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A CRITICAL RAW MATERIAL SUPPLY-SIDE INNOVATION ROADMAP FOR THE EU ENERGY TRANSITION

December 2024

SYSTEMIQ

ABOUT THIS REPORT

Quotes:

Lord Adair Turner, Chair, Energy Transitions Commission

"In the long-term, the shift to a clean energy system will lead to a circular system with limited need for further resource extraction. However, in the immediate future, we must intensify our efforts to secure critical raw materials essential for the energy transition. Simultaneously, we must strive to mitigate the environmental and social impacts of extraction, striking a delicate balance between progress and preservation."

Julia Reinaud, Senior Director, Europe, Breakthrough Energy

"Accelerating investment for R&D and deployment and creating a supportive regulatory and trade environment that establishes robust domestic supply chains for critical raw materials is a necessity for the EU to secure a leadership role in the clean energy sector. By leveraging innovative technologies, the EU can reclaim competitiveness, bolster its strategic autonomy, and minimise the environmental footprint of mining and refining processes. Technological advancement and a more sustainable approach will be the cornerstones of Europe's resource independence and green industrial future."

Preface:

The European Union's Competitiveness Compass, recently announced by President Ursula von Der Leyen, aims to close the EU's innovation gap with the US and China, develop a joint plan for decarbonization and competitiveness, and enhance domestic security while reducing dependencies. For each of these objectives, it will be crucial to secure robust upstream mining and refining capacity of critical raw materials (CRMs) within the EU and strategic partner countries as soon as possible.

While the Critical Raw Materials Act (CRMA) has set clear targets for domestic mining and refining by 2030, progress has yet to build up to the necessary momentum to meet these benchmarks. Mining projects face significant delays, and refining capacity remains inadequate relative to volumes required to reach net zero for most CRMs. These challenges threaten to undermine the EU's leadership aspirations in the clean energy sector and its wider strategic autonomy.

In response to these pressing issues, this report focuses on innovative solutions in primary supply that could accelerate our progress towards CRMA targets, while bolstering the rapidly expanding battery value chain. We have centred our analysis on six critical materials that will be crucial to support the energy transition and face substantial future supply-demand challenges: copper, nickel, cobalt, lithium, graphite, and rare earth elements. These technologies not only offer the opportunity to rapidly boost the total supply of these materials, but also to significantly reduce the environmental impacts of their production across GHG emissions reduction, water conservation, limiting chemical waste streams and improved tailings management.

This project first establishes the landscape of emerging innovation across CRM exploration and development, extraction, mine site processing, refining and tailings management and reprocessing. It explores a set of ~20 technologies with technical readiness level above 5 that, before focussing on seven key solutions identified as having the highest potential to resolve the EU's key supply and environmental issues in the short-to-mid-term.

This report does not advocate for specific technologies; our aim is rather to provide policymakers with a comprehensive framework for supporting innovations that can enhance supply security, sovereignty, and sustainability. We recognise that achieving a sustainable and competitive CRM strategy demands an integrated approach, incorporating not only supply-side innovations but also material substitution, materials efficiency and recycling as central components of Europe's long-term strategy.

This report is designed to equip policymakers, industry leaders, and other key stakeholders with actionable insights to develop a cohesive innovation roadmap for securing Europe's CRM needs. We believe this is an essential foundation for our clean energy transition and our continued leadership in the global fight against climate change.

As we navigate the complexities of this transition, it is crucial that we act decisively and collaboratively. The path forward requires innovation, strategic planning, and a shared commitment to sustainability. With the right approach, Europe can not only meet its own CRM needs but also set a global standard for responsible and efficient resource management in the clean energy era.

ACKNOWLEDGEMENTS

Authors

This report was developed between September and December 2024 by Systemiq with the support of Breakthrough Energy. The Systemiq team consisted of Lloyd Pinnell, Benjamin Neves and Pravin Steele and was led by Eveline Speelman and Alasdair Graham. The Breakthrough Energy team consisted of Pénélope Le Menestrel and Julia Reinaud.

Expert Review

This report was developed with data and support from **Minviro** and **Benchmark Mineral Intelligence**, and analysis from the Energy Transitions Commission.

We would also like to thank the following individuals for their inputs and review: Lord Adair Turner, Philip Varin, Scott Crooks, Craig Weich, Ben Dixon, Niklas Niemann, Tilman Vahle, Louis Millon, Max Held, Phoebe O’Hara.

Systemiq was founded in 2016 to drive system change for a sustainable future and the achievement of the Paris Agreement and the UN Sustainable Development Goals. Systemiq's Energy practice are leading experts in the decarbonisation of the "harder-to-abate" sectors and the issues that connect them.

The **Energy Transitions Commission** is a global coalition of leaders from across the energy sector, industry, finance, and environmental organizations dedicated to achieving a net-zero emissions economy by mid-century.

Founded by Bill Gates, **Breakthrough Energy** is a global network of climate leaders committed to accelerating the world’s journey to a clean energy future

Expert Interviews[1]

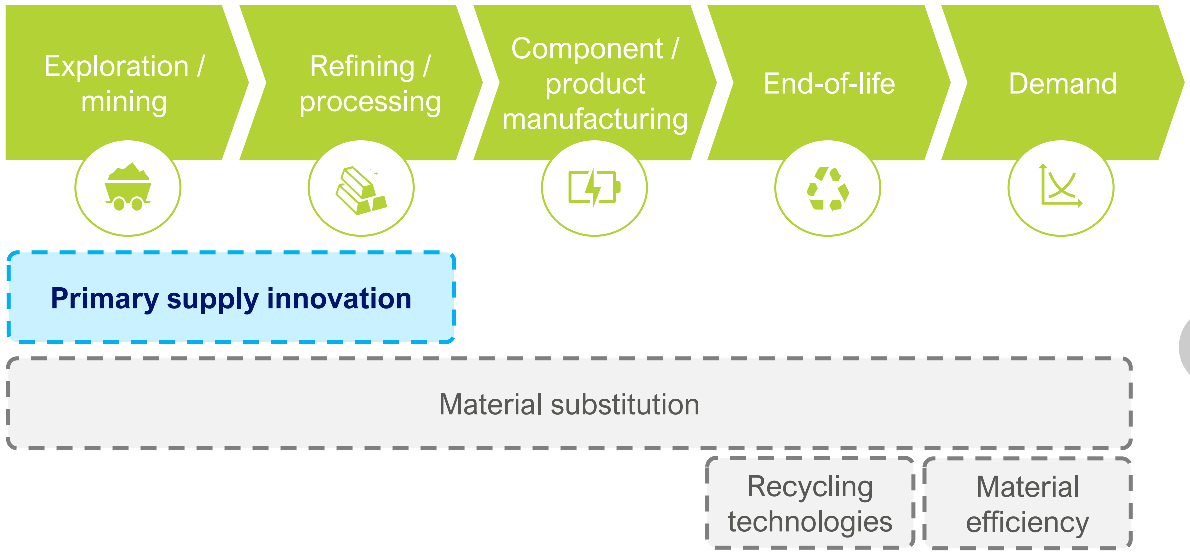
We would like to thank a number of individuals who have generously contributed their time and expertise during the research process for this report, notably:

Abraham Jalbout (Auxilium), Adam Burley (Nuton, Rio Tinto), Aditya Ramji (UC Davis), Adriana Zamora (Minviro), Alan Morales (World Economic Forum), Alexander Allen (Nth Cycle), Alvaro Baeza (Glencore), Anthony Weiss (TechMet), Antonio Valente (Ecoinvent), Arnaud Jouron (Arthur D. Little), Batchimeg Ganbataar (Nomadic Venture Partners), Brenda Haendler (Breakthrough Energy Fellow), Brendan Smith (SiTration), Buff Lopez (CleanTech Group), Caleb Boyd (Molten Industries), Chris Beatty (TechMet), Cristobal Undurraga (Ceibo), Darryl Steane (Ceibo), Emily Ritchey (Transport and Environment), Eric Dusseux (Breakthrough Energy Ventures), Eric McShane (Electroflow), Francisco Jeria (Ceibo), Gareth Taylor (S&P Global), Gero Frisch (University of Freiburg), Henry Finnegan (TechMet), Ian Hayton (CleanTech Group), Jared Deutsch (GeologicAI), Javiera Alcayaga (Nuton, Rio Tinto), Jenni Kiventera (EIT Raw Materials), Jonathan Dunn (Anglo-American), Jordan Lindsay (Minviro), Joseph Bertin (Tokia Cobex), Julia Poliscanova (Transport and Environment), Karan Bhuwalka (University of Stanford), Katarina Nilsson (ETP SMR), Kevin Bush (Molten Industries), Laura Sonter (The Biodiversity Consultancy), Laure Latour (Tokai Cobex), Libby Wayman (Breakthrough Energy Ventures), Lucy England (FLSmidth), Ludivine Wouters (Latitude Five), Luis Arbulu (Sunna VC), Madeleine Luck (QCF), Marcus Clover (Energy Revolution Ventures), Mat Ganser (Lilac Solutions), Mouna Tatou (DGALN), Nathan Flaman (I-Rox), Nigel Steward (Rio Tinto), Nour Amrani (FLSmidth), Philip Newman (Rio Tinto – HDS Technologies), Roland Gauss (EIT Raw Materials), Romain Dechelette (Infravia), Rosemary Cox-Galhorta (Breakthrough Energy Fellows), Saad Dara (Mangrove Lithium), Sam Jaffe (Addionics), Scott Thomsett (Rovjok), Stephen Northey (University of Sydney), Sylvain Eckert (Infravia), Tae-Yoon Kim (IEA), Thomas Requet (DGALN), Vincent Pedailles (Carbon Scape).

Note: 1. Inclusion in list of experts interviewed does not constitute an endorsement of findings or conclusions.

REPORT CONTEXT

Focus of this report



🟦 *Exclusive focus of report*

⬜ *Not included in report scope*

Report approach

1 **Critical Raw Material Selection**
Focus on **six CRMs**[1] essential for the energy transition that face significant future supply-demand imbalances

2 **Key Supply & Environmental Challenges**
Identify the key **short-to-mid-term challenges** related to mining and refining for these selected CRMs at both the EU and global level

3 **Innovation Landscape**
Assess a set of ~20 emerging **supply-side innovations** with technical readiness levels (TRL) above 5 across the mining and refining value chain for these selected CRMs[2,3]

4 **Deep Dive on Breakthrough Technologies**
Deep-dive into **7 breakthrough technologies** that can play a major role in solving identified key supply and environmental challenges in the **next 10-15 years**

5 **Policy Recommendations**
Define **key priority policy actions** for EU policymakers to accelerate the development and adoption of these technologies in the EU and strategic partner countries

Note: 1. Critical raw materials (CRMs) are raw materials of high economic importance for the EU, with a high risk of supply disruption due to their concentration of sources and lack of good, affordable substitutes. The 6 CRMs selected are the following: Cu – Copper; Ni – Nickel; Co – Cobalt; Li – Lithium; C – Graphite (Carbon); Nd – Neodymium. | 2. Across exploration, development, extraction, mine-processing, refining and tailings. | 3. This report does not explore the topic of deep-sea mining, as this is subject to an evolving regulatory landscape at both the European and international levels. The lack of a unified legal framework or consensus among EU Member States creates a challenge for incorporating it into an actionable roadmap.

Source: Systemiq analysis

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2	**Key Environmental Impacts**	• Comparison of environmental impact for selected CRMs mining and refining based on production process and location, across: **emissions, water use, acidification, land use and tailings**	*24-32*
3	**Innovation Landscape**	• **Overview of emerging technologies** with potential to increase supply and/or mitigate environmental impacts of selected CRMs and review of current **commercialisation status**	*33-40*
4	**Selected Technologies**	• Deep-dive into 7 selected **new technologies** with **high-impact potential** to resolve key identified supply and environmental challenges for CRM production in the EU and strategic partner countries over next 10-15 years	*41-50*
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EXECUTIVE SUMMARY

KEY SUPPLY CHALLENGES | COPPER FACES A MAJOR GLOBAL SHORTFALL, WHILE LITHIUM AND GRAPHITE ARE ALSO AT HIGH RISK IN THE EU

Global challenges

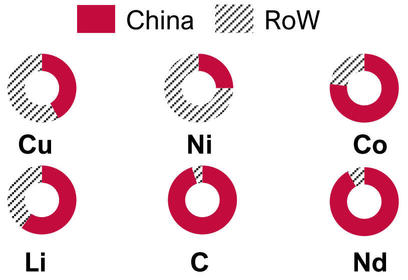
I A major supply shortfall is expected for most critical raw materials by 2035…

- The energy transition will drive a **major increase in demand for critical raw materials (CRMs)** as clean technology deployment accelerates in the next 10-15 years.
- The largest increase in global annual demand is expected for **lithium (6x by 2035) and graphite (4x),** while demand for nickel, cobalt and REEs[1] is set to roughly double.
- In the long-term, evolving battery chemistries, material innovation and improved recycling rates mean that **primary supply requirements for CRMs may fall significantly over time**.
- However, a **significant gap** is nonetheless projected to emerge between the supply and demand for most CRMs **in a net-zero scenario by 2035.**
- The largest shortfalls are expected to be for **copper, lithium and graphite**, with demand forecast to exceed supply from existing and new announced mines by 40%, 110% and 80%, respectively. A substantial increase in **new project development** beyond current plans will therefore be required to bridge the gap.

II … and global CRM supply chains are currently heavily concentrated

- **Globally, CRM mining is typically highly concentrated in certain countries**. For example, Indonesia and DR Congo account for ~40% and ~70% of global nickel and cobalt mining, respectively, while China has almost 70% of global market share for graphite and REEs.
- **At the refining stage, China dominates global production for all CRMs**, controlling >40% of global copper output, >60% for cobalt and lithium, and >85% for graphite and REEs.
- **However, global reserves are much more widely distributed than current production**, indicating a strong potential for diversification in future.

China vs. rest of world market share of refining stage production by CRM



EU challenges

III EU mining and refining output has declined over the past decades, increasing reliance on imports…

- **Europe's share of global minerals production has fallen from 25% to less than 7%** over the last 40 years, with a similar decline also occurring for metal refining.[2] However, the **EU will require large volumes of CRMs to meet its climate objectives**, especially as inputs into electric vehicle (EV) batteries.
- The **EU Critical Raw Materials Act (CRMA),** which entered into force earlier in 2024, aims to reverse this trend by setting targets for the **EU's domestic share of mining, processing and recycling of CRMs by 2030, set at 10%, 40% and 25% of annual consumption**, respectively. It also sets a limit on the total annual consumption of any strategic raw materials that can be sourced from a single external country to 65%.
- **The EU currently imports a large share of the CRMs it consumes**. While there is an established industry for copper, nickel and cobalt mining and refining, the EU has **virtually no existing domestic capacity for lithium, graphite and REEs production at scale.** The EU is therefore virtually entirely import-dependent for these CRMs.

IV … and the EU is off track to meet its CRMA mining and refining targets for several key materials

- While many CRM projects have been announced in the EU in recent years, the vast majority remain at an **early development stage at present**.
- Several major projects have **struggled to progress due to local opposition and permitting challenges**, making it highly unlikely that these will be realised in time to meet 2030 CRMA targets.
- **Copper is the only CRM for which the EU appears on track to meet its targets** based on existing output and announced new projects.
- A **large pipeline of prospective lithium mining and refining projects** have emerged, which could supply more than half of domestic EU demand by 2030, but these **face high uncertainty at present**.
- The current average timeline for new mines and refineries to come online after feasibility studies are completed is ~5 years, meaning **new projects going forward will need be expedited to be ready for 2030.**

Note: 1. REEs – rare earth elements, e.g., neodymium. | 2. See terminology page for definitions for minerals and metal refining.

KEY ENVIRONMENTAL IMPACTS | CRM PRODUCTION CAN HAVE IMPORTANT LOCAL IMPACTS, BUT THESE ARE SMALL VS ENABLED CARBON SAVINGS

Key environmental impacts of CRM mining and refining

I The impacts of CRMs varies significantly by production method and location…

- Globally, **copper accounts for the largest share of GHG emissions, water use and tailings generation from CRM production**, due to large production volumes (despite having relatively low impacts per tonne).
- **Nickel and cobalt stand out** as having particularly high average GHG emissions, water use and acidification impacts, as well as elevated biodiversity and human rights risks, mainly because mining is concentrated in regions that employ more harmful practices.
- A **significant share of GHG emissions for all CRM production occurs at the refining stage**, where grid emissions intensity is a key factor. Production in China, where most output is concentrated at present, relies on carbon intensive electricity due **to the high share of coal in the power mix at present**, though this is decarbonising rapidly.
- Therefore, **relocating to Europe**, especially in regions with low-carbon power, **would result in significantly lower emissions per tonne in the next 5-10 years for most CRMs.**

II … though these will increase without efforts to reduce production intensities…

- If no action is taken to reduce the environmental impacts of CRM mining and refining, **total global emissions from the sector could double to reach ~1 $GtCO_2$-eq by 2035** (i.e., assuming current average intensities per tonne by production process employed remain constant).
- **Synthetic graphite production** is expected to become the largest single source, with nickel also accounting for an important share.
- Similarly, **water consumption and acidification levels could also rise by 60-70%**, driven in large part by nickel production. **Copper continues to dominate absolute volumes of tailings generated**, with a ~50% increase beyond current levels to 5,500 Mt in total.
- It is, therefore, **important to find solutions to address these challenges** and reduce the environmental impact of mining and refining, both today and in the future.

III … however, CRMs enable the transition to a vastly lower-impact clean energy system

- **CRMs provide the inputs required** for the construction of clean technologies, such as **solar PV and batteries for EVs**, enabling the **transition towards a renewable energy system**.
- The **emission savings enabled by CRMs therefore vastly outweigh their emissions footprint from production.** For comparison, the maximum emissions from the production of all materials (including steel etc.) for clean technologies in a net-zero scenario would be 80x lower than the total annual emissions from the extraction and consumption of fossil fuels today.
- While the latter is recurring, the former is temporary as **materials can subsequently be recycled**.
- In addition, while water and land requirements for mining can be significant at the local level, these are very small (<1%) relative to those used for agriculture across the world today.

The role of innovation…

Incremental improvements are important, but breakthrough technologies could have a significant impact

- **There are a clear set of measures to mitigate environmental risks at mine sites that should be adopted both in the EU and around the world.** This includes, for example, improving water recycling, soil remediation, dry stacking of tailings etc.
- The **most important lever for decarbonising raw material production is electrification** (including for fleets), which can drastically cut emissions in the coming years.[1]
- However, **emerging 'breakthrough' innovation could also offer an opportunity to boost the supply of CRMs quickly and sustainably.**
- We identify a set of **seven key technologies that could have a major impact in future for both the EU and strategic partner countries.**[2] These offer the EU an opportunity to reverse its structural decline in CRM production, support the energy transition, increase strategic autonomy and leapfrog incumbent processes *(see next page).*

Note: 1. For example, the current emissions intensity of copper production could be reduced by 85% by switching half of all energy use from fuels used to electricity powered by renewables. | 2. Refers to countries that the EU currently has strategic partnerships with or may in the future, including members of the Minerals Security Partnership e.g., Chile, Argentina, DRC.

INNOVATION LANDSCAPE | NEW TECHNOLOGIES CAN SUSTAINABLY INCREASE CRM SUPPLY FOR THE EU

⬚ *See next slides for potential impact on EU battery production*

2 new technologies could boost domestic EU CRM supply significantly in the short-to-mid-term…

(Geothermal) Direct Lithium Extraction

Li

Could supply **~7% of EU lithium** demand by 2035 from 2 projects if commercialised

While reducing **emissions by >90%** vs incumbent processes (imports from China)[1]

With initial estimates suggesting **similar costs** vs existing production is feasible

Novel Synthetic Graphite Production

C

Could supply **~40% of EU graphite** demand by 2035 from 4 projects if developed

While reducing **emissions by >90%** vs incumbent processes (imports from China)[2]

Higher cost than competition in China but limited impact on final battery costs (<5%)

…2 technologies can also boost mining output in EU strategic partner countries…

Primary Sulfide Leaching

Cu

Could supply **~12% of global copper** demand by 2035 if deployed at scale where feasible[3]

While reducing **emissions by ~40%** per tonne copper vs incumbent processes[3]

At **comparable costs** to current existing production processes

Less effective in **colder climates** like the EU

Application of AI to Geological Data

All

Preliminary results indicate **75% discovery success rate** compared to historic rate of 5%[4]

Up to **25% reduction in exploration drilling costs** due to optimised drilling[4]

Applicability **constrained** by varying quantity and quality of **geological data**

…3 technologies are further from large-scale deployment but have major long-term potential

Novel Rock Comminution

All

Pulse power technology can reduce total mining **energy consumption by 30%**[5]

Novel Electrochemistry Applications

Li **Cu**

Offers major **energy efficiency** improvement, reduction in **chemical use** and **waste**

Tailings Reprocessing Technologies

All

Tailings could provide a large **source of additional CRM supply** in theory, with copper grades in some facilities that exceed those at some new mines[6]

All technologies need to prove **technical and economic feasibility** at scale, show **consistent performance** across a range of inputs, and overcome high initial upfront **capital costs**

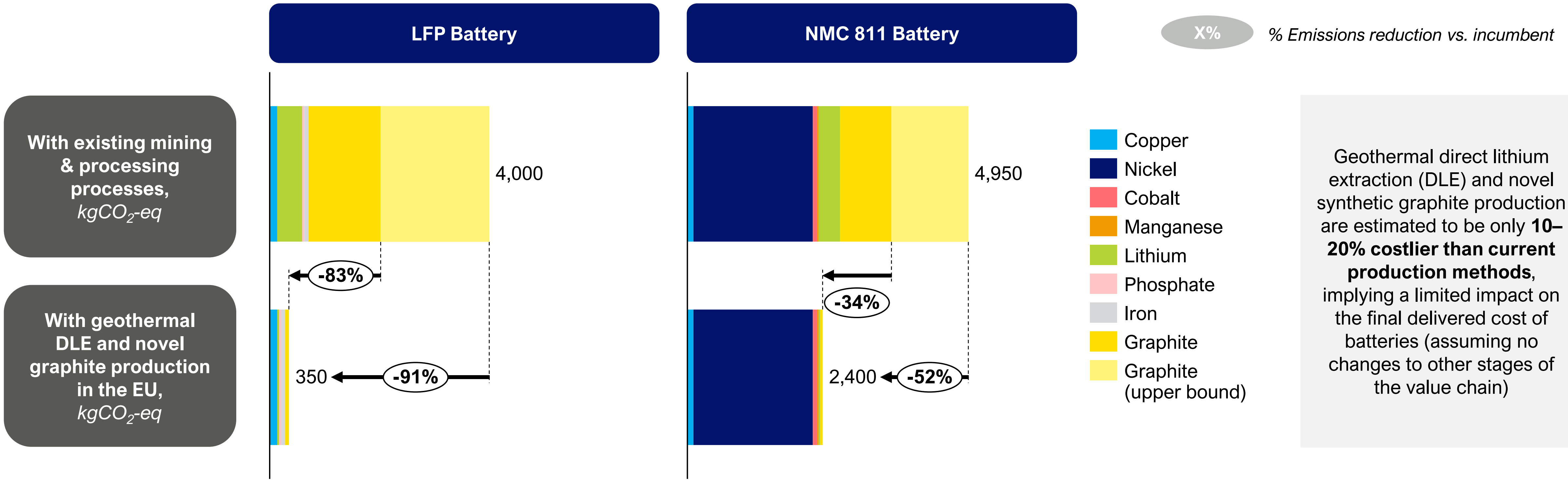
Source: Systemiq analysis based on multiple sources and expert interviews [see section 4 for further information]

Note: Selected technologies are not intended to be exhaustive. Demand projections from Section 1 (European Commission JRC forecasts); excludes innovative production outside the EU. Strategic partner countries refers to countries that the EU currently has strategic partnerships with or may in the future, including members of the Minerals Security Partnership. | 1. Weighted average emissions of LCE from spodumene ~20kgCO$_2$ per tonne (66% of the market) and from brines ~3 kgCO$_2$ (33% of the market) vs near-zero emissions from geothermal DLE | 2. Synthetic Graphite emissions estimated between 20 and 50kgCO$_2$-eq vs < 3kgCO$_2$ for novel synthetic production routes. | 3. From 35 mines across North America, Latin America and Africa; based on indicative values for production through pyrometallurgical routes compared to bio-leaching primary sulfide tailings. | 4. Based on Earth AI data – 3 discoveries from 4 exploration drills. | 5. Based on i-ROX technology replacing conventional ball mill and sag mill; comminution refers to the process of crushing, grinding and milling rock during mining/processing. | 6. For certain historical tailings that are currently not exploited.

SELECTED TECHNOLOGIES (1/2) | NEW TECHNOLOGIES COULD SIGNIFICANTLY CUT MATERIAL EMISSIONS (EUROPEAN BATTERY EXAMPLE)

Scaling low-carbon lithium and graphite production in the EU could cut EV battery pack emissions by ~80-90% for LFP and ~35-50% for NMC batteries, with minimal cost impact

GHG emissions of cathode and anode materials contained in 60-kWh battery pack by type manufactured in the EU, by source of CRMs



Geothermal direct lithium extraction (DLE) and novel synthetic graphite production are estimated to be only **10–20% costlier than current production methods**, implying a limited impact on the final delivered cost of batteries (assuming no changes to other stages of the value chain)

Source: Systemiq analysis based on Visual Capitalists, *The Key Minerals in an EV Battery*; Carbone4 (2023), *Increase the accuracy of carbon footprint for Li-ion battery*; and multiple other sources [see chapter 4 and appendix for further information].

Note: Only includes emissions from mining and refining of key materials needed in LFP and NMC 811 cathode and anode (with 100% graphite). Other materials and manufacturing emissions currently estimated at ~2.2 tCO2-eq (Carbone4) but not included on this chart. Calculations are based on the CRM mass in the respective battery types multiplied by carbon footprints. The weighted average emissions for lithium, cobalt, and nickel were calculated based on their respective production routes and market shares. For lithium, brines (30% share, 3 kgCO$_2$eq per kg LCE) and spodumene (66% share, 20 kgCO$_2$eq per kg LCE) result in a weighted average of 14.2 kgCO$_2$eq per kg LCE. For nickel, Class 1 (30% share, 18 kgCO$_2$eq per kg) and Class 2 (70% share, 69 kgCO$_2$eq per kg) lead to a weighted average of 53.7 kgCO$_2$eq per kg. For cobalt, production from copper (70% share, 5 kgCO$_2$eq per kg) and nickel (30% share, 38 kgCO$_2$eq per kg) yields a weighted average of 14.9 kgCO$_2$eq per kg. Manganese emissions are estimated at 6 kgCO$_2$eq/kg of metal; copper (pyrometallurgical route) at 5.3 kgCO$_2$eq/kg; iron and phosphate at 1.8 kgCO$_2$eq/kg. Synthetic graphite emissions remain a topic of debate within the industry, with estimates ranging from ~20 kgCO$_2$ per kg to 40–50 kgCO$_2$ per kg, with almost all production currently located in China; the upper bound of the range assumes 50 kgCO$_2$/kg. Emissions related to other cathode or anode materials, such as oxygen, are excluded. | 1. DLE emissions are estimated to be 1 kgCO2/kg of LCE and production is estimated to be 10% more expensive than the average incumbent LCE route today [1 LCE is equal to 5.323 tonnes of lithium]. | 2. New synthetic graphite production estimated to emit 1 kgCO2/kg and production is estimated to be 20% more expensive than the incumbent process today. | 3. Nickel, Cobalt, Manganese, Copper and other metal emissions assumed to remain constant between 2024 and 2035.

SELECTED TECHNOLOGIES (2/2) | NEW TECHNOLOGIES CAN BOOST GLOBAL AND EU SUPPLY CONSIDERABLY BY 2035 FROM BOTH PLANNED AND NEW PROJECTS

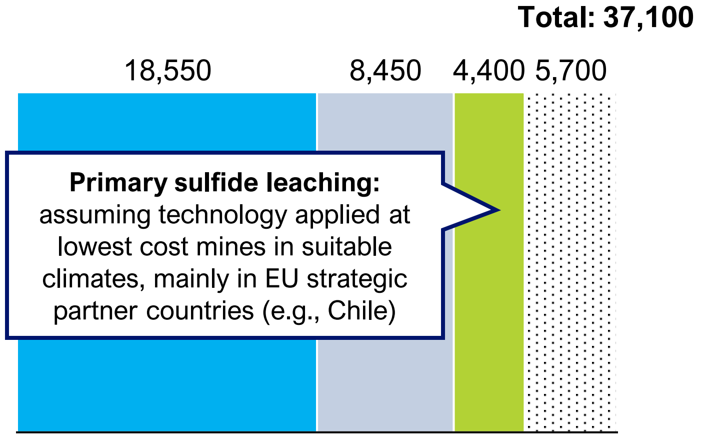
Scaling primary sulfide leaching, geothermal direct lithium extraction, and novel synthetic graphite production in Europe and globally could help the EU close its 2035 supply-demand gap while enhancing strategic autonomy

Supply-demand gap for copper, lithium, and graphite mining in 2035, kt p.a.

Non-exhaustive list of projects

- 🟦 Conventional planned primary supply
- ⬜ Secondary supply
- 🟩 Additional supply potential from new technlogy
- ▨ Remaining supply-demand gap

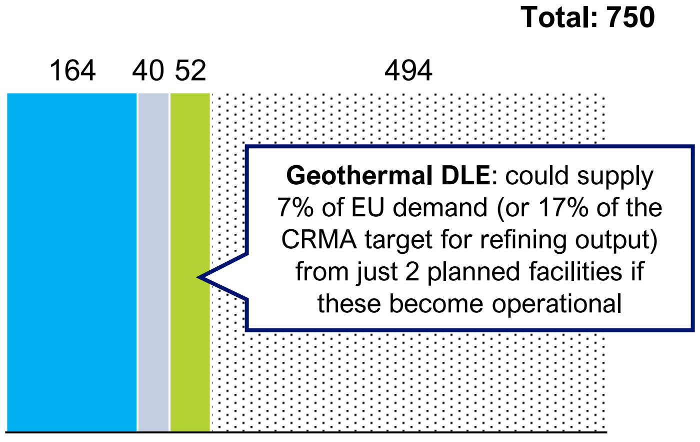
Copper – Global[1] Cu



Primary sulfide leaching: assuming technology applied at lowest cost mines in suitable climates, mainly in EU strategic partner countries (e.g., Chile)

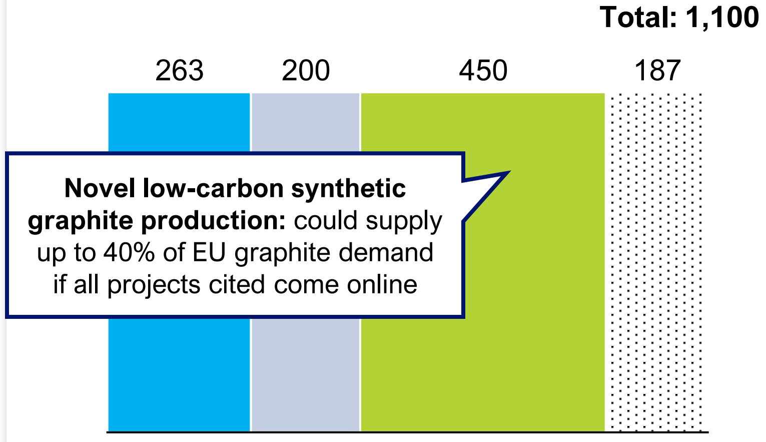
Top-down global modelling – *moderate uplift scenario*

Lithium (Carbonate Equivalent) – EU[2] Li



Geothermal DLE: could supply 7% of EU demand (or 17% of the CRMA target for refining output) from just 2 planned facilities if these become operational

Graphite (Battery-Grade) – EU[3] C



Novel low-carbon synthetic graphite production: could supply up to 40% of EU graphite demand if all projects cited come online

EU announced projects forecast – *not an upper bound, higher potential if further projects developed beyond current pipeline*

Source: Systemiq analysis based on Benchmark Mineral Intelligence (2024); IEA Critical Minerals Data Explorer (May 2024); IEA (2024), *Global Critical Minerals Outlook 2024;* S&P Capital IQ Pro; Advanced Propulsion Centre UK (2024), *Automotive quarterly report Q1 2024*; IEA (2024), *Recycling of Critical Minerals; press releases.*

Note: Supply figures refer to EU-27 countries only; all numbers are rounded; non-exhaustive list of innovators included; all assessed announced projects are assumed to come online. | 1. Copper is analyzed globally due to the limited impact of primary sulfide leaching in the EU; primary sulfide leaching potential derived from an analysis using S&P data explained in the corresponding technology deep-dive (see chapter 4). | 2. Projects referred to are Vulcan Energy & Eramet; Supply numbers are sourced from BMI, with 5% recycling assumed based on the IEA (2024) Recycling Report; 52 kt p.a. supply from Vulcan Energy and Eramet DLE projects (see DLE section) is included, while total expected demand is calculated as follows: battery demand in a NZS scenario for Europe is estimated at ~1.5 TWh by 2035, assuming an average consumption of 0.5 kg LCE/kWh for NMC/LFP batteries, this equates to ~750 kt of LCE demand annually. | 3. Graphite supply numbers are derived from BMI data for natural and synthetic graphite, combined with supply from the Talga natural graphite mine. Demand figures for Europe are sourced from the Advanced Propulsion Centre UK, while new technology supply estimates are based on announced plans from Tokai Cobex, Vianode, CarbonScape, and Molten (non-exhaustive list); recycling potential is estimated at 200 kt p.a. by 2035, according to BMI, but recycling projects were not analyzed in detail in this analysis. | 4. The CRMA sets a target to domestically process at least 40% of the Union's annual consumption of strategic raw materials by 2030

POLICY IMPLICATIONS | SEVERAL TOOLS, ESPECIALLY FOR PROJECT FINANCE AND OFFTAKE, CAN HELP STIMULATE SUPPLY-SIDE INNOVATION IN THE EU

Innovation Support

Accelerate investment in breakthrough technologies to **leapfrog traditional processes**, delivering lower environmental impacts in longer-term

1. Focus existing **EU innovation support** programmes, including Horizon Europe, the ERA-MIN network, ETP SMR, and EIT Raw Materials, on innovation areas where competitive and technological advantages can be secured in future[1]

Project Financing

Increase public funding available, and 'crowd in' private funding, for **first-of-a-kind deployment at commercial scale**, using blend of capex and opex support mechanisms

1. Direct **greater investment** for commercial deployment of new technologies, e.g., via an expanded EU Innovation Fund, the EIB, the EBRD and other blended finance programs[2]
2. Enhance production-based support, e.g., introduce **tax credits*,** expand **loan guarantees through the InvestEU programme**
3. Include mining/refining CRMs within target investment areas of the **STEP initiative** and a new European '**sovereignty fund**'[3]

Offtake & Price Volatility

Support innovators in securing **offtake agreements** offering price stability for domestically produced materials to provide project certainty

1. Provide **loans to** downstream sectors which are **conditional** on sourcing a proportion of CRMs domestically*, e.g., for EIB loans[4]
2. Introduce **incentives** for domestically produced CRMs in **downstream sectors**, e.g., EV tax credits
3. Set up **mandates** for domestically produced CRMs at downstream sector-level or country-level*

Enabling Environment

Streamline administrative process and facilitate coordination to **fast-track high-impact projects**

1. Enforce CRMA provisions to limit **permitting timelines** for projects deploying innovative technologies
2. Implement coordinated action to build **integrated downstream value chains**, alongside CRM innovations
3. Including responsible mining/refining of CRMs within the **EU taxonomy for sustainable activities**[5]

International Competitiveness

Promote EU production by targeted **trade measures** where necessary, while promoting innovative technologies in **partner countries**

1. Require **technology and skills transfer** from foreign investors to EU partners when investing in CRMs or downstream value chains
2. Promote piloting and scaling innovations that reduce environmental footprint in partner countries through Strategic Partnerships and the **Minerals Security Partnership**

⬚ Top priority for further exploration
X New initiatives
X Continuation/extension of existing initiatives

Early-stage techs[6]

Key challenge for EU companies: developing first-of-a-kind commercial facilities[7]

Source: Systemiq analysis based on expert interviews; see chapter 5 for further information.

Note: Non-exhaustive list of options. All CRM Projects should uphold the highest environmental and social standards in line with best practice (e.g., IRMA initiative). Strategic partner countries refers to countries that the EU currently has strategic partnerships with or may in the future, including members of the Minerals Security Partnership. | *Policies are primarily implemented at Member State rather than EU-level. | 1. ERA-MIN: European Research Area Networks Cofound on Raw Materials, ETP SMR: European Technology Platform for Sustainable Mineral Resources, EIT: European Institute of Innovation & Technology. | 2. EIB: European Investment Bank, EBRD: European Bank for Reconstruction and Development. | 3. STEP - Strategic Technologies for Europe Platform. | 4. This could be through a mechanism similar to the European Hydrogen Bank's resilience criteria. | 5. With added provisions that high environmental and social standards are upheld. | 6. Including inter alia novel rock comminution, novel electrochemistry applications, tailings reprocessing. | 7. Including inter alia (geothermal) direct lithium extraction, novel synthetic graphite production.

