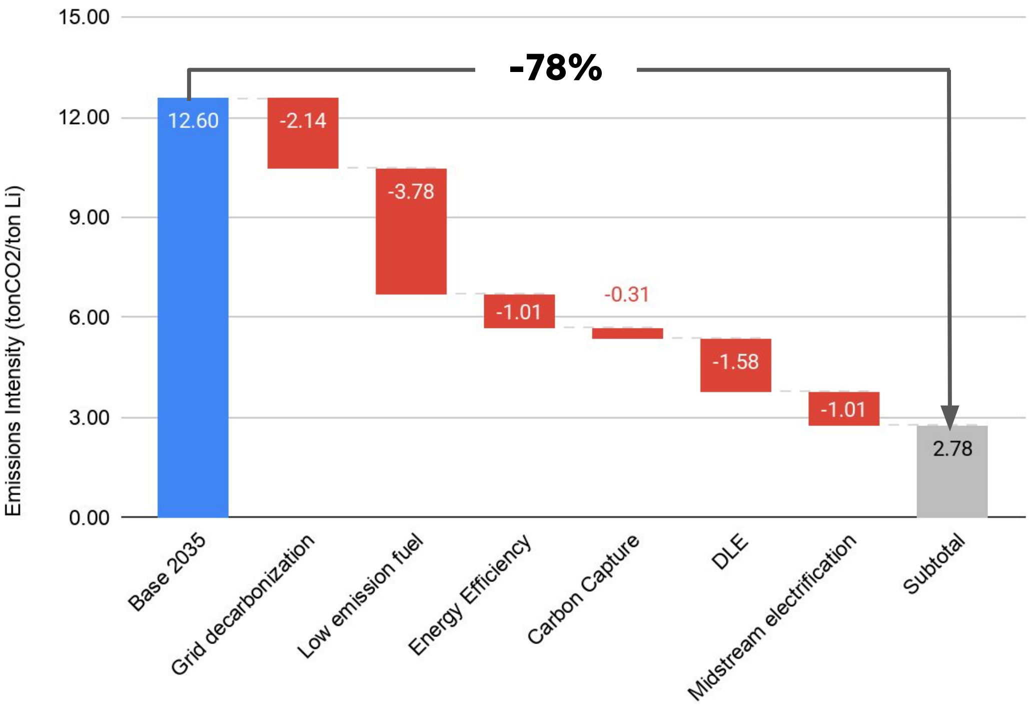
Lithium demand growth could drive a 76% rise in Li sector emissions under business as usual operations



Notes: (1) IEA Global Critical Mineral Outlook 2025 - Stated Policies Scenario. (2) Based on emission intensities from internally developed database, assuming a business-as-usual scenario—i.e., maintaining the same contribution shares to meet demand across producing countries.

Deploying available and emerging technologies could cut lithium emissions by 78% by 2035

Lithium emissions abatement potential by lever in 2035



Key levers:

- DLE: Replaces solar evaporation with **selective adsorption**, cutting upstream process emissions by ~50%.
- Midstream electrification: **Electrochemical processes** (bipolar membrane electrodialysis) replace natural gas in LiOH conversion — pilot-scale demonstrations confirm battery-grade output.
- Residual emissions (~0.9 $MtCO_2$): Hard-to-abate with current technology, **carbon offsets** can bridge the gap to carbon neutrality.

Direct lithium extraction is a commercially emerging technology with high decarbonization potential

Direct lithium extraction (DLE) | Upstream — brine route

How it works:

Replaces conventional solar evaporation ponds with selective adsorption membranes, extracting lithium directly from brine without the energy-intensive concentration stage.

Why it reduces emissions:

- Eliminates brine pumping and evaporation, addressing ~50% of upstream process emissions.
- Reduces water consumption by up to 90%.
- Shorter cycle time, leading to lower total operational energy demand.

Examples:

Early commercial

Vulcan Energy — Germany

Geothermal DLE + renewable heat targeting carbon-neutral lithium. Phase I: $2.5bn. Adsorption-type process powering production directly from geothermal energy.

Pilot stage

Litus — Canada

Nanotechnology-based DLE achieving 99.5% lithium recovery and 99% impurity rejection. Field deployment announced 2025.

Sources: Vulcan Energy Corporate Presentation (Feb 2026); Litus DLE pilot, Canadian Mining Journal (2025).

Midstream electrification can address the hardest-to-abate emissions in lithium processing

Midstream electrification | LiOH conversion — brine & spodumene routes

How it works:

Replaces natural gas (brine route) and coal (spodumene route) in LiOH conversion with electricity-driven electrochemical processes, principally bipolar membrane electrodialysis (BMED) and membrane electrolysis.

Why it reduces emissions:

- Natural gas accounts for ~45% of brine route emissions; coal for ~61% of spodumene route.
- BMED produces battery-grade LiOH with zero direct combustion emissions.
- Combined with renewables: 53–86% reduction in GHG intensity.

Examples:

Pilot Stage

BMED — Salton Sea, California

Battery-grade LiOH (>99.5% purity) via bipolar membrane electrodialysis from geothermal brine. Levelized cost: $4.6/kg.

