Metallurgical Capacity: A Novel Metric for Quantifying Available Production of Mineral and Metal Products with a Case Study on Primary Non-Ferrous Nickel

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Environmental Studies

in

Sustainability Management

Waterloo, Ontario, Canada, 2023

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Minerals and metals are indispensable to society. Beyond conventional uses in all goods and services, significant deployment of new minerals and metals in clean technologies will be necessary for decarbonization efforts. Modern mineral and metal supply chains are highly complex, with distributed production and disjointed ore bodies, processing routes, products, and operational characteristics. This research addresses the need for an assessment metric, "metallurgical capacity," on the intricacies and nuances of mineral and metal supply that captures limitations and promises of midstream capacity. A bottom-up facility-by-facility approach is adopted for the metric. The underlying approach aims to provide accessible information for stakeholders to evaluate the ability of midstream operations to meet mineral and metal product requirements. To validate the utility of the metric and its approach, a case study of primary non-ferrous nickel supply was conducted for 2021. Nickel was selected due to its highly fragmented nature and utility in critical new technologies. Details and nuances of the metallurgical capacity metric were considered, and derivates of the metric related to attributes, such as operating status, excess capacity, ownership, feedstock, processing technologies, product class, product application, battery potential, and carbon neutrality commitments, were assessed. Data on operational, technical, product, and environmental attributes of applicable midstream operations were collected, primarily from published company annual reports. In total, 42 operations, producing 141 products, were assessed. Results show the metallurgical capacity of primary non-ferrous nickel products for 2021 was 1.6 million metric tonnes. Nickel products are primarily advertised towards metallurgical applications, and there remains a lack of products suitable to meet the projected demand from batteries, particularly high-quality nickel sulphate. The scope and granularity afforded by the approach allowed for an extensive discussion of potential supply chain bottleneck risk. Insufficient midstream non-ferrous nickel supply capacity expansion could result in considerable supply bottlenecks for nickel applications that could reverberate to alternative mineral and metal supply chains. In all, the metallurgical capacity demonstrates considerable promise in expanding knowledge of mineral and metal supply chains. Applying the metric to other mineral and metal supply chains would support efforts to improve decision-making among stakeholders.

Acknowledgements

First, I want to thank Steve for his support, patience, and teachings throughout this process and, more importantly, for taking a chance on me. I would also like to thank Komal for her enthusiasm over the years and insightful role in reviewing my thesis. Finally, I want to thank Stephen for agreeing to review my thesis and for all his commentary.

I would also like to thank all my former colleagues I have had the privilege to learn from over the years; your insights and perspectives have paid dividends. Further, I am forever grateful for the memories and support of my friends – including those no longer with us. I am eternally indebted to my parents; your support and care throughout this process and over the years will never be forgotten. And finally, my sister, whose encouragement and guidance over the years have been instrumental in getting to this point, I can only wish to be half the person that you are.

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List of Abbreviations

LIB: Lithium-ion Battery

BEV: Battery Electric Vehicle

NCA: Nickel-Cobalt-Aluminum

NMC: Nickel-Manganese-Cobalt

LME: London Metals Exchange

FeNi: Ferronickel

NPI: Nickel-Pig-Iron

USGS: United States Geological Survey

EOL: End-of-Life

BGS: British Geological Survey

MFA: Material Flow Analysis

TMS: The Minerals, Metals & Materials Society

HPAL: High-Pressure Acid Leach

ROM: Run-of-Mine

tpa: Tonnes per annum

MHP: Mixed Hydroxide Precipitate

MSP: Mixed Sulphide Precipitate

MP: Mixed Precipitate

C&M: Care and Maintenance

TP: Third-Party

CY: Calendar Year

LFP: Lithium-Iron-Phosphate

SMM: Sumitomo Mining and Metals

ASX: Australian Stock Exchange

LSE: London Stock Exchange

JSE: Johannesburg Stock Exchange

NI 43-101: National Instrument 43-101

JORC: Joint Ore Reserves Committee Code

SAMREC: South African Code for the Reporting of Mineral Resources and Mineral Reserves

Chapter 1

Introduction

1.1 Mineral and Metal Metrics

Minerals and metals have played an indispensable role advancing civilization. Their favourable properties have been leveraged in countless applications that are foundational to every sector of the modern global economy. A lack of materials with comparable properties diminishes their ability to be readably substituted, thus further solidifying their criticality to modern life (Graedel et al., 2015). In the future, their societal role will remain critical, absent novel material developments. However, given the impending need to hastily reduce climate change inducing emissions, the importance of minerals and metals in society is anticipated to grow considerably, some at an unprecedented rate (Hund et al., 2020; IEA, 2021a).

Modern mineral and metal supply chains are highly complex, expansive, and interconnected, all the while being exceedingly opaque (IEA, 2021a; Verhoef et al., 2004; S. Young & Dias, 2011; S. B. Young, 2018). Such characteristics present considerable challenges to dependent stakeholders lacking sufficient understanding of the nuances involved. This matter is compounded when considering the scarcity of satisfactory information on readably accessible mineral and metal supply chain assessments and relevant metrics. While a limited number of accessible tools to evaluate mineral and metal supply chains persist (Weber & Reichl, 2022), they often lack the sufficient granularity to support the particular needs of individual stakeholders or identify potential supply chain bottleneck risks. As such, there remains a critical need amongst mineral and metal supply chain stakeholders for readably accessible assessments and accompanying metrics sufficient to evaluate the intricacy and nuances of mineral and metal supply with suitable granularity.

Available and accessible tools for evaluating mineral and metal supply chains have predominately centred around a narrow set of supply chain attributes. Most notably, resource and reserve estimates, deposit qualities, mined production, global trade flows, and projected supply and demand scenarios (IEA, 2021a; Jowitt & McNulty, 2021; Rogich & Matos, 2008; U.S. Geological Survey, 2022; Verhoef et al., 2004). Considerable efforts to expand the granularity and accessibility of such assessments have proven valuable. However, there remains a lack of understanding, let alone detailed understanding, regarding supply chain attributes involved in upgrading and transforming extracted minerals and metals into consumable products for first-use applications. Such a gap in understanding remains detrimentally prohibitive to relevant supply chain stakeholders, namely downstream consumers of minerals and metals. There is a fundamental need for novel assessments and metrics to address the inherent knowledge gap such that relevant supply chain bottleneck risks can be reasonably identified and more targeted policies to remedy the potential risk can be developed (G. M. Mudd, 2021).

The need for novel, accessible assessments, and incidental metrics to assess the entirety of mineral and metal supply chains is imperative. Progress in assessments related to the geological availability and mining operations of minerals and metals remains encouraging. However, the considerable knowledge gap related to upgrading and transforming facets of mineral and metal supply chains presents an imminent opportunity to develop suitable assessments and supporting metrics. While intrinsic growth in demand for minerals and metals would inherently necessitate the need to address the gap, forthcoming growth in demand for minerals and metals foundational to clean technologies vital to climate change strategies further exacerbates the need for novel tools. This is further exacerbated when considering the condensed timeframe in which supply is required to occur and the heightened awareness concerning specific attributes of mineral and metal supply chains, notably sustainability and geopolitical risk (Hund et al., 2020; IEA, 2021a).

1.2 Fossil Fuel Based Society to Material Based Society

As the need to address climate change increases, efforts to decarbonize the global economy are expected to intensify (Rockström et al., 2017). Planned abatement strategies require the expedited deployment of countless clean technologies to meet internationally agreed-upon goals (Chen et al., 2022). The mineral and metal intensity of compulsory clean technologies is set to increase demand for relevant minerals and metals drastically (Hund et al., 2020). Predicted increases in demand for individual minerals and metals range from 5-50x current production levels by 2040. Given the limited displacement from equivalent fossil fuel technologies and the lack of sufficient secondary supply, such demand growth will necessitate novel primary extraction (IEA, 2021a). In turn, the global economy is expected to shift from fossil fuel reliance to mineral and metal dependence.

The unprecedented growth in demand will be challenging to achieve, given the timeliness of the transition. Heightened societal awareness towards sustainability matters and, in turn, growing obligations for sustainable mineral and metal supply chain practices (Fleury & Davies, 2012), will likely present considerable challenges given the detrimental precedent set by past minerals and metals extraction and processing operations (Jacka, 2018). Further, the finite nature of mineral and metals, geographic concentration of exploitable deposits, and high barriers to entry of mineral and metals supply chains has resulted in highly geographically concentrated and monopolized supply chains (IEA, 2023b). Intensified geopolitical tensions and awareness towards the susceptibility of minerals and metals supply chains for critical technologies have resulted in governments and organizations implementing policies and strategies to minimize potential supply risks (Graedel et al., 2012).

While established assessments and metrics of mineral and metal supply chains have been leveraged to demonstrate the availability, geographic distribution, and sustainability challenges of extracting minerals and metals (Hund et al., 2020; IEA, 2021a), a limited number of accessible studies have been conducted on equivalent matters relating to upgrading and transforming mined minerals and metals. The need to rapidly scale supply coupled with sustainability and geopolitical challenges further exacerbates the need for readily accessible assessment and metrics with sufficient nuance to account for such attributes. Applicable assessments and metrics are pivotal to supporting relevant stakeholders as it relates to this critical stage of the supply chain, specifically clean technology producers requiring timely procurement of minerals and metals with distinct qualities and provenance.

1.3 Research Objective

As such, the main objective of this research is to develop a novel metric, namely "metallurgical capacity", and an accompanying methodology to assess the ability of operations responsible for upgrading and transforming viable feedstocks within mineral and metal supply chains in relation to their respective output products abilities to satiate discrete downstream applications. The utility of the metric and methodology is then to be validated through a comprehensive case study of a specific mineral or metal supply chain, as further discussed in Sections 1.4, 1.7, and 3.3.2.

1.4 Case Study

While any mineral and metal supply chain would have sufficed for validating the metric and methodology, the primary non-ferrous nickel supply chain was selected for several unique reasons. First, the supply chain is highly divergent in relation to its mineralogy, processing pathways, product quality, geographic distribution, and sustainability characteristics (Campagnol et al., 2017; Fraser et al., 2021; Mistry et al., 2016; G. M. Mudd & Jowitt, 2014; Reck et al., 2008). Further, nickel is anticipated to play a central role in numerous clean technologies, most notably in batteries (IEA, 2023b). As such, the supply chain presented a considerable opportunity to assess a highly complex and intricate supply chain critical to clean technologies.

1.5 Nickel Overview

1.5.1 Current and Future Supply and Demand

Historically, nickel has been predominately used in metallurgical applications. At present, the most significant first-use application of nickel is stainless steel, accounting for 69% of global nickel consumption. In contrast, batteries, non-ferrous alloys[1], plating, alloy steels, and foundry applications account for 11%, 7%, 6%, 3%, and 2% of first-use consumption, respectively (Nickel Institute, n.d.). Although metallurgical applications for nickel are expected to remain the dominant first-use application, anticipated growth for batteries is expected to exert considerable shifts amongst demand applications (IEA, 2023b).

Global mined nickel production in 2020 was estimated at 2.5 million metric tonnes (U.S. Geological Survey, 2022). However, according to the IEA, demand for nickel is anticipated to reach between 4.0-6.3 million metric tonnes by 2040 (2021b). While sustained growth from traditional metallurgical first-use applications is expected to contribute to the increased demand, the bulk of the growth is predominately driven by demand for battery applications (Mitchell & Pickens, 2022). It is forecasted that by 2040, clean energy technologies will account for between 31-61% of demand compared to 8% in 2020 (IEA, 2021b). The growth in demand, coupled with shifts in demand applications, will have drastic and likely disproportionate impacts on the nickel market.

1.5.2 Batteries

While batteries are portrayed as a viable technology to help decarbonize critical economic sectors, their inherent mineral and metal intensity is emblematic of the broader societal shift to mineral and metal dependency (IEA, 2023b). An array of battery technologies have been successfully developed and commercialized (Van Noorden, 2014). However, lithium-ion batteries (LIB) have emerged as the dominant chemistry for countless applications, namely battery electric vehicles (BEV) and grid storage (T. Kim et al., 2019).

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[1] Alternatively termed Superalloys.

Numerous LIB variants have been commercially developed, each with unique cathode, electrolyte, and anode designs (T. Kim et al., 2019). Two cathode variants, for which nickel is a substantial constituent, have seen widespread adoption amongst BEV manufacturers. They include Nickel-Cobalt-Aluminum (NCA) and Nickel-Manganese-Cobalt (NMC) (Xu et al., 2020). The addition of nickel improves the energy density and storage capacity of LIB. Nickel content of such cathodes ranges from 30% to 80% of the mass of the cathode (Nickel Institute, 2021). The substantial nickel content is reported to be achieved through the use of battery-grade nickel sulphate, which is reported to be predominately derived from high-grade nickel products, namely Class 1 (>99.8%) nickel powders (Campagnol et al., 2017; Fraser et al., 2021).

The need for copious quantities of high-quality nickel products coupled with the need to rapidly scale production to meet climate goals, the ability to source sufficient allotments of nickel with requisite qualities within a condensed timeframe could pose a considerable bottleneck to the deployment of BEV reliant on nickel-based LIB. While feasible to recover and produce nickel of sufficient quality from end-of-life (EOL) LIB (Xu et al., 2020), the lack of available EOL supply within the immediate future necessitates growth in primary supply (IEA, 2021a).

When considering the projected needs for battery applications and the importance of equivalent nickel products in other critical first-use applications and their respective projected growth, insufficient growth of primary supply could extend likely supply chain bottlenecks incurred by batteries to other competing applications. For example, if produced Class 1 nickel is wholly allocated to battery manufactures, plating producers will be unable to secure necessary supply as they require Class 1 nickel (Rose et al., 2022). As such, it remains vital to assess the state of primary nickel production in relation to non-ferrous nickel products to identify potential direct and indirect supply chain bottlenecks.

1.5.3 Geological Availability

Primary nickel is generally sourced from two distinct ore groups: sulphide and laterites. According to the United States Geological Survey (USGS), global terrestrial nickel resources are estimated to be greater than 300 million metric tonnes, while reserves are estimated to be greater than 95 million metric tonnes (U.S. Geological Survey, 2022). Sulphide-containing ores, accounting for approximately 40% of global resources, are predominantly located in Australia, Canada, and Russia. In contrast, laterite-containing ores, accounting for approximately 60% of global resources, are generally concentrated in Brazil, Indonesia, and the Philippines.

1.5.4 Processing

Established processing routes to convert ores to functional products vary drastically amongst and within each mineral type. Further, a range of metallurgical processing technologies are commonly employed, including both hydrometallurgical and pyrometallurgical technologies. The variability is primarily associated with the technical and economic viability of converting ores into commercial products sufficient to meet the needs of a spectrum of downstream demand sectors (Crundwell et al., 2011). In turn, a range of nickel products are commercially produced (Fraser et al., 2021).

1.5.5 Products

The nickel industry informally segregates nickel products into two distinct commodity product groups: Class 1 and Class 2 (Campagnol et al., 2017). Products are partitioned according to their respective nickel contents. Products greater than or equal to 99.8% nickel by weight are considered Class 1, while products with nickel content inferior to 99.8% nickel by weight are classified as Class 2. The classification is further ratified by the London Metals Exchange (LME) standards for deliverable nickel products, in addition to other impurities and form factor requirements, as outlined in Appendix A (London Metal Exchange, 2022).

The composition, quality, and form factor of nickel products plays a deterministic role in the ability of nickel products to service downstream applications. For example, nickel products used in the production of stainless steel broadly include low-quality ferrous Class 2 products, namely Ferronickel (FeNi) and Nickel-Pig-Iron (NPI), although high-quality Class 1 products are commonly used, albeit in lesser quantities (Johnson et al., 2008; Nickel Institute, 2016). In contrast, Class 1 nickel products are vital for producing non-ferrous alloys and plating applications as their negligeable concentration of impurities are necessary for the applications (deBARBADILLO, 1983; Holt & Wallace, 1976; Fraser et al., 2021; Rose et al., 2022).

The classification method presents considerable challenges as it relates to battery applications. For example, while nickel sulphate products are classified as Class 2 as a result of their lower nickel content, stringent impurities exigencies for battery-grade nickel sulphate misrepresent the dynamics of the available supply when assessing the supply chain through the established classification system (Fraser et al., 2021; Sherritt, 2021b). This matter is further exacerbated when considering the ability to directly produce battery-grade nickel from primary sources and through the conversion of Class 1 nickel products (Fraser et al., 2021).

Production of Class 1 nickel products and battery-grade nickel sulphate can technically be achieved using laterite or sulphide ores (IEA, 2021a; Nickel Institute, 2016). Due to their technical and economic viability, sulphide ores have historically been the leading source of high-grade nickel products (IEA, 2023b). More recently, advancements in processing technologies have provided the requisite technical and economic conditions for the production of high-grade nickel products from select laterite deposits. However, operational regressions amongst laterite facilities employing advanced processing technologies have limited the proliferation of high-grade nickel products derived from laterite ores, notwithstanding recent efforts to overcome such shortcomings (Durrant, 2023; Gabb, 2018). Projected deficiencies of novel sulphide projects and historical impediments to scaling the production of high-grade nickel products from laterite deposits are projected to result in significant supply shortfalls (Fraser et al., 2021; Gabb, 2018).

1.5.6 Environmental, Social, and Governance

Considerable environmental burdens are exerted from upgrading and transforming nickel from primary sources, irrespective of ore type or processing pathway. The extent of environmental impacts varies amongst operations due to disparities in mineralogy, processing technologies, and product output, amongst other factors (Eckelman, 2010; Mistry et al., 2016; G. M. Mudd, 2010). Curtailing associated environmental impacts are imperative to surmounting indirect emissions associated with nickel end-use applications, particularly for battery and metallurgical applications. Production of primary nickel with marginal environmental impact has become increasingly desirable to downstream consumers (Azevedo et al., 2020). Implementing improved operational practices and technologies is fundamental to meeting the growing demand and requirements for sustainable production methods. However, the lack of accessible assessments with sufficient granularity concerning the sustainability capabilities of nickel upgrading and transforming operations limits the ability of stakeholders to adequately compare value chains in line with their respective adopted sustainability goals and metrics.

1.5.7 Criticality

The geographic concentration of nickel deposits and subsequent upgrading and transforming facilities has presented considerable concern amongst countless governments and enterprises lacking access to sufficient regional deposits and production capabilities (IEA, 2021a). The current concentration of supply and processing among a limited number of countries has resulted in import-dependent countries implementing policies to diversify supply and, in some instances, policies to reduce their import dependence altogether (J. Burton, 2022; Department of Mineral Resources and Energy, South Africa, 2022; European Commission, 2023; Government of Canada, 2022; IEA, 2021a; G. M. Mudd & Jowitt, 2014). As such, a considerable need remains to assess the geographic distribution of relevant nickel operations and products to identify supply chain risks.

1.6 Case Study Research Gap

The production potential of nickel products with specific attributes, namely quality, spatial distribution, and sustainability performance, remains absent from academic literature. Similarly, the correlations between critical attributes, such as mineralogy, processing pathways, production capacity, product quality, sustainability, and geographic distribution are broadly devoid from academic literature. While resource and reserve metrics provide valuable estimates of the potential availability of minerals and metals, the lack of consideration for subsequent supply chain stages encumbers the extent to which such metrics can contrive actionable conclusions.

A select number of publicly accessible studies have been published improving the granularity of the nickel industry; however, they have mainly focused on mining operation (Heijlen et al., 2021; G. M. Mudd & Jowitt, 2014). Accessible assessment of nickel upgrading and transforming operations are limited in breadth and predominately technical in nature or focus on environmental impacts (Dalvi et al., 2004; Diaz et al., 1988; Eckelman, 2010; R. Ferreira & Pinto, 2021; Vahed et al., 2021; Warner et al., 2006, 2007). While a scarce number of reports have been published by consulting, industry, and government groups as it relates to the assessment of individual operations or the industry as a whole, the underlying methodology and data is restricted (Berlin et al., 2022; Campagnol et al., 2017; R. Ferreira & Pinto, 2021; Fraser et al., 2021; McKay, 2023). The lack of accessible literature related to this critical stage in nickel supply chains prohibits the advent of fruitful discussion on the development of coherent abetment policies to potential industry shortcomings. A comprehensive global assessment of primary non-ferrous producing upgrading and transforming operations is indispensable for identifying potential supply chain bottleneck risks.

1.7 Case Study Questions

As outlined in Section 1.3, the objective of this research is to develop the metallurgical capacity metric and its underlying methodology. While the metric and approach are indented to be suitable for assessing any mineral or metal supply chain, a case study was conducted to demonstrate their utility. The case study conducted herein aims to determine the metallurgical capacity of primary non-ferrous nickel. Given the complexity and importance of the primary non-ferrous nickel supply chain, a series of questions aimed at supporting topics of concern relevant to numerous nickel supply chain participants were addressed. In essence, the case study questions are distinct from the research objective, as illustrated in Figure 1-1.

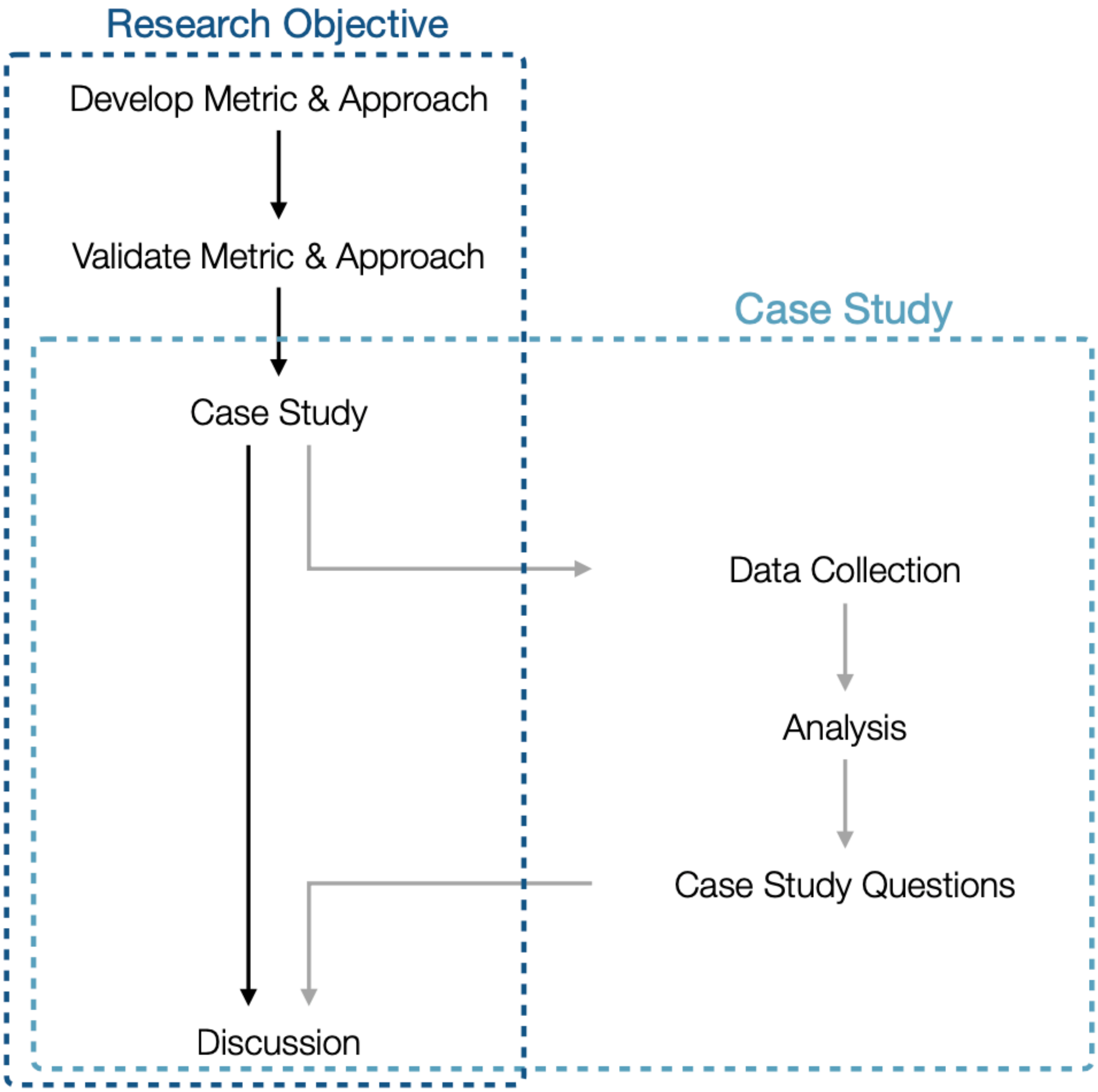

Figure 1-1: Research Framework

Case Study Question: *What is the current primary global nickel processing capacity for the production of non-ferrous nickel products, and what bottlenecks exist to expanding capacity?*

Case Study Sub-Questions:

1. *What is the current state of non-ferrous nickel products in terms of production capacity, composition, quality, form factor, and indented end-use application?*
2. *What is the correlation between ore type, processing technology, and product quality?*
3. *How much spare capacity remains dormant across operations?*
4. *Are operations or product production capacity geographically concentrated or monopolized?*
5. *What are the carbon neutrality goals of operations?*
6. *Are operations investing in expansion or battery recycling capacity?*

Through the adopted approach, an array of data points were collected in reference to individual operations within the supply chain, including, but not limited to, operational performance, governance, and sustainability. Accumulated data was subsequently synthesized into an open-sourced database, included in Appendix B, and thoroughly examined in order to address the case study questions and identify additional insights. The assessment included a global scope, and data were referenced to 2021, with historical production data extending to the fiscal year 2000.

Employing a bottom-up facility-by-facility analysis of nickel processing operations is intended to grant unparalleled insight into the primary non-ferrous nickel supply chain. Results and data will be of considerable value to organizations within the nickel value chain. In particular, details will support decision-makers within procurement, environmental, engineering, legal, and business development teams of relevant enterprises. Additionally, the research will support a myriad of efforts by governments and researchers, notably within policy and technology development disciplines.

Subsequent chapters of the thesis will, first, provide a more detailed overview of the primary non-ferrous nickel product supply chain and review published literature as it pertains to the research objective and case study. A description of the metallurgically capacity metric, the methodology employed, and a description of the conducted analysis is then followed. Thereafter, relevant data and results from the study will be presented and case study question addressed. A comprehensive discussion of germane observations, implications, abetment strategies, and considerations for future endeavours proceeds. Finally, a summary of the research, results, and discussion is presented.

Chapter 2

Literature Review

When considering the research objective and scope of the case study, deliberation of connected themes is necessary. As such, a review of pertinent literature specific to each theme was conducted to provide sufficient context and background for the reader. Specifically, a review of relevant literature on approaches, metrics, and evaluations suitable for assessing mineral and metal supply is presented for the research objective. As it relates to the case study, a simplified overview of the non-ferrous nickel supply chain is outlined, and a review of relevant literature on applicable attributes specific to the case study is provided.

