POLYMETALLIC NODULES AND THE CRITICAL MINERALS SUPPLY CHAIN:

A NORTH AMERICAN APPROACH

By Rifat Jabbar, Demi de Silva, Duncan Kluwak, and Michael McCaffrey

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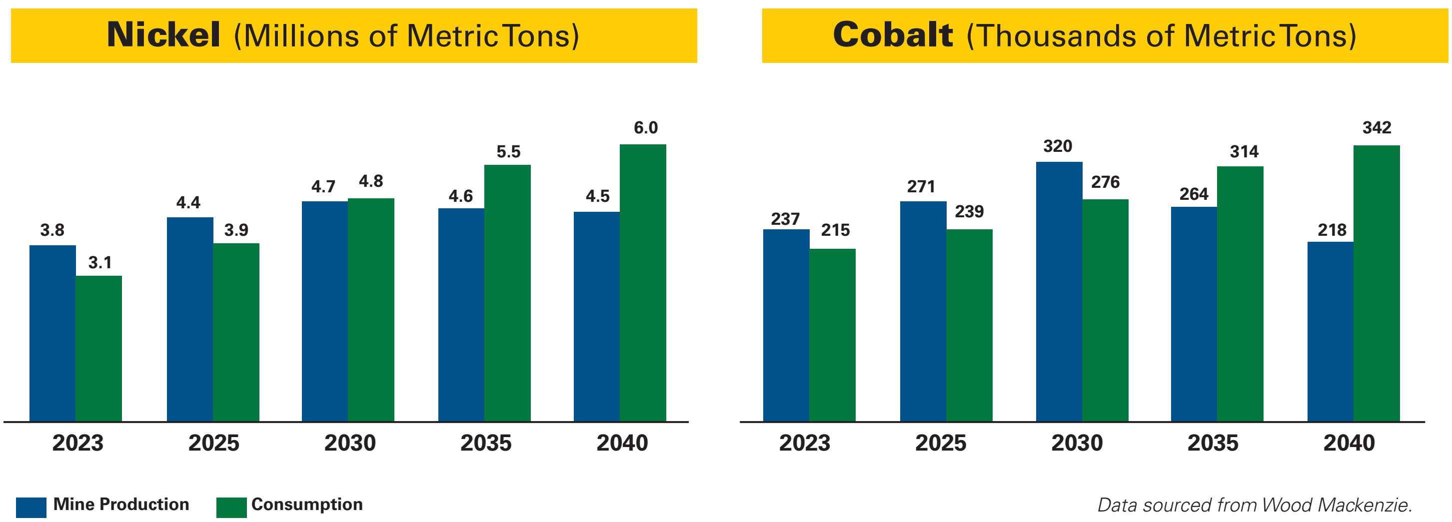
Critical Minerals Supply Chain Challenges in North America

Critical minerals play an essential role in the development of North America's technological and economic landscape. Global demand for critical minerals has dramatically increased over the last decade as North America and many other parts of the world have focused on electrifying their energy needs. Unfortunately, for many of these critical minerals, such as nickel and cobalt, supply will not increase at the same rate as consumption, leading to a forecasted global deficit, as shown in Figure 1.

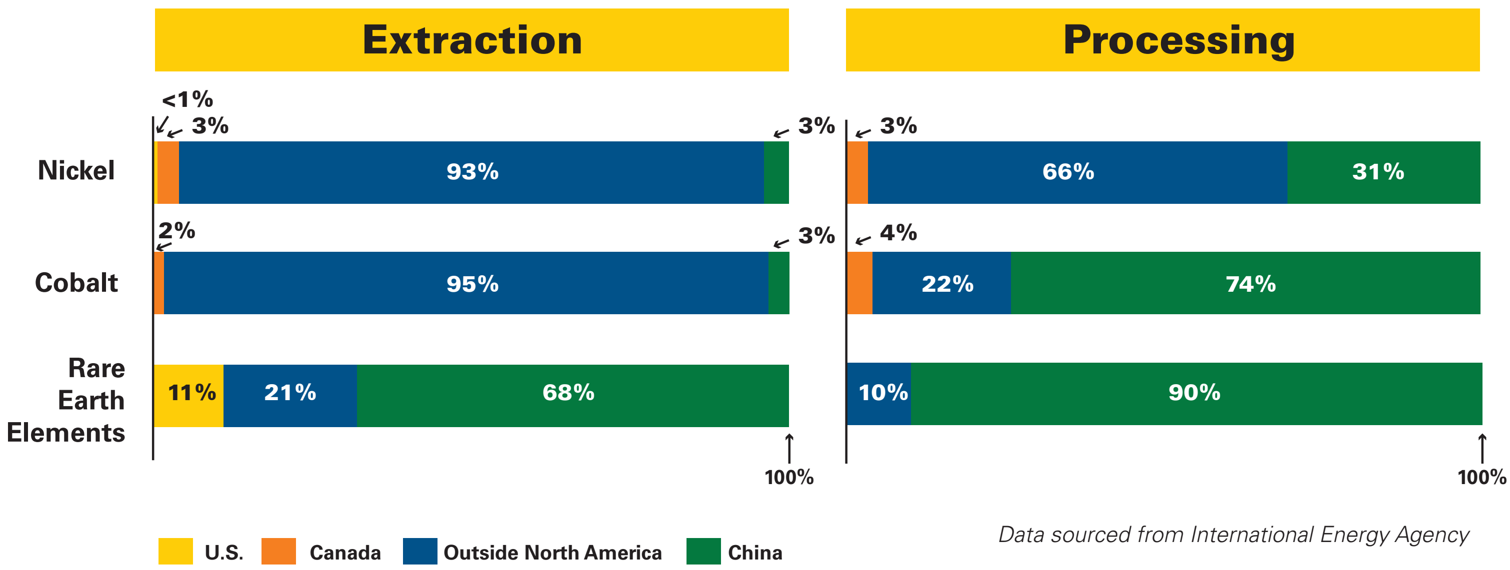
Figure 1: Mine production and consumption forecasts for nickel and cobalt