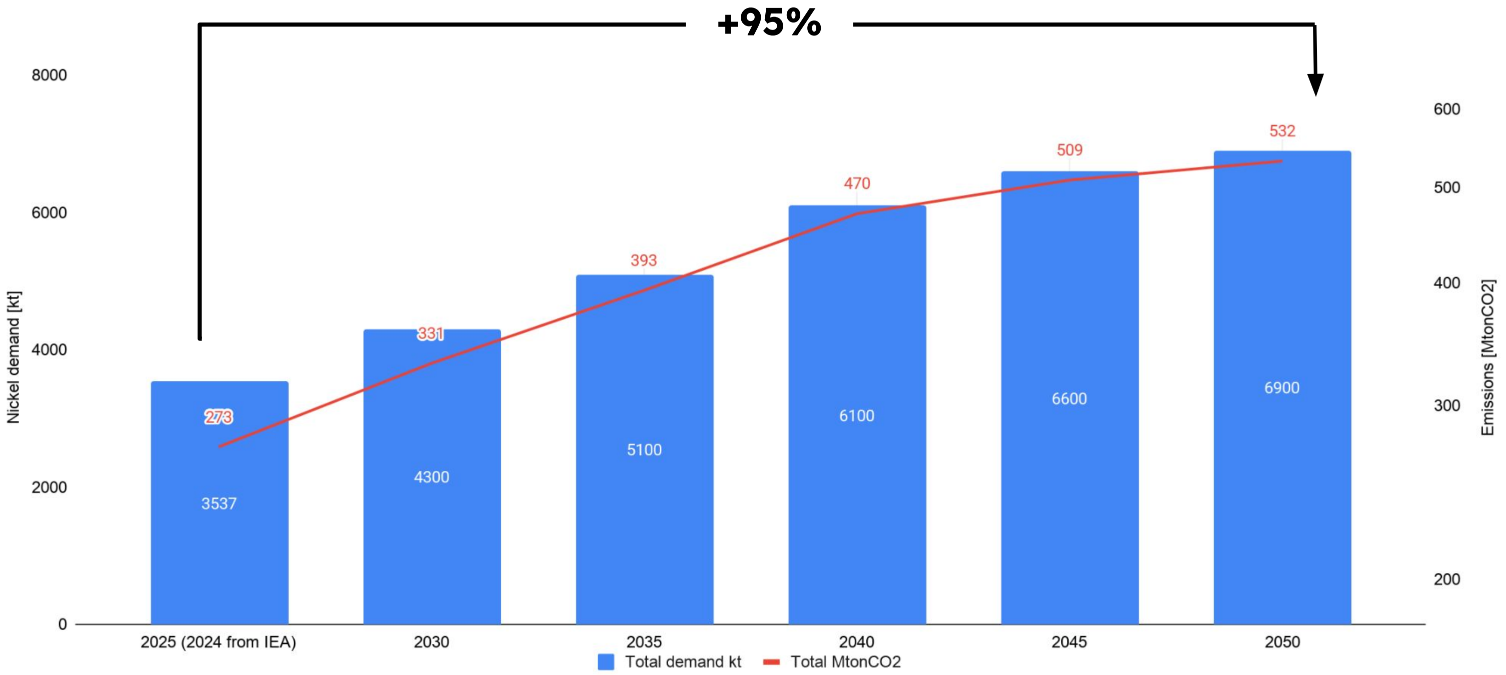
Lab Pilot

Membrane electrolysis — LiCl→LiOH

Direct electrochemical conversion of LiCl to battery-grade LiOH (98.2% purity), replaces multi-step chemical processes that rely on fossil fuel heat.

Sources: Electro-driven direct lithium extraction from geothermal brines to generate battery-grade lithium hydroxide, Nature Communications (2025); A sustainable and energy-efficient electrolysis approach for converting lithium chloride to high-purity lithium hydroxide, ScienceDirect (2025).

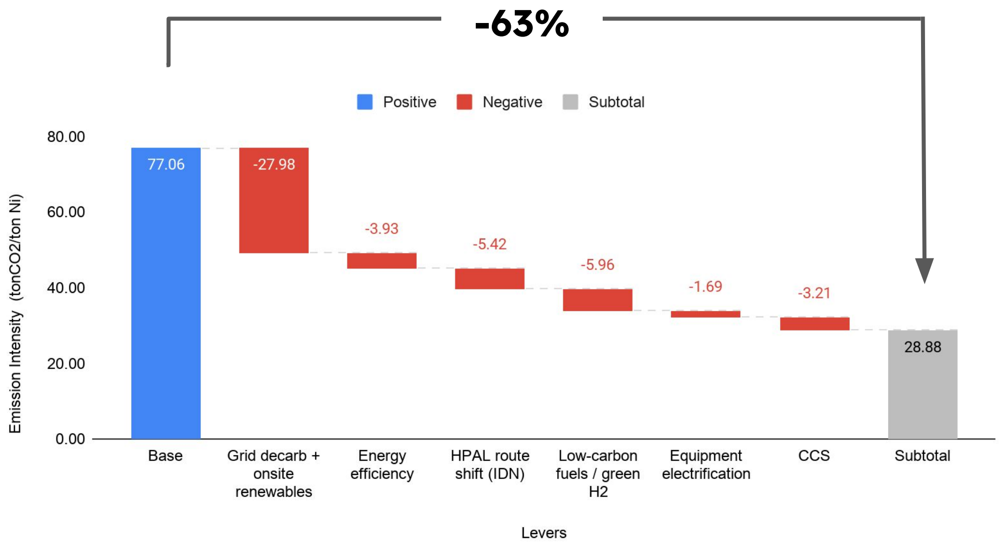
Nickel demand growth could drive a 95% rise in its production-related emissions by 2050



Notes: (1) IEA Global Critical Mineral Outlook 2025 - Stated Policies Scenario. (2) Based on emission intensities from internally developed database, assuming a business-as-usual scenario—i.e., maintaining the same contribution shares to meet demand across producing countries.

Strategic shifts in power and processing can achieve a 63% reduction in Nickel emissions

Nickel emissions abatement potential by lever in 2035



Key levers:

- Moving away from captive coal is the critical prerequisite. In key regions like Indonesia, this single lever accounts for the largest reduction potential
- HPAL is the preferred technology for the EV battery supply chain over RKEF (stainless steel focus)
- Deep decarbonization of remaining process emissions also relies on Green Hydrogen and Energy Efficiency

Integrated waste heat recovery cuts site emissions by up to 34%

Laterite Pyrometallurgy (RKEF) | Downstream - Smelting & Refining

How it works:

Captures 350–450°C exhaust from electric furnaces to pre-dry wet ore (35% moisture) and displaces fossil fuels burned for thermal drying.

Why it reduces emissions:

- By recycling heat that is otherwise lost to the atmosphere, the facility eliminates the need for auxiliary coal or oil combustion in the drying and pre-heating stages.
- It reduces site-wide emissions by 14–34% by optimizing the thermal balance between drying and smelting stages.

Examples:

Early commercial

IMIP and IWIP — Indonesia

Smelters in Kolaka (South Sulawesi) report up to 25% energy savings through integrated furnace heat recovery systems.

Sources: Saiful, S., Yandri, Y., Hilmi, H., & Nasrullah, N. (2026). Design of development waste heat recovery in metal casting industry: Exploring energy saving potentials. Journal of Energy and Biorefinery Technology

Green hydrogen and sustainable bioreductants eliminate fossil-based agents to cut reduction-phase CO_2 by up to 84%

Laterite & Sulfide Hydrometallurgy | Downstream - Refinery

How it works:

It replaces metallurgical coal/coke with Green Hydrogen or Bioreductants (sustainable biomass like wood waste or palm shells)

Why it reduces emissions:

- Hydrogen reduction releases only water vapor instead of CO_2.
- Direct green hydrogen injection into mineral dryers and furnaces can cut direct emissions by 28% in the near term. Next-generation hydrogen plasma technology can eliminate up to 84% of reduction-phase emissions.

Examples:

Pilot stage

Rio Tinto (Brazil)
Piloting hydrogen-based direct reduction. While commercial scaling is slow, 2026 focus is on achieving Final Investment Decisions (FID) for integrated electrolyzer plants

Eramet / Weda Bay (Indonesia)
Exploring the use of Bioreductants (sustainable charcoal/biomass) to replace a portion of metallurgical coal in RKEF furnaces

Sources: (1) Max-Planck-Gesellschaft. (2025, April 30). Green nickel for sustainable electrification. ScienceDaily, (2) WRI Indonesia. (2026). Decarbonization roadmap for Indonesia's nickel industry. WRI Reports.

Transitioning to hydrometallurgy enables reduction in carbon footprint for the EV battery supply chain

Laterite & Sulfide Hydrometallurgy | Downstream - Refinery

How it works:

Bioleaching and advanced HPAL replaces energy-intensive molten smelting (>1,300°C) with biological oxidation or chemical pressure at significantly lower temperatures (250°C for HPAL). The advanced HPAL version utilizes electric boilers powered by renewables.