2.1 Approaches, Metrics, and Evaluations for Mineral and Metal Supply

The complexity and opacity of mineral and metal supply chains present considerable limitations when attempting to adequately evaluate and develop metrics representing distinct characteristics of a mineral and metal supply chains (Weber & Reichl, 2022). In turn, a limited body of published research related to the supply potential of minerals and metals persists. While available approaches and metrics for quantifying the supply of mineral and metal supply chains provide valuable insight, limitation inherent to their underlying methodologies and scopes often restricts their utility.

2.1.1 Resources and Reserves

Resource and reserve are prominent metrics for evaluating the geological availability of minerals and metals. The United States Geological Survey (USGS) and British Geological Survey (BGS) publish periodic commodity summaries containing resource and reserve data of individual minerals and metals (Idoine et al., 2023; U.S. Geological Survey, 2022). Determination of the metrics often employed aggregated data from various sources, such as mining and exploration companies and national databases. Further, reported metrics provide limited insight into spatial, temporal, systematic, physical, and fiscal considerations, thus limiting the utility of the metrics.

The variability between employed methodology amongst national geological surveys when evaluating mineral and metal resources and reserves has resulted in considerable discrepancies among reported figures, according to Jowitt and McNulty (2021). The researchers found that the reliance on published data from mining and exploration companies is a considerable limitation to the metric as companies are not required to follow standardized methodologies when evaluating a metric and can thus tailor the approach to their specific needs.

To improve the resolution of resource and reserve metrics, Mudd utilized a bottom-up facility-by-facility approach to evaluate the published resource and reserve estimates of applicable mining and exploration operations across numerous minerals and metals (G. M. Mudd et al., 2013; G. M. Mudd & Jowitt, 2014; Weng et al., 2015). The studies considerably improved the granularity and resolution of the underlying data used to evaluate the metrics. Nevertheless, the lack of consideration for subsequent supply chain operations limits their utility to specific supply chain stakeholders.

2.1.2 Mine Production

While resource and reserve metrics provide insight into the availability of exploitable minerals and metals, mine production is a prominent metric for evaluating the annual production of minerals or metals from primary sources. Similar to resource and reserve metrics, commodity summaries published by USGS and BGS include annual mine production figures for minerals and metals (Idoine et al., 2023; U.S. Geological Survey, 2022). The system boundaries for evaluating mine production vary by mineral and metal as well as publication. However, they are often constrained to the contained content of the mineral or metal in the extracted ore. Analogous to resource and reserve, the underlying data for mine production is often collected from published reports of relevant mining companies, in addition to global trade data. While the metric provides a temporal component, the metric affords limited information regarding spatial, systematic, physical, and fiscal components of primary production.

Apart from improving the resolution of resource and reserve metrics, Mudd collected a limited subset of data related to specific attributes of pertinent mining operations (G. M. Mudd et al., 2013; G. M. Mudd & Jowitt, 2014; Weng et al., 2015). In turn, superior resolution of data on mined production and other pertinent operational attributes of mining operations was achieved. However, the sparsity and inconsistency of the collected data due to reporting practices, limited the extent of the analysis. While mined production provides insight into the annual extraction of minerals and metals through an expanded examination of applicable supply chains relative to resource and reserve metrics, the lack of consideration for subsequent supply chain stages and secondary sources limits the utility of the metric.

2.1.3 Material Flow Analysis and Recycling Rates

Material Flow Analysis (MFA) is a scientific approach for evaluating the flows and stocks of materials and products throughout their respective lifecycles and their distribution across distinct economic sectors (Brunner & Rechberger, 2003). As such, the approach is often employed to evaluate the lifecycle and distribution of minerals and metals (Harper et al., 2006). While the approach affords valuable insight into pertinent mineral and metal supply chain characteristics, it commonly employs aggregated trade data and generalized system boundaries when evaluating mineral and metal supply chains. In turn, considerable margins of error persist, which limits the granularity, and therefore, utility of subsequent results. The availability of more granular, facility-level data can significantly improve the resolution of MFA evaluations. Further, the approach commonly evaluates production and provides limited insight into supply chains' net production potential, in essence, capacity.

The scope and resulting data afforded by MFA are often expanded to evaluate EOL outcomes of minerals and metals (Bailey et al., 2004). The complexity of manufacturing supply chains and distributed use of minerals and metals has resulted in the development of numerous recycling metrics used to evaluate EOL outcomes of various mineral and metal flows generated throughout their respective supply chains (Graedel et al., 2011a). While developed recycling metrics provide pertinent insight into the supply of minerals and metals from secondary sources, similar to MFA, the reliance on aggregated data and generalized system boundaries limits the utility of the metrics. Specifically, the lack of consideration for the quality of the recycled product provides limited utility to stakeholders with specific feedstock considerations.

2.1.4 Mineral and Metal Supply Chain Evaluations

While the opacity of mineral and metal supply chains often constrains the scope of accessible evaluations pertaining to the supply of distinct minerals and metals, many supply evaluations persist with varying degrees of accessibility. Most notably, periodic reports published by companies responsible for extracting and processing relevant minerals and metals. Reports range from quarterly results to annual reviews of key market trends (Berlin et al., 2022; Glencore, 2022a; McKay, 2023; Vale, 2019). While the reports provide a varying degree of resolution related to spatial, temporal, systematic, physical, and fiscal considerations, the variable scope and restricted methodological approaches and underlying data often limit their utility.

Countless industry groups, government organizations, and third-party entities have conducted evaluations of mineral and metal supply chains (Campagnol et al., 2017; Fraser et al., 2021; Hund et al., 2020; IEA, 2021a). Reference data is often obtained from primary sources, notably from relevant operations, and secondary sources, such as published company reports, as such a more representative representation is provided. The ability to retrieve these publications and their underlying data is either confined to subscribed members, requires exorbitant cost, or completely inaccessible (Weber & Reichl, 2022). Further, citing acquired assessment is often restricted, thus limiting the communicability of the evaluations.

Attempts to improve the transparency and availability of mineral and metal supply chain evaluation with facility-level granularity have been limited. Accessible evaluations often focus on specific characteristics of supply chain stages. A prominent example includes The Minerals, Metals & Materials Society (TMS) World Nonferrous Smelter Survey series (Battle, 2004). The limited series included an evaluation of Copper (Kapusta, 2004), Platinum Group Metals (Jones, 2004), Nickel Laterite (Warner et al., 2006), and Nickel Sulphide (Warner et al., 2007) smelting operations. While the attempt provided granular data, the lack of consideration towards alternative unit operations and supply chains limited the utility of the surveys. Alternatively, Marsden (2006) evaluated gold production methods to compare processing techniques employed amongst facilities. However, data was aggregated on a country level limiting the ability to distinguish between operations. The most prominent example of an equivalent evaluation includes a substance flow analysis of tantalum conducted by Achebe (2016). As part of the evaluation, a facility-level bottom-up assessment of 48 tantalum processing facilities was conducted to quantify the global mass flow of tantalum and investigate conflict-free production. While the study provided an overview tantalum producers, evaluated facilities were limited to those included in a restricted database. Nevertheless, the study and its approach is in line with the current study.

2.2 Nickel Supply Chain Background

Assessing the nickel supply chain provides a novel opportunity to evaluate a highly divergent material supply chain. Given the fragmented nature of the supply chain and limited scope of the case study, a cursory overview of the supply chain is provided. The following section provides a brief and simplified overview of the prevailing attributes of the primary non-ferrous nickel supply chain, as illustrated in Figure 2-1. Detailed descriptions of relevant supply chain attributes is provided in Appendix A.

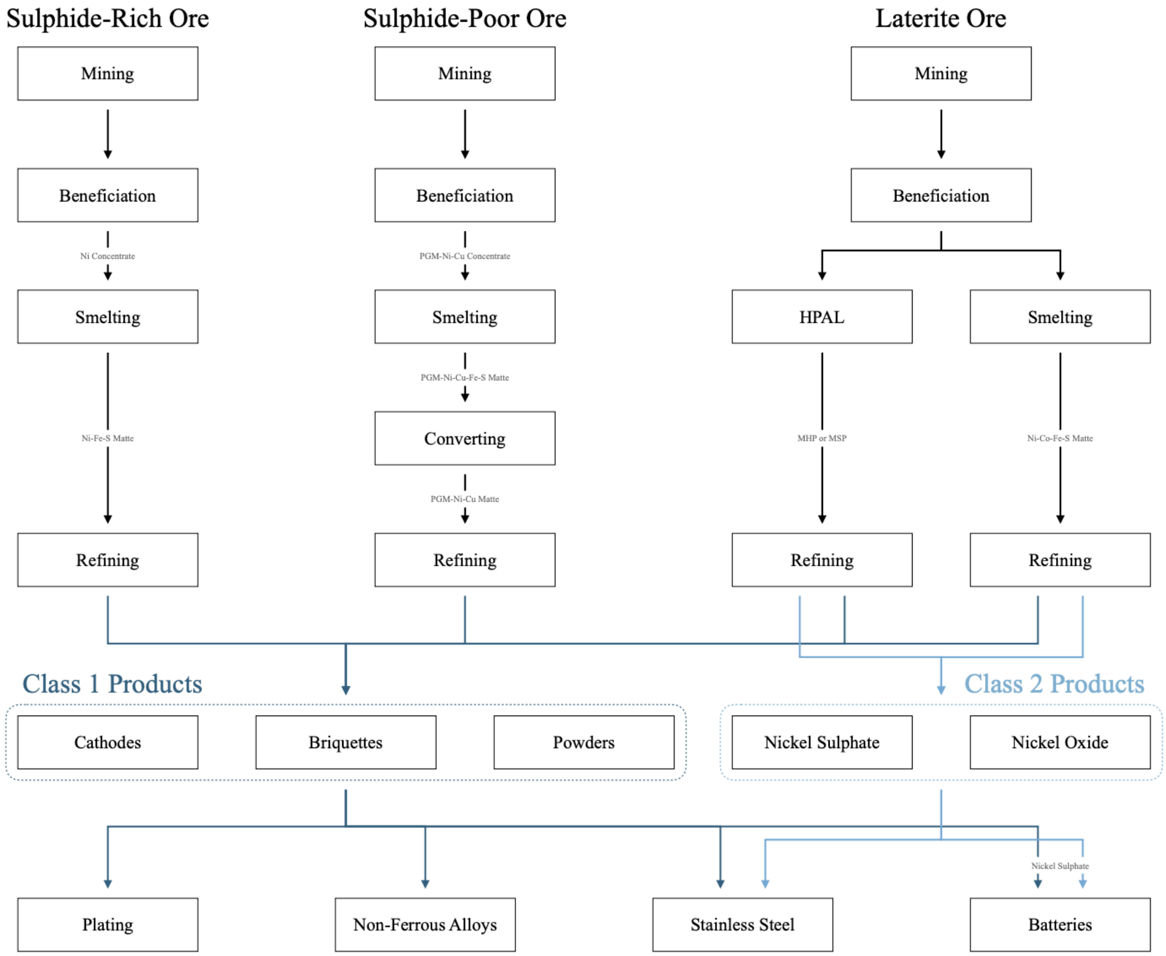

Figure 2-1: Simplified Representation of Primary Non-Ferrous Nickel Product Supply Chain

2.2.1 Geology

Terrestrial nickel is predominately derived from two distinct ores: sulphide and laterites (2016; Nickel Institute, 2016). The ores are often further classified: with sulphide ores commonly including sulphide-rich and sulphide-poor forms; and laterite ores commonly including saprolite and limonite layers (Dalvi et al., 2004; Naldrett, 2004). Given that lateritic saprolite ores are primarily transformed into ferrous nickel products, such as FeNi and NPI (Dalvi et al., 2004; Rao et al., 2013), further evaluation of the ore type in the following sections is not considered; however, additional details are provided in

Appendix A. As such, lateritic limonite ores are referred to as laterites throughout the remainder of the chapter.

Sulphide-rich ores are commonly co-deposited with economic concentrations of copper and cobalt. They are predominantly located in Australia, Canada, China, and Russia. Alternatively, sulphide-poor ores are commonly co-deposited with economic concentrations of precious group metals (PGM) and are located in South Africa, Botswana, and Zimbabwe. In contrast, laterite ores are commonly located in Australia, Indonesia, and the Philippines (Heijlen et al., 2021; G. M. Mudd & Jowitt, 2014). Further, laterite ores are often found in close approximation to the surface and contain economic concentration of cobalt as well as significant concentrations of iron, and marginal concentrations of magnesium oxide (Crundwell et al., 2011).

2.2.2 Mining and Beneficiation

For both sulphide ore types, mining and beneficiation routes follow a common pathway; however, their respective output streams vary. The ores are mined through either open-pit or underground methods and then subjected to various comminution and flotation operations to isolate nickel-containing minerals. For sulphide-rich ores, flotation operations often separate copper and nickel into two distinct concentrate streams. In contrast, for sulphide-poor ores, nickel, copper, and PGMs are often separated from gangue material and form a combined metal concentrate (Crundwell et al., 2011). Open-pit mining methods are commonly employed for laterite ores, given their close approximation to the surface. Minimal beneficiation operations are employed following extraction due to technological and economic constrains (Dalvi et al., 2004).

2.2.3 Processing

Following beneficiation operations, nickel concentrates derived from sulphide-rich ores are transformed using a pyrometallurgical process, notably smelting, into an intermediate nickel-iron-sulphur matte product. The matte product is then refined through either hydrometallurgical processes, such as solvent extraction and electrowinning, or vapour-metallurgical processes, such as carbonyl refining. In a similar manner, concentrates derived from sulphide-poor ores are converted into a nickel-copper-PGM-iron-sulphur matte product using pyrometallurgical technologies. The matte product is then converted to remove impurities using an additional pyrometallurgical process. Base metals, including copper and nickel, are separated from PGMs in the converted matte using a hydrometallurgical process. The separated base metal stream is then subjected to a series of hydrometallurgical processing where nickel is isolated and refined (Crundwell et al., 2011).

Laterite ores follow two distinct processing routes. The most common route employs a hydrometallurgical process, namely high-pressure acid leach (HPAL). Contingent on the employed reducing agent, the process produces either an intermediate mixed sulphide precipitate (MSP) or mixed hydroxide precipitate (MHP), herein collectively referred to as mixed precipitate (MP). Produced MP products contain economic concentrations of nickel and cobalt (Kyle, 2010). The nickel contained in the MP product is then separated and refined using hydrometallurgical processes, such as solvent extraction and hydrogen reduction (Dalvi et al., 2004). Alternatively, beneficiated laterite ores are transformed using pyrometallurgical processes, namely smelting, to produce an intermediate nickel-cobalt-iron-sulphur matte product. Nickel contained in the matte is then separated and refined by employing either a combination of pyrometallurgical and vapour metallurgical processes or through a hydrometallurgical process (Crundwell et al., 2011).

2.2.4 Products

As mentioned in Section 1.5.5, nickel products are traditionally segregated using an informal industry classification in which products are classified based on their respective nickel content. Products with nickel content greater than 99.8% are considered Class 1, while products with nickel content below 99.8% are considered Class 2 (IEA, 2021a).

In addition to the array of products with distinct nickel contents, products with various form factors and chemistries are commonly produced (Fraser et al., 2021). The stringent nickel content requirements for Class 1 products effectively confine produced products to metallic states. Nevertheless, Class 1 products are commonly formed into cathodes, briquettes, rounds, and powders (Campagnol et al., 2017). In contrast, the range of nickel content attributed to Class 2 products gives rise to distinct chemistries and form factors. Most common among non-ferrous Class 2 products include nickel sulphate powders, nickel chloride powders, and nickel oxide briquettes (Fraser et al., 2021).

While possible to produce both Class 1 and Class 2 products from either source, sulphide ores predominately produce Class 1 products, while laterite ores produce Class 2 products (IEA, 2021a). Further, operations often produce an array of products with distinct characteristics. The ability to extract nickel contained in a given ore and transform it into a specific product is highly dependent on technical and economic considerations. Further, certain products can be transformed into alternative products, including Class, form factor, and composition. For example, Class 1 nickel powder can reasonably be transformed into Class 2 nickel sulphate and vice versa (Crundwell et al., 2011).

2.2.5 First-Use Applications

A range of first-use applications employ nickel. As discussed in Section 1.5.1, metallurgical applications, namely stainless steel, account for the majority of nickel demand (Nickel Institute, n.d.). Alternatively, clean energy technologies, namely batteries, which currently account for a marginal share of demand, are anticipated to account for a sizeable share of demand by 2040 (IEA, 2021b).

First-use application manufacturing processes often require nickel products with distinct characteristics, as discussed in Appendix A (Fraser et al., 2021). For example, although stainless steel production processes employ Class 1 and Class 2 non-ferrous products, in addition to ferrous Class 2 products (Nickel Institute, 2016), processes often employ metallic or nickel oxide chemistries and tend to utilize either briquette or rounds form factors due to technical limitations (Fraser et al., 2021; Johnson et al., 2008). In contrast, non-ferrous alloys and plating applications often require high-purity Class 1 products and tend to utilize either cathode, powder, or rounds form factors (Crundwell et al., 2011). Alternatively, battery applications typically require high-quality nickel sulphate, commonly referred to as battery-grade nickel sulphate, in powder format (IEA, 2023b). To achieve the stringent impurity specifications, Class 1 nickel powders are frequently transformed into nickel sulphate to achieve the desired quality (Campagnol et al., 2017). Nevertheless, it remains feasible to produce battery-grade nickel sulphate devoid of preceding Class 1 nickel products (Crundwell et al., 2011; Sumitomo Metal Mining, 2021).

2.3 Primary Non-Ferrous Nickel Product Supply Chain Studies

Limited studies have been conducted evaluating the primary non-ferrous nickel product supply chain. Available studies largely evaluate specific attributes of the supply chain, such as geology, mining, processing technology, or material flow. As such, they are predominately restricted to a subset of stakeholders. The following section outlines pertinent studies related to specific attributes of the supply chain and in line with the proposed research approach.

2.3.1 Bottom-Up Facility-by-Facility Approach

As mentioned in Section 2.1.1, the bottom-up facility-by-facility adopted by Mudd to evaluate the geological availability of minerals and metals provided considerable insight relative to alternative approaches. The utility of the approach in reference to nickel was demonstrated by Mudd and Jowitt (2014) through an evaluation of known terrestrial nickel deposits in 2011. The study provided a comprehensive overview of relevant attributes of nickel mining operations, notably resources and reserves. More recently, utilizing a similar approach, Heijlen et al. (2021) conducted an equivalent analysis in relation to known terrestrial deposits in 2019 and added commentary on marine asset potential. In each of the studies, the resolution afforded by the approach provided novel insights into the upstream nickel operations. However, the lack of consideration for subsequent supply chain operations limits the outcome of the studies.

2.3.2 Midstream Operations

The opacity of mineral and metal supply chains is particularly acute as it relates to midstream operations. Available studies on midstream operations are often related to technical aspects of the operation or are limited in scope. This is best reflected in the industry survey conducted by Warner et al., on laterite (2006) and sulphide (2007) smelting operations in which insight into the technical attributes of participating facilities was provided. In contrast, Vahed et al., (2021) provided a generalized overview of select nickel sulphide and laterite operations and their accompanying technologies. In either case, the limited scope and focus on technical considerations restricted the value of the findings.

While not restricted to non-ferrous nickel product midstream operations, evaluated nickel laterite operations by Dalvi et al. (2004) provided considerable discernment into the state of several operations. Similarly, the Latin American and Caribbean nickel operations assessed by Ferreira and Pinto (2021) provided insight into the challenges faced by regional operators. Regardless, the limited spatial and physical scope considered in the studies bounds the utility of the results.

2.3.3 Supply Capabilities

Given the predicted growth in demand for products derived from the supply chain, countless studies evaluating the supply chain have recently been published by industry groups (Hund et al., 2020; IEA, 2021a), mining companies (Berlin et al., 2022; McKay, 2023), and consulting firms (Campagnol et al., 2017; Fraser et al., 2021; Mitchell & Pickens, 2022) in an effort to evaluate its supply capabilities. The scope of the studies varies considerably. Further, the underlying methodology and evaluated data are often inaccessible, thus limiting the communicability of the studies.

Conducted academic studies evaluating the nickel supply chain have been broad in scope and relied on restricted data. Bradley (2021) developed a model to evaluate future nickel supply chain dynamics in response to potential energy system adoption scenarios. While the author utilized mine-level data from Mudd and Jowitt (2014), smelting and refinery data was generalized and restricted. Although the author recognized that the data utilized in the study was substandard, the model provided a novel assessment of supply chain dynamics which could benefit from facility level data. In contrast, Young (2021) evaluated potential battery nickel supply chain bottlenecks concerning future demand scenarios. Specifically, the author assessed potential supply timelines and sustainability limitations given the current nickel processing infrastructure and technologies. While the study's appraisal of midstream processing operations provided novel insight into future supply dynamics for batteries, the generalization of operational attributes, precisely related to an operation's product quality and sustainability data, misrepresented the intricate dynamics of operations. Further, the use of restricted data limits stakeholders' ability to consider scenarios concerning their needs.

Chapter 3

Methods and Analysis

3.1 Research Approach

Established research approaches for identifying mineral and metal supply chain bottleneck risks, specifically those related to midstream mineral and metal processing operations, remain absent from academic literature. While a number of studies have been developed outside academia, a severe lack of transparency regarding the adopted approaches limits their further commutability. Nevertheless, academic research approaches developed to assess mineral and metal mining operations provide surrogate frameworks sufficiently malleable for contemporary research topics. Prominent approaches to quantify the geological abundance, mine production, and operational attributes of upstream operations on a mine-by-mine level, specifically those developed and applied by Mudd to countless minerals and metals, yield a cursory framework adaptable for the application considered herein (G. M. Mudd et al., 2013; G. M. Mudd & Jowitt, 2014; Weng et al., 2015). Through the approach, novel metrics for assessing the production of minerals and metals can be adequately developed.

3.2 Proposed Framework

The scope and granularity afforded by the framework applied by Mudd granted a highly nuanced understanding of evaluated attributes of upstream mineral and metal operations. The malleability of the framework permitted its broad applicability across countless minerals and metals while maintaining sufficient data granularity and consistent spatial and temporal scope. The improved granularity and depth, in turn, increases the materiality of the results relative to alternative approaches.

Mudd employed a bottom-up facility-by-facility approach when evaluating upstream mineral and metal operations. In this manner, data is collected directly from facilities responsible for extracting pertinent minerals and metals. Further, by assessing individual facilities, the approach allowed the authors to collect data on pertinent operational attributes and metrics, namely, resources and reserves, operational performance, ownership, and environmental impact, specific to each facility, as opposed to aggregated industry data common in alternative approaches. Minimizing data aggregation enabled data to be readily segregated and itemized in relation to relevant attributes. Through this approach, the subsequent analysis yielded a more nuanced understanding of assessed systems. As such, an equivalent bottom-up facility-by-facility framework was used to assess midstream metallurgical operations within a given mineral or metal supply chain such that the production capacity of products suitable for first-use applications can be quantified.

3.2.1 Bottom-Up Facility-by-Facility

Evaluating midstream metallurgical operations on an individual basis is valuable to assessing the availability of mineral and metal products. By isolating individual facilities per defined system boundaries, it is possible to extract data related to specific attributes, yielding highly granular data. In contrast, top-down approaches generalize supply chains inhibiting the ability to assess incongruities. Such aggregation approaches are particularly detrimental for mineral and metal supply chains when assessing their ability to satiate discrete downstream demand sectors. This matter is most apparent when considering the array of distinct mineral and metal products a midstream operation produces and the complexity of their value chains, as further discussed in Section 3.2.2.2. Using a bottom-up facility-by-facility approach it is possible to account for the complexity and intricacies of midstream operations.

Adopting a bottom-up facility-by-facility approach supports multiple research goals, most notably in collecting highly granular data with sufficient segregation to assess multiple operational and supply chain attributes. Conducting such an approach throughout the supply chain of a given mineral or metal provides the necessary scope and resolution to meet stated goals. Due to data aggregation, alternative approaches to assessing midstream metallurgical operations do not provide sufficient data granularity and segregation. Therefore, employing a bottom-up facility-by-facility analysis is necessary to meet the stated research goals.

3.2.2 Midstream Metallurgical Operations and System Boundaries

Mineral and metal supply chains are highly complex and intricate. Accurately defining consistent and standardized system boundaries sufficiently adaptable for assessing every mineral or metal supply chain is an unattainable task due to the high degree of variation and incongruities inherent within supply chains. Nevertheless, a generalized definition of appropriate system boundaries for metal supply chains and midstream metallurgical operations is needed to assess the ability of midstream metallurgical operations to satiate discrete downstream applications. Adopting generalized system boundaries when assessing supply chains will undoubtedly lead to respectable criticism and potential misrepresentation of results. However, ensuring detailed and transparent interpretations of system boundaries can significantly limit such outcomes.

When considering the vast array of minerals and metals produced, it is evident that countless exhibit analogous supply chain dynamics. A contributing factor to this relationship can be accredited to the geological anatomy of countless minerals and metals and the narrow breadth of suitable processing pathways (Verhoef et al., 2004). The co-occurrence of minerals and metals and the limited range of processing technologies gives rise to the economic and technological conditions necessary for their co-production. While co-production is endemic to several minerals and metals, it is not inherent to all minerals and metals (Nuss & Eckelman, 2014). Further, the extent to which geologically related minerals and metals are conjointly processed ranges due to varying points in which processing pathways diverge to form distinct homogenous metal processing streams. Additionally, the array of downstream demand applications each with distinct mineral and metal feedstock requirements for their respective processes exacerbates the convoluted nature of mineral and metal supply chains. Defining system boundaries sufficiently capable of accounting for such complexities is vital.

As such, mineral and metal supply chains were delineated into three distinct stages, as illustrated in Figure 3-1. The adopted stages are analogues to those used by the petroleum industry. They include upstream, midstream, and downstream operations. Due to the inconsistencies across mineral and metal supply chains, included and excluded characteristics within each stage are generalized and accompanied by numerous exceptions. In addition, each stage is described from the perspective of the individual mineral or metal suitable for downstream applications, rather than the ore or final end-use product.

