BMAC Battery Metals Association of Canada

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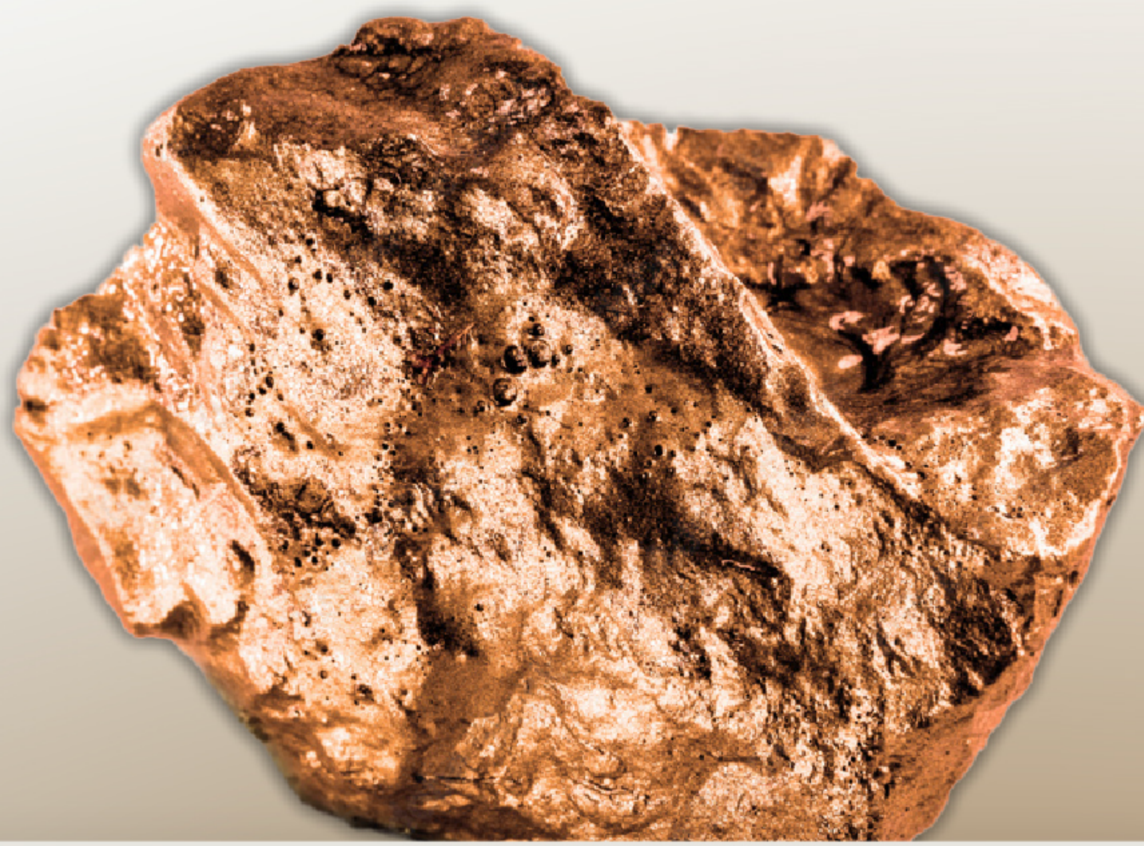
COPPER



FROM
ROCKS
TO
POWER

Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, & Beyond

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From Rocks to Power: Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, and Beyond

Focus on Copper

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About Us

BMAC | Battery Metals Association of Canada

The Battery Metals Association of Canada (BMAC) is a national non-profit association of industry participants and champions from across all segments of the battery metals value chain. From mining to specialty chemical refining, manufacturing, end use and recycling, BMAC is focused on coordinating and connecting the segments of this value chain, ensuring Canada captures the economic potential of the sector and is able to attain its electrification targets. Together, our members collaborate to accelerate the development of the battery metals ecosystem in Canada.

The Transition Accelerator | L'Accélérateur de transition

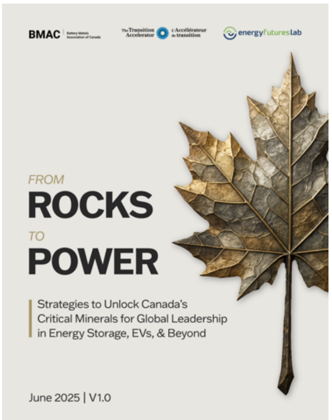
The Transition Accelerator drives projects, partnerships, and strategies to ensure Canada is competitive in a carbon-neutral world. We're harnessing the global shift towards clean growth to secure permanent jobs, abundant energy, and strong regional economies across the country. We work with 300+ partner organizations to build out pathways to a prosperous low-carbon economy and avoid costly dead-ends along the way. By connecting systems-level thinking with real-world analysis, we're enabling a more affordable, competitive, and resilient future for all Canadians.

energy futures lab

The Energy Futures Lab is an award-winning, Alberta-based not-for-profit that brings together a diverse network of innovators, influencers, and system actors from across Canada's energy landscape. Established in 2015, the Lab was created to address growing polarization around Canada's energy transition and respond to its most pressing challenges.

Through trusted leadership and creating non-partisan spaces for collaboration, the Lab convenes stakeholders and Rights and Title Holders to generate and test innovative, enduring solutions to complex, system-level issues. By empowering communities and change-makers to work across divides, the Lab fosters the conditions for meaningful progress toward a shared vision of a resilient and sustainable energy future.

About This Report



This chapter is part of a larger report, *From Rocks to Power: Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, and Beyond*. The full report identifies clear, investable priorities in eight minerals, each of them critical to building resilient EV and energy storage value chains. By looking at specific opportunities and providing detailed justifications for its recommendations, *From Rocks to Power* offers a way out of our perpetual planning cycle and towards a new momentum for Canada's critical minerals sector—and our future economic prosperity.

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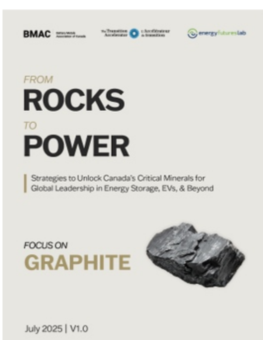

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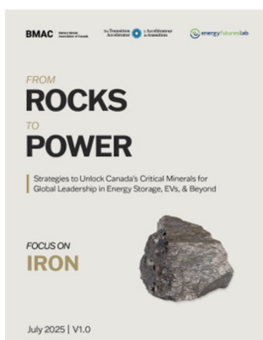

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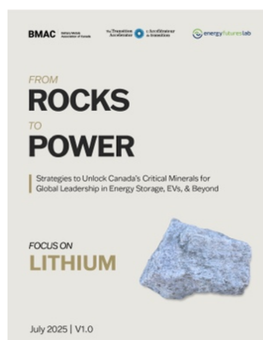

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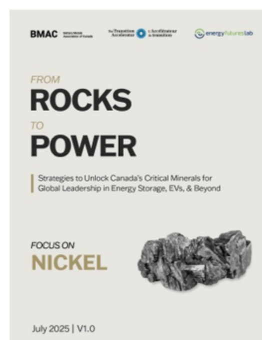

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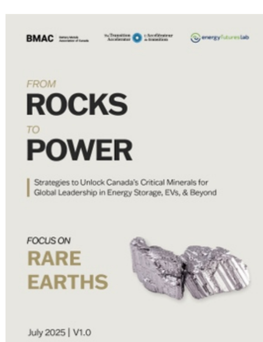

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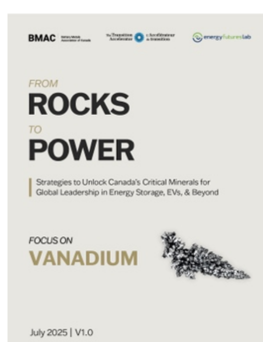

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Copper

1 The Canadian Strategy for Copper

1.1 Copper in Canada

Table 1 Non-exhaustive selection of operational and future copper extraction and processing projects in Canada