Why it reduces emissions:

Bioleaching consumes 90% less energy than conventional production methods because ore does not require fine grinding

Examples:

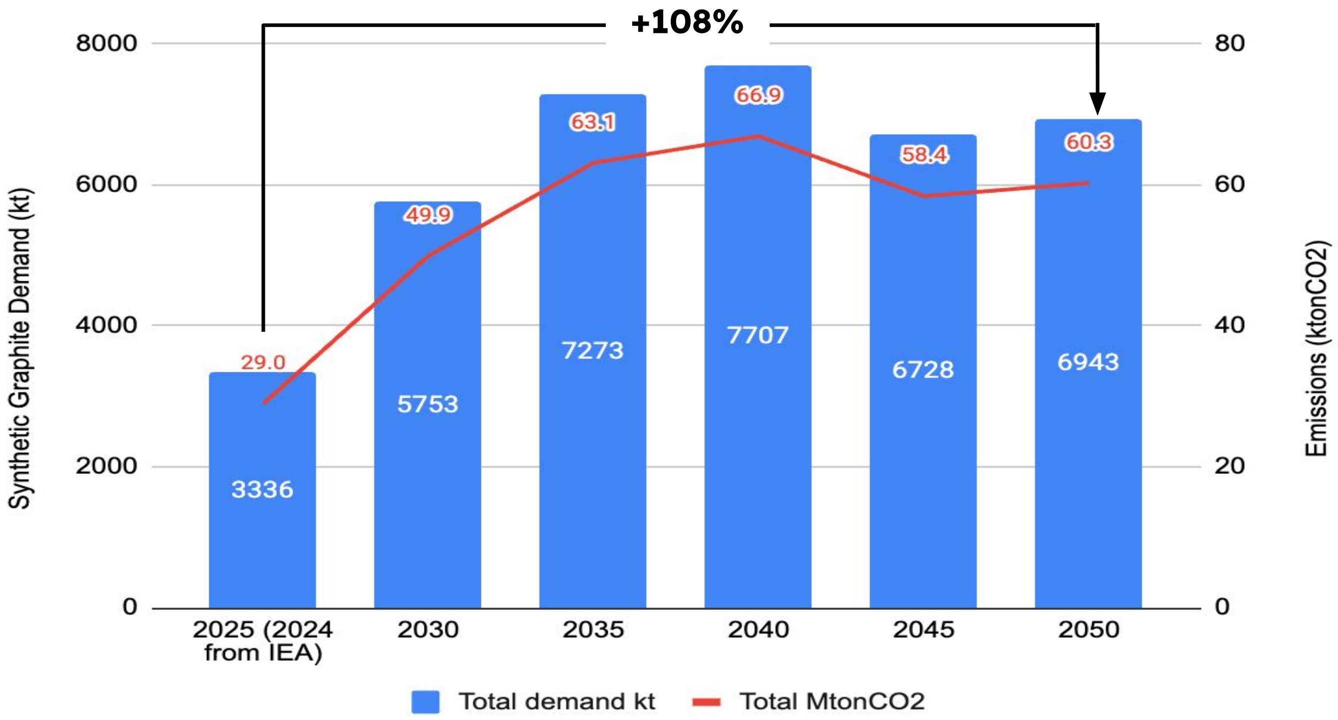
Early commercial

Terrafame — Finland

Achieved an industry-leading carbon footprint of 1.75 kgCO2e/kg Ni for nickel sulphate in its latest 2026 LCA update (a 60% decrease from previous intensity of 4.4 kgCO2e/kg Ni)

Sources: Terrafame Ltd. (2026, March 25). Carbon footprints of Terrafame's nickel products now even smaller

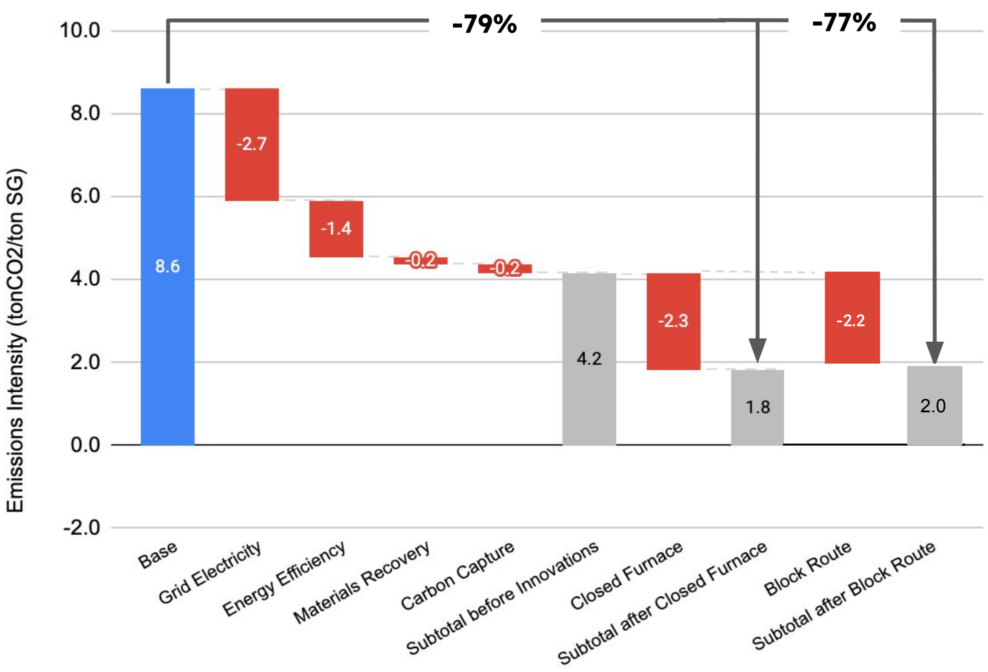
Synthetic Graphite demand growth could drive a 108% rise in SG emissions under business as usual operations



Notes: (1) IEA Global Critical Mineral Outlook 2025 - Stated Policies Scenario. (2) Based on emission intensities from internally developed database, assuming a business-as-usual scenario—i.e., maintaining the same contribution shares to meet demand across producing countries.

Deploying available technologies could cut SG emissions by 79-77% by 2035

SG emissions abatement potential by lever in 2035



Key levers:

- Grid electricity: Sourcing low-carbon power delivers the **single largest abatement** lever
- Energy efficiency: Crucible reuse, micronization yield improvements, waste-heat recovery, and tighter process controls cut kWh per tonne and reduce embedded material emissions
- Process innovations: New graphitization architectures with **closed furnaces** (induction furnaces) and **block route** (lengthwise graphitization)
- Both innovations are **furnace-level technologies** targeting the same emission source, so they are **two separate scenario branches**, not a single additive chain

Notes: Emission reduction for each technology is calculated under the assumption that 35% is due to technology and 65% due to cleaner energy mix

Closed induction furnace is a commercially available technology with high decarbonization potential

Induction furnace | Upstream — graphitization

How it works:

Uses electromagnetic fields to directly heat carbon material during graphitization inside a sealed chamber, eliminating the packing coke and crucibles of Acheson furnaces.

Why it reduces emissions:

- Direct electromagnetic heating of the carbon eliminates the ~48% heat loss and resistive packing-coke losses
- Crucibles and coke don't have to be manufactured, replaced, and disposed of each cycle
- Sealed environment captures fugitive process emissions and enables waste-heat recovery

Examples:

Commercial

Vianode — Norway and Canada

Proprietary enclosed batch induction furnaces: Via ONE at Herøya (4 full-size induction furnaces, ~2,000 tpa, commercial since Oct 2024). Scaling Herøya toward 60,000 tpa and building Via TWO in Ontario (50,000 → 150,000 tpa, production 2028)

Pilot stage

NOVONIX — United States and Canada

Proprietary continuous induction graphitization furnace: First mass-produced commercial sample delivered Sep 2025; mass production starts 2026. Combined Riverside + Enterprise South (Chattanooga) capacity: >50,000 tpa.

Sources: (1) Vianode Reaches OEM Qualification Milestone for via ONE, Supporting North American industrial-scale supply. Vianode, 2025. (2) NOVONIX Achieves Critical Operational Milestone. NOVONIX Limited, 2025.