Data sourced from Wood Mackenzie.

In addition to this, most of the extraction and processing of critical minerals such as nickel, cobalt, and rare earth elements (REEs) currently occurs outside North America, as shown in Figure 2. Canada is the main North American player in nickel and cobalt extraction and processing, yet it accounts for less than 5% of global activity in both categories. The US mainly participates in the extraction of REEs, but this represents a small fraction of global activity. While China does not register as a major player in nickel and cobalt extraction, it has effective control of a large proportion of Indonesian nickel extraction and Congolese cobalt extraction. China also holds a strong, if not dominant, position in the extraction of REEs and overall processing of critical minerals.

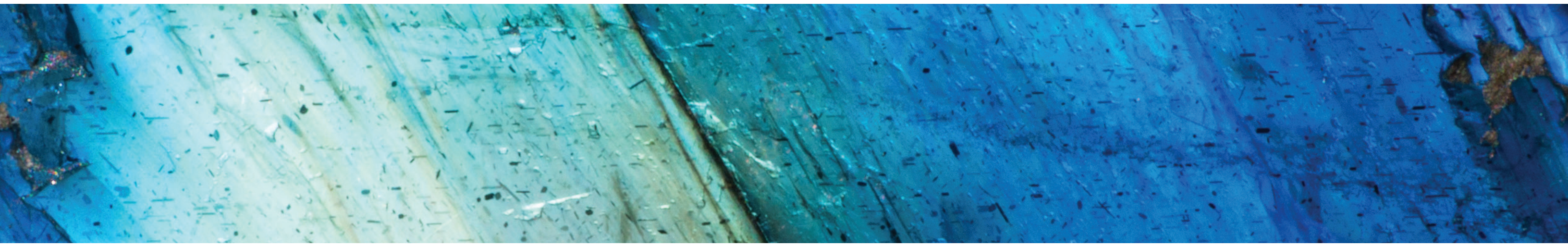
Figure 2: **Breakdown of global critical minerals extraction and processing**



Data sourced from International Energy Agency

The continued reliance on foreign sources for critical minerals poses significant risks to the overall value chain in North America, where these minerals play a crucial role in the clean energy transition. Nickel and cobalt are required for the production of electric vehicle (EV) batteries, specifically the NMC[1] type which is a widely adopted battery chemistry globally. Both metals also have direct applications in matters of national and regional security. Nickel is used in military plating and cobalt is used in fighter jets, as well as armor-penetrating munitions. REEs are essential for the production of magnets that are used in fighter aircraft and missile guidance systems, as well as in EVs and wind turbines. REEs also have the highest supply risk amongst critical minerals given the dominant market share held by China.

Establishing a domestic or regional supply chain for critical minerals would therefore reduce the long-term risk posed by the reliance on foreign sources. However, mineral exploration and mining activity in North America is unlikely to be sufficient for this purpose. Furthermore, greenfield mine development can take more than a decade, delaying the addition of new critical minerals to the supply chain.



The Potential for Deep Sea Mining to Counter Challenges

Over the last 50 years, deep-sea mining has increasingly been viewed as a potential alternative to conventional land-based mining to secure critical minerals. While there is a high degree of controversy and disagreement about the environmental impact of deep-sea mining, data continues to be collected and scientific studies are pending. The technology and resources required for deep-sea mining of critical minerals have yet to reach commercialization but have already been successfully applied to the extraction of other commodities such as diamond mining and offshore oil drilling.

There are three types of deep-sea deposits that are of economic interest:

- **Polymetallic nodules** are potato-sized rocks containing manganese, nickel, cobalt, copper, and REEs. They are distributed across the seabed at depths of 13,000 to 21,000 ft and lie in the sediment, unattached, allowing for a less invasive extraction process.
- **Polymetallic massive sulfides** are found around hydrothermal vents, which can occur at depths of up to 13,000 ft. They are formed as a result of hot mineral discharge from the vents coming into contact with cold sea water, and contain metals such as zinc, copper, cobalt, and platinum. Hydrothermal vents are known to support complex ecosystems which complicates mineral extraction.
- **Cobalt-rich ferromanganese crusts** are found on the seabed at depths of up to 16,000 ft and are formed by minerals that precipitate from sea water and deposit on sediment-free surfaces. These crusts contain cobalt, nickel, manganese, platinum, and REEs. Unlike polymetallic nodules, crusts are tightly attached to hard rock deposits and cannot be separated easily, meaning that both have to be extracted together which can be challenging.