Selection of Operational Copper Extraction Sites				
Project Name	**Company**	**Province**	**Type**	**Status**
Ming Mine	FireFly Metals	NL	Copper Sulfide, Underground	Operational
Kidd Mine	Glencore	ON	Copper Sulfide, Underground	Operational
Sudbury Operations (5 mines)	Vale	ON	Copper/Nickel Sulfide, Underground	Operational
Snow Lake-Lalor Mine	Hudbay	MB	Copper Sulfide, Underground	Operational
Copper Mountain Mine	Hudbay + Mitsubishi	BC	Copper Sulfide, Open Pit	Operational
Gibraltar Mine	Taseko	BC	Copper Sulfide, Open Pit	Operational
Highland Valley Copper Mine	Teck	BC	Copper Sulfide, Open Pit	Operational
Mount Milligan	Centerra Gold	BC	Copper Sulfide, Open Pit	Operational
Mount Polley	Imperial Metals	BC	Copper Sulfide, Open Pit, Underground	Operational
Myra Falls	Trafigura Mining	BC	Copper Sulfide, Underground	Care and Maintenance
New Afton Mine	New Gold	BC	Copper Sulfide, Open Pit, Underground	Operational
Red Chris	Imperial Metals	BC	Copper Sulfide, Open Pit, Underground	Operational
Many nickel deposits contain significant amounts of copper, which is why nickel plants can produce copper concentrates and products. Refer to the nickel chapter for more information.				
Selection of Future Copper Extraction Projects				
Project Name	**Company**	**Province**	**Type**	**Status**
Corner Bay Project	Doré Copper Mining Corp	QC	Copper Sulfide, Underground	PEA 2022
Gaspé Copper	Osisko Metals	QC	Copper Sulfide, Open Pit	PEA expected in 2026
Marathon Palladium & Copper Mine	Generation Mining	ON	Copper Sulfide, Open Pit	Amended FS 2024
McIlvenna Bay	Foran	MB	Copper Sulfide, Underground	FS 2022
Berg Project	Surge Copper Corp	BC	Copper Sulfide, Open Pit	PEA 2023

Galore Creek	Newmont + Teck	BC	Copper Sulfide, Open Pit	PFS 2025
KSM	Seabridge Gold	BC	Copper Sulfide, Open Pit, Underground	PFS 2022
Kutcho	Kutcho Copper Corp	BC	Copper Sulfide, Underground	FS 2021
Schaft Creek	Teck + Copper Fox Metals	BC	Copper Sulfide, Open Pit	PFS 2025
Yellowhead	Taseko	BC	Copper Sulfide, Open Pit	FS 2014, Updated 2019
NICO Cobalt-Gold-Bismuth-Copper Mine	Fortune Metals	NT	Copper Sulfide, Open Pit, Underground	Updated FS 2021
Casino	Casino Mining Corp	YT	Copper Sulfide, Open Pit	FS 2022

Selection of Operational and Projected Copper Metallurgical Plants

Project Name	Company	Province	Type	Status
Horne Smelter	Glencore	QC	Pyrometallurgy to copper anode	Operational
Montréal CCR	Glencore	QC	Copper electro-fining plant: Anode to Cathode	Operational
NICO Hydrometallurgical Plant	Fortune Metals	AB	Hydrometallurgy to copper cement	Updated FS underway

In 2022, Canada ranked 12th in global copper production, 16th in refining, and 13th in copper reserves. The 30 operating copper mines located nationwide, mining copper as a primary product or a by-product, mined an estimated 520,000 tonnes of copper in 2022, according to the USGS, or 511,000 tonnes, according to NRCan.[11,12] The Canadian export of copper-based products represented $9.4 billion the same year. Important players in the Canadian copper sector include Teck, Taseko Mines, Hudbay Minerals, Centerra Gold and Glencore.

Around 53% of the 2022 Canadian output came from British Columbia, while operations in Sudbury, Ontario accounted for 31%. The most significant operations are in British Columbia, with the Highland Valley Copper site, Gibraltar, Copper Mountain and Mount Milligan. Most deposits there are of the porphyry type with sulfide ores. Smaller operations exist in Newfoundland and Labrador, Manitoba, and Quebec.

Large copper mining projects have mainly focused on northern British Columbia's Golden Triangle/Copper Corridor. Those projects include Galore Creek, operated by Teck and Newmont; KSM, by Seabridge Gold; Kutcho, by Kutcho Copper Corp; Schaft Creek, by Teck and Copper Fox Metals; and Yellowhead, by Taseko. Casino is another very large mining project situated in Yukon. Foran is developing a copper-zinc mine project called McIlvenna in the Flin Flon greenstone belt but in east Saskatchewan. Finally, another project of interest is Fortune Metal's NICO mining and refinery project: the company plans to mine a deposit of cobalt, bismuth, copper and gold in the Northwest Territories, and refine the concentrates in a hydrometallurgical facility in Alberta's industrial heartland to produce copper cement, on top of cobalt sulfate, bismuth and gold doré.

Canada's only remaining copper metallurgical facility is the Glencore-owned Horne smelter in Rouyn-Noranda, Quebec. The feedstock can be a mixture of copper ores sourced from Glencore's Sudbury operations and scrap. Since 1975, the Noranda reactor plant has been producing a high-grade matte which, since 1988, has been converted in the Noranda continuous converter to blister copper. A sulfuric acid plant is also integrated into the facility.[13] The impure copper anodes are then transported to the CCR refinery in Montreal, the only existing Canadian copper electro-refinery. In addition to refining copper anodes to cathode copper, the plant also produces refined silver, gold, selenium, tellurium, as well as platinum/palladium concentrate.

Table 2 Canadian mine production of copper contained in concentrates, by province and territory in 2022[12]

Province	**Provisional Production in 2022** (tonne x 10^3)	**Percentage**
British Columbia	270	52.8%
Ontario	159	31.2%
Newfoundland and Labrador	22	4.2%
Manitoba	20	4.0%
Others	40	7.8%
Total	**511**	**100.0%**

1.2 Targets

Our previous report, 'Roadmap for Canada's Battery Value Chain,' did not specify objectives for copper. In the present study, we used the same target: Canada, aiming to reach 10% of the 2030 North American EV market as a baseline and a potential leader scenario, with a goal of 35%. The exact vehicle fleet modelling and EV market penetration assumptions were made, this time using estimates of copper content in different EVs from a 2022 S&P analysis.[14] Canada hosts significant resources that can be developed in BC, but the province lacks accompanying metallurgical processing capacity.

Table 3 Copper Targets

Copper Mandated Benchmark (10% of 2030 North American Market)		
	2030	**2040**
Copper (ktpa elemental)	75	153
Copper Leader scenario (35% of 2030 North American Market)		
Copper (ktpa elemental)	263	535

1.3 Scenario Outline

Canada already has expertise in copper mining, processing and refining. However, the copper processing rate has declined since the Hudbay Flin Flon smelter closed in 2011. The Kidd Creek copper smelter in Timmins, Ontario, closed one year earlier in 2010. There has been a slow but steady decrease in copper mining output since then. A future scenario for the copper industry in Canada would include accelerating near-term copper production, boosting the midstream segment by integrating BC copper corridor operations in a new metallurgical plant, and developing a longer-term pipeline of mineral supply.

- **Accelerate Near-Term Copper Production:** Advance life extensions and expansions of current copper mining operations while supporting the implementation of mining projects in development, especially in BC, and expand concentrate production.
- **Boost the Midstream Segment by Building a New Metallurgical Plant:** All the copper concentrate produced in British Columbia is shipped overseas, mostly to China, for processing. However, enough copper concentrate is produced in British Columbia to justify the development and operation of a new copper smelter, provided suitable economic conditions can be found to justify such a change. Building a new, clean, pyrometallurgical plant in BC, taking feed from the existing and projected material, plus scrap, would securely advance the Canadian copper supply chain. A cost/benefit analysis would be required. mines, projected ones, and scrap would advance the Canadian copper supply chain. If the social mandate does not allow it, supporting R&D and optimizing viable hydrometallurgical operations of copper sulfide should be pursued. Scaling existing operations, such as the Horne smelter and Montreal copper refinery, should also be supported.

1.4 Signature Projects

- Advance life extension and expand current mines and smelter
- Develop several mining projects in BC and YT
- Build a large copper metallurgical facility in BC

1.5 Strategic Priorities

Extend and Expand Current Copper Operations:

- **Extend the life** of currently operational copper mines operations in BC, ON & MB.
- **Support the expansion** of currently operational copper mines. The modernization and expansion of Horne smelter in Quebec should also be supported.