SG production via E3BAM® block route is an emerging technology with high decarbonization potential

E3BAM® block route | Upstream — crushing, milling, mixing, forming, carbonization

How it works:

Graphitizes pre-shaped solid carbon blocks (formed from petroleum coke and pitch binder) directly inside the furnace, rather than heating loose powder packed in crucibles

Why it reduces emissions:

- Pre-shaped blocks are graphitized directly without the disposable graphite crucibles that Acheson powder-route furnaces consume each cycle
- Solid blocks conduct heat more uniformly and densely than loose powder
- Larger batch volumes, meaning more carbon mass per furnace cycle

Example:

Early commercial

Tokai COBEX — France

The only company that has commercialized (started late 2022) the block route specifically for battery anode materials at industrial scale. Currently mass-producing E3BAM® and ramping toward a targeted ~10% global market share in the high-end anode segment

Sources: Carrère, Tristan, Bénédicte Allard, and Till Reek. "Towards Greener Aluminium Production -A Carbon Footprint Assessment of Graphitized Cathodes for Electrolysis Pots." 2024.

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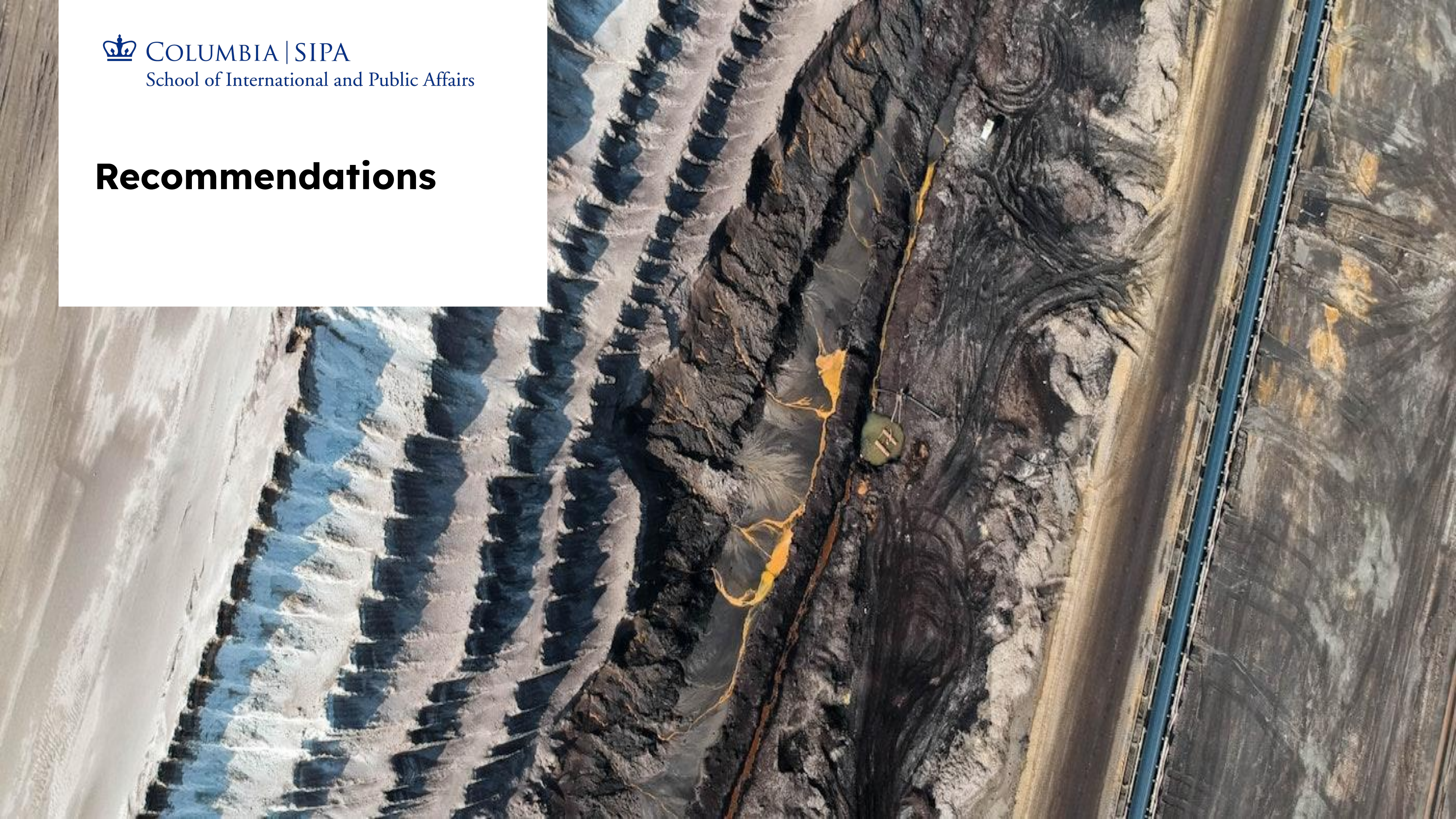
Recommendations



Recommendations for mining sector

Act now with available levers: Transition to zero-emission electricity sources, electrify mining fleets and processing equipment, and assess low-emission fuel options. The technology is ready and the economics are improving fast.

Invest in R&D for hard-to-abate processes: High-temperature process heat remains the largest decarbonization gap across all four minerals. Targeted innovation funding is needed now to have solutions at scale by 2035.

Collaborate across value chains and engage governments: Closing the cost gap for low-carbon minerals requires coordinated action between miners, refiners, OEMs, and policymakers. No single actor can absorb the cost alone.

Assess low-carbon technologies today, before the next equipment cycle: Capital decisions made in the next 5 years will lock in emissions for 20+ years. The time to evaluate alternatives is before replacement, not after.

Extend emissions accounting across the full value chain: The largest emissions sources often sit outside the mine gate, in upstream reagent and chemical suppliers or in downstream refining and processing. Engaging both suppliers and end users is essential for credible decarbonization claims, as synthetic graphite's coal-powered Chinese graphitization illustrates.

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Future work

Future work

- **Expand value chain emissions coverage**, upstream supplier (feedstock, chemicals) and downstream processing emissions.
- Expand the emissions database to **include underrepresented producing regions**, particularly China, where data availability remains limited despite its dominant role in refining and processing across all four minerals.
- Deepen analysis of **hard-to-abate processes**. Several high-emission process steps lack viable low-carbon alternatives today. Targeted research is needed to assess technical feasibility, costs, and timelines for decarbonizing these bottlenecks.
- Extend the methodology to **Cobalt and Rare Earths**, two critical minerals not covered in this study.
- Estimate the **capital investment** required to deploy low-carbon production technologies, alongside the **price differential** needed for commercial viability, and identify which policy instruments could close both gaps.