Of the three types of deep-sea deposits, the extraction of polymetallic nodules from the seabed has been most closely examined from technical and economic feasibility perspectives and is therefore closest to commercialization. The resource potential for metals such as nickel and cobalt in polymetallic nodules has been estimated conservatively to be at least 270 million tons and 40 million tons, respectively. This exceeds land-based reserves and is more than sufficient to supply the requirements for hundreds of millions of electric vehicles. The manganese resource is estimated to be nearly 6 billion tons, which also exceeds land-based reserves.

Currently, several countries and resource firms are actively involved in deep-sea mining exploration. The International Seabed Authority (ISA), which was established under the United Nations Convention on the Law of the Sea (UNCLOS), has administrative authority for regulating all exploration and exploitation activities by UNCLOS signatory-nations in international waters. As the US only holds observer status and is not a UNCLOS signatory, it cannot participate in voting on deep-sea mining regulations and cannot sponsor firms that apply for exploration contracts from the ISA.

While the regulations for deep-sea mining in international waters continue to be formalized, countries such as Norway, Japan, and the Cook Islands have already taken steps to investigate opportunities for deep-sea mining within their exclusive economic zones. Meanwhile, active exploration for polymetallic nodules is ongoing in the northwest Pacific Ocean and the Indian Ocean. Exploration activity is especially concentrated in the Clarion-Clipperton Zone (CCZ), an area spanning 1.7 million square miles between Hawaii and Mexico that is known to be an abundant source of polymetallic nodules. Presently, 17 different parties have secured contracts from the ISA and are conducting exploration activities in the CCZ.

Processing Requirements to Produce Critical Minerals from Polymetallic Nodules

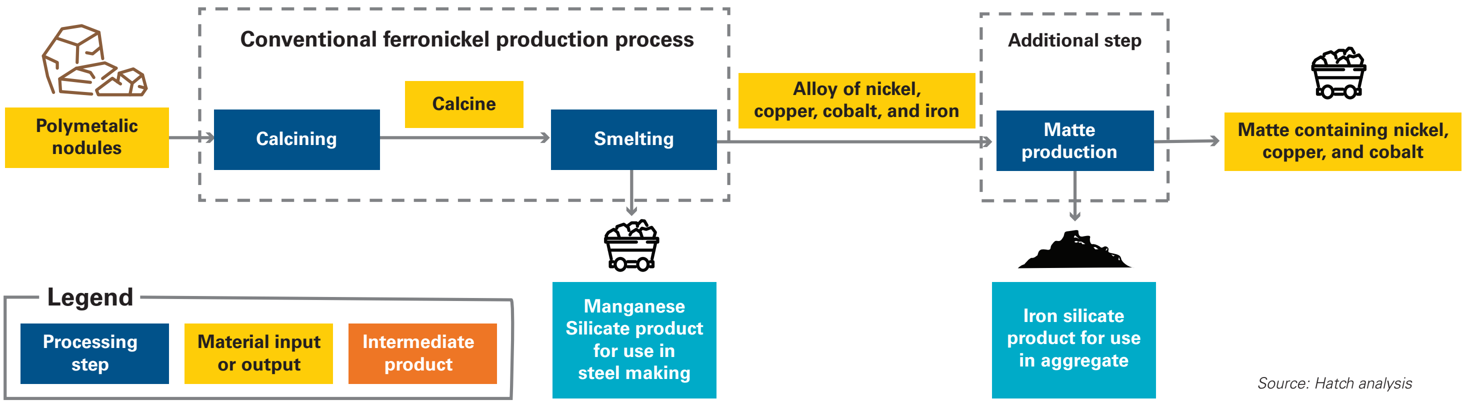
Once removed from the seabed in the CCZ, nodules will have to be transported to onshore facilities where they can be processed to extract metals such as nickel and cobalt. Various processing methods have been studied since the 1970s, involving hydrometallurgical (chemical treatment) steps or a combination of pyrometallurgical (thermal treatment) and hydrometallurgical steps. These methods represent a wide range of maturity and development, as some have not progressed beyond theoretical models and simulation while others have been studied through laboratory and pilot plant test work using real samples.

A two-stage process consisting of pyrometallurgical, and hydrometallurgical processing is closest to commercialization given the existing industrial precedents in both stages, namely smelting and refining. Each stage can be performed in different locations, or both can be co-located. An alternative approach would be an end-to-end hydrometallurgical process, which has not yet been proven commercially and requires further development to address some inherent flaws.

Two-stage Approach: Pyrometallurgical Stage

The first stage of the two-stage process is the pyrometallurgical stage, shown in Figure 3. This stage makes use of the conventional ferronickel production process, which is used to convert nickel laterite ore into ferronickel, an alloy of nickel and iron. It is well-suited for polymetallic nodules as they have a low nickel concentration, similar to laterite ores.