1 KEY SUPPLY CHALLENGES

	Chapter	Content	Pages
	Executive Summary		*6-12*
1	**Key Supply Challenges**	• **Global and EU supply outlook** for selected critical raw materials (CRMs) relative to forecast demand in a net-zero scenario, including review of **new project timelines** and **geographic concentration** of production	*13-23*
2	**Key Environmental Impacts**	• Comparison of environmental impact for selected CRMs mining and refining based on production process and location, across: **emissions, water use, acidification, land use and tailings**	*24-32*
3	**Innovation Landscape**	• **Overview of emerging technologies** with potential to increase supply and/or mitigate environmental impacts of selected CRMs and review of current **commercialisation status**	*33-40*
4	**Selected Technologies**	• Deep-dive into 7 selected **new technologies** with **high-impact potential** to resolve key identified supply and environmental challenges for CRM production in the EU and strategic partner countries over next 10-15 years	*41-50*
5	**Policy Implications**	• **Key challenges** for the deployment of selected new technologies in the EU and **recommended actions for policymakers**	*51-58*
	Appendix		*59-81*

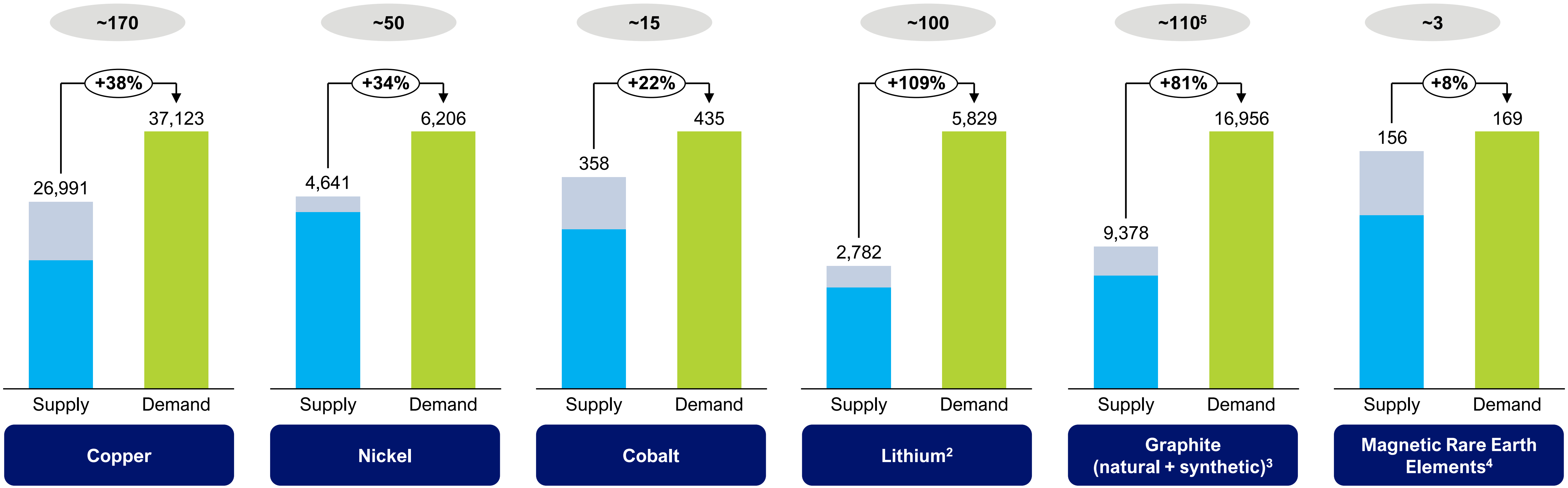
A MAJOR GLOBAL SHORTFALL IS EXPECTED IN THE SHORT-TO-MID-TERM FOR MOST CRMS

For all CRMs in focus, supply from existing and announced projects is below forecast demand by 2035 in a net-zero scenario, with largest gaps projected for copper (~40%), lithium (~110%) and graphite (~80%)

🟩 Total demand 🟦 Primary supply ▨ Secondary supply

Projected global mine supply vs. total demand in 2035, kt p.a. (note axis scales differ)
Supply – IEA base case; Demand - IEA net-zero emissions by 2050 Scenario (NZE)

XX Potential no. of new mines required to meet projected demand, beyond existing and announced (high-likelihood) mines [1]



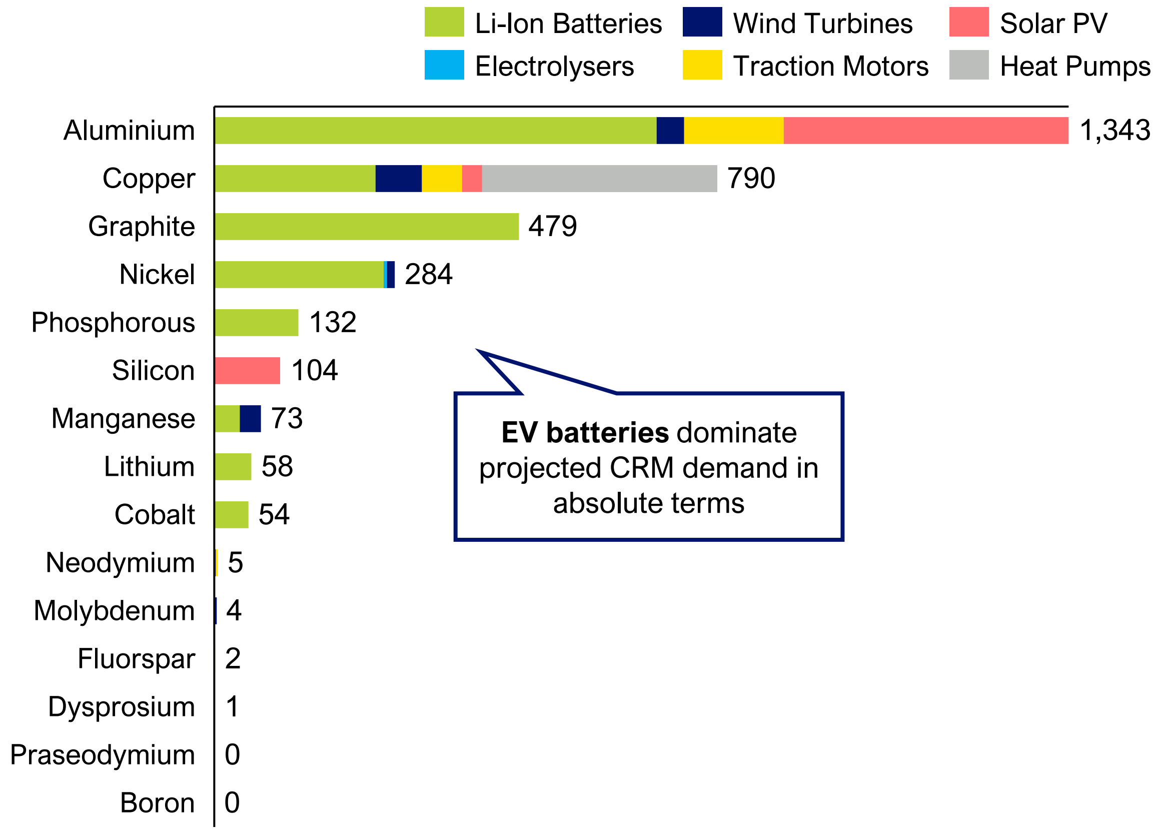
Source: IEA Critical Minerals Data Explorer (May 2024); IEA (2024), *Global Critical Minerals Outlook 2024;* S&P Capital IQ Pro.

Note: Base case is assessed through probability of coming online based on factors such as status of financing, permitting and feasibility studies. For 2035 secondary supply figure – mid-point of 2030 and 2040 values used, based on Global Critical Minerals Outlook. | 1. Estimated based on global average 2022 mine production for each metal: *Copper – ~60 kt p.a.; Nickel – ~30 kt p.a.; Cobalt – ~5 kt p.a.; Lithium – ~30 kt LCE p.a.; Graphite – ~70 kt p.a.; REE – ~5 kt p.a.;*. values are purely illustrative and do not consider the potential for increased output from existing or newly opened mines, which may meet a significant portion of future demand. | 2. LCE (lithium carbonate equivalent) content - mining includes extraction from hard rock ore, clays and brines | 3. Different grades of graphite are required for different use cases - graphite for the energy transition (63% of 2035 demand) is for EV batteries and stationary storage. | 4. Praseodymium (Pr), neodymium (Nd), terbium (Tb) and dysprosium (Dy). Weight is indicated in RREE content, not in oxide equivalent (REO). | 5. This includes both natural graphite mines and synthetic graphite production facilities.

SIGNIFICANT VOLUMES OF CRMS WILL BE REQUIRED FOR THE DEPLOYMENT OF CLEAN TECHNOLOGIES IN THE EU IN COMING YEARS

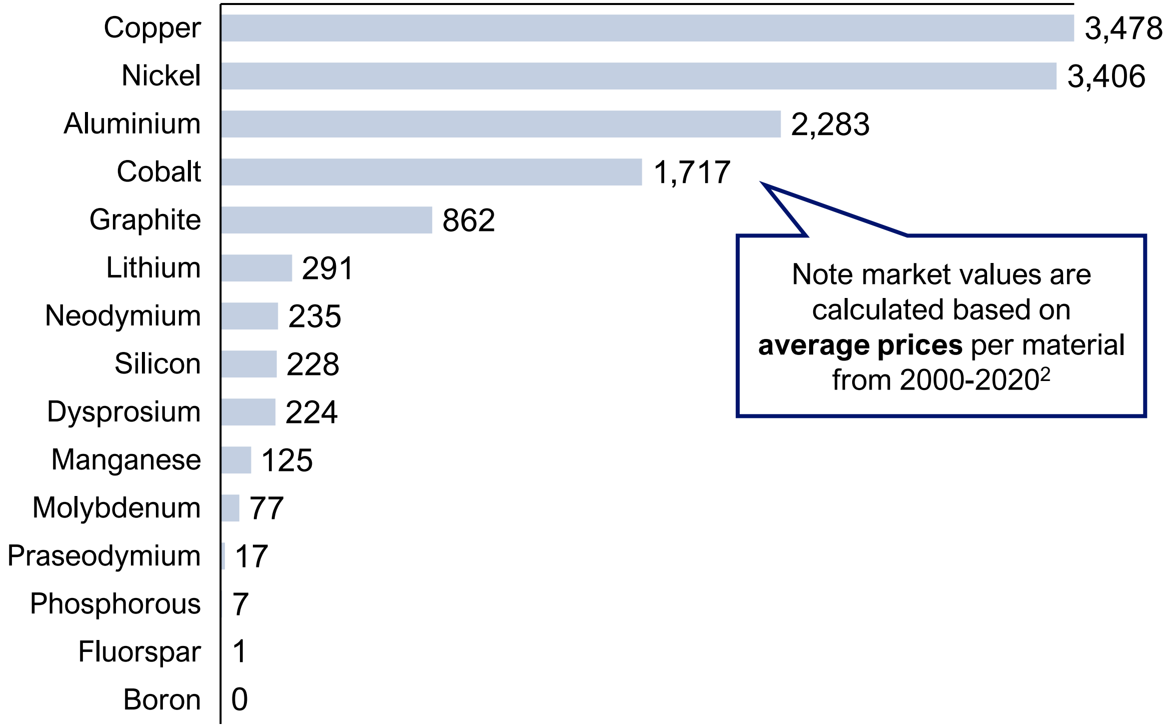
Top CRMs for energy transition based on absolute demand and market value by 2030 under green-deal aligned decarbonisation scenario

Projected 2030 EU demand for top 15 critical raw materials by end use, kt p. a
JRC (2023) high demand scenario[1]



EV batteries dominate projected CRM demand in absolute terms

Projected 2030 EU market value for top 15 critical raw materials, € mn p.a.
JRC (2023) high demand scenario



Note market values are calculated based on **average prices** per material from 2000-2020[2]

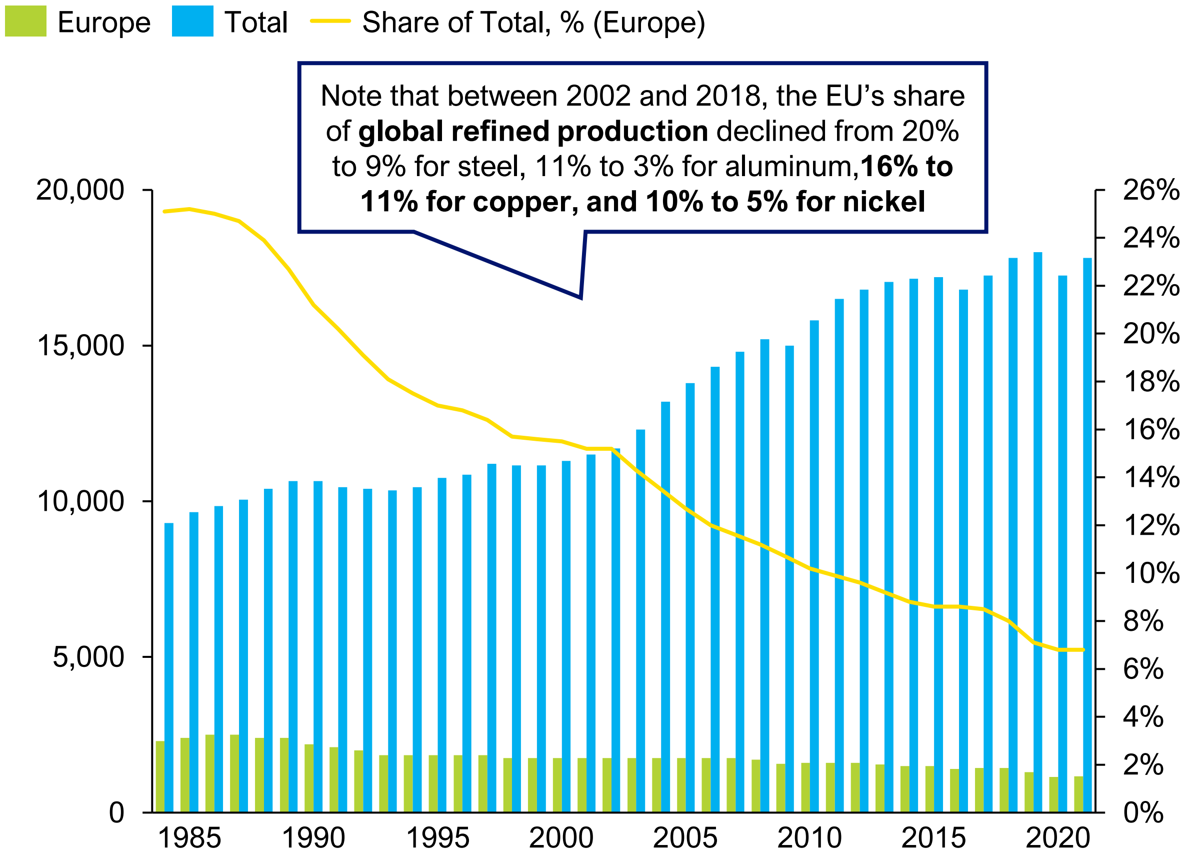
Source: European Commission, *JCR Science for Policy Report: Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study* (March 2023); Solutions for Critical Raw materials – a European Expert Network, (2023) Factsheets; Energy Transitions Commission, Materials Factsheet: Graphite (2023)

Note: 1. High demand scenario - future technology expansion is in line with the ambitious energy and climate change mitigation targets set by countries/regions (e.g. the REPowerEU targets for the EU in 2030), and more robust digitalisation trends. Top 15 materials by demand, based on CRMs in EU CRMA. | 2. Price data from SCRREEN, except for Graphite (ETC). Based on multiplying 2030 demand by 2000-2020 average price (different sets of years used for neodymium, fluorspar, dysprosium, and praseodymium due to data availability). Phosphorous rock, lithium carbonate, dysprosium oxide, and praseodymium oxide are used for relevant materials.

EUROPEAN MINING OUTPUT HAS STEADILY DECLINED, BUT THE CRMA AIMS TO INCREASE LOCAL PRODUCTION

European share of global minerals production has fallen from 25% to <7% over last 40 years while total output has doubled, leading to increased import reliance – CRMA aims to reduce vulnerability by setting targets for domestic shares of consumption

Global vs European Total Mine Output, Mt p.a.



Note that between 2002 and 2018, the EU's share of **global refined production** declined from 20% to 9% for steel, 11% to 3% for aluminum,**16% to 11% for copper, and 10% to 5% for nickel**

EU Critical Raw Materials Act

Sets benchmarks **by 2030** for the proportion of EU's **annual consumption** of strategic raw materials from **domestic capacity**:

>10%	**Extraction[1]**
>40%	**Processing[2]**
>25%	**Recycling[3]**

Limits annual total consumption of each strategic raw materials sourced from **any third country** to:

<65%[4]

Selected strategic projects will benefit from shorter **permitting timeframes** and a **mechanism to connect projects with offtakers**

27 months	**Extraction**
15 months	**Processing/Recycling**

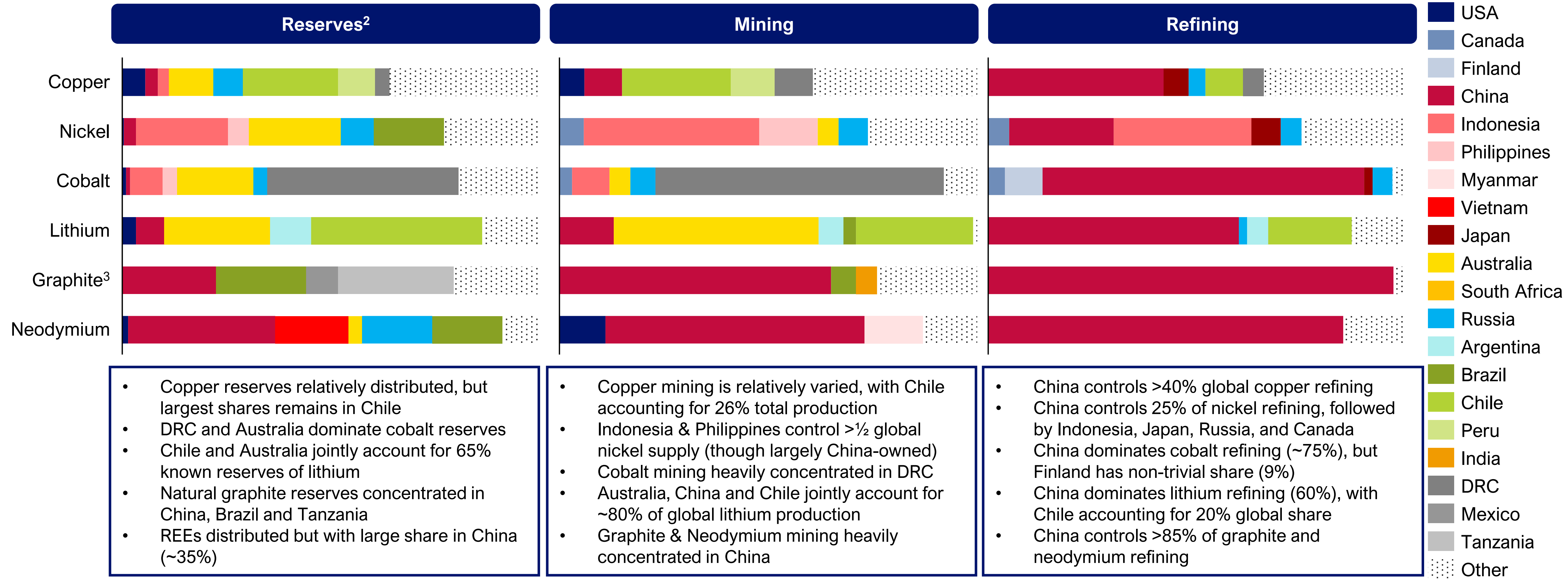
Source: World Materials Forum (2023), *Declining minerals production in Europe;* European Commission (16th March 2023); *Proposal for a regulation of the European parliament and of the council establishing a framework for ensuring a secure and sustainable supply of critical raw materials; J.* Perger (May 2022) *Regional shifts in production and trade in the metal markets: a comparison of China, the EU, and the US,* Mineral Economics, Volume 35, pages 627–640.

Note: 1. For ores, minerals and concentrates. | 2. Including for all intermediate processing steps. | 3. Including for all intermediate recycling steps. | 4. At any relevant stage of processing.

SUPPLY CHAINS FOR KEY CRMS ARE CHARACTERISED BY HIGH GEOGRAPHIC CONCENTRATION

CRM mining is concentrated in certain countries, while China dominates the refining stage for most CRMs – but global reserves for many are much more widely distributed than current mine production, indicating a potential for diversification

Share of Global Reserves, Mining and Refining Production by CRM & Country[1]



- Copper reserves relatively distributed, but largest shares remains in Chile
- DRC and Australia dominate cobalt reserves
- Chile and Australia jointly account for 65% known reserves of lithium
- Natural graphite reserves concentrated in China, Brazil and Tanzania
- REEs distributed but with large share in China (~35%)

- Copper mining is relatively varied, with Chile accounting for 26% total production
- Indonesia & Philippines control >½ global nickel supply (though largely China-owned)
- Cobalt mining heavily concentrated in DRC
- Australia, China and Chile jointly account for ~80% of global lithium production
- Graphite & Neodymium mining heavily concentrated in China

- China controls >40% global copper refining
- China controls 25% of nickel refining, followed by Indonesia, Japan, Russia, and Canada
- China dominates cobalt refining (~75%), but Finland has non-trivial share (9%)
- China dominates lithium refining (60%), with Chile accounting for 20% global share
- China controls >85% of graphite and neodymium refining

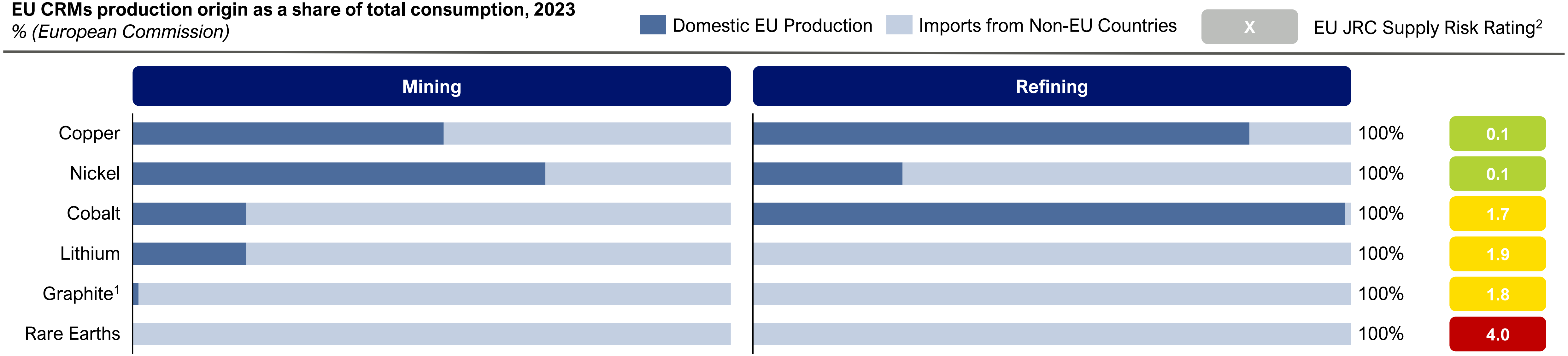
Source: European Commission (2024), *Raw Materials Information System Profiles*; US Geological Survey (2023), *Mineral Commodity Summaries*; Mining Technology (October 2024).

Note: 1. 2023 for Reserves. For Refining/ Mining – most recent year of RMIS data (between 2019 and 2021). | 2. A dynamic working inventory of economically-extractable minerals/commodities that re currently recoverable. Figures show shares of resources for rare earths (including neodymium) but specifically shares of neodymium for mining and refining stages. | 3. Natural graphite only for mining; natural and synthetic graphite for refining. Graphite refining figure from Mining Technology

THE EU IS CURRENTLY HIGHLY RELIANT ON IMPORTS FOR MOST CRMS, ESPECIALLY FOR NEW BATTERY MATERIALS

Europe mines above 50% of the total raw copper and nickel it consumes, as well as processed copper and cobalt, but is highly dependent on imports for remaining CRM mining and refining – especially for lithium, graphite, and REEs (neodymium)[1]

EU CRMs production origin as a share of total consumption, 2023
% (European Commission)



- Raw copper in EU is mainly from Poland (20%), Spain (9%), Bulgaria (5%) & Sweden (4%), South America accounts 35% consumption
- Raw nickel imports are mostly Canada (~60%) and South Africa (~20%)
- Russia accounts for 25% EU raw cobalt consumption, USA and Finland next largest (16% each), DR Congo only 9%
- Portugal accounts for all domestic lithium mining in EU (19%)
- China accounts for 41% of natural graphite consumption in EU
- China accounts for 80% raw REEs consumed in EU[3]

- Largest sources of refined supply of copper in the EU is from Germany (18%)
- Russia accounts for 38% of EU refined nickel consumption, Norway 14%
- EU largely self-reliant for refined cobalt – mainly from production in Finland
- Imports for Chile accounts for almost 80% EU consumption of refined lithium
- EU entirely dependent on imports for refined graphite and rare earths (primarily from China)

Source: European Commission, *JCR Science for Policy Report: Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study* (March 2023); European Commission (2024), *Raw Materials Information System Profiles;* EU CRMS 2023, *Solutions for Critical Raw Materials Factsheets.*

Note: Figures do not include CRMs contained in imported products (e.g., EV batteries). 1. Natural and synthetic. | 2. Index calculated based on a function of country concentration of production, country governance, recycling input rate, and substitution index. | 3. For Neodymium, Lanthanum, Praseodymium, Samarium.

EU MINING CAPACITY TODAY IS LIMITED, BUT EMERGING PIPELINE SHOWS GROWTH POTENTIAL – MOST PROJECTS AT EARLY DEVELOPMENT STAGE

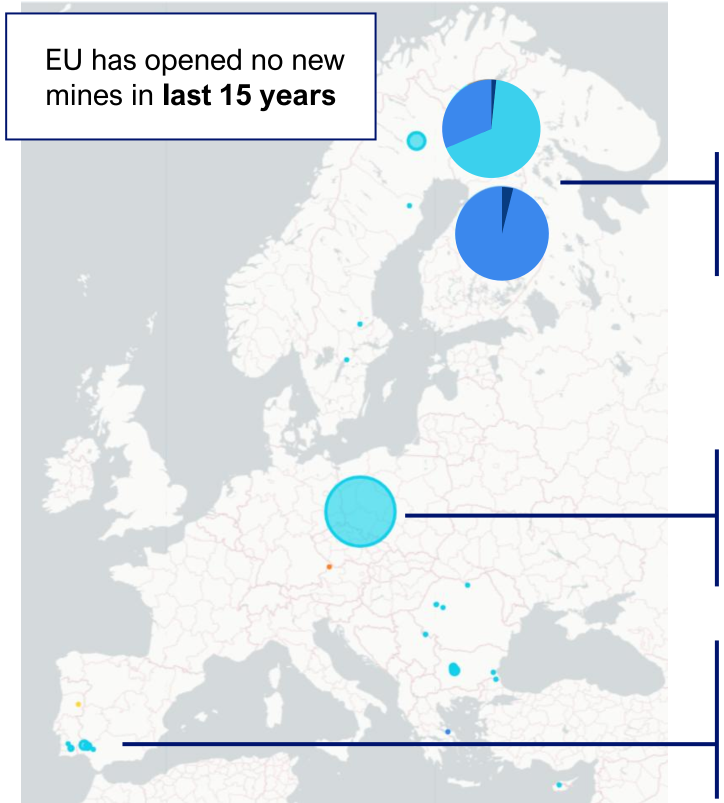
Existing and planned CRM mines in the EU

As of 24 October 2024

■ Cobalt ■ Nickel ■ Copper ■ Lithium ■ Graphite ■ Rare Earths

● Operating (size proportionate to 2023 production) ★ Advanced Development ▲ Early Development

Existing operating mines in the EU by CRM, 2024



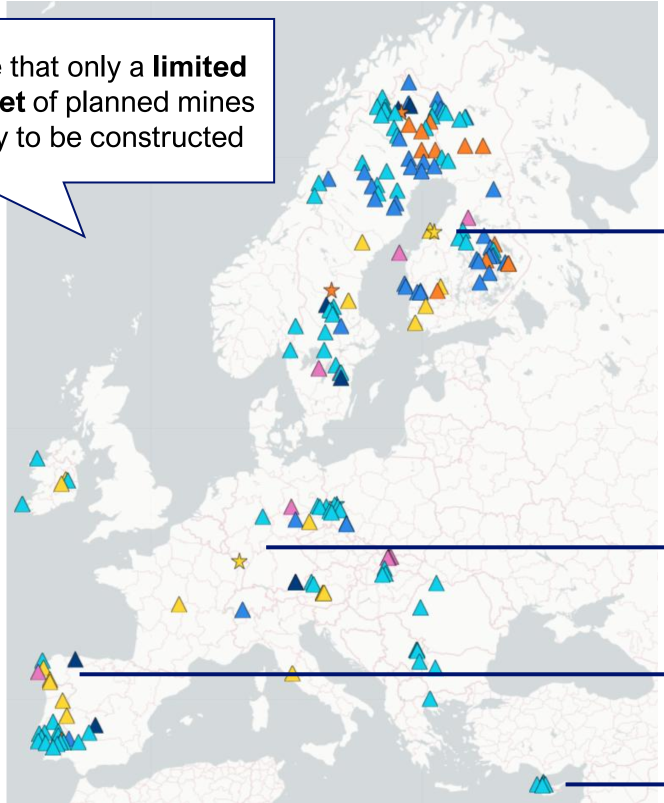
EU has opened no new mines in **last 15 years**

Large-scale Kevitsa and Terrafame mines in Finland – producing **copper, nickel, and cobalt**

13 **copper mines** in total across Romania, Bulgaria, and Poland – largest by production is **KGHM in Poland**

Aljustrel and Neves-Corvo **copper mines** in Portugal and Las Cruces, MATSA, and Huelva Rio Tinto **copper mines** in Spain

Planned mines in the EU by CRM, 2024



Note that only a **limited subset** of planned mines likely to be constructed

103 planned projects in Finland and Sweden – only advanced projects are Vittangi and Woxna **graphite mines** in Sweden, and Keiliber **lithium mine** (spodumene) in Finland

21 planned **lithium projects** spread around the EU – only advanced project is **Vulcan (geothermal brine) in Germany**

18 planned **cobalt/nickel/copper mines** in Iberia – none are at advanced stage

5 planned **copper mines** in Cyprus – all early stage

Source: Systemiq analysis based on S&P Capital IQ Pro data; EuroMetaux.

Note: 'Advanced Development' includes following S&P filters: *commissioning* and *construction started.* 'Early Development' includes following S&P filters: *target outline, exploration, reserves development, grassroots, advanced exploration, prefeasibility/scoping, feasibility started, feasibility, feasibility complete, and satellite.*

THERE ARE ALSO SEVERAL EXISTING CRM REFINERIES ACROSS THE EU, BUT NEW PROJECT PIPELINE IS RELATIVELY LIMITED

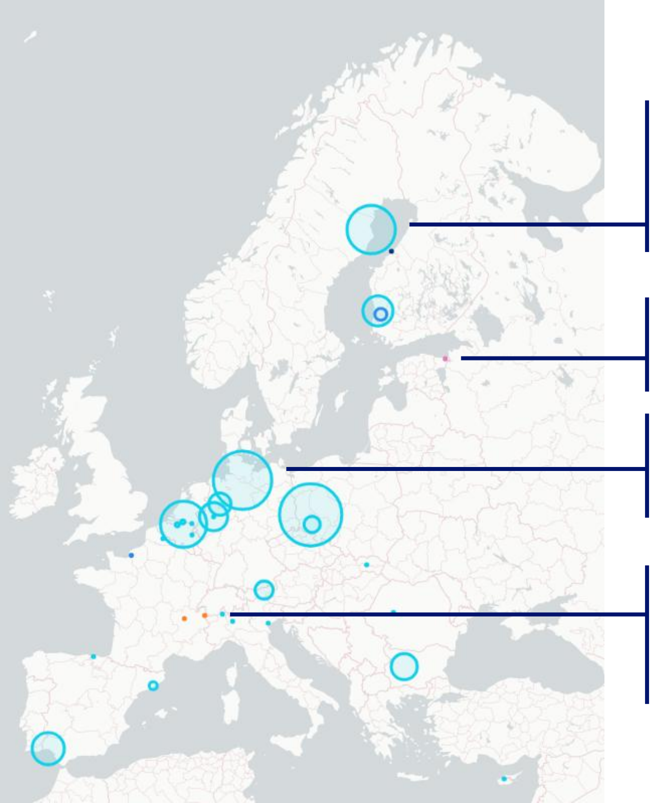
Existing and planned CRM refineries in the EU

As of 24 October 2024

■ Cobalt ■ Nickel ■ Copper ■ Lithium ■ Graphite ■ Rare Earths

● Operating (size proportionate to capacity) ★ Advanced Development ▲ Early Development

Existing operating refineries in the EU by CRM, 2024



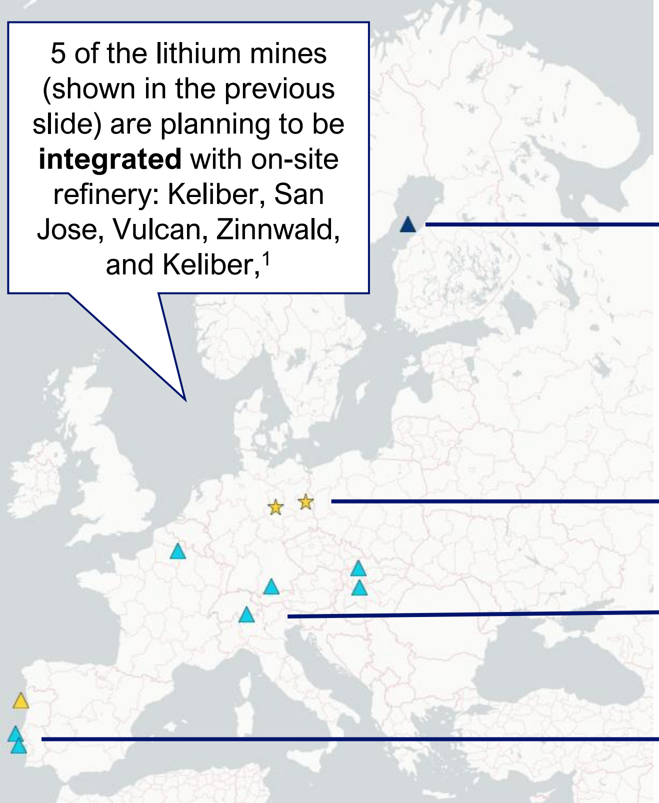
Copper – Pori (Finland) and Ronnskar (Sweden); **Nickel** – Harjavalta in Finland; **Cobalt** – Kokkola in Finland

Only operational **REE refinery** in Europe is the NPM Silmet refinery in Estonia

8 **copper refineries** in Belgium and Germany – largest is Aurubis refinery in Hamburg

2 **synthetic graphite** facilities in France Tokai Cobex and SGL Carbon

Planned refineries in the EU by CRM, 2024



5 of the lithium mines (shown in the previous slide) are planning to be **integrated** with on-site refinery: Keliber, San Jose, Vulcan, Zinnwald, and Keliber,[1]

Kokkola **cobalt refinery** expansion project in Finland

Guben and Bitterfeld **lithium refineries** in Germany (Bitterfeld started first production in Sept. 2024)

7 planned **copper refineries** at early development stage, including 2 in Portugal (Barreiro and Sines)

Estarreja **lithium refinery** in Portugal

Source: Systemiq analysis based on S&P Capital IQ Pro data.

