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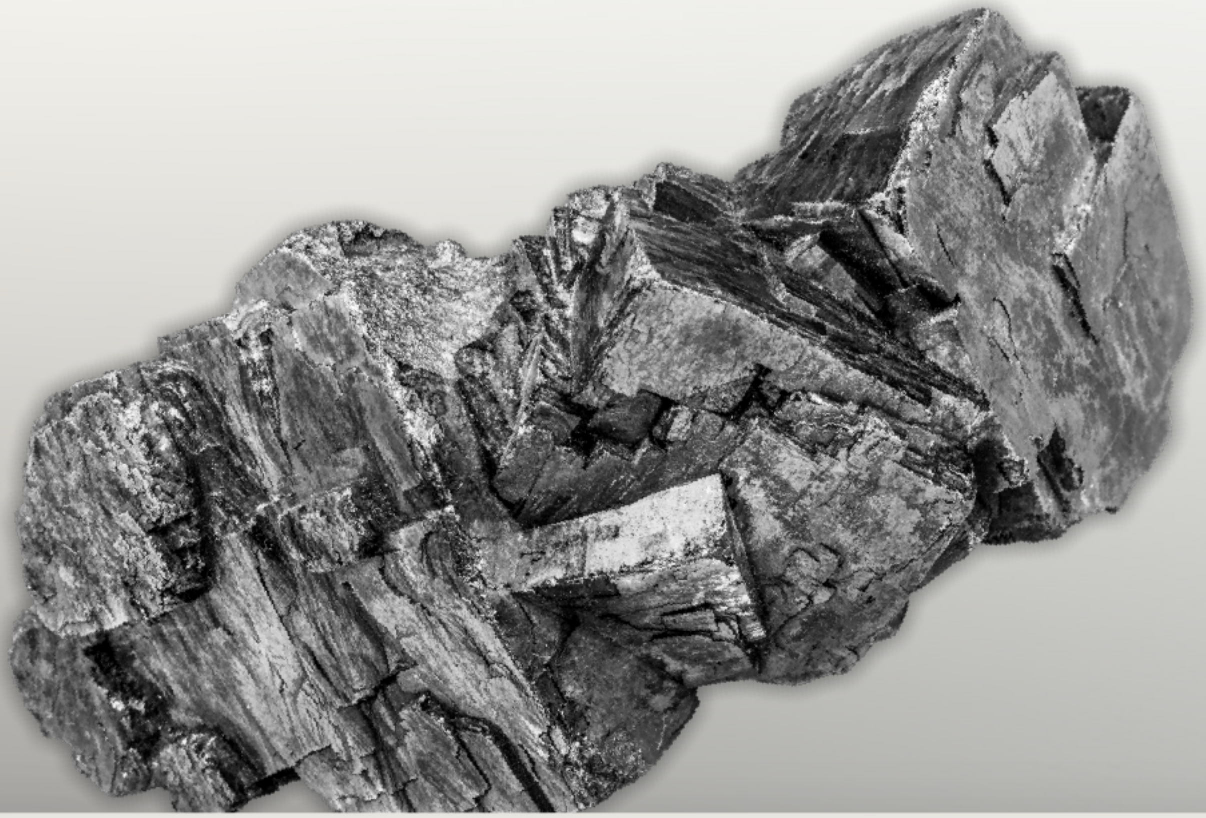
FOCUS ON

NICKEL



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 Nickel

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About Us

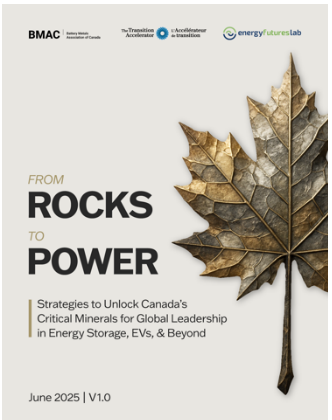
The Battery Metals Association of Canada (BMAC) is a national non-profit association of industry participants and champions from across all segments of the battery metals value chain. From mining to specialty chemical refining, manufacturing, end use and recycling, BMAC is focused on coordinating and 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 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.

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

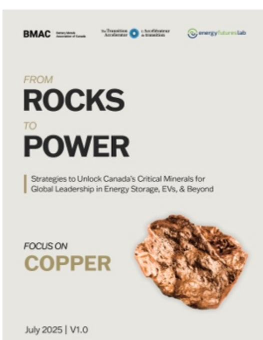


This chapter is part of a larger report, *From Rocks to Power: Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, and Beyond*. The full report identifies clear, investable priorities in eight minerals, each of them critical to building resilient EV and energy 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.

Read the full report here »

Additional chapters are available for download below:

Copper »



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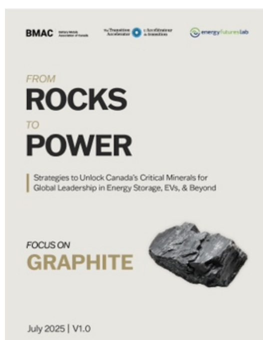

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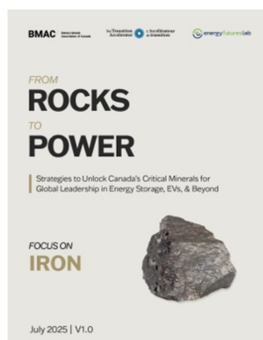

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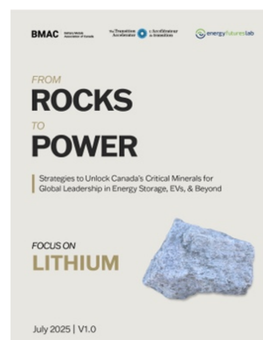
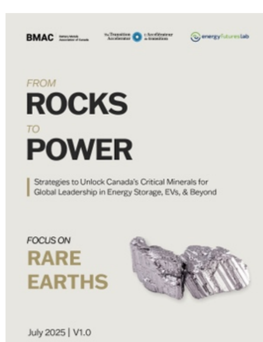


Phosphate »

Rare Earths »



Vanadium »

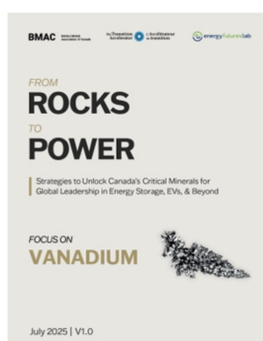


Table of Contents

Table of Figures

Table of Tables

Nickel

1 The Canadian Nickel Strategy

1.1 Nickel in Canada

Table 1 Non-exhaustive selection of former and future nickel extraction and processing projects in Canada

Selection of Operational Nickel Extraction Sites				
Project Name	**Company**	**Province**	**Type**	**Status**
Voisey's Bay	Vale	NL	Nickel Sulfide	Operational
Raglan	Glencore	QC	Nickel Sulfide	Operational
Nunavik Nickel	Canadian Royalties	QC	Nickel Sulfide	Operational
Sudbury Intergrated Nickel Operations	Glencore	ON	Nickel Sulfide	Operational
Strathcona	Glencore	ON	Nickel Sulfide	Operational
Nickel Rim South	Glencore	ON	Nickel Sulfide	Operational
Coleman Mine	Vale	ON	Nickel Sulfide	Operational
Garson	Vale	ON	Nickel Sulfide	Operational
Clarabelle	Vale	ON	Nickel Sulfide	Operational
Copper Cliff Complex	Vale	ON	Nickel Sulfide	Operational
Creighton	Vale	ON	Nickel Sulfide	Operational
Fraser	Vale	ON	Nickel Sulfide	Operational
Totten	Vale	ON	Nickel Sulfide	Operational
Thompson Mine	Vale	MB	Nickel Sulfide	Operational
Selection of Future Nickel Extraction Projects				
Project Name	**Company**	**Province**	**Type**	**Status**
Dumont	Dumont Nickel	QC	Nickel Sulfide	FS 2019
Crawford Project	Canada Nickel	ON	Nickel Sulfide	FS 2023
Eagle's Nest	Wyloo	ON	Nickel Sulfide	FS 2025
Makwa-Mayville	GridMetals Corp	MB	Nickel Sulfide	PEA 2014
Minago	Norway House Cree Nation	MB	Nickel Sulfide	FS 2011
Baptiste Nickel Project	FPX Nickel	BC	Awaruite	PFS 2023
Turnagain Project	GigaMetals	BC	Nickel Sulfide	PFS 2023

Selection of Former, Operational and Future Nickel Metallurgical Plants				
Project Name	**Company**	**Province**	**Type**	**Status**
Long Harbour Nickel Processing Plant	Vale	NL	Hydrometallurgy	Operational
Sudbury Smelter	Glencore	ON	Pyrometallurgy	Operational
Copper Cliff Smelter & Refinery	Vale	ON	Pyrometallurgy	Operational
Thompson Smelter	Vale	MB	Pyrometallurgy	Closed in 2018
Fort Saskatchewan Refinery	Sherritt	AB	Hydrometallurgy	Operational
NetZero Nickel	Canada Nickel Company	ON	Pyrometallurgy	2027
Selection of Future Nickel Sulfate Plants				
Project Name	**Company**	**Province**	**Type**	**Status**
Bécancour Nickel Sulfate Plant	Vale	QC	Nickel Sulfate Plant from Vale's products	2026
North American Nickel	Electra Battery Materials	ON	Nickel Sulfate Plant + pCAM	Unknown

The U.S. Geological Survey ranks Canada as the 6th largest nickel producer in the world for extraction in both 2021 accounts and 2022 estimates, which agrees with data from Natural Resources Canada.[1–3] Historically, Canada was much more prominent in the nickel sector during the most part of the 20th century,[4] and was especially leading the way for both extraction & refining in the Sudbury area. Canada now only accounts for 4–5% of the world's nickel production. Production decreased in 2021 due to a 70-day strike at Vale's Sudbury mine over bargaining for a better collective worker agreement with United Steelworkers.[5–7] Domestic production is located in four provinces: Quebec with the Raglan mine in Nunavik (Glencore), the Sudbury region in Ontario (Glencore, Vale), Labrador at the Voisey Bay mining site (Vale), and Thompson, Manitoba (Vale). All operated deposits are sulfide ores.

The main nickel processing plants and refineries in Canada: There are currently several operational nickel refineries in Canada: one in Fort Saskatchewan, AB, operated by Sherritt, converts mixed sulfide precipitates (MSP) from its operations in Moa Bay, Cuba, to nickel powder according to an ammonia pressure hydrometallurgical process.[8,9] Glencore (previously Falconbridge) owns an electric furnace smelter in Sudbury, ON to refine its sulfide concentrates from the Raglan mine and its neighbouring Sudbury INO mine.[10–13] The obtained nickel matte is shipped to Nikkelverk, Norway, for leaching and subsequent nickel cathode production by electrolytic refining.[14] Within the Sudbury Basin, Vale (previously Inco) also owns a nickel smelter and refinery in Copper Cliff. The same company previously owned a refinery in Thompson, Manitoba, which was shut down in 2018.[15] Vale has also opened a hydrometallurgical plant in 2009 in Long Harbour, Newfoundland, to process concentrates from its Voisey Bay site to pure nickel cathode.

Three sizeable Canadian projects concerning low-grade ultramafic nickel sulphide mining are currently at an advanced stage. One is in the Golden Triangle/Copper Corridor of North British Columbia; GigaMetals operate the Turnagain deposit; the Crawford project is operated by Canada Nickel near Timmins, Ontario; and the Dumont project is managed by Dumont Nickel and is located in Abitibi in Northwestern Quebec. All three projects can be upgraded into good concentrates, which can be treated through various processes such as hydrometallurgical pressure oxidation, pyrometallurgical flash smelting or roast-EF smelting. All three projects also plan to sequester carbon in the tailings by mineralizing CO_2 into magnesium carbonate, starting from serpentinite or brucite. Several smaller nickel sulfide projects also exist in Ontario and Manitoba, such as Wyloo's Eagle's Nest project, an underground mine project with nickel, copper and PGEs in the Ring of Fire, the Makwa-Mayville projects in the Bird River Greenstone Belt in Manitoba, and the Minago project by the Norway House Cree Nation in Manitoba's Thompson Nickel Belt.

Additionally, FPX is looking to open an awaruite mine in Baptiste, BC. Awaruite is not a sulfide nor an oxide nickel ore but a high-content native nickel–iron ore. Simple beneficiation processes after mining could provide 60% Ni concentrate, ready for leaching for battery cathode purposes and would yield MHP as a by-product. This process would bypass pyrometallurgy or early hydrometallurgy stages and be among the lowest carbon-intensive nickel production sites in the global nickel market.[16–19] A scoping report for such a leaching facility was published in early 2025.[20]

Bécancour, QC– A new hub for nickel-rich battery material production: With its proximity to major highways, railways and deep-water port, important government incentives and inexpensive access to green hydropower, Bécancour, Quebec, has attracted many midstream actors of the EV value chain.[21,22] Vale, General Motors, and South Korean company Posco Chemicals will build a refinery and cathode active material plant capable of producing 25,000 tonnes of nickel sulfate per year starting in 2026 that General Motors will use for its Ultium batteries. The quantity of nickel is sufficient to supply batteries for 350,000 electric vehicles a year.[23–25] Concurrently, Ford, SK On and EcoPro BM formed a joint venture and secured federal and provincial government funding to open their own cathode active material plant in Bécancour in 2026.[26–29] Currently, SK On is known for supplying Ford with NMC9 batteries to Ford for its EV truck F-150 Lightning using cathode materials from EcoPro BM. The new site was announced as capable of manufacturing up to 45,000 tonnes of cathode active materials per year, sufficient to support the fabrication of 225,000 electric vehicles annually. However, Ford recently announced that it is backing off from this project, leaving EcoPro BM and SK On to find another off-taker. Additionally, BASF was previously clearing land for a future cathode active material and recycling site, with the ambition to expand up to a production of up to 100,000 tonnes of cathode active material a year.[30,31] However, this project seems to have been cancelled as well. Finally, Northvolt, a Swedish battery cell manufacturer, has begun construction of its new plant on the southern shore of Montréal, despite overall financial challenges and the filing for bankruptcy protection in the U.S. and Sweden.[32,33]

In Ontario, Electra Battery Materials is building a cobalt sulfate refinery in Temiskaming Shores and plans to explore the feasibility of a battery nickel sulfate refinery as well. Additionally, Electra plans to operate battery recycling operations, from black mass to recover materials such as MHP and lithium carbonate. Several other Canadian players, such as Li-cycle, Lithion, Battery X and Recyclico, are interested in producing nickel sulfate from black mass.