Figure 3: Pyrometallurgical processing of polymetallic nodules to produce matte



Source: Hatch analysis

The main steps in this process include:

- **Calcining**, where some of the oxygen bonded to the metals in the nodules is removed through reactions with a carbon source such as petroleum coke, coal, or sustainable biochar. This reaction takes place in a kiln which is heated using natural gas, producing a hot material known as calcine.
- **Smelting**, where calcine is heated further using electrical energy, causing it to melt and separate into two molten phases. One phase is a manganese silicate product that can be sold to the steelmaking industry as it has comparable characteristics to manganese feedstock that is traditionally used. The other phase is an alloy of nickel, copper, cobalt, and iron.

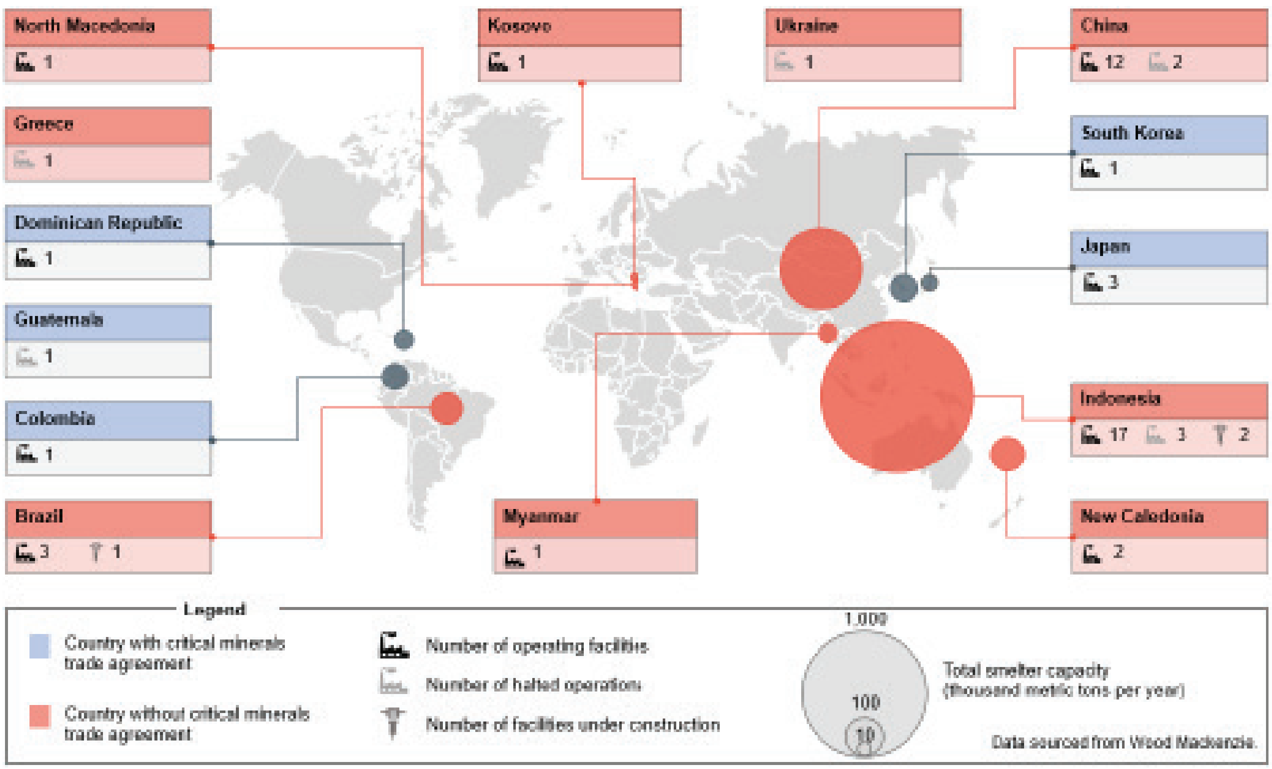
Some pyrometallurgical processes stop at this step and transfer the resulting alloy to the hydrometallurgical stage for further processing, although this has not yet been demonstrated at commercial scale. A more well-understood approach involves an additional step:

- **Matte production**, where the molten alloy reacts with liquid sulfur, which displaces iron and forms a combination of metal compounds known as matte that is easier to subject to size reduction and acid leaching. The displaced iron reacts with oxygen and silica to produce an inert iron silicate product, which can be used as aggregate material instead of being treated as waste.

The matte production step will require an investment in reaction vessels known as converters and gas handling infrastructure to deal with the hot gases that are generated by the reaction.

There are several countries with existing smelting facilities, shown in Figure 4, most of which produce ferronickel, while some produce nickel pig iron (NPI), a similar product but with lower nickel content. The primary concern is that none of the facilities are located on the North American continent, and most countries with operational facilities do not have a critical minerals trade agreement with the United States[2]. Furthermore, production in countries that do not have a critical minerals trade agreement far exceeds production in countries that do, by an order of magnitude.