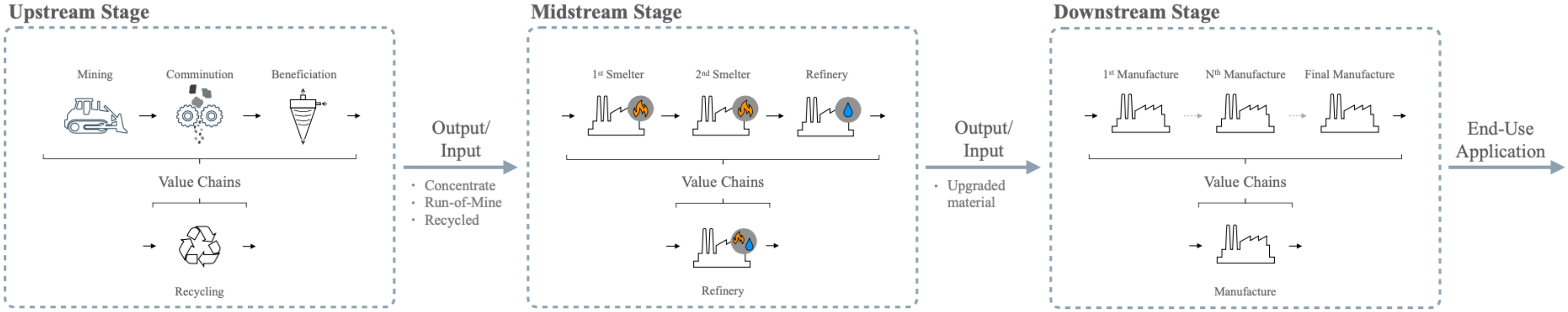

Figure 3-1: Generalized Mineral and Metal Supply Chain Stages and System Boundaries

3.2.2.1 Upstream Operations

Primary upstream operations encompass geology, mining, and beneficiation processes. More broadly, it consists of all activities and elements leading up to and including the production of either run-of-mine ore (ROM) or concentrates, for which require subsequent processing to be suitable for first-use applications. Inclusion of such unit operations is consistent with those adopted by Mudd and USGS in similar analyses (G. M. Mudd & Jowitt, 2014; U.S. Geological Survey, 2022). Further, limiting the system boundaries to the production of ROM or concentrates reflects the operational practices of countless mining operations.

For most minerals and metals, mined ore is commonly subjected to one of two pathways following on-site comminution unit operations. The first pathway includes the direct shipment of comminuted ores to midstream operations for use as feedstock material. This pathway is common amongst industrial metals such as iron and aluminum (H. Ferreira & Leite, 2015; Tan & Khoo, 2005), as well as metals that are converted into ferroalloy products such as chromium, manganese, and silicon (Gasik, 2013).

Alternatively, comminuted ores are subjected to beneficiation processes, for which are commonly co-located with mining operations, that produce a concentrate with greater homogeneity of a given mineral or metal within the ore. The concentrate is then transferred to midstream metallurgical operations for use as feedstock material. This pathway is common amongst base metals, such as copper and nickel (IEA, 2021a), minor metals, such as cobalt (Dehaine et al., 2021), and precious metals, such as gold (G. M. Mudd, 2007). Such bifurcation necessitated careful examination of mining operations when evaluating mineral and metal supply chains to ensure consistent system boundaries.

Secondary upstream operations exhibit considerable variability given the range of distinct products for which minerals and metals comprise. Generally, secondary upstream operations include those responsible for facilitating feedstock production amenable to midstream operations. The feedstocks often resemble homogenous concentrates produced by primary upstream operations or feedstocks similar to midstream output products. Upstream secondary operations include collection and pre-processing (Reck & Graedel, 2012).

3.2.2.2 Midstream Operations

Metallurgical processes necessary to liberate and transform minerals and metals contained in upstream feedstocks into suitable products for downstream operations are highly complex and unique. They often employ several sequential and distinct unit operations to achieve the required product characteristics. Process unit operations are either entirely located within an individual facility or distributed through a network of facilities, herein considered value chains. The location and configuration of necessary unit operations are a function of countless factors. Chief among them are technical and economic elements.

Processes for which the entirety of the required unit operations are confined to a single facility typically transform a small subset of minerals and metals contained in their feedstock to states suitable for downstream operations. Minerals and metals in the feedstocks not converted into suitable products for downstream applications at the facility commonly obey two outcomes. First, minerals and metals reporting to streams for which they cannot technically or economically recovered, such as refinery slags, are discarded. Alternatively, minerals and metals reporting to streams for which it remains technically and economically feasible to be recovered are often sold to dedicated facilities specializing in their recovery. For example, zinc concentrates are often processed entirely within a given facility; however, indium contained in the concentrates reports to various waste streams, such as sludges, which are often processed by dedicated indium refining facilities (Lokanc et al., 2015).

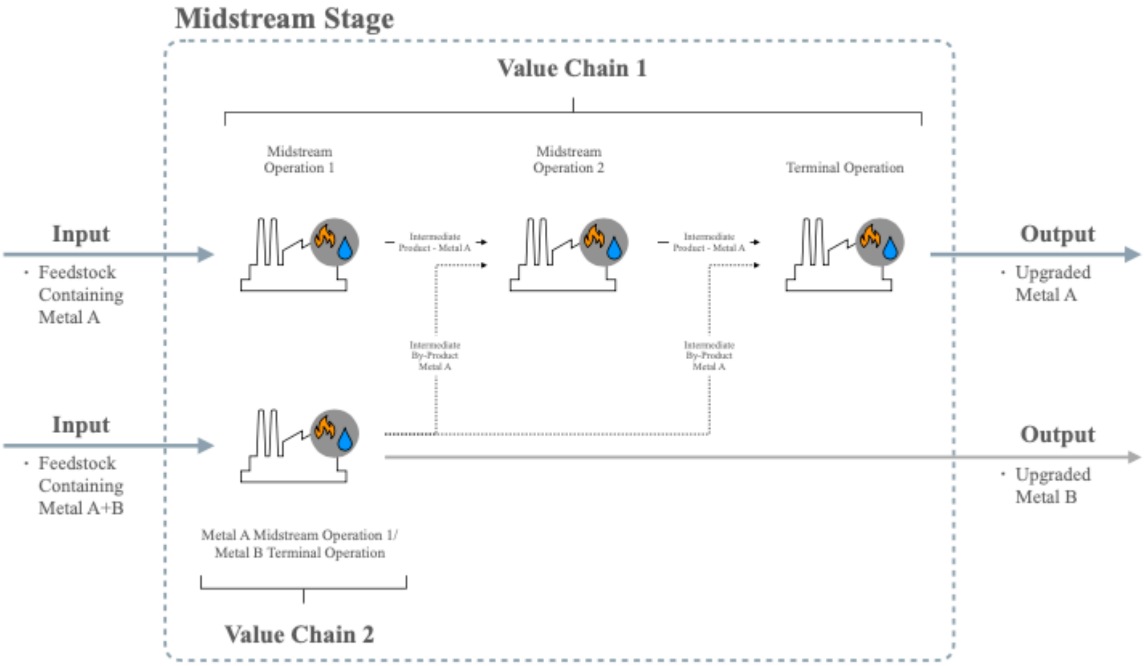

Figure 3-2: Midstream Value Chain with Intermediate By-Product Streams

In contrast, when considering processes for which unit operations are distributed through a network of facilities, intermediate products with varying characteristics are produced and subsequently exchanged by facilities within the network until reaching a terminal refining facility, as illustrated in Figure 3-2. For example, copper sulphide concentrates are often smelted to produce an intermediate blister copper anode which are then sent to a terminal refining facility to be electrolytically refined (Moskalyk & Alfantazi, 2003). Often, terminal refining facilities process feedstocks from multiple value chains, each with a varying number of preceding operations, as illustrated in Figure 3-3.

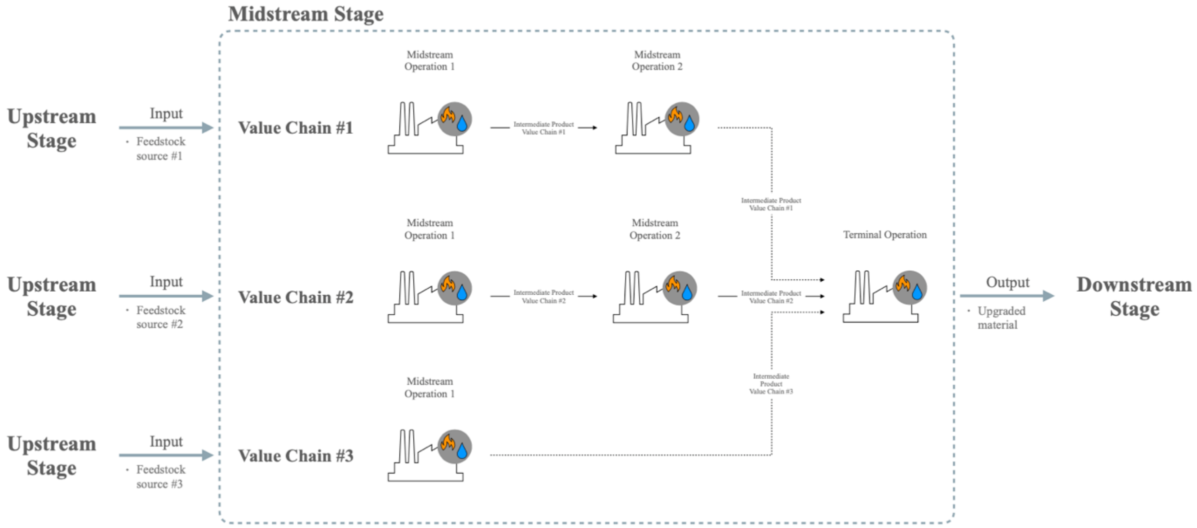

Figure 3-3: Terminal Operation with Three Value Chains

Given the multi-metal nature of ores, midstream operations within mineral and metal supply chains often exhibit a combination of fully integrated facilities and network value chains. Further, integrated facilities can often support feedstocks from a network of value chains. Specifically, it remains feasible for integrated facilities to utilize intermediate products derived from third-party value chains to supplement specific unit operations within the facility, effectively bypassing trailing unit operations. For example, integrated zinc-cadmium smelting and refining operations accept third-party cadmium dust from steel recycling operations which is then used as part of the cadmium recovery circuit

(Butterman & Plachy, 2004). However, the extent to which operations can exchange feedstocks, specifically amongst specific unit operations, requires considerable technical and economic evaluation.

Further, demand for products with distinct characteristics signifies that intermediate products within certain value chains can be considered refined products within others. For example, nickel sulphate is both an intermediate product within nickel value chains and a refined product suitable for downstream applications (Fraser et al., 2021). However, it remains imperative to assess the products in relation to alternative characteristics, notably elemental composition.

The complexity and uniqueness of midstream operations within mineral and metal supply chains present considerable challenges when assessing their capacity to produce products with distinct characteristics. As such, attributing traditional definitions, such as smelting and refining, to operations responsible for transforming upstream products would misrepresent the complexity and nuance inherent to the supply chain stage. Further, the range of metallurgical technologies employed throughout midstream operations limits the pertinence of such terms (Battle, 2004). Therefore, a midstream operations was defined as those responsible for converting upstream feedstocks into marketable products suitable for downstream users.

3.2.2.3 Downstream Operations

Given the vast array of products employing metals, the ability to define downstream stages is highly dependent on the perspective chosen. From the perspective of an individual metal, downstream stages include consumers who convert the metal into a non-commodity states or end-use product. The boundary between midstream and downstream stages is far opaquer relative to the distinction between upstream and midstream operations due to the multitude of potential transformation stages possible. While assessing the boundary through the perspective of a mineral or metal is more encompassing of the supply chain, it is limited by the ability of downstream users to transform a given metal into specialized products.

3.2.2.4 Metric System Boundaries

When assessing metal supply chains through the lens of the three stages described above, it is evident that midstream operations, in which metallurgical transformations are performed, are a critical bottleneck to assessing the ability of metal supply chains to satisfy discrete demand sectors. The dependence of upstream operations on midstream operations to convert their respective products into suitable products for downstream applications is endemic to the criticality of midstream operations. Additionally, the inability of upstream operations to bypass midstream operations to satisfy downstream operations, albeit with few exceptions, further highlights the importance of midstream operations. The bottleneck is further exacerbated when considering the relatively small number of terminal facilities within the midstream stage relative to the number of upstream producers and downstream consumers (S. Young et al., 2019).

Therefore, assessing the midstream stage of mineral and metal supply chains is vital to evaluate their ability to satisfy discrete downstream demand sectors. Similarly, it was assumed that a bottom-up facility-by-facility assessment would be necessary to sufficiently account for the complexity and intricacies inherent to operations within the midstream stage. Through this approach, it is estimate that unambiguous supply chain bottlenecks can be more adequately identified, and more targeted abetment policies or strategies to such bottlenecks can, in turn, be developed.

3.3 Metallurgical Capacity

We define metallurgical capacity as the aggregate production capacity of established midstream metallurgical operations capable of producing a specified metallurgical product in accordance with defined parameters. Assigned parameters include temporal, spatial, physical, systematic, and fiscal components of operations. In effect, the metric is the summation of production capacity across a set of midstream metallurgical operations able to produce a given mineral or metal product, as demonstrated in Equation 1.

Equation 1: Metallurgical Capacity

$$Metallurgical\ Capacity = \sum_{i=1}^{k} Capacity_{i,p_1,\dots,p_n}$$

Where Capacity represents the production capacity of the assessed midstream operation, *k* represents the total number of compatible midstream operations within the midstream stage according to defined parameters, *i* represents the i^{th} midstream operation assessed, *p* represents defined parameters, and *n* represents the total number of defined parameters.

Assessing the available capacity of midstream metallurgical operations to produce products with distinct characteristics can, in turn, yield a superior understanding of a commodity's available supply. Further, the malleability of the metric affords the faculty to assess distinct parameters of the midstream stage as assigned by the researcher. While the metric is assumed to be most beneficial for assessing the terminal midstream operation of presently established operations, it remains feasible to assess alternative points throughout the midstream stage and across different periods, geographies, processing technologies, companies, and economic capabilities. For example, it is possible to defined parameters suitable for evaluating terminal operations in Australia producing zinc sulphate from primary ores through hydrometallurgical processes in 2009.

Derivates of the metrics related to temporal, systematic, physical, spatial, and fiscal attributes for specific mineral or metal products or producers not defined as part of the required parameters can further be contrived, contingent upon data availability. Further, it remains feasible to evaluate derivatives of capacity across one or more of such attributes, as illustrated in Equation 2.

Equation 2: Metallurgical Capacity Derivative

$$Metallurgical\ Capacity'_{a_1,\ldots,a_x} = \sum_{i=1}^{k} Capacity_{i,p_1,\ldots,p_n}$$

Where *a* represents the attributes considered, and *x* represents the total number of attributes considered. Derivates can reasonably be tailored to the needs of individual stakeholders. In such a manner, more targeted evaluations of capacity can be achieved. Examples include accounting for ownership structure, operating cost, production from recycled sources, geopolitical risk, environmental impact, labour conditions, product quality, and production cost.

At present, accessible metrics for quantifying the production of a given mineral or metal, notably the USGS mined production statistics, aggregate production across multiple mineral and metal supply chains and across multiple distinct product types (U.S. Geological Survey, 2022). Such an approach misrepresents the often-delineated nature of mineral and metal supply chains for which multiple mineral and metal products with distinct characteristics are produced.

From the perspective of downstream stakeholders, this presents a considerable challenge given their diverse and distinct product requirements. Moreover, when considering mined production in mineral and metal supply chains with multiple output products, the lack of nuanced supply chain representation can overrepresent the available supply of mineral or metal products with distinct characteristics. This matter is particularly acute given the inability to readily substitute mineral or metal products in many downstream applications, as discussed in Section 1.1.

In a similar manner, the focus on annual mined production provides a constrained representation of the ability of mineral and metal supply chains to satiate downstream demand. Specifically, the lack of consideration for established production capacity limits the ability to assess the full potential to which mineral and metal supply chains can satiate demand. The inability to consider idle established capacity presents a unique problem for downstream stakeholders requiring expeditious supply growth.

The aggregated nature of existing mineral and metal supply chain production metrics and a lack of consideration for established production capacity present considerable shortcomings for stakeholders with insufficient understanding of mineral and metal supply chains. Additionally, the growing demand for products with distinct supply chain attributes, notably provenance and sustainability, further exaggerates the need for novel metrics sufficient to consider the needs of downstream stakeholders.

The metallurgical capacity metric was designed to consider the complex intricacies inherent to multi-output product mineral and metal supply chains. Assessing supply chains through a bottom-up facility-by-facility approach provides the requisite data to evaluate the metric. In such a matter, a more representative understanding of the available production capacity for a given mineral or metal product can be achieved.

3.3.1 Originality of Metallurgical Capacity

The current state of accessible knowledge on mineral and metal supply chains remains limited in scope and granularity. Such limitations can be attributed to the methodology and system boundaries applied to existing assessments of supply chains. Prevailing MFA methodologies are constrained to the availability of data which often includes aggregated data and consolidated supply chains system boundaries, directly limiting their scope and granularity, as discussed in Section 2.1.3. Similarly, bottom-up facility-by-facility assessments of upstream operations, while granular and comprehensive, are bounded to upstream operations limiting their applicability to downstream stakeholders, as discussed in Sections 2.1.1 and 2.1.2. While recycling metrics provide valuable reference points for the flow of minerals and metals in applications at their EOL, the use of aggregated and generalized data due to data availability constraints, coupled with a lack of insight regarding the quality of products produced, limits their adaptability in light of the stated research objective, as discussed in Section 2.1.3.

Although studies related to the research objective persist, as discussed in section 2.1.4, the lack of accessibility to the studies, their underlying methodologies, and data limits their communicability. This presents a novel challenge for relevant stakeholders with insufficient resources to access the studies or needing to reference the often constrained set of accessible results from the studies. Further, the limited number of studies related to the research objective, which are accessible, as highlighted in Section 2.1.4, highlight the need for more formalized metrics and evaluation methods.

While the methodology applied herein was adopted from existing research assessing the upstream mineral and metal operations, the lack of accessible assessment of midstream metallurgical operations provides a novel opportunity to expand the methodology. Assessing midstream metallurgical operations of mineral and metal supply chains through a bottom-up facility-by-facility approach attempts to provide broader cognition and a more detailed understanding of mineral and metal supply chains by expanding the scope of the current state of knowledge relative to alternative approaches.

Further, providing access to the underlying methodology and data when assessing mineral and metal supply chains through the developed approach is anticipated to improve the communicability of the results and analysis. Afforded representation of available mineral and metal products and production capacity is expected to support policy and product development. This matter is particularly acute when considering the condensed timeline required to deploy clean technologies, as discussed in Section 1.5.2. The ability of policy developers to access highly granular data can significantly improve the focus of their proposed policy. In contrast, researchers developing novel technologies can sufficiently consider available mineral and metal products and, in turn, design within available constraints. In doing so, developed products can be expeditiously deployed by leveraging existing mineral and metal supply chains, as opposed to develop novel supply chains.

3.3.2 Case Study

Demonstrating the feasibility of assessing midstream metallurgical operations through a bottom-up facility-by-facility approach to determine the metallurgical capacity of a mineral or metal supply chain is critical to validating the novelty of the approach and metric while addressing the research objective. As such, a case study of a selected metal was necessary to ratify the approach and metric. While any mineral or metal would have been sufficient for this exercise, a subset of criteria was adopted to select a suitable mineral or metal to achieve the desired research goals.

Prevailing selection criteria included a mineral or metal for which multiple products are commonly produced across its established supply chain, each sustaining discrete downstream consumers. In this manner, the complex relationship between the midstream and the downstream stages can be illustrated. Additional supporting thresholds were integrated in the selection process. They included minerals or metals with (1) existing and accessible bottom-up facility-by-facility studies of their respective upstream stages to support collected data, (2) adequate production volumes to validate relevance, and (3) supply chains with reasonably segregated primary and secondary production pathways to simplify conceptual understanding. Given the selection criteria, nickel was chosen as the inaugural metal for validating the utility of the metric and its accompanying methodology as it satisfies all relevant thresholds.

3.3.2.1 Nickel Supply Chain

The nickel supply chain exhibits a highly fragmented and diverging structure, specifically when considering available products and their respective downstream consumers. As discussed in Section 2.2.4, nickel products are informally classified into two distinct categories by their respective nickel content, namely Class 1 (>99.8wt% Ni) and Class 2 (<99.8wt% Ni). While such traditional categorization remains beneficial to a select number of downstream consumers, the array of available nickel products limits the applicability of the classification amongst producers requiring products with distinct characteristics beyond nickel content. Such divergence is best exemplified when considering the needs of stainless steel and LIB producers. Stainless steel producers consume Class 1 products, such as briquettes and rounds, as well as Class 2 products, such as FeNi and NPI. In contrast, LIB producers require high-purity nickel sulphate, which is commonly derived from Class 1 nickel powders but classified as Class 2 given its low final nickel content. In addition, process restrictions limit the ability of the producers to exchange feedstock material, often absent considerable preceding product, or process conversions. Dislocation amongst available midstream products and suitable products to downstream producers coupled with an archaic product categorization system yielded the ideal condition for the case study.

Beyond the principal selection criteria, nickel addressed supplemental selection criteria. A number of studies assessing upstream nickel mining operations utilizing a bottom-up facility-by-facility approach, for which underlying data is readily accessible, have been conducted (Heijlen et al., 2021; G. M. Mudd & Jowitt, 2014). The accessibility of the data supports efforts to validate collected data from the case study. In terms of production volume, according to the USGS, nickel was the 9th most mined metal by mass in 2021, providing adequate scale to demonstrate the utility of the metric (U.S. Geological Survey, 2022). Further, primary and secondary nickel processing pathways exhibit notable segregation. This results from the majority of nickel being recycled through the stainless steel loop, which is unsuitable for processing primary nickel feedstocks (Reck et al., 2008).

In addition to the required selection criteria, using nickel for the purpose of this initial case study provided alternative benefits. The designation of nickel as a "critical" metal amongst several countries presented a timely opportunity to expand the state of knowledge related to the metal (J. Burton, 2022; Department of Mineral Resources and Energy, South Africa, 2022; Government of Canada, 2022). In turn, the analysis is intended to support efforts to expedite the proliferation of clean technologies reliant on the metal, most notably batteries, and support efforts to decarbonize the steel industry.

Alternatively, nickel is also interesting in that its supply chain bifurcates with respect to suitable ores and product classifications (IEA, 2021a). Established supply chains are relatively distinct, with few similarities in terms of upstream and midstream processing technologies. However, the supply chains do exhibit considerable output-product overlap, as demonstrated in Section 2.2.3. The ability to explore the relationships between ore, processing technology, product, and application while transparently presenting knowledge is inherently unique compared to similar studies on the metal, as discussed in Section 2.3.

3.3.2.2 Scope of the Nickel Case Study

While the objective of the case study was to demonstrate the utility and relevance of the metallurgical capacity metric and its underlying approach through the nickel supply chain, a number of concessions concerning the scope of the supply chain assessed were adopted due to feasibility and time constraints.

Table 3-1: Case Study Parameters

Parameter	**Consideration**
Physical	*Non-Ferrous Products*
Physical	*Primary Feedstock*
Systematic	*Terminal Operations*
Spatial	*Global Scope*
Temporal	*2021 Reference*
Systematic	*Defined Capacity*

Evaluated parameters for the case study, as outlined in Table 3-1, considered global terminal operations producing non-ferrous nickel products derived from primary sources in 2021. Although the scope of the case study was reduced, the utility of the data and its applicability to quantifying the metallurgical capacity remain desirable.

The most notable exclusion in the case study is the lack of consideration for ferrous nickel products, specifically, FeNi and NPI products. The products were excluded as time constraints limited the ability to assess the operations in sufficient detail. Similarly, producing non-ferrous nickel products derived from secondary sources was excluded. While possible to account for secondary sources when determining the metallurgical capacity of a mineral or metal, secondary non-ferrous nickel products were excluded due to their marginal recycling rates and outstanding prevalence within stainless steel recycling pathways (Graedel et al., 2011b; Reck et al., 2008), which is essentially a closed-loop industry that is distinct from primary nickel.

When considering the generalized system boundaries described in Section 3.2.2, the metallurgical capacity of the case study is fundamentally determined in reference to the nameplate capacity of established terminal midstream operations producing non-ferrous nickel products from primary sources for the calendar year 2021. Assessing nameplate capacity provides the ability to consider total available capacity of a facility, as opposed to actual production, which would not consider underutilized capacity. This consideration is particularly relevant when assessing minor metals for which suitable operations often remain under care and maintenance (McNulty & Jowitt, 2021). Established operations include built facilities which can sufficiently process feedstock material during the assessed period, irrespective of their current operating status. For example, the capacity of operations placed under and maintenance and those actively producing nickel products were included in the metric. Terminal operations include those providing feedstock material for downstream users, as illustrated in Figure 3-3.

While the determination of metallurgical capacity considered the capacity of terminal operation, preceding midstream value chain operations and their respective capacities were evaluated to support subsequent analysis. A global perspective was considered to assess the entirety of the supply chain. Fiscal considerations were not considered as part of the analysis due to a lack of familiarity and time constraints.

The expanse of operations producing nickel as a by-product presented a considerable challenge when attempting to assess applicable facilities, as further discussed in Section 3.6.4.2. While the facilities often reported the production of primary non-ferrous nickel products, they seldomly reported capacity. As a result, terminal facilities for which production capacity of non-ferrous products could not reasonably be determined were excluded for the analysis.

Identifying operations conforming to the defined parameters was primarily achieved through an extensive market and academic literature review. Market reviews, often published by major producers, were a leading source in identifying facilities. For example, Nornickel's Quintessentially Nickel and BHP's Economic and Commodity Outlook often included the names of competing facilities (Berlin et al., 2022; McKay, 2023). Additionally, company reports, as described in Section 3.4.1.1, included competitors' names. Alternatively, international research groups, such as the Nickel Institute and the International Nickel Study Group, provided commentary on member companies and their respective facilities (R. Ferreira & Pinto, 2021; Nickel Institute, n.d.). The LME's list of approved brands was found to be valuable in identifying several facilities, as illustrated in Appendix C. Articles published by consulting firms, news publications, and government agencies were also valuable in identifying facilities, as discussed in Section 3.4.1.3. Finally, academic articles such as industry reviews and technical reviews of facilities were valuable in recognizing facilities, as discussed in Section 3.4.1.2.

3.4 Data

Evaluating the metallurgical capacity of a given mineral or metal requires a considerable number of unique data points, specifically when assessing distinct supply chain attributes. As the inaugural case study on metallurgical capacity of primary non-ferrous nickel, data collected herein was of notable scale. Due to the complexity of the supply chain and evolving need amongst downstream stakeholders to consider multiple supply chain and product attributes when procuring products, data was collected with the objective of developing several derivates of the metric sufficient to support an array of stakeholders, as further discussed throughout Section 3.5. Additionally, collected data points supported recommended abatement strategies and policies to identified supply chain bottlenecks, as discussed throughout Section 5.4.

3.4.1 Data Sources

Given the limited number of accessible studies on primary nickel midstream metallurgical operations, collected data was confined to a finite number of sources. Data used in the study relied exclusively on secondary data to enable complete transparency and reproducibility. This matter was of interest as existing bottom-up facility-by-facility studies on upstream operations actively and openly published supporting data. Constraining data to secondary sources limited the spectrum of adequate sources. As such, collected data was predominantly derived from three sources: corporate filings, academic articles, and grey literature. While each source presented notable benefits, considerable limitations persisted, as further explored in Sections 3.6 and 5.6.6. Examples of data sources are provided in the accompanying data and links provided in Appendix B.