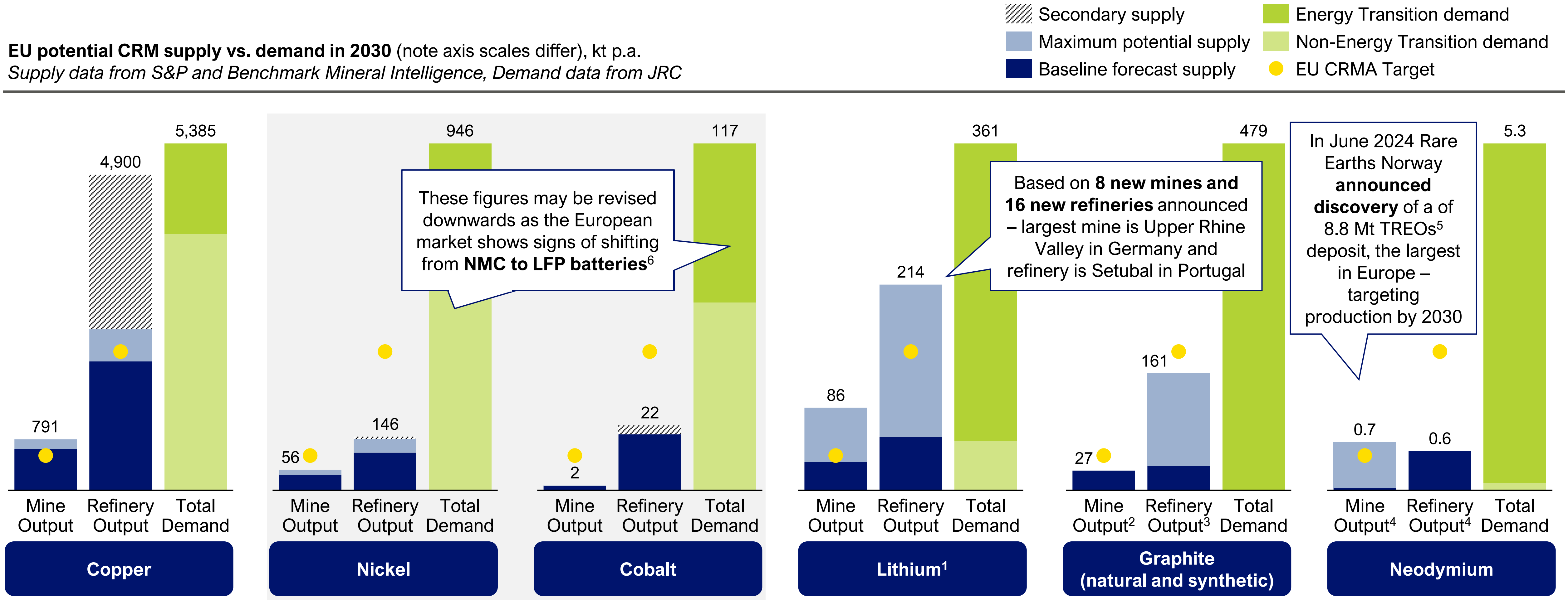
Note: 'Advanced Development' includes following S&P filters: *commissioning* and *construction started.* 'Early Development' includes following S&P filters: *target outline, exploration, reserves development, grassroots, advanced exploration, prefeasibility/scoping, feasibility started, feasibility, feasibility complete, and satellite.* | 1. Note there are several other planned early development Lithium projects (not in S&P database), e.g., Arvene (France, integrated), Eramet (France, integrated DLE), Viridan (France, refinery), Lithium Iberia (Spain, integrated), LusoRecursos (Portugal, integrated), RockTech (Germany, refinery), European Metals (Czechia, integrated), RockTech (Romania, refinery).

THE EU IS CURRENTLY OFF TRACK TO REACH ITS CRMA TARGETS FOR SEVERAL KEY MATERIALS

Capacity expansion required for nickel and cobalt beyond current plans, while large emerging pipeline of lithium and graphite remains highly uncertain at present

EU potential CRM supply vs. demand in 2030 (note axis scales differ), kt p.a.

Supply data from S&P and Benchmark Mineral Intelligence, Demand data from JRC



These figures may be revised downwards as the European market shows signs of shifting from **NMC to LFP batteries**[6]

Based on **8 new mines and 16 new refineries** announced – largest mine is Upper Rhine Valley in Germany and refinery is Setubal in Portugal

In June 2024 Rare Earths Norway **announced discovery** of a of 8.8 Mt TREOs[5] deposit, the largest in Europe – targeting production by 2030

Source: Benchmark Mineral Intelligence (2024); S&P Capital IQ Pro; KU Leuven & EuroMetaux (April 2022), *Metals for Clean Energy: Pathways to solving Europe's raw materials challenge;* European Commission (March 2023), *JRC Science for Policy Report: Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study;* Press research.

Note: Primary supply data from S&P for Copper, Benchmark for other materials. Secondary supply data from KU Leuven. Demand data from EU JRC. Maximum potential supply is based on pipeline of announced projects from Benchmark. For copper – baseline supply is from existing assets, maximum potential is from new assets coming online.

1. Lithium Carbonate (LCE) equivalent | 2. Flake graphite concentrate | 3. Flake graphite uncoated spherical purified graphite (USPG) + synthetic graphite anode material | 4. Praseodymium neodymium oxide | 5. Total Rare Earth Oxides. | 6. For example, ACC has paused its projects in Italy and Germany partly to explore Lithium Iron Phosphate (LFP) battery production instead of Nickel Manganese Cobalt (NMC).

THE OUTLOOK FOR NICKEL AND COBALT IS LESS CERTAIN DUE TO SHIFTING BATTERY CHEMISTRIES

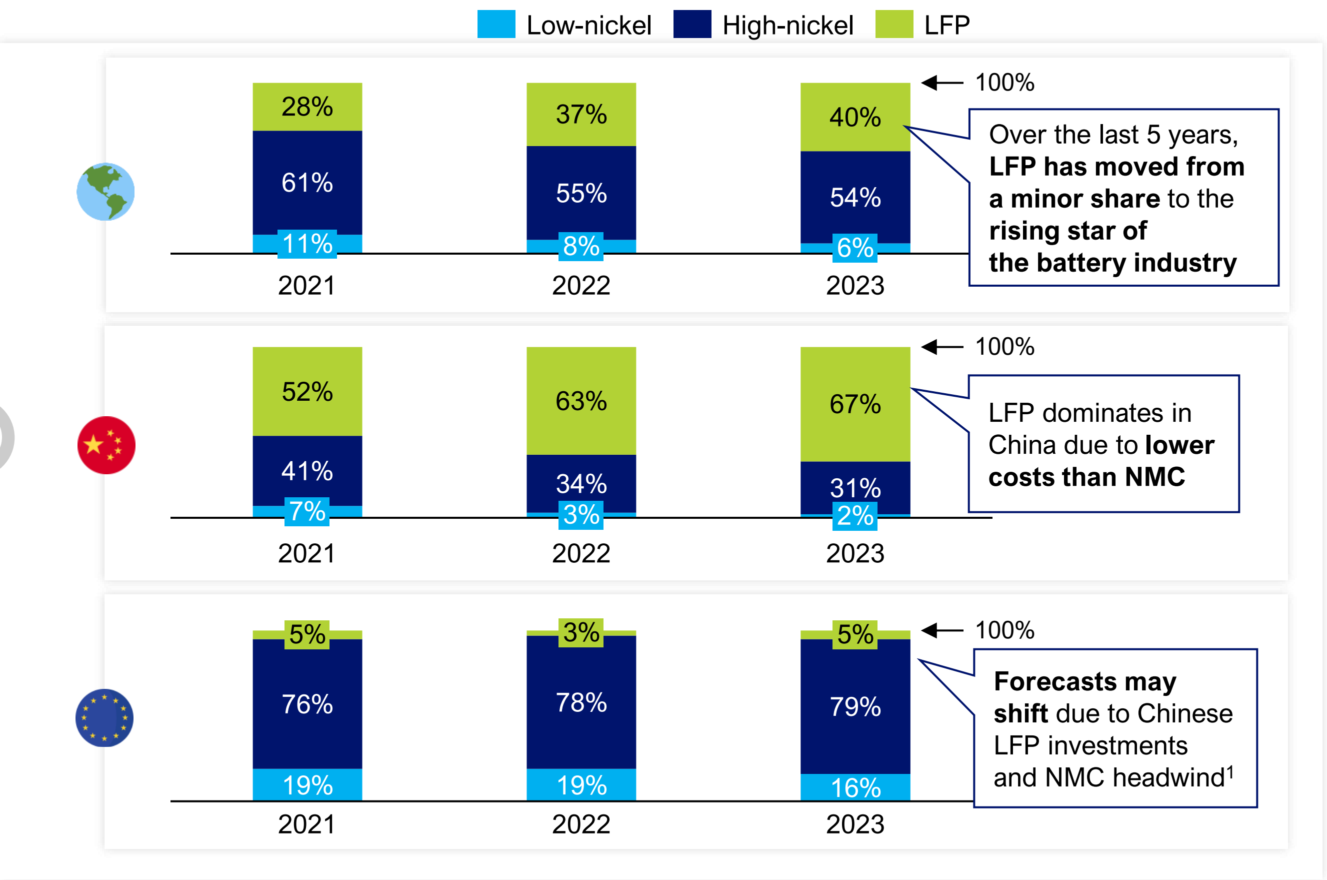
Substitution may affect markets for all CRMs, but the nickel and cobalt outlook is particularly uncertain given the rapid shift from NMC to LFP batteries over recent years, easing the need for new domestic capacity to meet CRMA targets

🔴 *Low substitutability* 🟡 *Medium substitutability* 🟢 *High substitutability*

	Substitutability	Explanation
Copper	🟡	Demand can be reduced through recycling, scrap use, and aluminum substitution, but copper is critical for key applications like lithium-ion anodes and subsea cable
Nickel	🟡	Possible to shift more towards lithium iron phosphate (LFP) or lithium manganese iron phosphate (LMFP) at the expense of long-range EVs
Cobalt	🟢	Ongoing efforts to reduce cobalt use in cathode chemistries (e.g. LFP, LMFP)
Lithium	🔴	Limited options to reduce demand. Sodium-ion may ease concerns, but its suitability for adoption adopted in major transport segments is yet to be demonstrated
Graphite	🟡	Silicon could take a growing share of anode material, but unlikely to challenge graphite in the near term
Rare Earths	🟡	Alternative new technologies have lower magnetic density and coercivity, and may struggle to compete commercially with REEs, which produce the strongest known permanent magnets

Share of battery capacity of EV sales by chemistry and region, 2021-2023, %

IEA Global EV Outlook 2024



Over the last 5 years, **LFP has moved from a minor share** to the **rising star of the battery industry**

LFP dominates in China due to **lower costs than NMC**

Forecasts may shift due to Chinese LFP investments and NMC headwind[1]

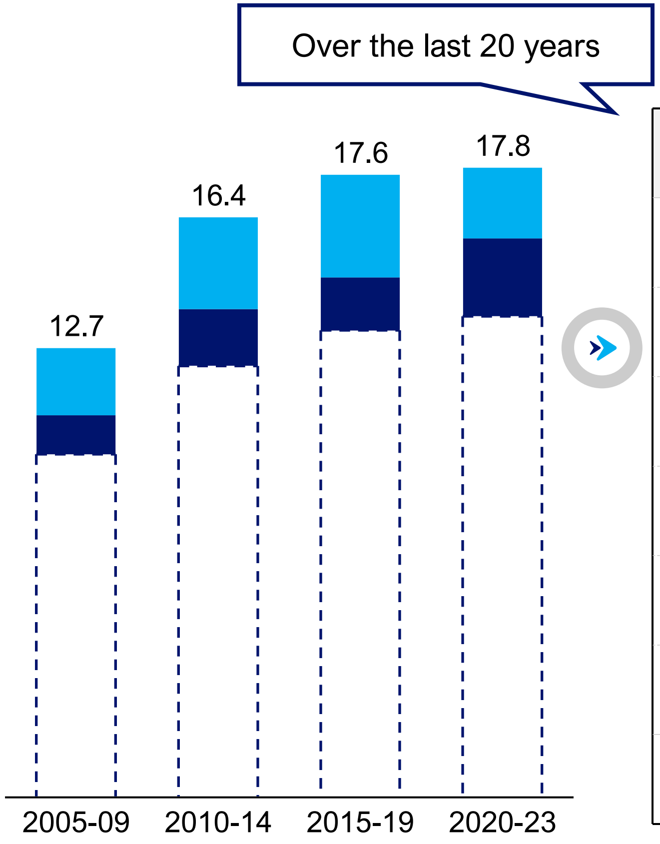
Source: Systemiq analysis based on IEA (2024), *Global Critical Minerals Outlook 2024;* IEA (2024), *Global EV Outlook 2024*

Note: 1. For example, ACC has paused its projects in Italy and Germany partly to explore LFP battery production instead of Nickel Manganese Cobalt (NMC). Other relevant examples include investments by Chinese companies in Morocco's LFP sector, e.g., Gotion High-Tech's $1.3 bn gigafactory in Kenitra (20-100 GWh capacity by 2026), BTR's $497 mn LFP cathode plant, and Tinci Materials' $280 mn LFP materials plant in Casablanca.

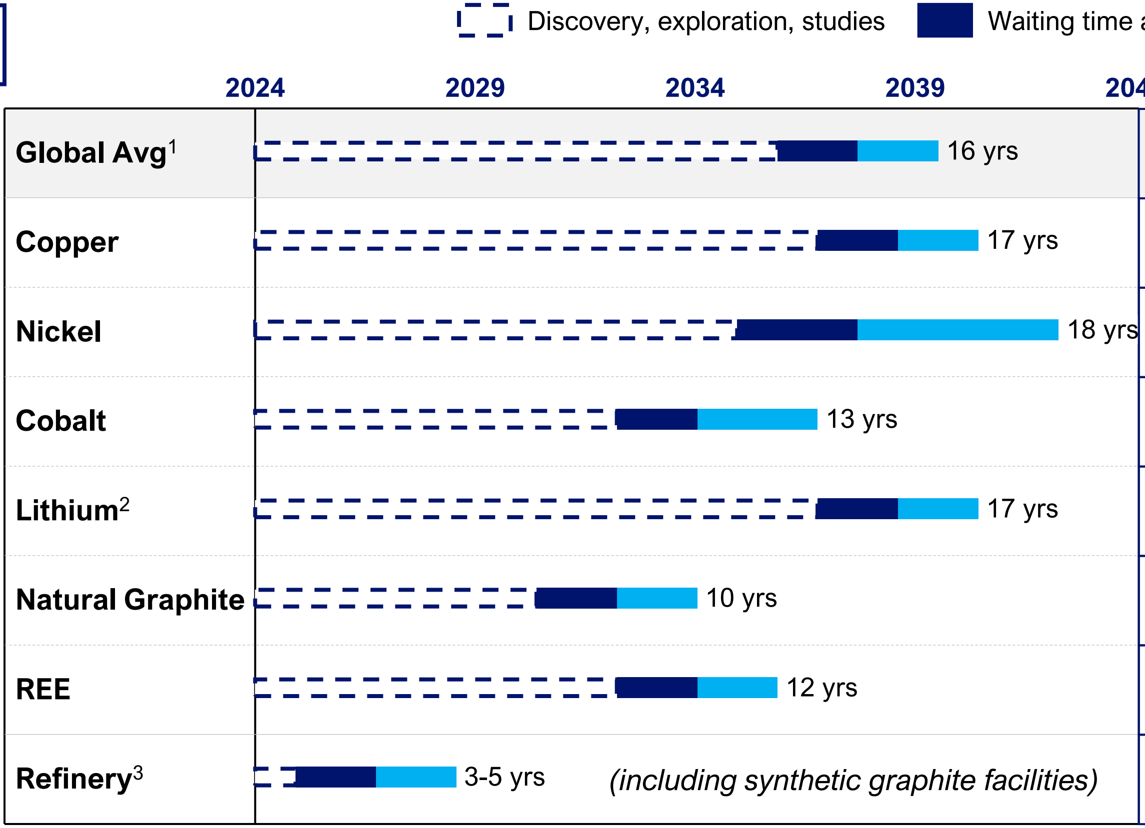
TIMELINES FOR NEW MINING PROJECTS ARE LONG AND RISING, REDUCING THE SECTOR'S ABILITY TO RESPOND TO SUPPLY SHORTAGES

The average global project lead time for new mines has increased by >5 years since the late 2000s, driven primarily by longer discovery, exploration and study periods

Typical project lead time by opening period, # years



Typical project lead time (based on projects opened between 2000 and 2023)[1], # years



Global Avg[1]	16 yrs	On average ~12 yrs for discovery, exploration & feasibility studies, and 2-5 yrs to production
Copper	17 yrs	Lead times can be reduced by 4-6 years by development at brownfield sites
Nickel	18 yrs	Recent projects in Indonesia developed faster (~5 yrs) following rapid granting of permits
Cobalt	13 yrs	Significant variation from mineral type, size, ore grade, location, mine type, quality of governance
Lithium[2]	17 yrs	Timelines significantly shorter for brine-based projects (4-7 years)
Natural Graphite	10 yrs	Synthetic graphite lead times only 1-2 yrs due to licence procedure and technical realisation times
REE	12 yrs	LKAB estimate it will take 10-15 years to start recovering rare earths at new deposit in Sweden
Refinery[3]	3-5 yrs	Building new refining capacity quicker than mines, but can also be a limiting step in supply chains

Source: S&P Capital IQ Pro; Energy Transition Commission (July 2023), *Materials and Resource Requirements for the Energy Transition*; IEA (2024), Global *Critical Materials Outlook 2024;* McKinsey (2024), *Solutions for supplying critical raw materials faster and better;* Press research.

Note: 1. Based on S&P study of 136 mines that opened between 2000 and 2023. | 2. Spodumene/hard rock mining only. | 3. Example case for lithium carbonate refinery.

2

KEY ENVIRONMENTAL IMPACTS

	Chapter	Content	Pages
	Executive Summary		*6-12*
1	Key Supply Challenges	• **Global and EU supply outlook** for selected critical raw materials (CRMs) relative to forecast demand in a net-zero scenario, including review of **new project timelines** and **geographic concentration** of production	*13-23*
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	Appendix		*59-81*

THE ENVIRONMENTAL IMPACTS OF CRMS VARY SIGNIFICANTLY BY PRODUCTION METHOD & LOCATION, BUT SOME KEY ISSUES STAND OUT

Nickel and cobalt have very high emissions intensities and acidification levels, and are associated with biodiversity/human rights risks, while current synthetic graphite production is highly emissions intensive

🔴 *High intensity per tonne material produced*
🟡 *Mid intensity per tonne material produced*
🟢 *Low intensity per tonne material produced*

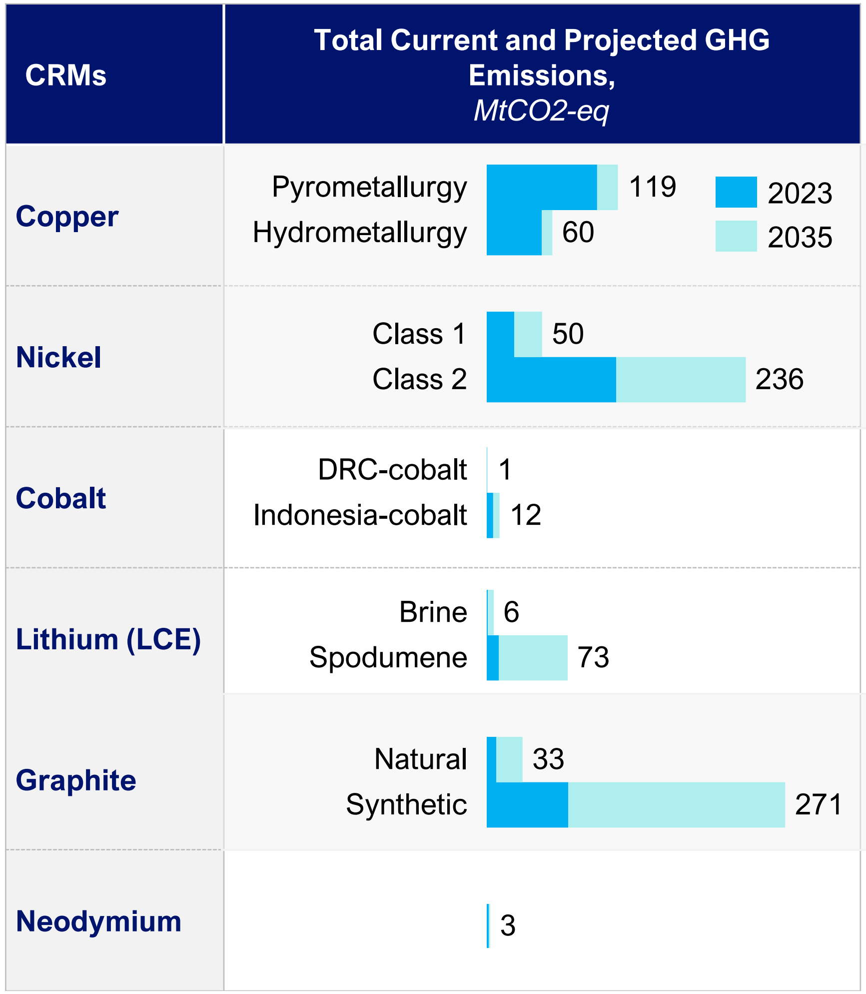
	Production 2035 *(Mt/yr.)*	**GHG Emissions**	**Water Use**	**Acid-ification¹**	**Tailings**	**Bio-diversity**	**Key Challenges**
Copper	18.5	🟡	🟡	🟡	🔴	🟡	• Moderate emissions and water intensity per tonne, but large production volumes mean **overall global impact high** – with local water scarcity issues in some regions (e.g. Chile) • Large volume of **rock moved** per tonne output due to low ore-grades; accounts for major share of **tailings production** (>90% across selected CRMs) – with risk of contamination etc.
Nickel	4.3	🔴	🔴	🔴	🟡	🔴	• High energy use/emissions and water intensity in production, especially for class 2 laterite ores – in large part due to heavy reliance on **coal power for smelting** in Indonesia • High level of **acidification** due to **sulphur dioxide emissions** from smelting process**,** as well as eco-toxicity impacts from processing & local deforestation/biodiversity risks
Cobalt	0.3	🔴	🔴	🔴	🟡	🔴	• High **energy use/emissions** and water intensity in production, but low overall impacts due to relatively small production volumes • Large share of cobalt production strongly linked to **human rights issues –** including child labour and health & safety concerns – as well as local deforestation/biodiversity risks
Lithium	2.3	🟡	🔴	🟡	🟢	🟢	• Lithium production from brine has high land use and water loss from evaporation, with the net impact on **local freshwater sources** still debated and differing by region • **Sodium sulphate waste streams** from refining stage can be a challenge if produced in large volumes without industrial offtake
Graphite	7.5	🔴	🟡	🟡	🟢	🟢	• Synthetic graphite has very **emissions intensity** (produced from pet coke with high energy use) – with large **variability by region** due to different grid mixes • Natural graphite has lower emissions intensity of production, but use of hydrofluoric acid creates **risk of groundwater contamination** and requires strict handling protocols
Neodymium	0.1	🟡	🟡	🟡	🟡	🟢	• Mining rare earths, including neodymium, can result in **radioactive waste** and **water contamination** in some cases, requiring careful environmental management • Limited impact in absolute terms due to small total **production volumes**

Source: See appendix for underlying figures, calculations and Source. IEA (2024), *Global Critical Minerals Outlook 2024.*

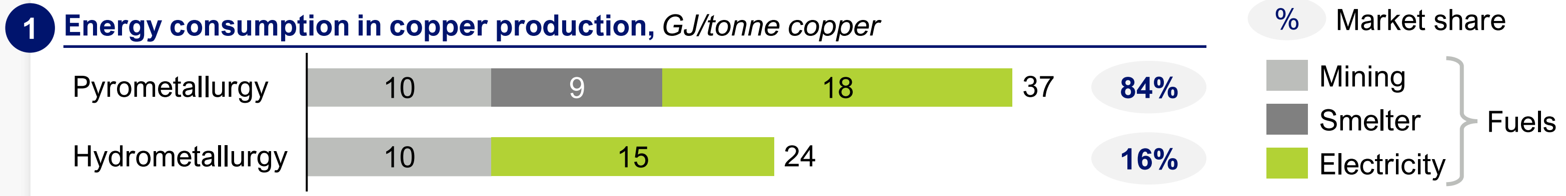
Note: Ratings based on intensity per tonne of material for selected metrics produced across both mining and processing/refining stages. Production figures refer to global total annual output across both existing and announced new mines (IEA forecast); Acidification refers to measure of acidic pollution of land and water; Graphite production figures include both natural and synthetic graphite.

COPPER, NICKEL & SYNTHETIC GRAPHITE DOMINATE CRM EMISSIONS

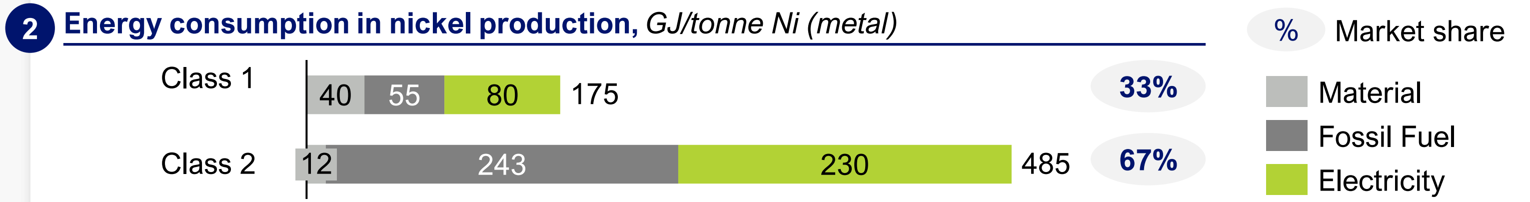
If no action is taken to reduce emissions intensity, CRM production could double to reach ~1 GtCO2-eq by 2035 – with synthetic graphite, nickel (class 2 from laterite ores) and copper dominating absolute emissions



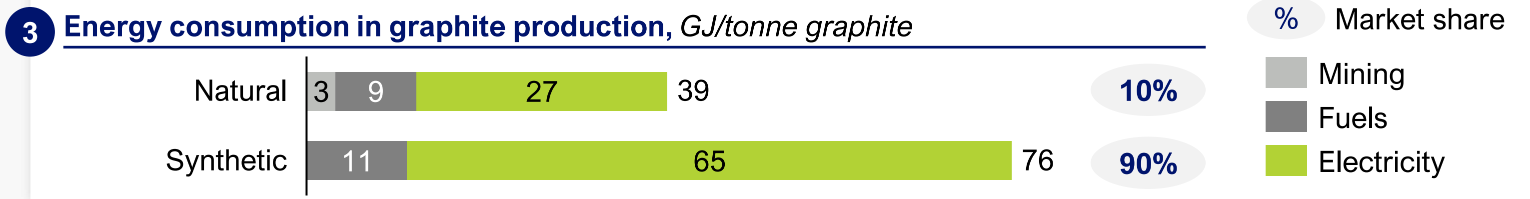
Copper: per-unit CO_2 impact **(~5kgCO_2/kg)** is modest but adds up due to high production volumes - electrification of mining and **grid decarbonization** (currently ~467gCO_2/kWh) are key decarbonisation levers



Nickel: Class 1 nickel, with 30% market share, emits **14-20 t CO_2-eq** and uses 174 GJ/tonne, while **Class 2**, covering 70%, emits 40-70 t CO_2-eq and requires 485 GJ/tonne of Ni content when nickel oxide is produced.[1]



Graphite: Natural graphite emits 10-15 kg CO_2-eq/kg with a 15-hour heat treatment at 1,300°C, while **synthetic graphite**, derived from petroleum coke, emits **20-50 kg CO_2-eq/kg** due to prolonged heating at 1,000°C, graphitization at 3,000°C and the consumption of graphite crucibles within the graphitization process.[2]



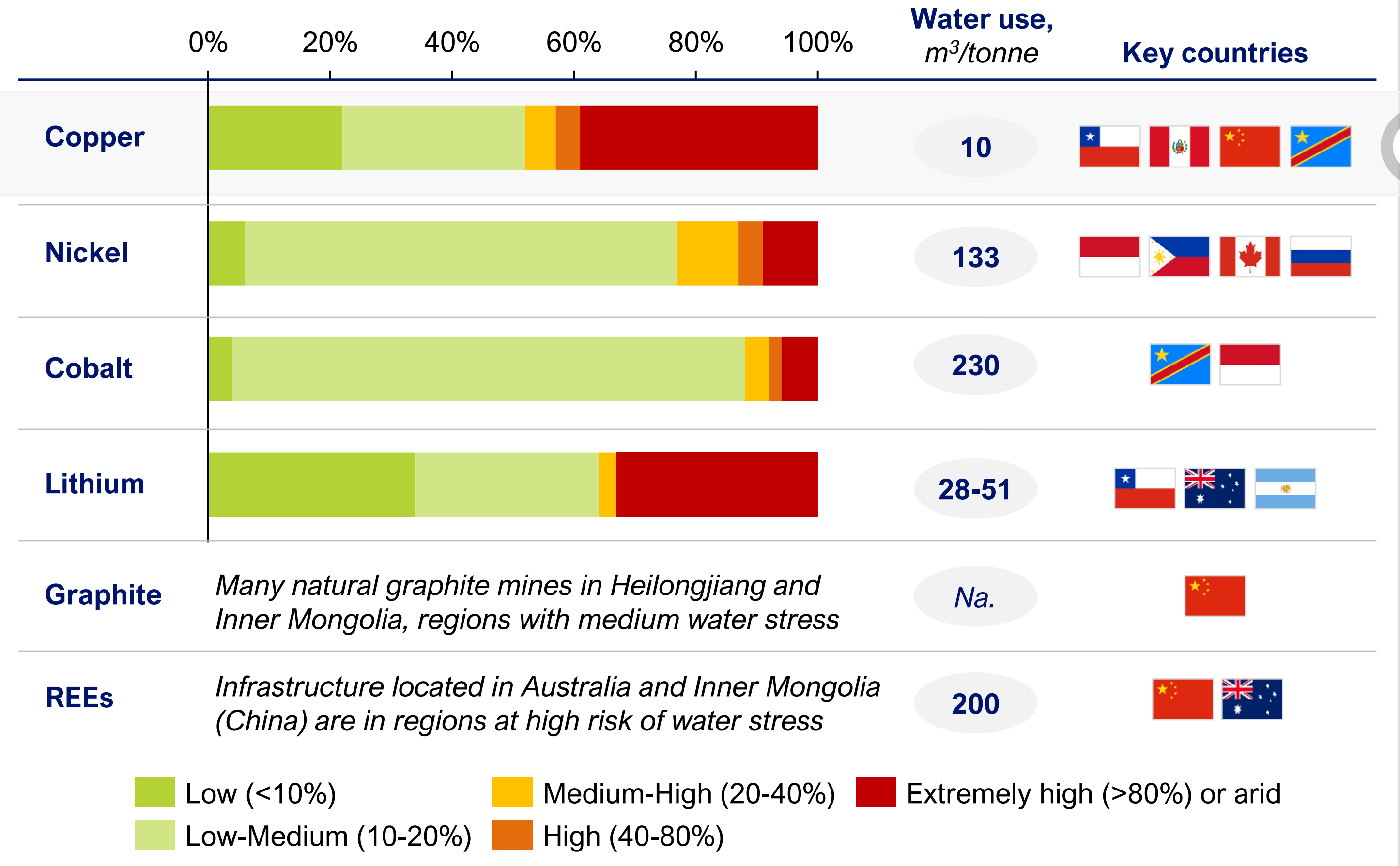
Source: Systemiq analysis based on S. Moreno & Leiva et al. (2019), *Renewable energy in copper production: A review on systems design and methodological approaches*; P. Engels et al. (2022), *Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data*; Wired (2022), *The Surprising Climate Cost of the Humblest Battery Material*; *Market*; IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*; ETC (2023), *Fossil Fuels in Transition: Committing to the phase-down of all fossil fuels;* T. Carrere et al. (2024), *Carbon footprint assessment of manufacturing of synthetic graphite battery anode material for electric mobility applications.*

Note: 1. Nickel production routes include: nickel metal, nickel oxide, ferronickel, and nickel pig iron (first two routes considered here); energy consumption and GHG emissions are reported for 1 tonne of nickel metal (i,e., converted from nickel oxide to nickel content). | 2. The emissions intensity of synthetic graphite is a topic of ongoing debate within the industry, with some experts estimating this to be ~40-50 kg CO_2 per kg, while others suggest an average closer to 20 kg CO_2 per kg (almost all production currently located in China).

WATER USE FOR MINING CAN BE A CHALLENGE IN CERTAIN REGIONS, BUT INTENSITY AND RISK IN THE EU ARE RELATIVELY LOW AT PRESENT

Water consumption from CRM mining and refining could reach ~8 bn m³ globally by 2035, but only a major issue in locations experiencing high water stress – acute challenge for some copper and lithium production in South America

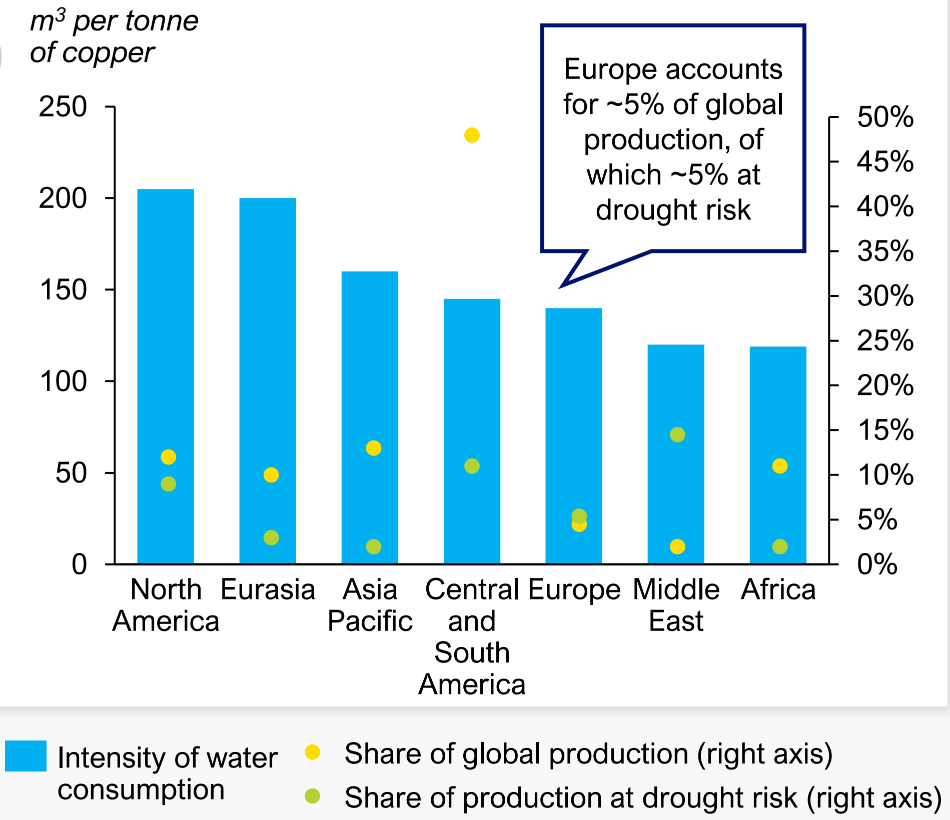
Share of global production exposed to water stress by region, %



		Water use, m^3/tonne
Copper		10
Nickel		133
Cobalt		230
Lithium		28-51
Graphite	*Many natural graphite mines in Heilongjiang and Inner Mongolia, regions with medium water stress*	*Na.*
REEs	*Infrastructure located in Australia and Inner Mongolia (China) are in regions at high risk of water stress*	200

Copper: ~10% global copper production exposed to drought risks

Water consumption intensity and drought risk by region, 2022[1]



Europe accounts for ~5% of global production, of which ~5% at drought risk

Source: Systemiq analysis based on Skarn Associates (2024).

Note: Missing comparable data on graphite (mainly synthetic) and REEs; 1. Production at risk is the exposure percentage of the production at risk due to drought. It reflects the interaction of how water is used on site in the context of identified external climate risks, the operations water source matrix, its water efficiency and operational resilience. Drought risks are based on statistical analysis of monthly precipitation data and trends.

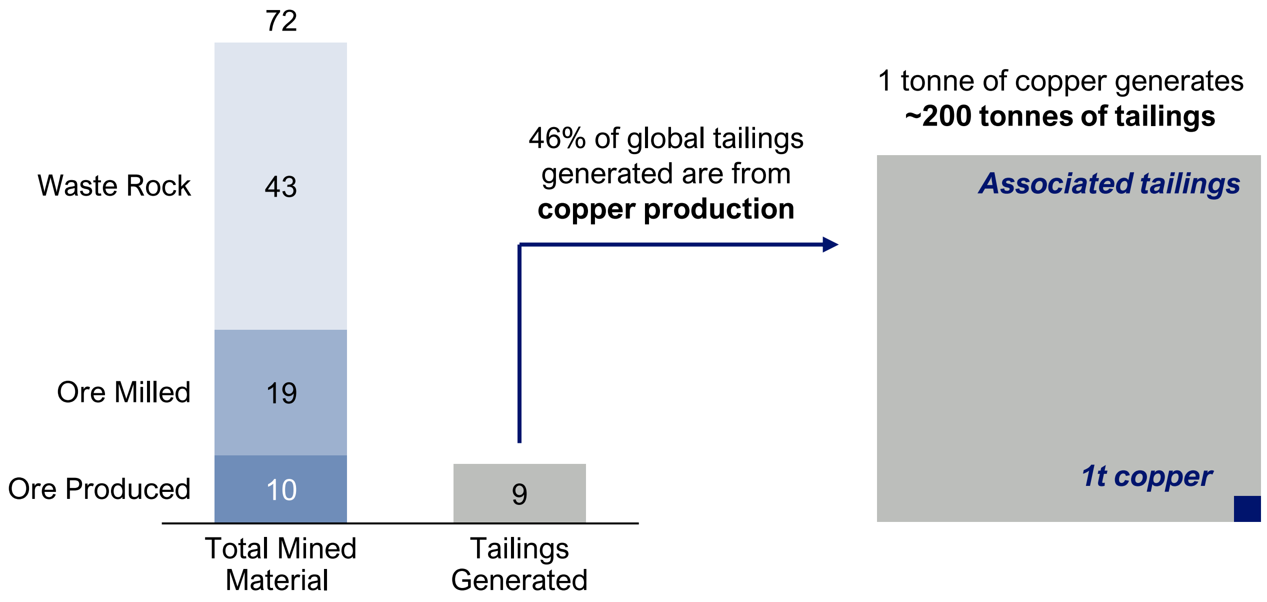
MINE TAILINGS ARE BOTH A MAJOR LIABILITY AND OPPORTUNITY

There are 280 bn tonnes of mine tailings globally today, with 8 bn tonnes added per year from 8,500 active tailings[1], of which almost half comes from copper – creating a major liability but also an opportunity for additional supply in future

Mining generates large tailings storage facilities that continue to grow each year…

Tailings are what **is left over after economic minerals are separated** from mined rock. They comprise **ground rock material** and **liquid waste from mineral processing** plants. At most mines, tailings are pumped into **large dams**, which **remain in situ** in some form after the mine closure.