Figure 4: Total 2023 production capacity for ferronickel and nickel pig iron smelting, and number of existing smelting facilities by country



Indonesia, in particular, has seen significant growth in domestic NPI production over the last decade, driven by Chinese interest in its nickel reserves, and is now the number one nickel processor globally. Nearly 25% of Indonesia's NPI production capacity is currently tied to the Morowali integrated steelmaking operation owned by Tsingshan Holding Group, a private Chinese company. Tsingshan also owns a majority stake in the Weda Bay mining project, which accounts for nearly 30% of Indonesia's NPI production capacity.

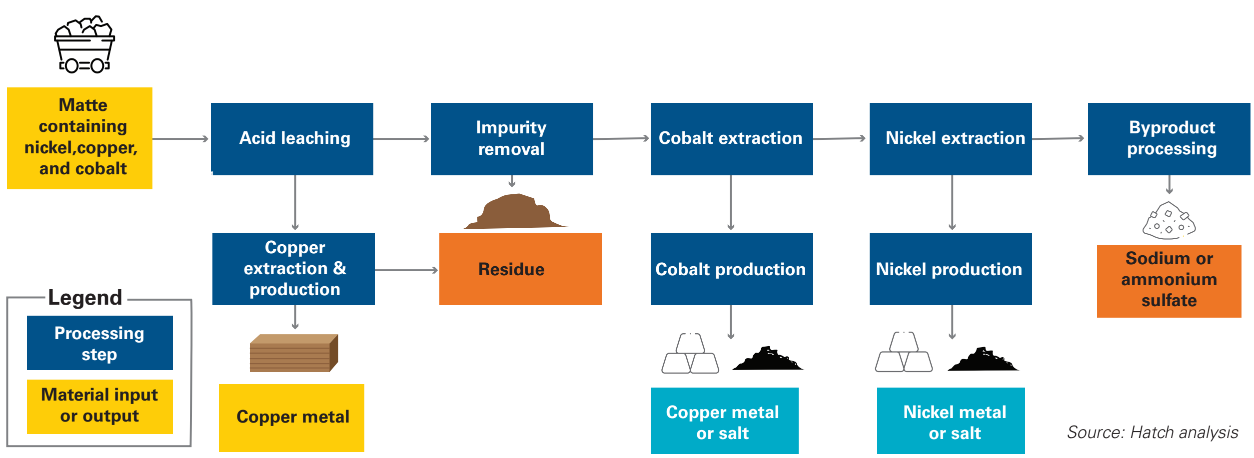
The repurposing of existing smelting facilities in countries that do not have a critical minerals trade agreement for processing polymetallic nodules may be a partial substitute for developing smelting facilities in North America or countries with a trade agreement, depending on economic and geopolitical factors. Many smelting facilities, namely in the Western Hemisphere, are integrated with mines and therefore may not have excess capacity to process polymetallic nodules for the foreseeable future.

However, some facilities may investigate the potential to expand their existing operations or divert to nodule processing when their mines' resource potential has been maximized, as this may represent a viable alternative to closure. Facilities that are not integrated with mines, most of which are in the Eastern Hemisphere, currently depend on sourcing their feedstock from producers and may see the transition to processing nodules as a more realistic short- or medium-term objective. This represents a short-term opportunity to shorten time to market by leveraging these smelters to produce matte that can be transported to North America or country with a trade agreement for the second stage.

Two-stage Approach: Hydrometallurgical Stage

In the second stage of the two-stage approach, the matte produced in the pyrometallurgical stage undergoes hydrometallurgical treatment in a facility known as a nickel refinery, as shown in Figure 5. Nickel is the typically the predominant component of matte and the main product, along with other metal

Figure 5: Hydrometallurgical processing of nodule-derived matte to produce metals or salts



Source: Hatch analysis

The main steps in this process include:

- **Acid leaching**, where the matte is treated with either sulfuric or hydrochloric acid to selectively dissolve nickel and cobalt while most of the copper is filtered out.
- **Copper extraction and production**, where iron and other impurities are separated from the filtered copper in solution. Electrowinning is then used to draw copper out of the solution using an electrical current to deposit it as a solid and form plates known as cathodes that can be sold.
- **Impurity removal**, where most of the remaining impurities are removed from the acid solution as a residue. This residue, along with the residue from the previous step, are the only stages where waste is produced. This waste can be sent to a smelting facility for re-processing to alleviate the need for waste deposition.
- **Cobalt extraction**, where reagents are used to selectively extract cobalt from the acid solution. Then, as part of **cobalt production**, electrowinning can be used to produce cobalt in metal format. Alternatively, a cobalt sulfate salt can be produced.
- **Nickel extraction** and **nickel production**, which follow a similar sequence as cobalt to produce nickel in metal or salt form.
- **Byproduct processing**, where the reagents used in the cobalt and nickel extraction steps are precipitated as byproducts, either as sodium or ammonium sulfate. As discussed before, sodium sulfate is challenging to sell. Ammonium sulfate, once purified, is sellable as a fertilizer product.