3.4.1.1 Corporate Filings and Websites

The principal data source used throughout the case study was corporate filings published by the primary owner or operator of the evaluated midstream metallurgical operation. While various corporate filings were referenced, data was predominantly extracted from annual corporate summaries, financial disclosures, sustainability reports, investor and public presentations, and corporate news releases.

Such documents were the prevalent sources of data for several reasons. Chief among them were the credibility of the information. Corporate filings, specifically those required for financial disclosure purposes, provide authentic data which is often audited. Additionally, collected data could easily be replicated and referenced to its source, thus improving the data quality. Finally, corporate fillings were valuable in ensuring consistency across attributes as the unit of analysis was clearly defined.

In addition to corporate filings, information published on company websites was referenced. Data from company websites was referenced when insufficient corporate filings containing relevant data points persisted. As such, data from company websites was limited when possible.

3.4.1.2 White Papers

Although a limited number of publicly available studies and reports on nickel midstream metallurgical operations are accessible, available reports were leveraged as an alternative data source when corporate filings were inadequate. A notable source of white papers included academic articles and conference presentations. Although such sources focused primarily on technical components of operations, they were beneficial as, in many instances, the studies were commissioned or directly sponsored by the owner or operators of the facility in question, thus improving the quality of the data extracted.

3.4.1.3 Grey Literature

Grey literature, including reports and documents prepared by governments, industry organizations, and consulting firms, was referenced to address relevant gaps. Similarly, news articles containing relevant data were referenced, specifically for historical data points. While data contained in these reports and articles included few, if any, referenced data points, when possible, data from these sources were validated by a second source in order to improve data quality.

3.4.2 Data Points

A multitude of data points were collected as part of this case study to support and validate the metric and stated research goals. Data were categorized into seven categories: (1) facility overview, (2) operational overview, (3) metal production, (4) feedstock, (5) environmental, (6) investment, and (7) nickel products. An overview of collected data fields is provide in Appendix B.

Data was initially set to be collected in reference to the calendar year 2019 but was later revised to 2021. 2019 was initially selected for two reasons. First, company annual reports are commonly published during the first quarter of the subsequent fiscal year. This presented a challenge as most companies had fiscal years ending in December, and data collection began in May 2021. Therefore, few companies had reported data for 2020. Secondly, it was assumed that due to disruptions incurred by Covid-19, 2020 would not provide a representative depiction of an operation's capabilities. However, upon further analysis of 2020 reports, it was evident that many operations incurred no or minor production setbacks, as shown in Section 4.2.4. Due to extended research delays, it became feasible to re-evaluate operations in relation to 2021 and provide a more representative analysis of current supply chain dynamics. Nevertheless, a limited number of data points remained in reference to

2019. Such data points seldomly included sufficient data for analysis. As such, the data points were not included as part of the analysis.

Given the limitation associated with collected data, as discussed in Section 3.6, it was not possible to capture data on each category for each operation. Similarly, several data points required a certain degree of subjectivity due to the quality of available data. In such instances, detailed notes explaining the data points and assumptions were provided, as discussed in Section 3.6. Further, a table of key terms and their relevant definition is included in the supplemental data files and Appendix B.

3.4.2.1 Facility Overview

The Facility Overview section included data on a facility's ownership, location, and development history. This data was valuable in contextualizing non-technical dynamics of operations while providing necessary foundational knowledge on the facility in question.

3.4.2.1.1 Facility Name

Identification of the facility using relevant naming conventions was established. When possible, the operation's name, as documented in the relevant company reports, was employed. Absent reports with a unique name for a given operation, the commercial name of the operation, as represented through company compositions, such as their respective website, was selected as a reference. In addition, the name of the operation's primary owner, as described in Section 3.4.2.1.2, was prefixed to the name in order to distinguish facilities using similar naming conventions. For example, Boliden and Nornickel refer to their respective operations in Harjavalta in relation to the name of the city. Therefore, the operations were reported as 'Boliden – Harjavalta' and 'Nornickel – Harjavalta', respectively.

3.4.2.1.2 Ownership

Complex ownership dynamics of midstream operations required considerable deliberation when ownership was mixed. For facilities operated under joint ventures, the primary owner of the facility was defined as the entity with majority interest in the facility. In contrast, facilities controlled by a single entity were wholly designated to the entity as the primary owner. Since a substantial portion of facilities are owned by multiple proprietors, commonly through joint ventures, data was captured to explore such dynamics. This included the number of entities in the joint venture, the name of each entity, and their respective controlling share.

The primary operating company of each facility was further analyzed to assess their proprietorship type and was categorized into three distinct categories: public, private, and state. Additionally, the country in which the primary operating company is headquartered was collected. The stock exchange on which the primary owner is listed was also captured for publicly listed companies.

3.4.2.1.3 Location

Geographic data of each facility was equally captured. The data included the country where the facility was located, the region allocated by continent, and the facility's latitude and longitude coordinates. Latitude and longitude coordinates were collected using Google Maps and enabled visual verification of the facility's location. The coordinates for all facilities but one, the Fukang Refinery, could be confirmed. The coordinates of Xinjiang Xinxin Mining Industry's accompanying smelting facility, which was visually located on Google Maps and, according to the company, is a 5 hour drive from the refinery, was used in place as it directly supplies the refinery (Xinjiang Xinxin Mining Industry, 2007).

3.4.2.1.4 Development

Dates related to the development history of each facility were captured to highlight the evolution of the supply chain. Data was collected in reference to individual years as data pertaining to the exact months and days of significant events was limited, specifically amongst mature facilities. As such, data on the year in which construction of the facility began, the year in which construction of the facility was completed, the year in which the first production occurred, and the year in which the facility reached its nameplate capacity was collected when possible.

3.4.2.2 Operational Overview

Operational attributes of each facility were captured as they provided valuable insight into more technical dimensions of the facility. Data regarding operational metrics are valuable to accomplishing several research goals as well as for subsequent analysis.

A wide array of operational details were collected for each facility. Defining each data stratum within this segment was arduous, given the lack of established standards and definitions. As such, definitions used to categorize the attributes collected within this segment were developed and are further explained in Appendix B. Data segments included the facilities targeted production metal, operation type, process type, materials recovered, metallurgical technologies, smelting integration, and major unit operations.

3.4.2.3 Metal Production

Data associated with metal production is vital to determining the metallurgical capacity. While several operations produce multiple output products of distinct minerals and metals, data related to nickel was of primary importance. Additionally, data on cobalt and copper production was also captured in detail. Finally, data on other metals and materials were also captured when available, albeit in a less exhaustive manner.

3.4.2.3.1 Nickel Production

Numerous data points regarding nickel production were gathered when assessing facilities. This included commercial names of nickel products produced, nickel content of each product, annual nickel production capacity, 2019 production for each nickel product, historical annual production of nickel from 2000 to 2021, and nickel recovery rates.

Production data was captured in reference to reported units and subsequently converted to the study's unit of analysis, as further described in Section 3.5.1. For example, facilities reporting production figures in reference to the mass of nickel sulphate (e.g., 10,000 tonnes of nickel sulphate per year), data were converted to the relevant unit of analysis, a metric tonne of nickel per year, using available product quality data and relevant stoichiometric conversion factors.

3.4.2.3.2 Cobalt and Copper Production

The co-production and processing of cobalt and copper from nickel-containing deposits presented a considerable opportunity to examine understudied production pathways for each of the respective metals as well as their unique relationship to nickel. Similar data attributes to those collected on nickel production were collected on cobalt and copper production. Data categories included product name, product metal content, annual metal production capacity, 2019 annual product production, historical production from 2000 to 2021, and recovery rates. Similar to nickel, for production data published in reference to the mass of an individual product, metal content and relevant stoichiometric conversions were used to normalize data into relevant units of analysis, metric tonnes of metal per year.

3.4.2.3.3 Auxiliar Material Production

Numerous by-products beyond cobalt and copper are commonly produced from nickel processing facilities. Therefore, when possible, data related to such by-products was collected. This included the name of the by-product produced, the quality of the product, the annual production capacity of each product, 2019 annual product production, and associated recovery rates. However, as mentioned, collected data on by-products is limited and not exhaustive.

3.4.2.4 Feedstock

Assessing material flow across a supply chain is vital to understanding the interdependent relationships among supply chain actors. This is particularly important for understanding the relationship between upstream and midstream operations. Similarly, understanding the relationship amongst midstream value chain operations is equally vital given the complexity of value chains within the midstream stage. Determining the sources of the material procured by midstream facilities provides unique insight into the metal supply chain. As such, data on the feedstock material for each facility was collected. This included the name of the preceding facilities supplying feedstock, the number of unique feedstock suppliers, the type of feedstock used, the 2019 annual feedstock volume, the content of nickel, cobalt, sulphur, and iron in feedstock, and the contents of other notable elements contained in the feedstock.

3.4.2.5 Environmental

The environmental impact of the extraction and processing of minerals and metals has become a noteworthy point of interest. As companies aim to reduce or eliminate their associated environmental impacts, understanding the extent of the impact related to the midstream operation is vital to ensuring that progress is maintained. Various data points related to environmental topics were collected for each facility. This included 2021 net zero commitments, the target year of net zero commitments, 2019 annual Scope 1, Scope 2, and Scope 3 emissions, the purview of reported emissions, 2019 water consumption, 2019 energy consumption, 2019 renewable energy mix, and LIB recycling capabilities.

3.4.2.6 Investment

Predicted growth in demand for minerals and metals will require unprecedented supply expansion. Understanding the level of investment facilities intend to allocate is vital to assessing the future supply of minerals and metals. Given the fluidity of investment decisions, a limited number of data categories were targeted. They included expansion plans, capital investment, and investment timelines.

3.4.2.7 Nickel Products

In addition to nickel production data outlined in Section 3.4.2.3.1, data related to produced nickel products at each facility were collected in reference to 2023 capabilities. Data included the elemental composition of each nickel product using available product data sheets or other relevant sources, product form factors, primary advertised applications, secondary advertised applications, product quality standards, LME-approved products, and product carbon footprints. Such data were collected and analyzed in a separate document, as discussed in Section 3.4.3.2.

3.4.3 Data Management

The vast sums of data collected throughout the case study required unique data management approaches. Ensuring the requisite granularity, scope, and quality required for subsequent analysis was maintained and easily accessible was paramount. The collection, storage, and review of data were carefully considered as part of this analysis.

3.4.3.1 Data Collection

Compiled data for the case study were primarily retrieved from company websites, industry groups, and academic libraries. Collecting historical data, notably data related to historical annual production and developments, required more extensive searches to locate relevant company reports. Data and reports not readily available on company websites or for data relating to defunct companies were retrieved through various internet archive websites and portals.

Aggregating vast quantities of data across numerous facilities and sources required a streamlined approach to ensure adequate efficiency. A Qualtrics form was generated to input and manage data for each data category concerning each operation, with the exception of product specific data, as outlined in Section 3.4.2.7. The form was completed for each facility to ensure sufficient segregation. Modifiable or pre-listed input fields were used for all relevant data categories. Each data category also included a corresponding notes field for relevant comments on collected data points. Further, each data input included an accompanying field to register relevant sourcing data. References were primarily inputted as the ULR of the site in which the data was retrieved, the name of the accompanying document, or academic reference.

For data related to the nickel products produced at each facility, data was collected manually and inputted directly into a unique Excel workbook. In a similar manner, accompanying references for each product were included, as well as a notes field with pertinent commentary.

Data was further updated throughout the analysis as novel information was uncovered. In such instances, data was updated in the relevant analysis databases, including all applicable references.

3.4.3.2 Data Storage

Upon completing the assessment of each facility throughout the midstream stage, data inputted into the Qualtrics forms was downloaded into an Excel file for subsequent evaluation. The data from the Excel file was then cleaned and organized into a new Excel file for subsequent storage. A third file was then created to aggregate data for subsequent analysis. A fourth file was created in order to store and analyze data as it related to nickel products produced at each facility. A link to accompanying datasheets is provided in Appendix B.

3.4.3.3 Data Review

Dr. Steven B. Young was responsible for reviewing all data to ensure the validity and diligence of the collected data. This included comprehensive reviews of data discrepancies, subjective interpretations, and subsequent analyses.

3.5 Analysis and Assumptions

Validating the utility of metallurgical capacity and addressing stated research goals necessitated a detailed analysis of collected data. As part of the analysis, the metallurgical capacity of primary non-ferrous nickel in 2021 was determined. Several metric derivatives related to pertinent attributes were subsequently determined to compare and contrast against differentiable characteristics while addressing relevant research questions. Additionally, the analysis was conducted with the intent of identifying supply chain bottlenecks and developing viable solutions to the respective bottlenecks. Pertinent compromises and judgements sustained during the analysis are described in the following sections.

3.5.1 Metallurgical Capacity: Nickel Case Study

As stated in Section 3.3, the metallurgical capacity for a given mineral or metal product or supply chain is the summation of suitable midstream processing capacity according to defined parameters. In relation to the case study, the absolute metallurgical capacity of the nickel supply chain was not determined; rather, a restrained segment of the supply chain was determined as a result of limitations, as discussed in Section 3.6. Nevertheless, collected data permitted the ability to determine the metallurgical capacity of nickel supply chains with the potential to produce non-ferrous products from primary sources in 2021. While not representative of the whole of nickel supply, the case study demonstrates the validity and utility of metallurgical capacity, as the constrained metallurgical capacity computed presents significant utility to various stakeholders, as further discussed in Section 5.2.

The complexity of midstream stage operations presented considerable challenges when assessing metallurgical capacity. A notable point of contention was the exclusion of midstream metallurgical operations producing FeNi and NPI. Such operations were excluded from the analysis as their respective products are, to the best of current understanding, principally used in ferrous applications. While converting FeNi and NPI products into non-ferrous products remains technically feasible (Sherritt, 2021a), the lack of known commercial facilities operating within the assessed period justified their exclusion from this analysis[2]. In contrast, while ferrous nickel products, such as matte products, are generated within the value chains of assessed operations, their role as intermediate products in which additional upgrading could be reasonably traced, distinguishes their inclusion.

The presence of intermediate products that are both present within value chains and marketed for first-use applications presented additional challenges. While the capacity of the terminal operation within a given midstream stage value chain was designated as the relevant capacity for determining the metallurgical capacity, as noted in Section 3.3.2.2, a lack of value chain transparency prohibited conclusive determination of terminal operations amongst several value chains.

Such opacity was most prevalent amongst operations producing intermediate products, notably value chains producing MP intermediate products. Although the terminal operations could be reasonably determined for numerous value chains producing MP intermediate products, several terminal operations could not be reasonably determined. For value chains in which the terminal operation could not reasonably be identified, the capacity of the final operation that could be reasonably identified within the value chain was considered part of the metallurgical capacity. Further, such facilities were categorically differentiated from other facilities when conducting subsequent analysis, as further discussed in the Section 3.5.2. This approach was assumed reasonable as it accounts for the total primary production of nickel and limited double counting.

Considerations regarding the inclusion of production capacity for operations subjected to their operability status presented additional conflict when determining the metallurgical capacity. As deliberated in Section 3.3, metallurgical capacity is agnostic to the operating status of a given operation as it encompasses established operations that can reasonably process feedstock during the evaluated

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[2] While Tsingshan successfully converted NPI-to-matte at its Morowali Park facility in Indonesia, reported timelines of when production occurred remain unclear; therefore, it was not included in the analysis (SMM, 2022).

period. As a result, operations that either began processing feedstock, were actively operating, or were placed on care and maintenance in the calendar year 2021 were included. In contrast, operations considered mothballed, for which are actively being or planned to be dismantled, were excluded. Additionally, planned operations or operations under construction in calendar year 2021 were excluded as they have not demonstrated agency to process feedstock.

The unit of analysis used to calculate the metallurgical capacity as part of this case study was a metric tonne of nickel per year. This unit was chosen as it represents a commonly reported unit throughout the industry. In addition, the most recent available production capacity figures were used for each facility. As mentioned in Section 3.4.2.3.1, facilities reporting production capacity using alternative units of analysis were converted into the defined unit of analysis using available product composition data, stoichiometric relationships, and time ranges. Calculated figures were then rounded down to the nearest metric tonne.

Results of the analysis including the metallurgical capacity are demonstrated in Section 4.2.1. While not distinctly distinguished in the metric, derivates of the metric delineated across relevant attributes were subsequently determined, as explained in the following sections.

3.5.2 Metallurgical Capacity: Derivatives

Metallurgical capacity as a whole is valuable in demonstrating the established midstream stage processing capacity for given products according to specified parameters. However, the metric is insufficient when evaluating distinct attributes of metallurgical supply chains. Derivates of the metric, in which the metallurgical capacity of one or more differentiable attributes are analyzed and contrasted against one another, for example metallurgical capacity in relation to carbon neutrality commitments as illustrated throughout Section 4.2.17, are valuable for identifying supply chain bottleneck risks. The extent to which derivates can be contrived is proportional to the quality and quantity of data collected. As such, derivates can be highly contextual and tailored to a stakeholder's deliberations. As part of the analysis, several derivates were determined to address the proposed research questions.

3.5.3 Data Counts

Sparse and limited data coverage across specific data categories confined the extent to which such data could be further analyzed. These issues were most exemplified when analyzing commercially sensitive topics, particularly those related to upstream sources and nickel products. Therefore, for attributes in which data was insufficient for determining a derivative of the metallurgical capacity, a cumulative count of relevant data was carried out in place.

3.5.4 Output Product Classification

Classifying the output products of midstream metallurgical operations required judgment. The ambiguity of industry designations for output products, the advertised utility of output products, and a lack of value chain transparency inhibited consistent and reasonable capacity categorization. Fortunately, the majority of output products, and in turn, capacity, could reasonably be classified into three categories: refined, intermediate, and intermediate/refined.

Capacity designated as refined constituted operations producing products directly suitable for first-use applications. This included nickel cathodes, briquettes, rounds, oxides, and sulphates. Intermediate capacity included operations for which the assessed terminal operation produced an intermediate product requiring additional refining. Such categorization was most prevalent among facilities producing MP. However, considerable ambiguity persists amongst facilities attributed to the category as MP are occasionally advertised as suitable products for first-use applications, limiting the ability to differentiate between categories. Capacity designated as Intermediate/Refined included operations producing intermediate and refined products. Comprised operations predominantly included operations advertising marketable nickel sulphate and MP.

3.5.5 Operating Status

Assessing capacity relative to a facility's operating status is necessary to evaluate the dynamic between active and idle capacity relative to total capacity. Operations were classified into three distinct categories: Operating, Care and Maintenance, and Uncertainty. Facilities designated as operating could reasonably be confirmed to be operating during the assessed period. Similarly, facilities designated as Care and Maintenance included those whose respective owners stated that the facility was placed under care and maintenance. One facility, Korea Nickel Corporation, was categorized as Uncertain as the operating status of the facility could not be determined. Nevertheless, it was possible to confirm that the facility was in good standing through the company's reporting on the assets (Vale, 2022a). Confirmation of a facility's operability was determined through reported production figures, company reporting, industry reports and news articles.

3.5.6 Excess Capacity

While an operations nameplate capacity provides valuable insight into the potential production of an operation, operations often do not operate at their nameplate capacity for a myriad of reasons. As such, evaluating the annual production of an operation relative to its nameplate capacity is necessary to understand dormant capacity amongst operating facilities. Therefore, an evaluation of the annual production of facilities relative to their nameplate capacity was conducted. Additional details of the analysis are provided in Section 4.2.4

3.5.7 Geographic Distribution

Assessing the spatial distribution of metallurgical capacity is critical to evaluating the geographic concentration of supply. The geographic distribution of capacity was evaluated by utilizing the geographic coordinates of each facility. In addition to displaying the geographic distribution of metallurgical capacity, the geographic distribution of several metallurgical capacity derivates were subsequently illustrated, including the distribution of carbon neutrality commitments, product quality, and battery potential.

3.5.8 Ownership

Evaluating the complex ownership dynamics of midstream operations is vital for assessing geopolitical supply and monopolization risks. Several derivates based on ownership were developed to understand the unique relationship among key supply chain stakeholders. Derivates included assessing the metallurgical capacity relative to the primary operator, as defined in Section 3.4.2.1.2, headquartered country of the primary operator, the enterprise structure of the primary operator, and stock exchanges associated with public companies.

3.5.9 Operational Sovereignty

Understanding the relationship between domestic and foreign ownership of critical supply chains is vital to evaluating geopolitical risk. Utilizing available data, a unique derivate to assess the autonomy of metallurgical capacity, aptly named Operational Sovereignty, was developed. The derivate evaluates the metallurgical capacity of a given country relative to domestic capacity operated by domestic entities, domestic capacity operated by foreign entities, and foreign capacity operated by domestic entities. Through this derivate, it remains feasible to assess the geopolitical influence of metallurgical capacity.

3.5.10 Year of Establishment

Determining the year which a facility was established required careful analysis of available data. The sparsity of available data resulted in several key concessions. Given available data, it was determined that the year the facility first produced nickel would be considered its establishment year. For facilities for which such data points were unavailable, the following precedent was utilized to determine the year of establishment: the year construction was completed, the year construction first started, and the year facility reached maximum capacity.

3.5.11 Feedstock Source

Understanding the dependency between feedstock material and relevant operational attributes provides valuable insight into the criticality of different feedstock materials. Determining the feedstock sources for facilities was principally achieved by assessing a facility's upstream value chains to determine the origin of the material. Collected data was then cross-referenced with available data from relevant nickel upstream assessments. (Heijlen et al., 2021; G. M. Mudd & Jowitt, 2014). Feedstock data were categorized into four distinct categories: black-shale[3], laterite, sulphide, and unknown. Data categorized as unknown included facilities where the origins of feedstock material could not be accurately determined. Facilities procuring feedstock from multiple sources were categorized in a combination of two or more categories. Additionally, operations declaring to be processing third-party feedstocks were considered. Associated metallurgical capacity was then attributed to each category to compute relevant derivates and facility counts.

3.5.12 Midstream Integration

As stated in Section 3.2.2.2, midstream stages of mineral and metal supply chains often include a combination of vertically integrated operations and operations reliant on a network of complex value chains. While the evaluated metallurgical capacity considered the terminal operation within given value chains, collected data permitted the ability to evaluate the level of integration for a given value chain. Considering the number of preceding midstream upgrading facilities for a given terminal operation with a known value chain, it was feasible to demonstrate the complexity of an operation. The value

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[3] Black-Shale is processed at one facility in Finland and is not a common ore source. However, the operation utilizes a biometallurgical process which is distinctly unique. Additional information is provided in Appendix A.

chains of facilities procuring intermediate feedstocks were not considered due to a lack of transparency on the provenance of the intermediate products and were therefore categorized as unknown.

The level of integration for a terminal operation was represented as a count of preceding facilities within the midstream stage value chain which were either owned by a dissimilar company or located in a dissimilar country. Specifically, the level of integration was contingent upon the country of origin and ownership of the feedstock material. For example, a terminal facility with a single value chain for which the feedstock originated from a smelting operation within the same country but owned by a different company as the terminal operation was categorized as 1. In contrast, a terminal facility procuring feedstock material from a smelting operation within the same country and owned by the same company as the terminal operation was categorized as 0.

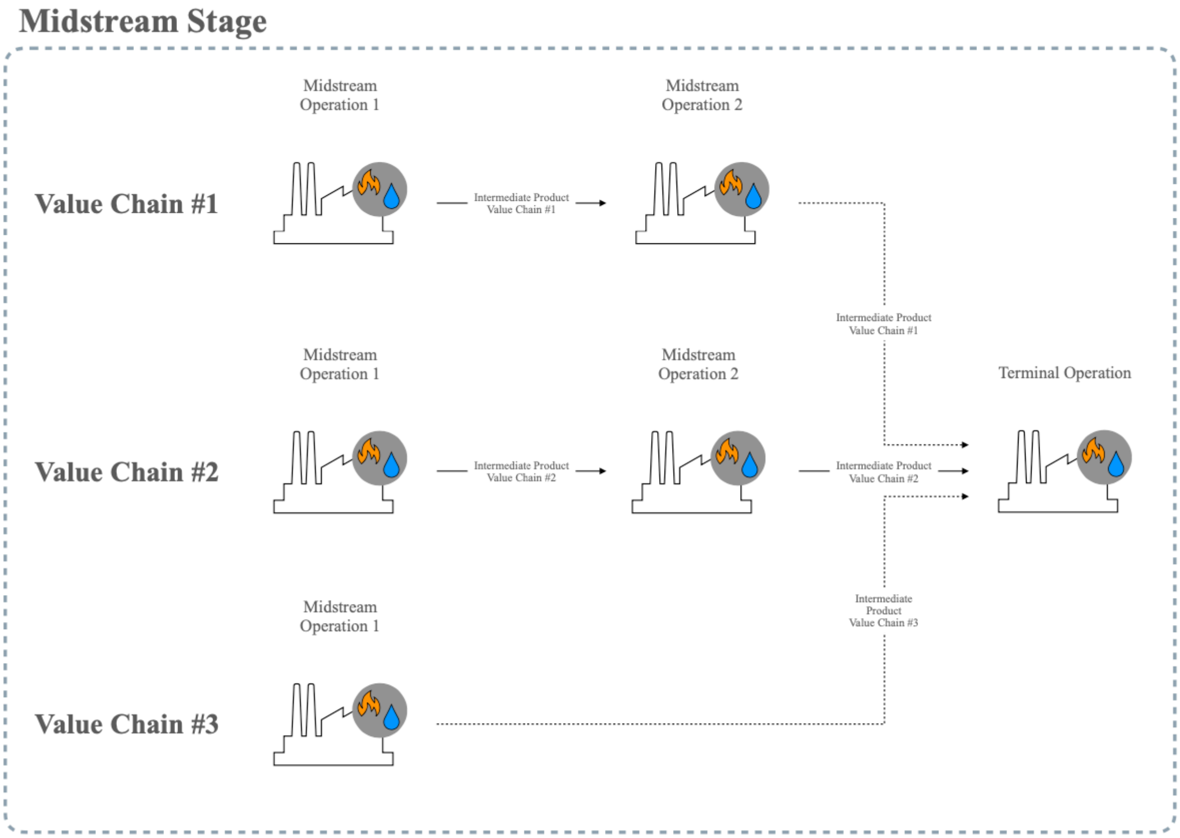

Figure 3-4: Example Value Chain with 1,2,2 Integration

For facilities procuring feedstock from multiple sources, each with varying degrees of integration, all input value chains were considered. For example, the terminal operation depicted in Figure 3-4 with three value chains would be classified as 1,2,2 given value chains #1 and #2 include two trailing operations while value chain #3 include one trailing operation. In contrast, facilities vertically integrated with upstream operations and do not procure from no other value chains were categorized as 0.

3.5.13 Metallurgical Processing Technology

Extracting and transforming minerals and metals from complex ore bodies requires elaborate processing technologies. Value chain integration data provided valuable insight into the metallurgical technologies used throughout a given value chain. While several operations employ similar unit operations, the high degree of variation across ore bodies coupled with the array of metal products produced across the metal supply chain results in flowsheets similar in concept but unique in function. Categorizing highly ambiguous processes required a more generalized means of comparison.