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Appendix

1. Case Studies
2. Database
3. Decarbonization

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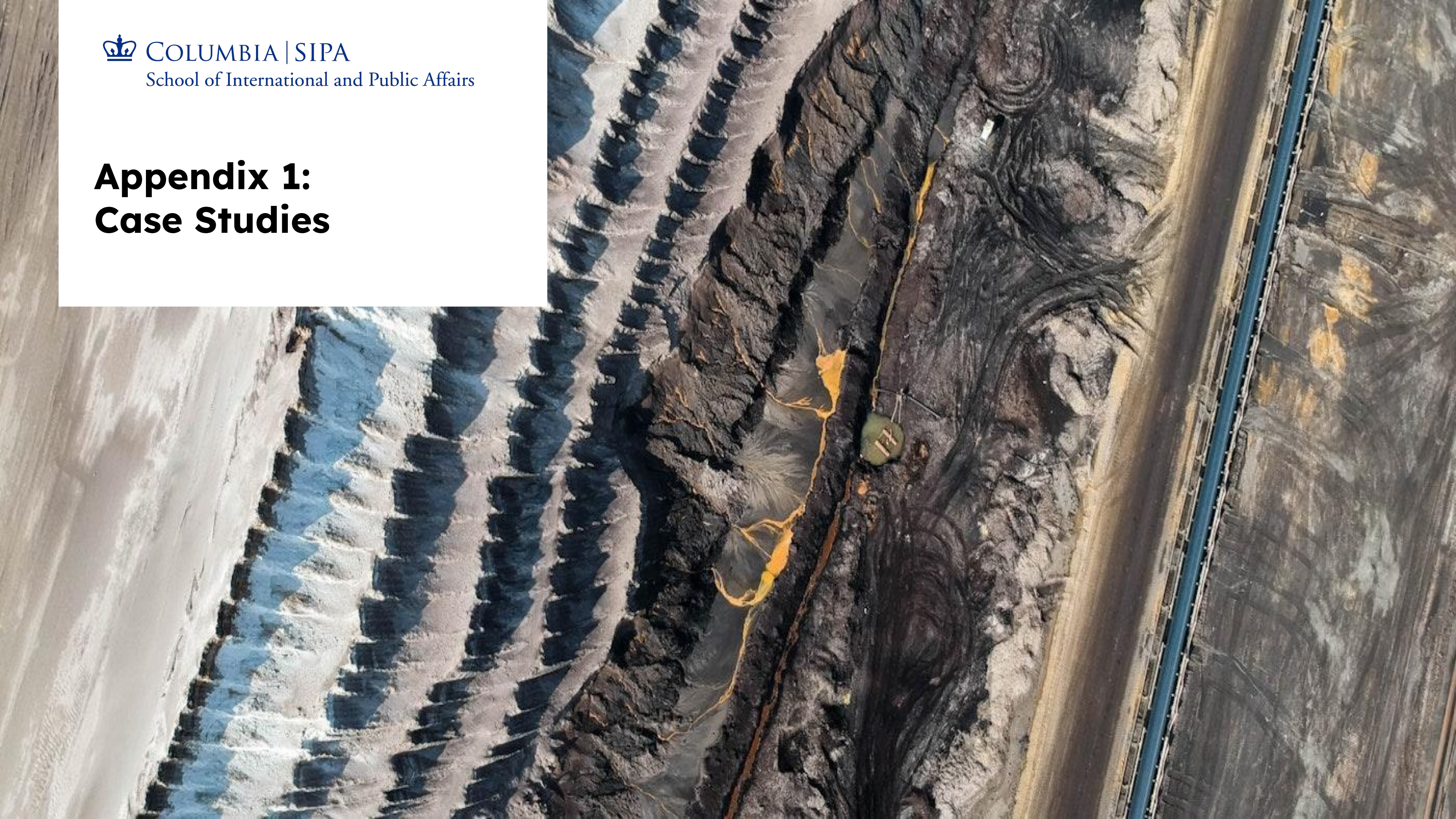
Appendix 1: Case Studies



Novel heap leaching could reduce processing energy intensity by up to ~50%

SandLix™

Anglo American's SandLix enables recovery of low-grade, complex ores, including sulfide ore(chalcopyrite) efficiently. SandLix allows 'stranded' ores to be economically processed in a sustainable way, lowering up to ½ of water and energy use vs conventional flotation and smelting processes.

Value chain	**Extraction** · Transport · **Smelting** · Refining
Technology	Heap Leaching
CO2 emissions	-Reduces energy-intensive grinding, flotation, and smelting requirements -Potentially lowers processing energy intensity by up to ~50%
Cost	TBC
TRL	Late Pilot
Risks / challenges	-Commercial scalability under development -Cost and deployment timeline still uncertain

Novel heap leaching could bypass conventional smelting, reducing energy intensity

RioTinto

Nuton

Nuton harnesses naturally occurring microorganisms to extract copper directly from sulfide ores, producing copper cathode on-site without a conventional concentrator or smelter facility. Achieves up to 85% recovery from primary sulfide ore. Processing costs reduced up to 40% vs traditional production methods.

Value chain	**Extraction** · Transport · **Smelting** · Refining
Technology	Heap Leaching
CO2 emissions	-Eliminates energy-intensive concentration and smelting, producing lowest-carbon primary copper in U.S. on Scope 1 & 2
Cost	Up to 40% lower processing costs vs conventional production
TRL	Early Commercial
Risks / challenges	-Single demonstration site to date in Arizona -Scalability to larger and more complex ore bodies not yet proven

Novel electrochemical technology to reduce costs & emissions while enhancing Cu recovery

Still Bright's RACER™

Still Bright is a US-based company developing a fully electric, low-temperature process that uses a vanadium-based solution to up to 99% Cu from sulfide ores and waste. The technology is positioned as a near-zero emission alternative to traditional smelting and refining while maximising Cu recoveries from mine wastes.

Value chain	Extraction · Transport · **Smelting** · **Refining**
Technology	Electrochemical Reduction
CO2 emissions	From: High-temperature smelting To: Fully electric process - potentially 100% decarbonization contingent on clean electricity supply
Cost	~80% lower upfront CapEx vs conventional smelter, comparable OpEx
TRL	Demonstration unit (500tCu/year), planned for 2027 or 2028
Risks / challenges	Pilot facility designed for 2tCu/year (not yet operational as of late 2025)

Vulcan Energy aims to become Europe's leading integrated sustainable lithium business

VULCAN ENERGY

Zero Carbon Lithium™

Simplified two-stage process to convert lithium-rich brine into a battery-quality product. This commercially leading, Adsorption-type lithium production is powered by **renewable heat, with renewable energy** supplied directly to the grid and lithium delivered straight to offtake partners.

Value chain	**Extraction** / **Evaporation** / Transport / **Processing**
Technology	Geothermal & Lithium Extraction Plant (G-LEP) **Geothermal electricity and heat**
CO2 emissions	Potential carbon-neutral lithium production
Cost	$2.5bn USD for phase I
TRL	Demonstration / early commercial
Risks / challenges	Geothermal exploration is expensive

Sources: Vulcan Energy, Corporate Presentation February 2026. https://v-er.eu/corporate-presentations/

Enel X and SQM piloted the first electric truck for large-scale mining in Chile, a 28 ton Yutong model

1° electric truck for large-scale mining

With a range of up to 200 kilometers and 28 tons of capacity, Chile's first electric mining truck was proved at SQM's operations in the Antofagasta Region. The goal was to test the technology and progressively replace high-tonnage diesel trucks.

Value chain	Extraction / Evaporation / **Transport** / Processing
Technology	Electric mine truck - 28 tons
CO2 emissions	-0.13 tons/km per truck (compared to diesel)
Cost	TBC
TRL	Commercially available
Risks / challenges	Truck autonomy, adaptation to plant's regular schedule

Sources: SQM press center, Enel x and SQM to bring first electric truck for large-scale mining to Chile, 2021.