Global annual volumes of material mined vs tailings generated, bn tonnes p.a.[2]



46% of global tailings generated are from **copper production**

1 tonne of copper generates **~200 tonnes of tailings**

… creating a major liability with important environmental risks, but equally presenting an opportunity for future supply

1. **Land use**: for example, tailings ponds at Chuquicamata mine in Chile larger than size of Manhattan
2. **Toxicity:** traditional landfilling of industrial slag can lead to toxic metal leaching and long-term contamination
3. **Environmental catastrophes:** 5-6 major cases of dam collapses reported annually on a global scale since 2000[4]

Tailings pose a **long-term liability** for mining companies due to associated storage costs and environmental risks, with strong waste management policies required to avoid local impacts. However, tailings can in many cases be safely **reprocessed or remediated**, despite often being viewed as high-risk due to stability and environmental concerns.[1]

Source: Systemiq analysis based on 1. *Global Tailings Review (2020), Towards zero harm – a compendium of papers prepared for the global tailings review.* | 2. USGS (2016), *USGS Mineral Commodity Summaries 2016.* | 3. L. Adrianto et al. (2023), *Toward sustainable reprocessing and valorization of sulfidic copper tailings: Scenarios and prospective LCA.* | 4. J.R. Owen et al. (January 2020), *Catastrophic tailings dam failures and disaster risk disclosure,* International Journal of Disaster Risk Reduction, Vol. 42.

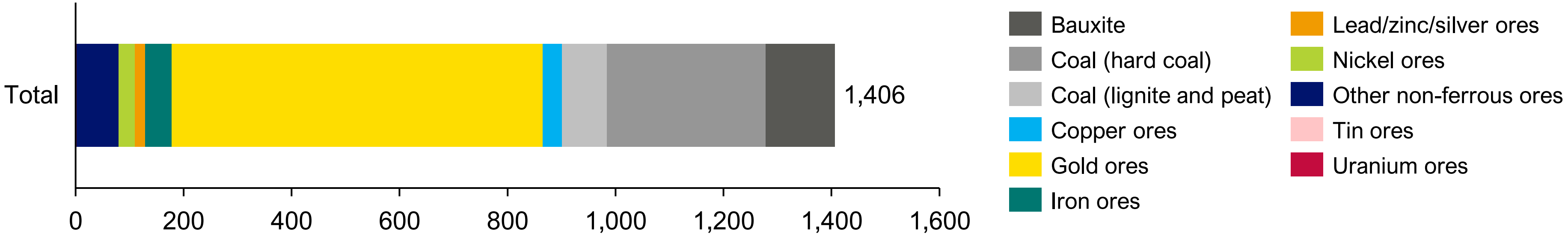
Note: Global Tailings Review tracked a total of 1,743 tailings. However, a more recent estimate including active, inactive and closes facilities sums at around 8,500. 1. See further discussion in chapter 4; Note that in some areas, the liability for storage facilities transfers to governments at mine closure or years later, reducing the mining company's responsibility.

CRMS ACCOUNT FOR RELATIVELY SMALL SHARE OF BIODIVERSITY IMPACT FROM RESOURCE EXTRACTION

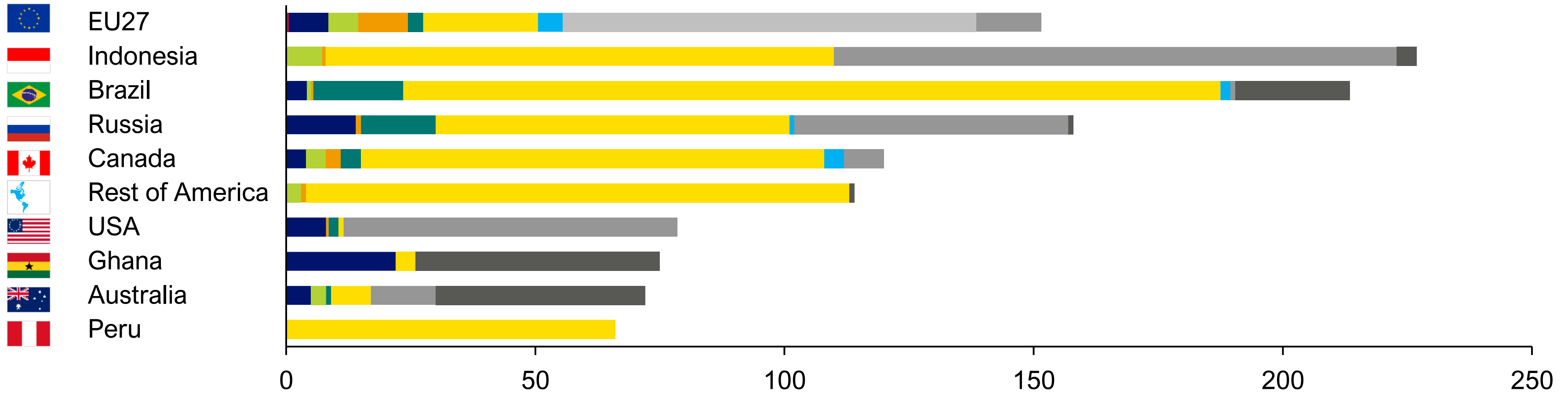
EU consumption was estimated to have caused ~1,400 km² of mining-driven forest loss from 2001 to 2019 – primarily driven by coal and gold, with CRMs accounting for less than 10% of this, largely from copper and nickel

EU CRM consumption as share of total forest loss from commodities

Total mining-related forest loss associated with EU-27 consumption by mined commodity, km²



Mining-related forest loss associated with EU-27 consumption by region and mined commodity, top 10 regions, km²

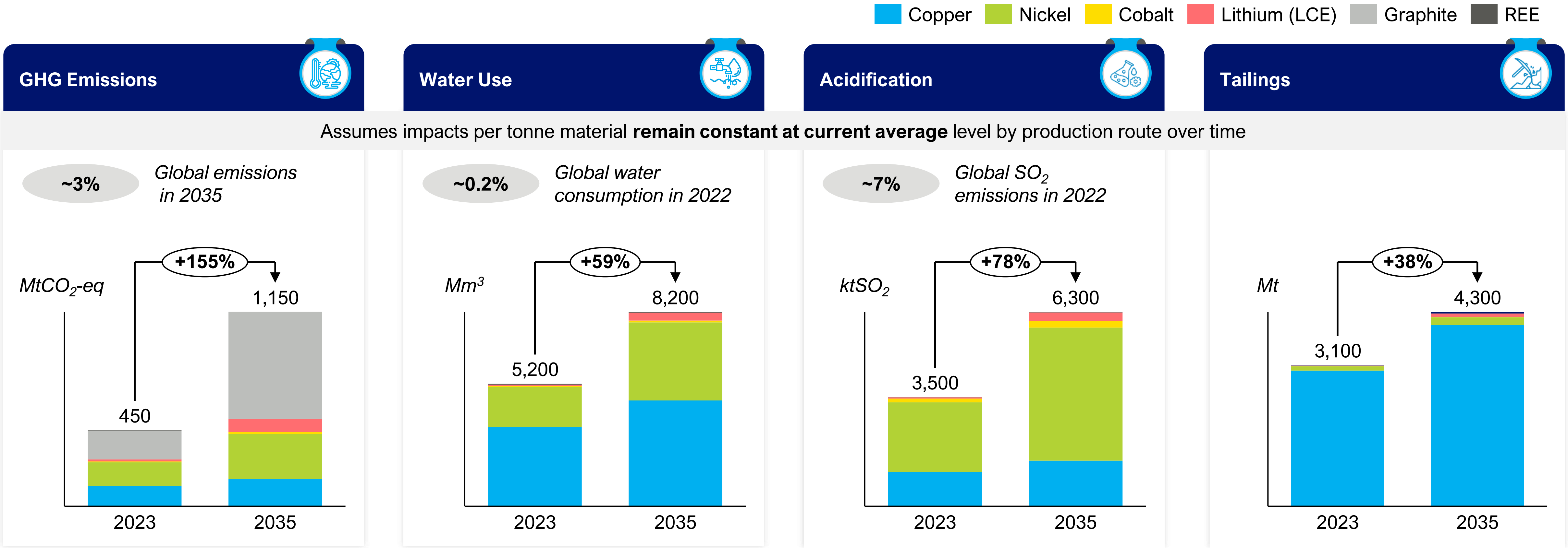


- **Figures show data on mining-related forest loss** embodied in the final material demand in the EU
- **Total forest loss**: 1,416 km² within mining areas due to EU demand from 2001 to 2019
- **Geographic impact**: 89% of this forest loss occurred outside the EU, with Indonesia and Brazil as the most affected regions
- **Breakdown by material:** Copper (35 km²), nickel (30 km²), and other non-ferrous metals (80 km²)
- **CRMs**: accounted for less than 10% of EU-driven mining forest loss but are expected to rise in impact

Source: Systemiq analysis based on S. Luckeneder et al. (Sept. 2024), *EU consumption's hidden link to global deforestation caused by mining.*

CRM MINING AND REFINING IMPACTS WILL INCREASE WITHOUT EFFORTS TO REDUCE INTENSITY

In absolute terms, copper and nickel are the largest drivers of impact due to their outsized scale of production – but graphite accounts for largest source of emissions by 2035 assuming no change in intensity per tonne



Assumes impacts per tonne material **remain constant at current average** level by production route over time

Source: Systemiq analysis based on IEA (2024), *Global Critical Minerals Outlook 2024;* KU Leuven/EuroMetaux (April 2022), *Metals for Clean Energy: Pathways to solving Europe's raw materials challenge;* Engels et al. (2022), *Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data;* J.C. Kelly et al. (2021), *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*; Lithium Harvest (2024), *The Lithium Mining Market;* Nickel Institute (2020), *Life Cycle Assessment of Nickel Products; Meissner (2021), The impact of metal mining on global water stress and regional carrying capacities – A GIS-based water impact assessment.*

Note: These figures were calculated by multiplying primary supply needs by corresponding emissions, water, acidification, or tailings factors. Primary supply needs were determined as demand minus secondary supply, with the remainder covered by planned and new primary sources. Copper water consumption calculated using the water consumption intensity and drought risk data for copper production by region (2022) from the IEA, with global production shares weighted by water consumption intensity in each region. No water consumption data is available for graphite or the energy-related water consumption of rare earth elements. The breakdown for nickel and LCE follows the same methodology as above on GHG emissions. LCE refers to lithium carbonate equivalent, where 1 tonne of LCE equals 5.323 tonnes of pure lithium. Currently global water consumption is around 4,000 bn m3 per year. Graphite water consumption is missing. The emissions intensity of synthetic graphite is a topic of ongoing debate within the industry, with some experts estimate this to be ~40-50 kg CO_2 per kg, while others suggest an average closer to 20 kg CO_2 per kg (almost all production currently located in China); upper bound of range refers to emissions assuming 50kgCO2/kg. EBIT (Energy, Building, Industry and Transport) emissions in 2035 are estimated to be at around ~26 GtCO2-eq in the ETC's ACF scenario. World water consumption is around 4,000 bn m^3.

SYSTEMIQ

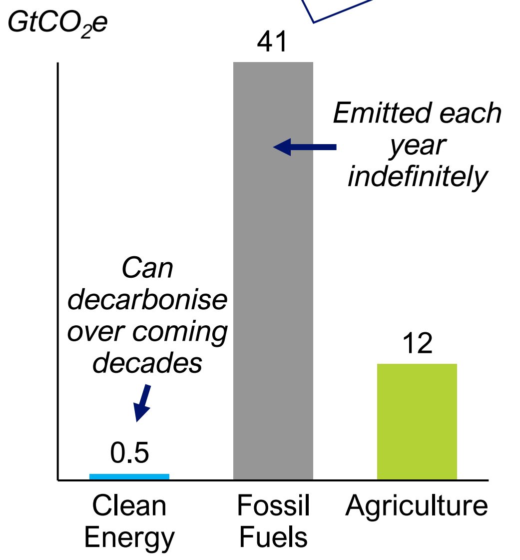
BUT A CLEAN ENERGY SYSTEM BUILT ON CRMS IS VASTLY LESS MATERIAL AND RESOURCE INTENSIVE OVERALL THAN A FOSSIL FUEL-BASED SYSTEM

Total emissions from CRM mining are small relative to those from fossil fuels, and only need to occur once as products can be recycled; land use and water consumption from mining is also small in absolute terms relative to the agricultural sector

Comparison of environmental impacts of energy, fossil fuels, and agriculture

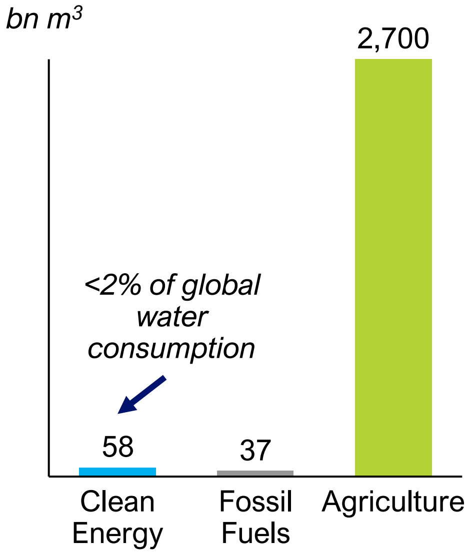
GHG Emissions[1]

Annual emissions from fossil fuel **extraction & consumption** 80x higher than for production of clean techs



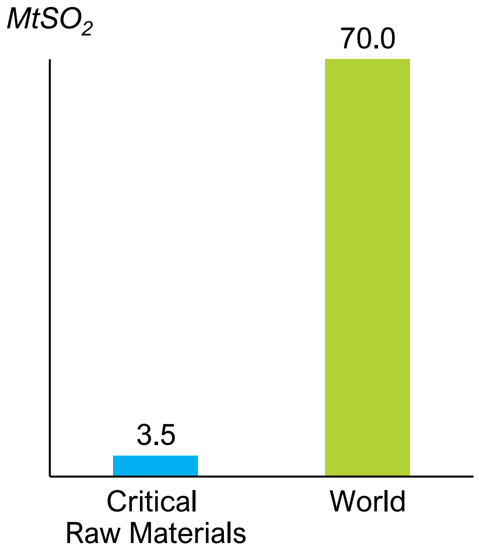
Water Use[2]

>70% total current global water consumption is for **agriculture**



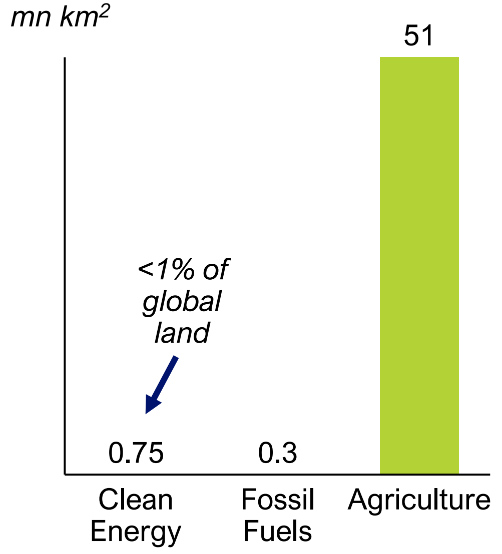
Acidification[3]

CRM mining and processing accounts for **<5% total** global SO_2 emissions



Land Use[4]

Agriculture accounts for almost half of all global **habitable land**, of which 80% is for livestock[5]



Source: Energy Transition Commission (July 2023), *Material and Resource Requirements for the Energy Transition;* Our World In Data (2023).

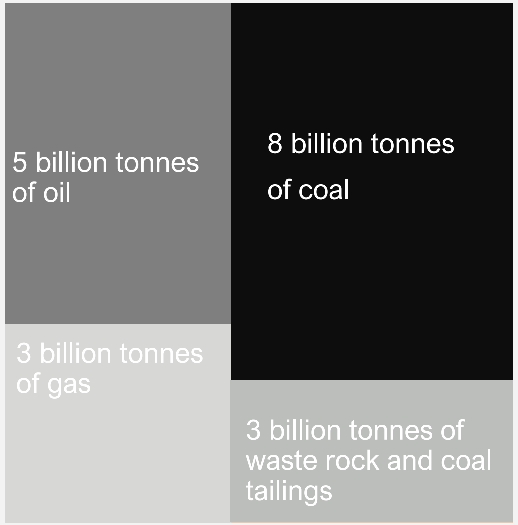
Note: 1. Clean energy: maximum potential emissions associated with production of materials for clean energy technologies, assuming current emissions intensities. | 2. Clean energy: water consumption in 2050 for cleaning solar panels, nuclear power, hydrogen electrolysis, and CCS. | 3. Clean energy: maximum additional material needs to build clean energy technologies in 2050, including e.g., steel for wind turbines, lithium in batteries, copper in cabling. | 4. Clean energy: land use for electricity generation in 2050 (not bioenergy), including for green hydrogen and DAC, assuming ground-mounted utility-scale solar and only direct land use for wind. | 5. 6 mn km^2 for cropland for animal feed and 32 mn km_2 for grazing land.

THE ENERGY TRANSITION WILL ALSO RESULT IN AN OVERALL REDUCTION IN THE VOLUME OF GLOBAL RESOURCE EXTRACTION

The energy transition will result in a shift away from the continuous extraction and combustion of 15 bn tonnes of fossil fuels per year to a system producing 13 bn tonnes of waste rock, but as a one-off for materials that can subsequently be recycled

Resource extraction requirements in net-zero clean energy system vs. existing fossil-fuel based system

2022: The fossil fuel system



***15 billion tonnes of fossil fuels** (30% of which is internationally traded)*

Fossil fuel reliance demands continuous extraction and consumption, leading to **indefinitely recurring** negative environmental impacts

2050: The clean energy materials system

*Up to **13 billion tonnes of waste rock** produced from all energy transition materials (stored on-site)*

0.3 billion tonnes** of materials in clean energy technologies – including **CRMs

Material extraction needs to build a clean energy system are largely a **one-off**, with durable technologies enabling long-term use and significant recycling

Source: Systemiq analysis based on ETC (2023), *Material and Resource Requirements for the Energy Transition*

Note: Waste rock accounts for both ore grade and for additional waste rock moved (e.g., overburden). Material requirements are based on the ETC's Baseline Decarbonisation scenario (see ETC report), where an aggressive deployment of clean energy technologies leads to global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The 13 billion tonnes total includes all materials assessed in the ETC report.

3

INNOVATION LANDSCAPE

	Chapter	Content	Pages
	Executive Summary		*6-12*
1	Key Supply Challenges	• **Global and EU supply outlook** for selected critical raw materials (CRMs) relative to forecast demand in a net-zero scenario, including review of **new project timelines** and **geographic concentration** of production	*13-23*
2	Key Environmental Impacts	• Comparison of environmental impact for selected CRMs mining and refining based on production process and location, across: **emissions, water use, acidification, land use and tailings**	*24-32*
3	**Innovation Landscape**	• **Overview of emerging technologies** with potential to increase supply and/or mitigate environmental impacts of selected CRMs and review of current **commercialisation status**	*33-40*
4	Selected Technologies	• Deep-dive into 7 selected **new technologies** with **high-impact potential** to resolve key identified supply and environmental challenges for CRM production in the EU and strategic partner countries over next 10-15 years	*41-50*
5	Policy Implications	• **Key challenges** for the deployment of selected new technologies in the EU and **recommended actions for policymakers**	*51-58*
	Appendix		*59-81*

BEFORE INNOVATION, THERE ARE A SET OF BEST PRACTICES TO REDUCE THE ENVIRONMENTAL IMPACT OF MINING THAT SHOULD BE ADOPTED

There are a clear set of measures to mitigate environmental risks at the mine level that should be adopted globally by mining and refining companies in the coming years

Emissions	Water Use	Chemical Pollution	Land Use & Biodiversity	Human Rights and Communities
Electrification of diesel generators, fleet, and other on-site equipment	Closed loop water recycling and aiming for Zero Liquid Discharge approach	Collection and treatment of leachate and run-off	Sustainable land use planning, including protection of 'no go zones'[3]	Enforcement of fair labour practices
On-site renewables	Wastewater treatment/grey-water recycling	Collection of run off in lined settlement ponds	Biodiversity management plan, with goal of no net biodiversity loss by 2030	Supply chain traceability
Renewables PPAs/JVs	Onsite desalination in arid locations	Safe storage and capping of waste heaps	Land reclamation, reforestation and revegetation	Community support (develop local infrastructure, training, etc.)
Energy efficiency measures and process optimisation	Integrated water resource mgmt.	Active treatment systems[1]	Dewatering/filtering tailings, avoiding new upstream dams, and dry stacking[4]	Stringent health & safety standards[5]
Dust suppression	Improved efficiency (monitoring pipelines, filtrating tailings, etc.)	Passive treatment systems[2]	Recontouring and soil remediation	Adherence to ambitious voluntary international standards[6]

Source: Systemiq analysis based on IEA (2024) *Global Critical Minerals Outlook 2024*; IEA (2022) *The Role of Critical Minerals in Clean Energy Transition*; Expert interviews.

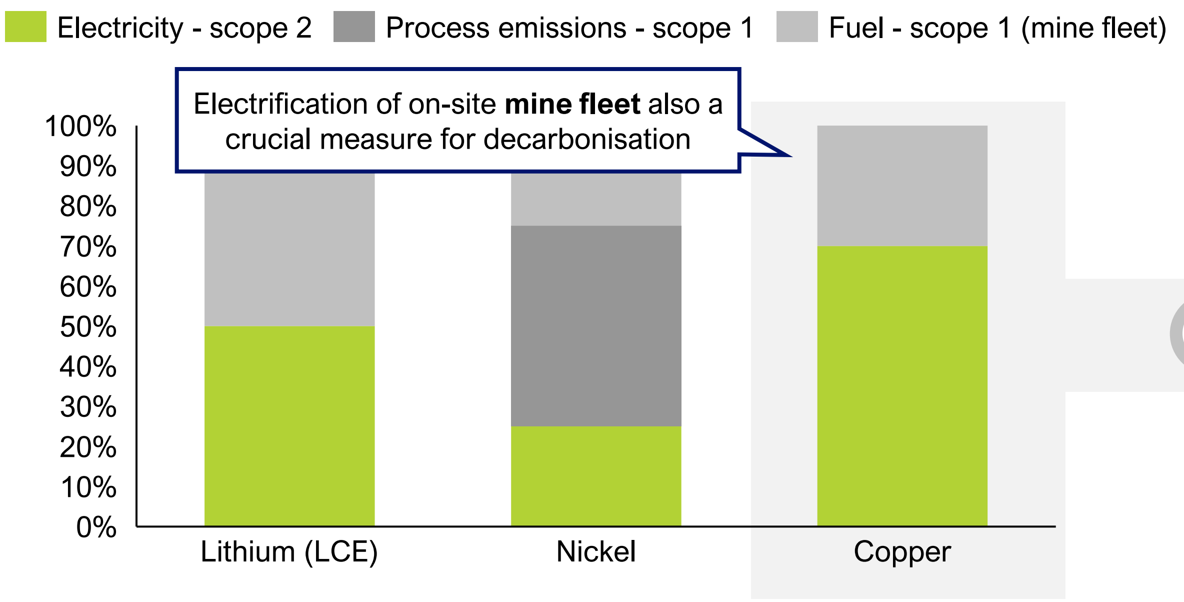
Note: Non-exhaustive list of measure. 1. E.g., chemical precipitation of acid mine drainage. | 2. E.g., neutralise acidity with limestone or other alkaline materials. | 3. Potentially defined as UNESCO biosphere reserves and World Heritage Sites. | 4. Modern method of managing tailings by de-watering to remove excess moisture and stacking remaining material in controlled manner; in locations with favourable climate. | 5. Permit systems which set requirements on the safety of work procedures, monitoring equipment, etc. | 6. Covering human rights, labour, and environmental standards e.g., UN Guiding Principles on Business and Human Rights, Extractive Industries Transparency Initiative, Initiative for Responsible Mining Assurance.

THE MOST IMPORTANT LEVER FOR DECARBONISING MINING IS CLEAN ELECTRIFICATION

Current emissions intensity of copper production could be reduced by 85% by switching 50% energy use to electricity powered by renewables – this should be top focus for mining majors in decarbonisation strategy

Emissions from power use are the largest contributor to scope 1 and 2 emissions for most CRMs…

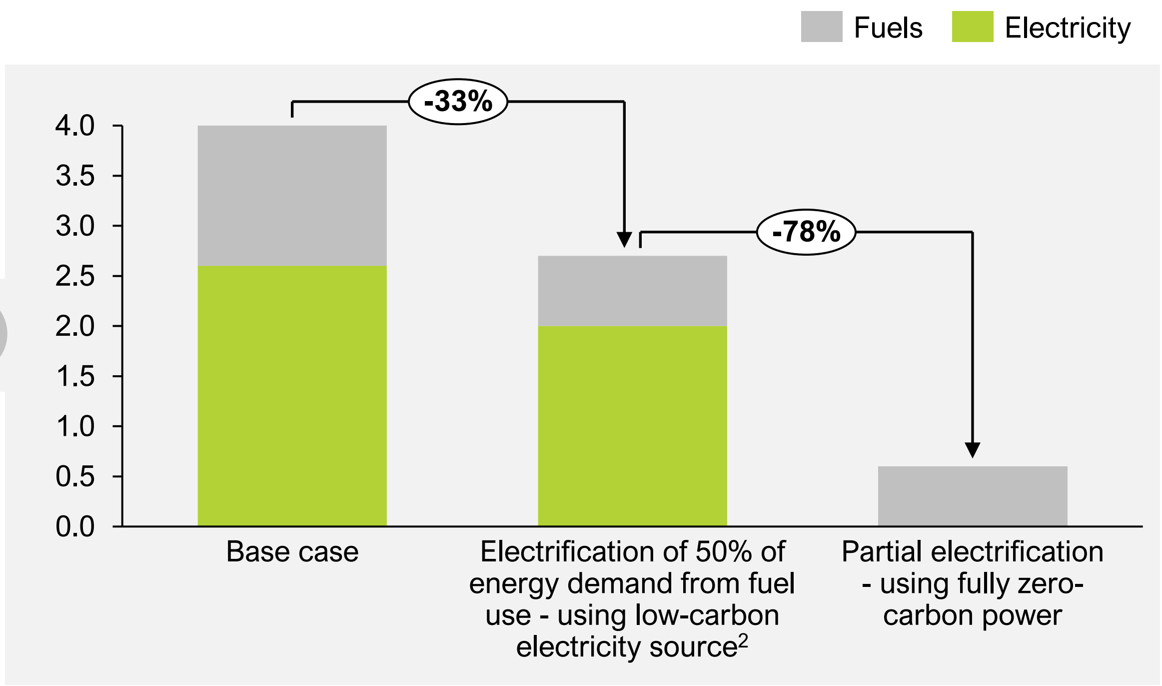
Primary emissions intensity 2023 by material, share of CO_2 by category[1]



Electrification of on-site **mine fleet** also a crucial measure for decarbonisation

… but clean electrification can substantially reduce emissions from production

Energy-related emissions for indicative refined copper production project, kg CO_2/kg refined copper[2]



Source: 1. McKinsey & Company (2024) *Global Materials Perspective 2024.* | 2. IEA (2022) *The Role of Critical Minerals in Clean Energy Transitions..*

Note: 1. Showing emissions intensity different consumption scenarios based on Cochilco mine (2020) - base case fuel mix is 33% coal, 33% diesel, 33% natural gas, electricity emissions intensity is 463 gCO2/kwh. | 2. Low-carbon electricity is 240 gCO2/kWh.

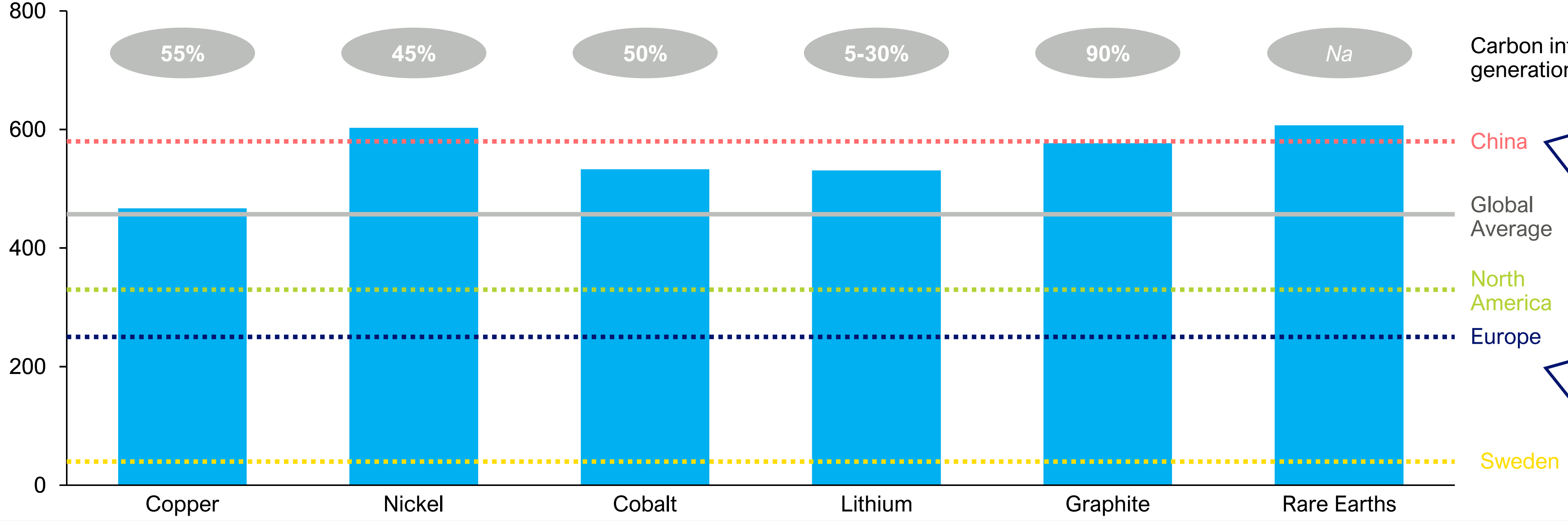
REDUCING EMISSIONS INTENSITY OF POWER FOR REFINING COULD SIGNIFICANTLY REDUCE OVERALL EMISSIONS FOR MOST CRMS

The current average carbon intensity of CRM refining is high due to concentration of production in regions with high grid intensities linked to coal-based power generation

Emissions from CRM refining

Weighted average grid carbon intensity of current refining regions 2023, gCO$_2$/kWh

X% *Share of energy requirements met by electricity[1]*



However, China is rapidly **decarbonising its grid** intensity with the government targeting a 40% non-fossil share of power generation by 2030

In most cases, **relocating refining to Europe** would reduce refining emissions considerably due to lower grid emissions intensity

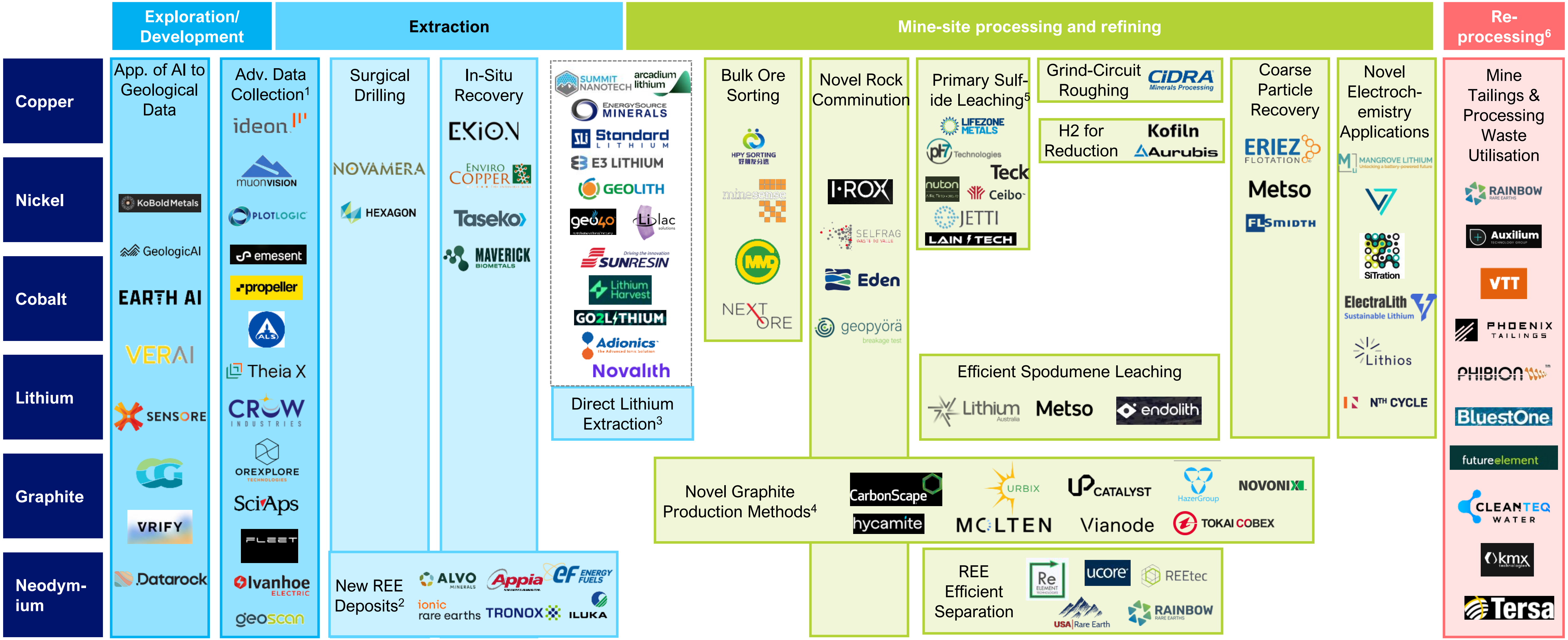
Source: Systemiq analysis based on IEA (2024), *Global Critical Minerals Outlook 2024;* Ember (2024) *Global Electricity Review 2024;* W. Wei et al. (2020), *Energy Consumption and Greenhouse Gas Emissions of Nickel Products;* S.Moreno-Leiva et al. (2019), *Renewable energy in copper production: A review on systems design and methodological approaches;* J.C. Kelly et al. (2021), *Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resource and their use in lithium ion battery cathodes and lithium ion batteries;* Expert interviews.

Note: 1. The carbon intensity for natural gas-based power generation is around 427 gCO$_2$/kWh. For all CRMs, the weighted average carbon intensity of the grid is above this level, indicating that production is concentrated in regions relying primarily on coal-based electricity. In some places (e.g., Indonesia), the rise of refining operations is being served mainly by off-grid power (largely coal). | 2. Cradle-to-Gate electricity requirement (i.e., includes mining and refining). | 3. Cobalt is calculated as the average of copper and nickel, as a by-product. | 4. Lithium carbonate from brines requires 30% electricity (minor energy requirements), while lithium hydroxide from spodumene requires 5% of electricity (major coal requirements).

BUT AN EMERGING SET OF NEW TECHNOLOGIES COULD ALSO OFFER AN OPPORTUNITY TO BOOST SUPPLY SUSTAINABLY

Critical raw materials supply-side innovation value chain mapping

Non-exhaustive, based on public info



Exploration/ Development

App. of AI to Geological Data
- KoBold Metals
- GeologicAI
- EARTH AI
- VERAI
- SENSORE
- VRIFY
- Datarock

Adv. Data Collection[1]
- ideon
- muon vision
- PLOTLOGIC
- emesent
- propeller
- ALS
- Theia X
- CROW INDUSTRIES
- OREXPLORE TECHNOLOGIES
- SciAps
- FLEET
- Ivanhoe Electric
- geoscan

Extraction

Surgical Drilling
- NOVAMERA
- HEXAGON

In-Situ Recovery
- EXION
- ENVIRO COPPER
- Taseko
- MAVERICK BIOMETALS

Direct Lithium Extraction[3]
- SUMMIT NANOTECH
- arcadium lithium
- ENERGYSOURCE MINERALS
- Standard Lithium
- E3 LITHIUM
- GEOLITH
- geo40
- Lilac solutions
- SUNRESIN
- Lithium Harvest
- GO2LITHIUM
- Adionics
- Novalith

New REE Deposits[2]
- ALVO MINERALS
- Appia
- EF Energy Fuels
- ionic rare earths
- TRONOX
- ILUKA

Mine-site processing and refining

Bulk Ore Sorting
- HPY SORTING
- minesense
- MMD
- NEXT ORE

Novel Rock Comminution
- I-ROX
- SELFRAG
- Eden
- geopyörä

Primary Sulfide Leaching[5]
- LIFEZONE METALS
- pl7 Technologies
- Teck
- nuton
- Ceibo
- JETTI
- LAIN TECH

Grind-Circuit Roughing
- CiDRA Minerals Processing

H2 for Reduction
- Kofiln
- Aurubis

Coarse Particle Recovery
- ERIEZ FLOTATION
- Metso
- FLSmidth

Novel Electrochemistry Applications
- MANGROVE LITHIUM
- SiTration
- ElectraLith Sustainable Lithium
- Lithios
- NTH CYCLE

Efficient Spodumene Leaching
- Lithium Australia
- Metso
- endolith

Novel Graphite Production Methods[4]
- CarbonScape
- hycamite
- URBIX
- MOLTEN
- UP CATALYST
- Vianode
- HazerGroup
- NOVONIX
- TOKAI COBEX

REE Efficient Separation
- ReElement Technologies
- ucore
- REEtec
- USA Rare Earth
- RAINBOW RARE EARTHS

Re-processing[6]

Mine Tailings & Processing Waste Utilisation
- RAINBOW RARE EARTHS
- Auxilium
- VTT
- PHOENIX TAILINGS
- PHIBION
- BluestOne
- futureelement
- CLEANTEQ WATER
- kmx
- Tersa

Note: See appendix for further information on all technologies included. Uncertainty around matching technology to relevant CRM – estimate based on information collected is presented here. Some companies are developing solutions which may match to more than one category – estimate of closest match is presented here 1. Drones, remote sensing, digital mapping, and technologies which enable on-site ore analysis. | 2. Ionic adsorption clay, heavy mineral sands. | 3. Other relevant companies include Solvay, Lithios, Controlled Thermal ReSource, Eramet, EnergyX, and Alma Energy. | 4. China Minemetals announced a new technology to produce high-purity graphite, but minimal public information. | 5. Can be applied to mine tailings, but since application is broader this has not been placed in *Re-processing* bucket. | 6. Solutions that enable *circularity* are excluded from the scope of this study, i.e., those that involve recycling of end-of-life products.