Facilities were categorized based on the metallurgical processing technology employed by their value chains. This included the exclusive utilization or sequential combination of two or more of the following metallurgical processing technology categories: pyrometallurgical, hydrometallurgical, vapour metallurgical, and biometallurgical. Facilities were categorized based on the aggregate employment of technologies throughout their respective value chains. For example, a terminal operation employing hydrometallurgical technology with two value chains, one of which employs hydrometallurgical technology while the other employs pyrometallurgical technology, would be categorized as pyrometallurgical+hydrometallurgical.

Operations employing two or more processing technologies would be aggregated together. For example, a vertically integrated operation sequentially employing biometallurgical and hydrometallurgical technology would be categorized as biometallurgical+hydrometallurgical. Similarly, a terminal operation utilizing multiple processing technologies and procuring from multiple value chains would be categorized based on the aggregation of employed technologies from the perspective of the processed nickel unit.

This approach was considered reasonable given the complexity of employed technologies and the expansiveness of value chains. Additionally, the inability to discern between processing technologies within a given facility or value chain limited the extent to which capacity could be associated with a given metallurgical technology.

3.5.14 Feedstock Target Metal

Upstream feedstocks processed by midstream metallurgical facilities generally contain multiple minerals and metals of economic value. The extent to which a metal contained in a given feedstock material is recovered is highly dependent on technological and economic factors. Understanding the relationship between production capacity and the principal economic mineral or metal within an upstream feedstock is valuable when evaluating the dependency of nickel on other metals. Determining the target mineral or metal in the feedstock material was assessed based on the reported or advertised primary mineral or metal stated by the facility's operator. Terminal facilities were allocated to the following categories: nickel, nickel+copper, copper, PGMs, and unknown.

3.5.15 Nickel Products

Assessing the metallurgical capacity as it relates to specific attributes of output products is vital to assessing the ability of midstream metallurgical operations to satiate discrete downstream demand sectors. Analyzing the characteristics of nickel products provides detailed insight for downstream users with distinct product requirements. Products produced by facilities were analyzed relative to product class, nickel content, chemical composition, form factor, and advertised application. A lack of available data regarding the production capacity as it relates to specific products limited the extent of the analysis.

3.5.15.1 Product Class

The informal classification of nickel products benefits countless downstream stakeholders. Assessing products and capacity in relation to such classification methods is critical to supporting procurement efforts. Products containing nickel greater than or equal to the threshold content of 99.8% nickel by weight were classified as Class 1, while products below the threshold were classified as Class 2. Due to insufficient nickel product composition data, a fraction of nickel products could not be attributed to a given group. In such instances, the products were thus categorized as either Probable Class 1 and Probable Class 2 based on relevant product characteristics and the ability to compare with equivalent products for which compositional data was readily available. A count of products unique to each category was determined. Additionally, the capacity of facilities was associated with relevant product categories, or a combination of, based on their respective product output. However, it was assumed that products determined as probable Class 1 or Class 2 were equivalent to Class 1 and Class 2 in subsequent analysis.

3.5.15.2 Product Nickel Content

Given the elevated nickel content threshold used to distinguish between industry product classification benchmarks, products below the threshold are often misrepresented. This matter is particularly relevant when considering the wide array of non-ferrous nickel products attributed to Class 2, such as nickel sulphate and nickel oxide products. Categorizing nickel products relative to their respective nickel content using more nuanced thresholds provides a more representative state of available products. Nickel products were classified into the following ranges relative to their reported nickel content: 100-99.8wt.%, 99.8-90wt.%, 90-50wt.%, 50-22.4wt.%, 22.4-0wt.%, and unknown. Data was represented as a count of products attributed to each category. The upper tranche was chosen to represent Class 1 nickel products. In contrast, the lower tranche was chosen to represent nickel sulphate products as the theoretical nickel content in pure nickel sulphate hexahydrate is 22.32wt%, thus representing an upper limit. Products for which nickel content was not reported were categorized as unknown.

3.5.15.3 Product Chemical Composition

Downstream processes are often constrained to the chemical composition of suitable mineral and metal product. Analyzing the composition of nickel products provides valuable insight for downstream stakeholders when assessing supply chain resilience and product availability. Nickel products were categorized according to their chemical composition, for example, nickel sulphate, nickel metal, and nickel oxide. Insufficient data on the production capacity of specific nickel products at facilities producing numerous products limited the ability to determine the metallurgical capacity according to product chemical composition. Therefore, a count of nickel products corresponding to a given category was determined.

3.5.15.4 Product Form Factor

Product form factor is another critical product attribute limited by downstream process requirements. As such, nickel products were categorized according to their respective form factors, namely: Powder, Cathode, Rounds, Briquette, Industrial, Pellets, Granule, and Unknown. Analogous to data limitation encountered in determining the metallurgical capacity relative to product composition, the lack of available data prohibited the determination of metallurgical capacity according to product form factor. Therefore, a count of nickel products relative to their form factor was determined.

3.5.15.5 Product Application

Considering the range of nickel first-use applications, their respective nickel feedstock requirements, limited ability to interchange nickel products with alternative characteristics, and the array of nickel products produced with distinct characteristics amongst midstream facilities, evaluating the suitable application for each product can provide valuable insight for downstream stakeholders looking to diversify supply.

When evaluating products produced at a given facility, the primary advertised application for a given product was collected, as stated by the producer. The primary advertised application was regarded as the foremost listed application amongst the products' advertised applications. This approach was assumed reasonable as facilities often advertise products relative to their suitable application. Additionally, it was not found that advertised applications were not listed in alphabetical order, thus, further reinforcing the validity of the approach.

Given the range of advertised applications, products were categorized into six categories: Steel, Plating, Industrial Applications, Batteries, Metallurgical, and Unknown. Products attributed to steel were primarily advertised for stainless steel applications. Products allocated to industrial applications were advertised for industries such as electronics, chemicals, and aerospace. Products associated with Metallurgical applications included those advertised for non-ferrous alloys and additive manufacturing. Products for which no application was advertised were classified as Unknown. Data was represented as a count of products ascribed to each category.

3.5.16 Battery Potential

The predicted increase in demand for nickel stemming from battery applications is anticipated to considerably disrupt the nickel market. A lack of industry standards for nickel pre-cursor materials established by battery manufactures' limits the ability to assess products relative to their suitability for battery applications deterministically. Nevertheless, according to the IEA (2021a), nickel sulphate is assumed to be the dominant format for nickel pre-cursor material by battery manufactures. Conversely, given the range of produced nickel sulphate products, each with distinct impurities profiles, the extent to which battery manufacture can adopt a produced nickel sulphate product is unclear. The complexity of the matter is further compounded when considering that BHP's new nickel sulphate refinery utilizes Class 1 nickel while Vale's proposed nickel sulphate refinery intends to employ high-grade Class 1 inputs (BHP, 2021c; Vale, 2022d). In a similar vein, it has been proposed that MP's can be utilized as suitable precursor cathode active material in the production of batteries (BASF & Eramet, 2020).

Therefore, deterministically evaluating nickel products relative to their respective impurity profile remains limited. Nevertheless, assessing produced products and metallurgical capacity relative to their ability to potentially satiated battery applications remains valuable. As such, the capacity of facilities relative to their respective product's prospect to satiate battery application was evaluated.

Nickel products were first evaluated based on their primary advertised application and characteristics. Products were categorized into three categories: Suitable, Potential, and None. Products categorized as Suitable included either LME-approved nickel products or products whose advertised application included batteries. Products designated as Potential primarily included those for which insufficient data was available regarding the quality of the product or its advertised application. Additionally, it included nickel sulphate products that were not exclusively advertised for battery applications or advertised as crude nickel sulphate and required additional refining prior to being suitable for battery applications. In contrast, products prescribed as None included those requiring considerable transformation before being suitable for battery applications, such as nickel oxides.

After designating each product, facilities and their respective capacities were then categorized relative to the ability of their products to satiate battery applications. Facilities were further subdivided into the following categories: Full, Partial, Potential, and None. Facilities attributed to Full indicate that the entirety of their respective products produced, and in turn, capacity, could be suitable for battery applications. In contrast, facilities designated as partial include facilities for which only a subset of their respective products, and in turn, capacity, could be suitable for battery applications. Facilities attributed to Potential indicated that their respective products and capacity could potentially be suitable for battery applications; however, further product analysis is likely required. Finally, facilities attributed to None indicate that none of their products are readily suitable for battery applications.

3.5.17 Cobalt and Copper By-Products

The co-occurrence and processing of minerals and metals give rise to unique relationships between contained minerals and metals. Cobalt and copper are common by-products in nickel processing. Given the importance of cobalt to clean technologies and its precarious ESG risk, as discussed in Section

5.4.8, a more nuanced understanding of its production as it relates to nickel is of value to downstream stakeholders. Similarly, a more nuanced understanding of copper supply relative to nickel is valuable to countless downstream stakeholders, given its economic importance and utility in clean technologies (IEA, 2021a).

Data related to the production of cobalt and copper among facilities assessed varied considerably. A count of facilities producing cobalt as a by-product was determined. Similarly, a count of facilities producing copper as a by-product was subsequently determined. Facilities were categorized based on the refinement level of cobalt or copper products. For example, facilities producing cobalt products contained in MP were classified as intermediates, while facilities producing cobalt cathodes were classified as refined. In addition to their ability to produce cobalt or copper, the production capacity of either metal was evaluated amongst facilities with reported data.

3.5.18 Carbon Neutrality Commitments

Midstream metallurgical operations are responsible for considerable environmental impacts (Norgate et al., 2007). These operations are also in a position in the supply chain where actors can exert influence on upstream suppliers to enhance environmental performance (S. B. Young, 2018). Mitigating these impacts has been of preeminent concern amongst numerous operators. Considerable efforts have been taken to increase transparency and data related to the extent of environmental impacts (Perez & Sanchez, 2009). Additionally, increased demand from downstream users for products with minimal environmental impact has exacerbated efforts (London Metal Exchange, 2020). A notable area of focus includes the greenhouse gas impact of operations, often termed carbon footprint.

Evaluating the extent to which nickel midstream metallurgical operations have established carbon neutrality targets is beneficial to modelling future impacts associated with increased nickel production. An analysis of carbon neutrality targets for assessed facilities was conducted. A binary categorization of facilities was carried out to contrast facilities with stated carbon neutrality commitments and facilities without stated carbon neutrality commitments. The metallurgical capacity of facilities within each category was then assessed.

To demonstrate the time horizon of stated decarbonization efforts, facilities with stated carbon neutrality commitments were further categorized into the respective year in which they anticipate achieving carbon neutrality. The metallurgical capacity of facilities for relevant years was subsequently evaluated.

3.5.19 Research Questions and Discussion

Analyzed themes in the preceding sections were considered as they supported relevant research questions and discussion topics. However, given the complexity of the topic and in order to effectively communicate the pertinent results, the analysis provided a cursory evaluation of each theme. As a result, additional analysis was conducted to provide a more nuanced perspective of relevant themes when addressing specific research questions and discussion topics. Details of supplementary examinations accompany applicable commentary in the ensuing sections.

3.6 Limitations

The comprehensiveness of the analysis was, in part, restricted due to numerous limitations. The basis of the limitations encountered varied significantly. However, a preeminent limitation related to data. The extent to which data limited the analysis of select themes ranged considerably. Efforts to preserve the authenticity of the data were paramount to the analysis. Therefore, data extrapolation and interpolation were restricted when possible. The following section outlines limitations incurred concerning the case study; limitations related to the metric are further discussed in Section 5.6.

3.6.1 Data Gaps

Numerous data gaps persisted across several data categories. Such gaps were most prevalent for data related to historical production, historical developments, environmental data, and future initiatives. The extent to which data gaps occurred within a category varied by facility. Data gaps were most apparent amongst private or state-owned enterprises due to a lack of reported data. Similarly, data gaps persisted amongst facilities owned by public enterprises for which facility ownership changed during the assessed period.

3.6.2 Data Assumptions

Incomplete data and substandard data quality across various data categories required the enactment of subjective assumptions to complete the analysis. To preserve the quality of the analysis, assumptions were limited and adopted with considerable diligence. Minimizing assumptions innately diminished the scope of the analysis. All data assumptions were explicitly stated in the accompanying note sections of relevant data categories and within subsequent analysis workbooks.

3.6.3 Coverage

The utility of metallurgical capacity and its subsequent derivatives and analysis is directly proportional to the degree of coverage attained across the given mineral or metal supply chain. Given the novelty of the metric coupled with the opaque nature of mineral and metal supply chains, determining the degree of coverage could not be conclusively determined. Specifically, the lack of accessible and comparable studies limited the ability to assess nuanced aspects. Nevertheless, a close approximation can be determined using reported figures from reports published by industry organizations and government bodies.

Nornickel's nickel market report provides the most appropriate reference point for comparing the results of the study. The report provides a sufficiently detailed state of the market with similar temporal scope. Further, the report segregates production by product category, thus making it easier to decipher between products with similar characteristics to those considered herein. The company estimates that the 2022 global nickel production of non-FeNi and NPI nickel products[4] was 1.352 million metric tonnes (Berlin et al., 2022). This contrasts with the 1.407 million metric tonnes of operating metallurgical capacity in 2021, determined as part of the current study. The facilities included in Nornickel's analysis are unknown, limiting the ability to confirm the coverage of operatable metallurgical capacity.

Using 2022 production estimates in place of 2021 figures more accurately represents evaluated conditions as a small fraction of facilities included in operating metallurgical capacity were brought online in 2021. Additionally, as demonstrated in Section 4.2.4, several facilities were operating below their reported production capacities, further aligning the study results to those reported by Nornickel. The superior metallurgical capacity figure derived herein relative to reported 2022 production estimates by Nornickel further reinforces the extent of coverage of the conducted analysis. Therefore, 2022 production data from Nornickel reflect their market presence.

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[4] Non-FeNi and NPI categories and supply include: Nickel Oxide & Utility Nickel (39 kt Ni), Class 1 Nickel (817 kt Ni), Nickel Compounds (407 kt Ni), MHP (89 kt Ni). Report published on November 30th, 2022 (Berlin et al., 2022).

In a similar vein, the discrepancy between estimated production and total metallurgical capacity results from the exclusion of facilities under care and maintenance as well as those with unknown operating status. The focus of Nornickel's analysis on production and the lack of clarity regarding facilities included limits the ability to certify the net metallurgical capacity.

3.6.4 Data Reporting

Data inconsistencies primarily stemmed from reporting methods of companies. The lack of established reporting requirements resulted in several facilities for which nominal quantities of data pertaining to the facility are publicly accessible. This matter was most prevalent amongst private and state-owned facilities in developing regions. While publicly owned and operated facilities are required to disclose data for fiduciary purposes, variability amongst reporting standards, as established by exchanges on which companies are listed, further engrossed data consistency and quality challenges. Such challenges were most acute for data related to operational and sustainability aspects of facilities.

3.6.4.1 Metallurgical and Operational Accounting

The dependence of the study on company reports, as discussed in Section 3.4.1.1, is likely a limiting factor to the study. While numerous companies, irrespective of ownership type, publish periodic reports outlining the performance of their respective operations, the scope and granularity of reported data varies considerably amongst companies. For example, in Vale's financial disclosures, refined nickel production figures are referenced in relation to the upstream operation rather than the midstream operation responsible for upgrading upstream feedstocks (Vale, 2022a). In contrast, Nornickel reports a relatively more granular depiction of the performance of its upstream and midstream facilities in its financial disclosures (Nornickel, 2022).

It was found that company reporting methodologies evolved considerably over time, further limiting the ability to ensure consistency in reported data. Similarly, the fluid nature of an operation's ownership exacerbated the inability to ensure data consistency. Such fluidity also presented considerable challenges when accessing historical data. A lack of adopted metallurgical accounting standards limits the ability to compare operations in a granular manner.

While a lack of standardized accounting methodology was most prominent concerning metallurgical attributes, a lack of standard accounting methodologies related to complementary operational attributes further limited the comprehensiveness of the report. This matter was most acute for sustainability data.

In addition to the sparsity of reported sustainability data, inconsistencies in reported data limited the ability to assess specific attributes with sufficient granularity. This was most relevant when assessing water consumption, energy consumption, renewable energy mix, and carbon emissions. In general, sustainability data was found to be aggregated across operations, regions, or products. The lack of segregated sustainability data specific to each operation limited the ability to compare operations. Adopting standardized sustainability reporting practices across operations and companies would significantly improve the value and confidence in reported data (Azadi et al., 2020).

Reported metallurgical and operational data provided valuable insight into numerous operations; however, the inability to audit reported data required assuming reported data to be authentic. While reported data was often verified by independent third parties, most notably reported data by publicly owned companies, several data inconsistencies were discovered. The most commonly reported data point was referenced in such instances, and discrepancies were noted.

3.6.4.2 By-Product Reporting

A considerable limitation of the study was a severe lack of reporting amongst facilities producing nickel as a by-product. The presence of nickel in multiple ores, coupled with the inability to wholly segregate metals of interest during upstream and midstream processing operations, gives rise to the presence of low concentrations of nickel in non-targeted processing routes (Crundwell et al., 2011). This matter is particularly prominent among operations refining copper and precious metals. The presence of nickel in the processes is often technically and economically feasible for many operations to recover.

Reporting on the by-production of nickel from auxiliary refining operations varies by facility. For example, Glencore’s Canadian Copper Refinery, a midstream metallurgical operation tailored to copper refining, recovers nickel as nickel sulphate. The company confirms nickel sulphate production at the facility (Glencore Canada, n.d.), but does not report data related to its production in annual disclosures (Glencore, 2022a). As discussed in Section 3.3.2.2, operations for which capacity could not be identified were excluded from the analysis. Therefore, the lack of reported data related to the by-production of nickel from auxiliary refining operations further limited the comprehensiveness of the analysis.

While the by-production of nickel from auxiliary refining operations limits the analysis, such operations are assumed to account for a limited portion of capacity and production volume. For example, according to the Indian Bureau of Mines (2023), Hindustan Copper Limited Ghatsila Copper

Smelter, a facility designed to refine copper, includes a circuit suitable for the production of 390 metric tonnes of nickel sulphate annually as the result of the presence of low nickel concentrations in the feedstock. Additionally, nickel sulphate production at the facility has not been reported since 2004-05. The marginal production capacity and lack of reported production suggest that the by-production of nickel contributes negligibly to overall metallurgical capacity, if at all. Nevertheless, given the considerably higher global annual production of copper relative to nickel, such sources could account for a significant share of metallurgical capacity in aggregate.

3.6.4.3 Complex Value Chains and External Feedstocks

A considerable limitation of the study was the potential of double counting reported data. This matter was most prominent amongst companies with complex value chains and operations processing external feedstocks. For companies with complex value chains, a lack of operational-specific data gave rise to the potential double counting of reported data. To minimize the extent of double counting amongst companies with complex value chains, the capability of value chain operations was considered when reviewing reported data. In such a manner, reported data were contrasted against the capabilities of the value chain to ensure representative reporting.

In contrast, operations processing external feedstocks posed a significant risk to double counting. Midstream operations process external feedstocks through direct purchase or tolling agreements with third parties. Such arrangements are most prominent amongst operations processing low-sulphur ore feedstocks, laterite operations producing or consuming MP products, and operations with sizeable capacities. The inability to accurately assess the provenance and accounting of external feedstocks gives rise to the potential double counting of nickel units from a global perspective. As such, the ability to assess the study's exhaustiveness is limited as it remains feasible that both parties report nickel units contained in external feedstocks. In either instance, the intricacies of collected data were clearly defined to ensure reproducibility.

3.6.5 Other Limitations

Beyond limitations encountered from the opacity, sparsity, and inconsistency of reported data, further limitations to the study's comprehensiveness were incurred. Most prominent was the potential bias incurred from one researcher conducting data collection and analysis. While an auxiliary researcher reviewed data and assumptions, the lack of supplemental researchers supporting data collection and analysis potentially introduced unintended biases and interpretations.

In contrast, the tools utilized to collect and analyze data limited the study. Specifically, the rigidity of the Qualtrics data collection survey confined the ability to adapt relevant fields when collecting data. This was most prominent when collecting data on nickel products, as the tool's structure limited the ability to capture composition data. Similarly, employing an internet archive tool would have been beneficial when collecting data. The fluidity of company websites sometimes limited the ability to revisit referenced ULRs containing relevant data.

Chapter 4

Results

4.1 Research Objective

As discussed in Section 1.3, the objective of the research was to develop the metallurgical capacity metric and an applicable approach to support its assessment. Implementation of metallurgical capacity and its underlying methodology was successfully achieved through the case study on the primary non-ferrous nickel product supply chain. The following sections outline the metallurgical capacity from the case study as well as numerous derivates of the metric related to precarious supply chain attributes. A discussion of the utility, limitations, and recommendations specific to the metric are outlined in Sections 5.5, 5.6, and 5.6.6.

4.2 Results

A comprehensive analysis of collected data was completed that demonstrates several unique insights and trends as it relates to the supply of non-ferrous nickel from primary sources. The analysis provides a basis for addressing the case study questions and support strategic discussion points. Graphically representing and deciphering pertinent results from the analysis is vital to improving the further communicability of metallurgical capacity as a beneficial metric. Given the vast sums of collected data, the expanse of possible interpretations of evaluated data is of notable significance. A summary of germane results is presented in the following sections.

4.2.1 Metallurgical Capacity: Nickel Case Study

A total of 42 operations were identified conforming to the defined parameters, as established in Section 3.3.2.2. Of the confirmed operations, annual production capacities yielded the metallurgical capacity for the case study, which was determined to be 1,622,762 metric tonnes of nickel per year.

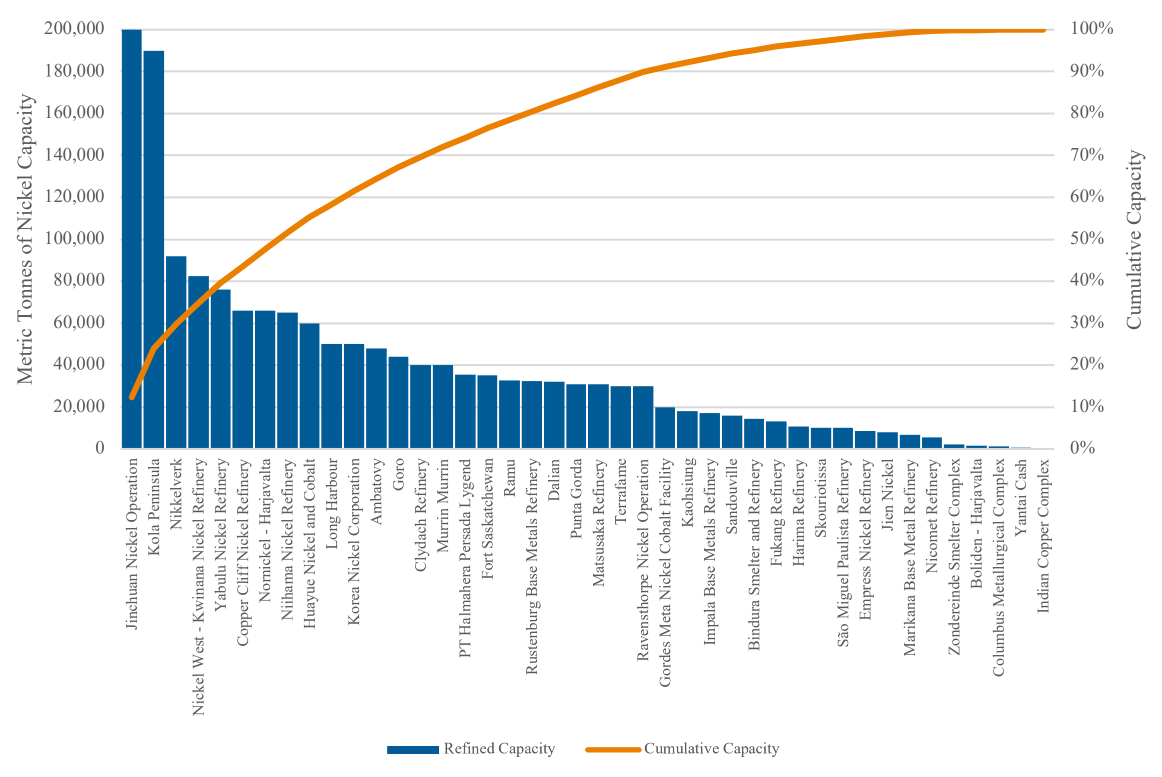


Figure 4-1: Metallurgical Capacity by Operation and Cumulative Capacity Curve

Figure 4-1 demonstrates the range of annual production capacities across operations. The mean production capacity of evaluated operations was 38,637 metric tonnes of nickel per year. In contrast, the median production capacity was 31,000 metric tonnes of nickel per year. Such differences suggest a skewed distribution towards smaller facilities, with a small subset of outlying facilities with much greater production capacities. In particular, the two largest operations, Jinchuan's Nickel Operation and Nornickel's Kola Peninsula, exhibit sizeable capacities relative to competing operations.

When assessing the distribution of production capacity, the seven largest operations account for approximately 50% of metallurgical capacity. This is further amplified when considering that the largest operation has an annual production capacity approximately 500x greater than that of the smallest operation.

A myriad of factors can influence the production capacity of a facility. The primary limiting factor is the availability of feedstock which is, in turn, related to the production capacity of upstream mining operations and their respective reserves and resources. Additionally, technological factors, including processing equipment; environmental factors, such as water availability; and social factors, such as labour force capabilities, can further influence production capacity.

A leading factor owing to the relative size of smaller operations relates to the targeted metals contained in their respective feedstocks. Smaller operations primarily extract nickel as a by-product from material streams generated while producing alternative metals such as copper or PGMs. Lower concentrations of contained nickel in the upstream feedstock material or limitation in processing technologies inhibits the nickel production potential of such facilities (Ndlovu, 2014).

4.2.2 Output Product Classification

Parameters adopted as part of the case study related to the requisite criteria for the inclusion of evaluated operations were predicated upon the provenance of the feedstock material as well as the quality of the output product. The intended objective included assessing operations producing non-ferrous nickel products from primary sources for which products did not require subsequent midstream refining. However, insufficient transparency related to the provenance of several value chains prohibited the ability to accurately determine all midstream operations within the value chain.

As such, a derivative of the metallurgical capacity was determined, for which the metallurgical capacity was further subdivided into three distinct categories, as discussed in Section 3.5.4, to reflect the level of refinement of the output products. Such categorization of assessed operations was necessary to limit duplicative summation of production capacity.