Copper Corridor: Develop Mining Operations at Scale in British Columbia:

- **Developing substantial mining operations in British Columbia** could involve establishing a network of mines capable of consistently supplying a local copper smelter or hydrometallurgical plant. The chemical collaboration metallurgical complex described below could be this midstream facility. This long-term strategy would ensure a steady flow of raw materials, foster regional economic growth, and create numerous job opportunities within the mining and processing sectors.
    - Advanced Projects such as Galore Creek, Schaft Creek, Kutcho, KSM or Yellowhead in BC, and Casino in YT should be supported.
- **Fund exploration of copper deposits:** to keep pursuing the discovery of new viable deposits for the long-term supply.

Develop a Copper Metallurgy Plant in British Columbia: Probably a smelter, perhaps a leaching plant, and potentially a mix of both.

The collaboration described here can involve mutualizing industrial processes to handle copper concentrate from various mines sourced locally or even internationally. The goal is to convert these concentrates into copper intermediates, such as matte, blister, cathode, or other forms, within a centralized metallurgical hub. This approach aims to achieve scalability and maximize the economic viability of the operations by pooling resources and optimizing processing techniques.

Identifying the most suitable technological pathways that align with the selected scenario is crucial. These pathways include options like smelters and/or hydrometallurgical plants.

- **Pyrometallurgy:** Smelters are advantageous because they can process various input feeds, including scrap. However, they were often perceived as having significant environmental drawbacks, including releasing greenhouse gases (GHG), sulfur dioxide and other pollutants like metal dust. In 2025, a modern copper smelter can be built with the highest environmental standards; a review of advanced plants in Europe or Japan could testify to this situation. Such a plant would produce sulfuric acid either for the chemical industry or as feedstock necessary for hydrometallurgical operations. Thus, a smelter handling copper concentrates to produce anode copper could be considered in BC. Further electrorefining can be carried out on-site or at a different location, depending on several factors, including access to affordable green electricity.

  - Around 100–200 ktpa minimum of contained copper in feed material is considered convenient for a smelter to reach a viable scale; there is currently available material of this quantity in British Columbia. With the new mines coming online, there is a case for investigating the building of a new copper metallurgical plant in British Columbia.
  - Commercial smelters buying concentrates on the market often sometimes operate on thin margins; an integrated business of owning mines and processing plants could be considered.vA joint venture or cooperation arrangement could also be considered.
  - Finding an off-taker or a market for the sulfuric acid by-product would be required.
  - British Columbia hosted several copper smelters around the turn of the last century, including the Trail region, until WWI.
  - Low Treatment Charges (TCs) and Refining Charges (RCs) can be an issue. In the short term, global copper smelting capacity is under utilized, and many smelters' economic model is to buy copper concentrates on the international market and smelt an agreed number of tonnes according to a TC rate. TCs are predicted to be low in 2025, making short-term viability of copper smelting difficult.[15]
  - If the economic viability and environmental assessment are valid and a social mandate allows it, a smelter project should be advanced in BC.

- **Hydrometallurgy:** In contrast, hydrometallurgy of sulfide ores is tailored to specific mineralogy and requires substantial investment in research and development to be effective. This method also involves high costs for scaling up operations, making it a less flexible but potentially more environmentally friendly option, depending on the leach residue.
  - Hydrometallurgical processing of sulfide ores is technically viable, with options such as pressure oxidation, which Sherritt developed in the 1980s. Dynatec and CESL also pursued research. However, no commercial-scale plant was built. They could potentially operate at a smaller scale than smelters.
  - Hydrometallurgical plants can have significant environmental issues that need careful attention in a new facility. These include safe handling and storage of leach residues and control of liquid effluents. Environmental concerns linked to sulphur dioxide or metal dust are non-existent in this case.
  - Hydrometallurgical plants can cleanly treat high-arsenic copper concentrates. This was previously a limit for pyrometallurgy, but modern smelters can also treat those concentrates, provided correct safeguards are in place.

- Barriers against hydrometallurgical plants can include an expected lower potential economic viability of operations, lower recovery of precious metals, and the reluctance of industry players to choose this pathway.
    - A technical, economic and environmental trade-off would be required to choose a pathway between pyrometallurgy and hydrometallurgy.
- **Using Both Routes:** A metallurgical complex merging both routes could be an option: smelting ores of various grades and mineralogy while feeding a nearby hydrometallurgical plant with the sulfuric acid necessary for treating some specifically complex ores, perhaps imported.
    - The potential for the processing of concentrates or intermediate materials from outside the country could be examined. This might be interesting for **the processing of high-arsenic ores from overseas**, which could benefit from being treated more sustainably on Canadian territory. This strategy is already in place for other metals, such as nickel intermediate materials from Cuba being treated at the Fort Saskatchewan plant operated by Sherritt.
- **Scrap Intake:** Regardless of the option, scrap should be integrated as a feedstock to promote a higher level of circularity.
- **Clean Power:** If inexpensive and abundant clean electricity is available, a copper refining facility for electrorefining and/or electrowinning can be integrated to produce high-purity copper cathodes.
- **Copper Refining:** An electro refinery (similar to for example, the copper refinery in Montréal) can potentially be built if a smelter is considered. However, it does not need to be co-located with the smelting operation. If the copper processing plant is a leaching process, then an electrowinning operation producing cathode copper will likely be integrated. In both cases, low-cost electricity is advantageous, and electrowinning requires more power per tonne of copper than electrorefining.
- **Copper Cementation:** An alternative route to copper refining could be optimized copper cementation/precipitation from Cu(II) solution. This can theoretically bypass the need for electricity. Cementation is a known process, but it was previously not possible to obtain adequate copper purity without refining. Optimized copper precipitation, such as processes developed by Canadian company Destiny Copper, can reach a high-purity copper powder product. This could support *in situ* leaching in some mines, scrap leaching, and recycling, and it could even potentially become an alternative for copper electrorefining and electrowinning.
- **Brass Mills & Copper Mills:** Should also be integrated to the value chain.

Developing Synergies Between Industries:

- **Producing Sulfuric Acid:** A copper smelter can enhance its profitability by generating additional revenue through the resale of sulfuric acid. The difficulty relies on the fact that this could be market-dependent. Still, another solution is to co-locate an industry with sulfuric acid needs nearby, such as chemical facilities or a hydrometallurgical plant. As mentioned above, the acid byproduct can be utilized in a hydrometallurgical facility, including processing and refining other metals or further copper operations.

- **Processing Pyrites:** Copper mines have the potential to capitalize on pyrites contained in the same deposit as copper-bearing ores by converting them into sulfuric acid. This process not only adds value to what might otherwise be a waste product but also contributes to the performance of the mining operation.

Exploiting Canadian Opportunities:

- **Canada's High Sustainability Standards:** Leveraging the higher sustainability standards prevalent in Canada, such as those outlined in the Towards Sustainable Mining (TSM) initiative by the Mining Association of Canada (MAC), can provide a significant competitive advantage. These standards ensure environmentally responsible practices, enhancing the reputation and marketability of Canadian copper products.
- **Refining Where It Makes Sense:** As mentioned above, establishing electrolytic refineries in regions where the electric grid is both clean and affordable can significantly enhance operational efficiency. These refineries can take advantage of renewable energy sources, reducing their carbon footprint and operational costs.
- **Regional Market:** Taking advantage of the extensive North American market and the availability of scrap feedstock can facilitate a steady supply of raw materials, ensuring continuous production.
- **Infrastructure & Logistics:** Access to well-developed sea and railway networks can optimize logistics for export activities. Efficient transportation options enable timely and cost-effective delivery of copper products to global markets.