WE FOCUS ON SEVEN TECHNOLOGIES THAT CAN PLAY MAJOR ROLES IN SOLVING KEY SUPPLY & ENVIRONMENTAL CHALLENGES IN NEXT ~15 YEARS

We identify the most critical short-to-mid-term supply and environmental challenges for CRM mining and refining that must be addressed, both globally and within the EU

Key Challenges

		CRMs[1]
1	Increase **global primary supply of CRMs** beyond existing and announced capacity to avoid shortfall relative to projected demand	Cu Li C
2	Ensure new **EU based** mining & refining projects developed in time to meet CRMA targets by 2030	Li C Nd
3	Accelerate **project timelines for new mines** globally and in the EU, especially across the exploration and discovery phase	Cu Li
4	Reduce the **emissions intensity of CRM production,** especially by reducing energy use	Cu Ni C
5	Manage **existing and new tailings** to reduce risks of dam failures and long-term contamination both globally and in the EU	Cu
6	Manage the production of **chemical waste streams** from the mining and refining process,	Li Nd

Technological Solutions – Applicability by CRM and Key Challenges[2]

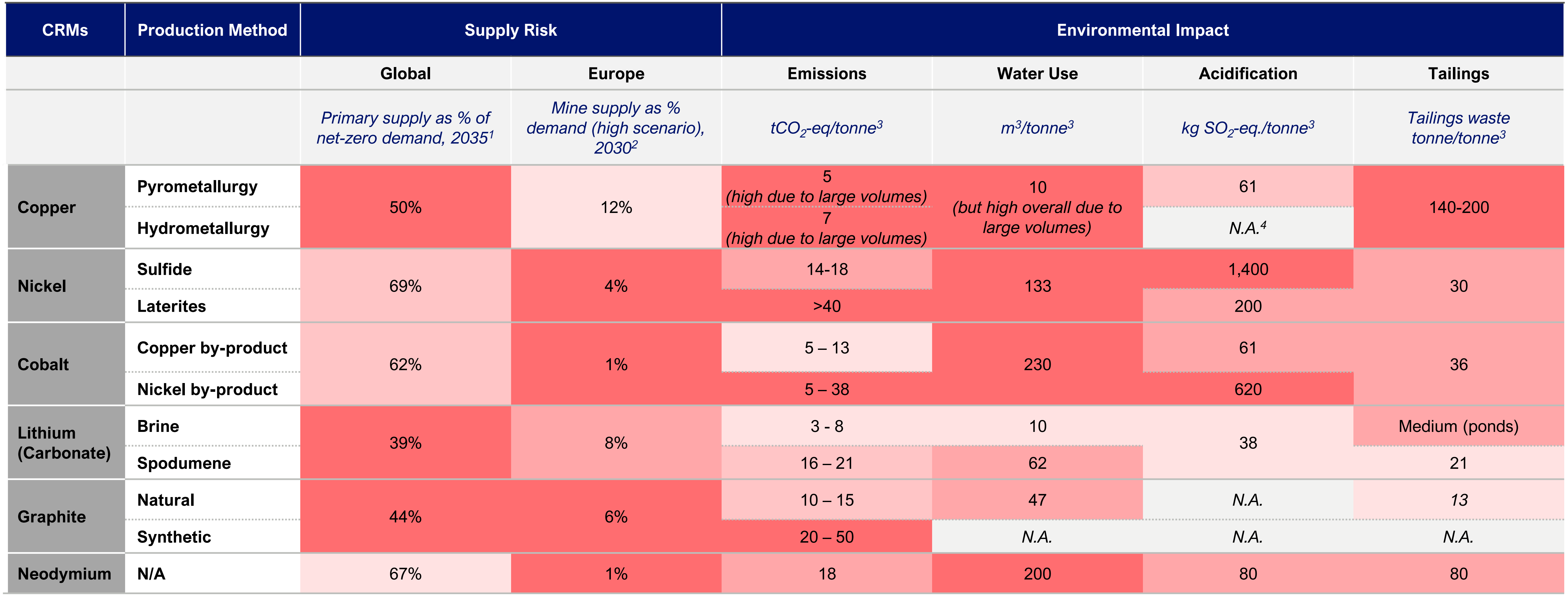
(Geothermal) Direct Lithium Extraction	Li	1 2 4
Novel Synthetic Graphite Production	C	1 2 4
Primary Sulphide Leaching	Cu	1 4
AI for Geological Data	All	3
Novel Rock Comminution	All	4
Novel Electrochemistry Applications	All	4 6
Tailings Reprocessing Technologies	All	1 5

Source: See sections 1 & 2 for supporting evidence.

Note: See appendix for information on full list of reviewed technologies. | 1. Shows CRMs for which identified challenge is most acute. | 2. Note this is not a comprehensive or exhaustive list but a selection of technologies considered to have highest impact potential for specific challenges identified in short-to-mid-term (10-15 years). | 3. Solution also has potential to increase global CRM supply from existing/new tailings resources.

SUMMARY OF SUPPLY & ENVIRONMENTAL RISKS FOR INCUMBENT PRODUCTION

Low Risk | Mid Risk | High Risk



CRMs	Production Method	Supply Risk		Environmental Impact			
		Global	**Europe**	**Emissions**	**Water Use**	**Acidification**	**Tailings**
		Primary supply as % of net-zero demand, 2035[1]	*Mine supply as % demand (high scenario), 2030*[2]	*tCO_2-eq/tonne*[3]	*m^3/tonne*[3]	*kg SO_2-eq./tonne*[3]	*Tailings waste tonne/tonne*[3]
Copper	**Pyrometallurgy**	50%	12%	5 *(high due to large volumes)*	10 *(but high overall due to large volumes)*	61	140-200
	Hydrometallurgy			7 *(high due to large volumes)*		*N.A.*[4]	
Nickel	**Sulfide**	69%	4%	14-18	133	1,400	30
	Laterites			>40		200	
Cobalt	**Copper by-product**	62%	1%	5 – 13	230	61	36
	Nickel by-product			5 – 38		620	
Lithium (Carbonate)	**Brine**	39%	8%	3 - 8	10	38	Medium (ponds)
	Spodumene			16 – 21	62		21
Graphite	**Natural**	44%	6%	10 – 15	47	*N.A.*	*13*
	Synthetic			20 – 50	*N.A.*	*N.A.*	*N.A.*
Neodymium	**N/A**	67%	1%	18	200	80	80

Source: Supply Risk - Systemiq analysis based on IEA (May 2024), *Global Critical Minerals Outlook 2024*; Benchmark Mineral Intelligence (2024), S&P Capital IQ Pro, European Commission [see slides 24 for further information]; environmental impact – Systemiq analysis based on multiple Source [see appendix 1].

Note: See appendix for information on full list of reviewed technologies. Figures refer to impacts per CRM across both mining and refining stages. | 1. IEA base case supply forecast (excluding secondary supply), demand from IEA net-zero emissions by 2050 scenario (NZE). | 2. CRMA sets target of mining to meet 10% of demand and refining to meet 40% of demand by 2030. Baseline supply from Benchmark Mineral Intelligence, apart from copper, which is based on operational projects in S&P database. Demand data from JRC. | 3. Figures refer to impact per tonne metal produced; ranges refer to different production methods and locations. | 4. Acidification from copper hydrometallurgy is expected to be negligible, as the process does not involve the roasting or smelting of sulfide ores, which are the main sources of SO_2 emissions.

SUMMARY OF SUPPLY & ENVIRONMENTAL IMPACT FOR NEW TECHNOLOGIES RELATIVE TO INCUMBENT PROCESS

⬜ Low positive impact/no impact
▫ Moderate positive impact
🟩 Large positive impact

CRMs	Technology	2035 Supply impact vs incumbent		Environmental impact vs to incumbent			
		Global	**Europe**	**Emissions**	**Water Use**	**Acidification**	**Tailings**
All	Novel Rock Comminution	-	-	**~7% reduction** in global energy use for copper production by 2035[3]	-	-	-
	Application of AI to Geological Data	Acceleration of **exploration timelines** possible		Reduction in exploration drilling requirements	Potential reduction in impacts if enhanced exploration data leads to improved mine design		
	Novel Electrochemistry Applications	Early-stage tech but potential to boost overall supply significantly		Reduced chemical inputs which can have high emissions intensity	N.A.	Electricity replaces the use of most chemical reagents	More efficient processes
Copper	Primary Sulfide Leaching (PSL)	**~12%** of global demand (~1/3rd supply gap)[2]	Limited applicability in EU in due to low ambient temps	Can replace energy-intensive pyrometallurgy but depends on chosen tech[4]	May replace water-intensive pyro routes	Depends on chosen tech – bioleach or using chemical reagents[4]	Can reduce overall tailings if PSL is applied to tailings
	Tailings Reprocessing Technologies	Breakthrough technologies at early stages of development and challenges to overcome for production at scale		Depends on tech, but likely to be energy-intensive process	Dewatering tailings + recycling reduces total water consumption	If applied to legacy tailing – regeneration of environmental liabilities	Potential to reduce need for new mining operations
Lithium	Direct Lithium Extraction[1]	**~15%** total global supply in 2030 from DLE if commercialised	**~7%** EU demand from 2 planned geothermal projects if developed	Up to **> 90% emissions** reduction for geothermal DLE specifically[1]	If brines reinjected and process water recycled[2]	Depends on DLE technology and method[2]	Fewer lithium mines with reduced land use compared to evaporation ponds
Graphite	Novel Synthetic Graphite	High potential	**40%** EU demand from 4 planned projects if developed	**>90% emissions** reduction	N.A.	N.A.	Reduces need for new graphite mines

Source: Analysis from Systemiq based on multiple Source [see slides in section 4 deep dives for underlying data and calculations]

Note: See appendix for information on full list of reviewed technologies. | 1. DLE's environmental impact is highly contingent on the technology, the location and the practices. For instance, water use can be minimised with recycling processes and if brines are reinjected. | 2. Based on phased adoption of PSL of mineralised waste – see deep dive for underlying assumptions. | 3. Based on 80% reduction in energy use for rock comminution, and assumption of average energy intensity of 0.32 kgCO_2e/kWh; with phased adoption of technology at top 10 largest mines. | 4. Chemical-intensive leaching technologies may have higher emissions. Some technologies also require additional crushing.

4 SELECTED TECHNOLOGIES

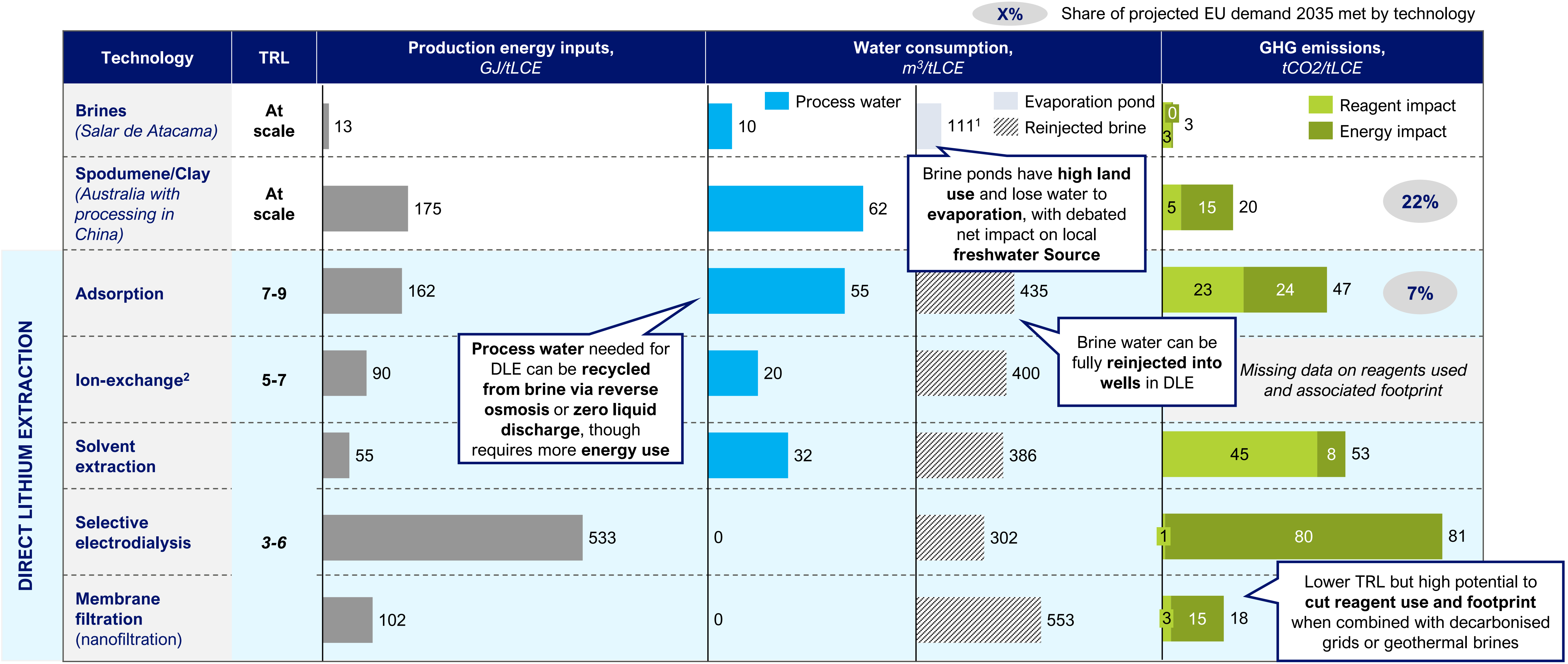
	Chapter	Content	Pages
	Executive Summary		*6-12*
1	Key Supply Challenges	- **Global and EU supply outlook** for selected critical raw materials (CRMs) relative to forecast demand in a net-zero scenario, including review of **new project timelines** and **geographic concentration** of production	*13-23*
2	Key Environmental Impacts	- Comparison of environmental impact for selected CRMs mining and refining based on production process and location, across: **emissions, water use, acidification, land use and tailings**	*24-32*
3	Innovation Landscape	- **Overview of emerging technologies** with potential to increase supply and/or mitigate environmental impacts of selected CRMs and review of current **commercialisation status**	*33-40*
4	**Selected Technologies**	- Deep-dive into 7 selected **new technologies** with **high-impact potential** to resolve key identified supply and environmental challenges for CRM production in the EU and strategic partner countries over next 10-15 years	*41-50*
5	Policy Implications	- **Key challenges** for the deployment of selected new technologies in the EU and **recommended actions for policymakers**	*51-58*
	Appendix		*59-81*

SELECTED TECHNOLOGIES

- **A** Direct Lithium Extraction
- **B** Novel Graphite Production
- **C** Primary Sulfide Leaching
- **D** Application of AI to Geological Data
- **E** Novel Rock Comminution
- **F** Tailings Reprocessing Technologies
- **G** Novel Electrochemistry Applications

A. DIRECT LITHIUM EXTRACTION | ENVIRONMENTAL IMPACT

DLE technologies have higher energy intensities relative to both existing production processes, but can reduce freshwater consumption relative to spodumene mining (2/3^{rds} of existing global production), especially if water is recycled



Technology	TRL	Production energy inputs, *GJ/tLCE*	Water consumption, *m^3/tLCE*: Process water	Water consumption, *m^3/tLCE*: Evaporation pond / ▨ Reinjected brine	GHG emissions, *tCO2/tLCE*: Reagent impact	GHG emissions, *tCO2/tLCE*: Energy impact	GHG emissions, *tCO2/tLCE*: Total	Share of projected EU demand 2035 met by technology
Brines *(Salar de Atacama)*	**At scale**	13	10	111[1]	3	0	3	
Spodumene/Clay *(Australia with processing in China)*	**At scale**	175	62		5	15	20	22%
Adsorption	**7-9**	162	55	435	23	24	47	7%
Ion-exchange[2]	**5-7**	90	20	400	*Missing data on reagents used and associated footprint*			
Solvent extraction	*3-6*	55	32	386	45	8	53	
Selective electrodialysis		533	0	302	1	80	81	
Membrane filtration (nanofiltration)		102	0	553	3	15	18	

DIRECT LITHIUM EXTRACTION: Adsorption, Ion-exchange, Solvent extraction, Selective electrodialysis, Membrane filtration

Brine ponds have **high land use** and lose water to **evaporation**, with debated net impact on local **freshwater Source**

Process water needed for DLE can be **recycled from brine via reverse osmosis** or **zero liquid discharge**, though requires more **energy use**

Brine water can be fully **reinjected into wells** in DLE

Lower TRL but high potential to **cut reagent use and footprint** when combined with decarbonised grids or geothermal brines

Source: Systemiq analysis based on S. Nikfar et al. (2025), *Unlocking sustainable lithium: A comparative life cycle assessment of innovative extraction methods from brine;* J. Kelly et al. (2021), *Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore reSource and their use in lithium-ion battery cathodes and lithium-ion batteries;* Lilac (2024), *Unlocking Lithium Brine Production with Ion Exchange;* Expert interviews, company websites, press research.

Note: See appendix for further supporting information. LCE for lithium carbonate equivalent. Brines and spodumene converted into Li_2CO_3 (lithium carbonate), emissions would be higher for lithium hydroxide. | 1. To produce 1 tonne of LCE in Salar de Atacama, ~111 m³ of brine is required. This calculation is based on 39 mn m³ of brine, with 60% used for lithium extraction, a lithium concentration of 0.17%, and an LCE equivalent of 5.323 per Li unit. | 2. Ion-exchange figures refer to upper values from Lilac Solutions' report.

B. NOVEL GRAPHITE PRODUCTION | SUPPLY AND ENVIRONMENTAL IMPACT

Planned production could meet 75% of the projected graphite demand in EU by 2035, with 40% sourced from new production methods, 14% from natural mines, and the remainder supplied via the existing Chinese production route imported into Europe

X% Share of projected EU demand 2035 met by technology

🟦 Novel technology

	Production Route & Location	TRL	Carbon Intensity[1], *Mt CO2-eq/Mt graphite*	Companies	Targeted Volumes, *Kt p.a. graphite in 2035*		Key Information
	Natural Graphite (Sweden)	9	1.7	talga BGV GROUP MANAGEMENT	150	14%	Talga: 100kt p.a. graphite input - FEED completed in April 2024, ~€600m capex Ukraine: BGV mine (50kt p.a.)
INCUMBENT SYN. ROUTE	**Synthetic Graphite –** *Acheson route* (China)[2]	9	20.0 – 30.0 – 50.0				Synthetic graphite production in China
	Synthetic Graphite – *Acheson route* (Northern Europe)	9	8.0 – 22.0 – 30.0	璞泰来 PUTAILAI 杉杉科技 Shanshan Technology	200	18%	Shanshan: 100 kt p.a. plant in Finland, €1.3bn Capex Putalai: 100 kt p.a. plant in Sweden, €1.5bn Capex
NEAR-ZERO ALTERNATIVES	**Synthetic Graphite –** *Lengthwise graphitization* (France)	8	3.0	TOKAI COBEX	150	14%	50 kt p.a. production unit in France by 2028, in process of raising €500 mn Another 100 kt p.a. production unit planned in Europe
	Synthetic Graphite – *Induction furnace* (Norway)	8	1.9	Vianode NOVONIX	100	9%	Vianode: One 100kt p.a. plant by 2035 Novonix: primarily focusing on the North American market
	Bio-Graphite	7	-2.7	CarbonScape	100	9%	100 kt capacity by 2035 (i.e., 25kt plant + 50kt additional production line + 25kt under licensing)
	Methane Pyrolysis[3]	5-6	1.4	MOLTEN	100	9%	Gigafactory planned of 20,000t p.a. for 2027 - $25M Series A raised in 2024 One industrial 100,000t p.a. production plant by 2035

Location-based (Inner Mongolia highest emissions)

-40%

Lower TRL and higher risk – still at **early deployment stage**

Source: Systemiq analysis based on Talga (2021), *Robust Vittangi Anode Project DFS*; Benchmark Source (2023), *China's Shanshan to build €1.28 billion synthetic anode plant in Finland;* Fastmarkets (2023), *China's Putailai to build anode factory in Sweden;* Carrere et al. (2024), *Carbon footprint assessment of manufacturing of synthetic graphite battery anode material for electric mobility applications;* Carbone4 (2023), *Increase the accuracy of carbon footprint for Li-ion battery;* Expert interviews, company websites, press research.

Note: See appendix for further supporting information. Non-exhaustive list of companies. Graphite-anode battery demand in Europe expected to be around 1,100kt in 2035 [Benchmark projections], to distinguish with overall graphite demand. All technologies assure cost parity with incumbent Chinese synthetic processes. The emissions intensity of synthetic graphite is a topic of ongoing debate within the industry, with some experts estimate this to be ~40-50 kg CO_2 per kg, while others suggest an average closer to 20 kg CO_2 per kg (almost all production currently in China). | 1. 2024 shared emissions taken. | 2. Forecasted emissions vary and can go up to 40kgCO_2-eq/kg depending on source. | 3. Emissions per ton of graphite would be -2.3kgCO2e/kg if biomethane or renewable nature gas used in methane pyrolysis..

C. PRIMARY SULFIDE LEACHING | COST AND ENVIRONMENTAL IMPACT

Technology can reduce emissions and water impacts at comparable costs – however note significant variation depending on ore deposit, copper grade, recovery rate, weather conditions, and leaching technology (*figures below indicative*)

Technology	TRL	Description	Capex, *000 USD/t p.a*	Opex, *000 USD/t*	Energy consumed, *GJ/t*	Water consumption, *m³/t*	GHG emissions, *tCO2/t*
Conventional pyrometallurgy (primary/secondary sulfides)	**At scale** (~80% of global production)	• Ore is mined, crushed & ground, and concentrated through flotation • Concentrate is then smelted and refined	3-5[1]	2[1]	37[2]	91[1]	5[1]
Conventional hydrometallurgy (oxides)	**At scale** (~20% of global production today)	• Ore is mined, crushed & ground, and leached (usually with sulfuric acid) • Pregnant leach solution then goes through solvent extraction and electro-winning	2-5[3]	3-6[3]	24[2]	*N/A*	7[4]
Conventional hydrometallurgy (secondary sulfides)	**At scale** (e.g., Escondida, Morenci mines)	• Hydrometallurgy applied to secondary sulfide ores • Alternatives to sulfuric acid are bio-leaching, chlorides, nitrates, or other catalysts	2-5[3]	3-6[3]	*N/A*		
Primary sulfide bio-leaching of tailings	**6-8**	• Hydrometallurgy applied to primary sulfide ores • Bio-leaching: acid creates environment where microbes oxidise the ore • Applied to tailings[1]	4-6[1]	3-4[1]	*N/A*	45[1]	2[1]
Primary sulfide bio-leaching waste rock	**6-8**	• Same process as above applied to waste rock[2]	*N/A*				0.4[5]

Emissions may be higher than pyro route due to use of **chemical reagents**

New technology (*detail to follow*)

Incurred only if **new SX-EW facility** needs to be built

Techs differ by cycle time – **faster cycles have reduced evaporation losses**

Source: International Copper Study Group (2024) *The World Copper Factbook*; Arthur D. Little (October 2023), *Securing Europe's cleantech, digital, and industrial future by fostering innovation across the critical minerals value chains*, World Materials Forum; Mokmeli, M. (2019). *Pre feasibility study in hydrometallurgical treatment of low-grade chalcopyrite ores from Sarcheshmeh copper mine;* Moreno-Leiva et al. (2019) *Renewable energy in copper production: A review on systems design and methodological approaches;* Kuipers et al. (2018) *Assessing environmental implications associated with global copper demand and supply scenarios from 2010 to 2050;* Nuton data from International Mining (October 2022); CarbonChain.

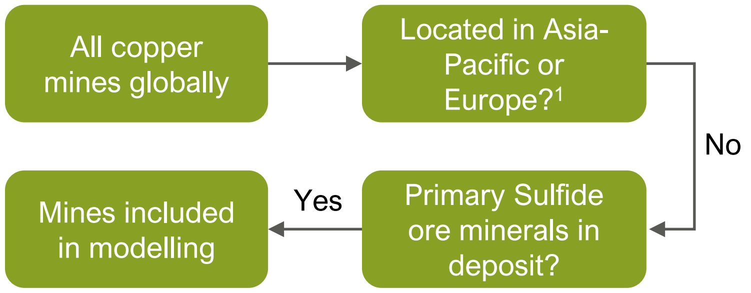
Note: See appendix for further supporting information. Costs expressed per tonne copper refined. Cost impact same for leaching secondary sulfides and oxides. | 1. ADL. | 2. Moreno-Leiva et al. | 3. Mokmei. | 4. Kupiers et al (2018) | 5. Nuton

C. PRIMARY SULFIDE LEACHING | SUPPLY IMPACT

PSL of waste rock could increase copper production by 5 Mt by 2035, but requires barriers identified to be overcome – other PSL applications were not modelled although these could generate significant additional supply

Based on bottom-up mine-level modelling…

Filters

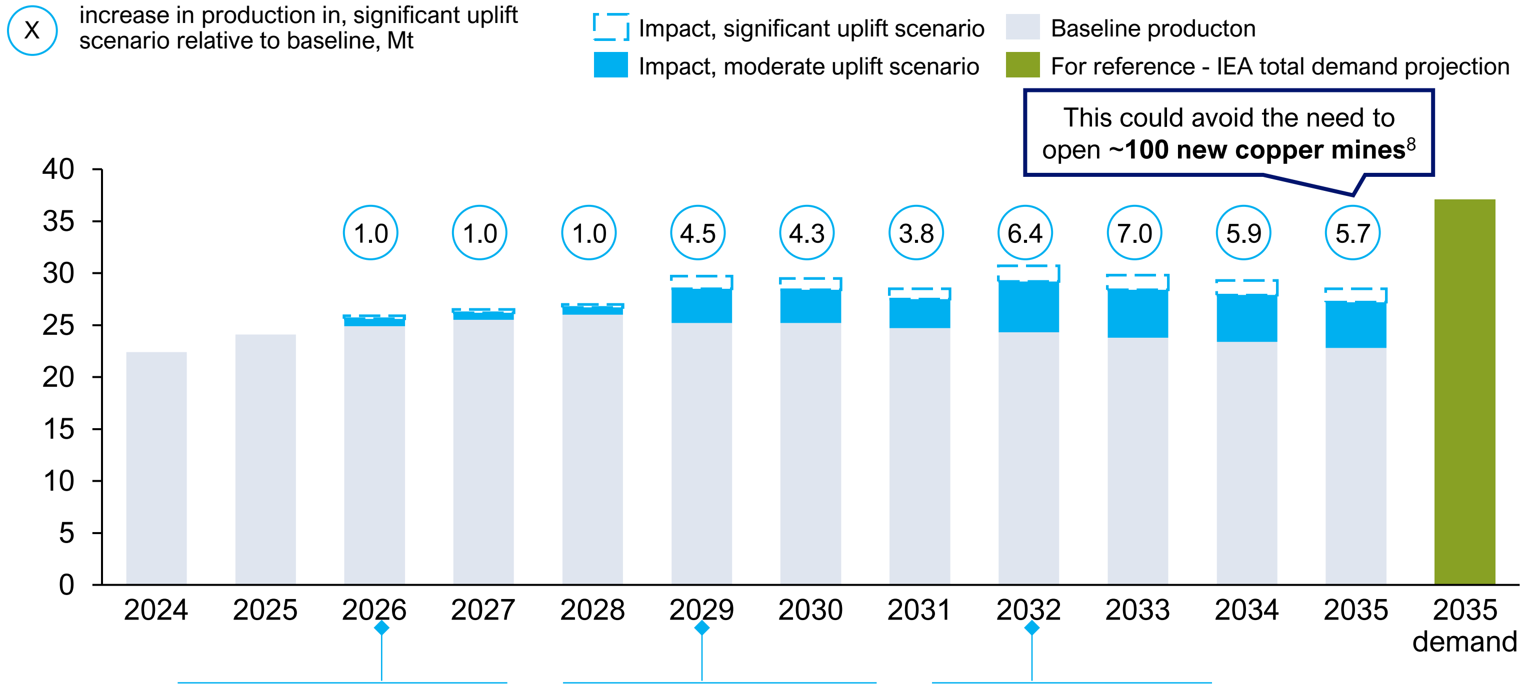


Calculation of production from PSL

Waste rock from ongoing operations, Mt p.a[2]		
x		
Proportion which is mineralised[3]	30%	60%
x		
Waste copper grade	0.1%	0.3%
x		
Recovery rate[4]	30%	70%
=		
Output from leaching		

…phased adoption of primary sulfide leaching could add 30-40 Mt to 2025-35 cumulative copper supply

Potential copper production from primary sulfide leaching of waste rock, Mt copper p.a



This could avoid the need to open **~100 new copper mines**[8]

Phase 1: location and mineral filters, major ownership[5], existing SX-EW facilities

Phase 2: location and mineral filters, all major and mid-tier[6] ownership

Phase 3: location and mineral filters, all ownership, top 25% most productive[7]

Source: Systemiq analysis based on S&P Capital IQ Pro; Expert input

Note: Analysis applied to all mines expected to produce 2024-2035 in S&P database (some of these are not currently producing). Note S&P database forecast differs from IEA forecast presented elsewhere in report. 1. Sulfide leaching generally challenging in colder and wetter weather. | 2. For mines where S&P does not have waste data, factor of 300x production was assumed. | 3. I.e., contains ore deposits | 4. Measure of effectiveness of leaching operations. Rates for dump leaching to date have been 40-50%. | 5. Companies ranked 1-10 in 2023 production rankings. | 6. Companies ranked 10-20 in 2023 production rankings. | 7. 25th percentile and below in 2023 mine average cost. | 8. Estimated based on global average 2022 copper mine production for each metal: ~60 kt p.a.

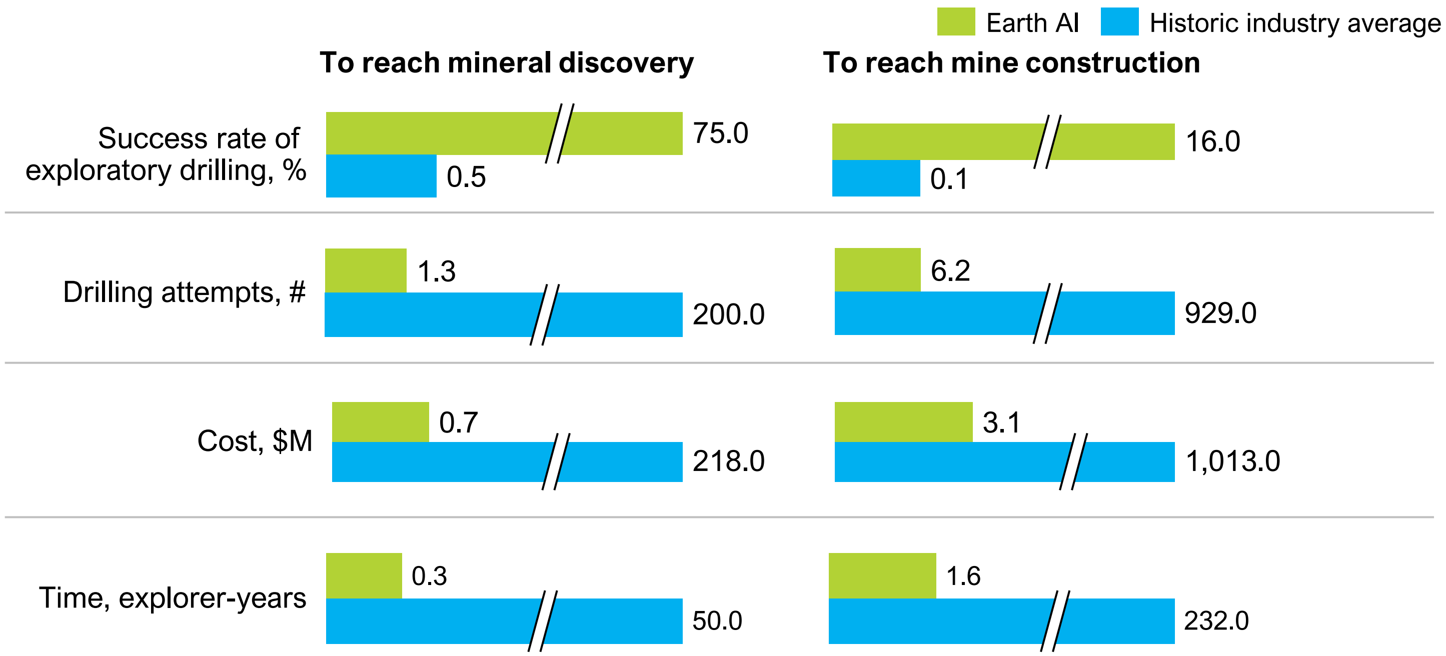
D. APPLICATION OF AI TO GEOLOGICAL DATA | SUPPLY & ENVIRONMENTAL IMPACT

Through improved location prediction and optimised drilling, AI could transform the pace of minerals exploration and reduce timelines for the discovery of new deposits

Advantages of application of AI to geological data

1. More **accurate and faster prediction** of mineral locations and **quantification of deposit content**
   - AI models are trained on geological data to identify patterns of known mineral occurrences
   - On average, **exploration drilling requires ~450 kWh per project**[2] – fewer exploration projects result in significant energy consumption reduction
2. Rapid analysis of exploration drilling results enables **ongoing optimisation of drilling**
   - Currently cores[3] are logged after drilling and selected for assaying and sent to labs – results take **weeks to months**
   - AI provides **detailed results quickly**, allowing for optimisation of location for next drill holes, planned drilling depths, project continuation/cancellation etc. – **lowering exploration drilling costs by up to 25% and reducing timelines**
   - Improved drilling data provides **transparency to investors**
   - Improved mine design due to enhanced data collection can generate **5% Capex saving in mine construction and 10-15% Opex saving over the lifetime of the mine lifetime**

Example: performance of Earth AI compared to current industry average on key exploration metrics
(based on sample of 3 mineral discoveries from 4 exploration drills – all at pre-feasibility stage)[1]



Note: AI efficacy dependent on quality and availability of geological data, which varies across regions

Assuming 22% of discoveries progress to mine construction[4]

Source: Geologic AI; Earth AI (2024) Not Boring by Packy McCormick; Arthur D. Little (October 2023), *Securing Europe's cleantech, digital, and industrial future by fostering innovation across the critical minerals value chains*, World Materials Forum; Expert interviews, company websites, press research.

Note: 1. Earth AI is a predictive explorer and driller for critical materials, founded in 2016. Its model predicts the location of mineral deposits, and its drilling platform verifies those deposits. Earth AI data is based on a small sample size - 3 discoveries in its first 4 attempts. | 2. Based on 1.3 kWh/m energy consumption to drill hole, average hole depth of 100m, and 3.5 holes drilled per exploration project. | 3. Cores are small diameter rock samples which are extracted during exploration drilling and analysed for prospective minerals. | 4. Earth AI discoveries have not yet proven feasibility – based on 22% conversion from discovery to construction (Australia 2013-23 average).