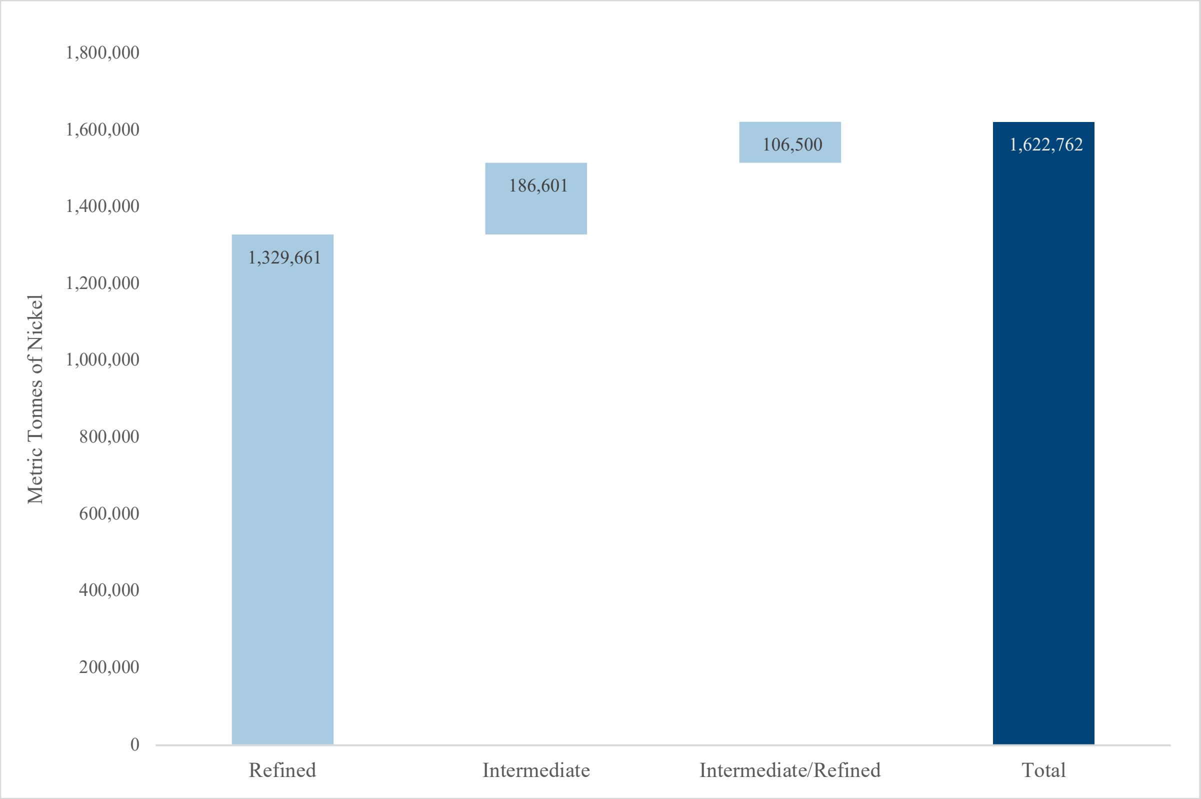


Figure 4-2: Product Classification of Metallurgical Capacity

As illustrated in Figure 4-2, the majority of operations assessed could reasonably be categorized as Refined. In contrast, five facilities were considered Intermediate, accounting for 11% of metallurgical capacity. Similarly, four facilities were deemed Intermediate/Refined equivalent to 6% of metallurgical capacity.

4.2.3 Operating Status

A contributing factor influencing supply availability relates to the time required for supply to be accessible. When assessing metallurgical capacity, the operating status of a facility was not considered. It was assumed that facilities placed under care and maintenance could promptly resume operation within a reasonable time frame providing a more rapid supply response relative to the time required to develop greenfield or brownfield operations. Alternatively, it is pertinent to understand the operating status of facilities to evaluate potential idle capacity within the supply chain.

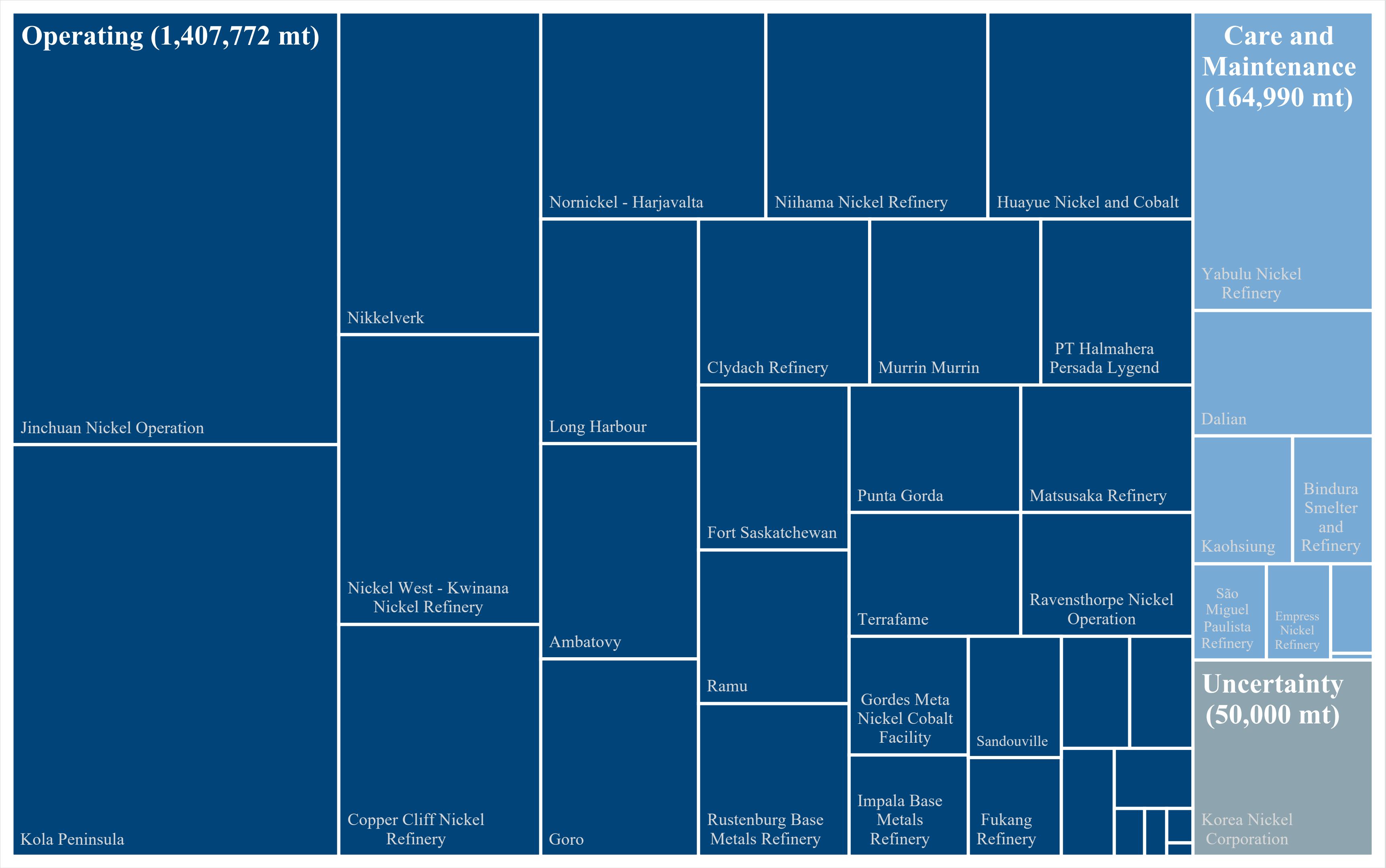


Figure 4-3: Metallurgical Capacity by Operating Status

As can be seen in Figure 4-3, most facilities assessed, and in turn, metallurgical capacity, were operating within the examined period. In contrast, eight facilities, accounting for only 10% of metallurgical capacity, were under care and maintenance. Additionally, one facility, Korea Nickel Corporation, could not reasonably be determined to be operable during the assessed period and was categorized as uncertain due to data limitations.

Detailed analysis of facilities placed under care and maintenance demonstrates that such facilities primarily produce products marketed toward metallurgical applications. Further, such facilities generally rely on complex value supply chains that exacerbate the economic and technical challenges of extracting nickel. Notably, the largest of the facilities under care and maintenance, the Yabulu Nickel Refinery, utilizes a dated processing technology, the Caron process, that limits the operations' economic feasibility. Additionally, the facility has been subject of political contention (G. Mudd & Jowitt, 2016).

4.2.4 Excess Capacity

Excess production capacity within metal supply chains can take two forms. The primary form includes facilities placed under care and maintenance. Alternatively, spare capacity can take the form of underutilized capacity at an operating facility whereby the operation is producing below its nameplate production capacity. Exploiting either form of spare capacity has notable trade-offs which must be considered in detail.

As detailed in Figure 4-3, eight operations, accounting for 164,990 metric tonnes of annual production capacity, were placed under and care and maintenance in 2021. As discussed in Section 4.2.3, factors ranging from inadequate economic conditions, political controversy, and insufficient feedstock supply were among the leading factors contributing to operations being placed under care and maintenance. Such circumstances, unique to each operation, are vital to comprehend when deliberating on accessing the dormant capacity.

The surrogate condition for which excess capacity can be derived requires a detailed evaluation of an operation's historical production in relation to its nameplate production capacity. The inherent volatility of nickel prices, coupled with their intrinsic impact on production, can significantly influence the ability of an operation to operate at nameplate capacity. Further, price volatility can have laggard effects on production contingent upon the structure of off-take agreements or the economic sustainability of individual operations. Additionally, exogenous factors, such as global conflicts, as well as endogenous factors, such as equipment breakdown or maintenance, can meaningfully impact the production output of operations.

Given the capricious nature of nickel prices during the assessed period, 2021, as demonstrated in Appendix A, in addition to the impacts of the Covid-19 global pandemic on operations (R. Ferreira & Pinto, 2020), assessing the excess production capacity of facilities operating during 2021 required careful consideration. Further, while historical production figures are commonly reported for publicly listed companies, data on privately owned operations is sparse, thus limiting the scope of the analysis. Likewise, while publicly listed companies report annual production figures, data is often aggregated, most notably amongst companies with multiple operations, limiting the ability to assess excess operating capacity deterministically.

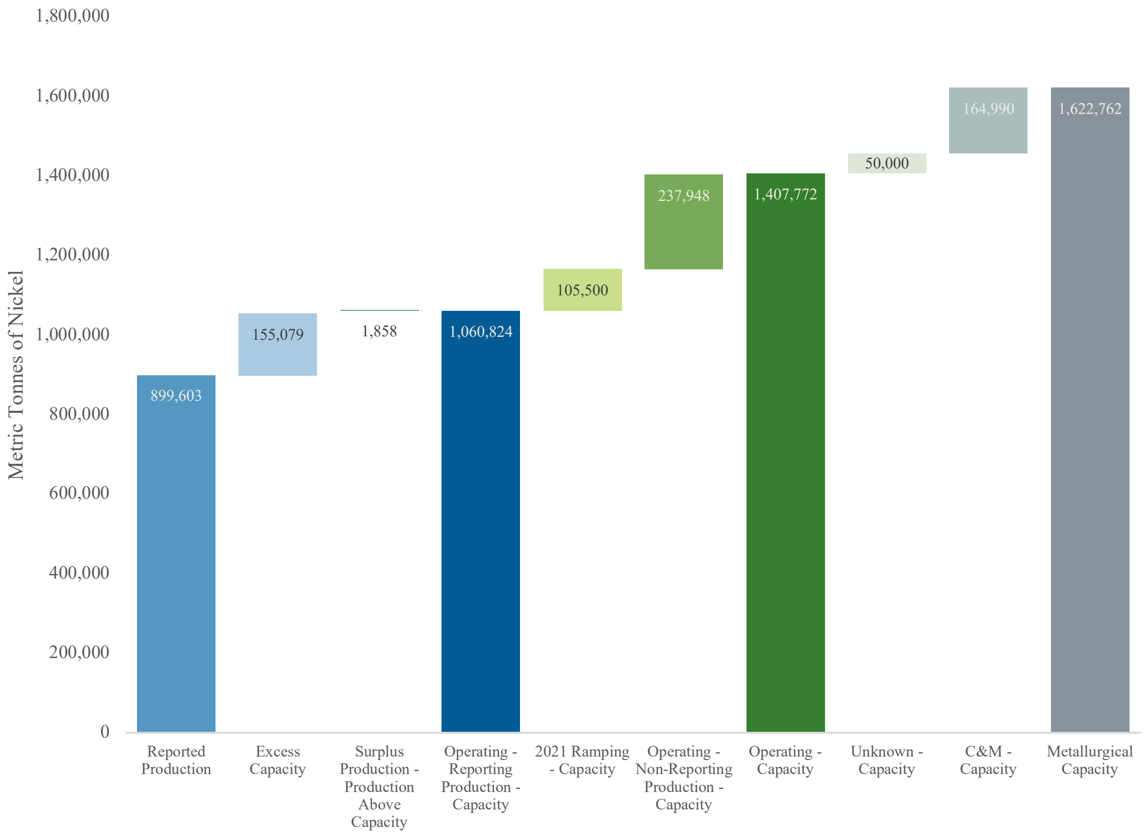
Of operating capacity in 2021, 23 operations reported production volumes, accounting for 76% of total operating capacity. A total of seven operations were operational in 2021 but did not report their respective production. Several notable peculiarities persist when examining such operations. First, three facilities were established and began production in 2021, accounting for 7% of operating metallurgical capacity. Similarly, of operating facilities established prior to 2021 and which did not report production volumes, one facility, Jinchuan Nickel Operation, accounted for 84% of associated capacity. Such outsized weighting indicates that the remaining operations exhibit relatively small production capacities. As such, it can be reasonably assumed that results derived from operating facilities reporting their respective production volumes provide sufficient macro resolution.

As a result of global events that transpired during the assessed period, most notably the influence of Covid-19 on nickel supply and demand, careful examination of production figures was required. As such, the annual production volumes amongst reporting facilities between 2019-2021 were considered. The range provided a more representative assessment of an operation’s production potential while accounting for variability in production incurred over the assessed period as a result of exogenous factors encountered.

The time range was considered as 2019 provides the most recent representation of production volumes prior to the impacts of Covid-19. While it would be reasonably assumed that 2020 would represent considerable reductions in production volumes due to the pandemic, as demonstrated in Appendix C, several operations sustained the highest production ratios that year. In contrast, 2021 represents the most recent production volumes. In turn, the highest ratio of annual production relative to nameplate capacity between 2019-2021 was considered when assessing excess production capacity.

It should be noted that several assumptions were made when evaluating excess capacity due to inconsistent reporting methods amongst operating companies and ownership changes taking place between 2019 and 2021. Chief among them was Vale's production reporting for its Clydach, Copper Cliff, Long Harbour, and Matsusaka operations. Due to the company's reporting methodology, where refined production is referenced to its mining operations output, it was assumed that the totality of reported refined production from its mining operations, except for Onça Puma, and reported third-party feedstocks were processed at the four refining operations (Vale, 2022a). As such, the aggregated refined production was compared to the aggregate of the four terminal operation's capacity to determine the company's excess capacity. This was assumed reasonable, given the reported feedstocks exchanged between the company's operations. Additionally, given that Vale sold the Goro facility in 2020 and its Dalian operation was placed under care and maintenance in late 2020 and was slated to be sold in 2022, the company's production was referenced relative to 2021 due to the complexity of accounting for 2020 and 2019 operational performance (Vale, 2022a). Similarly, 2021 annual production was used to evaluate Goro’s excess capacity to account for change in ownership (Prony Resources, 2021).

In a similar vein, Sumitomo Metal and Mining's Niihama and Harima refineries were aggregated and compared relative to their combined capacity due to the company's combined reporting of nickel sulphate data produced at each facility (Sumitomo Metal Mining, 2022). Additionally, changes in an operation's capacity during the period were considered when evaluating excess capacity, as was the case for BHP's Kwinana Refinery (BHP, 2019, 2021a). Similarly, production data was relative to a company's fiscal year. This was assumed reasonable as the exercise is indented to illustrate the magnitude of excess capacity at an operation. Tables outlining the combined data are provided in Appendix C.



I) Data reflects the highest ratio of annual production to annual capacity between 2019-2021 to account for potential disruptions incurred by Covid-19.

II) Vale's production and capacity reflects 2021 figures to account for the sale of Goro in 2020 and Dalian being placed under C&M in 2020

III) Vale's operations reflect combined capacity of Long Harbour, Clydach, Copper Cliff Nickel Refinery, and Matsusaka. See Appnedix C.

IV) Goro reflects 2021 production due to change in ownership incurred during 2020

V) Operating capacity for BHP was adjusted to reflect increased production capacity realized during 2020. See Appendix C.

VI) SMM operations reflect combined capacity of Niihama and Harima. See Appnedix C.

Figure 4-4: Excess Production Capacity

As can be seen in Figure 4-4, minimal excess capacity persists, suggesting operations are producing within proximity to their respective nameplate capacity. In total, approximately 155,000 metric tonnes of excess capacity remained unexploited. Accessing the dormant capacity requires subsequent analysis, as further discussed in Section 4.3.4.

In contrast, two operations, Murrin Murrin and Ramu, reported production marginally in excess of their nameplate capacities. The ability of these operations to operate above their nameplate capacities requires the historical context of each operation. Murrin Murrin, which was initially established in 1998 by Anaconda Nickel, had an original design nameplate capacity of 45,000 tonnes per annum (tpa). However, it encountered significant commissioning setbacks, which contributed to the financial downfall of Anaconda Nickel. Glencore subsequently acquired the company and the operation. Since the acquisition, the operations underwent re-configurations that resulted in a reduced nameplate capacity (Gabb, 2018). At present, the operation has a nameplate capacity of 40,000 tpa (Glencore, 2016). Similarly, Ramu, which began operations in 2012, experienced notable setbacks during commissioning as it did not reach nameplate capacity until 2017. The operation claims that recent production figures above nameplate capacity result from systemic operational efficiency gains (Ramu Nico, 2021).

When considering operations established in 2021, the ability to access excess production capacity is likely limited for two reasons, each of which is related to their adoption of HPAL technologies. The primary reasons relate to the historical challenges in commissioning and operating HPAL operations, as exhibited by Murrin Murrin, Ramu, Goro, and Ambatovy (Gabb, 2018). Additionally, HPAL operations process laterite ore and are primarily vertically integrated, and rarely accept third-party feeds, as demonstrated in Appendix C. Given the historical operational regression incurred amongst HPAL facilities coupled with their limited feedstock flexibility, their ability and willingness to accept alternative feeds is likely limited. Nevertheless, the favourable commissioning of Huayue Nickel and Cobalt, as well as PT Halmahera Persada Lygend in 2021, could amend the historical precedent endemic to HPAL operations (Asmarini, 2021; Michael Jiang, 2021). However, alternative challenges could further plague HPAL operations, as further discussed throughout Section 5.4.1.1.

4.2.5 Geographic Distribution

Heightened awareness towards the geographic concentration of supply chains for critical technologies has prompted the need for detailed assessment of such supply chains, including the provenance of raw materials. Mapping the geographic concentration of metallurgical capacity is vital to understanding potential supply vulnerabilities.

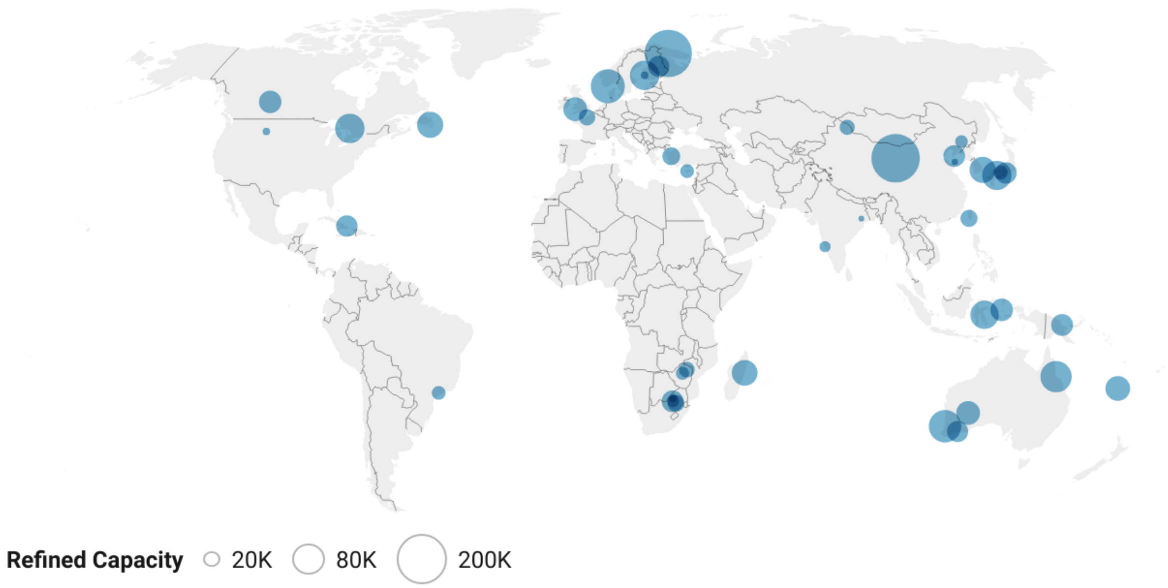


Figure 4-5: Geographic Distribution of Capacity

As can be seen in Figure 4-5, metallurgical capacity is concentrated in three regions: Northern Europe, East Asia, and Oceania. Further analysis of facilities in each region demonstrates several unique relationships, particularly concerning the provenance of feedstock material. A notable portion of operations in Northern Europe and East Asia rely on imported feedstock material. Alternatively, facilities in Oceania and southern Africa are primarily integrated with established upstream mining operations providing a reliable feedstock stream, as illustrated in Figure 5-4. However, operations in southern Africa are marginal in size as they primarily produce nickel as a by-product of PGM feedstocks.

In contrast, a limited or complete absence of established metallurgical capacity is apparent across Central and South America, as well as Northern Africa. The lack of operations in Northern Africa can be attributed to numerous factors, notably the lack of regional sources of nickel (Heijlen et al., 2021; G. M. Mudd & Jowitt, 2014). Contrary to Northern Africa, numerous lateritic nickel deposits are known and currently exploited in Central and South America. While extracting nickel from such deposits is feasible, established midstream operations in the region produce lower-grade nickel products such as FeNi (R. Ferreira & Pinto, 2021).

4.2.6 Ownership

The high barriers to entry of midstream metallurgical operations result in unique ownership structures. Understanding ownership dynamics is valuable when assessing potential production risk culminating from exogenous factors such as geopolitical events or legal proceedings. Recent systemic consolidation of upstream and midstream assets raises additional risk as it gives rise to the potential monopolization of resources and production capacity (IEA, 2023a). Evaluating the concentration of metallurgical capacity as it relates to ownership amongst primary owners of midstream facilities provides unique insight into the degree of consolidation. The following chart outlines the metallurgical capacity of primary owners of midstream operations as well as the number of operations controlled by the respective company.

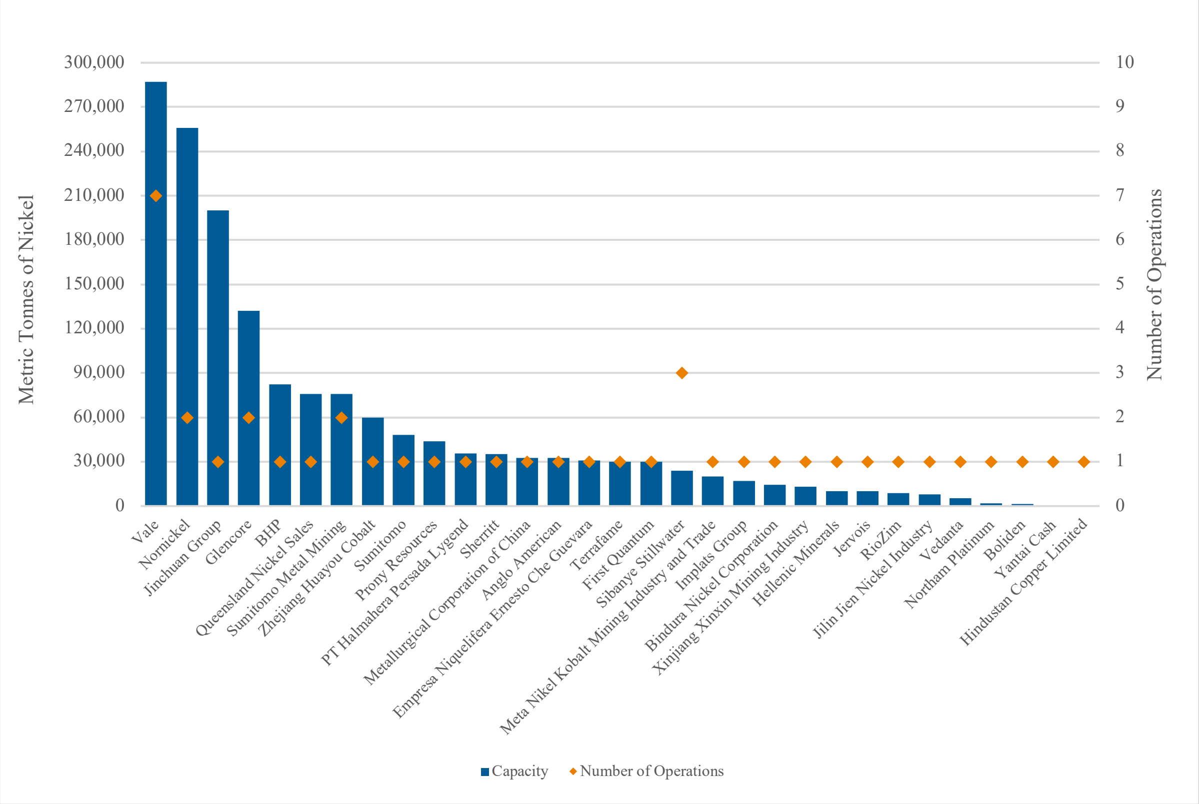


Figure 4-6: Metallurgical Capacity and Number of Operations by Primary Owner

Figure 4-6 demonstrates that most metallurgical capacity is owned by a small number of companies. Approximately 60% is controlled by five companies. The degree of concentration stems from the size of the facilities operated by the companies rather than the number of operations. With the exception of Vale, the remaining four companies each respectively operate one or two facilities. In turn, the concentration is the result of facilities individually accounting for a substantial proportion of production capacity or culminating in notable production capacity. The control of metallurgical capacity is further exemplified when considering metallurgical capacity relative to the country in which primary owners are headquartered.