Volkswagen is currently building its first North American EV battery cell gigafactory in St. Thomas, Ontario, planned to open in 2027.[34,35] Volkswagen currently relies on nickel-rich batteries such as NCM 712 for its EVs. Stellantis and Energy Solution Battery have opened a battery cell factory in Windsor, Ontario, to manufacture NMC units. The production of modules is operational while cell manufacturing is planned for later in 2025.[36–38]Umicore had announced interest in opening a CAM plant in Loyalist, Ontario, but the project was paused in 2024. The same year, Honda announced a major project to manufacture both electric vehicles and batteries in Alliston, Ontario. Finally, General Motors previously planned the manufacture of battery modules and packs at its Ingersoll site in Ontario, but the current status of the project is unknown [39]

1.2 Target

Our previous report, 'Roadmap for Canada's Battery Value Chain,' established nickel objectives: Canada can reach 10% of the 2030 North American EV market as a baseline, but a leader scenario aiming at 35% should be implemented. Canada hosts much larger nickel resources than the USA, making a target much higher than the 10% share of the vehicle market relevant and necessary for re-shoring supply chains.

Table 2 Nickel Targets

Nickel Mandated Benchmark (10% of 2030 North American Market)		
	2030	**2040**
Nickel (ktpa elemental)	37	74
New mines	1	2
New refining facilities	1	2
Nickel Leader scenario (35% of 2030 North American Market)		
Nickel (ktpa elemental)	130	175
New mines	3–4	4–5
New refining facilities	2	3

1.3 Scenario Outline

Canada should maximize nickel production to capture a significant share of the North American market and aim to bring 130,000 tpa online by 2030 through ongoing project, new ones and operating assets.

- Ramp up the current mining and processing nickel sulfide chain (NL, QC, ON) and imported laterite processing (AB).
- In the short term, the import and processing of international supplies in Canada (MHP, MSP or Matte).
- In the long term, mining operations in BC and a large processing centre should be developed to produce $NiSO_4$, nickel metal, or pCAM with black-mass integration for future battery circularity.

1.4 Signature Projects

- Strengthen brownfield expansion of existing nickel mining and processing structures (NL, QC, ON, AB)
- Develop 3–4 large new mining operations (35–40 ktpa of elemental nickel).
- Build a large metallurgical facility in BC using either hydrometallurgy alone or a mix of hydro-and pyrometallurgy and integrating black mass on top of nickel ores as a feedstock. It should first use imported laterite precipitates as feedstock while supporting domestic sulfide concentrates when it comes online later through pressure oxidation.

1.5 Strategic Priorities

- **Build a Large Nickel Processing Complex in BC for Emerging Supply based on Synergies:**
    - **Smelt Turnagain sulfide concentrates to matte:** The planned complex will specialize in smelting Turnagain sulfide concentrates to produce matte, a semi-refined form of nickel. This involves the pyrometallurgical treatment of concentrates at extremely high temperatures to separate nickel from other elements. The resulting matte will serve as an intermediate product and will be further refined.
    - **Sulfur Capture and Synthesis of Sulfuric Acid:** In the smelting process of sulfide concentrates, sulfur dioxide (SO_2) is a common byproduct, which will be captured and processed into sulfuric acid. This conversion mitigates harmful emissions and generates a valuable chemical used extensively in mining and chemical industries. The sulfuric acid can be utilized on-site for leaching processes or sold to other industrial users, creating a beneficial byproduct stream that enhances the economic viability of the complex.

- **Additional Sulfuric Acid from Zinc Smelting Operations at Trail:** The zinc smelting operations at Trail could serve as a supplementary source of sulfuric acid. This integration allows the nickel complex to leverage existing infrastructure and resources, ensuring a consistent supply of sulfuric acid for leaching operations. This collaboration also exemplifies efficient resource use, promoting sustainability by reducing the need for new acid production facilities.
- **Leaching Decar Awaruite Ores with Sulfuric Acid:** The Decar Awaruite ores differ from the traditional nickel sulphide ores in that it does not contain sulphur and it is strongly magnetic. The sulfuric acid produced by the Turnagain ore smelting and/or originating from the Trail smelter could potentially be used to perform hydrometallurgical processing of awaruite. The legacy infrastructure from the pulp and paper industry, such as the sulfuric plant in Prince George, is another alternative. Indeed, the treatment of awaruite concentrates by pressure leaching with sulfuric acid leads to the production of nickel sulfate. Alternatively, another innovative approach would be to involve the pressure oxidation of sulfide concentrate, using a small quantity of awaruite as a neutralizing agent. This method not only breaks down sulfide minerals more effectively but also manages the acidity levels in the process, reducing the need for additional neutralizing chemicals. This alternative route offers flexibility in processing different types of ore, enhancing the adaptability of the complex to various feedstocks.
- **Utilization of Kitimat Port for Importing Reagents:** Kitimat port's strategic location will be crucial for importing necessary reagents and raw materials, such as acids, bases, and other chemicals essential for ore processing. The port's infrastructure supports efficient logistics, ensuring timely delivery and reducing potential bottlenecks in the supply chain. This accessibility is vital for maintaining continuous operations and optimizing production schedules.
- **Securing Sodium Hydroxide Supply:** Sodium hydroxide (NaOH) is an essential reagent in various hydrometallurgical processes, including concentrate leaching and neutralizing acidic waste streams. Ensuring a steady supply of NaOH will be critical for the complex's operations. This involves determining the optimal location for NaOH production and addressing the management of chlorine byproducts, a common issue in NaOH production. Another option for treating low-magnesium materials would be to use ammonia as a base to make ammonium sulfate by-products.
- **Access to Affordable and Green Power:** The complex's energy requirements will most likely be substantial, necessitating access to affordable and green power. British Columbia's rich hydroelectric resources offer a sustainable and cost-effective energy source, aligning with global sustainability goals. This access will not only lower operational costs but

also reduce the carbon footprint of the nickel production process, enhancing the complex's appeal to environmentally conscious markets and investors.

- **Production of $NiSO_4$ for pCAM or Direct pCAM Production:** The facility will focus on producing nickel sulfate ($NiSO_4$), a key precursor for precursor cathode active material (pCAM), used in the manufacturing of lithium-ion batteries. The $NiSO_4$ can be obtained through the leaching of nickel matte from the nickel sulfide smelter or from the leaching of awaruite concentrates or nickel sulfide concentrates. Producing pCAM directly from the nickel sulfate solution may be possible without the solid nickel sulfate hexahydrate intermediate. The choice between producing $NiSO_4$ or directly producing pCAM will depend on several factors, including the stability of pCAM and the proximity to battery manufacturing facilities. If pCAM is stable only for a few days or weeks, the production facility must be located near battery manufacturers to prevent degradation. However, if pCAM can be stored for months, the complex can operate with greater flexibility regarding location and logistics.
- **Production of Nickel Metal for Export and Market Hedging:** Alternatively, or in addition to producing battery materials such as $NiSO_4$ or pCAM, the complex could produce refined nickel metal in the form of nickel cathodes. This output will cater to various industries, including stainless steel manufacturing, which is a significant consumer of nickel. Producing nickel metal provides a hedge against market fluctuations and uncertainties in battery technology by allowing transactions with the LME as a market of last resort, ensuring the complex remains economically viable even if demand for battery-grade materials fluctuates.
- **Integration of Black Mass Leaching and Recycling:** The facility should incorporate processes for leaching and recycling black mass, the mixture of materials recovered from end-of-life batteries. This initiative is critical for establishing a sustainable and circular supply chain for nickel and other valuable elements, such as lithium and cobalt. While economically and technically challenging, starting these processes now will position the complex as a leader in sustainable resource management.
- **Connection to U.S. Markets and Western U.S. Battery Manufacturing:** Providing that tariff tensions are eased and geopolitical circumstances allow it, establishing robust connections with U.S. markets and Western U.S. battery manufacturing facilities can be a strategic priority. This connection will facilitate the export of nickel products and support the development of an integrated North American market for nickel-based products. It will also help the complex tap into the growing demand for electric vehicles and renewable energy storage solutions in the region. Diversifying by tapping into different markets from friendly nations will be necessary if the tariff war lags on.

- **Collaboration with Downstream Industries:** The complex should actively collaborate with downstream industries to define export destinations for its products, focusing on major markets such as Japan, Korea, and the U.S., if the situation allows. This collaboration will ensure that the complex produces materials that meet the specifications and quality standards required by these markets, enhancing the competitiveness and marketability of its products.
- **Clear Definition and Coordination of the Processing Facility:** The successful operation of the processing facility requires clear definition and coordination across different industries involved in the supply chain. This includes aligning production schedules, ensuring consistent quality control, and facilitating effective communication between all stakeholders. A coordinated approach will optimize the facility's output, reduce inefficiencies, and maximize economic returns.

- **Research & Development:**
  - **Prioritizing Proven Technology:** While innovation is essential, the immediate focus should be on implementing proven technologies that can be quickly and reliably deployed. This approach minimizes risks and ensures that the nickel projects proceed without unnecessary delays. By leveraging existing technologies, the complex can achieve rapid development and start generating revenue sooner.
  - **Preparing for Battery Circularity and Black Mass Recycling:** As mentioned for the planned metallurgical complex, developing industrial processes for recycling black mass is crucial for achieving a circular economy in the battery industry. This involves recovering valuable metals such as nickel, cobalt, and lithium from spent batteries, which can then be reused in new battery production. Establishing efficient recycling processes will reduce the demand for virgin materials and lower the environmental impact of battery production and disposal.
  - **Developing Economically Viable Salt-Splitting Methods:** Developing economically viable salt-splitting methods is essential for addressing the challenges associated with sodium sulfate (Na_2SO_4) disposal. Sodium sulfate is a byproduct produced when sodium hydroxide neutralizes sulfuric acid in leaching or purification processes, for example, when MHP or awaruite is refined, or when pCAM is produced. It is often a voluminous waste, especially for mines and battery material plants outside of China. Disposal of sodium sulfate-containing effluents to ocean waters is a viable approach for coastal locations but may be more difficult to permit. Disposal of effluents *via* deep wells —similar to what is done widely in the oil industry— may be feasible in some locations (such as Alberta and Saskatchewan) but may also introduce permitting challenges. Salt-splitting would involve separating sodium and sulfate ions into valuable sodium hydroxide and sulfuric acid products, reducing waste and potential environmental impacts. Long-term demonstrations and validation of these

methods are crucial to ensure they are both technically feasible and economically viable for large-scale implementation. It is worth mentioning that if magnesia or ammonia is used as a neutralization agent, sodium sulfate is not the issue.

  - **Optimizing Hydrometallurgical Methods:** Smelters are more universal than hydrometallurgical processes to treat nickel concentrates, but they emit GHGs, and other air contaminants including SO_2 and metals-bearing dusts. Research efforts should focus on optimizing hydrometallurgical methods to process a broader range of nickel feeds. Typically, other transition metals such as copper, cobalt, zinc and iron, and alkali/alkali-earth elements like sodium, magnesium, potassium and calcium can be contaminants of concern for hydrometallurgical processes. Arsenic, selenium and antimony are usually easily addressed.
  - **Developing Robust Processes for Dealing with Impurities:** Managing impurities becomes a critical aspect of maintaining product quality. Research will focus on developing robust processes for removing impurities such as arsenic, lead, and other undesirable elements. These processes will ensure that the final products meet the stringent purity standards required for high-value applications, including battery manufacturing.
  - **Re-Processing of Value Tails and Slags:** Reprocessing value tails and slags offers an opportunity to recover additional valuable elements, including platinum group elements (PGE) and other byproducts. This initiative not only maximizes resource utilization but also reduces the environmental impact of waste disposal. By extracting these elements, the complex can generate additional revenue and enhance its overall economic viability.
    - **Optimization of PGE Recovery and Other Value-Added Elements:** In particular, optimizing the recovery of Platinum Group Elements (PGEs) and other value-added elements is essential for maximizing the economic returns from the complex. These elements include ruthenium, rhodium, palladium, osmium, iridium and platinum. Those elements would be absent from any imported MHP/MSP, but could be present in economic quantities from imported matte.
  - **Public-Private Partnerships for Applied R&D:** Engaging in public-private partnerships will facilitate applied research and development, leveraging the expertise and resources of both sectors. These partnerships will accelerate the development of new technologies and processes, ensuring that innovations are quickly brought to market.
- **Build a Net-Zero and Competitive Nickel Supply Chain:**
  - **Access to Clean and Affordable Electricity or Alternative Sources with Offsets:** As mentioned earlier in the specific requirements for a large nickel processing complex, ensuring access to clean and affordable electricity is fundamental to the successful operation of a nickel supply chain that aims to be both competitive and environmentally sustainable. The integration of

this requirement into a national clean energy strategy for critical minerals is required. Additionally, exploring options for carbon offsets to compensate for any non-renewable energy used will further align the supply chain with global carbon reduction goals.