Similar to the situation with smelting facilities, most nickel refineries are located in countries without a critical minerals trade agreement, as shown in Figure 6, and only two are located on the North American continent. Most major refineries are capable of producing separate nickel, copper, and cobalt products. Some, however, can only produce nickel products, and any cobalt and copper contained in the matte would end up as an unrefined residue that would need to be sent to other facilities for further processing and refining.

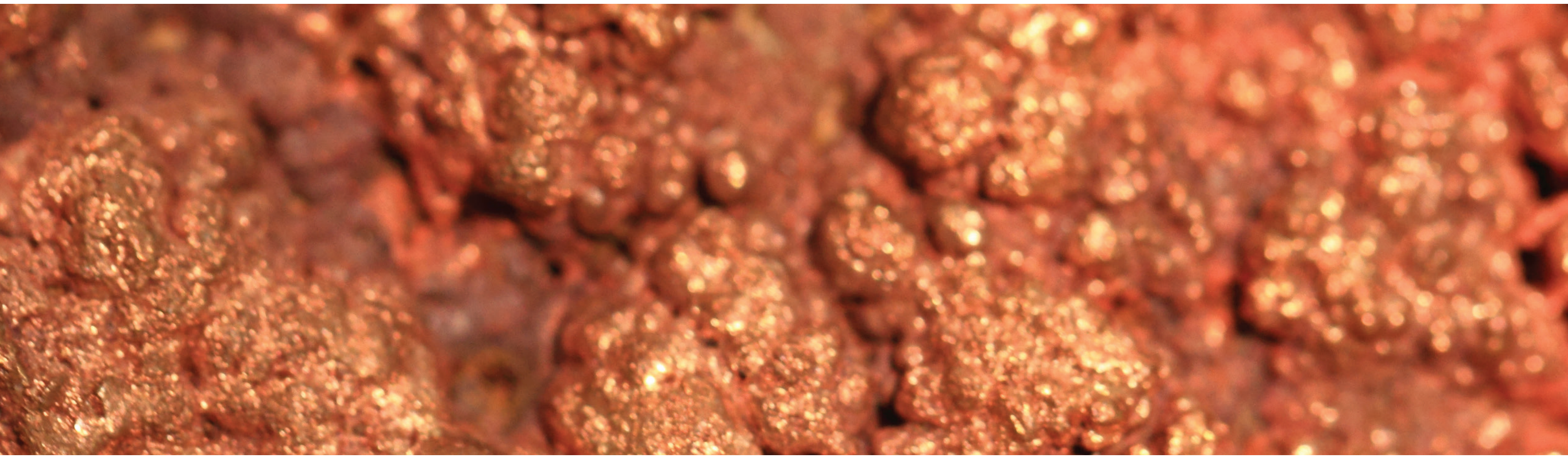
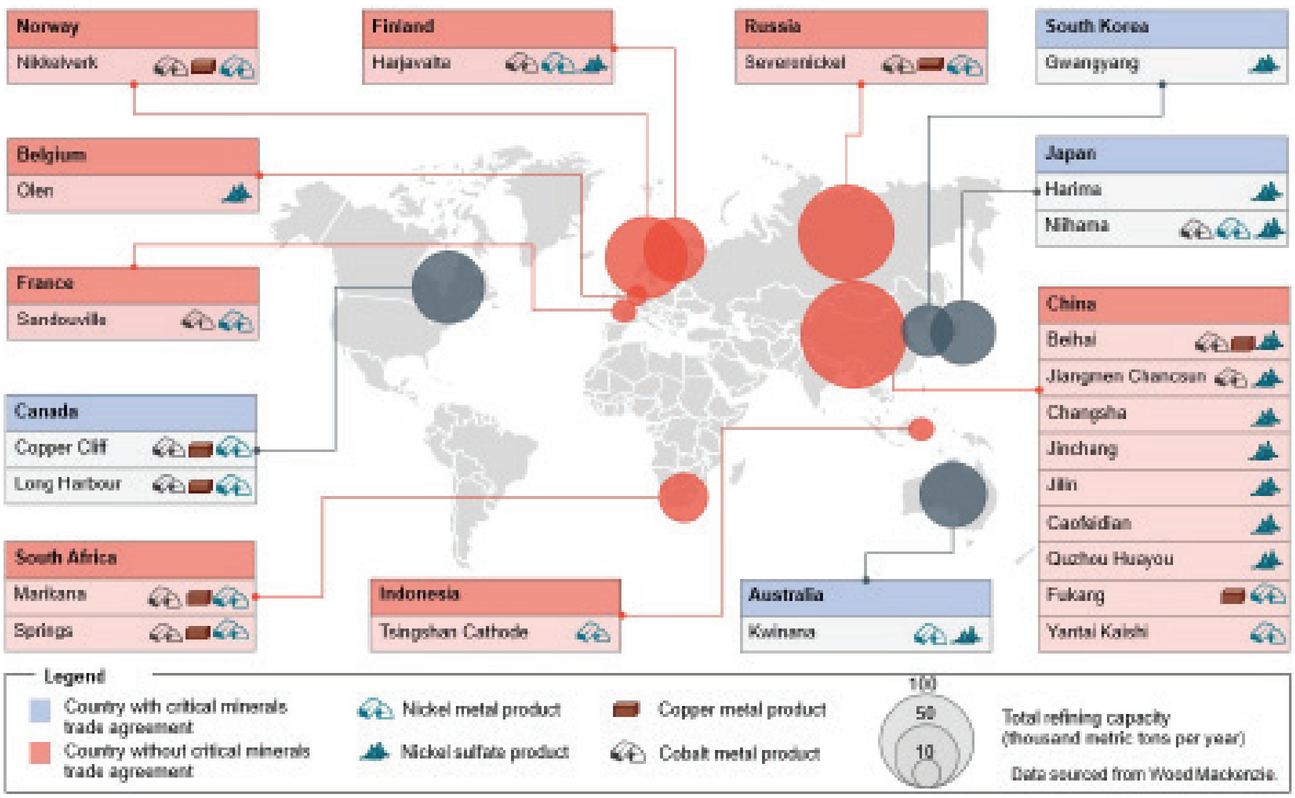