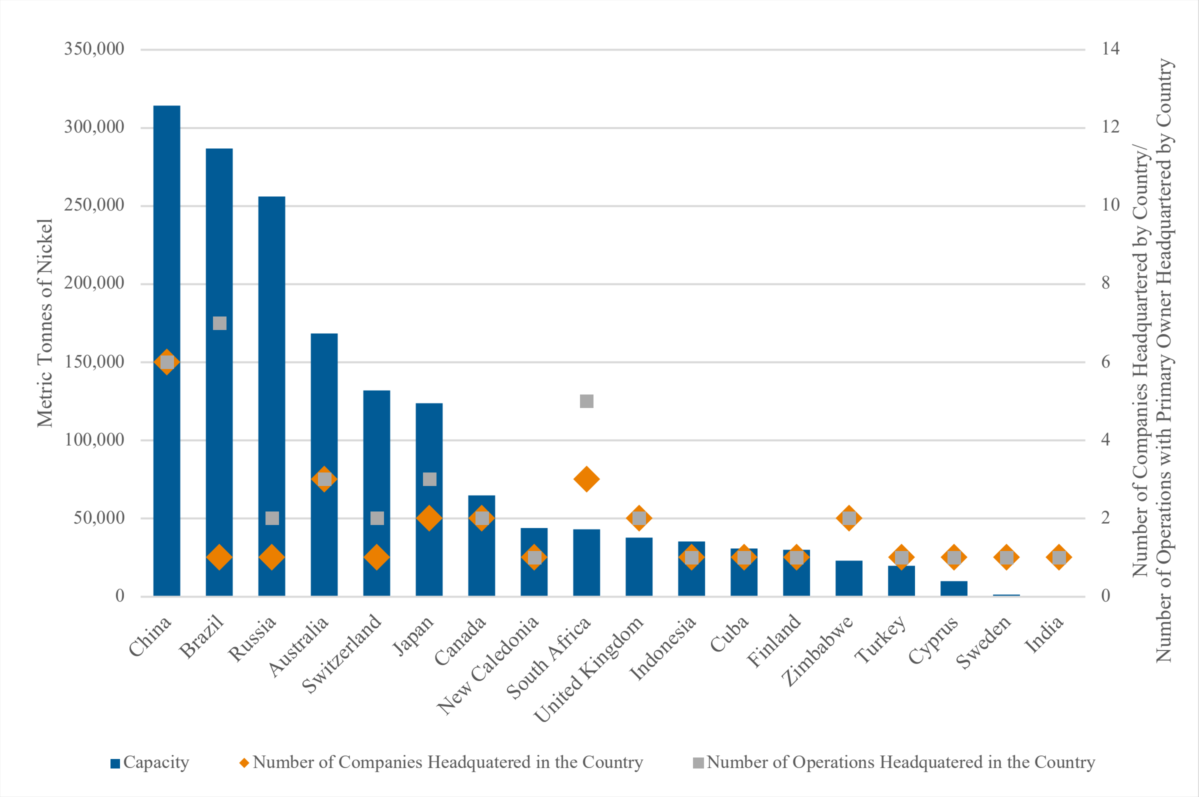


Figure 4-7: Metallurgical Capacity, Number of Companies, and Number of Operations by Headquartered Country of Primary Owner

As demonstrated in Figure 4-7, approximately 80% of metallurgical capacity is owned by companies headquartered in just six countries. The considerable concentration of metallurgical capacity owned by companies headquartered in a select number of countries presents a considerable supply risk at it relates to potential market manipulation and legal elements.

4.2.7 Ownership Type

The economic and social benefits of midstream operations are vital to local communities and national economies. Such opportunities have provided the grounds for nations endowed with mineral resources to consider nationalizing upstream and midstream operations to support regional development. Understanding the degree to which governments or government entities own metallurgical capacity is vital to identify potential bottlenecks.

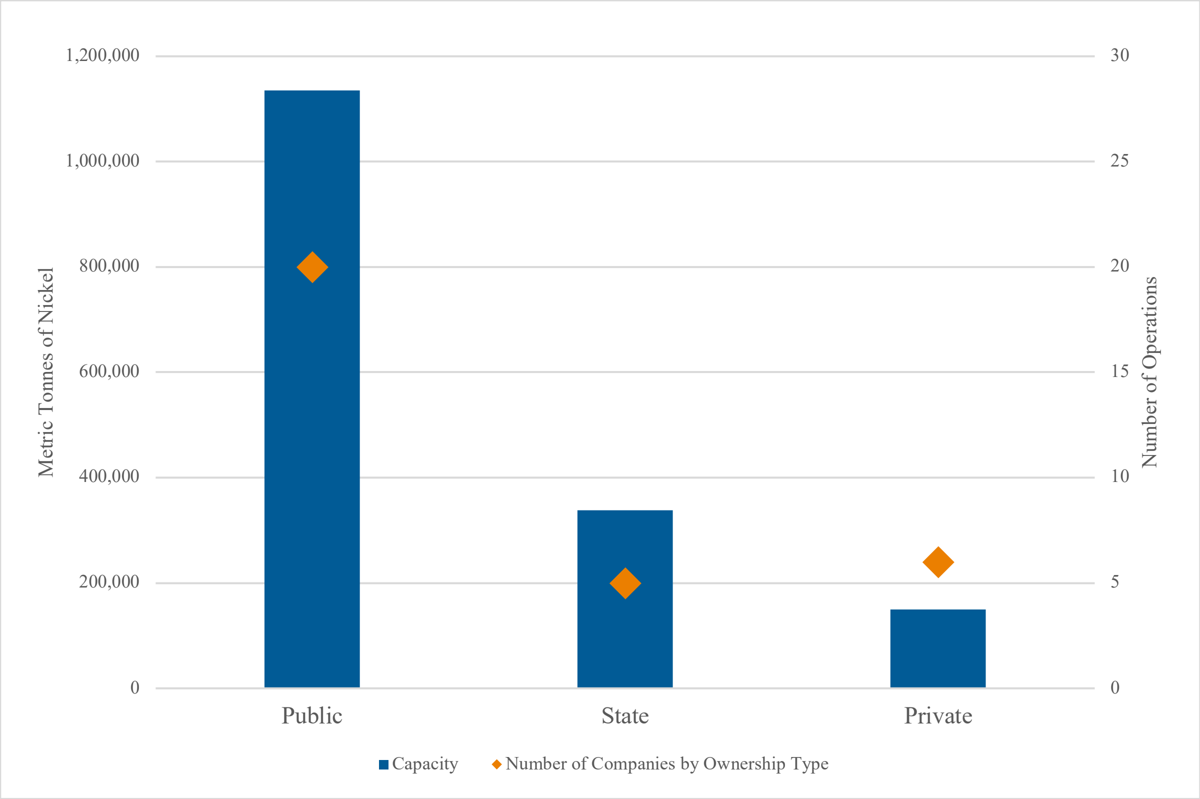


Figure 4-8: Metallurgical Capacity and Number of Operations by Ownership Type of Primary Owner

As can be seen in Figure 4-8, metallurgical capacity is largely owned by publicly traded companies. In comparison, state enterprises own a smaller fraction of midstream operations. Similarly, numerous smaller operations are owned by private enterprises. Given the large fraction of production owned by public companies, understanding the exchanges on which the companies are listed is of importance given associated regulatory requirements.

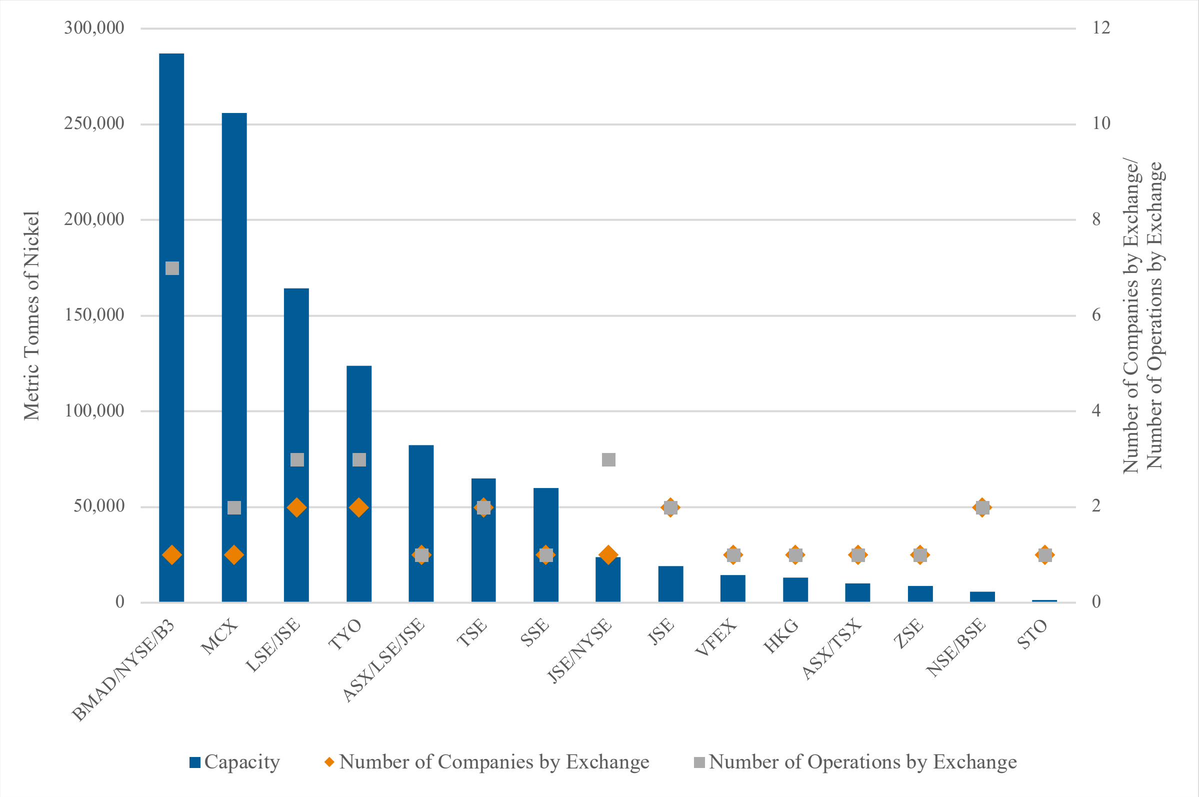


Figure 4-9: Metallurgical Capacity, Number of Companies, and Number of Operations by Listed Exchange Among Public Primary Owners

As depicted in Figure 4-9, the majority of publicly listed metallurgical capacity is primarily owned by companies dually listed. Exchanges such as the Australian Stock Exchange (ASX), London Stock Exchange (LSE), and Johannesburg Stock Exchange (JSE) are the most frequently listed exchanges among public owners.

4.2.8 Operational Sovereignty

While consolidation of metallurgical capacity is particularly relevant to downstream consumers, for government stakeholders, investors, and operating companies, the relationship between domestic and foreign production is of particular interest. Consequently, the operational sovereignty, as defined in Section 3.5.9, of midstream operations within a nation is critical to political, financial, and operational considerations.

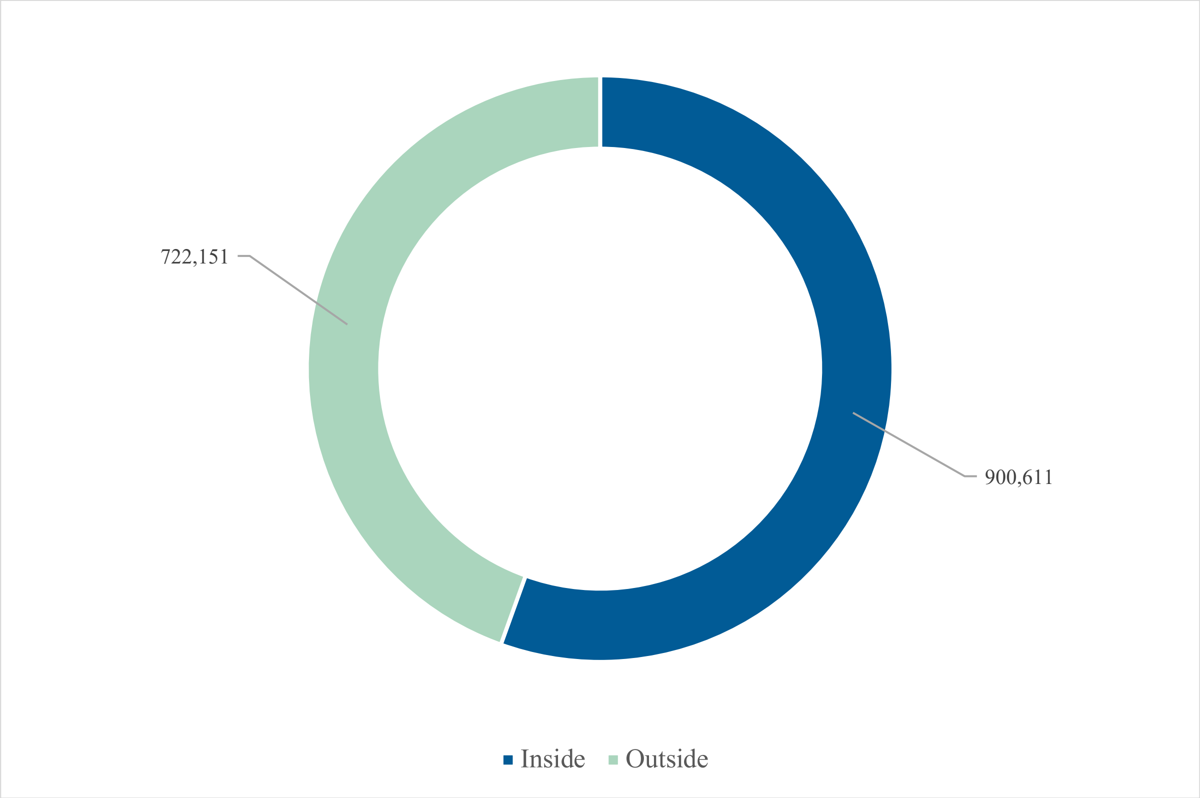


Figure 4-10: Metallurgical Capacity by Operational Sovereignty

Figure 4-10 demonstrates the operational sovereignty of capacity at the most basic level whereby the country which the facility is located and the country which the primary owner is headquartered are evaluated. The figure indicates that the majority of metallurgical capacity is primarily owned by companies headquartered in the same jurisdiction, represented as Inside. In contrast, a significant share of metallurgical capacity is owned by companies headquartered in foreign jurisdiction to that of the operation, represented as Outside. The sovereignty of metallurgical capacity can have considerable consequences when considering geopolitical risk, as further explored in Section 5.4.1 and 5.5.3. A more detailed analysis of country-level metallurgical capacity sovereignty is demonstrated in the following chart.

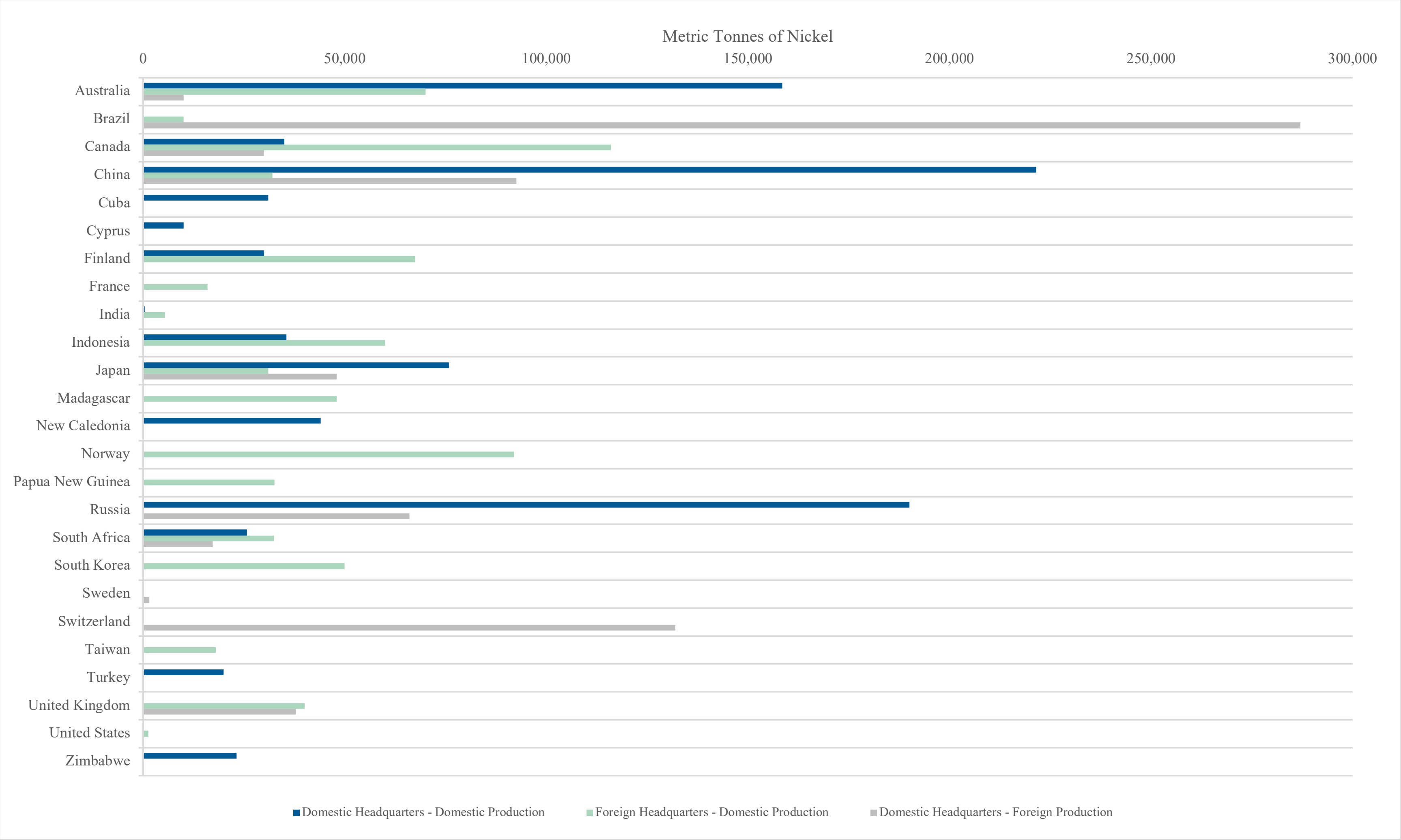


Figure 4-11: Country Level Metallurgical Capacity According to Operational Sovereignty

As can be seen in Figure 4-11, considerable variation exists in the sovereignty of metallurgical capacity within a given country. Companies headquartered in countries such as Brazil and Switzerland own and operate a considerable fraction of metallurgical capacity in foreign markets. However, the countries are either absent of, or domicile to trivial amounts of domestic metallurgical capacity owned by either domestic or foreign entities. Alternatively, metallurgical capacity in countries such as France, Madagascar, Norway, Papua New Guinea, South Korea, Taiwan, and the United States are exclusively operated by foreign enterprises. Additionally, the countries possess no domestic entities operating domestic or foreign production facilities. Countries such as Australia, Canada, China, Japan, and South Africa are home to domestic entities with domestic and foreign production in addition to foreign entities with domestic production.

4.2.9 Year of Establishment

Evaluating the historical expansions and developments of midstream operations overtime can provide valuable insight into periods of supply inflections. Due to data limitations, the ability to accurately determine expansions and contractions in the number of midstream operations as well as their respective metallurgical capacity over time was not possible. However, it remained feasible to determine the year in which evaluated operations were of established, as defined in Section 3.5.10.

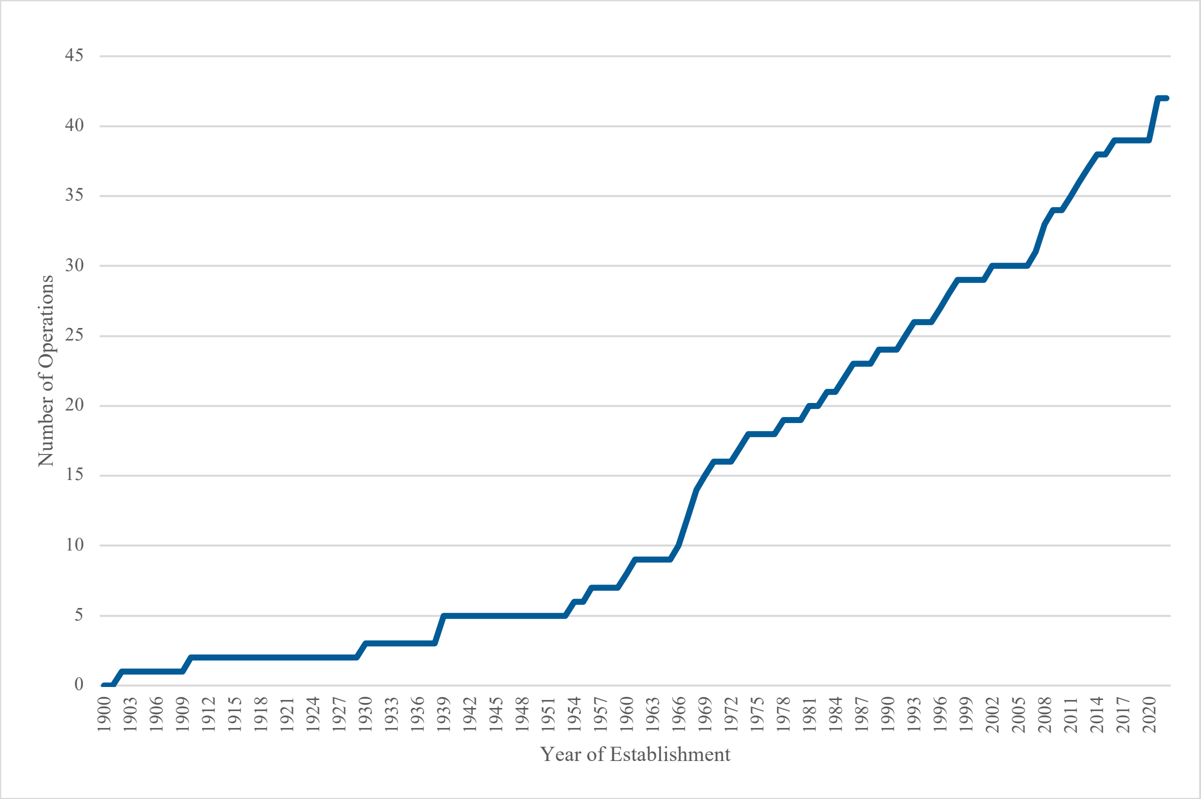


Figure 4-12: Cumulative Count of Operations by Year of Establishment

Figure 4-12 demonstrates periods for which outstanding stepwise changes in the number of operations established occurred. Most notably, a steep incline occurred between 1965 and 1978, in which nine facilities were established. This is due mainly to the development of base metal refineries in southern Africa as well as the exploitation of novel sulphide deposits in Australia, Canada, and China. More recently, a similar phenomenon occurred between 2007 and 2016, in which nine new facilities were established. Facilities established during the period primarily process lateritic ores using hydrometallurgical technology owing to advancements of the technology and challenges in developing sulphide deposits, as discussed in Section 5.4.5. In contrast, a relatively limited number of evaluated operations were established between 1902 and 1953.

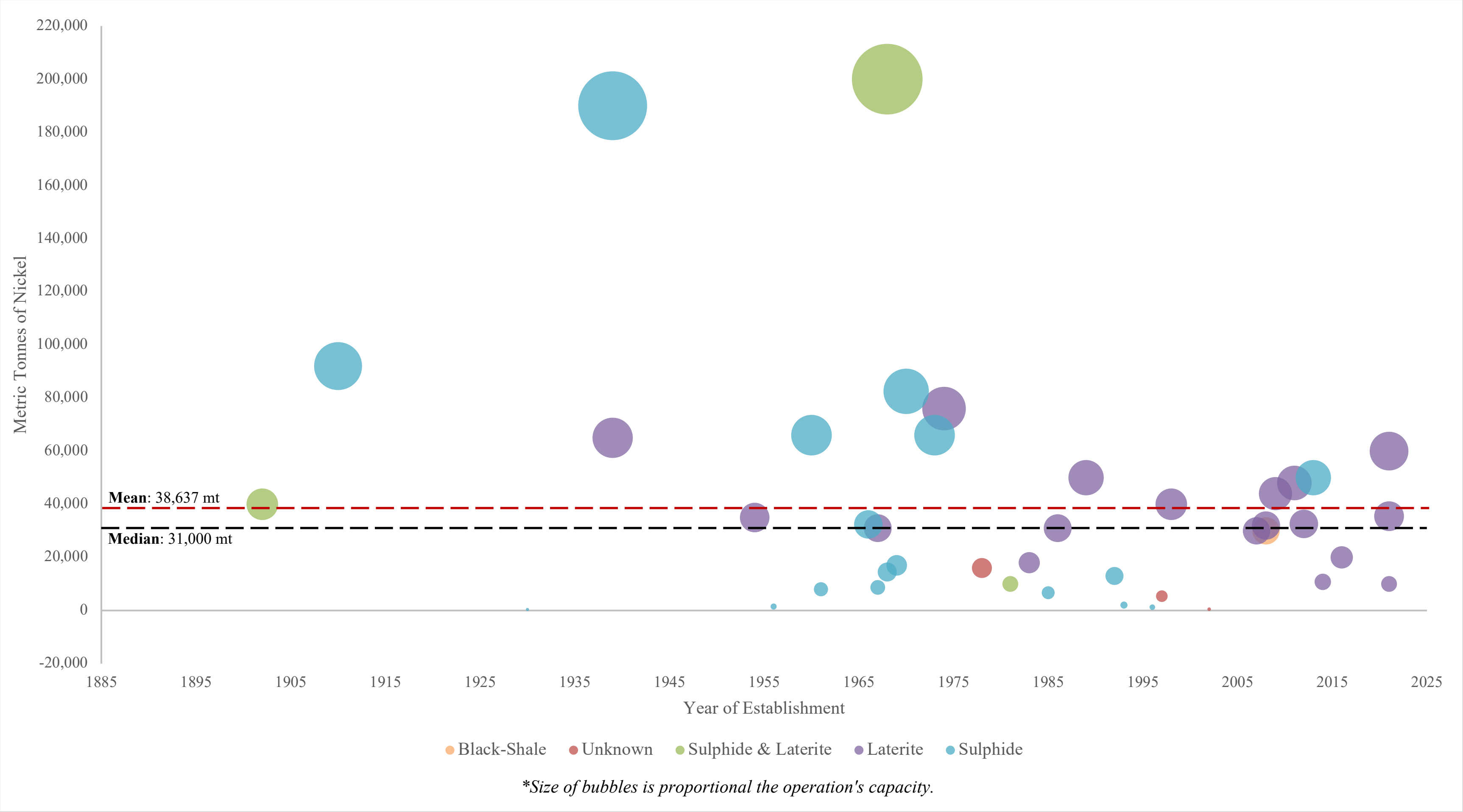


Figure 4-13: Metallurgical Capacity by Operation Size, Ore Type, and Year of Establishment

As illustrated in Figure 4-13, operations established prior to 1985 are predominantly sulphide and possess production capacity significantly above average capacity. Alternatively, operations established after 1985 typically process laterite feedstocks and possess production capacity near the average capacity.