Research and Development:

- **Involving Academia:** Increasing funding at the university level to support graduate research is essential for driving innovation within the sector. Fostering robust academic-industry collaboration will enhance overall efficiency and sustainability and build capacity to refine and implement new process technologies.
- **Incentives for Innovation:** Setting up incentives for research and development can encourage private and public sector investment in innovative technologies and processes. These incentives can take the form of grants, tax breaks, or subsidies to reduce the financial burden on companies investing in R&D.
- **Copper Sulfide Hydrometallurgy:** While at present all copper sulfide ore are subjected to a mineral flotation step to produce a copper concentrate for smelting, researching copper sulfide ore leaching could lead to the development of a new economically viable hydrometallurgical route at site. This research can lead to breakthroughs in processing low-grade ores, making previously uneconomical deposits feasible for mining. Optimizing recovery of other metals or leach residue management could be a competitive advantage.
- **Process Tailings:** Developing advanced technology for reprocessing tailings where economically feasible can help recover additional value from mining operations. This approach maximizes resource utilization and mitigates the environmental impact of tailings storage.

Strengthen Competitivity:

- **Bolstering Competitiveness:** Ensuring competitiveness in energy, equipment, and labour is crucial for maintaining an edge in the global market. This involves investing in efficient technologies, securing affordable energy sources, and maintaining a skilled and productive workforce.
- **New Technologies:** Investigating the potential of artificial intelligence (AI) and robotic equipment to reduce operational costs can lead to significant efficiency gains. Automation and AI can optimize mining and processing operations, reducing labour costs and increasing precision and safety.
- **Energy Access**: Securing access to low-cost energy sources is essential for maintaining cost-effective operations. Companies can reduce operational expenses and environmental impact by exploring renewable energy options or negotiating favourable energy contracts.

Circularity:

- **Circular Copper Economy:** Designing an integrated circular value chain for copper is essential to enhance recycling and resource efficiency. Current systems in Canada face challenges related to logistics and supply chain coordination, which need to be addressed to facilitate easier recycling. Given that the market may or may not provide Canada with a technical advantage in recycling, Canada should establish policies and regulatory conditions that best support recycling.
- **EPR:** Enforcing Extended Producer Responsibility could significantly enhance copper recycling rates. This approach requires producers to take responsibility for the end-of-life disposal of their products, similar to the highly integrated and recycled lead batteries used in internal combustion engine (ICE) vehicles.
- **Analysis:** Developing a comprehensive strategy based on existing circularity analyses, such as those conducted by the International Council on Mining and Metals, can provide a robust framework for improving recycling practices and resource efficiency.
- **Scaling Up Recycling:** Considering end-of-life and scrap copper at regional and North American scales can optimize recycling efforts. This approach ensures that recycling systems are efficient and effective at multiple local and continental levels.
- **Tax Credits:** Taking advantage of tax credits and grants from provincial and federal governments based on local job creation for secondary smelter projects can provide significant financial benefits. Programs similar to the support given to Indiana's Exurban Secondary Copper Smelter project by the Indiana Economic Development Corporation in the United States can serve as models.

Coordination with the Government:

- **Coordination Between Industry and Different Levels of Government:** Strengthening coordination between industry and government is vital for refining and implementing an effective strategy. Regular consultations and collaborative efforts can help align industry needs with government policies and support mechanisms. Coordination between the different levels of government (federal and provincial) is necessary.

- **Closer Ties with the Federal Government:** Fostering closer ties with the federal government is essential to effectively communicating the needs and priorities of the mining and metallurgy sector. Coordination across federal government departments is also necessary. This can facilitate the development of supportive regulations and incentives that drive industry growth.
- **Supporting Policies:** Government policy should include tax incentives and assistance providing land to support industry growth. These measures can lower operational costs and encourage investment in new mining and processing projects

Regulatory Framework:

- **Balanced Regulations:** The regulatory framework should be competitive with similar Western countries and not overly restrictive. A balanced approach to regulation can ensure environmental protection while fostering innovation and growth within the mining and metallurgy industry.
- **Indigenous Rights and Adding Certainty:** Pursue regulatory frameworks that appropriately reflect Indigenous rights while increasing certainty for communities and companies involved.

2 The Role of Copper: A Conductive Metal Driving Electrification

2.1 General Properties

Copper, a reddish metal, stands out for its remarkable electrical and thermal conductivity, which is second only to silver. Its relative resistance to corrosion and outstanding ductility makes it highly workable. A desirable property of copper is that it retains its chemical properties even after use, making it easily recyclable. Copper's properties are significantly influenced by its purity and source, with variations arising from factors such as oxygen content, impurities like arsenic and bismuth, and the thermal and mechanical treatment of the metal.[16,17]

It was the earliest metal found and used in its native form by humans, dating from 8700 BCE in Iraq. The development of early metallurgical processing, specifically the smelting of copper ores, marked the end of the Neolithic age and the beginning of the Chalcolithic age. Although copper is easy to work with, its softness made it less ideal for tools and weapons, leading to the use of significantly tougher bronze, a copper alloy containing around 12% tin. The high malleability and workability of brass, another copper alloy comprising 5–40% zinc, was also uncovered around the bronze age and later widely spread throughout the Roman world for coinage and military purposes. As iron metallurgy developed and supplanted the use of bronze, pure copper became less popular for millennia. It was only with the advent of electricity by the mid-19th century that the outstanding electrical conductivity of copper made it the metal of choice for wires and conductors.

Copper is essential for various biological functions, including enzyme activity and the development of red blood cells, collagen, and the central nervous system.[18] Copper deficiency can lead to serious health issues, while acute copper toxicity is rare.[19] Chronic exposure is typically non-problematic, except in specific conditions like Wilson's disease or vineyard sprayer's disease, an occupational exposure affliction caused by workers applying copper sulfate and lime as a fungicide to grape vines. Copper and copper alloy surfaces have shown effective antimicrobial properties, controlling various moulds, algae, bacteria, and harmful microbes, thus reducing hospital infection rates.[20–22]

2.2 Role in Clean Technologies and Energy Storage

With the need to transition to a low-carbon economy, a scaled-up and more widespread electrification based on cleaner energy sources appears as a solution. This is why copper, a crucial element for electricity production (copper coils in generators), conversion from electrical to mechanical energy (copper windings in motors) or conduction (copper wirings), is considered an element of significant priority. Indeed, copper, along with steel, is the most widely used metal in different clean energy technologies.[23–26] The consensus is that copper is critical for the electricity grid and networks, as well as for solar photovoltaic, wind power, electric vehicles, and bioenergy. In contrast, copper's more moderate but significant role is recognized for hydroelectric, geothermal, nuclear, concentrated solar, and components in hydrogen electrolyzers.

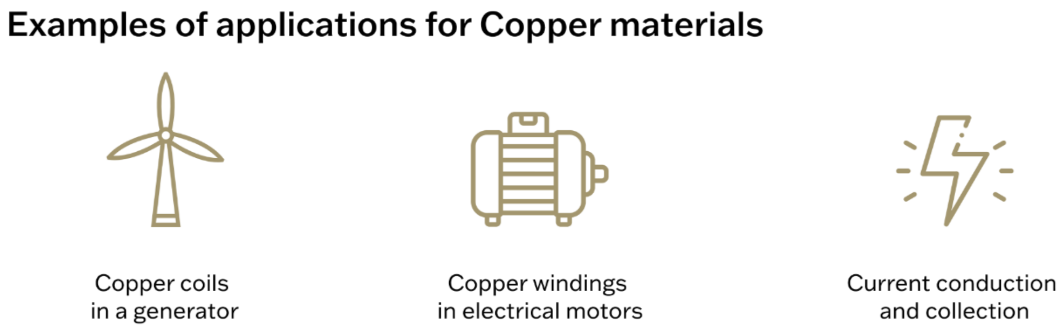


Figure 1 Examples of applications for copper materials

In general, low-carbon electricity production and clean technologies are also more copper-intensive than fossil fuel-generated electricity: producing 1 TWh of energy from solar and wind could consume 300% and 200% more equivalents of copper than 1 TWh from a gas power plant,[26] or even more.[27] In those cases, copper is needed for the wiring, cables, turbine, and transformer of a wind turbine and the heat exchanger, as well as for the wiring and cabling of a solar panel. The widespread use of copper throughout diverse clean energy techniques and the material intensity of those technologies highlight the crucial importance of the copper supply chain for the energy transition.