SQM has reduced 18% emissions by switching from Diesel to Propane to fuel their dryers

Changing from Diesel to Propane

Retrofitting equipment to be powered by gas instead of diesel is a major step forward in reducing the carbon footprint, and at Salar de Atacama they know it. The team at the MOPGIII Plant did just this, **changing dryers from diesel to gas.**

Value chain	Extraction / Evaporation / Transport / **Processing**
Technology	**Retrofitting dryers** at the Granulated Potassium Chloride Plant from diesel to propane
CO2 emissions	Reduced 18% emissions from plant operations
Cost	TBC
TRL	Proven technology
Risks / challenges	Cost of retrofit can be high

Sources: SQM press center, Salar Builds the Sustainable Future Today, 2021.

Litus has an operating pilot for their nanotechnology that extracts lithium at exceptional rates

Litus

DLE + cutting-edge nanomaterials

Advanced nanomaterials enable the low-cost and selective extraction of lithium from low-concentration sources, providing a more efficient and sustainable approach to lithium production.
First pilot achieved up to 99.5% recovery and 99% impurity rejection.

Value chain	**Extraction** · **Evaporation** · Transport · Processing
Technology	**Modular solution with nanotechnology** for brine extraction
CO2 emissions	Improved recovery percentage
Cost	TBC (Litus claims to be competitive)
TRL	Pilot under development
Risks / challenges	TBC

Sources: Canadian Mining Journal, Litus announces field deployment for its lithium extraction pilot unit, 2025.

Bioleaching could reduce up to 60% of emissions by switching to Microbial Oxidation fuel

Terrafame Sotkamo (2021)

Terrafame operates an integrated production chain from an open-pit mine to a battery chemicals plant on a single site. The core technology is **heap bioleaching**, which utilizes naturally occurring microorganisms to extract metals from ore at ambient temperatures, completely bypassing energy-intensive smelting. By 2026, the facility is producing nickel sulphate for approximately **1 million electric vehicles annually**.

Value chain	Extraction / Transport / Smelting / **Refining**
Technology	Heap Bioleaching
CO2 emissions	From: 4.4 kgCO2e/kg Ni To: 1.75 kgCO2e/kg Ni (60% reduction)
Cost	**90% lower** thermal energy use than traditional smelting
TRL	Proven tech
Risks / challenges	Long leaching residence times, cold climate cycle management

Hydrometallurgical refining up to 70% of emissions by switching to low-carbon hydroelectric power

VALE

Long Harbour Refinery (2014)

The Long Harbour facility processes nickel concentrate using a **hydrometallurgical refining process** instead of traditional smelting. The refinery uses **pressure leaching** and **solvent extraction** to produce high-purity nickel products.

Powered largely by **hydroelectric electricity,** the process significantly reduces carbon intensity compared to conventional pyrometallurgical refining.

Value chain	Extraction / Transport / Smelting / **Refining**
Technology	Hydrometallurgical refining (pressure leaching)
CO2 emissions	From: 10 - 15 kgCO2e/kg Ni To: 4 – 7 kgCO2e/kg Ni (50 - 70% reduction)
Cost	Lower energy intensity due to elimination of smelting.
TRL	Fully commercial refinery
Risks / challenges	High capital cost, complex chemical processing, dependence on stable low-carbon electricity supply

Switching Coal-Powered RKEF Smelting to Renewable Electricity could Reduce Up to 30-40% of Emissions in Laterite Nickel Production

Indonesia Laterite RKEF Smelters

Indonesia hosts the world's largest laterite nickel processing capacity using **Rotary Kiln Electric Furnace (RKEF) technology** to produce ferronickel and nickel matte.

The process is highly carbon intensive because it relies on coal-powered electricity and coal as a reductant. Since electric furnaces consume large amounts of power, switching to low-carbon electricity offers the largest opportunity to reduce emissions without changing the metallurgical process.

Value chain	Extraction · Transport · **Smelting** · Refining
Technology	Renewable-powered RKEF smelting
CO2 emissions	From: 40 – 120 tCO_2e/t Ni To: 12 – 48 tCO_2e/t Ni (30 - 40% reduction)
Cost	Moderate retrofit cost, requires renewable generation and grid upgrades near smelters
TRL	Proven smelting tech, but depends on energy system transition infrastructure
Risks / challenges	Reliance on coal, renewable integration and grid stability, high electricity demand of electric furnaces

Using induction furnaces during graphitization could reduce up to 68% of SG emissions

Vianode®

Switching Acheson furnaces out for induction furnaces

Induction furnaces have tighter temperature control, higher yield, and better energy-recovery measures. The closed production system minimizes waste and maximizes material recovery, which the LCA identifies as a key driver of the 90% emission reduction result.

Value chain	Feedstock / Carbonization / **Graphitization** / Refining
Technology	Batch induction furnace technology
CO2 emissions	From: 8 tonCO2/ton synthetic graphite To: 2.6 tonCO2/ton synthetic graphite (67.5% reduction, assuming clean grid)
Cost	Proprietary tech has a higher upfront cost
TRL	Commercial
Risks / challenges	High upfront cost

Sources: Life Cycle Assessment for Vianode: Sustainable Battery Material Innovation (2024) Minviro.com.

Using block route during graphitization could reduce SG emissions up to 63%

TOKAI COBEX

Replace traditional powder route for block route

Solid blocks have a higher density and allow for better "furnace loading" (more material in the same space). This means less electricity is wasted heating empty space or packing media. The powder route requires graphite crucibles (canisters) to hold the loose powder in the furnace.

Value chain	Feedstock / Carbonization / **Graphitization** / Refining
Technology	E3BAM® block route (lengthwise graphitization)
CO2 emissions	From: 8 tonCO2/ton synthetic graphite To: 3 tonCO2/ton synthetic graphite (62.5% reduction, assuming clean grid)
Cost	cost-competitive in the European market due to efficient use of materials and reduction in expensive consumables
TRL	Early commercial
Risks / challenges	block route requires extensive mechanical milling, which can lead to reduced material yield and shape variance

Sources: Carrère, Tristan, Bénédicte Allard, and Till Reek. “Towards Greener Aluminium Production -A Carbon Footprint Assessment of Graphitized Cathodes for Electrolysis Pots.” 2024.