- **Implementation of CO_2 Sequestration at the Mine Site:** To minimize the carbon footprint of nickel mining operations, CO_2 sequestration techniques can be implemented at the mine site for some deposit types. This involves capturing carbon dioxide emissions from the air directly or from emissions produced during mining and processing and storing them underground or using them in industrial applications. Notably, natural deposits of brucite or serpentine can be used to mineralize carbon dioxide by forming new, stable and storable rocks. These strategies are envisioned for large nickel projects such as Turnagain or Crawford, and they could potentially achieve net zero at the mine level. This potential for net zero has still to be nuanced by the fact that there is currently no viable technology option today for capturing CO_2 for heavy equipment, the most likely source at mine sites. CCS could be viable in the case of a large stationary emitter, such as a fossil-fuel plant or in-site refinery. Capturing CO_2 at a centralized smelter or refinery and transporting it to the mine site would not be successful unless the CO_2 price reaches >$200/t.
- **Design of Efficient Waste Disposal Systems for Slag, Leach Residues, and Other Solid Residues:** The design and implementation of efficient waste disposal systems for slag, effluents from leaching facilities, and solid residues are critical to maintaining environmental sustainability. This involves developing processes to treat and manage waste materials generated during nickel extraction and processing. Techniques such as solidification, stabilization, and recycling of waste products will be explored to minimize environmental impact.
  - **The Different Environmental Issues Between Smelters and Hydrometallurgical Facilities:** Smelters have SO_2 and metal-bearing dust, which can cause widespread pollution issues. Slag as a solid residue is more benign and can sometimes be used as a construction material, mainly as an aggregate replacement. Hydrometallurgical plants have fewer air pollution issues but can have challenging effluent and leach residues. The effluents are often managed by ocean disposal (*e.g.* sulfate-chlorides effluents from the Long Harbour plant). Leach residues are more voluminous than slag and are generally less chemically stable.
- **Implementation of a Hub and Spoke Model for Concentrate Production and Refining:** A hub and spoke model will be adopted, wherein nickel concentrate is produced at the mine sites and then transported to central hubs for further refining. This model optimizes logistics and processing efficiency by centralizing complex refining operations while keeping initial processing close to the ore source. The refined products, such as mixed

sulfide precipitate (MSP) and mixed hydroxide precipitate (MHP) or high-purity end products, can then be distributed to various markets. This approach reduces transportation costs and environmental impact while ensuring consistent product quality.

- **Development of Transportation Infrastructure for Concentrates and Intermediates:** Developing robust infrastructure and leveraging the existing one for transportation is essential for efficiently moving nickel concentrates and intermediates from mine sites to refining hubs and final markets. This includes constructing and maintaining roads, railways, ports and dry ports, as well as establishing efficient logistics networks. A nominal 35 ktpa nickel mine will produce 150–350 ktpa of nickel concentrates to be transported to central processing facilities.
- **Securing a Stable Supply of Sodium Hydroxide, Ammonia or Magnesia:** As previously noted, sodium hydroxide (NaOH) is a critical reagent in the hydrometallurgical processing of nickel. Securing a stable and reliable supply of NaOH is essential for continuous operations that utilize this reagent. This involves negotiating long-term contracts with suppliers, exploring options for local production, and ensuring efficient storage and handling facilities. Addressing potential supply chain disruptions and managing the environmental impact of NaOH production and use will be key considerations. Alternatively, ammonia or magnesia are also viable reagents for different parts of the processes with different supply chain complexities. Ammonia reduces waste management issues but introduces byproduct management issues: the ammonium sulfate produced can be sold as fertilizer.

- **Collaboration with the Government**
  - **Coordinated Efforts Between Government and Industry for the Midstream segment:** A coordinated effort between government and industry is crucial to investing in refining and processing capacity for nickel. This involves establishing policies and incentives that encourage private investment and facilitate public-private partnerships. A significant issue that appears to hang over the nickel supply chain is the lack of interest in substantial expansion and cooperation by the dominant companies in Canada. By working together, stakeholders can build a robust and integrated battery nickel supply chain, leveraging each other's strengths and resources.
  - **Facilitation of Government-Level Coordination and Interprovincial Collaboration:** Effective coordination between different levels of government and interprovincial collaboration will be necessary to develop a seamless supply chain. This includes aligning regulatory frameworks, sharing resources, and fostering communication between provinces. Such collaboration will streamline operations, reduce bureaucratic hurdles, and

ensure that all regions benefit from the development of the nickel supply chain.

  - **Development of an Integrated Supply Chain for New Mines Starting Production:** Ensuring that the supply chain is ready for new mines expected to start production before 2030 involves forward planning and investment in infrastructure, technology, and human resources. This preparation will enable a smooth transition from mining to processing and distribution, ensuring that new operations are integrated into the supply chain without delays.
  - **Funding to Support Mine Production:** Funding programs, such as those from the Canada Infrastructure Bank (CIB) or the Critical Mineral Infrastructure Fund (CMIF), will play a crucial role in bringing new mines into production. These funds can be used to develop necessary infrastructure, support technological innovation, and enhance operational efficiency. Depending on geopolitical imperatives, the U.S. Department of Energy (DOE) and the Department of Defense (DoD), as well as Japan, Korea, the European Union and its member countries, can also be potential funding sources.
  - **Creation of Incentives for Businesses in the Critical Minerals Space:** Creating incentives for businesses operating in the critical minerals sector will attract investment and innovation. These incentives can include tax breaks, grants, and subsidies for research and development, as well as streamlined regulatory processes. Encouraging businesses to invest in nickel processing and refining will enhance the supply chain's capacity and competitiveness.
- **Protection from Price Volatility and Secure Off Taker:**
  - **Facilitation of Stability and Certainty through Government Procurement:** Government procurement policies can provide stability and certainty for the nickel supply chain by ensuring a consistent demand for locally sourced critical minerals. This can be achieved through contracts for differences, government-guaranteed future purchases, or buffer stock mechanisms. Contracts for differences have been successfully applied in Alberta for the development of renewable energy.[40] Such measures will protect the supply chain from market fluctuations and ensure a steady revenue stream for producers. Several mechanisms are explored in a recent report published by the Centre for Net-Zero Industrial Policy.[41]
  - **Securing Korean and Japanese Cathode and Battery Manufacturing Companies:** Attracting Korean and Japanese cathode and battery manufacturing companies to Canada as off-takers will create a reliable demand for nickel products. These companies are key players in the global battery market and securing their business will strengthen the supply chain's market position. Negotiating fair technology transfer agreements will also ensure that Canadian companies benefit from the expertise and

innovation of these international partners. Canadian firms also hold intellectual property of value, especially in the metal processing space.

2 Nickel: The Most Wanted Metal for High-Performance NMC Battery Cathodes

2.1 General Properties

Nickel is a silver-white metal with a brilliant polish aspect, ductile and malleable properties and a hardness superior to iron. Along with iron, cobalt, and gadolinium, nickel is one of only ferromagnetic elements around room temperature, *i.e.*, it exhibits a strong attraction to magnetic fields and the possibility of becoming a permanent magnet. On the other hand, its electrical conductivity is more moderate, only slightly surpassing iron. Nickel also bears a relatively high melting point (1,455ºC), and along with its alloys, it maintains its strength and integrity at elevated temperatures, making it suitable for high-temperature uses. One significant chemical property of nickel is its good corrosion resistance, especially in alkaline environments (with a basic/high pH) marine or industrial atmospheres, where a protective oxide layer formed primarily of nickel oxide NiO readily forms. However, an acidic or highly oxidizing environment can significantly weaken this protective layer and jeopardize the metal's integrity. Because of those versatile characteristics, nickel forms numerous alloys, improving strength, toughness, corrosion resistance, and high-temperature properties. Almost 60% of nickel production is used for stainless steel, but other alloys have found significance in aerospace, chemical processing, the oil and gas industry, shipbuilding, or naval armour. Nickel plating on base metals commonly strengthens used items (keys, pins, scissors, paper clips, *etc.*). Finally, nickel and its compounds play an essential role as a catalyst, as it can absorb 17 times its volume of hydrogen. Nickel catalysts are used for several important reactions within the chemical industry, such as hydrogenation (fats and oil for the food industry), reforming of hydrocarbon (production of gas and fuels), methanation (production of synthetic natural gas), ammonia synthesis (critical for fertilizer industry) or steam reforming (H_2 production from hydrocarbons), thus highlighting the crucial role of this metal for several strategic sectors.

Examples of applications for Nickel materials

Figure 1 Examples of applications for nickel materials

The unintentional use of nickel in alloys such as bronze dates back to 3500 BC.[42] An alloy of 60% copper, 20% nickel and 20% zinc, known as Baitong/Paktong, sometimes translated as "white copper", was produced in China as early as 1700–1400 BC. It was exported to Europe around the 17th century and was used for knives, forks and spoons as an inexpensive alternative to silver.[4,43] The element was first isolated and analyzed by Swedish mineralogist Axel Fredrik Cronstedt in 1751 from a sample of what is now thought to be a nickel arsenide ore from a cobalt mine in Los, Sweden. He coined it nickel, which comes from "Kupfernickel" or "false copper," the nickname given by Saxon miners who initially thought it was a copper ore from which they could not extract the red metal properly.[4,43,44] Refined metallic nickel was first produced in Germany in 1838, and small quantities of sulfide ores were mined in Norway, Sweden, Germany and Russia. The earlier uses of nickel remained copper-nickel-zinc alloys such as German Silver or nickel-silver, for those alloys were easy to cast, cheap to fabricate and resistant to tarnishing. By 1857, the United States Mint was the first to issue a coin containing 12% nickel, and by the 1870–1880s, the first alloy steel incorporating nickel was used, thus increasing the demand. Nickel-steel armour plates such as the Harvey or the Krupp armour became crucial for steel naval amor in the 1890s, accelerating nickel production because of the significant military applications. France dominated nickel production from 1875–1905, thanks to Garnier's discovery of laterite ores in Kanaky-New Caledonia in 1863. Canada later took the lead throughout the 20th century after discovering a large sulfide deposit in the Sudbury Basin and its exploitation in 1886. By 1950, the Sudbury area supplied 95% of nickel to Western countries.[4] Canada's position in the nickel sector has been displaced since the 1980s, mainly due to a decrease in deposit grade and the recent exploitation of laterites in Indonesia, Australia, and the Philippines.

Nickel is an essential nutrient for some plants and anaerobic bacteria but can be toxic to others.[45] In nickel-rich soils, "hyper-accumulator": plants can accumulate up to 1% nickel by dry weight.[43] While nickel levels in food and water are usually low, and its absorption by humans is usually minimal,[46] it poses a risk of chronic dermatitis from skin contact and cancer from inhalation of nickel fumes or soluble compounds, which are known human carcinogens linked to lung, nasal, and paranasal cancers.[45] Metallic nickel is also anticipated to be a human carcinogen, having caused local sarcomas in animal studies.[47] About 100,000 Canadians, primarily in industrial machinery repair, welding, and metal manufacturing, are estimated to be exposed to nickel at work.[48] High lung cancer risks have been observed among calcining workers in Canadian nickel smelters and hydrometallurgy workers in Norway due to exposure to water-soluble nickel compounds like nickel sulfate and nickel chloride.[49] Significant work has been done to understand this issue, making current workplace health impacts well-managed through appropriate engineering control and PPE. Québec City has been noted to have nickel contamination issues due to historic shipping of fine nickel concentrate.[50–54] Hypersensitivity by contact with nickel can cause allergic reactions such as dermatitis, asthma or conjunctivitis, a well-documented phenomenon due to the abundance of nickel-plated jewelry items— it is estimated that 10–20% of the population reports a reaction to nickel.[43,47,55]

2.2 Role in Energy Storage

The IEA identifies nickel as highly critical for EVs, battery storage, geothermal and hydrogen, and moderately critical for wind, concentrating solar power and nuclear.[56] While the major use of nickel for clean technologies remains as cathodes for Li-ion batteries, additional strong demand growth is expected from alkaline hydrogen electrolyzers and stainless steel in wind turbines.[57]

Nickel is critical as it is used in the most energy-dense of currently available battery technologies and nickel-based batteries are expected to remain a substantial part of the battery transition over the coming decades. Indeed, nickel shows excellent performance as a rapid and reversible redox centre necessary for repeated charge-discharge cycles. This is likely due to nickel's particular electronic configuration, geometry, and crystal structure when associated with oxygen.[58,59]

Historically, most applications were first found by the nickel-iron batteries patented at the end of the 19th century by Edison and Jungner. They even powered EVs as early as 1910, but as nickel-iron stopped being a material of choice, the rugged nickel–cadmium cathodes gradually came to dominate the broader rechargeable batteries market. Due to the toxicity of cadmium, they were succeeded first by nickel metal hydride batteries (NiMH), featuring nickel hydroxide $Ni(OH)_2$ as a cathode, and then the much more energy-dense lithium-ion batteries (Li-ion).