Similarly, producing battery or fuel-cell electric vehicles is more copper-intensive than building an internal combustion engine (ICE). A 2022 S&P Global analysis estimated that light-duty battery-electric vehicles contain 60 kg of copper per vehicle, compared to 24 kg for an ICE vehicle.[14] Other studies confirm the higher copper intensity of both hybrid and battery-electric vehicles.[28,29]

Copper is generally found in three parts of EVs: the motor, the wiring connections of electronics and battery packs, and inside the battery.[30] EV motors contain more than a mile of copper wiring in the stator windings (the static part of the motor). This is where the electrical current is converted to a rotating magnetic field that can drive the movement of the rotor.[30] For Li-ion batteries, copper foil is used as a current conductor for the graphite anode, while aluminum foil is used for the cathode for better stability. The copper current collector makes up around 8% of the weight of the total battery and has a thickness of 6–20 μm. This foil can reach 35 kg of copper for mid/large-sized EV batteries.[31] Thinner foils improve efficiency but are more challenging to obtain.[32] Future opportunities include replacing a flat sheet structure with either meshes or foam.[33] Surrounding the actual battery, busbars, cables and wiring made of copper are also required for the overall battery pack.

Autonomous electric vehicles will require various sensors, such as radar, lidar, or cameras. Each sensor requires printed boards using 50–100g of copper and additional wiring.[34] Furthermore, the multiplication of charging stations for EVs will also increase copper cabling demand.[27]

2.3 Substitutes

The properties of copper make it difficult to substitute. Still, aluminum is generally considered in some cases as an adequate candidate for replacing copper wirings, as it is cheaper, more abundant and lighter (30.5% the density of copper). It is the most common conductor used for transmission lines.[35–37] Aluminum wiring was also popular in North America during the 1960s—1970s but was phased out due to fire hazards and faulty installations.[38] The main drawbacks include a lower conductivity (only 60% as conductive) and more brittleness, pressing for ongoing research to create more conductive aluminum materials.[39] Aluminum production processes are also more GHG-emitting than copper processing, and aluminum cannot replace copper for anode current collectors or subsea and underground cables. Plastics and aluminum are also used as replacements for copper pipes and plumbing, as well as titanium and stainless steel for heat exchanger applications.

2.4 Supply and Demand

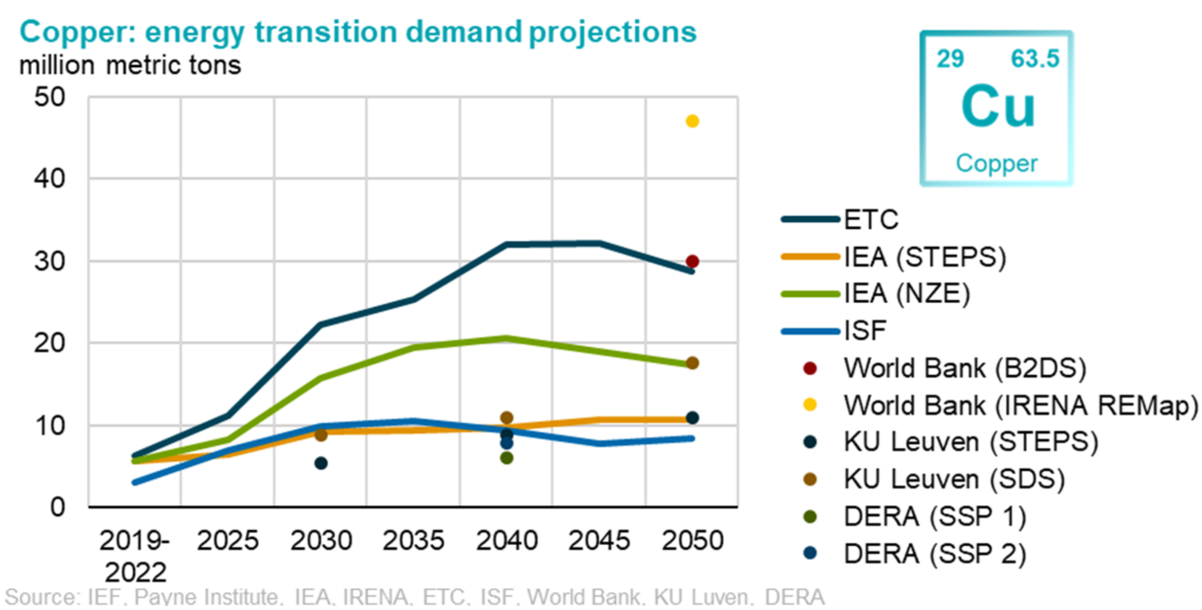


Figure 2 Copper demand projections to 2050 according to various energy transition scenarios[40]

The difference between the increased demand for copper and the projected production will lead to a problematic gap, also called the *copper crunch*. In a 2023 analysis, McKinsey projected 36.6 million tonnes of global copper demand by 2031, while current supply projections forecast 30.1 million tonnes the same year.[41] In their critical minerals report and mineral outlook, the IEA also estimated a comparable gap,[23] reaching a 4.5 Mt shortfall by 2030 in their NZE scenario. In all scenarios, this gap would only worsen in the future decade.[42] S&P Global Market Intelligence forecasted that the demand might rise to 50 million tonnes by 2050, and the potential supply gap could be as large as 9.9 million tonnes by then.[14] In general, more copper production than the projected one by accounting for current projects will be required. Some aggravating factors for this issue are that most mines' copper content grade is declining over time and that the development time necessary for opening new projects can take around 17–20 years on average from discovery to production.[23,43,44] Supply risks are also increasing, notably for copper from Latin America, due to social and environmental issues and water stress challenges.