E. NOVEL ROCK COMMINUTION | ENVIRONMENTAL IMPACT

Technology could reduce total energy consumption by 7% if adopted at top 10 global copper mines by 2035; overall impact could be higher if applied to more copper mines or to other materials

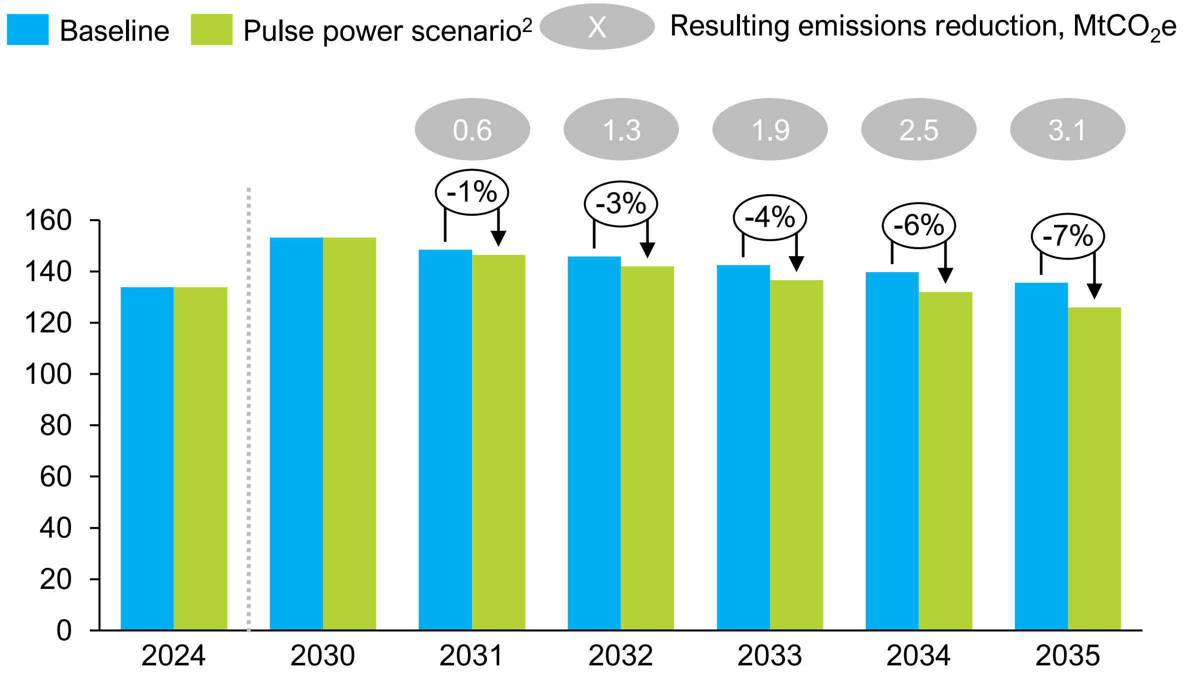
Based on top-down modelling…

Assumptions

- Open pit + concentrator production
- **Energy consumption**:
  - Non-comminution (mining diesel + other processing): 4,267 kWh/t Cu
  - Comminution baseline: 2,400 kWh/t Cu
  - Comminution - pulse power : 480 kWh/t Cu[1]
- **Emissions intensity of energy for comminution**: 0.32 kgCO2e/kWh
- **Pulse power scenario**: phased adoption of technology at top 10 largest mines from 2031[2] (1 in EU – KGHM Polska)

..preliminary assessment indicates energy consumption could be lowered by >5% by 2035…

Global total energy consumption for copper production by modelled scenario, TWh p.a.



…but there are significant barriers to scaling technology to overcome

- Relevant companies (e.g., i-ROX, Selfrag) are at TRL 4-6 – **significant investment** required to reach **large-scale deployment**
- The comminution stage is the most **capex-intensive stage of mining** (e.g., Escondida's 3rd concentrator opened in 2016 required $4.2 bn investment[3])
  - Companies reluctant to deploy new technology due to **heightened cost and timeline risks**
  - Opportunities to replace only arise when **machinery is replaced** (long lifetimes)
- However, there is also potential for i-ROX tech to have benefits beyond lower energy comminution
  - Breaking rock to expose more metal particles – increased **recovery in flotation** step
  - **Selective rock breaking** – break mineralised ores whilst keeping barren rocks intact – enhances energy-efficiency of application

Source: Systemiq analysis based on: S&P Capital IQ Pro; Engeco (2021) *Mining Energy Consumption 2021*; Norgate and Haque (2010) *Energy and greenhouse gas impacts of mining and mineral processing operations;* i-ROX.

Note: See appendix for further supporting information. 1. Based on 80% reduction in comminution energy consumption. Note that current tech – i-ROX generates 60% reduction by replacing ball mill. Aim is to replace both ball and sag mill, generating 85% reduction. | 2. 2031 chosen as i-ROX is aiming to have a commercial plant operational by this year; Top 10 mines included; Esondida, Grasberg, Collahuasi, Cerro Verde, Antamina, Buenavista, KGHM Polska Miedz, Kamoa-Kakula, Morenci, El Teniente. | 3. Based on Organic Growth Project One – ball mills, hydro-cyclones, coarse ore handling system, pebble crushing circuity, and concentrate and tailings thickeners.

F. TAILINGS REPROCESSING | TECHNOLOGY OVERVIEW

Existing technologies can enable the reprocessing or dewatering of tailings to reduce liabilities, while new innovative technologies could enable CRM extraction from tailings – though significant barriers to scale still exist

Existing technologies can be used to reprocess tailings but often lack an economic case today

Off-the-shelf technologies:
Companies like Future Element and Regeneration are leveraging established technologies, including coarse flotation, fine flotation, and various leaching methods, to extract metals from tailings

Lack of economic case:
Tailings reprocessing has yet to scale due to the absence of a viable business model, hindered by high reprocessing costs, liability challenges, and limited political support

Further applications:
Beyond metal recovery, reprocessing tailings can help to stabilise areas, create landforms, and supply construction materials (out of scope in this report)

Selected Examples

NEW CENTURY RESOURCES

New Century Resources **reprocessed tailings from Australia's Century Mine** (closed in 2015), extracting ~270 kt of zinc concentrate, rehabilitating 800 hectares of land, and reducing closure costs from $387M to $73M

AngloAmerican

Anglo American's **Hydraulic Dewatered Stacking (HDS) technology** promises over 80% water recovery, enabling up to 20% higher metal production, producing drier and more stable tailings, and accelerating land rehabilitation post-mining[1]

Several startups are developing innovative technologies to extract CRMs from reprocess tailings, but commercial-scale deployment remains challenging[2]

Selected Examples

SiTration

Sitration's **electro-filtration technology** uses **electric fields and a silicon-based membrane** to selectively capture metals from water solutions, avoiding high heat or chemical use

Auxilium TECHNOLOGY GROUP

Auxilium **combines chemical and biological technologies** to concentrate metals, enabling the recovery of copper along with nickel, cobalt, zinc, and rare earth elements when present

PHOENIX TAILINGS

Phoenix **uses water and recyclable solvents** to extract oxidized metals, which are processed in **molten salt with electricity**, targeting REE and nickel from mining waste

Key barriers for deployment at scale

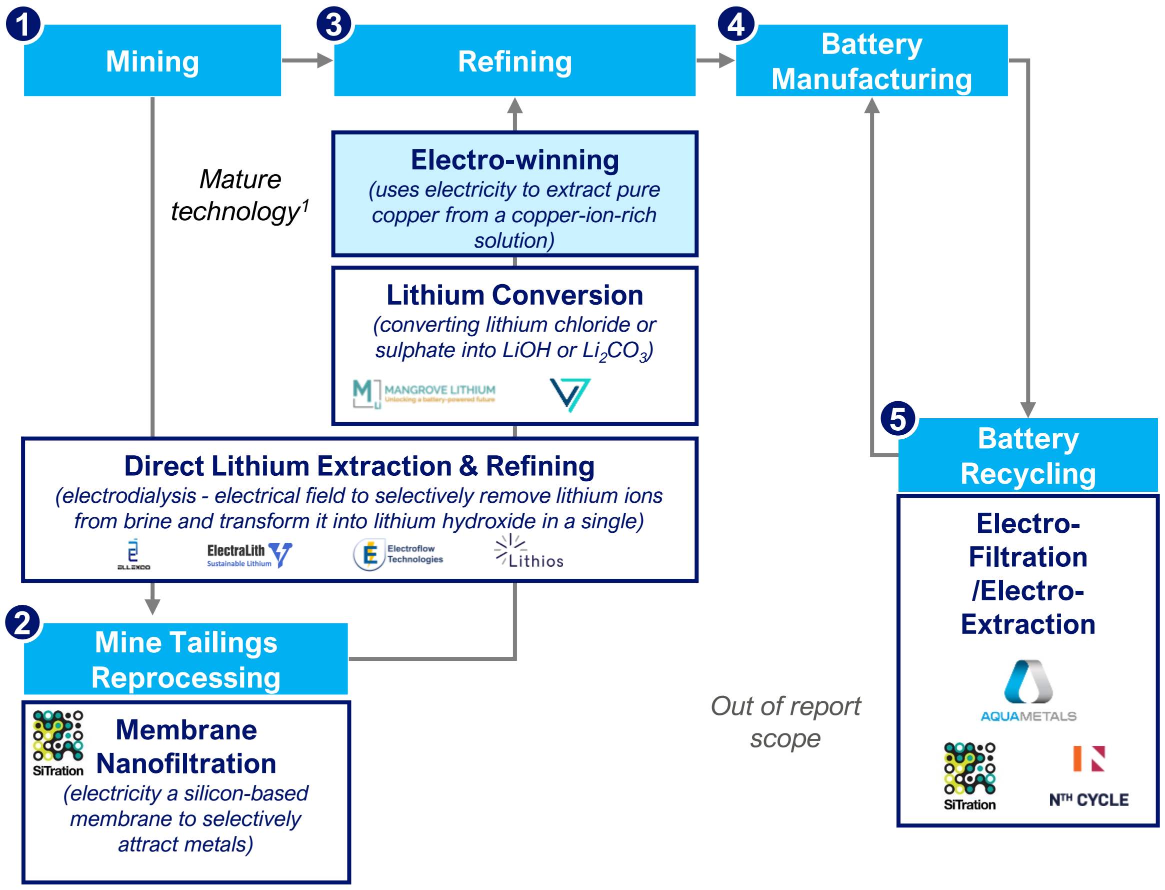
1. **High up-front costs:** securing major capital expenditure required to build out large scale pilot plants (projects typically low-margin at present)
2. **Technical challenges**: demonstrating consistent performance at scale in real world conditions, especially given variability across different tailings
3. **Permitting hurdles**: regulatory challenges complicate reprocessing initiatives[3]
4. **Liability issues**: inactive tailings pose liability risks, especially with unclear regulatory frameworks[4]
5. **Residual tailings management:** extracting metals still leaves >99% of tailings behind, requiring sustainable disposal

Source: Systemiq analysis based on FutureElement (2024), *Century's rehabilitation success: 3 insights that could transform how you think about tailings*; Expert interviews; press releases.
Note: Non-exhaustive list of companies. | 1. Technology still under development, not yet proven at scale. | 2. Several other innovators are exploring alternative products from tailings, such as Americas Tailings, which focuses on producing bio-mineral fertilisers, and TerraCO2, which develops cementitious materials from copper tailings. | 3. Wet tailings present significant environmental risks and require stabilization. | 4. E.g., solutions being trialed in Quebec involve "ring-fencing" only the reprocessed portions.

G. NOVEL ELECTROCHEMISTRY APPLICATIONS | OVERVIEW OF TECHNOLOGY

Novel electrochemistry applications offer a cleaner, scalable alternative for refining CRMs, and can apply across other stages of the value chain, but technologies are at low TRL, requiring support to reach deployment at scale

Electrochemistry spans the entire battery value chain…



① **Mining**

③ **Refining**

④ **Battery Manufacturing**

Mature technology[1]

Electro-winning
(uses electricity to extract pure copper from a copper-ion-rich solution)

Lithium Conversion
(converting lithium chloride or sulphate into LiOH or Li_2CO_3)

MANGROVE LITHIUM

Direct Lithium Extraction & Refining
(electrodialysis - electrical field to selectively remove lithium ions from brine and transform it into lithium hydroxide in a single)

ElectraLith Sustainable Lithium · Electroflow Technologies · Lithios

② **Mine Tailings Reprocessing**

Membrane Nanofiltration
(electricity a silicon-based membrane to selectively attract metals)

SiTration

Out of report scope

⑤ **Battery Recycling**

Electro-Filtration /Electro-Extraction

AQUAMETALS · SiTration · Nth CYCLE

…offering a cleaner, scalable alternative for refining CRMs like lithium, but currently low TRL with important challenges to overcome for deployment at scale

Pros

- **Efficient and low energy systems**
- **Reduced waste and chemical use**
- **Modular and scalable design**: allowing for flexible scaling based on project requirements
- **Broad applicability across lithium source** (brines, hard rock, oil fields, geothermal)
- **Effective on low-concentration brines** (< 50 ppm lithium grade)
- **Minimal downstream refining**: by enabling more efficient extraction at the source, electrochemical methods often require less downstream refinement
- **Flexibility:** electro processes can easily adjust operation based on electricity availability, helping stabilizing the grid

Cons

- **Low TRL technology**, requiring more research to reach commercial viability
- Insufficient data on **performance at an industrial scale** or outside controlled laboratory settings
- **High-specification components** like membranes and electrodes are costly and difficult to produce at scale, making the **cost profile** of these systems a significant consideration
- **Area-based** (electrode size constraints) **rather than volume-based processes:** posing a cost linearity challenge with Capex[2]
- **Maintenance and impurity management**: electrochemical systems are sensitive to impurities in feedstocks, leading to potential maintenance challenges that increase operational costs and downtime

Source: Systemiq analysis based on Medium (2023), *The technology overview: closing the lithium supply gap with direct lithium extraction (DLE) and battery recycling*; Expert interviews, company websites, Press research.

Note: 1. Combined with solvent extraction. | 2. Volume-based processes such as pyro/hydro-metallurgy experience economies of scale as production volumes increase (from e.g., increasing capacity of tanks/reactors/furnaces). Area-based processes such as electrochemistry typically see linear cost increases to scale as these rely on membranes and electrodes that must be stacked as volumes increase

5 POLICY IMPLICATIONS

	Chapter	Content	Pages
	Executive Summary		*6-12*
1	Key Supply Challenges	• **Global and EU supply outlook** for selected critical raw materials (CRMs) relative to forecast demand in a net-zero scenario, including review of **new project timelines** and **geographic concentration** of production	*13-23*
2	Key Environmental Impacts	• Comparison of environmental impact for selected CRMs mining and refining based on production process and location, across: **emissions, water use, acidification, land use and tailings**	*24-32*
3	Innovation Landscape	• **Overview of emerging technologies** with potential to increase supply and/or mitigate environmental impacts of selected CRMs and review of current **commercialisation status**	*33-40*
4	Selected Technologies	• Deep-dive into 7 selected **new technologies** with **high-impact potential** to resolve key identified supply and environmental challenges for CRM production in the EU and strategic partner countries over next 10-15 years	*41-50*
5	**Policy Implications**	• **Key challenges** for the deployment of selected new technologies in the EU and **recommended actions for policymakers**	*51-58*
	Appendix		*59-81*

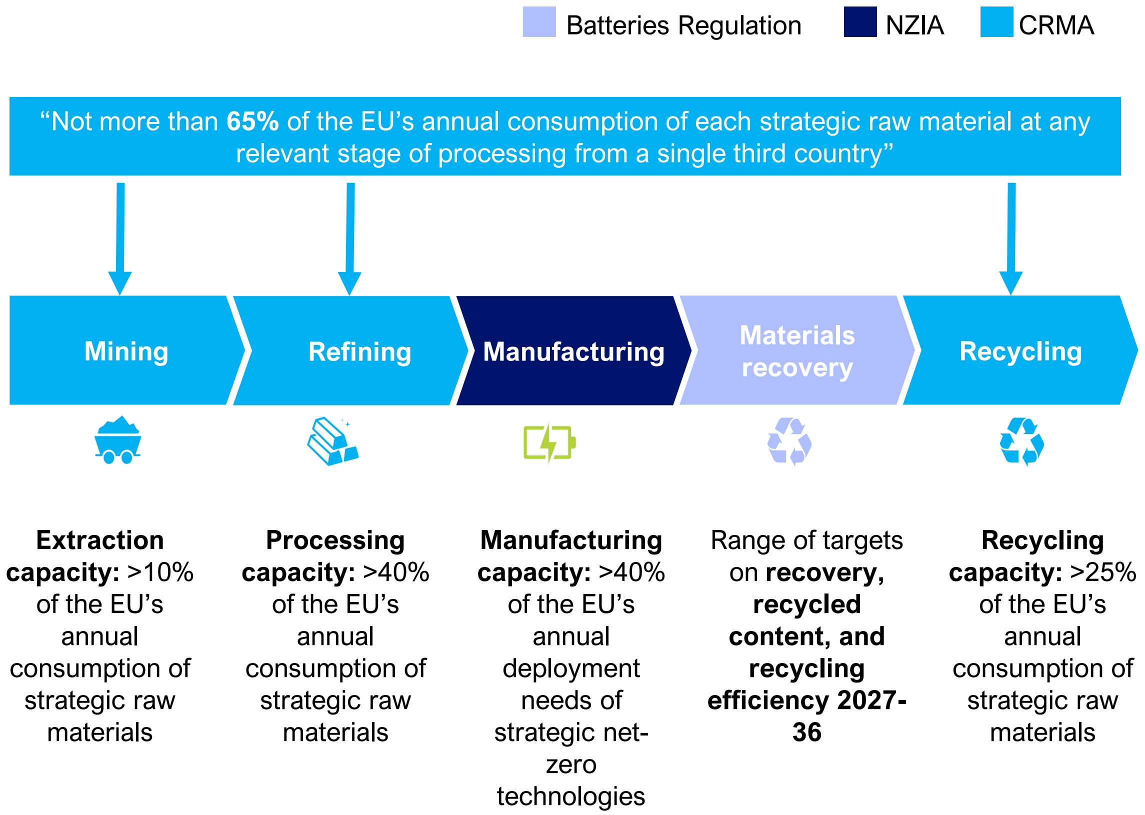
CONTEXT | THE EU HAS INTRODUCED SEVERAL IMPORTANT POLICIES THAT AFFECT THE CRM VALUE CHAIN

Non-exhaustive

The EU has introduced several policies relevant to CRMs and the wider clean technology manufacturing…

Policy	Date adopted	Key details
Net Zero Industry Act (NZIA)	June 2024	• Sets 2030 target for net-zero manufacturing capacity in EU (*see RHS*) and target for the EU to reach 15% of global market value by 2040 • Covers 8 technologies, including battery technologies[1]
Critical Raw Materials Act (CRMA)	May 2024	• Designates list of *strategic* and *critical* raw materials • Sets 2030 targets for EU demand met through extraction, processing, and recycling (*see RHS*) • Establishes criteria for *strategic projects* designation, with associated permitting timeline restrictions • Mandates mechanism to connect *strategic projects* with offtakers and joint purchasing platform for CRMs
EU Batteries Regulation	July 2023	• Declaration requirements and maximum CO$_2$ footprint limits on EVs, light transport and industrial batteries • Sets range of targets for material recovery, minimum levels of recycled content, and recycling efficiency
EU Taxonomy Regulation	July 2020	• Establishes the basis for the EU taxonomy by defining 4 conditions that an economic activity must meet to qualify as environmentally sustainable • Platform on Sustainable Finance under the European Commission maintains the list of sustainable activities and associated conditions

…with associated targets for 2030 that apply across the value chain



Extraction capacity: >10% of the EU's annual consumption of strategic raw materials

Processing capacity: >40% of the EU's annual consumption of strategic raw materials

Manufacturing capacity: >40% of the EU's annual deployment needs of strategic net-zero technologies

Range of targets on **recovery, recycled content, and recycling efficiency 2027-36**

Recycling capacity: >25% of the EU's annual consumption of strategic raw materials

Source: Systemiq based on public sources.

Note: Solar photovoltaic and solar thermal technologies, onshore wind and offshore renewable technologies, batter/storage technologies, heat pumps and geothermal energy technologies, electrolysers and fuel cells, sustainable biogas/biomethane technologies, Carbon Capture and storage technologies, grid technologies.

DEVELOPING NOVEL TECHNOLOGIES IN THE EU SHOULD FORM A CORE PART OF EU POLICY OBJECTIVES TO ACHIEVE CRMA TARGETS

High-level policy objectives overview to achieve CRMA targets		
Existing Technologies	**EU-level actions**	• Ensure rapid **development of new mines and refineries** within the EU using best practice conventional technologies to meet CRMA targets in time • Minimise the environmental footprint of mining in the EU by supporting the continued adoption of **environmentally responsible mining practices** and **clean electrification** of energy use (including for fleets) in the sector
	Actions with strategic partner countries	• Accelerate **strategic relationships with partner countries** to diversify supply chains for EU CRM imports, focusing on locations with existing production at scale and lowest environmental impacts of production
Novel Technologies	**EU-level actions**	• Support **early-stage technologies** with high long-term impact potential to develop first **pilot/demonstration facilities** (e.g. novel rock comminution, tailings reprocessing, novel electrochemistry applications) • Support more **mature new technology players** to **develop FOAK[1] plants and be deployed at commercial-scale at new sites** (e.g., novel synthetic graphite producers, geothermal DLE)
	Actions with strategic partner countries	• Encourage the **global adoption of novel technologies** that can sustainably boost CRM supply in the short-term (e.g., primary sulfide leaching, application of AI to geological exploration) and from 2030 onwards (e.g., novel rock comminution, tailings reprocessing, novel electrochemistry applications)

Focus of next slides

Source: Systemiq analysis based on IEA Critical Minerals Policy Tracker; IEA (2024) *Global Critical Minerals Outlook 2024;* Press research.

Note: Strategic partner countries refers to countries that the EU currently has strategic partnerships with or may in the future, including members of the Minerals Security Partnership | 1. FOAK: First-of-a-kind.

CRM INNOVATORS IN THE EU FACE A CLEAR SET OF CHALLENGES AT PRESENT

Supply-side innovators highlight a series of recurring issue areas that restrict their ability to scale in the EU, limiting the EU's ability to compete globally in CRM mining and refining

Innovation Support

EU innovation funding support is strong, but few programs cover breakthrough CRM mining and refining technologies at present, while **administrative requirements** can delay access to funding for primary R&D in some cases

Project Financing

Companies looking to develop first-of-a-kind commercial facilities highlight **lack of available public funding** and **government de-risking support** in the EU as key barrier

Offtake & Price Volatility[1]

Highly volatile CRM prices create uncertainty in project economics, often leading to cancellations or delays during downturns – **securing long-term industrial offtake** agreement is a major challenge

Local Enabling Environment

Planning and permitting timelines,[2] combined with **social acceptability issues**, administrative hurdles, and **elevated energy and labour costs**, identified as recurring key challenges

International Competitiveness

Competitive pricing from established external suppliers from other geographies creates barriers to entry, especially in absence of policy **to level the playing field** and incentivize superior **emissions/ environmental performance**

Most **important challenges** for companies in the EU today aiming to develop **production at scale**
(see supporting information in appendix)

Source: Expert interviews

Notes: 1. For critical raw materials: for example, lithium price volatility reflects sharp market fluctuations, primarily at the refining stage of the value chain. While spodumene (raw ore) sees minor shifts, refined products like lithium hydroxide and carbonate experience significant swings. | 2. In the U.S., individuals often own underground resources, allowing direct deals for use, while in the EU, governments own them, requiring companies to get permits and concessions, making the process more complex.

THERE ARE MULTIPLE POLICY OPTIONS TO HELP INNOVATORS OVERCOME THESE KEY CHALLENGES

High-level overview of policy options

🟦 Current EU policy
▨ Mandated by EU policy but not yet enacted
☐ Not in place for CRMs at EU-level

Innovation Support

1. 🟦 **Grant funding** for projects developing innovations, at academic or company level
2. 🟦 Supporting early-stage innovators beyond funding, e.g., **networks, training** for entrepreneurs etc.
3. ☐ **Tax credits** for R&D investment
4. 🟦 Creating **multi-stakeholder alliances** to foster innovation

Project Financing & Derisking[1]

1. 🟦 **Grants and concessional loans**
2. 🟦 **Equity investments**
3. ☐ Project support through **tax credits or reduced royalties**
4. 🟦 Credit and offtake **risk guarantees**
5. ☐ **First loss** guarantees
6. ☐ **Other blended finance** instruments

Volume & Price Stability

1. ☐ **Strategic stockpiles** of CRMs[4]
2. ☐ **Price floors** or contracts-for-difference schemes for CRMs
3. ▨ State mechanisms to **connect suppliers** with off-takers
4. ▨ Aggregate **purchasing platform** for CRMs
5. ☐ Incentives for **domestic CRM content** in intermediate or final goods, e.g., tax credits, purchasing mandates/targets

Enabling Environment

1. 🟦 Policies to reduce the **cost of energy**
2. 🟦 **Workforce training** and re-skilling programs
3. 🟦 Fast-tracking **project permitting**[5]
4. ☐ National/regional **geological surveys**
5. 🟦 Emissions thresholds for downstream **intermediate/ final goods**, e.g., batteries
6. ☐ Local community **engagement**[5]

Trade Policy

1. ☐ **High import tariffs** on CRMs
2. 🟦 **Export financing**
3. ☐ **Carbon border adjustment mechanism** applied to CRMs

Relevant for early-stage techs developing pilot facilities[2]

Relevant for more mature new techs looking to develop FOAK plants and be deployed at commercial-scale at new sites[3]

Source: Systemiq based on expert interviews, public sources; IEA Critical Minerals Policy Tracker; IEA (2024) *Global Critical Minerals Outlook 2024.*

Note: 1. Funding can be provided through direct government investment, development banks, government investment banks which also raise capital privately, or public-private partnerships. | 2. E.g., novel electrochemistry applications, novel comminution, tailings re-processing | 3. E.g., Novel graphite producers, geothermal DLE. | 4. This can be used to counteract market fluctuations. | 5. Note that this should be considered a baseline for all projects across both new and existing mines/technologies, in parallel to the adoption of high environmental and social standards (e.g., IRMA initiative).

THE EU SHOULD ADOPT A COMPREHENSIVE TOOLKIT AIMED FOR CRM INNOVATION – SEVERAL IMPORTANT INITIATIVES ALREADY IMPLEMENTED

EU actions mapped to high-level overview of policy actions

■ Current EU policy
▣ Mandated by EU policy but not yet enacted
□ Not in place for CRMs at EU-level

Innovation Support[1]

1. ■ **Innovation funding**
   ERA-MIN3, European Technology Platform on Sustainable Mineral Resources, eit InnoEnergy, eit RawMaterials, BATT4EU
   Horizon Europe
   EU Innovation Fund
2. ■ **Networks for early-stage businesses and training for entrepreneurs**
   European Technology Platform on Sustainable Mineral Resources, eit RawMaterials, eit InnoEnergy
3. □ Tax credits for R&D investment
4. ■ **Multistakeholder alliances**
   EUROPEAN RAW MATERIALS ALLIANCE ERMA

Project Financing & Derisking[1]

1, 2. ■ **Grants and concessional loans, equity investments**
   eit RawMaterials, eit InnoEnergy, European Investment Bank
   European Bank for Reconstruction and Development — EU Innovation Fund
   Member State CRM funds:
   - INFRAVIA
   - KFW
   - 'Made in Italy' Fund
3. □ Project support through tax credits or reduced royalties
4. ■ **Credit guarantees**
   INVEST EU
5. □ First loss guarantees
6. □ Blended finance

Volume & Price Stability

1. □ Strategic stockpiles of CRMs
2. □ Price floors for CRMs
3. ▣ CRMA: system to **connect Strategic Projects with offtakers**
4. ▣ CRMA: **joint purchasing platform** for CRMs
5. □ Incentives for domestic CRM content in intermediate or final goods

Enabling Environment

1. ■ Policies to reduce **energy costs**, e.g., gas storage requirements, demand-side management
2. ■ **Funds for training through financing programmes**
   eit RawMaterials
3. ■ CRMA: States **mandated to permit designated Strategic Projects** within 27 months for extraction and 15 months for processing projects
4. □ National/regional geological surveys
5. ■ **Batteries Regulation:** declaration requirements and CO2 footprint limits on EVs and industrial batteries

Trade Policy

1. □ High import tariffs on CRMs
2. ■ **Guarantees and loans** to banks providing trade finance
   European Bank for Reconstruction and Development
3. □ Carbon border adjustment mechanism applied to CRMs

There are several existing EU initiatives - however more targeted and scaled-up action, based on global best practice, is required to promote CRM innovation

Source: Systemiq based on expert interviews and public sources.

Note: 1. See appendix for further details of current EU funding programs. BATT4EU: Public-private partnership between the Batteries European Partnership Association and the European Commission; ERA-MIN: European Research Area Networks Cofound on Raw Materials; ETP SMR: European Technology Platform for Sustainable Mineral Resources; EIT: European Institute of Innovation & Technology; IPCEI: Important Projects of Common European Interest; EIB: European Investment Bank; EIF: European Investment Fund; EBRD: European Bank for Reconstruction and Development. KFW: Germany's state economic investment bank.

… BUT SUCCESSFUL POLICIES ADOPTED IN OTHER REGIONS ALSO OFFER POTENTIAL IDEAS FOR THE EU

Non-exhaustive

Innovation Support

Canada – Clean Technology Manufacturing Investment Tax Credit: A refundable 30% tax credit for investments in machinery and equipment used to manufacture clean technologies or extract, process, and recycle 6 critical minerals (e.g., crushing & grinding equipment).

Project Financing & Derisking[1]

USA – IRA Section 45X offers a **10% tax credit for the costs of critical minerals, for domestic projects that produce refined materials[1]**

USA – The Department of Energy (DOE) has announced **~$4.8 bn in investment for projects across the batteries value chain, including CRM mining and refining under the Bipartisan Infrastructure Law**

Canada – CMETC: A **30% non-refundable credit for eligible critical mineral exploration** expenses in Canada

USA – IRA EV tax credits are fully available only **if minerals are sourced from North America or a USA free trade** and battery components are assembled in North America

Volume & Price Stability

Chile – Variable royalty system with **rates ranging from 6.8% to 40% based on market prices.** Aim is to ensure miners remain competitive during price fluctuations while securing public revenues.

Chile – Chile's Copper Stabilisation Fund mitigates price volatility by saving surplus revenues during high-price periods and providing a buffer during downturns. Aim is to stabilise sector and enable sustained investment.

Enabling Environment

Australia – The Critical Minerals Facilitation Office coordinates efforts to streamline regulations and provide support to CRM projects, to foster for innovation. Aims to reduce bureaucratic hurdles and accelerate project development.

Canada – $1.5 bn CMIF funds projects that enhance critical minerals production in Canada, focusing on economic, infrastructure, and community benefits

Trade Policy

Japan – State-owned Nippon Export and Investment Insurance provides **loan insurance for procurement of critical minerals from abroad and investing in foreign minerals projects**

Source: IEA Critical Minerals Policy Tracker; IEA (2024) *Global Critical Minerals Outlook 2024;* U.S. Department of Energy (2024), *Bipartisan Infrastructure Law: Battery Materials Processing and Battery Manufacturing Recycling Selections*; U.S. Department of Energy (2024), Loan Programs Office; Oxford Academic (2018), *The Copper Sector, Fiscal Rules, and Stabilization Funds in Chile: Scope and Limits*; Government of Canada (2024), *Canadian Critical Minerals Strategy Annual Report 2024;* Press research.

Note: IRA: Inflation Reduction Act; pCAM: Precursor Cathode Active Material; CMIF: Critical Minerals Infrastructure Fund; CMETC: Critical Mineral Exploration Tax Credit. | 1. Regardless of where the minerals are mined

POLICY IMPLICATIONS | SEVERAL TOOLS, ESPECIALLY FOR PROJECT FINANCE AND OFFTAKE, CAN HELP STIMULATE SUPPLY-SIDE INNOVATION IN THE EU

Innovation Support

Accelerate investment in breakthrough technologies to **leapfrog traditional processes**, delivering lower environmental impacts in longer-term

1. Focus existing **EU innovation support** programmes, including Horizon Europe, the ERA-MIN network, ETP SMR, and EIT Raw Materials, on innovation areas where competitive and technological advantages can be secured in future[1]

Project Financing

Increase public funding available, and 'crowd in' private funding, for **first-of-a-kind deployment at commercial scale**, using blend of capex and opex support mechanisms

1. Direct **greater investment** for commercial deployment of new technologies, e.g., via an expanded EU Innovation Fund, the EIB, the EBRD and other blended finance programs[2]
2. Enhance production-based support, e.g., introduce **tax credits*,** expand **loan guarantees through the InvestEU programme**
3. Include mining/refining CRMs within target investment areas of the **STEP initiative** and a new European '**sovereignty fund**'[3]

Offtake & Price Volatility

Support innovators in securing **offtake agreements** offering price stability for domestically produced materials to provide project certainty

1. Provide **loans to** downstream sectors which are **conditional** on sourcing a proportion of CRMs domestically*, e.g., for EIB loans[4]
2. Introduce **incentives** for domestically produced CRMs in **downstream sectors**, e.g., EV tax credits
3. Set up **mandates** for domestically produced CRMs at downstream sector-level or country-level*

Enabling Environment

Streamline administrative process and facilitate coordination to **fast-track high-impact projects**

1. Enforce CRMA provisions to limit **permitting timelines** for projects deploying innovative technologies
2. Implement coordinated action to build **integrated downstream value chains**, alongside CRM innovations
3. Including responsible mining/refining of CRMs within the **EU taxonomy for sustainable activities**[5]

International Competitiveness

Promote EU production by targeted **trade measures** where necessary, while promoting innovative technologies in **partner countries**

1. Require **technology and skills transfer** from foreign investors to EU partners when investing in CRMs or downstream value chains
2. Promote piloting and scaling innovations that reduce environmental footprint in partner countries through Strategic Partnerships and the **Minerals Security Partnership**

⬚ Top priority for further exploration ● New initiatives ● Continuation/extension of existing initiatives

Early-stage techs[6]

Key challenge for EU companies: developing first-of-a-kind commercial facilities[7]

Source: Systemiq analysis based on expert interviews; see chapter 5 for further information.

Note: Non-exhaustive list of options. All CRM Projects should uphold the highest environmental and social standards in line with best practice (e.g., IRMA initiative). Strategic partner countries refers to countries that the EU currently has strategic partnerships with or may in the future, including members of the Minerals Security Partnership. | *Policies are primarily implemented at Member State rather than EU-level. | 1. ERA-MIN: European Research Area Networks Cofound on Raw Materials, ETP SMR: European Technology Platform for Sustainable Mineral Resources, EIT: European Institute of Innovation & Technology. | 2. EIB: European Investment Bank, EBRD: European Bank for Reconstruction and Development. | 3. STEP - Strategic Technologies for Europe Platform. | 4. This could be through a mechanism similar to the European Hydrogen Bank's resilience criteria. | 5. With added provisions that high environmental and social standards are upheld. | 6. Including inter alia novel rock comminution, novel electrochemistry applications, tailings reprocessing. | 7. Including inter alia (geothermal) direct lithium extraction, novel synthetic graphite production.

APPENDIX

	Chapter	Content	Pages
	Executive Summary		6-12
1	Key Supply Challenges	• **Global and EU supply outlook** for selected critical raw materials (CRMs) relative to forecast demand in a net-zero scenario, including review of **new project timelines** and **geographic concentration** of production	*13-23*
2	Key Environmental Impacts	• Comparison of environmental impact for selected CRMs mining and refining based on production process and location, across: **emissions, water use, acidification, land use and tailings**	*24-32*
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5	Policy Implications	• **Key challenges** for the deployment of selected new technologies in the EU and **recommended actions for policymakers**	*51-58*
	Appendix		*59-81*

APPENDIX

A Terminology

B Environmental and social impacts of CRM mining and processing

C Further information on emerging technologies

D Further information on selected technologies

E Supporting information on key challenges for European innovators and existing EU policy schemes

A. TERMINOLOGY

Relevant definitions in EU Critical Raw Materials Act

- **Exploration**: all activities aimed at identifying and establishing the properties of mineral occurrences.
- **Extraction**: the extraction of ores, minerals and plant products from their original source as a main product or as a by-product, including from mineral occurrence underground, mineral occurrence under and in water, and from brine and trees.
- **Union extraction capacity**: an aggregate of the maximum annual production volumes of extractive operations for ores, minerals, plant products and concentrates containing strategic raw materials, including processing operations that are typically located at or near the extraction site, located in the Union.
  - *Note target is for Union extraction capacity to equal 10% of consumption by 2030*
- **Mineral occurrences**: any single mineral or combination of minerals occurring in a mass or deposit of potential economic interest.
- **Reserves**: all mineral occurrences that are economically viable to extract in a particular market context.
- **Processing**: all physical, chemical and biological processes involved in the transformation of a raw material from ores, minerals, plant products or waste into pure metals, alloys or other economically usable forms, including beneficiation, separation, smelting and refining, and excluding metal working and further transformation into intermediate and final goods.
- **Union processing capacity**: an aggregate of the maximum annual production volumes of processing operations for strategic raw materials, excluding such operations that are typically located at or near the extraction site, located in the Union.
  - *Note target is for Union processing capacity to equal 40% of consumption by 2030*
- **Raw material:** a substance in processed or unprocessed state used as an input for the manufacturing of intermediate or final products, excluding substances predominantly used as food, feed or combustion fuel.
- **Strategic raw material**: raw materials, including in unprocessed form, at any stage of processing and when occurring as a by-product of other extraction, processing or recycling processes, listed in Annex I, Section 1.
  - *Note Annex I, Section 1 lists 17 raw materials*

Definitions used in this report

- **Exploration:** as defined by EU CRMA.
- **Mining:** extraction (as defined by EU CRMA) and processing (as defined by EU CRMA) typically located at or near the extraction site.
- **Refining:** processing (as defined by EU CRMA), excluding processing typically located at or near the extraction site.
- **Minerals:** solid, naturally occurring inorganic substances found in the Earth's crust. They have a unique chemical composition and crystal structure.
- **Metals:** elementary substances, such as gold, silver and copper. They are crystalline when solid and naturally occur in minerals.
- **Ore:** material from which minerals are extracted as the grade of the mineral is above the cutoff grade. The cutoff grade is the grade (concentration of mineral in the rock) above which it is economic to extract the mineral.
- **Waste rock:** mined rock that is not sent to the mill as it is below cut-off grade.
- **Tailings:** waste from processing stages at mine-site.
- **Critical Raw Materials (CRMs)**: the six raw materials which are the focus of this report – Copper, Nickel, Cobalt, Lithium, Graphite, Neodymium (in many cases the broader group of Rare Earth Elements are considered).
- **Rare Earth Elements (REEs):** 17 metals, including 15 lanthanides[1], scandium, and yttrium.
- **Magnetic REEs:** a subset of REEs comprising Praseodymium, Neodymium, Terbium, and Dysprosum.
- **Environmental impacts**: impacts related to GHG emissions, water use, acidification, tailings, and biodiversity.