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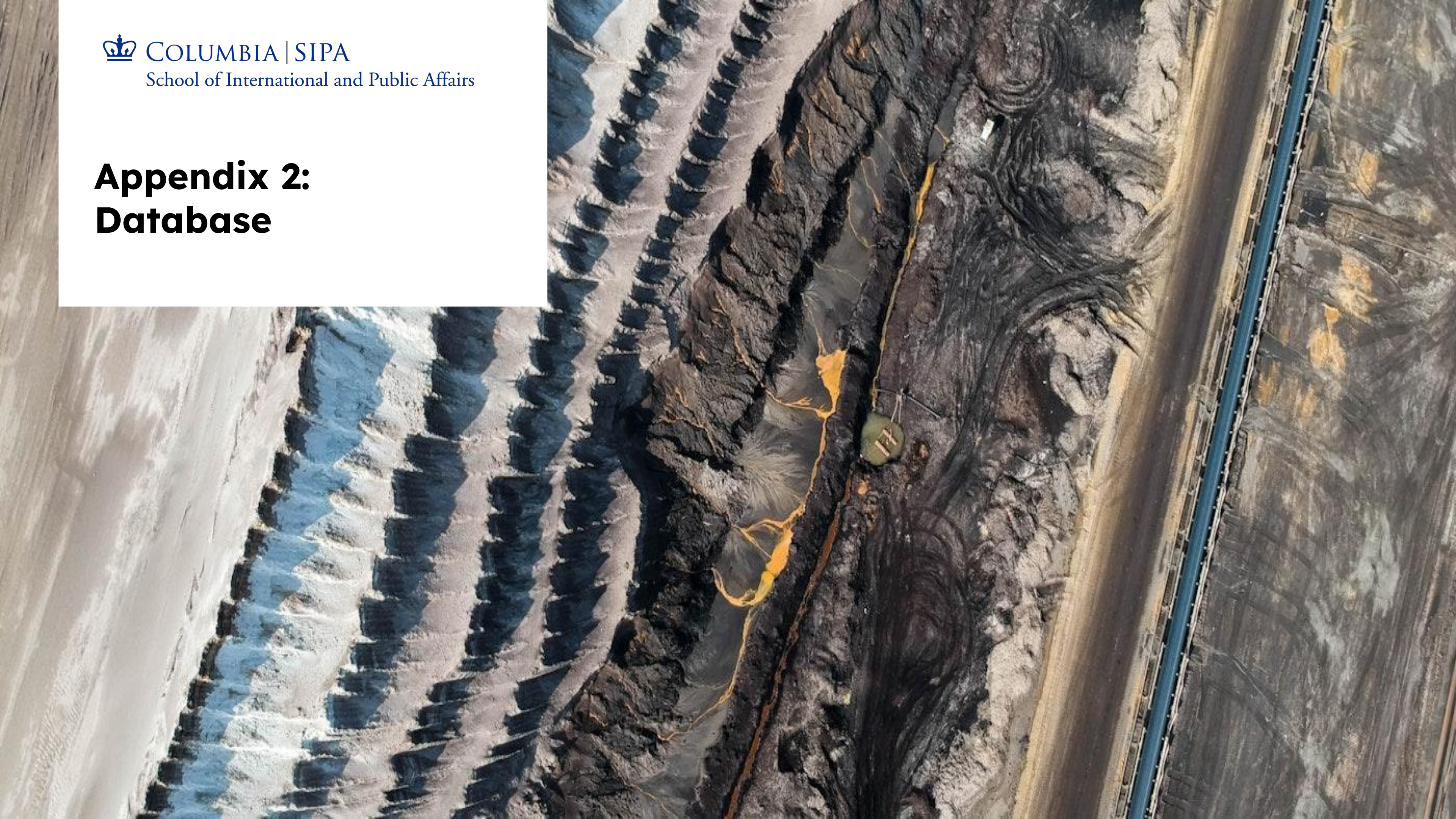
Appendix 2: Database



Data points across four minerals highlight significant gaps in data quality and availability

		Copper	Lithium	Nickel	Synthetic Graphite
Data availability	# of countries covered	4	5	7	6
Data quality	Data from academic papers	Good level of public data available	Good level of public data available	Good level of public data available	Low public data available
	Company reports	Good level of public data available	Good level of public data available	Low public data available	Low public data available
	Granularity for process steps	Good level of public data available	Low public data available	Low public data available	Low public data available

Good level of public data available · Low public data available · No public data

Emission factor inventory in Nickel ore grade calculations

Energy	Primary Energy	Emission Factor
Electricity (coal)	PEF: 0.34	1000 kgCO2-eq/kWh
Electricity (natural gas)	PEF: 0.4	500 kgCO2-eq/kWh
Electricity (oil)	PEF: 0.37	650 kgCO2-eq/kWh
Electricity (hydro)	PEF: 0.95	20 kgCO2-eq/kWh
Electricity (wind)	PEF: 0.5	4.6 kgCO2-eq/kWh
Electricity (solar)	PEF: 0.34	58 kgCO2-eq/kWh
Electricity (biomass)	PEF: 0.23	93 kgCO2-eq/kWh
Diesel (road transport)	43.3 MJ/kg	0.0752 kgCO2-eq/MJ
Diesel (sea transport)	43.3 MJ/kg	0.0748 kgCO2-eq/MJ
Diesel (stationary combustion)	43.3 MJ/kg	0.0743 kgCO2-eq/MJ
Natural Gas	50 MJ/kg	0.0562 kgCO2-eq/MJ
Coal	27.5 MJ/kg	0.0953 kgCO2-eq/MJ
Anthracite	29 MJ/kg	0.099 kgCO2-eq/MJ
Coke	28.5 MJ/kg	0.1077 kgCO2-eq/MJ

Note:

$$PEF_i = E_{plant} / E_{elecricity}$$

Where:

PEF_i = Primary Energy Factor from source

E_{plant} = energy consumed in power plant

$E_{electricity}$ = energy consumed by users

Sources: Wei et. al. (2020)