3 The Copper Flowsheet: From Sulfide and Oxide Ores to Wires

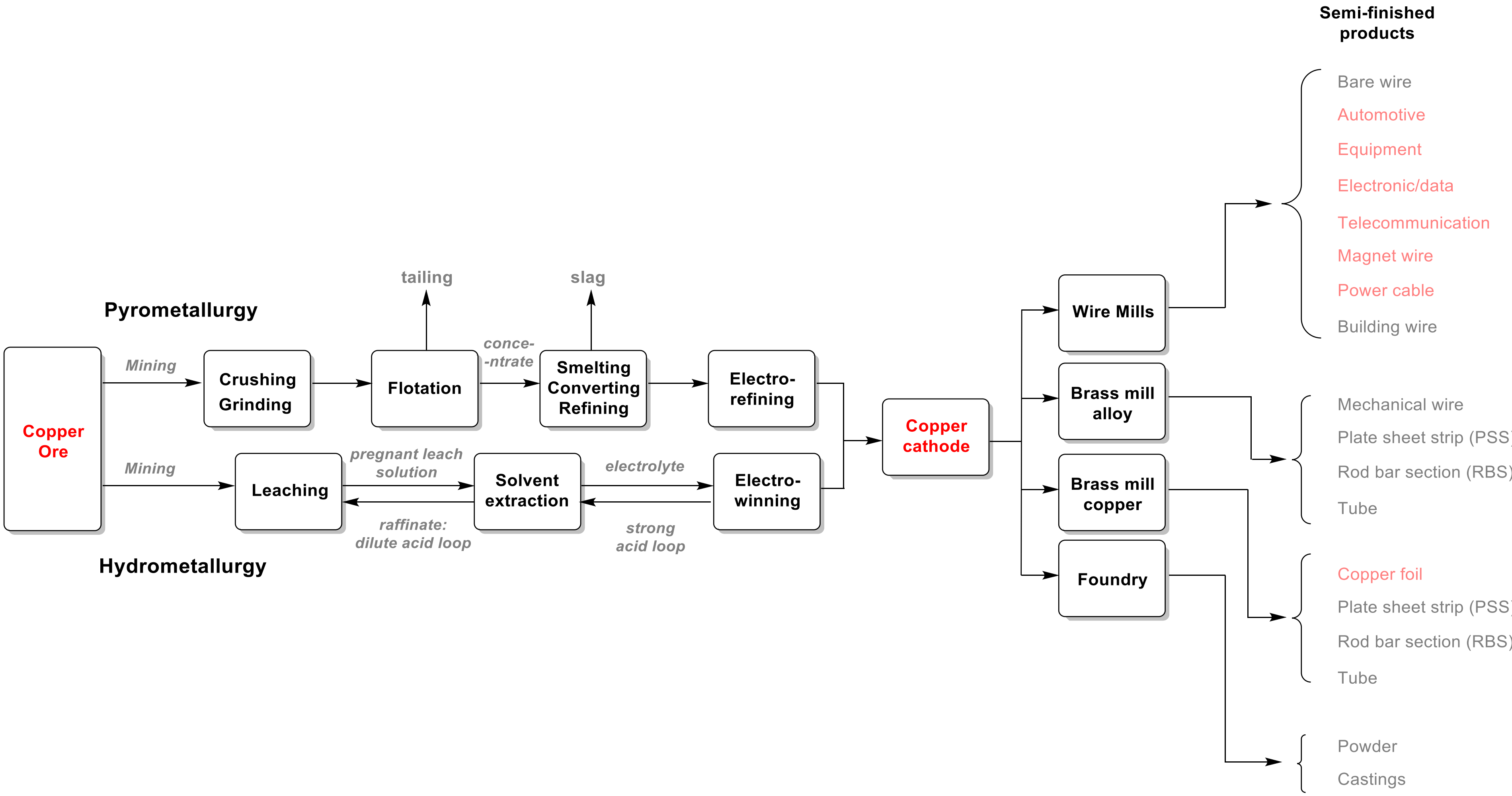


Figure 3 Simplified flowsheet of copper

3.1 Ores, Reserves and Mining

Copper is the 26th most abundant element in Earth's crust, twice as abundant as cobalt. It is moderately accessible, and given the known resources, it is highly improbable that we will run out of copper.[45]

Copper deposits can be classified according to their geological formation: ores are either of magmatic or sedimentary origin. Magmatic formations include liquid magmatic ores (such as the Ni-Cu ores in Sudbury, ON), pegmatitic ores, deposits from submarine volcanic exhalations, and hydrothermal ores (Chile, Peru, Mexico, Utah, Arizona, British Columbia). The latter, also called porphyry ores, are disseminated in igneous intrusions, forming small particles, fractures, and veins. Those deposits generally contain less than 1% copper, representing around two-thirds of global copper resources and 50–60% of production.[16,46] Sedimentary deposits comprise sandstones, partly metamorphized sedimentary ores (African copper belt), marine precipitates and deep-sea concretion nodules.

In terms of mineral formation, copper has a strong affinity for sulfur and often forms sulfide compounds, such as chalcopyrite $\mathbf{CuFeS_2}$, chalcocite $\mathbf{Cu_2S}$, bornite $\mathbf{Cu_5FeS_4}$, covellite **CuS**. About half of the global copper output is from chalcopyrite.[46] Copper oxides include azurite $\mathbf{Cu_3(CO_3)_2(OH)_2}$, chrysocolla $\mathbf{(Cu,Al)_2H_2Si_2O_5(OH)_4 \cdot \mathit{n}H_2O}$, malachite $\mathbf{Cu_2CO_3(OH)_2}$, cuprite $\mathbf{Cu_2O}$ and tenorite **CuO**. Oxides were formed near the surface when copper minerals came into contact with water. Sulfides, particularly chalcopyrite, are difficult to process through hydrometallurgical methods, so most copper production was generated through smelting. While oxides ores can be technically treated by smelting, as was carried out in the not-so-distant past, the preferred economic method today is by leaching.

Table 4 Reserves, production, and refining of copper by country in thousands of tonnes[11]

Country	Mining Production in 2022[a] (tonnes x 10^3)	Country	Refinery in 2022[a] (tonnes x 10^3)	Country	Identified Reserves in 2024[a] (tonnes x 10^3)
Germany	/	**Canada**	**278**	Germany	/
Japan	/	Indonesia	310	Japan	/
Korea	/	Zambia	349	Korea	/
Poland	393	Peru	391	**Canada**	**7,600**
Canada	**520**	Australia	401	Kazakhstan	20,000
Kazakhstan	593	Mexico	486	Zambia	21,000
Mexico	754	Kazakhstan	494	Indonesia	24,000
Zambia	797	Poland	586	Poland	34,000
Australia	819	Germany	609	China	41,000
Russia	936	Korea	638	United States	50,000
Indonesia	941	United States	952	Mexico	53,000
United States	1,230	Russia	1,010	Congo (Kinshasa)	80,000
China	1,940	Japan	1,550	Russia	80,000
Congo (Kinshasa)	2,350	Congo (Kinshasa)	1,770	Peru	120,000
Peru	2,450	Chile	2,150	Australia	100,000
Other countries	2,850	Other countries	2,830	Other countries	180,000
Chile	5,330	China	11,100	Chile	190,000
World total (rounded)	**21,900**	**World total (rounded)**	**25,900**	**World total (rounded)**	**1,000,000**

[a]Data from the 2024 U.S. Geological Survey.[11]

In terms of production companies, the copper sector is not as concentrated as that of other critical minerals. According to the latest data from the United States Geological Survey, Chile continues to lead in copper ore mining, accounting for 24% of global output in 2022.[11] Peru (11%), DRC (11%), China (9%), and the U.S. (6%) are the key actors in copper mining. Moreover, the top four copper mining companies, Freeport-McRoran, BHP, Codelco, and Anglo American, represent less than 30% of global output, showing a relatively diversified sector.[47] However, copper smelting and refining are primarily dominated by the Chinese industry, which accounts for 43% of refined copper produced in 2022. Other leading refining countries do not compare in scale. In addition to being a leading miner and refiner, China accounts for approximately 54% of the global refined copper consumption.[48] Worldwide copper reserves are primarily localized in South America, with Chile and Peru making up 31% of global reserves, while Australia, Russia and the DRC hold significant accessible reserves. Canadian reserves are quite small, about 1% of total world reserves.

The majority of global copper output comes from mega-mines that can reduce costs with large-scale capacity and economies. This is the case for Chile, home to two of the largest three copper mines in the world. For instance, the open-pit Escondida mine, owned by BHP, Rio Tinto, and JECO, contributed 7% of global copper production in 2020.[49]

Several factors affecting the copper extraction segment can threaten global value chains. First, a global decrease in ore quality and copper concentration pushes production costs upwards, increasing the quantity of tailings and the cost of emission controls.[50] Secondly, as over one-third of copper supply originates from South America, interruptions in operations there can have global repercussions. Social and labour unrest in Chile over the past 5 years have impacted copper supply and prices.[51,52] Public dissatisfaction with the royalty arrangements as well as local disagreements related to environmental performance led to the shutdown of the Cobre Panama mine, the 16th largest copper mine in 2020.[53] Thirdly, copper, like lithium, is particularly exposed to climate risks and water stress: mines in South America, Zambia and Australia overlap regions recognized by the IEA as having high to extremely high water stress levels, and 80% of copper output in Chile is concerned by this issue.[54] Fourthly, copper supply can be locally intimately tied to the supply of other critical minerals: this is the case for cobalt and copper in DRC, where around 70% of cobalt is extracted as a by-product of copper mines.[50] Molybdenum is also an important by-product of copper mining.

3.2 Processing

Two main metallurgical routes are presently in use. The **pyrometallurgy** of copper sulfides requires concentration of the mineral before smelting and conversion, which results in **copper matte and blister**. The following **electro-refining** step will produce purified copper anode products necessary for wire or foil manufacturing. **Hydrometallurgical routes**, traditionally used for copper oxide ores, follow an acid-leaching and solvent extraction process to obtain and concentrate **copper sulfate**, resulting in a pure copper cathode after **electrowinning**. Commercial processes can be either heap leaching or dump leaching, leaching methods based on sulfide ores are under development.