The latter used mixtures of lithium nickel oxide $LiNiO_2$ with other lithium metal oxides for improved stability, such as $LiCoO_2$, $LiMnO_2$ and $LiAlO_2$. Those cathode technologies include lithium nickel manganese cobalt oxides (NMC) batteries, representing 60% of the battery market share in 2022, lithium nickel cobalt aluminum oxide (NCA), representing a share of about 8%, and lithium nickel cobalt manganese aluminum oxide (NCMA) batteries.[60] All those chemistries hold the advantage of yielding good specific energy, making them particularly suitable for long-range electric vehicles, especially when compared to LFPs. Nickel-based cathodes powered 80% of the battery capacity in new plug-in electric vehicles in 2021.[61] Although LFP has been rising to about 50% of global market share, and have especially dominated the Chinese market, nickel-based batteries are expected to remain a significant part of the battery mix for decades to come. Nickel-based batteries are expected to remain the dominant battery chemistry ex-China.

In addition to their widespread use, the nickel content ratio has significantly increased over the years. In the case of NMCs, it has evolved from NMC 333 (one part nickel, one part manganese, one part cobalt) to NMC 622 to the current NMC 811 (eight parts nickel, one part manganese, and one part cobalt).[62,63] A Korean manufacturer has recently revealed plans to produce NMC with 95% nickel content.[64] Higher nickel content leads to increased energy density, better storage capacity, lower costs, and stepping away from cobalt's human rights and geopolitical challenges. This trend toward nickel-rich batteries will likely continue, but specific optimization and stability challenges must be overcome first.[65] In 2020, the average battery contained 29 kg of nickel, which could go up to 80 kg for some models.[66,67]

2.3 Substitutes

The substitution of nickel is highly dependent on battery technology and cathode markets. High nickel chemistry cathodes can be replaced by more cobalt, but the political and social implications of using more cobalt could be harmful. Cobalt can also be cost-prohibitive as it is also more expensive than nickel. Replacing NMC and NCA batteries with lithium iron phosphate batteries (LFP), an already mature technology that circumvents nickel for cathodes, is growing in popularity and would be more likely. However, this would be a trade-off in reduced energy density and poor performance in cold weather.[57,68] Stainless steel applications can reduce their nickel content by using ultrahigh-chromium alloys, or by moving to a lower quality 200 series stainless steel, with the additional drawback of having a sub-par performance products. Titanium alloys can also substitute regular stainless steel in corrosive environments but are generally much more expensive.[1]

2.4 Supply and Demand

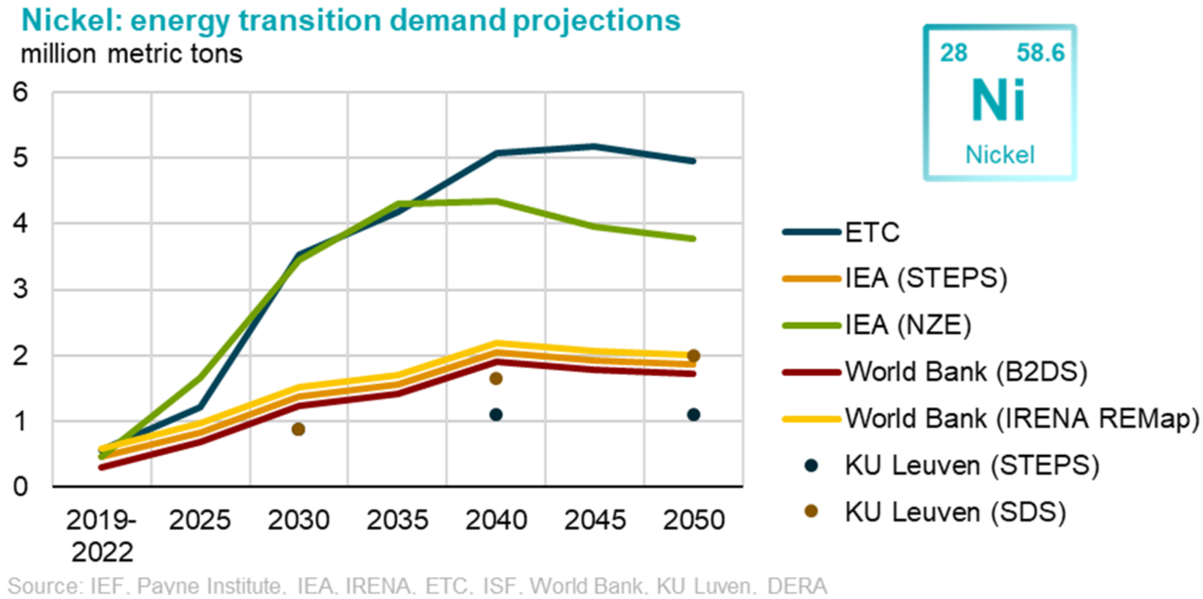


Figure 2 Nickel demand projections to 2050 according to various energy transition scenarios[69]

The overall nickel market is thought to be well-supplied, but the increasing demand for batteries will put pressure on higher purity nickel (class 1) production; as such, this metal is identified as a critical material for the medium-term 2025–2035 by the U.S.[68] The IEA accounted for a 40% rise in demand for nickel from 2017 to 2022, strongly driven by the energy sector.[70] According to Benchmark Mineral Intelligence, the 2021 global nickel market demand only accounted for 12% for battery purposes, while 69% was still reserved for stainless steel. However, this demand would evolve to 43% for batteries and 45% for stainless steel in 2035.[71] Last year, the U.S. Department of Energy estimated in its highest demand scenario that about 43% of the nickel demand is expected to be from electric vehicles batteries, stationary storage batteries and solid oxide electrolyzers in 2025 while this demand could jump to 78% in 2035.[68] Initially, most nickel sulfate, the chemical intermediate necessary for cathode batteries, came from class 1 nickel, a higher purity grade of metal obtained from sulfide ores. However, nickel sulfate production has increasingly relied on laterite sources, as the sulfide ore production was insufficient. Diverse and more impure nickel intermediates obtained from laterite ores, such as mixed hydroxide precipitates (MHP) or nickel matte obtained from nickel pig iron, have already increased in popularity as alternative supply chain routes had to diversify. Today, class 1 nickel is obtained from sulfide and laterite ores, with MSP and MHP being the primary source of nickel sulfate now.

3 The Nickel Flowsheet: A Complex Journey from Sulfide and Laterite Ores to Stainless Steel and Nickel Sulfate

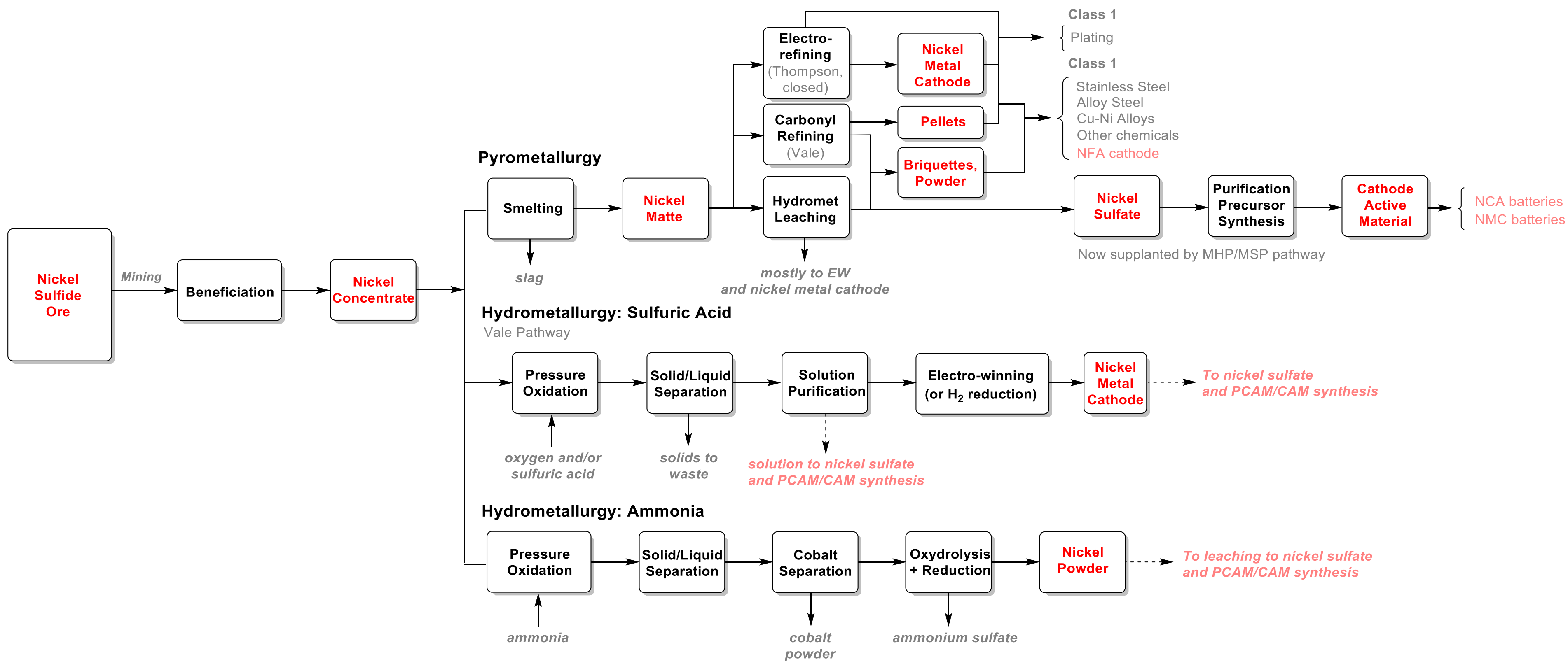


Figure 3 Simplified nickel sulfide flowsheet

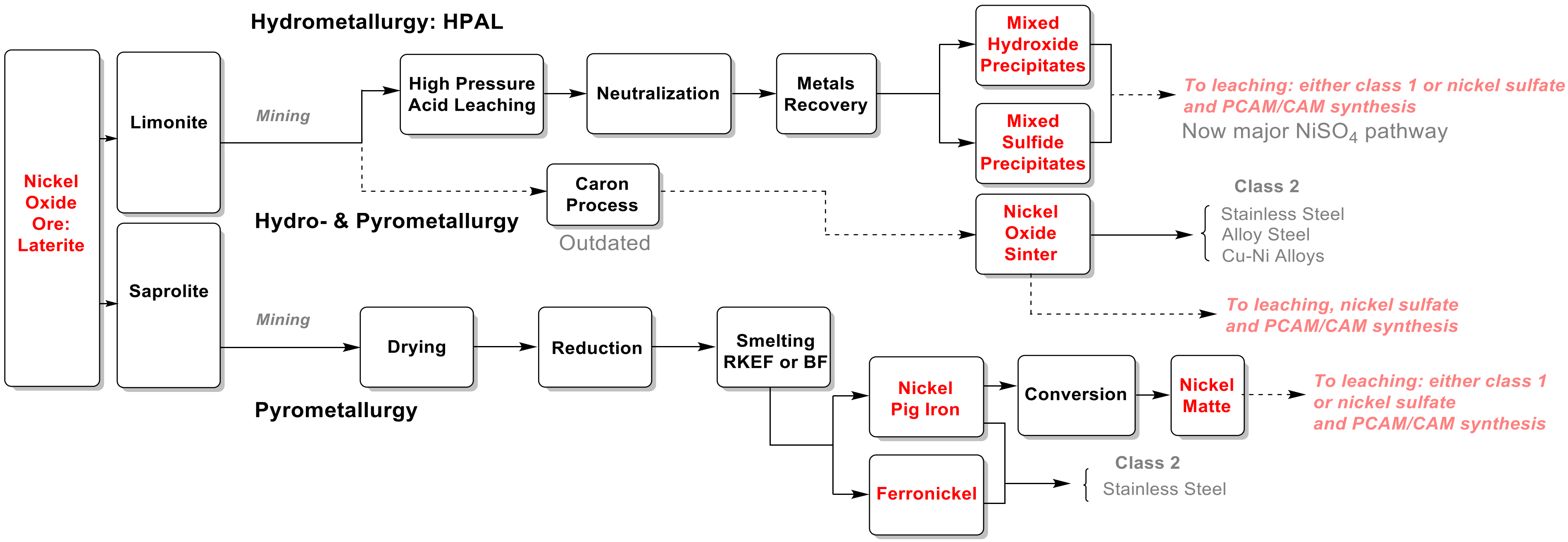


Figure 4 Simplified nickel oxide flowsheet

3.1 The Types of Nickel Ores, Mining and Reserves

Although nickel makes up for around 3% of the Earth's composition, it only comprises about 0.009% of Earth's crust, most nickel being buried in deeper layers such as Earth's core. As such, it is ranked 23rd or 24th most abundant element in the crust,[4,43,44] which is comparatively more common than copper, zinc or lead.

Sulfide ores are massive deposits formed thousands of meters deep by either magmatic activity or hydrothermal alterations after a reaction between nickel-bearing rocks with sulfur. The main mineral of interest in **pentlandite** $(Ni,Fe)_9S_8$, and nickel sulfide ores are commonly associated with copper and cobalt metal, most often with **chalcopyrite** $CuFeS_2$ and **pyrrhotite** Fe_7S_8 minerals.[4,44] Historically, significant reserves were mostly found in northern regions: Russia, Canada, Finland, and also Australia and South Africa (associated with high platinum values). Those types of ores are the main sources of **class 1 nickel products**.