Figure 6: Total 2023 production capacity by country for products refined from matte, and product types by refining facility



Refined products produced by major refineries are generally in metal form rather than salt. While this is useful for most end customers, there is a growing preference among pCAM producers[3] for nickel and cobalt in sulfate salt form to avoid the additional step of having to re-dissolve metals in acid to produce the sulfate salts themselves. Many Chinese refineries, therefore, focus on producing nickel sulfate instead of metal to meet the demand from the Chinese battery production industry. Given China's strong interest in deep-sea mining, there is a possibility that Chinese refineries may look to divert capacity towards nodule-derived matte if deep-sea mining becomes feasible from a commercial, technical, and regulatory perspective.

Most refineries outside China belong to major mining firms such as Glencore (Switzerland), Vale (Brazil), BHP (Australia), and Nornickel (Russia), and rely on smelting facilities within the firms' respective value chains for most of their matte feedstock, which is tied to production from their mines. For these firms, processing nodules would likely be a long-term transition and would therefore not account for a significant portion of the firms' production for quite some time.

Localizing processing capabilities in North America

Technological development of the two-stage approach is the most advanced to producing critical minerals from polymetallic nodules, and existing facilities in other countries could potentially be leveraged to accelerate the production timeline at a lower capital expense. However, available capacity and the logistical requirements associated with these facilities could necessitate the development of facilities in North America. While this comes at a higher cost, it would greatly reduce supply chain risk and the reliance on foreign sources for critical minerals.

Ultimately, since the nodules are sourced from the oceans, the logistical requirements will likely weigh heavily when considering trade-offs between various options. For example, localizing the first stage in North America would mean that a significant quantity of manganese silicate would likely have to be shipped to Asia and other regions, as the North American steelmaking industry does not have sufficient demand to consume most of this product. However, increased steelmaking activity in North America would benefit from a domestic source of manganese silicate, especially since the US is currently a net importer.

Localizing a smelting facility in North America has its advantages. Low-cost electricity generated from renewable sources can be used to achieve a lower carbon footprint than Indonesian operations that make use of coal-fired power generation. The facility would be engineered to meet or exceed North American environmental guidelines, which are more stringent than other countries' regulations. Additionally, a North American smelter can be co-located with a refinery to eliminate the need to transport matte and achieve cost synergies.

While North America does not have any existing ferronickel smelting facilities, there is already a precedent for developing and constructing refineries domestically, and there are existing nickel, copper, and zinc refineries across the continent. Localizing a refinery in North America would make final products more directly accessible to the domestic critical minerals value chain and could help to strengthen the growing EV battery industry. Co-locating a refinery with a smelting facility would allow for residues to be re-processed, eliminating the need to dispose waste into land or water. This synergy could still be achieved without co-location, although the residue would have to be transported back to the smelting facility.