3.2.1 Pyrometallurgy

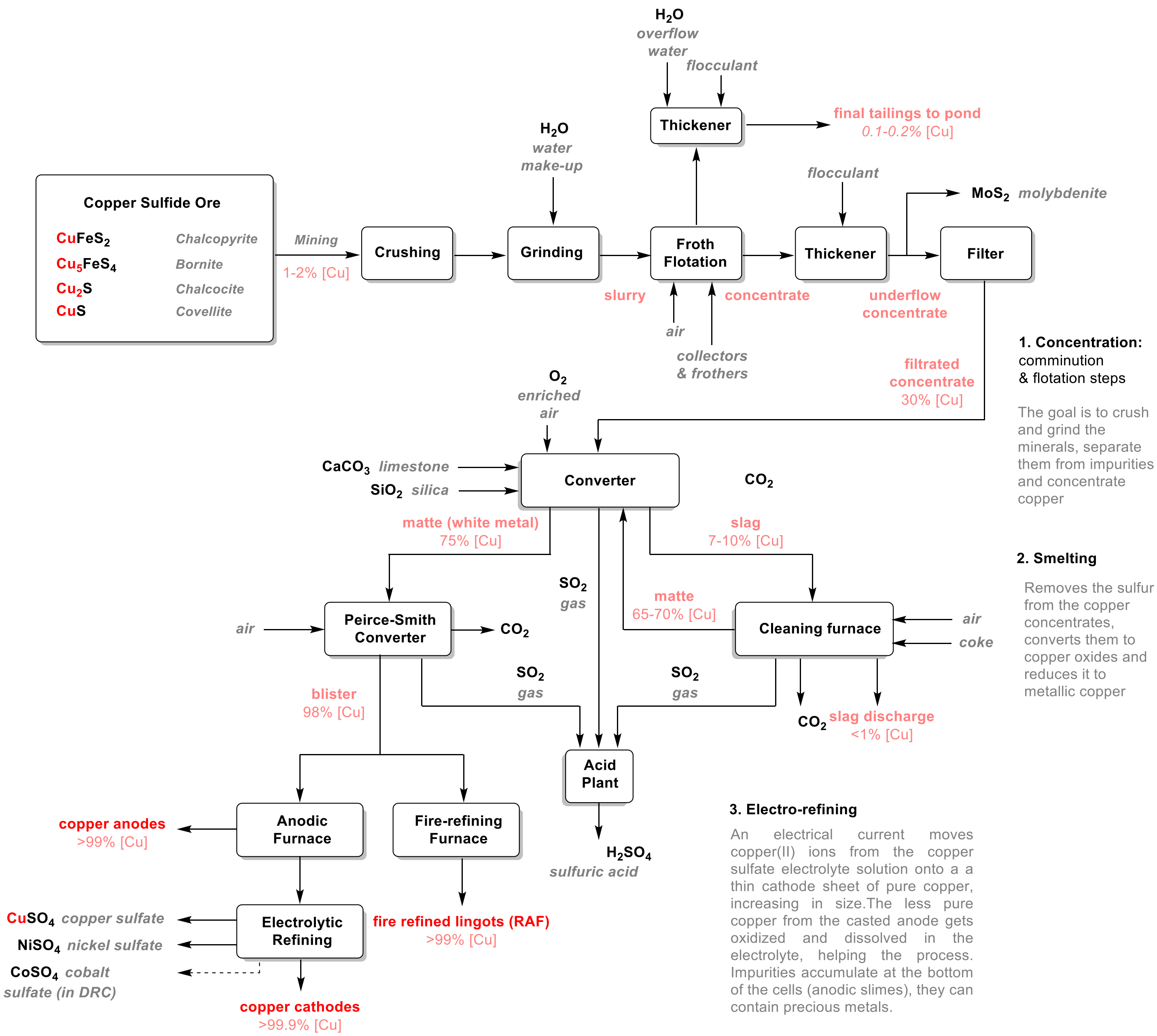


Figure 4 Flowsheet of the pyrometallurgy of copper

Copper sulfide concentrates are typically treated through pyrometallurgical steps, *i.e.* smelting. This is the traditional way of obtaining copper and is still the mainstream category of technology used today. The main copper sulfide minerals present in sulfide ore is predominantly chalcopyrite. However, bornite, chalcocite, and covellite can also be present.

The concentration of copper ores comprises comminution and flotation steps. The goal is to crush and grind the minerals, and concentrate by flotation the copper content from 0.5–2% to around 20–40%. Water, flocculants, air, frothers, lime and collectors are necessary for those processes, while dried and filtered copper concentrate is produced, and tailings are stored near the mine. Molybdenum can be separated at this stage for further processing. While most concentrators are also co-located with the mine, in former times, the smelter was typically located at the mine site. An example being the Gaspé smelter in Canada (now closed, which commenced operation in the 1950s. With the rise of custom smelter plants, in particular after WW2, the smelter is now typically distant from the mining site. This is the situation in British Columbia.

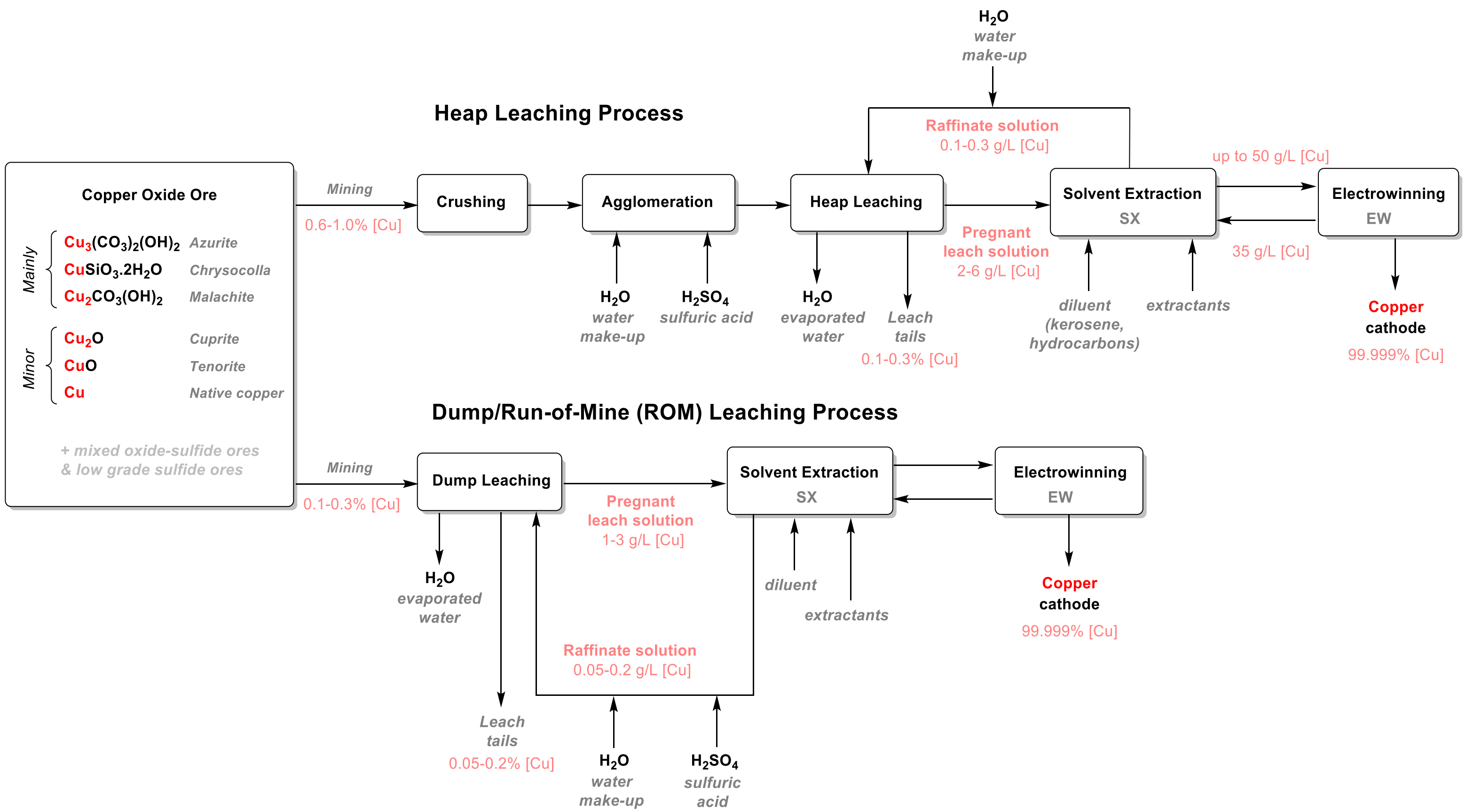
After concentration, copper is then smelted and converted. The chemical reactions occurring during the smelting processes aim to remove sulfur, iron, and silicates from the copper concentrate, and reduce it to metallic copper, either as a matte product (75% Cu) after smelting or blister product (98% Cu) after subsequent converting. Iron and silicate are separated in the slag, which is discarded, while sulfur is oxidized to sulfur dioxide gas $\mathbf{SO_2}$, which can be captured to produce sulfuric acid. If not recycled, sulfur dioxide gas can be toxic and responsible for acid rain. Arsenic emission can also be a concern, depending on the ore mineralogy. Fossil fuels such as coal, fuel oil, or natural gas are necessary for heating and as a reducing agent; thus, most processes emit GHG. Fluxes such as limestone, silica, or dolomites are also essential inputs, as they help to form more liquid slag.