In contrast, the main source for **class 2 products** comes from **nickel oxide ores**, also called **laterites**. They are formed by infiltration of water and weathering of peridotite rocks over a long period. The laterite weathering process requires a tropical or subtropical humid environment, thus explaining why the majority of nickel oxide deposits are confined around the equatorial belt, such as Indonesia, the Philippines, the Caribbean and New Caledonia.[72] Other resources from Australia, Brazil, or Madagascar are much older. Similar host rocks exist in northern regions but have not seen similar weathering.

Two types of laterites can be found: **limonite** in the most superficial layers and **saprolite** (nickel silicate or garnierite) in deeper layers. Saprolites are higher in nickel content and magnesium, while iron is lower than limonites. In 2019, 70% of worldwide nickel production came from laterite ores, while 30% came from sulfide resources. The share of laterite ores production has been rapidly increasing for several years and the laterite dominance is expected to increase in the future decade.[73]

Awaruite Ni_3Fe is another type of nickel ore which is not a sulfide nor laterite but rather a native nickel-iron alloy that can be found in potentially economic level in British Columbia.[16,17,19] Finally, in addition to land deposits, extensive nickel resources could also be found among **manganese nodules** on the ocean floor.[74]

3.2 International Nickel Production and Reserves

Table 3 Estimated reserves & mining production of nickel by country in tonnes

Country	2022 Ni mining production[a] (in tonnes)	Country	Ni Reserves in 2024[a] (in tonnes)
United States	17,500	United States	340,000
Brazil	88,500	China	2,100,000
China	114,000	**Canada**	**4,200,000**
Canada	**143,000**	Philippines	4,800,000
Australia	155,000	New Caledonia	7,100,000
New Caledonia	200,000	Russia	8,300,000
Russia	222,000	Other countries	>9,100,000
Philippines	345,000	Brazil	16,000,000
Other countries	404,000	Australia	24,000,000
Indonesia	1,580,000	Indonesia	55,000,000
World total (rounded)	**3,270,000**	**World total (rounded)**	**>130,000,000**

[a]Data from the 2024 U.S. Geological Survey, NRCan's dataset differs slightly.[1,3]

Global nickel production has grown and increased by around 1.5 times from 2015 to 2023, with Indonesia and the Philippines contributing significantly to this expansion, representing 59% of global output in 2022 estimations,[1,74] Indonesia alone accounts for an impressive 48% of global production. Both countries rely on laterite ores and are expected to drive around 70% of global production by 2025.[75] This nickel boom in Southeast Asia also shifted the principal extracted ores globally from sulfides to laterites. Other significant mining players are Russia, New Caledonia, Australia, Canada and China.

Indonesia also dominates nickel reserves, accounting for 42% of the world's available global reserves. Both Australia and Brazil hold significant reserves compared to their nominal production.

3.3 Processing

3.3.1 Overview of the Processing Supply Chain

The overall value chain of nickel is quite complex and although the industrial processing routes are interwoven, the principal differences and key steps rely on the type of nickel source (nickel sulfide or laterite), the different intermediates (concentrate, matte, mixed precipitates, nickel pig iron, *etc.*), and the different purity of end-products (Class 1 vs. Class 2). Both hydro- and pyrometallurgy technologies are available for the different sources of nickel ores, except for saprolite/garnierite which specifically require smelting.

The most crucial chemical product for cathode active material manufacturing is nickel sulfate, which is why securing routes for its production is considered strategic.

3.3.2 Class 1 & 2 Nickel Products

Nickel market products are commonly divided into two different classes according to their nickel content, with Class 1 being of higher purity (> 99.7% nickel content) than Class 2 (< 99.7%). Contrarily to other metals such as copper, which usually requires a high purity because of its electrical and thermal applications, nickel's use as an alloy metal does not require the same imperatives: Class 2 products such as nickel oxide, metallized nickel oxide, ferronickel or nickel pig iron have a sufficient purity for applications such as stainless steel, despite significant levels of cobalt, copper, and other traces of impurities. That is why they are usually thought of as "charge nickel", meaning they are nickel forms that can be thrown into a stainless-steel furnace charge. Class 2 products originate solely from the processing of laterite nickel oxides. Nickel metals such as briquettes, powders, pellets, or cathodes are categorized as Class 1 products and can be leached with sulfuric acid to produce the nickel sulfate destined for EV batteries. This was formerly the route of choice for nickel sulfate production. Class 1 products were usually obtained by processing sulfide ores through hydrogen reduction, electrolytic methods, or carbonyl refining. Impurities of most metals are mostly removed, while trace cobalt levels can remain high in some produce forms.[4] Most projections predict an incoming shortage of Class 1 nickel products. However recent developments of Class 1 nickel refining capacity in China and Indonesia will mitigate this. Indeed, both the IEA and Benchmark Mineral estimate that the development of different processing routes connecting laterite ores to nickel sulfate (either through high-pressure acid leaching HPAL of laterites,[72] or nickel matte obtained from nickel pig iron) will be both necessary and desirable to fulfill the increasing demand for electric vehicles, as sulfide ore processing will not be enough to sustain this market transition to electric batteries.[56,71] Additionally, the processing of MHP to nickel sulfate has proven more affordable and faster than production *via* Class 1 nickel, thus favouring the industry to choose this direction. Those recent developments have shown the critical growth of nickel sulfate production without going through the traditional Class 1 or Class 2 nickel products.

3.3.3 The Importance of Nickel Sulfate as a Platform Chemical

Leaching Process:
to nickel sulfate

Using sulfuric acid to dissolve nickel from various sources (Nickel matte, pure nickel metal, mixed hydroxide precipitates, mixed sulfide precipitates, nickel oxide sinter,...), a useful nickel sulfate hexahydrate powder $NiSO_4(H_2O)_6$ intermediate can be obtained after crystallization. Nickel refineries can also produce nickel sulfate solution, although the main product is usually nickel metal obtained through electrowinning. Copper electrolytic refining can also produce nickel sulfate as a byproduct. Nickel sulfate is an important intermediate for the synthesis of precursor for cathode active materials.

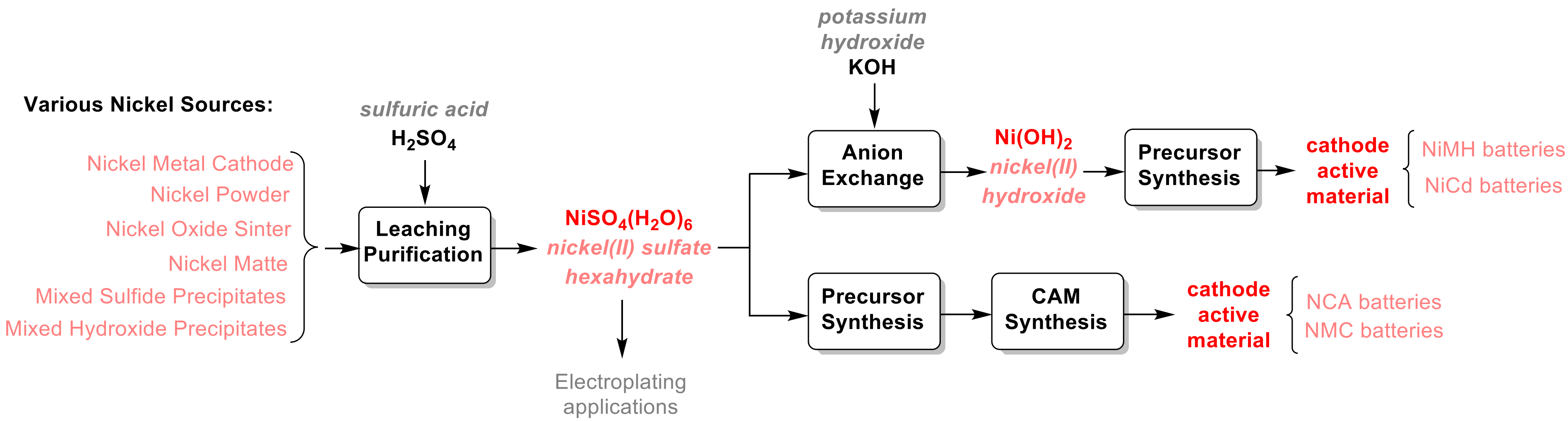


Figure 5 Nickel sulfate flowsheet

The ubiquitous chemical used to synthesize nickel-based cathode active materials for Li-ion batteries is nickel sulfate hexahydrate $NiSO_4 \cdot 6\ H_2O$, a blue-green crystal readily soluble in water. This compound can be obtained through various nickel sources, either from pure nickel powder, MHP, nickel oxide NiO, nickel carbonate $NiCO_3$, or even from impure nickel matte originating from sulfidic ores or lateritic nickel pig iron. Nickel sources are typically dissolved by sulfuric acid and crystallized to yield nickel sulfate, generating either more sulfate as a byproduct while leaching sulfide sources (matte or concentrate) or hydrogen gas when leaching nickel powder.[55] Some impure nickel sulfate is also obtained as a by-product of electrolytic copper refining.[45] This specific low-purity grade of nickel sulfate, although marginal, would be considered as Class 2, while most pure nickel sulfate would be Class 1. On top of being used as a precursor chemical for cathode materials, nickel sulfate is used as an electrolyte in nickel electrolytic refining and plating. Nickel hydroxide $Ni(OH)_2$ is another related platform compound that was previously important, as it was the precursor for cathode material in slowly phasing out nickel-cadmium NiCd batteries and for anode material in nickel metal hydride NiMH batteries.

3.3.4 Mixed precipitates: MHP& MSP

While nickel concentrate and nickel matte are the traditionally obtained intermediates along the nickel sulfide ore processing chain, mixed hydroxide precipitates (MHP), as well as mixed sulfide precipitates (MSP), are the primary intermediates produced when processing laterite ores through the high-pressure acid leaching route. They present an exciting way to convert abundant laterite resources into the pure Class 1 nickel products or nickel sulfate necessary for batteries. Those intermediates bear the advantages of being readily available from the numerous refining projects existing in Indonesia; they can be easily converted to nickel sulfate while providing interesting volumes of cobalt as a by-product. Converting MHP or MSP to nickel sulfate could also be significantly cheaper than leaching nickel metal.[76,77] However, potentially higher carbon emissions linked to some specific laterite processing route projects and problematic tailings management in Indonesia are usually described as their drawbacks.[56,71,78] The increased moisture content of MHP is another significant concern, as it would increase the need for water management and transportation quantities are higher than for MSP or nickel matte.[77]

3.3.5 Indonesia: The New Global Nickel Giant

In addition to dominating the upstream nickel extraction process, Indonesia's ban on nickel ore exports in 2019–20 and its push for domestic processing have further solidified its role in the global nickel supply chain. This resulted in 2020 Indonesian nickel ore exports to China dropping by nearly 90%, while nickel pig iron exports doubled compared to 2019. In response, Chinese companies have invested heavily over USD 30 billion in

Indonesia's nickel supply chain to secure resources.[56] Consequently, Indonesia now has the upper hand in planned nickel refineries, representing 88% of future refining facilities for 2023–2030 while overtaking China as the largest nickel refiner (Indonesia refined 43% of nickel in 2022 *vs.* 17% in China).[79] As Chinese companies have high stakes in Indonesian metallurgy plants, this can hinder their eligibility for specific policies such as the U.S. Inflation Reduction Act.[80]

Indonesia currently relies on the pyrometallurgy of saprolites to produce nickel pig iron, and ferronickel through smelting for class 2 products and on the hydrometallurgy (High-Pressure Acid Leach, HPAL) refining of limonites for MHP intermediates, nickel sulfate and class 1 products. Recently, a technique previously used for copper smelting, the oxygen-enriched side blow furnace (OSBF), has been adapted to the smelting of limonites to matte and Class 1 products. The nickel pig iron to nickel matte route, pushed forward by Tsingshan, is a way to crossover the different routes and value saprolite feedstock for class 1 and EV purposes, but at a higher energy cost and environmental cost.[56,81] In 2023, the primary nickel production route in Indonesia was the smelting of saprolite through rotary kiln electric furnaces (RKEF), representing around 90% of the production *vs.* lower than 10% for the leaching of limonite through HPAL.[82] The Philippines is the second largest nickel mining country, but only two HPAL refining plants are operating, and a few more are being considered.[79,83]