Source: EU Critical Raw Materials Act; International Council on Mining and Metals; S&P Capital IQ Pro.

[1] Lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu),

B. ASSESSMENT METRICS FOR CRM SUSTAINABILITY IMPACTS

Categories	Sub-categories	Definition	Units	Low Risk	Medium Risk	High Risk
Climate	**Energy Use**	Total energy consumption to mine and process a metal	*GJ/tonne*	< 50	50 – 150	> 150
	Refining Grid Intensity	Weighted average grid carbon intensity of the regions refining minerals today	*gCO2/kWh*	<50	50 – 200	> 200
	Carbon Footprint	GHG emissions of mining and processing – mostly defined by the energy consumption and the energy mix	*tCO2-eq/tonne*	< 5	5 – 15	> 15
Water	**Water Consumption**	Process water consumption and energy water consumption – measure for the maximum freshwater intake	*m3/tonne*	< 25	25 – 100	> 100
	Water Stress	Share of mine production located in areas with high and extreme high-water stress and arid conditions	*Exposure to water stress*	< 10%	10 – 50%	> 50%
Pollution	**Acidic Waste**	Acid waste includes both liquid and solid materials that have acidic properties, typically defined by a pH level below 7	*Tonne moved/tonne*	< 50	50 – 200	> 200
	Acidification	Acidification is a measure of acidic pollution of land and water	*Tonne SO_2/tonne*	< 50	50 – 150	> 150
	Eutrophication	Eutrophication is a measure of nitrogen and phosphorus pollution of land and water	*Tonne PO43- /tonne*	< 10	10 – 20	> 20
Environment	**Rocks Displaced**	Mined rock that is not sent to the mill as it is below cut-off grade	*Tonne moved/tonne*	< 100	100 – 250	> 250
	Tailings Waste	Waste from processing stages at mine-site.	*Tonne moved/tonne*	< 25	25 – 50	> 50
	Biodiversity Risk	Share of production in high biodiversity risk areas	*% of production*	< 10%	10 – 50%	> 50%
Human Rights	**Human Rights**	Share of production in countries with low human rights rating/score based on fundamental rights assessment	*% of production*	< 10%	10 – 50%	> 50%
	Artisanal Mining	Share of artisanal and small-scale mining in total production	*% of production*	< 10%	10 – 50%	> 50%

Source: Systemiq analysis based on KU Leuven/EuroMetaux (April 2022), *Metals for Clean Energy: Pathways to solving Europe's raw materials challenge*; IEA (2024), *Global Critical Minerals Outlook 2024.*

B. ESTIMATED INTENSITY OF ENVIRONMENTAL IMPACT BY CRM

Low Risk
Mid Risk
High Risk

Key sustainability intensity metrics, *figures refer to global averages – high variability by production location & technology process*

		Climate			Water		Pollution			Environment			Human Rights	
CRM	**Technology**	**Energy Use**	**Refining Grid Intensity**	**Carbon Footprint**	**Water consumption**[1]	**Water Stress**[2]	**Acidic Waste**	**Acidification**	**Eutrophication**	**Rock Displaced**	**Tailings Waste**	**Biodiversity Risk**[3]	**Human Rights**[4]	**Artisanal Mining**[5]
		GJ/tonne	*gCO_2/kWh*	*tCO_2-eq/tonne*	*M^3/tonne*	*%*	*Tonnes/ tonne*	*kg SO_2-eq./tonne*	*kg P-eq./tonne*	*Tonnes/ tonne*	*Tonnes/ tonne*	*%*	*%*	*%*
Copper	Pyro/Hydro	24 – 37	467	5	10	38%	67	61	3	468	140	20%	28%	1%
Nickel	Sulphides	147	603	18[6]	133	23%	18	170 – 1,400	5 – 16	242	30	54%	31%	2%
	Laterites			69[7]										
Cobalt	Sulphate	*Na.*	533	5 – 13	230	12%	4	620	60	64	36	80%	80%	10%
	Metal			5 – 38										
Lithium (Carbonate)	Brine	13	531	3 - 8	15 - 50	75%	2	38	19	359	21	2%	14%	0%
	Spodumene	175		16 - 21	69 - 77									
Graphite	Natural	39	577	10 – 15	47	13%	*Na.*	*Na.*	*Na.*	*Na.*	9	*Na.*	*Na.*	*Na.*
	Synthetic	46		20 - 35	*Na.*	*Na.*	*Na.*	*Na.*	*Na.*	*Na.*	*Na.*	*Na.*	*Na.*	*Na.*
Neodymium	Leaching	*Na.*	607	18	200	13%	2,439	80	21	*Na.*	80	1%	64%	*Na.*

Source: KU Leuven/EuroMetaux (April 2022), *Metals for Clean Energy: Pathways to solving Europe's raw materials challenge*; F.I. Barre et al. (2024), *Limits to graphite supply in a transition to a post-fossil society*; CO2CARBON, *The road to industrial production of sustainable carbon materials;* Kelly et al, *(2021), 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.*

Note: Metrics per tonne refer to tonnes final metal produced. All numbers have been rounded to the nearest whole number. 1. Water consumption refers to process water consumption and energy water consumption. It is a measure for the maximum freshwater intake and is based largely on data from the Argonne GREET in the Appendix of the KU Leuven paper. | 2. Share of production in medium or high-water risk areas. | 3. Share of production in high biodiversity risk areas | 4. % of mine output in low human rights score countries | 5. Share of artisanal and small-scale mining. | 6. Class 1 Nickel. | 7. Class 2 Nickel. | Gradient shades were use for the cells where the values were given in range and both values belonged to different status in the legend | Some ranges reflect differences between end products (e.g., lithium hydroxide vs. lithium carbonate) or geographic variation (e.g., graphite: 14 in China, 24 in Inner Mongolia). "N/A" is used where data was unavailable, especially for graphite, where most impacts are in CO_2 and PM, resulting in many N/As.

C. OVERVIEW OF REVIEWED SUPPLY-SIDE TECHNOLOGIES (1/4)

We have reviewed innovative technologies above TRL ~5 with scope to reduce environmental impacts

Non-exhaustive, based on public info

Technology	Applicable CRM[1]	Description	Commercial status indicators	TRL
Application of AI to Geological Data	Li Cu Ni Co Nd C	• Applying AI and machine learning to geological data to expedite mineral discovery, and to optimise exploration drilling for identification and qualification of reserves	• There are many startups in this space, some of which are highly valued, e.g., KoBold metals at ~$1 bn (exploring 60+ projects) • EarthAI: 3 discoveries from 4 attempts (still at pre-feasibility)	7
Advanced Data Collection[2]	Li Cu Ni Co Nd C	• Using drones/advanced imaging, remote sensing, digital mapping technologies, and technologies which enable on-site ore analysis, to improve reserves identification and mine operations[1]	• Emesent, Ideon.AI, and OreExplore technology has been deployed at several sites, e.g., Ideon.AI at Vale, BHP, Teck, etc. • Several other active startups, e.g., MuonVision, Plotlogic, ALS Global	9
Surgical Drilling	Co Cu C	• Precision mining technique using advanced technology to target high-value ore (application focused on mining rather than exploration stage)	• Novamera's solution to be deployed at Great Atlantic ReSource' Canada gold mine in Canada	7
In-Situ Recovery	Li Cu Ni Co Nd C	• Materials recovered without digging • Main application is in-situ leaching – fluids injected into rock, minerals dissolved and pumped back	• In-situ leaching is mature but has not delivered consistently high recovery rates – several companies are looking to improve technology, e.g., Ekion: electronic extraction without drilling (early stage)	5 - 9 *Depending on tech*
New REE Deposits[3]	Li Cu Ni Co Nd C	• Ionic adsorbtion clay (IAC) contains REEs adsorbed to the clay minerals surface – loosely bonded REEs can be extracted • Extraction from heavy mineral sands (HMS) is a more mature technology	• Several companies pursing IAC extraction – Alvo Minerals developing the Bluebush IAC site in Brazil, Ionic Rare Earths constructing a demonstration plan in Uganda, Appia Rare Earths announced the discovery of an IAC rare earths deposit in Brazil • Number of HMS extraction companies are exploring REEs – Iluka building a refinery to process REEs, Base ReSource building a mine and refining plant at Toliara project in Madagascar	8

Source: Systemiq analysis based on Arthur D. Little (October 2023), *Securing Europe's cleantech, digital, and industrial future by fostering innovation across the critical minerals value chains*, World Materials Forum; Expert interviews, company websites, press research.

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1. From the priority list in this study – Copper, nickel, cobalt, lithium, graphite, neodymium | 2. Drones, remote sensing, digital mapping, and technologies which enable on-site ore analysis | 3. Ionic adsorption clay, heavy mineral sands

C. OVERVIEW OF REVIEWED SUPPLY-SIDE TECHNOLOGIES (2/4)

We have reviewed innovative technologies above TRL ~5 with scope to reduce environmental impacts

Non-exhaustive, based on public info

Technology	Applicable CRM[1]	Description	Commercial status indicators	TRL
Direct Lithium Extraction (DLE)[2]	Li	• Range of processes to selectively extract lithium from brine, which are more targeted than conventional extraction (involve pumping to the surface and evaporation) • Can be broadly categorised as **alumina adsorption, ion-exchange, solvent extraction, selective electrodialysis and electrochemical ion pumping**	• **Adsorption-type DLE has been commercially used for over 25 years**, starting with Livent in Argentina, followed by 5 Chinese producers in the late 2010s. New entrants for 2024-2026 include Eramet, Vulcan Energy, Compass Minerals, Rio Tinto, SQM, Albemarle, and ExxonMobil (partnering with Tetra Technologies on an A-DLE plant in Arkansas) • Among other DLE technologies, **ion-exchange** seems the most advanced, e.g., SunResin in China has 3 installed projects and is developing ~5 more • Other advanced DLE projects include Summit Nanotech in Argentina, Posco in Argentina's salt flat, EnergyX's membrane separation demo in Texas, and Lithium Harvest in North Dakota	3 - 9 *Depending on tech*
Bulk Ore Sorting	Li Cu Ni Co Nd C	• Using sensors to remove barren gangue (worthless rock) from a fully loaded conveyor belt based on the grade - increasing the grade that is processed	• MineSense's ShovelSense technology has been deployed in South America, e.g, Capstone Copper's Mantos Blancos copper mine in Chile • HPY Sorting and NextOre solutions have been deployed at several sites	9
Novel Rock Comminution	Li Cu Ni Co Nd C	• Crushing and griding rocks using advanced technologies, e.g., pulsed power shockwaves	• AngloAmerican has deployed 'smart blast design' at a pilot plant in Chile • Technology providers like i-Rox and Selfrag are yet to develop commercial-scale application	6
Efficient Spodumene Leaching	Li	• Process to extract lithium from spodumene ore via leaching without preliminary calcination	• Lithium Australia has piloted its LieNa process (spodumene reacts with caustic soda to form lithium sodalite, from which lithium is recovered) • Metso has piloted an alkaline leach process, which they are looking to extend to other hard rock minerals like petalite and zinnwaldite	8

Source: Systemiq analysis based on Arthur D. Little (October 2023), *Securing Europe's cleantech, digital, and industrial future by fostering innovation across the critical minerals value chains*, World Materials Forum; Expert interviews, company websites, press research.

[1] From the priority list in this study – Copper, nickel, cobalt, lithium, graphite, neodymium

C. OVERVIEW OF REVIEWED SUPPLY-SIDE TECHNOLOGIES (3/4)

Non-exhaustive,
based on public info

We have reviewed innovative technologies above TRL ~5 with scope to reduce environmental impacts

Technology	Applicable CRM[1]	Description	Commercial status indicators	TRL
Primary Sulfide Leaching[2]	Cu	• Leaching extended to primary sulfide ore bodies, where it has traditionally been applied to oxide or secondary sulfide ore bodies • 3 broad types are catalysts, high temperature bio-leaching, and copper chloride leaching • Has been explored by the industry for ~20 years, but technological developments could lead to deployment at greater scale in short-term	• BHP are progressing chalcopyrite leaching at all copper assets in South America following positive results at the Spence mine in Chile • Rio Tinto's Nuton (bio-leaching solution) is completing feasibility studies and has agreed several partnerships • Atalya is constructing an industrial-scale plant to use Lain Tech's solutions, following demonstration at pilot phase • pH7 technologies is developing new technology for primary sulfide leaching – pilot plant at Lower Mainland in Canada	6 - 8 *Depending on tech*
Grind-Circuit Roughing	Cu	• Recovering particles directly from the grind circuit, as a sponge attracts and holds mineralised particles. This reduces the recirculating load in ball mills, increasing mill throughput and efficiency	• A FEED study is ongoing for full implantation of CiDRA's grind circuit roughing technology at OZ Minerals' Carrapateena mine in Australia	7
H_2 for Reduction	Cu	• H_2 used as a reduction agent in smelting (current agents include diesel, ammonia, etc.)	• Aurubis is developing H_2-capable copper anode furnaces • KofilnSpA's technology uses green H_2, pilot plant operational	5
Coarse Particle Recovery	Cu	• Flotation and recovery of larger mineral particles (typically >150 microns) during flotation, which has traditionally been limited to finer particles	• Eriez hydroflotation units for coarse particle recovery have been deployed at many sites, e.g., AngloAmerican is constructing a plant at its Quellaveco copper project in Peru following a demonstration plant at the El Soldado copper mine in Chile	8
Novel Electrochemistry Applications	Li Cu Ni Co Nd C	• Electrochemistry relies solely on electricity as an input to efficiently extract and refine CRMs • Electrochemistry can reduce chemical use, eliminating heat and waste streams	• Electrochemical lithium conversion is in use at Vulcan's integrated plant, with Mangrove Lithium focusing on converting lithium chloride to lithium hydroxide, launching commercial pilot in 2025 in Vancouver • SiTration is testing nanofiltration for tailings reprocessing, while Lithios and Electralith are trialing single-step electrochemical DLE and refining. These early-stage technologies also hold potential for recycling	3 - 7 *Depending on tech*

Source: Systemiq analysis based on Arthur D. Little (October 2023), *Securing Europe's cleantech, digital, and industrial future by fostering innovation across the critical minerals value chains*, World Materials Forum; Expert interviews, company websites, press research.

1. From the priority list in this study – Copper, nickel, cobalt, lithium, graphite, neodymium | 2. Can be applied to mine tailings, but since application is broader this has not been placed in *Re-processing* bucket

C. OVERVIEW OF REVIEWED SUPPLY-SIDE TECHNOLOGIES (4/4)

We have reviewed innovative technologies above TRL ~5 with scope to reduce environmental impacts

Non-exhaustive, based on public info

Technology	Applicable CRM[1]	Description	Commercial status indicators	TRL
REE Efficient Separation	Nd	• Range of column-based processes to separate REEs • Include **solvent exchange** (blending aqueous and organic solutions), **continuous ion exchange**, and **high-pressure liquid chromatography (HPLC)**	• Ucore's (solvent exchange) demonstration plant is operational – aiming to fully commercialise in near-term • Texas Mineral ReSource is developing the Round Top project in Texas with USA Rare Earth – planning to deploy continuous ion exchange technology, and be operational by 2025 • REEtec (HPLC) is planning for its commercial plant in Norway to be operational by 2025	7 - 8 *Depending on tech*
Novel Graphite Production Methods[2]	C	• Range of processes to produce graphite • Tokai Cobex - directly heating coke blocks rather than heating the medium • CarbonScape – 'biographite' manufactured using timber industry by-products as feedstock • Molten Industries, Hazer Group, Hycamet - pyrolysis of methane to produce H2 and graphite • UP Catalyst - uses carbon captured from industry as a feedstock	• Tokai Cobex demonstration plant in France operational since 2022 • Hazer Group's demonstration plant in Australia is operational and Hycamet and BASF are building plants in Finland and Germany respectively • CarbonScape's pilot plant is operational, aiming for commercial plant to be operational by 2029 • UP Catalyst is developing a pilot plant • Urbix is completing its commercial scale demonstration plant and aims to expand production capacity to 28.5 ktpa by 2025	5 - 8 *Depending on tech*
Mine Tailings & Processing Waste Utilisation	Li Cu Ni Co Nd C	• Range of technologies to extract metals from tailings and processing waste • CleanTeq Water recovers metal contained in process waters and tailings dams • VTT recovers sodium sulphate wastewater into sodium hydroxide and sulphuric acid	• CleanTeq Water is at commercial scale • BluestOne's demonstration facility is operational and commercial production planned from 2025 • KMX Technology has entered LOIs with Cornish Lithium and CleanTec Lithium but technology still under development	3 - 5 *Depending on tech*

Source: Systemiq analysis based on Arthur D. Little (October 2023), *Securing Europe's cleantech, digital, and industrial future by fostering innovation across the critical minerals value chains*, World Materials Forum; Expert interviews, company websites, press research.

[1] From the priority list in this study – Copper, nickel, cobalt, lithium, graphite, neodymium | [2] China Minemetals announced a new technology to produce high-purity graphite, but minimal public information

D. SELECTED INNOVATION: SUMMARY OF SUPPLY & ENVIRONMENTAL IMPACTS

Innovation	TRL	Commercial Development	Supply Impact	Environmental Impact
Direct Lithium Extraction	**3-9**	Adsorption: commercial pilots Other techs: demo/pilot plant	DLE could supply **15% of global demand by 2035** if successful pilots demonstrate consistent production at scale by 2025. EU DLE projects could contribute 52 kt LCE by 2035 from 2 current planned geothermal projects – equivalent to 15% of total planned domestic EU lithium mining capacity and **7% of total projected EU demand**	DLE technologies are **more energy and reagent intensive than incumbent processes** (brines and hard rock mining), and typically consume more processing water than production from brine (not vs hard rock mining); however, achieving **near-zero impact DLE** is possible by reinjecting brine, recycling water, and co-producing geothermal energy
Novel Graphite Production	**5-8**	Industrial scale for LWG route[1] Early pilot stage for bio-graphite, pyrolysis	By 2035, novel synthetic graphite production could **supply 40% of total projected EU demand** from multiple currently planned projects (additional EU supply also planned from natural graphite projects in Sweden and 2 conventional Chinese plants in the Nordics)	New synthetic graphite production methods could **significantly reduce emissions, achieving near-zero emissions graphite** compared to the current standard for synthetic graphite, which produces around 15-25 kg CO_2 per kilogram
Primary Sulfide Leaching	**7-9**	Some techs starting to be deployed at mine sites	Production at scale remains challenging, but PSL of **waste rock could meet up to 12% global copper demand by 2035 (**assuming the technology is applied at 10 lowest-cost mines located in suitable climates and with primary sulfide ores present in deposit)	May reduce need for new mines by increasing productivity. Where PSL replaces production of concentrate for smelting, production is less energy and water-intensity (bio-leaching tailings consumes **50% less energy and water** compared to pyrometallurgical production)
Application of AI to Geological Data	**7**	Used for some discoveries and exploration sites	Impact uncertain – but could generate **new discoveries and expedite exploration, potentially enabling diversification of supply**. Overall impact expected to be limited due to inconsistent data and long permitting timelines.	Targeted discovery and optimised exploration drilling will reduce overall drilling requirements – **lowering energy and waste impacts**
Novel Rock Comminution	**6**	Early pilot stage	Improved efficiency could enable more rapid supply expansion, but **deployment by 2035 likely constrained** as requires highly expensive equipment with long lifetimes to be replaced at end-of-life.	Pulse power can reduce energy intensity of crushing & grinding by up to 80% - phased adoption of the tech could lead to a **20% reduction in energy consumption** for comminution for copper production by 2035
Mine Tailings Utilisation	**3-5**	Early lab/demo stage for most innovators	New technologies currently under testing at pilot stage, with potential deployment on both historical and active tailings. However, technologies remain at **early-stage development** and significant barriers to overcome for deployment at scale by 2035	The impact of tailings reprocessing largely depends on the technology chosen—conventional methods, nanofiltration, or biochemical approaches. These options hold **significant potential to lower ecotoxicity and reduce the demand for new mining operations**
Novel Electrochemistry Applications	**3-7**	Early lab/demo stage for most innovators	New applications remains mainly **at early development stages** at present with significant barriers to overcome for deployment at scale by 2035	Electrochemical methods could bring a notable environmental impact by replacing heavy chemical processes, **reducing waste, offering modularity, and complementing expanding DLE technologies**

Note: 1. LWG – Lengthwise Graphitisation: see chapter 4 for further information.

SYSTEMIQ

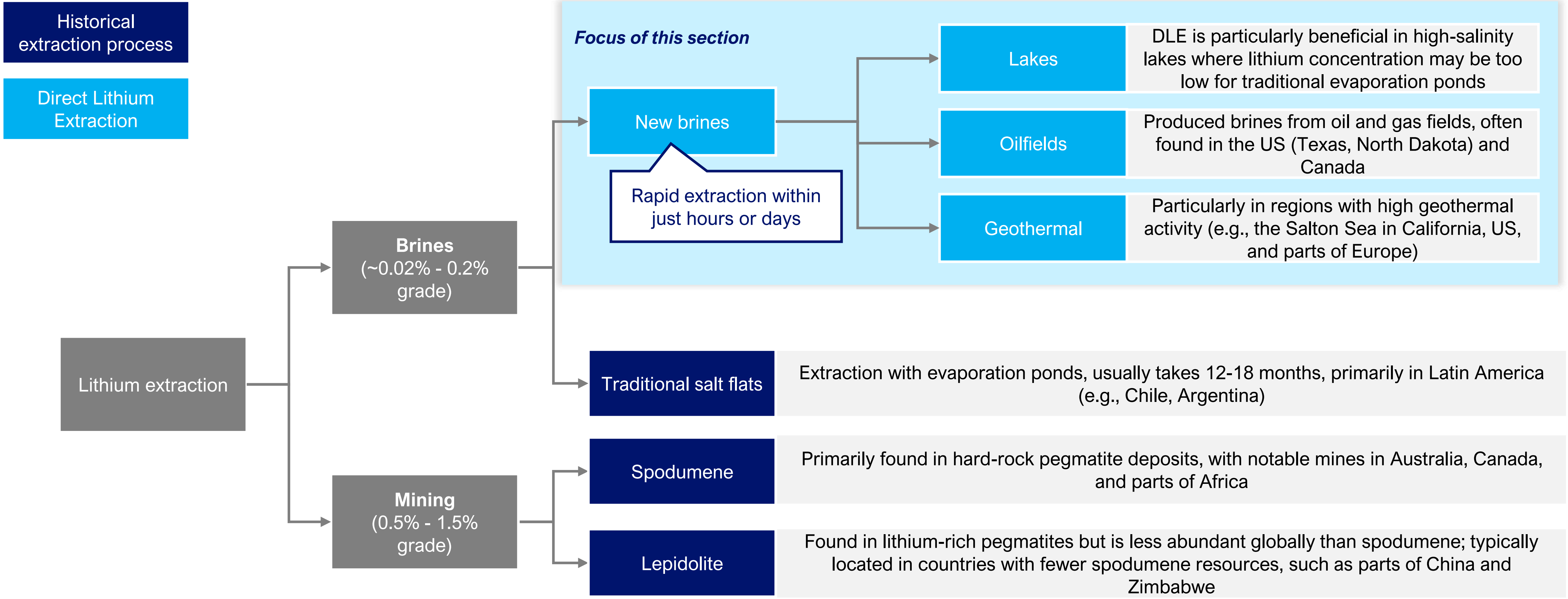
D. SELECTED INNOVATIONS: CHALLENGES AND APPLICABILITY TO EU

Innovation	Cost Outlook	Key Risks	EU Applicability
Direct Lithium Extraction	**DLE costs vary by location and technology:** DLE projects typically in the 2nd/3rd quartile of lithium cost curve[2] – with higher upfront capex expected to be offset by lower unit costs due to improved recovery rates	**DLE's growth is dependent on the results of commercial pilots set to launch in the next 2 years**; with important financial, market, technological and regulatory risks to overcome. Additionally, new battery chemistries like sodium-ion present a long-term demand risk for lithium.	**The EU holds lithium potential, especially in geothermal brines from areas like the Upper Rhine Graben**, with high Li concentrations (150+ mg/l). Extraction feasibility depends on brine salinity, temperature, and rock type, making targeted exploration and economic analysis essential.
Novel Graphite Production	Lack of data on production costs at scale but companies claim **cost competitiveness** with existing incumbent processes can be achieved in future under certain conditions (e.g., lower energy costs etc.)	**Market risk** from potential **demand peak** before 2035 if alternatives partially replace graphite use in batteries; **price risk** from existing low-cost supply (especially from China), requires **long-term offtake commitment**	Several major announced projects in EU, but could require support to bridge **cost differential with higher emissions incumbent** supply for new technologies
Primary Sulfide Leaching	Cost outlook uncertain as **applicability varies by sub-technology and there is limited data available**. Data on bio-leaching tailings indicates comparable Capex but higher Opex compared to conventional pyrometallurgy	Despite 10-20 years of development, **PSL has yet to deliver high-enough recovery rates to justify widespread at-scale deployment,** and site-specific engineering can be costly when construction/redesign of leach circuits is required	At-scale deployment in the EU unlikely as technologies developed to-date have been less effective in **colder climates**[2]
Application of AI to Geological Data	Total exploration cost could be reduced through more effective deposit prediction, and **AI-enhanced exploration drilling can reduce exploration spending by ~25%,** construction Capex by 5%, and lifetime Opex by 15%	Improved discovery rates will be **constrained by the quality of existing geological data**. Other barriers to mine development, e.g., long permitting timelines, still need to be overcome.	In theory high due to good quality free-access EU geological data – but **exploration drilling is challenging in the EU relative to other regions** due to permitting barriers
Novel Rock Comminution	Pilots indicate pulse power can generate **~20% Opex savings**, but technology needs to be proven at scale	Technology still at pilot stage, and comminution is the most capex-intensive mining stage– **companies reluctant to deploy early-stage technology and amend flow sheets**	Potential to trial at EU copper mining sites and implement when existing equipment lifetimes expire
Mine Tailings Utilisation	Unproven technologies require **demonstration at scale**; costs likely to be high in short-term as technology matures (new supply chains for specialised equipment required)	Proving technical performance, consistency and **economic viability at scale**, and managing liability and permitting challenges (in shorter-term, access to ore samples constrains progress)	Breakthrough technologies are unlikely to scale in the EU by 2035 due to development timelines, but **conventional tailings management methods** can still deliver significant impact, with tailings from active mines in the EU holding up to 100 kt p.a. of copper content
Novel Electrochemistry Applications	**Electrochemical technology costs are uncertain due to low TRL and lack of commercial-scale plants.** Major expenses include Capex (membranes, electrodes) and potential high maintenance costs	Electrochemical solutions face key risks beyond Capex and low TRL, including the need to develop **new equipment supply chains** and the linear cost increases from electrolyser stacking, which offer less economies of scale compared to traditional refining processes	**EU applicability is high if scaled**; electrochemistry could minimise acid, reagent, and waste usage, offering a cleaner alternative to incumbent refining methods and generating synergies with CRM recycling (that can use similar processes)

Note: 1. Goldman Sachs (2023), *Direct Lithium Extraction: A potential game changing technology* | 2. The optimum temperature for leaching is 30-40C and is particularly challenging in winter temperatures. Litvinov et al (2023) *Increasing the Duration of Dump Leaching of Copper Under Winter Conditions.*

D. DIRECT LITHIUM EXTRACTION | APPLICABILITY OF TECHNOLOGY

Direct lithium extraction (DLE) refers to several new technologies that can unlock production from lower lithium content brines such as oilfields, geothermal and lake resources, enabling an expansion in overall supply within much faster timeframes



Historical extraction process

Direct Lithium Extraction

Focus of this section

Lithium extraction

Brines
(~0.02% - 0.2% grade)

New brines

Rapid extraction within just hours or days

Lakes	DLE is particularly beneficial in high-salinity lakes where lithium concentration may be too low for traditional evaporation ponds
Oilfields	Produced brines from oil and gas fields, often found in the US (Texas, North Dakota) and Canada
Geothermal	Particularly in regions with high geothermal activity (e.g., the Salton Sea in California, US, and parts of Europe)
Traditional salt flats	Extraction with evaporation ponds, usually takes 12-18 months, primarily in Latin America (e.g., Chile, Argentina)

Mining
(0.5% - 1.5% grade)

Spodumene	Primarily found in hard-rock pegmatite deposits, with notable mines in Australia, Canada, and parts of Africa
Lepidolite	Found in lithium-rich pegmatites but is less abundant globally than spodumene; typically located in countries with fewer spodumene resources, such as parts of China and Zimbabwe

Source: Systemiq analysis based on expert interviews.

D. DIRECT LITHIUM EXTRACTION | OVERVIEW OF DIFFERENT DLE TECHNOLOGIES

There are broadly 6 DLE technologies with associated pros and cons; adsorption is currently the most mature

Technology	TRL	Description	Pros	Cons	Selected Companies
Adsorption	**7-9**	• A process where heated brine's LiCl molecules are physically adsorbed onto solid materials (typically aluminate-based), then released using freshwater, offering potential for efficiency improvements through adsorbent material optimisation	• Demonstrated in conjunction with pre-evaporation ponds • Requires less reagents • Low operating costs	• Post-treatment required due to low recovery rates • Significant freshwater demand • Requires temperatures >50°C	arcadium lithium SUNRESIN Standard Lithium
Ion-exchange	**5-7**	• This ambient-temperature process chemically absorbs lithium ions onto solid media, then strips them using dilute acid, presenting a lower-energy alternative to heat-dependent methods	• High selectivity and recovery rates • Minimal freshwater usage • Simple operating process	• Requires large amounts of base and acid • High operating costs • Degradation of ion-exchange media	Lilac solutions E3 LITHIUM GEOLITH Sustainable Lithium Solutions
Membrane filtration	**5-6**	• A continuous, pressure-driven process utilising specialised membranes for selective lithium-ion extraction, with variants including ultrafiltration, microfiltration, nanofiltration, and reverse osmosis, enabling high-volume production with minimal chemical inputs.	• Continuous process • High selectivity and recovery rates • Possible to recycle water	• Pretreatment is required • Possible membrane damage due to brine impurities • Elevated Capex and Opex	SUMMIT NANOTECH 中信 CITIC
Solvent extraction	**4-6**	• Employs liquid organic solvents to directly extract lithium from brine, with lithium recovery facilitated by freshwater, offering potential for increased efficiency through the development of highly selective, eco-friendly solvents	• High lithium selectivity and no additional post-extraction steps • Suitable for continuous operation	• Environmental and health risks from organic solvents • Equipment degradation and high operational costs	Adionics The Advanced Ionic Solution SOLVAY
Selective electrodialysis	**4-5**	• Harnesses electric fields to selectively remove lithium ions from brine using ion-selective membranes • Especially effective for brines with low lithium concentrations	• Low reagent use • Effective in brines with low lithium concentrations • Simple process set-up	• Energy-intensive due to high electricity demands • Membrane costs and pretreatment increase cost	ENERGYX posco
Electrochemical ion pumping	**3-4**	• This reagent-free process uses electrochemical devices with specialised electrode materials for reversible lithium-ion uptake and release • Opportunities for breakthrough efficiencies through advancements in electrode technology	• Environmentally friendly with no reagent usage • Simplified system architecture	• Long-term reliability and efficiency remain underexplored.	中南锂业 CENTRAL SOUTH LITHIUM

Source: Systemiq analysis based on International Lithium Association (2024), *Direct Lithium Extraction (DLE): An Introduction;* expert interviews; press releases

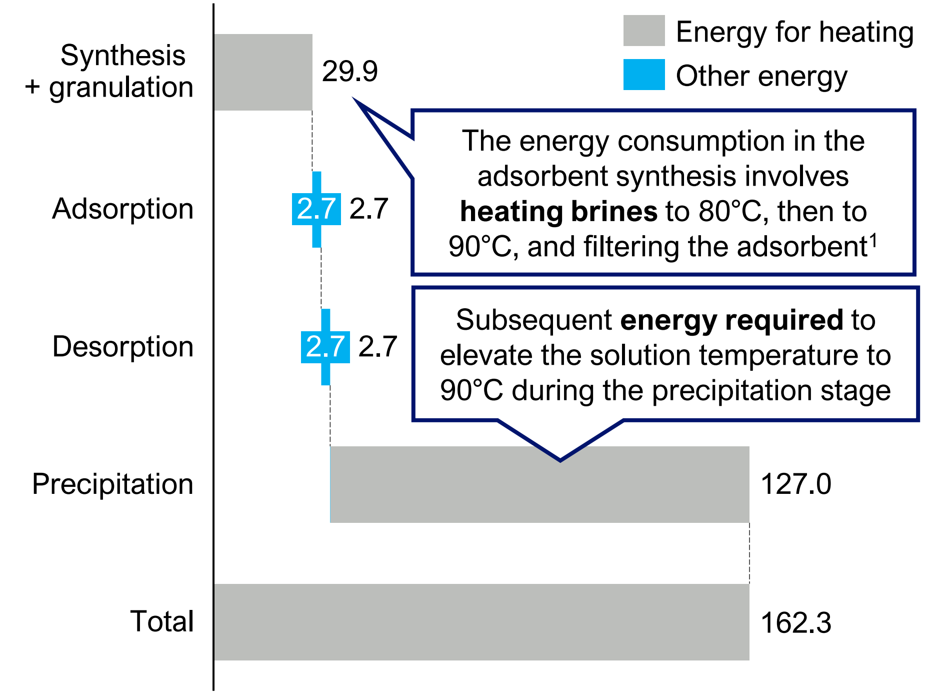
Note: Technology are classed against their maturity in DLE adoption – Adsorption being the closest technology to commercial development at present. TRL - Technology Readiness Level..

D. DIRECT LITHIUM EXTRACTION | GEOTHERMAL COPRODUCTION

Circular models that recycle brine water and utilise geothermal heat allow some DLE startups to achieve near net-zero emissions and a positive energy balance – outperforming conventional extraction in both water use and CO_2 footprint

Over 95% of total energy use in DLE adsorption process is for heating brines to reach optimal temperatures…

Breakdown of energy inputs in DLE adsorption process, GJ/tonne LCE



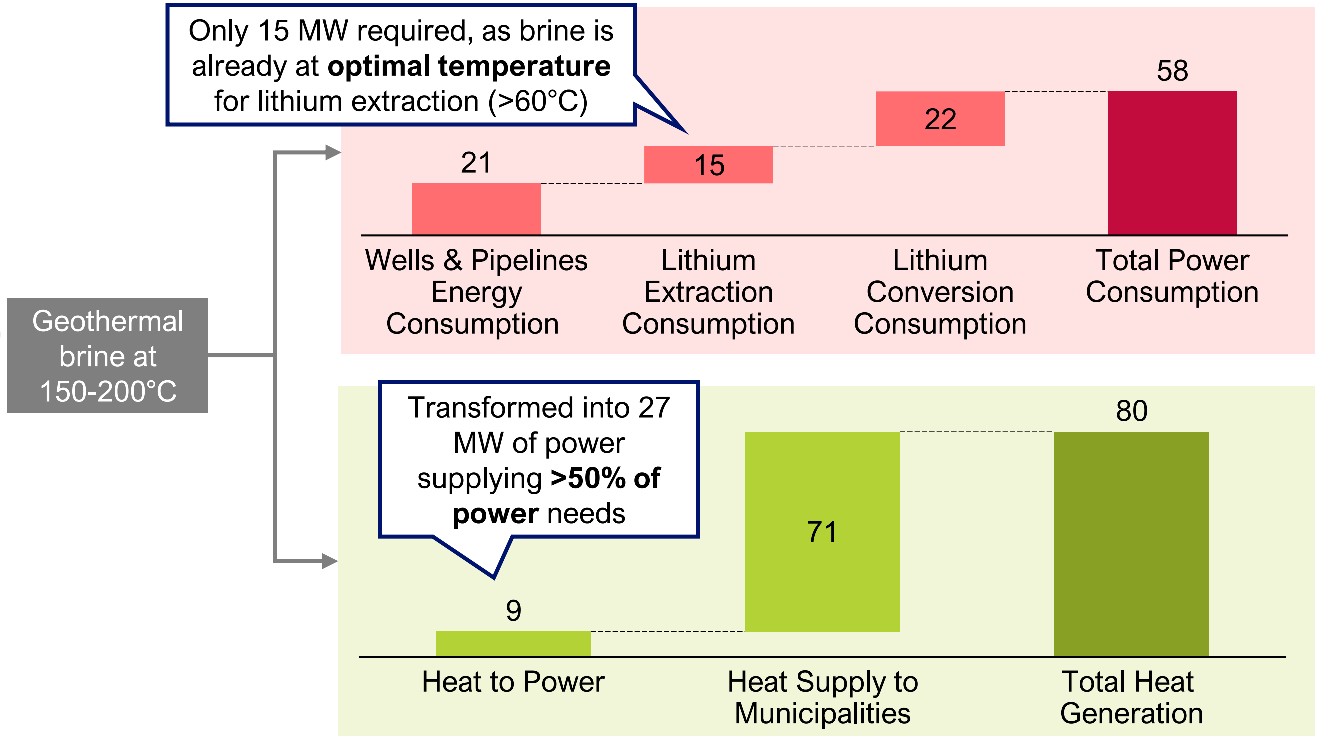
The energy consumption in the adsorbent synthesis involves **heeating brines** to 80°C, then to 90°C, and filtering the adsorbent[1]

Subsequent **energy required** to elevate the solution temperature to 90°C during the precipitation stage

… but using geothermal or oilfield brines provides opportunity to re-use existing heat in brines, reducing the operational footprint and enabling net-positive renewable energy production

Breakdown of energy inputs in a geothermal DLE adsorption process, MW

Illustrative



Only 15 MW required, as brine is already at **optimal temperature** for lithium extraction (>60°C)

Transformed into 27 MW of power supplying **>50% of power** needs

Source: Systemiq analysis based on S. Nikfar et al. (2025), *Unlocking sustainable lithium: A comparative life cycle assessment of innovative extraction methods from brine;* J. Kelly et al. (2021), *Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resource and their use in lithium-ion battery cathodes and lithium-ion batteries;* Expert interviews, company websites, press research.