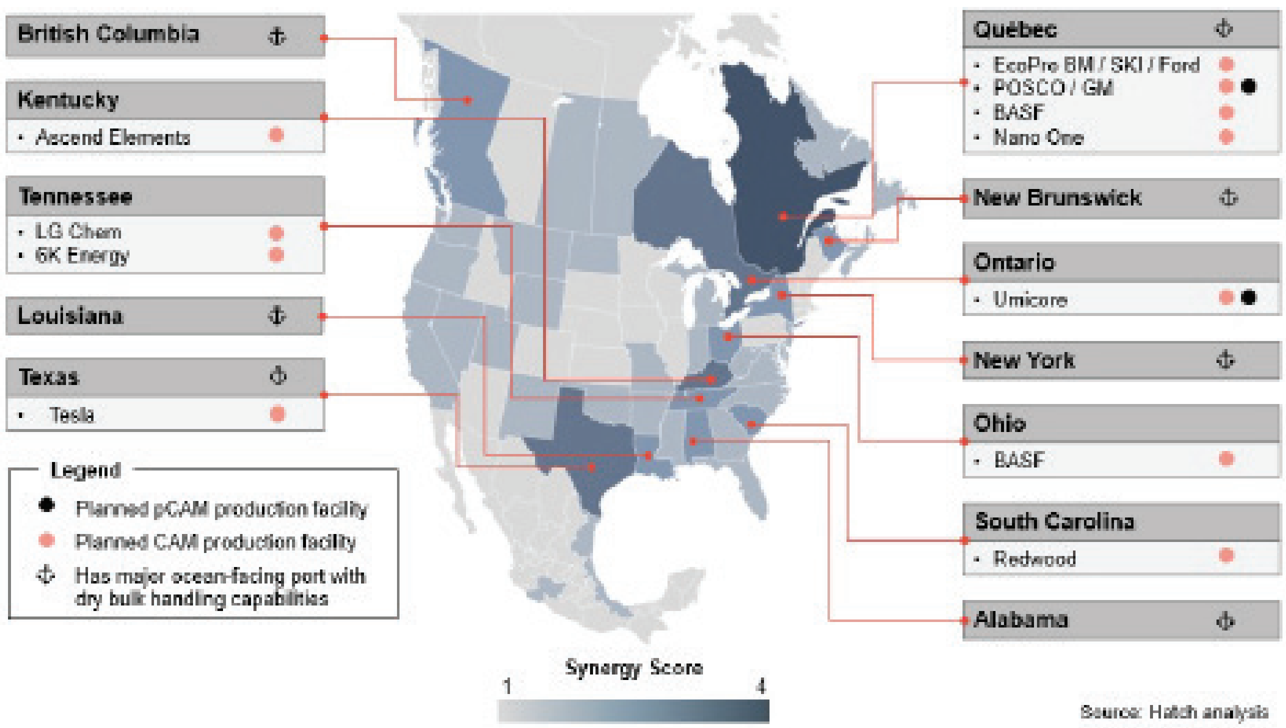
When considering potential locations for a smelting facility or a refinery in North America, the synergies offered by states or provinces can help to narrow down attractive options. For instance, both facilities would benefit greatly from access to low-cost electricity, which can help to minimize energy costs. A smelter would benefit from being near a major ocean-facing port that has bulk material handling capabilities and can receive large quantities of polymetallic nodules. A refinery may benefit from being near customer facilities.

A high-level screening of potential jurisdictions across North America that could host a smelting facility, or a refinery are shown in Figure 7. Each jurisdiction has been assigned with a score which considers how many synergies it can offer from the following:

- Access to **low-cost electricity**[4], which is effectively a base requirement.
- Access to **ports that have bulk material handling** capabilities.
- **Planned construction of pCAM production facilities** for potential refinery co-location, depending on customer needs for raw materials.
- **Planned construction of CAM production facilities**, as these may look to build pCAM production capability in the future.

While the above represent a preliminary list of some site selection criteria for a smelter or refinery, there are numerous other factors such as human capital, available infrastructure, and regulatory environment that should be considered. To provide greater resolution, a more detailed location assessment involving a broader set of selection criteria will have to be conducted as part of a technical feasibility study for a refinery that can process matte derived from polymetallic nodules.

Figure 7: Potential jurisdictions in North America to locate a smelting or refining facility



Key Takeaways

Of the three types of deep-sea mineral deposits, the extraction of polymetallic nodules is closest to commercialization. Several parties are currently engaged in exploration activities to extract polymetallic nodules from the Clarion-Clipperton Zone (CCZ) in the Pacific Ocean. Once these nodules can be commercially extracted, they would have to be transported onshore for further processing. A two-stage approach involving nickel smelting and refining technologies that are well understood and have been in use for several decades is currently best-suited to extract metals such as nickel and cobalt from the nodules. Final products can be made to directly suit the EV battery or defense industries' needs. To enable commercial production, existing smelting and refining capacity in other countries could be leveraged to accelerate the production timeline. However, this approach does not necessarily help to reduce North American reliance on foreign entities for critical minerals. Localizing processing capabilities offers the greatest opportunity to build a resilient supply chain for critical minerals domestically, and several jurisdictions across North America can offer the necessary benefits and synergies to enable the development of smelting and refining facilities necessary to achieve this goal.

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About the Authors: Rifat Jabbar, Demi de Silva, Duncan Kluwak, and Michael McCaffrey are consultants at Hatch, a global engineering, project management, and professional services firm with experience spanning over 150 countries in the metals, energy, and infrastructure sectors

Endnotes

1 NMC battery chemistry consists of nickel, manganese, and cobalt, among other materials.

2 Critical minerals trade agreement status is a key concern for electric vehicle manufacturers in the US as it is one of the eligibility requirements to secure incentives from the Inflation Reduction Act for produced EVs.

3 Precursor cathode active material (pCAM) is a combination of nickel, cobalt, and manganese salts that is used as a feedstock to produce cathode active material (CAM), a key component of electric vehicle batteries.

4 Low-cost is defined as being below the median cost among all North American jurisdictions.

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Woodrow Wilson International Center for Scholars
One Woodrow Wilson Plaza
1300 Pennsylvania Avenue NW
Washington, DC 20004-3027

www.wilsoncenter.org
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