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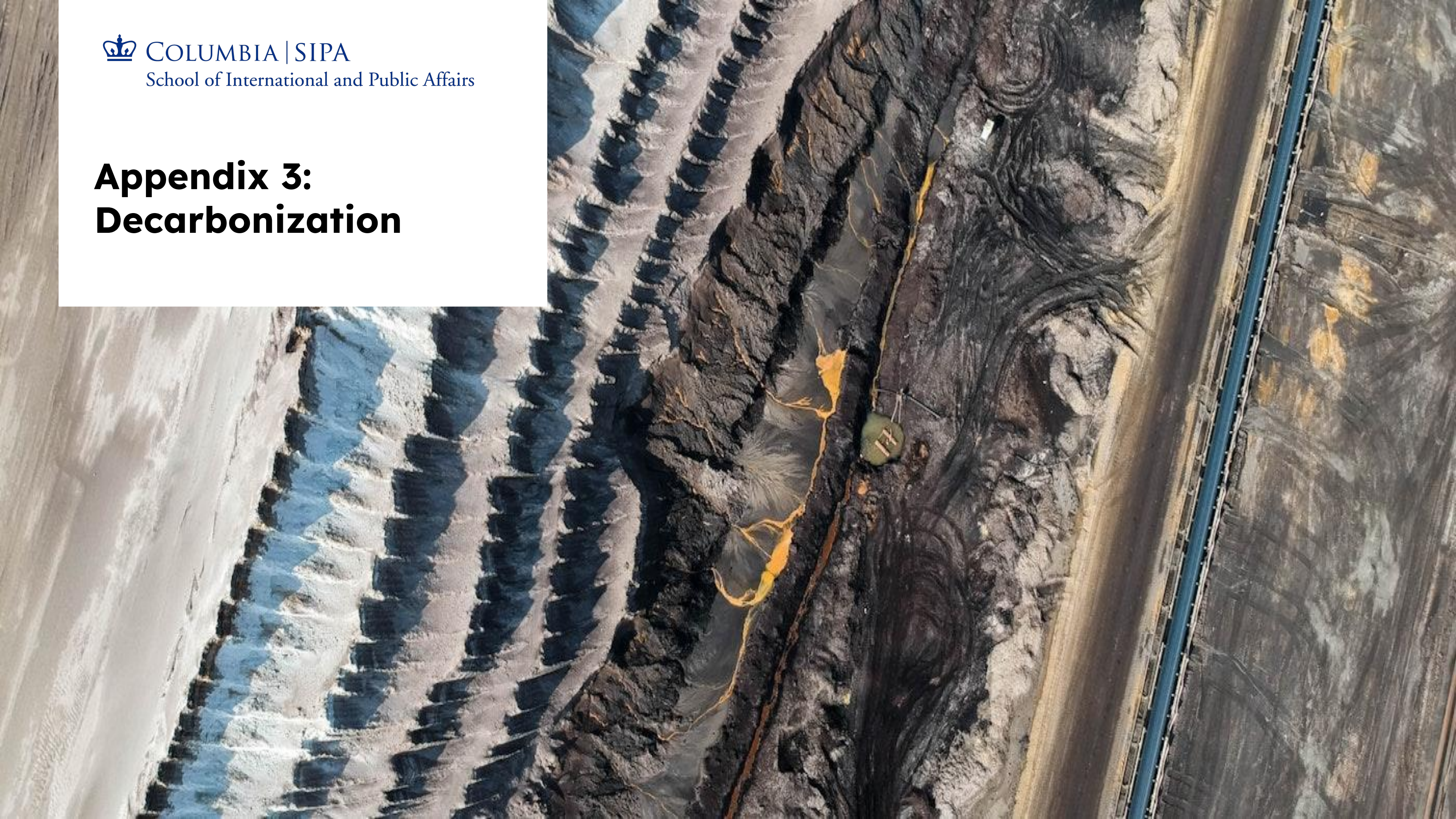
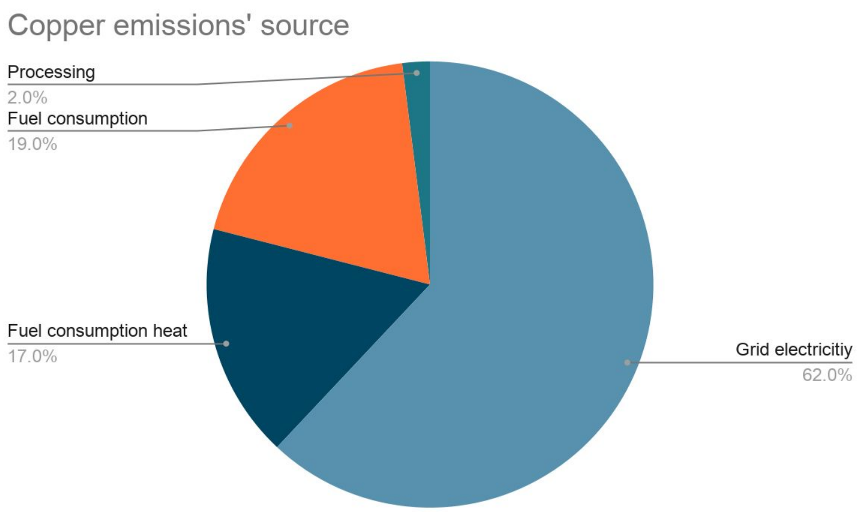
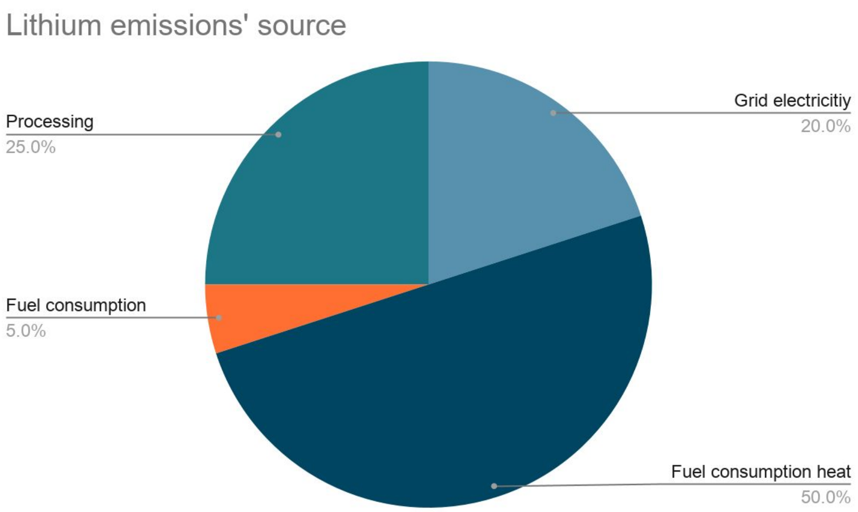
Appendix 3: Decarbonization



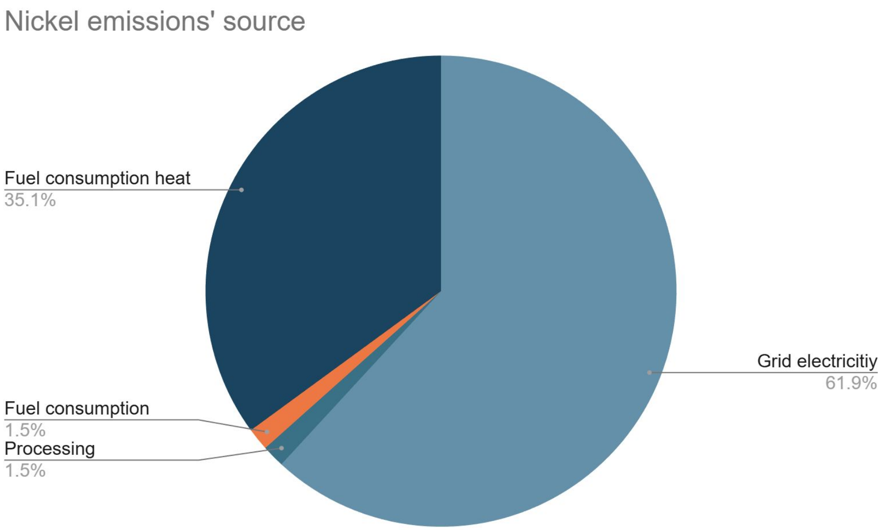
Emissions’ source by mineral (1/2)

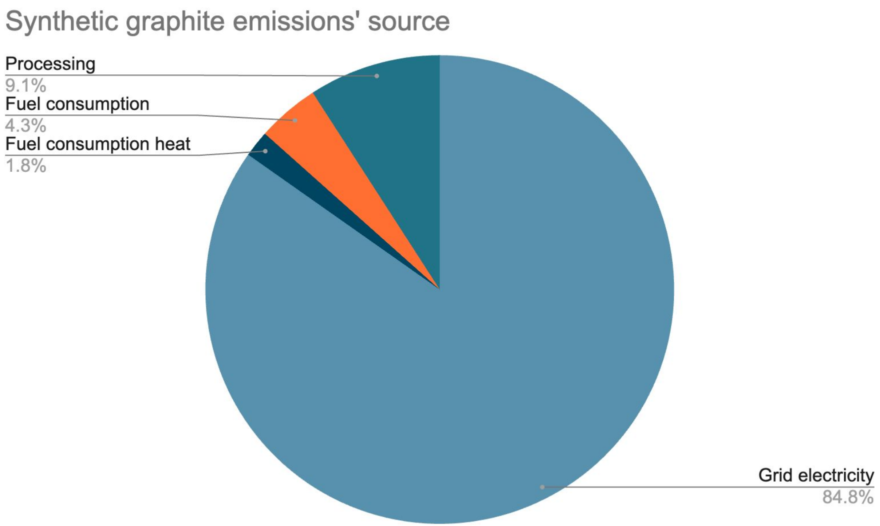




Note: Average numbers, values change when considering different pathways and regions.

Emissions’ source by mineral (2/2)





Note: Average numbers, values change when considering different pathways and regions.

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Decarbonizing Critical Mineral Supply Chains

May 11, 2026