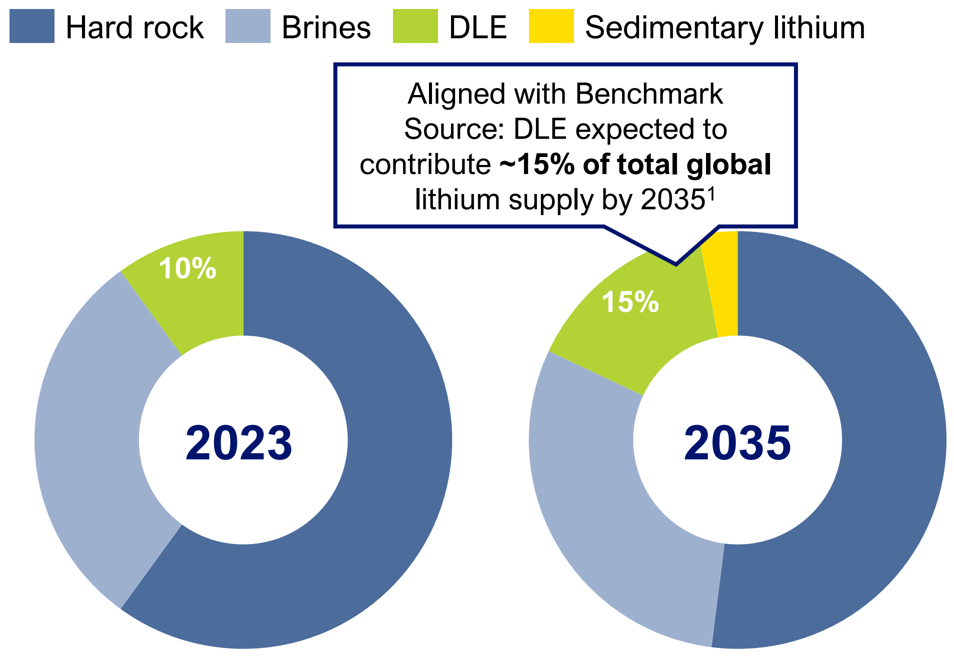
Note: LCE for lithium carbonate equivalent. Energy balance on the LHS for a 24,000 Lithium hydroxide plant from an alumina adsorption startup exploiting geothermal brines and extracting 80 MW of heat alongside lithium brines. 1. Adsorbent produced separately and added to heated brine during process.

D. DIRECT LITHIUM EXTRACTION | SUPPLY IMPACT

DLE is an emerging but uncertain technology, potentially supplying 15% of lithium globally by 2035 from new resources if commercial pilots launch by early 2025 – but several key challenges need to be overcome

DLE projected to supply ~15% of global lithium output by 2030-2035…

Lithium production capacity by source type and year, %



Aligned with Benchmark Source: DLE expected to contribute **~15% of total global** lithium supply by 2035[1]

… but technology still significant technical challenges and remains unproven at commercial scale

1. **Geological risk:** of determining volume and grades of resource and associated economic viability of extraction
2. **Technological risk**: from engineering and operational challenges associated with developing first-of-a-kind facility
3. **Market risk**: from lithium global price volatility and difficulty in securing long-term offtake agreements
4. **Financial risk:** to secure financing to cover high capital costs for commercial production at scale
5. **Regulatory risk:** from complex permitting process and associated project delays

Source: Systemiq analysis based on IDTechEx (2024), *Direct Lithium Extraction 2025-2035: Technologies, Players, Markets and Forecasts*; Benchmark Source (2024), *Rise of DLE will open up new source of lithium supply this decade;* Expert interviews, company websites, press research.

D. NOVEL GRAPHITE PRODUCTION | OVERVIEW OF NEW TECHNOLOGIES VS. INCUMBENTS

Novel methods for producing graphite offer lower emissions vs incumbent natural or synthetic processes but at lower TRL

🟦 Novel

Production Route	TRL	Description	Pros	Cons	Selected Companies
Natural Graphite	9	Graphite extracted directly from **natural ore deposits**, then separated using **flotation process** based on hydrophobic properties, followed by **high-temperature heating** (up to 1500°C) to purify, and **jet milling** to achieve fine particle sizes	• Lower emissions compared to synthetic graphite • Widely adopted established process	• Production limited to available natural resource • Reliant on **open-pit mining** (social acceptability issues in EU)	talga BGV GROUP MANAGEMENT SYRAH RESOURCES
Synthetic Graphite *(Acheson)*	9	Process involves **high-temperature heating** (around 3000°C) of **petroleum coke** or other carbon source in **crucibles**, with heating durations of up to a month	• Ensures consistent **battery-grade quality** • Mainstream scalable technology (>80% of today's production)	• Extremely high energy demand and **GHG emissions** (due to heating requirements and use of crucibles) • Long **production cycles** (~ 1 month)	璞泰来 PUTAILAI 杉杉科技 Shanshan Technology
Synthetic Graphite *(Lengthwise graphitization)*	9	Utilises **flotation** for mineral separation, followed by **forming and baking** stages – instead of traditional crucibles, the Joule effect is employed for **direct heating** within an enclosed environment, significantly reducing the heating timeframe to several days	• Lower **energy consumption** (-75%) and emissions relative to Acheson route • Faster **production cycle** (<1 week)	• Complex process requiring technological capabilities (LWG) • Expensive **specialised equipment** required	TOKAI COBEX
Synthetic Graphite *(Closed induction furnace)*	8	A **closed-furnace technology** transforming petroleum coke into high-quality graphite. Limited loss of energy and reduced material use ensures resource efficiency	• Lower **energy consumption** and emissions relative to Acheson route • Lower use of **raw materials** and **consumables**	• New technology needing to scale with higher **investment costs** at outset	Vianode
Bio-Graphite	7	Derived from **renewable biomass s**ource like **wood chips** - emerging process allows for replacement of fossil fuels in graphite production	• **Low-cost feedstock** (feedstock accounts for 20% Opex vs.40-60% for other routes) • **Negative CO_2 emissions** possible, provided sustainable feedstock	• Currently limited to **pilot-scale** production • Potential variability risk in product quality if feedstock inputs not consistent	CarbonScape
Methane Pyrolysis[1]	5-6	Process begins with **methane** (sourced from natural gas or biogas) subjected to **high-temperature pyrolysis –** at ~1000°C, methane (CH_4) splits into **hydrogen gas (H_2)** and **solid carbon** in the form of high-purity graphite	• Dual output of **hydrogen and high-purity graphite** • **No direct CO_2 emissions** from process, potentially **negative emissions** if biogas is used as a feedstock	• Limited **infrastructure in place** for widespread adoption • Currently limited to **pilot-scale** production	MOLTEN hycamite

Source: Systemiq analysis based on Expert interviews, company websites, press research.

Note: Non-exhaustive list of production routes, the routes in blue in the table refer to novel graphite production routes. 1. Also known as turquoise pyrolysis.

D. PRIMARY SULFIDE LEACHING | POTENTIAL APPLICATIONS BY MINE AND RESOURCE

Primary sulfide leaching (PSL) can be applied to waste stockpiles, tailings, or newly mined rock – with pros and cons for each; application differs depending on incumbent production routes

✓ Advantage ✗ Challenge

Application by Resource Type	**Application by Mine Type** *(if primary sulfide ores present in deposit)*	
	Mines currently producing copper from leaching oxide ores (including mines co-producing from sulfide ores)	**New mines OR existing mines currently only producing copper from sulfide ores through pyrometallurgy**
PSL of mineralised waste in existing waste stockpiles or in waste rock[1] from ongoing operations	✓ Can utilise existing leach circuits[2] – hence most promising for initial application. **Of existing ~5 Mt cathode copper capacity, ~2 Mt is idle** ✓ No additional mining ✓ Utilise mineralised waste ✗ Waste rock has low-grade ✗ Challenging if waste rock is backfilled as mines will not have built up stockpiles[3]	✗ Requires new leach circuits – high recovery rates necessary to justify capex[5]. ✓ **However, construction generally has significantly lower capex and timelines to operation are shorter and less uncertain relative to pyrometallurgy** ✓ No additional mining ✓ Utilise mineralised waste ✗ Waste rock has low-grade ✗ Challenging if waste rock is backfilled
PSL of existing stored tailings[4] or fresh tailings from ongoing operations	✓ Can utilise existing leach circuits ✓ No additional mining ✓ Utilise tailings – lower overall wate ✗ **Tailings cannot be leached on their own as they are very fine** – requires agglomeration with other material to ensure stability ✗ May be challenging to safely access tailings in tailings dams	✗ Requires new leach circuits ✓ No additional mining ✓ Utilise tailings – lower overall waste ✗ **Tailings cannot be leached on their own as they are very fine** – requires agglomeration with other material to ensure stability ✗ May be challenging to safely extract from tailings dams
Mining additional ore for PSL at existing mines	✓ Can utilise existing leach circuits ✓ Unlock new ore deposits that were previously below cut-off grade	✗ Can utilise existing leach circuits ✓ Unlock new ore deposits that were previously below cut-off grade – **enables extension of mine lifetimes** ✓ Alternative to concentrate production – **elimination of smelting reduces energy and water impacts[6]**
Mining ore for PSL at new mines		✓ Unlock new ore deposits that were previously below cut-off grade ✓ **Mine can come online faster as construction of leach circuits is faster** than construction of concentrators ✓ Alternative to concentrate production
	SX-EW plants produce refined copper, usually on-site, whereas the dominant process for sulfides produces concentrate, usually exported for refining	

Source: Goldman Sachs (March 2024) *Copper Leaching Breakthrough Technologies;* Expert interviews.

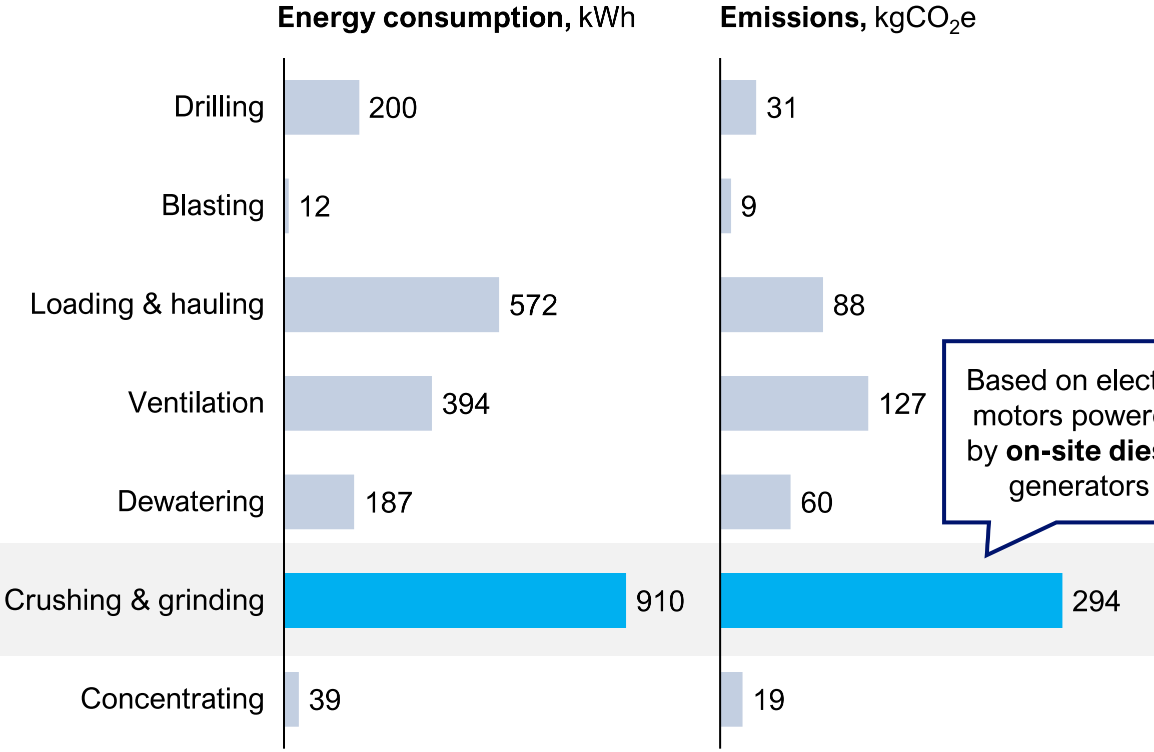
Note: 1. Mined rock that is not sent to the mill as it is below cut-off grade. | 2. Unlikely to be able to use existing oxide leach pads, however can utilise occupied space for new leach pads, and Solvent Extraction and Electro-Winning (SX-EW) facilities. | 3. Backfilling is where mine waste is used to fill void opening created during mining. Waste may be combines with additives to increase its strength. | 4. Waste from processing stages at mine-site. | 5. Note that some concentrate-producing mines previously produced from oxide ores, so have leach circuits that could be re-started. | 6. Note that in some cases life-cycle emissions may be similar/greater with leaching due to the impact of chemical reagents.

D. NOVEL ROCK COMMINUTION | ENVIRONMENTAL IMPACT

Pulse power technology can reduce energy demand at the most energy-intensive mining step; current focus is on copper production but in theory applicable to all comminution processes

Crushing and grinding account for almost 50% of total emissions of copper production…

Environmental impact by mining/processing stage per tonne copper concentrate



Based on electric motors powered by **on-site diesel** generators

… but electricity based pulsed power shockwave technology offers 50-80% reduction in energy consumption relative to existing SAG and ball mills

Process Description

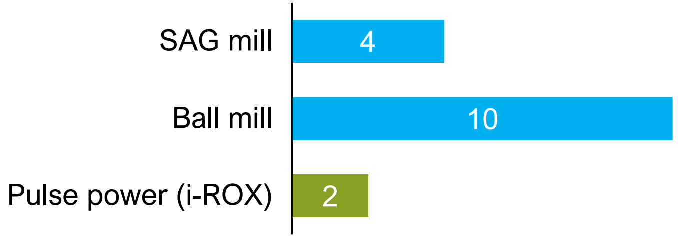
Incumbent

- Following blasting and transportation – ore is transported the mill
- The SAG mill[1] grinds material from ~150 mm particles to ~10 mm, and ball mill crushes material to ~0.1 mm
- SAG mill – rotating cylinder which grinds particles using steel balls and rock particles
- Ball mill – rotating cylinder which crushes particles using steel or ceramic balls

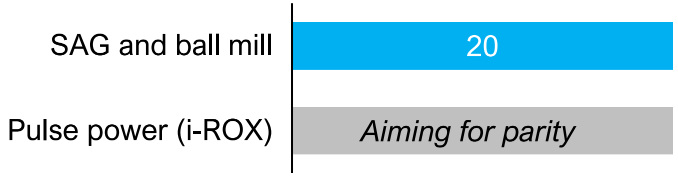
Pulse power

- Pulsed power breaks rock from the inside

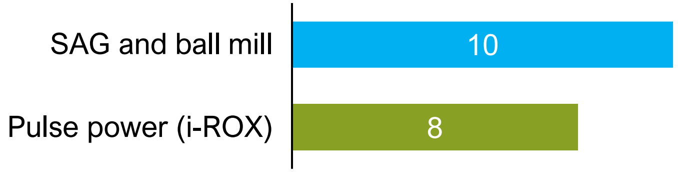
Energy consumption, kWh/tonne copper ore processed



Capex, $/tonne copper ore processed/year



Opex, $/tonne copper ore processed



Source: Norgate and Haque (2010) *Energy and greenhouse gas impacts of mining and mineral processing operations;* Thunder Said Energy; i-ROX; Expert interviews, company websites, press research.

Note: 1. SAG - semi-autonomous grinding mill.

D. TAILINGS REPROCESSING TECHNOLOGIES | SUPPLY POTENTIAL

Copper tailings represent a significant untapped resource, with historical and newly generated tailings to 2035 estimated to contain around 300 mn tonnes of copper – exceeding projected cumulative primary copper supply to 2035

Copper tailings reprocessing unlocks significant circular resource potential…

Building materials: transform tailings sands into valuable products for building/road materials

Landforms: Converting tailings into a landform for a specific use

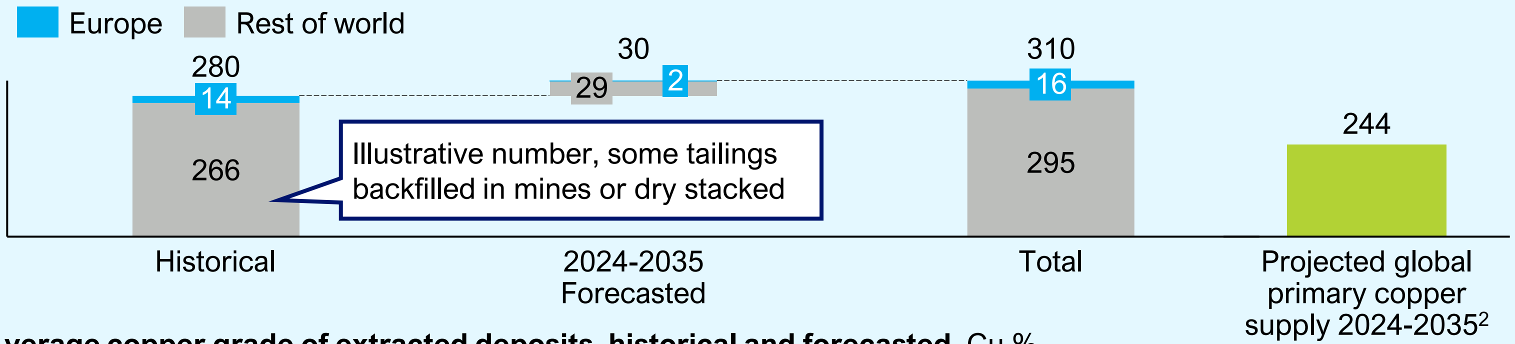
Materials: Reprocessing the tailings to extract value from the residual metals and minerals

The potential for recovery of CRMs from sources such as tailings, waste rock, coal ash, acid mine drainage and ore-processing facilities is currently difficult to estimate.

However, interest in these sources is growing, particularly as copper grades continue to decline.

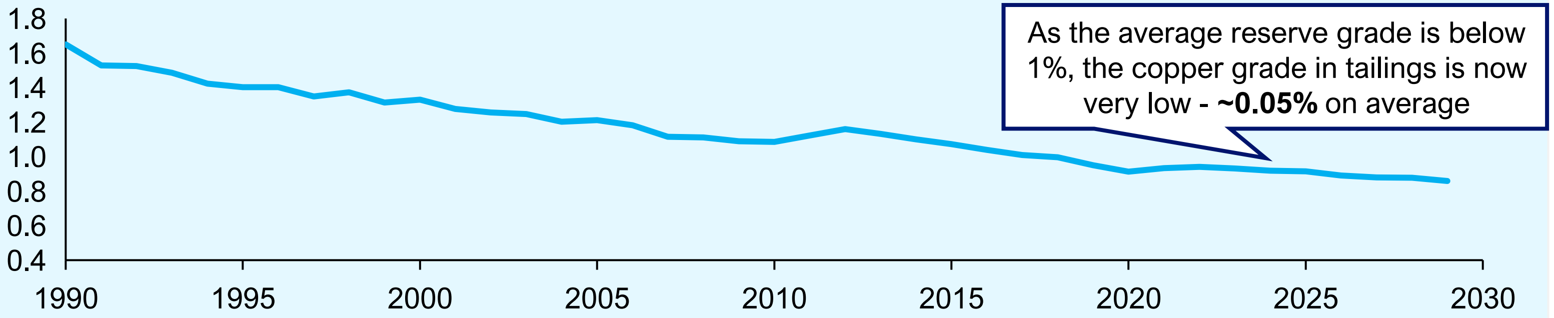
…an estimated theoretical 300 mn tonnes of copper in historical and newly generated copper tailings exceed the anticipated primary copper supply through 2035

Potential copper content in copper tailings - historical and forecasted through 2035[1], Mt



Illustrative number, some tailings backfilled in mines or dry stacked

Average copper grade of extracted deposits, historical and forecasted, Cu %



As the average reserve grade is below 1%, the copper grade in tailings is now very low - **~0.05%** on average

Source: Systemiq analysis based on L. Adrianto et al. (2023), *Toward sustainable reprocessing and valorization of sulfidic copper tailings: Scenarios and prospective LCA;* Global Tailings Review (2020), *Towards zero harm – a compendium of papers prepared for the global tailings review;* Mining (2021), *Mining copper tailings could answer supply deficits later this decade;* MOI Global (2017), *Copper Mining: Articulating a Contrarian Thesis;* The Intelligent Miner (January 2024), *Take two: why mine tailings are worth another look*; S&P Capital IQ Pro; Expert interviews.

Note: Treatments applied to extract copper from tailings include MW-roasting and leaching and Ion flotation and precipitation. As grades decrease, recoveries decline significantly: while primary mines with grades of 0.5–1.0% achieve ~90% recovery via flotation, tailings with grades of 0.05–0.2% may see recoveries as low as 50%. | 1. Historical tailings total an estimated 280 Bt (source: The Intelligent Miner), with ~50% assumed to be copper tailings (140 Bt) containing an average copper content of 0.2%, equating to 280 Mt of copper content. From 2024 to 2035, global primary copper production is projected to yield 300 Mt of copper, generating an additional 60 Bt of tailings with an assumed copper content of 0.05%, resulting in an additional 30 Mt of copper content. Assumed that 5% of tailings are in Europe, based on current production shares. | 2. Supply projections from S&P Capital IQ Pro

E. PROJECT FINANCING | GOVERNMENT SUPPORT FOR CRM MINING AND REFINING HAS SO FAR BEEN LIMITED IN THE EU VS THE USA

USA govt. financing of CRM mining/refining announced to date covers a greater ranger of projects and in larger volumes

🟩 Lithium 🟨 Graphite *Non-exhaustive*

Examples of US Department of Energy financing to CRM projects[1]

■ DOE loan □ DOE grant

Project	Companies	Date[2]	Financing (mn $)
Integrated Lithium project, Thacker Pass	Lithium Americas gm	October 2024	■ 2,260
DLE project, Arkansas	Standard Lithium equinor	February 2024	□ 225
DLE project, Arkansas and Texas	TerraVolta	September 2024	□ 225
Lithium refining, North Carolina	ALBEMARLE	October 2022	□ 149
Lithium refinery, New York	ABTC American Battery Technology Company	September 2023	□ 57
Synthetic graphite facility, Orangeburg	Birla Carbon	September 2024	□ 150
Innovative graphite refining	URBIX	October 2023	□ 125
Synthetic graphite production	ANOVION Battery Materials	October 2022	□ 117
Synthetic graphite facility, Tennessee	NOVONIX	October 2023	□ 117

Examples of EU financing to CRM projects

■ EIB loan □ EU Innovation Fund grant

Project	Companies	Date[2]	Financing (mn $)
DLE, Germany	VULCAN ENERGY	*Pending – under appraisal*	■ 530
Integrated Lithium project, Finland	Sibanye Stillwater	August 2024	■ 160
Anode refinery, Sweden	talga	June 2023	■ 160
Synthetic graphite production, Norway	Vianode	January 2024	□ 95
Anode refinery, Sweden	talga	October 2024	□ 75

Source: US DOE, EIB and EU websites.

Note: 1. Policy outlook uncertain following recent US elections. | 2. Date of announcement; Note that the EU has also provided financing for innovative mining machinery and equipment, inter alia for Sandvik and Metso, over recent years.

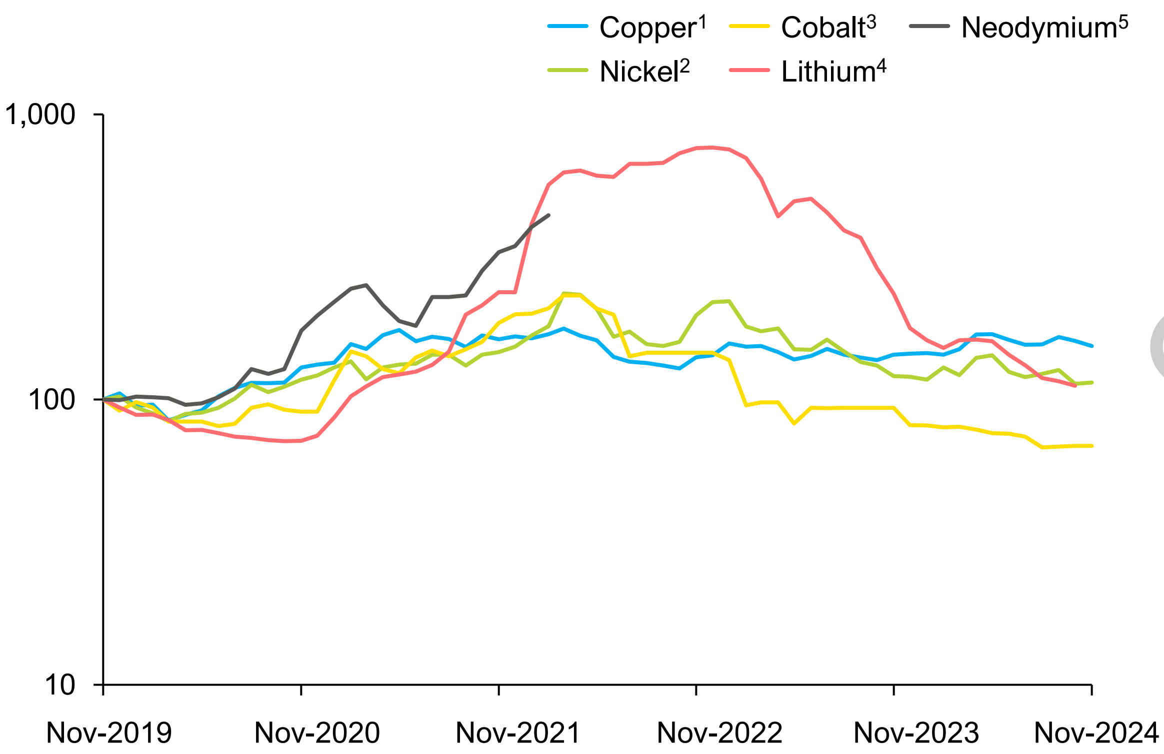
E. OFFTAKE & PRICE VOLATILITY | CRMS ARE SUBJECT TO HIGHLY VOLATILE PRICES AND INCREASING TRADE RESTRICTIONS

Prices have been volatile over the last 5 years - in particular for lithium - and export restrictions have increased as geopolitical concerns have grown

Non-exhaustive; as of 29 November 2024

Volatile prices make it challenging to develop new mining/refining projects…

Logarithmic monthly price series for select CRMs, $ per tonne (indexed Nov 2019)



… and the number of exported raw material products subject to at least one export restriction increased from ~4,000 in 2009 to ~17,000 in 2022

Notable restrictions introduced recently

From 2026: will apply a 25% tariff on **Chinese natural graphite and rare earth permanent magnet imports**

2024: tariff on **lithium-ion EV batteries** will increase from 7.5% to 25%

2023: introduced **graphite export restrictions** – exporters required to apply for permits to ship natural and synthetic graphite[6]

2023: introduced **ban on exporting REEs processing technologies**

2023: announced intention to **ban exports of unprocessed REEs**

2023: introduced **ban on exports of unprocessed lithium, cobalt, manganese, graphite and rare earths**

2023: announced that Lithium production will be nationalised [7]

2023: introduced **ban on exports of bauxite**

2020: introduced **ban on exports of nickel ore**

2022: nationalised Lithium production[7]

2022: introduced **ban on exports of unprocessed lithium**

Source: S&P Capital IQ Pro; OECD (September 2024) *OECD Inventory of Export Restrictions on Industrial Raw Materials*; Press research.

Note: 1. LME Copper Grade A Cash. | 2. LME Nickel Cash. | 3. LME Cobalt Cash. | 4. Lithium Carbonate Global Average (from Benchmark). | 5. Neodymium Oxide 99% China (from Refinitiv). Note Refinitiv coverage in S&P was discontinued in January 2022. | 6. Applies to "high-purity, high-hardness and high-intensity synthetic graphite material and natural flake graphite and its products". | 7. Private participation in the market prohibited, but stated that existing concessions will be respected.

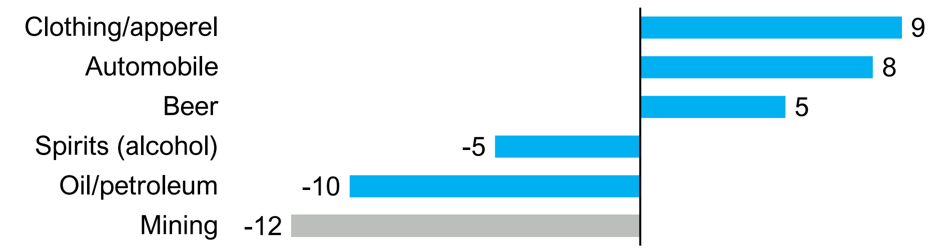
E. ENABLING ENVIRONMENT | A KEY BARRIER TO DEVELOPING NEW MINES IN EUROPE IS SOCIAL ACCEPTABILITY

Mining, including CRMs, faces resistance due to environmental concerns and objection from local communities

Non-exhaustive

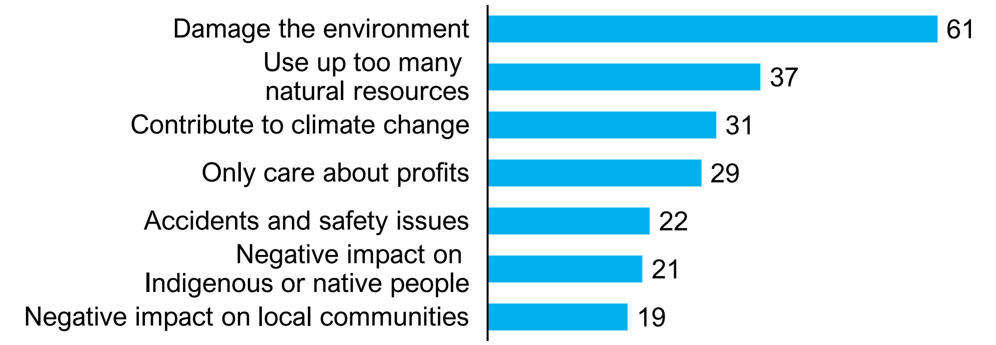
On average, the mining sector is seen to trail other sectors when it comes to fulfilling responsibilities to society, slightly behind O&G[1]

Survey: *performance of sectors in fulfilling responsibilities to society*, net performance, 2023



Damage to the environment is most cited reason for mining companies to be seen as below average in fulfilling societal responsibilities[2]

Survey: *reasons for saying mining companies are below average in fulfilling their societal responsibilities*, 2023



Mining projects in the EU are under pressure to balance economic potential with public opposition

RioTinto

Jadar Lithium Project (Serbia): Faced large-scale protests due to environmental concerns, following reinstatement of licence

IMERYS

Allier Lithium Project (France): Faces strong local opposition over environmental concerns, particularly its designation as a “national interest” project

GABRIEL Roșia Montană IN PARTNERSHIP

Roșia Montană Project (Romania): Planned to be Europe’s largest open-pit gold and silver mine, the project faced protests over environmental and cultural concerns. In 2021, its designation as a UNESCO World Heritage site effectively halted any future mining activities

QUANTUM MINERIA

Ciudad Real Rare-Earth Project (Spain): Potential to supply ~30% of the EU’s annual demand but suspended by regional authorities due to significant social and environmental concerns raised by local communities.

Source: Globescan/ICMM (2023), *Understanding Perceptions of Mining;* Press releases.

Note: 1. The worse sectors where selected (i.e., those with a performance score below 10); 2. Main reasons for saying mining companies are below average in fulfilling their social responsibilities (i.e., score above 15).

E. ENABLING ENVIRONMENT | OVERVIEW OF EXISTING EU FUNDING PROGRAMMES FOR CRM MINING AND REFINING

Non-exhaustive

Funding programme	Details	Scope[1]	Scale of Funding Available
Horizon Europe	• Current EU Framework Programme for Research and Innovation for 2021-27 • Raw materials R&I primarily funded through cluster 4 (Digital, Industry and Space) • Cluster 4 investment executed by HaDEA and coordinated by RTD, spend on batteries innovation is informed by BATT4EU	• Full raw materials value chain • EPRS analysis found the primary focus has been on recycling and recovery, over exploration and sustainable mining	• Over €470 mn allocated for raw materials R&I projects 2021-24
ERA•MIN 3	• Network of European and non-European research funding organisations, e.g., Business Finland, Vinnova (Sweden's innovation agency) • Aim to promote research & innovation co-oporation	• Focus areas and funding amounts vary across funding organisations • Main focus has been on TRL 2-6	• *Na.*
European Technology Platform on Sustainable Mineral Resources	• Projects – provides funding (*ongoing projects unclear),* policy contribution and networking opportunities	• Full raw materials value chain	• *Na.*
eit RawMaterials	• Funding for projects and companies, training and networking for entrepreneurs, business creation programmes, and advisory services	• Full raw materials value chain • Main focus has been on TRL 6 and above	• Over €200 mn startup investment to-date
eit InnoEnergy	• Startup investment, innovation marketplace, training and networking for startups • EBA Strategic Battery Materials Fund with Demeter	• Full batteries value chain (through the EBA) • Also focuses on Green H_2 and Solar PV	• Fund with Demeter: target size €500 mn
EU Innovation Fund	• Fund low-carbon technology demonstration projects using money raised by the ETS	• Energy intensive industries, renewables, energy storage, CCUS, net-zero mobility and buildings	• Budget for 2022 grants was €1.6 bn
IPCEI	• EU Commission approves state aid for at least one IPCEI per annum • 2 IPCEIs approved for batteries (2019 and 2021)	• Battery IPCEIs: full battery value chain	• 1st IPCEI on batteries: €3.2 bn • 2nd IPCEI on batteries: €2.9 bn
INVEST EU	• InvestEU Fund: budget guarantee that backs financial products provided by partners – EIB, EIF, CEB, EBRD, NIB, Member State development banks • Advisory Hub for project developers and portal to connect investors and projects	• Supply and processing of raw materials is a sub-category within Sustainable Infrastructure • Other categories: Research, Innovation and Digitalisation; SMEs, Social Investment and Skills	• Total budget guarantees of €26.2 bn, of which €9.9 bn for Sustainable Infrastructure
European Investment Bank	• Loans, equity, guarantees, advisory services and mandates & partnerships (e.g., blending facilities)	• 8 priority areas, including Climate and Environment, e.g., battery gigafactories	• ~€3 bn investment in battery manufacturing in 2023
European Bank for Reconstruction and Development	• Loans, equity investments, trade facilitation services (including trade finance), advisory services to SMEs • Joint fund with InvestEU to provide equity investments for CRM exploration	• Invests in Central Asia, Central Europe, and Eastern Europe • Natural Resources is a category of investment	• Cumulative investment of ~€9.2 bn in Natural Resources to date • Fund with InvestEU: €50 mn

Source: European Parliamentary Research Service (July 2024) *The role of research and innovation in ensuring a safe and sustainable supply of critical raw materials in the EU*; Press research.

Note: HaDEA: European Health and Digital Executive Agency; RTD: Directorate-General for Research and Innovation; BATT4EU: Public-private partnership between the Batteries European Partnership Association and the European Commission; ERA-MIN: European Research Area Networks Cofound on Raw Materials; ETP SMR: European Technology Platform for Sustainable Mineral Resources; EIT: European Institute of Innovation & Technology; EBA: European Battery Association; ETS: Emissions Trading Scheme; IPCEI: Important Projects of Common European Interest; EIB: European Investment Bank; EIF: European Investment Fund; CEB: Council of Europe Development Bank; NIB: Nordic Investment Bank EBRD: European Bank for Reconstruction and Development. | 1. EU countries unless stated otherwise.

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