3.3.6 From Sulfide Ores: A Cleaner Process for Higher Purity Nickel

3.3.6.1 Nickel Sulfide Ore Beneficiation

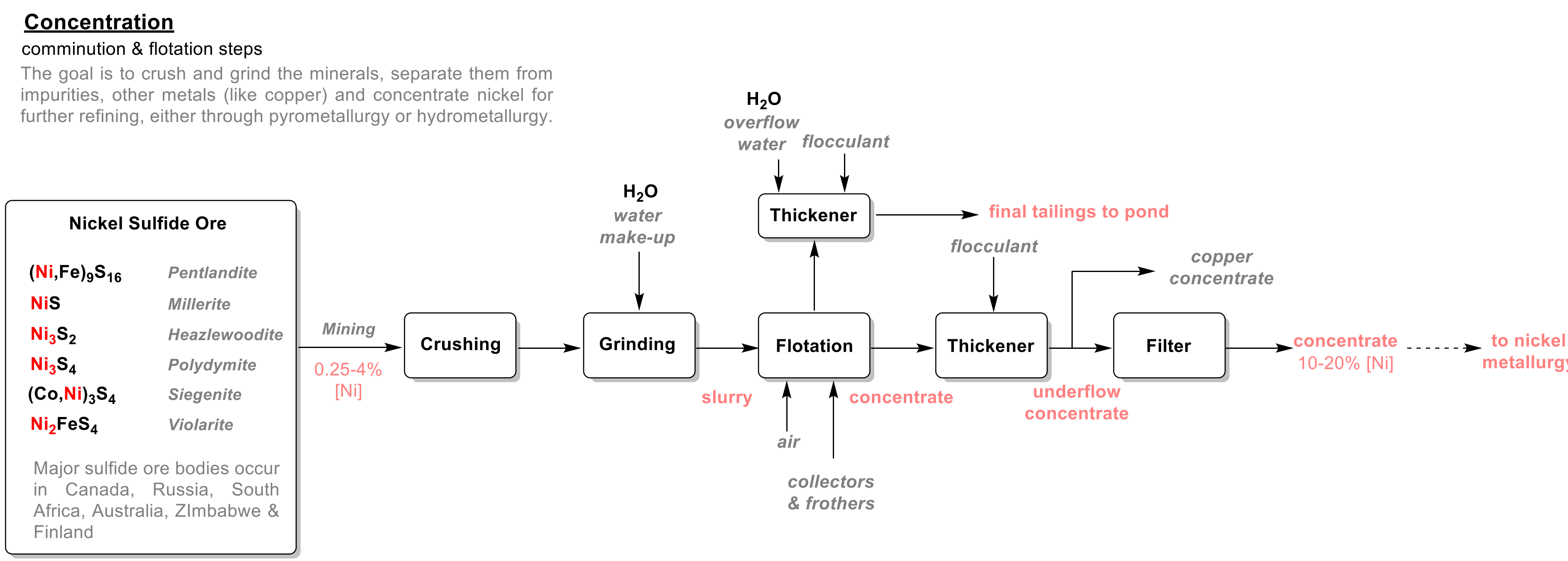


Figure 6 Nickel sulfide concentration flowsheet

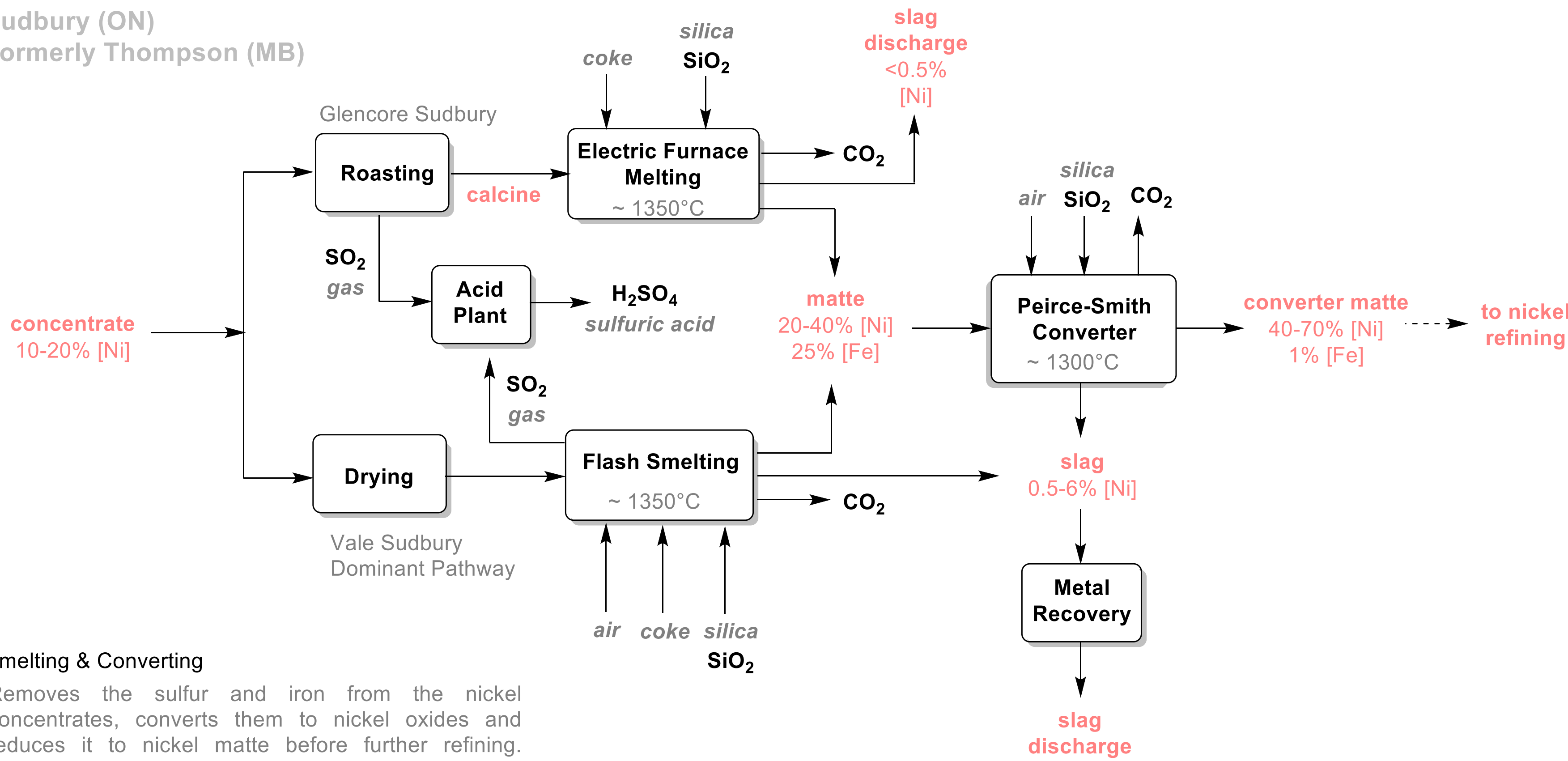
When nickel sulfide ores are treated, pentlandite $(Ni,Fe)_9S_8$ makes the majority of the mineral of interest, but heazlewoodite Ni_3S_2 and millerite NiS can be present, and more marginal minerals like polydymite Ni_3S_4, $(Co,Ni)_3S_4$ or violarite Ni_2FeS_4 can also appear. Arsenide and sulfarsenide nickel compounds can also be present. Nickel deposits often occur with copper, cobalt and platinum group elements (PGE), and they can be classified between high-grade, making most of the traditional nickel mines, and low- to mid-grade. Akin to the copper industry, a global decrease in ore grade for nickel deposits in the past decades has led the industry to start looking more closely at lower-grade deposits.

After mining, nickel sulfide ores undergo a beneficiation process. The goal is to crush and grind the minerals, separate them from other metals (such as copper), and transform the mined ores (0.25–4% Ni) into concentrates (10–20% Ni). Every deposit has a specific beneficiation process tailored to optimize this step, depending on the mineralogy of the site. Froth flotation is the primary method used in the nickel sulfide industry for beneficiation, where air and chemical additives are introduced into a slurry containing ground ore.[84] This process causes sulfide minerals to adhere to air bubbles and float to the surface, allowing them to be collected, while gangue minerals settle as tailings. While simpler ores may undergo straightforward processing, complex ores containing problematic minerals like talc or nickeliferous pyrrhotite present significant challenges, requiring more intricate flowsheets and larger equipment. Differential flotation is also used to separate nickel and copper, with the resulting concentrates often requiring additional processing to meet market and environmental standards.

3.3.6.2 Nickel Sulfide Pyrometallurgy: From Concentrates to Matte

Pyrometallurgy

Sudbury (ON)
Formerly Thompson (MB)



Smelting & Converting

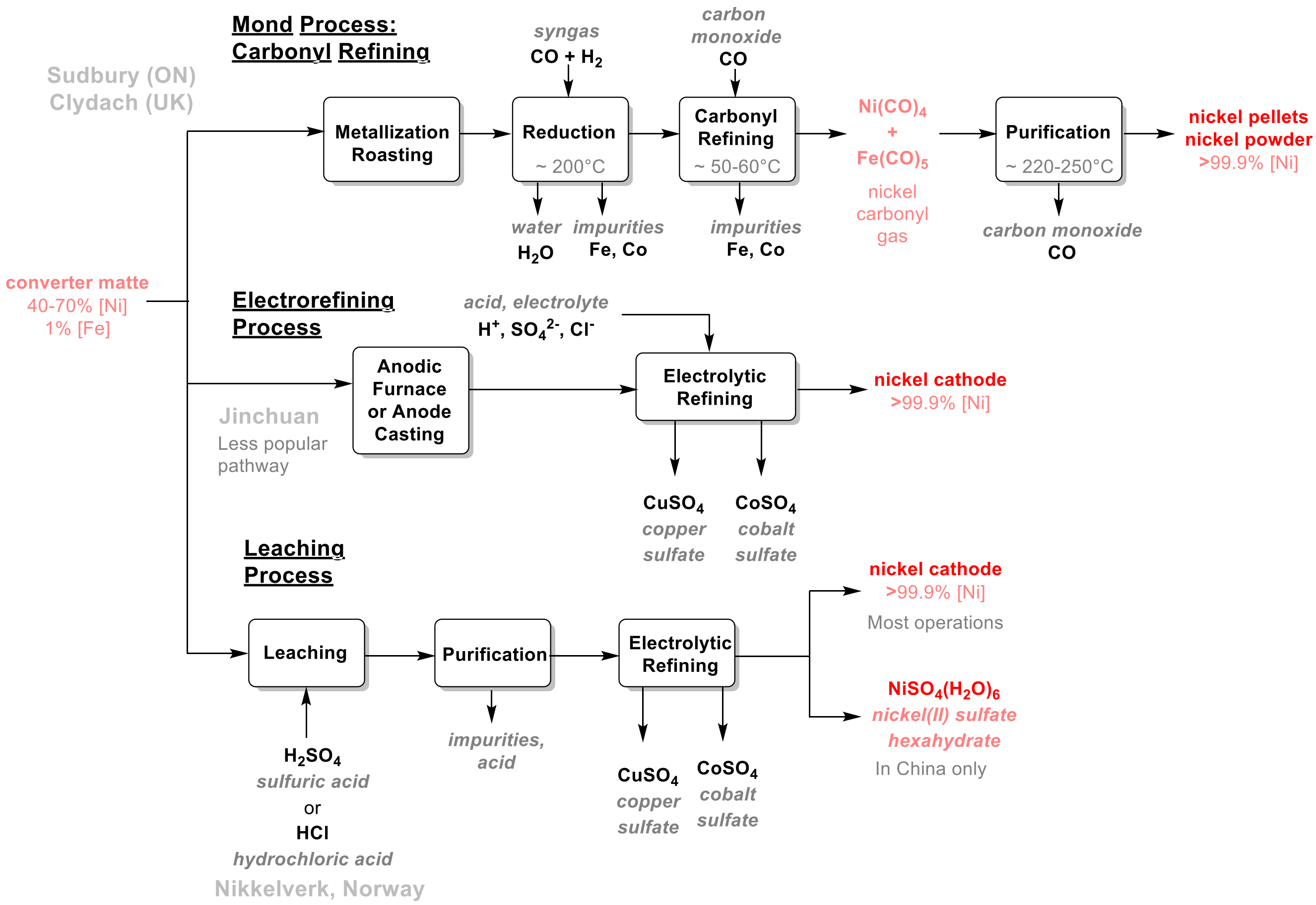
Removes the sulfur and iron from the nickel concentrates, converts them to nickel oxides and reduces it to nickel matte before further refining. Glencore owns an active smelter in Sudbury (ON), and Vale previously operated a smelter in Thompson (MB), which shut down in 2018.

Figure 7 Nickel sulfide pyrometallurgy: From concentrates to matte

Most sulfide ore concentrates undergo a series of pyrometallurgical processes, including roasting, smelting, and converting. Roasting removes much of the sulfur, while smelting further reduces sulfur content, producing an impure copper-nickel-iron-sulfur matte. It uses the energy released from sulfur oxidation and added energy, primarily electricity. The goal is controlled oxidation to convert much of the nickel to metal form, while most sulfur is converted to SO_2 gas for capture, and iron and other minerals like silicates are rejected as slag.[85] Smelting can be carried out in different types of furnaces, such as reverberatory furnaces, which use fossil fuel; electric furnaces or flash furnaces, which use a bit of fossil fuel and the exothermic heat from sulfide reacting with high-purity oxygen as energy. Electric furnaces typically have concentrate roasting ahead of the furnace, while flash furnaces typically oxidize all the desired sulfur in the furnace. Although the processes vary, coke is generally used as the reductant, and silica or lime as flux. Smelters are efficient at handling impurities like sulfur and iron and are excellent at recovering copper and platinum group elements (PGEs), but they struggle with cobalt and volatile impurities like arsenic. Typically, volatile mercury and arsenic dust can pose environmental issues. Smelter temperatures depend on the slag composition and, ultimately, the magnesium content, but they can vary between 1200–1400°C.[4] The process requires significant electricity, particularly in electric furnace smelting, and the viability of sulfuric acid byproducts is crucial for the economic operation of some smelters. Smelters in locations without viable sulfuric acid markets may emit very substantial amounts of sulfur dioxide to atmosphere rather than making a non-marketable byproduct.

During converting, a portion of the remaining iron and sulfur are removed from the impure matte produced during smelting, resulting in a sulfur-deficient copper-nickel matte with a higher grade. Converting is usually a batch operation, often in a Peirce-Smith converter, and the obtained slag can be recycled back to the smelting furnace. Silica flux addition is also necessary. A final nickel matte product is obtained, with a nickel content of 40–70%, remaining copper, iron (0.5–5%) and varying levels of PGEs. Typically the sum of nickel, copper and cobalt content is in the range of 70–75%.