Smelting operations are evolving, with various advanced technologies in use. Traditional reverberatory smelting, such as employed at the above-noted former Gaspé smelter, is no longer in use. Flash and bath smelters are among the main technologies. In 2022, flash technologies accounted for 66% of smelting operations. Notably, newly developd bath smelting Chinese technologies, are projected to contribute about 23% of smelting capacity by 2027. China, a significant player in the industry, produced nearly 50% of the world's smelted copper in 2022 and is home to 9 of the largest 20 copper smelters globally.[45]

After smelting and conversion, blister copper can be either fire-refined and melted as lingots for sale or cast in the shape of copper anodes in furnaces. Copper anodes are then electro-refined to cathode copper at the copper refinery. This plant consists of a series of electrolytic tanks, each containing anodes and cathodes. In electrorefining, the supplied electricity electrochemically dissolves copper from the anodes held in an acidified copper sulfate solution, and this causes selective plating of dissolved copper in the very pure form on the copper cathodes. The electricity requirement at a copper refinery is moderate, at approximately 350 kWh per tonne of cathode copper. This last electrochemical step is why electricity is crucial in copper refining: it requires large amounts of inexpensive and clean electricity, although less so for electrorefining than for electrowinning. Therefore, jurisdictions where electric power is cheap and plentiful are often attractive, but not necessarily in the exact location where ore is extracted or processed.

The obtained copper cathode is over 99.99% pure and is ideally suited for use in rod or wire mills, other electrical uses as well as at brass mills, or foundries to manufacture semi-finished products such as copper foil, wires, powders, castings, *etc*. Nearly 75% of copper is used in electrical wires or for wiring in industrial machinery.[43] As for copper foil used for current conductors in batteries, they are either rolled or electrodeposited.[32,33,55,56]

3.2.2 Hydrometallurgy



1. **Leaching** allows the obtention of copper sulfate solutions by using acid and water onto copper oxide ores. Copper sulfides are less susceptible to leaching but new technologies can process them (bioleaching, O_2 pressure, chloride, etc.)

2. **Solvent extraction (SX)** removes the copper(II) ions from the copper sulfate solution by mixing it with diluents (hydrocarbon, paraffin, kerosene, etc.) and extractants (specialty chemicals).This is a closed loop and increase the concentration of copper.

3. **Electrowinning (EW)** uses electricity and an inert lead anode to deposit pure copper on the cathode, while the concentrated copper solution from SX acts as an electrolyte.

Figure 5 Flowsheet of the hydrometallurgy of copper

Hydrometallurgy, or the processing of copper ores through in-solution chemical processes, typically using acid, has been used in the U.S. since at least the 1920s. Until 1968, copper was typically recovered as cement copper by deposition on iron. In 1968, the first copper ion exchange plant with copper electrowinning was operated in Arizona. This new technology was far superior, and the development accelerated the application of the leaching of copper oxide ores. Thus, leaching, solvent extraction and electrowinning processes, or SX-EW, represented 19.6% of global copper production in 2022, a trend steadily increasing since the 1960s.[45] Copper oxide ores are more fitting toward SX-EW techniques, as copper sulfide minerals cannot be leached directly without being oxidized first. Under the right conditions, bacteria can oxidize copper sulfides through specific bioleaching processes. Alternative technologies, such as O_2 pressure or chloride treatment technologies, were also developed for copper concentrates. Efforts are currently underway to enable low-grade sulfide ores to be heap leached at the mine sites. Copper sulfide leaching technologies can be expensive to develop, slow and usually focused on one deposit mineralogy rather than smelters, which are more universal in feedstock.

Leaching, the first step of the hydrometallurgical route allows the obtention of copper(II) ions by using acid and water on copper oxide ores. The primary acid is usually sulfuric acid, thus obtaining copper (II) sulfate **$CuSO_4$** in the solution. Alternative techniques using hydrochloric acid or ammonia are more marginal. Heap leaching is the primary process, and it is suitable for large-capacity operations with a higher grade of oxidic copper ores. Ores undergo crushing before being deposited on a pile for acid treatment, while the pregnant liquor is collected at the bottom. The treated copper oxide minerals are typically azurite, chrysocolla, or malachite, but sometimes cuprite, tenorite, or native copper are present.

Dump leaching, a more marginal process, typically has a lower production rate than heap leaching. It is relegated to lower-grade ores and depending, can bypass the need for crushing. Bacteria are required for the oxidation of sulfidic ores, and the entire process necessitates longer timelines of 1–2 years.

After acid treatment, the pregnant leach solution undergoes solvent extraction prior to electrowinning. The solvent-extraction (SX) process removes the copper ions from the pregnant leach solutions by mixing them with different solvents (hydrocarbons, paraffin, kerosene, *etc.*) and extractants (specialty chemicals selective for sequestrating copper ions). By working in a closed loop and Includeing mixing, gravity separation and stripping steps, the copper concentration is increased to 40–50 g/L. Iron is removed, nickel, cobalt, zinc, antimony, and various precious metals can also be recovered. The barren sulfuric acid can also be recycled for leaching.

The final step, electrowinning (EW), uses electricity and an inert lead anode to deposit a layer of pure copper on a stainless-steel sheet cathode. The higher concentration copper sulfate electrolyte solution produced from the solvent extraction step is used as the electrolyte, allowing copper ions to migrate and deposit onto the cathode. The main difference between electrowinning and electrorefining, as used on copper anodes at the end of the pyrometallurgical route, is that electrowinning needs a higher voltage potential, which makes this step more energy-intensive. Typical power usage averages about 2,000 kWh/tonne of cathode copper. The copper cathodes can then be sold and transported to rod and wire mills, brass mills and semifinished manufacturers.

Alternatively, copper precipitation and cementation is another process that allows the conversion of copper(II) ions in solution to metallic copper, without the use of electrical current. However, the purity of copper cement can typically be lower than that of copper cathodes obtained by electrolytic reduction (EW). Canadian start-up company Destiny Copper is developing a process to optimize copper precipitation at high purity, which could replace energy-intensive electrowinning and also be used for scrap leaching and recycling.

3.2.3 Scrap Recycling

Copper can be readily recycled, and the metal can be reused without losing quality. It is estimated that around two-thirds or more of all the copper ever extracted throughout history is still in use.[57] Depending on how recycled copper is counted, the reported average percent of recycled copper varies somewhat. Thus, the IEA estimates that the copper recycling rate is around 45.5%, while the ETC calculates a 60% rate.[25,50] According to the International Copper Study Group, in 2022, 32% of global copper use could be traced back to recycled copper. This represented around 8.7 million tonnes of copper per annum from end-of-life products (old scrap) or discarded copper products during manufacturing processes (new scrap). Another category of secondary copper source is direct scrap, obtained from melting and refining processes in copper manufacturing. At the refinery level, secondary refined copper production reached 16.2% of total refined copper production in 2022.[45]

Copper scrap is inspected, graded, and analyzed chemically if necessary. Depending on the purity of the collected scrap purchased, it can be either directly melted for relatively high-purity batches or fire-refined before casting into ingots, billets, or other shapes for further processing. Alternatively, it can be electrolytically refined if the purity is lower. Copper alloys can also be recycled after identification and melting.[58] Although secondary copper supply could meet 45% of the demand necessary for the energy transition, more primary output will be needed in the future.[25]

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