3.3.6.3 Nickel Refining: From Matte to Pure Nickel or Nickel Sulfate



Mond Process:
Carbonyl refining

Nickel oxide NiO impurities are reduced to metallic nickel by reacting with hydrogen H_2 present in syngas at 200°C. This impure nickel further reacts with carbon monoxide at 50-60°C to form nickel carbonyl gas $Ni(CO)_4$, leaving solid impurities behind. Heating nickel carbonyl at 200-250°C will decompose it back to solid metallic nickel, this time in a very pure form. The Mond process can produce nickel powder or pellets.

Electro-refining:

An electrical current moves nickel(II) ions from the nickel sulfate and nickel chloride electrolyte solution onto a a thin cathode sheet of pure nickel, increasing in size.The less pure nickel from the casted anode gets oxidized and dissolved in the electrolyte, helping the process. Impurities accumulate at the bottom of the cells (anodic slimes), they can contain precious metals. Some concentrate from Glencore is sent to Nikkelverk in Norway for electro-refining.

Leaching Process:
to nickel cathode

There are two different leaching processes used, sulfuric and chloride (i.e. Nikkelverk). Generally speaking they both use purification methods to make Cu, Co, and Ni cathodes although there is one that uses ammonia leaching on matte (Kwinana) and some that use sulfuric acid leaching followed by hydrogen reduction to make Ni powder (i.e Implats which is only a minor nickel producer). Only Chinese operations can go from sulfide matte to $NiSO_4$ directly.

Figure 8 Nickel Refining Flowsheet

For Class I products, nickel refining is indispensable. Depending on the copper content and desired product, the converter matte obtained is either cast into anodes for electrolytic refining or separated into nickel and copper sulfides, with nickel further refined through leaching and electrolysis or the carbonyl method.[44]

In the electrorefining process, an electrical current moves nickel(II) ions from the cast nickel anode into a nickel sulfate or nickel chloride electrolyte solution and then onto a thin layer of pure nickel bonded on a cathode sheet, increasing in size along the process. The cathode sheets are made of stainless steel or titanium, and the pure nickel layer is stripped after 1 or 2 days of deposition. The less pure nickel from the casted anode, originating from the converter matte, gets slowly oxidized and dissolved in the electrolyte, thus helping the process. Impurities accumulate at the bottom of the electrolytic cell in the form of anodic slimes, from which precious metals can be extracted and precipitated. Copper, arsenic, iron and cobalt can be isolated this way. Gold and PGE necessitate more complex processes. The nickel produced through electrorefining has a high purity of higher than 99.9%. Electrorefining matte anodes was the primary process used by the now inactive Thompson, Manitoba smelter and refinery.

The leaching of nickel matte materials through hydrochloric acid and sulfuric acid is another major pathway to nickel refining. The various leaching and purification processes are complex and vary greatly. Still, the matte is generally leached by a strong acid, and the resulting nickel-bearing leach liquor can be refined to a nickel cathode through electrowinning. Here, contrary to electrorefining, the nickel ions from the leach solution are directly deposited onto cathodes by applying an electrical current, and the ions do not originate from an impure nickel anode. Lead is used as the anode for the sulfate process, while titanium coated with a platinum group metal oxide is used in the chloride process.[4] Electrowinning is very electricity-intensive but also produces ultra-pure nickel. Some leaching processes do not go through electrowinning but rather through nickel reduction and precipitation *via* hydrogen, usually using an ammoniacal nickel sulfate solution.

It is worth noting that the leaching of nickel matte with sulfuric acid could directly produce the desired nickel sulfate $NiSO_4$ required to produce precursors to cathode active material (pCAM) for NMC batteries. This could bypass the various extra steps currently used for its current production, where nickel is first refined and purified from matte to pure nickel before being leached in sulfuric acid for nickel sulfate crystallization.

Finally, nickel oxide powder, obtained from the roasting and grinding of nickel matte, can be reduced to metallic nickel following the carbonyl refining process. By reacting with hydrogen H_2 present in syngas and at 200°C, an impure metallic nickel powder will form a complex with carbon monoxide at 50–60°C to form a nickel carbonyl gas, leaving solid impurities behind. After heating at 200–250°C, the nickel carbonyl will decompose back to a solid metallic form, but this time with a higher purity. This process, known as the Mond Process, can produce pure nickel powders or pellets. Contrary to other refining processes, the carbonyl refining pathway relies on particularly hard-to-handle toxic gas but produces extremely high purity nickel particles.

3.3.6.4 Nickel Sulfide Hydrometallurgy: From Concentrates to Nickel Products

Hydrometallurgical operations are more specific to the ore deposits than smelting and require a more complex flow and a steady supply of chemicals. They are also less susceptible to isolating precious byproducts such as PGEs, but they can be more efficient at cobalt recovery. However, hydrometallurgical facilities are more flexible to some impurities than smelters; they can operate economically on a smaller scale and provide versatility for the products they synthesize. Indeed, hydrometallurgical plants can produce pure class I metallic nickel after electrowinning or hydrogen reduction or intermediates such as MHP or MSP, which could be refined elsewhere, and they are also amenable to direct nickel sulfate production for pCAM.[86]

In Canada, one Vale facility is currently processing nickel sulfide concentrate through a chloride-assisted sulfuric acid pressure oxidation method, while Sherritt previously processed nickel sulfide concentrates following an ammonia-leaching hydrogen reduction method. These facilities are described further below. Internationally, the USA used to run sulfuric acid operations in the 1960s, while BHP's Kwinana plant in Australia currently refines nickel matte from its Australian smelter using the Sherritt ammonia leach-hydrogen reduction process and also produces nickel sulfate since 2021 by dissolving Class 1 nickel in sulfuric acid.

In 2014, Vale opened a new hydrometallurgical nickel refining plant in Long Harbour, NL. This facility refines nickel concentrates from the Vale-owned mine at Voisey's Bay, NL, but it can also refine nickel matte (**Figure 9**). Through pressure oxidation with sulfuric acid and oxygen metal removal, solvent extraction and electrowinning, nickel intermediates are converted to pure nickel cathode, while copper and cobalt metal are also isolated. This facility could potentially be suitable for directly producing nickel sulfate or pCAM from sulfide concentrates following solvent extraction of the nickel.

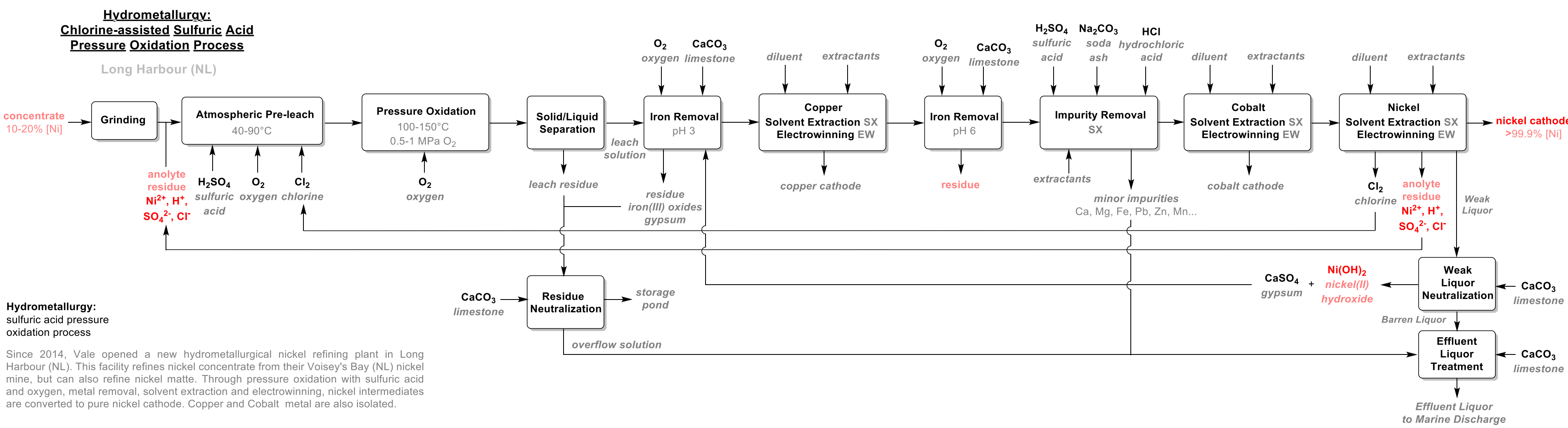


Figure 9 Vale Long Harbour's hydrometallurgical facility flowsheet

Sherritt's nickel refinery in Fort Saskatchewan, AB, previously used an ammoniacal leaching process to refine nickel sulfide concentrates until the 1990s (**Figure 10**). Currently, only mixed sulfide precipitates (MSP) obtained from Cuban laterites are refined in this plant. In the process, ammonia would dissolve nickel, copper and cobalt from their sulfide form using pressurized air, thus yielding metal-amine complexes. Ammonia levels and temperatures are adjusted to precipitate a cobalt-nickel intermediate which is refined to cobalt metal. A further solution treatment step uses sulfur and SO_2 to precipitate copper as copper sulfide. The nickel complexes are then reduced to a metallic nickel powder using H_2, and the ammonium sulfate byproduct obtained would be sold to the fertilizer industry. The process is complex, requires significant amounts of thermal energy, and depends on a cheap ammonia supply. The ammonia leach residues can also pose environmental issues.

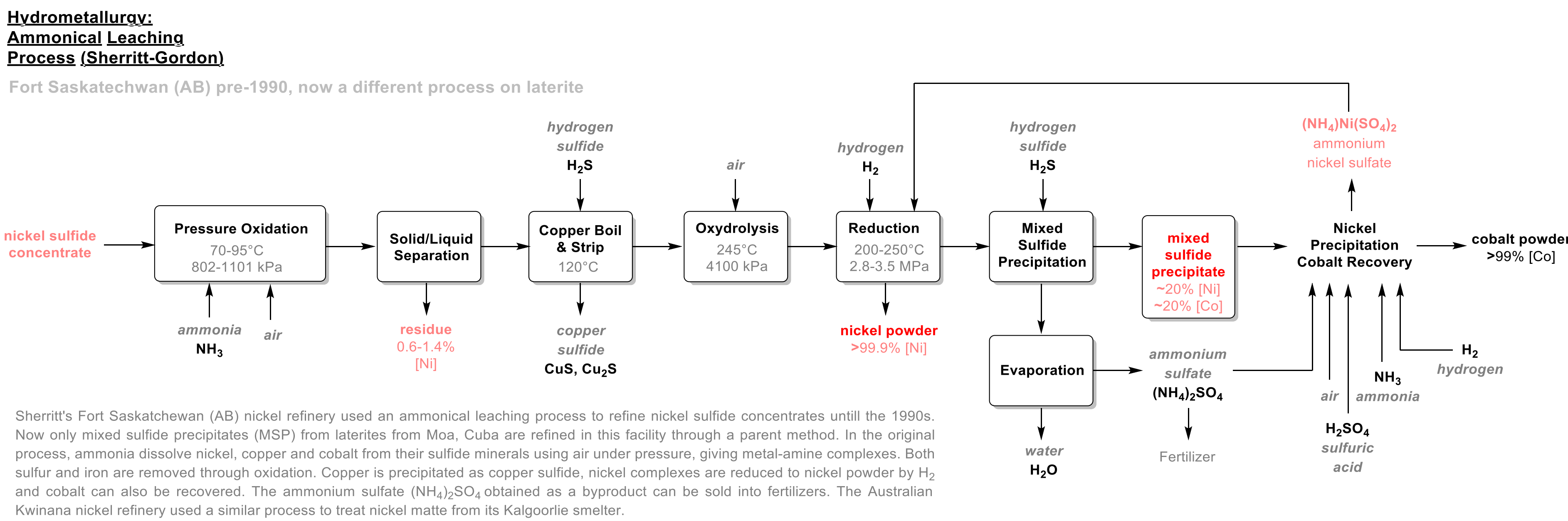


Figure 10 Former Sherritt ammonia process flowsheet

Alternatively, many processes exist for the hydrometallurgy of nickel sulfide concentrates and matte as a refining step after smelting. Amongst those other technologies, we can find chloride-based pressure leaching, nitric acid-based pressure leaching, atmospheric-pressure sulfuric leaching, nitric-acid leaching, bioleaching, *etc.* Although less widespread than their high-pressure sulfuric acid and ammonia counterparts, these methods have specific advantages and drawbacks. Chloride-based processes, for instance, allow for high recovery of metals but can be very corrosive to the plant's equipment and construction materials. Bioleaching uses microorganisms to produce MHP or MSP from sulfide ores or can also be used as an alternative concentrator, it can be a simple and flexible process, potentially helpful in recovering nickel from tailings and stabilizing arsenic waste, but the processing speed is slow and temperature sensitive. More details on these methods can be found in the literature.[8,87]

3.3.7 From Laterite Ores: An Abundant Source with Carbon-Intensive Steps

As laterite deposits are not present in Canada, this section will focus on giving a non-exhaustive brief overview of the techniques used to exploit, process and refine limonite and saprolite deposits, typically the mineralogy of ores found in Indonesia, Cuba, New Caledonia or the Philippines.

Laterites were traditionally refined to Class 2 stainless steel and industrial alloy products. Saprolites are mainly processed through smelting in blast furnaces or rotary kiln and electric furnaces (RKEF), yielding either ferronickel or nickel pig iron (NPI). On the other hand, limonites are processed either through a mixed hydro-pyrometallurgical method called the Caron process, producing nickel oxides, or through hydrometallurgy *via* a high-pressure acid leaching method (HPAL), yielding mixed precipitates such as MHP and MSP. The underlying advantage of the HPAL route is that the precipitate products can be transported and leached at different refineries to produce nickel sulfate for pCAM or other class 1 products. HPAL also allows cobalt recovery and is less energy-intensive than the Caron process. Facilities using the Caron process in Brazil, Australia and the Philippines have also gradually shut down, leaving only one operating plant in Cuba. Another available pathway is the Tsingshan/Eramet approach to convert a class 2 product, namely nickel pig iron (NPI) originating from saprolite smelting, into nickel matte, a potential class 1 intermediate. $NiSO_4$ could then be produced after matte leaching. One facility in Indonesia also uses a novel pyrometallurgical process with sulfur addition to making nickel matte.

Nickel Pig Iron (NPI), an 8–15% nickel intermediate product, was commercially produced at scale in China in the 2000s. The smelting of low-grade saprolite ores from Indonesia, the Philippines and New Caledonia to nickel pig iron (NPI) has been done in blast furnaces in China since 2006 and in Rotary Kiln – Electric Furnaces (RKEF) in Indonesia since 2015.

NPI produced by the RKEF route has a higher grade than the one made by blast furnaces. The process, similar to pig iron production for the steel industry, requires coke as a reductant, lime and laterite, rejecting slags, pollutants and GHGs.[88] This route appeared as an inexpensive, although carbon-intensive, way to produce class 2 nickel products that can be directly added to alloying and stainless steel mills.

High-grade saprolite ores are converted to ferronickel product for alloying applications through the Rotary Kiln- Electric Furnace (RKEF) pathway, but limonites can also be smelted this way (**Figure 11**). This represents most nickel processing operations in Indonesia, supplanting the blast furnace method. After preparing, drying, screening and crushing the saprolite ores, the mineral is calcined and pre-reduced inside a rotary kiln, using coal as a reductant and oil or natural gas as a fuel inside a rotary kiln. Temperatures can rise to 900–1000°C. The resulting calcine is then smelted at 1400–1650°C in an electric furnace, thus separating impurities in a dumped slag and producing crude ferronickel.[4] This crude ferronickel still contains a range of minor impurities and needs to be refined before being sold for alloying purposes. Both the calcination/pre-reduction step and the smelting are GHG-emitting processes, releasing air pollution in a similar way to coal power plants. The RKEF pathway is energy-intensive, both in terms of fossil fuel feed as well as electricity.[89] When electricity is supplied by coal-fired power plants, RKEF processing to lower grade (NPI) or higher grade (FeNi) iron alloy products is the most carbon-intensive method in widespread use for nickel production.

Pyrometallurgy
Rotary Kiln - Electric Furnace:

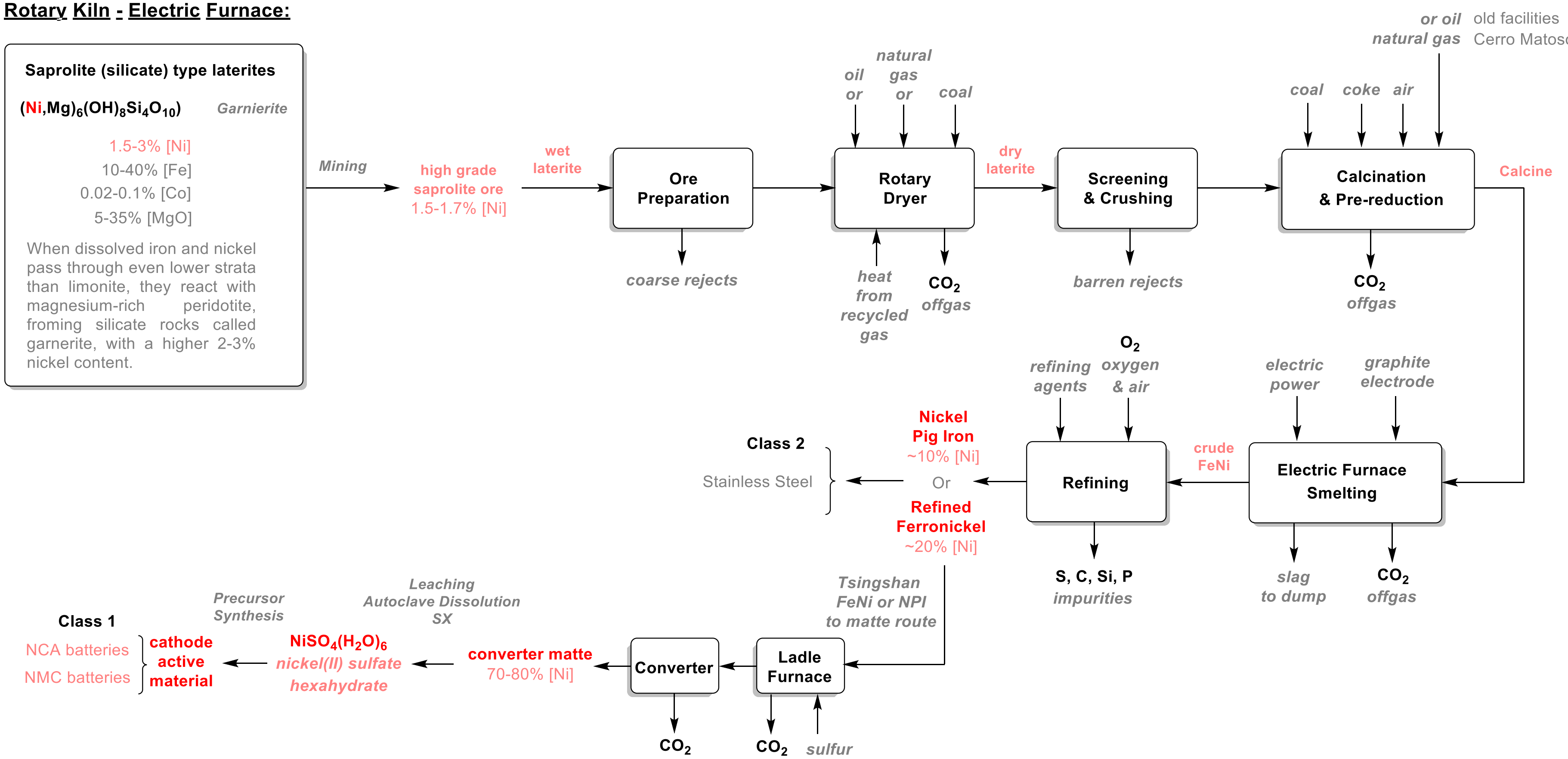


Figure 11 RKEF flowsheet from saprolite to NPI/FeNi

High-pressure acid Leaching (HPAL) is the most common technology for processing lower grades of limonite ores (**Figure 12**).[72] The ores are first delumped and slurried with water before being fed into an autoclave. Sulfuric acid at 250°C will leach the prepared materials under a pressure of up to 5,000 kPa. The subsequent pre-neutralization step requires limestone $CaCO_3$ to quench the acid, directly releasing CO_2. A multi-stage counter-current decantation step will then wash and separate the liquor into a pregnant solution containing nickel salts while rejecting tailings. After an additional neutralization step using limestone and emitting CO_2, iron and aluminum oxide are precipitated, and a residue can be recycled back to the decantation step. Nickel and cobalt are then precipitated using MgO or NaOH and undergo a solid-liquid separation, and a mixed hydroxide precipitate or MHP, containing 40% of nickel (dry), is produced. Alternatively, mixed sulfide precipitates MSP, containing >50% of nickel (dry), can be obtained after sulfurization with hydrogen sulfide H_2S. The HPAL method was pioneered in Cuba and has since been adopted in Australia, the Philippines, Papua New Guinea, Madagascar and New Caledonia, and is now becoming widespread in Indonesia. This approach has required a very high capital intensity, although that is being reduced through implementation in Indonesian industrial parks which provide significant infrastructure benefits. Acid supply is the biggest component of the opex, and high magnesium or aluminum content can increase the cost. This is why HPAL is sometimes not suitable for ores with a high MgO content. Most operational HPAL facilities failed to ramp up to design capacity.[84] However, HPAL recovers cobalt more efficiently than smelting, which can result in lowering the opex. Cuba's Moa Bay HPAL plant, operating since 1959, now supplies Sherritt's Fort Saskatchewan with MSP for its ammonia-based hydrometallurgical plant.

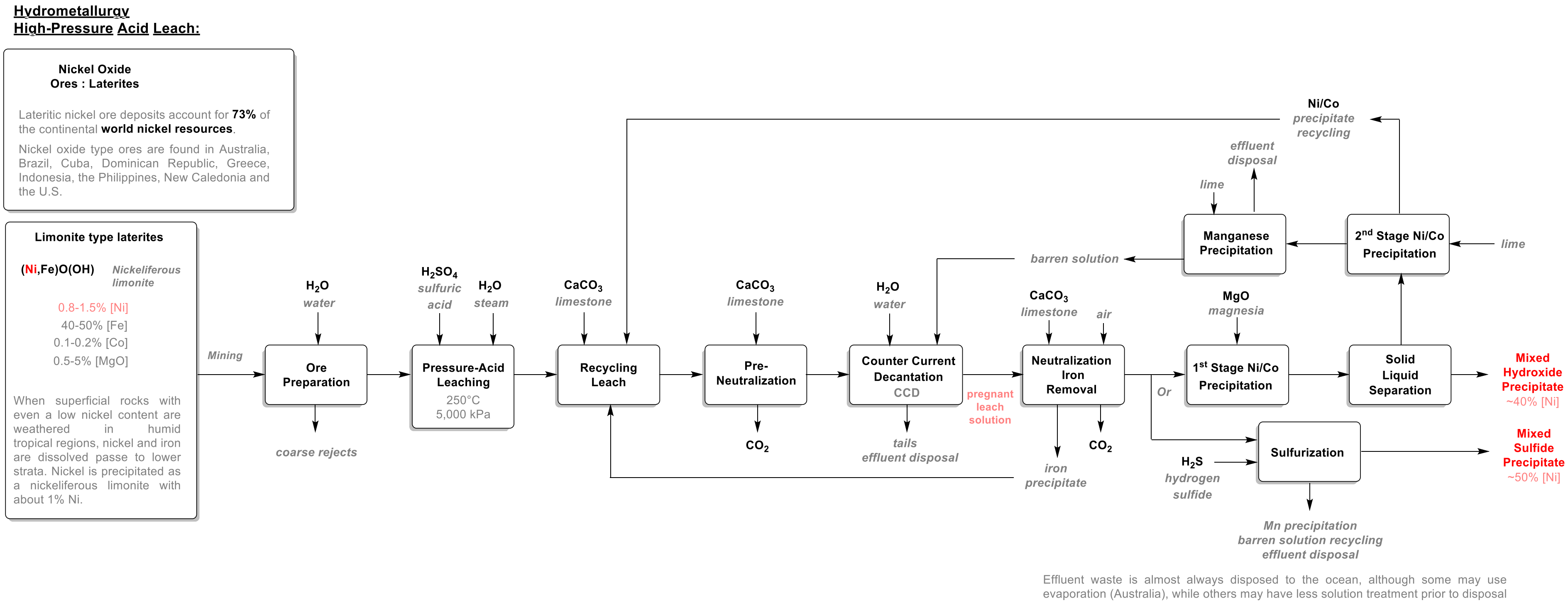


Figure 12 HPAL process flowsheet from nickel oxide to mixed precipitates

The Caron process converts limonite ores into nickel oxide, and it heavily relies on fossil fuels and syngas for energy and reduction, as well as on ammonia for leaching. On top of emitting GHGs, this process also rejects solid waste residues like all metallurgical processes. In this case, they are called tailings (or leach residues), like all metallurgical processes. Nickel oxide sinter is produced after calcination, a product suitable for industrial alloys and stainless steel. It is usually accepted that the Caron process is no longer seen as economic, as 50% of the energy requirement comes from the ore drying and reduction steps, which come from the high moisture content of limonite minerals.[4] This is now supplanted by HPAL.

Finally, the Tsingshan approach to the projected supply gap for $NiSO_4$ production is to convert NPI to matte. It is based on a mature technology previously used by Eramet in New Caledonia but shut down due to economic reasons. The process would add elemental sulfur to NPI inside a converter, while blown air would oxidize iron, which could be separated from a higher-grade nickel matte. However, this class 2 to class 1 reallocation solution could lead to several issues: an extra processing step adds up to higher production costs and could increase environmental problems as it is energy-demanding in carbon-intensive grids.[81] This approach is anticipated to be a swing producer, allowing NPI producers to make a value-added product when the price differential is high, and produce only NPI if price differential is low.

3.3.8 A Comparison of the Carbon Intensity of the Different Processing Routes to Nickel Sulfate Hexahydrate

It is generally accepted that the Indonesian's laterite processing to refined nickel products is more carbon-intensive than the Canadian nickel sulfide pyrometallurgical route. In a recent LCA analysis performed by Minviro for the German Association of the Automotive Industry (VDA), the pyrometallurgical route (RKEF) in Indonesia is estimated to have the highest GHG impact at 97.9 kg CO_2 eq. per kg of nickel in $NiSO_4 \cdot 6H_2O$, compared to 33.3 kg CO_2 eq. for the Indonesian HPAL route and 7.1 kg CO_2 eq. for Canadian smelters. A previous analysis by the same authors had similar findings; they concluded that both the worst and best South East Asia RKEF case scenarios have significantly more CO_2 intensity than any case of nickel sulfide pyrometallurgy in Canada.[78]

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