4.2.10 Feedstock Source

The dispersed and finite nature of mineral and metal deposits has resulted in geographic separation amongst several upstream and midstream operations. This is further compounded by the economic, social, and environmental barriers to developing and operating upstream and midstream operations. The finite nature of upstream operations presents an acute problem for midstream operations with the qualification to extend their lifespan. Additionally, the potential upside and development challenges of upstream operations gives rise to highly diverse ownership of deposits within a given region, while the high barriers to entry of midstream metallurgical operations constrains ownership. This matter is particularly prevalent to nickel upstream and midstream operations. Numerous upstream operations supply midstream metallurgical operations owned by a dissimilar owner. The extent to which midstream operations process third-party feeds can provide unique insight into their operational flexibility.

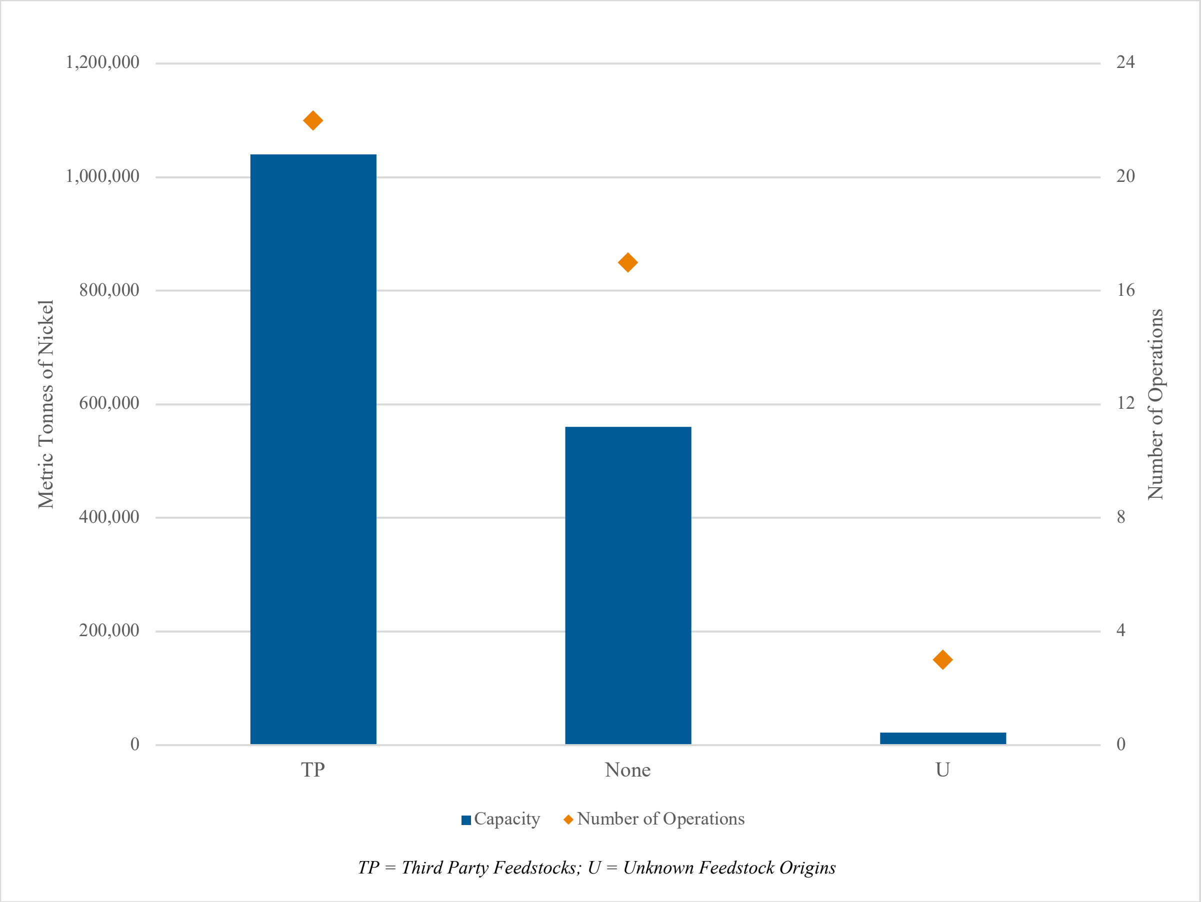


Figure 4-14: Metallurgical Capacity and Number of Operations Reporting Third Party Feedstocks

Figure 4-14 illustrates that a significant portion of facilities and capacity process third-party feedstocks. The ability of midstream metallurgical operations to accept third-party feedstocks suggests flexibility as it relates to acceptable input material. Nevertheless, given the bifurcated nature of nickel ores, a more nuanced understanding of feedstock sources for each facility is needed.

As described in Section 2.2.1, terrestrial nickel deposits occur nearly exclusively in two ores: sulphides and laterites. Unique chemical compositions native to each ore give rise to distinct processing technologies. The extent to which feedstocks can readably be interchanged generally remains unknown. Assessing the provenance of each facility's known feedstocks, the metallurgical capacity could reasonably be associated with each distinct ore type.

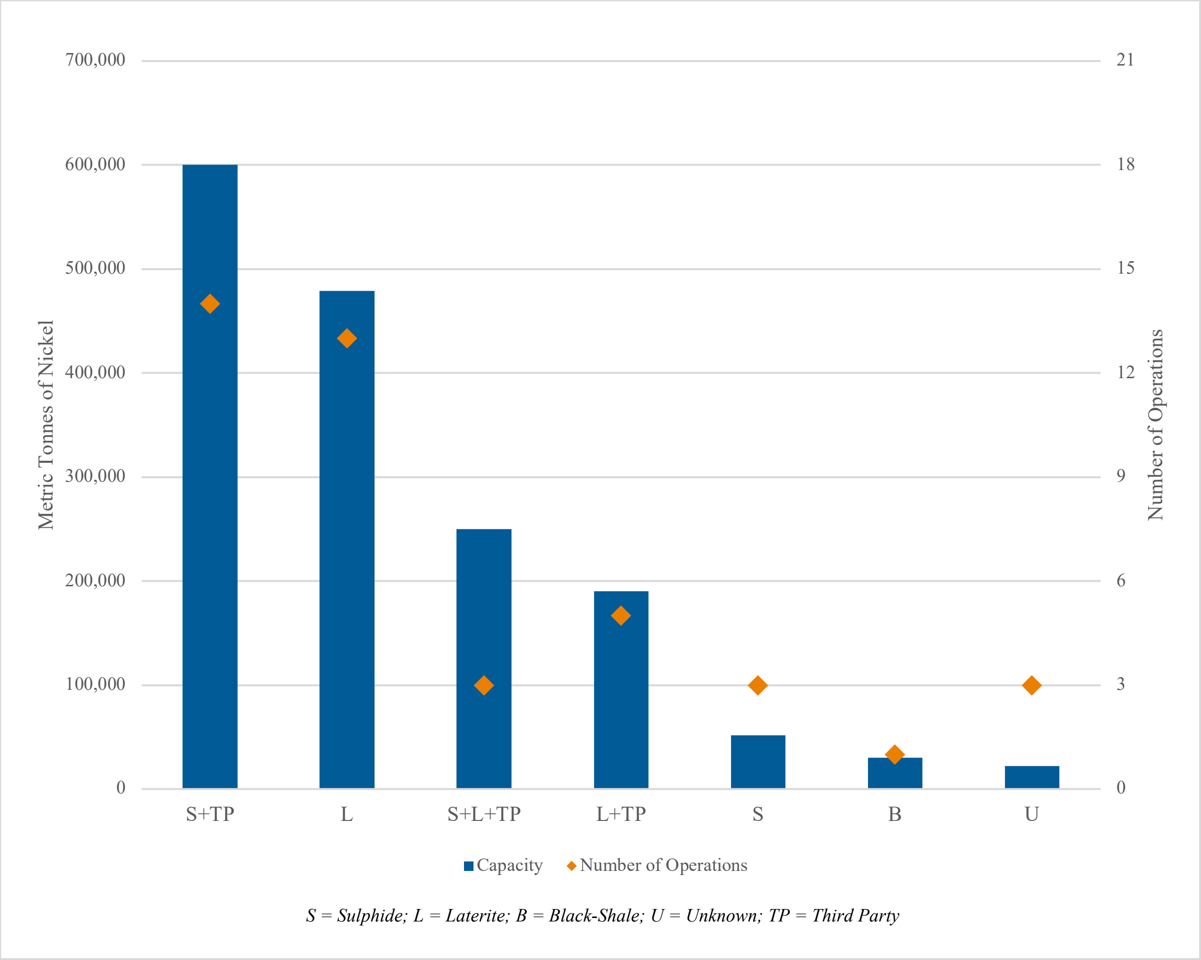


Figure 4-15: Metallurgical Capacity and Number of Operations by Feedstock Type

As demonstrated in Figure 4-15, operations processing sulphide ores predominantly process third-party feedstocks, while operations processing laterite ores do not process third-party feedstocks. The convoluted nature of mineral supply chains coupled with their inherent opacity limited the ability to determine the provenance of the feedstock for each midstream metallurgical operation and the degree to which third-party feedstocks accounts for an operation production. As can be seen, numerous facilities report procuring feedstock from unspecified third-party sources. The inability to identify counterparties and the respective source of the ore exchanged significantly limits the ability to definitely assess the dependence of an operation on a particular ore type or deposit. Such matter was particularly prevalent amongst operations processing sulphide ores. In contrast, it can be seen that lateritic operations exhibit significantly greater homogeneity in feedstock due to a lack of third-party feedstocks.

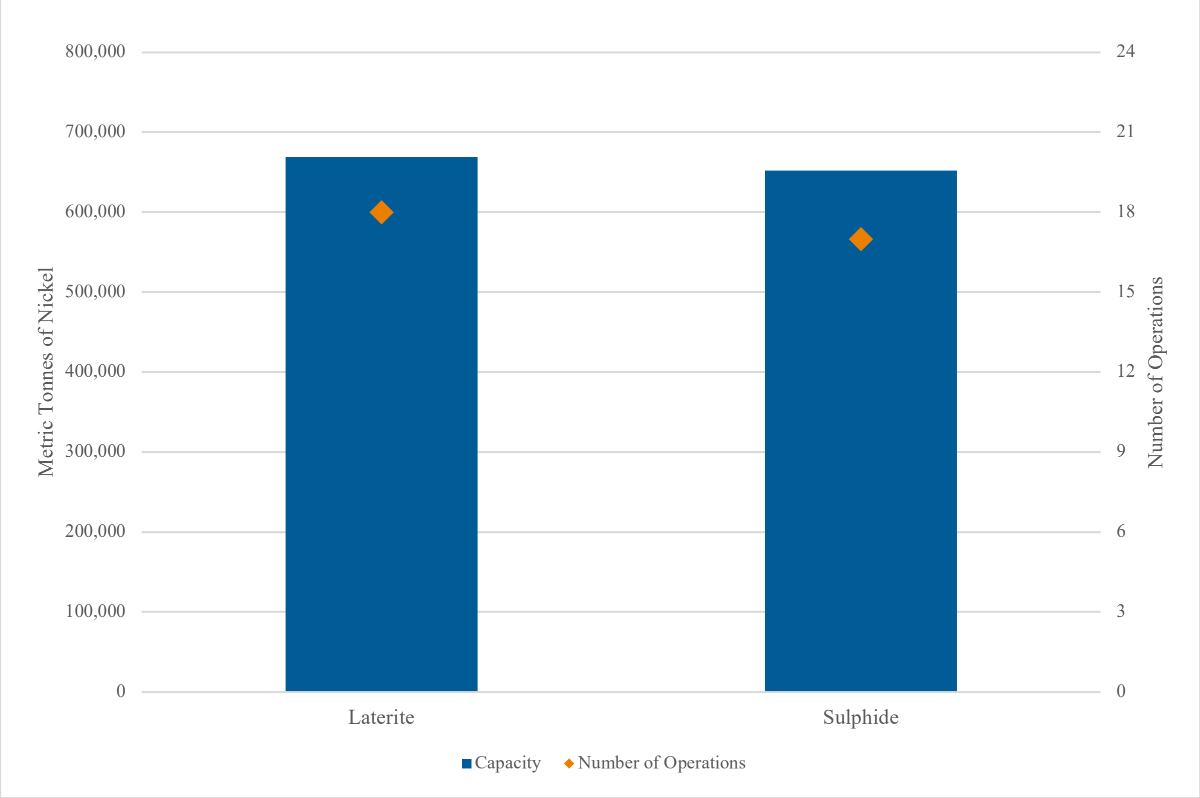


Figure 4-16: Metallurgical Capacity and Number of Operations by Sulphide and Laterite Feedstocks

While not possible to conclude the sourced ore type, it is reasonable to assume homogeneity amongst ore sources and third-party sources. When assuming third-party feedstocks are of equivalent ore classification to that explicitly stated, a relatively even distribution of metallurgical capacity is attributed to feedstocks derived from both sulphide and lateritic sources, as demonstrated in Figure 4-16. Additionally, when analyzing the number of operations in which the metallurgical capacity is distributed, it can be seen that a nearly equivalent number of operations process each of the respective ore types in question.

Nevertheless, when assessing the mean and median capacity of the operations in each category, it can be seen that notable discrepancies occur. For example, the mean capacity of sulphide operations is 40,746 metric tonnes in contrast to 35,769 metric tonnes amongst lateritic operations. In contrast, the median capacity for sulphide operations is 14,500 metric tonnes, while the median capacity for lateritic operations was 32,300. Such disparity between mean and median operation size can be attributed to numerous factors. For sulphide operations, considerable capacity variations exist amongst the largest and smallest operations due to the relative concentrations of nickel in high and low sulphur ores. Additionally, the number of sulphide operations utilizing third-party feedstocks suggests greater operational flexibility. In contrast, lateritic processers seldom utilize third-party feedstocks, which suggests they are constrained in operational flexibility, likely as the result of the complexity and differences among lateritic ores or process limitations.

The limited number of operations processing both sulphide and lateritic ores suggests that the ability to interchange feedstock is limited. This is likely due to technical and economic feasibility. However, when assessing the provenance of feedstock processed by Clydach Refinery, it is evident that several preceding processing operations are required, specifically amongst its lateritic ore value chain. Sulphide ores processed at Clydach are first converted into matte products through smelting processes carried out at Vale's Sudbury operations. In contrast, lateritic ores processed at Clydach are first smelted into a matte product at Vale's Indonesian operation before being further processed at the company's Matsusaka operation in Japan (Vale, 2022a). The foregoing processing suggest increased operational complexity for operations processing both sulphide and lateritic ores.

4.2.11 Midstream Integration

The complexity of mineral and metal supply chains lends itself to the distributed nature of supply and demand. Upstream operations are physically constrained to the location of exploitable deposits, while downstream operations tend to congregate in proximity to their respective end users. In contrast, the location of midstream operations is subjected to fewer geographical constraints as they are commonly located in relative proximity to either upstream or downstream operations. Given the challenges associated with cost-effectively processing ores with complex characteristics, several distinct operations will often sequentially process upstream feedstocks prior to producing a final product adequate for downstream applications. Alternatively, midstream operations can be uniquely tailored to specific feedstocks resulting in vertical integration between upstream and midstream operations.

The distribution of nickel deposits and the unique processing technologies employed to extract the contained nickel has resulted in a variety of midstream value chains with varying degrees of complexity. As a result, vertically integrated terminal operations and terminal operations reliant on a distributed network of operations are commonplace. Understanding the complexity of midstream value chains can provide unique insight into the dependency of facilities on imported feedstocks. Therefore, evaluating the level of integration amongst terminal operations relative to their midstream value chain, as defined in Section 3.5.12, is valuable to evaluating the sovereignty of an operation and its flexibility.

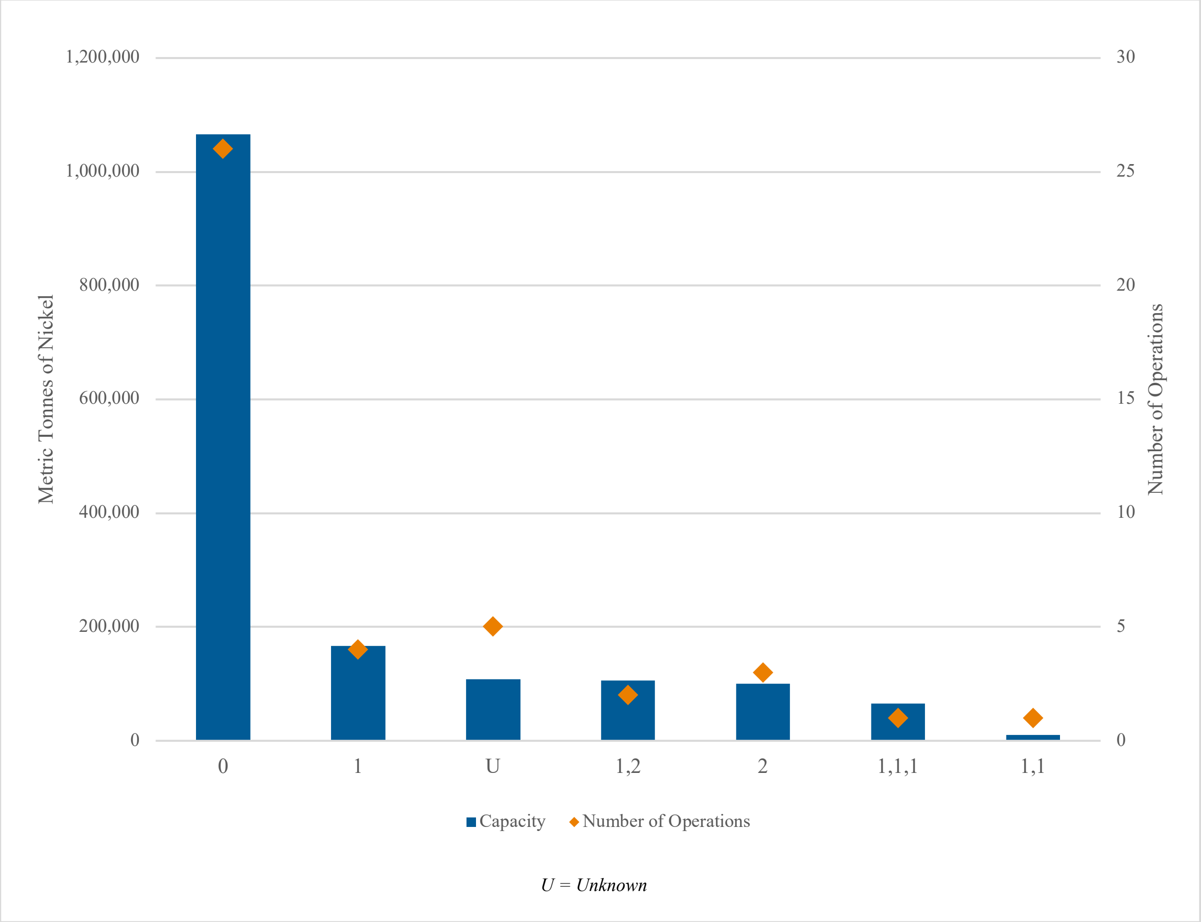


Figure 4-17: Metallurgical Capacity and Number of Operations by Degree of Midstream Integration

When excluding third-party feedstocks, and assuming intermediate operations, as discussed in Section 4.2.2, are terminal operations, Figure 4-17 demonstrates that the majority of midstream operations are vertically integrated, as defined in Section 3.5.12. When further analysing integrated operations, a considerable difference between laterite and sulphide operations persists, as further explored in Section 4.3.5. In contrast, a limited number of terminal operations attributable to the category procure material from a single preceding operation for which it is not exclusively integrated. For example, RioZim's Empress Nickel Refinery, located in Zimbabwe, procured matte feedstock from BCL Groups smelter, located in Botswana, prior to the later company being liquidated in 2016 (RioZim, 2017).

A small number of terminal midstream operations procure material from multiple value chains. In certain instances, these value chains include numerous preceding operations. A notable example includes Vale's Clydach operation, as outlined in Section 4.2.10. The operation procures material from two distinct midstream value chains, each with distinct numbers of preceding operations. Its most straightforward value chains include material procured from the company's smelting operation in Sudbury. In contrast, its most complex value chains procures material from the company's smelter in Japan, which in turn procures material from Vale's smelting operation in Indonesia. The ability to procure and transform material from two distinct value chains, which includes material originating from both laterite and sulphide ores, provides the facility with unparallel flexibility. However, the distributed and dispersed nature of the value chains consequently increases the complexity of the value chain, potentially leading to greater risk of supply disruptions.

4.2.12 Metallurgical Processing Technology

Midstream metallurgical operations employ complex metallurgical technologies to liberate and upgrade minerals and metals contained in feedstock materials. The complexity of adopted processes is related to a myriad of technical and economic constraints. Additionally, discrepancies in the compositions of feedstocks give rise to unique processes and technologies that are often distinct to an operation. This is particularly true of primary nickel midstream operations due to disparities in composition amongst laterite and sulphide ores. Therefore, understanding the relationship between the type of technologies employed across the midstream value chain is valuable for identifying variances across ore types.

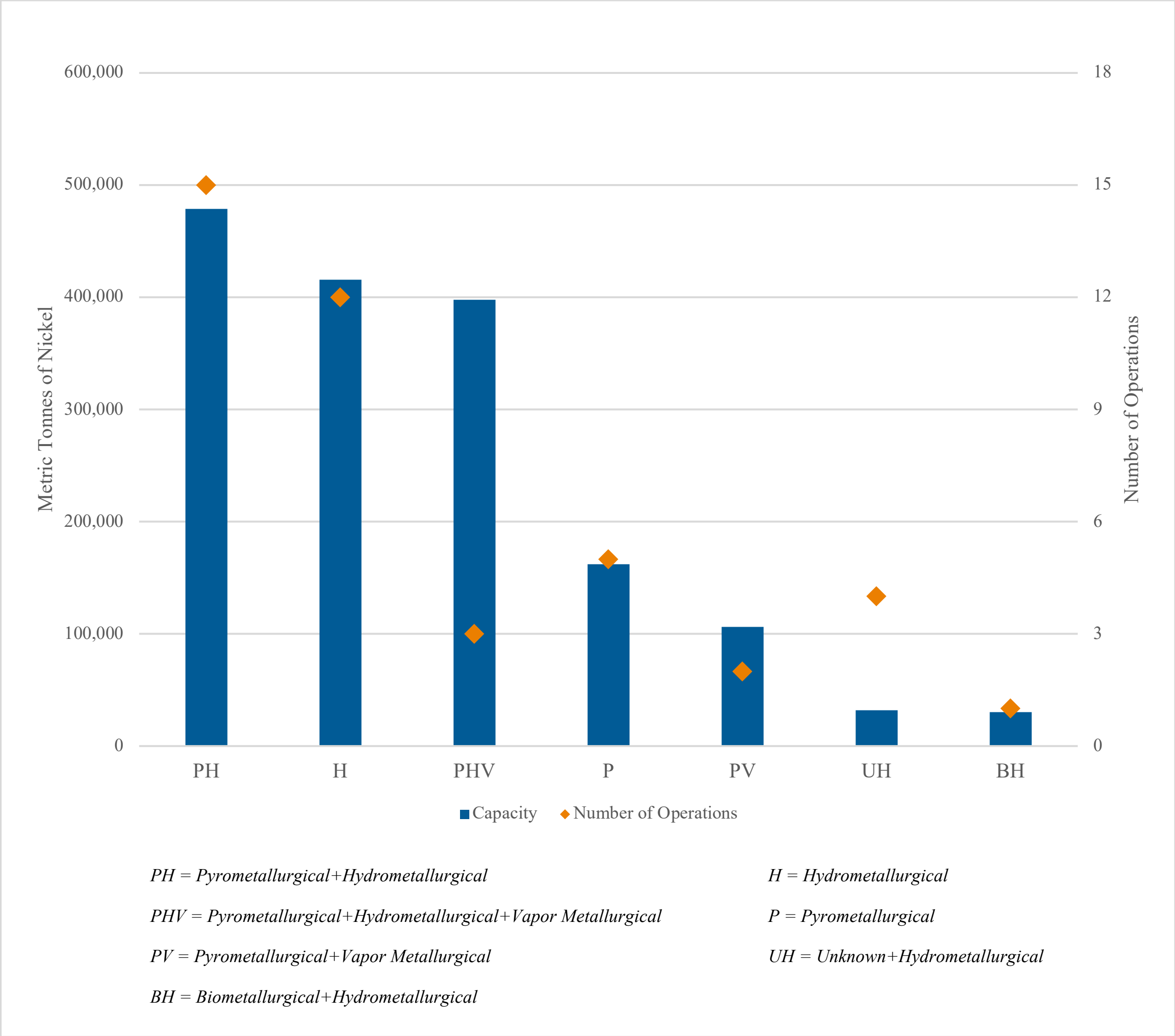


Figure 4-18: Metallurgical Capacity and Number of Operations by Aggregate of Employed Metallurgical Technology Throughout an Operation's Value Chains

As illustrated in Figure 4-18, three technologies, or combinations thereof, account for the majority of metallurgical capacity. Pyrometallurgical processing followed by hydrometallurgical processing is the most prevalent among operations. Similarly, a small number of operations employ a combination of pyrometallurgical, hydrometallurgical, and vapor metallurgical technologies, all at notable scales. However, it should be noted that vapor metallurgical operations account for a relatively small fraction of the overall output capacity at several operations, see Footnote 5, highlighting the fractured nature of an operation processing capabilities. A considerable number of operations, accounting for a sizeable share of metallurgical capacity, uniquely employ hydrometallurgical technologies. This is largely a reflection of lateritic operations utilizing HPAL processes. Uniquely, Terrafame employs novel biometallurgical technology in conjunction with hydrometallurgical technology (Gericke et al., 2022; Riekkola-Vanhanen, 2013).

The metallurgical technologies employed by the preceding value chain operations of four operations could not reasonably be determined. Nevertheless, each operation employs hydrometallurgical technologies as part of the terminal processing operation. Two such operations, Vedanta's Nicomet operation and Jervois' São Miguel Paulista Refinery, are currently under care and maintenance and are not processing feedstock (Jervois, 2020; Vedanta, 2022). Alternatively, the Sandouville operation was acquired by Sibanye Stillwater in 2021. The change in ownership has resulted in uncertainty regarding forerunning feedstock sources and, in turn, metallurgical processes (Sibanye-Stillwater, 2021a). Finally, while currently operating, Yantai Cash publishes limited publicly accessible information on the provenance of its feedstock, prohibiting the ability to determine its value chain accurately.

4.2.13 Target Metal

The multi-metal nature of ores presents unique challenges for midstream metallurgical operations from both technical and economic perspectives. Notably, the concentration of metals in an ore and the price of metals have a great impact on the extent to which metals are extracted. For nickel operations extracting nickel as a by-product, namely operations targeting PGMs, this matter is particularly acute as price fluctuations in by-product or the primary metal can limit the extent to which a metal is extracted from an operation (McNulty & Jowitt, 2021). Therefore, understanding the primary metal, or metals, targeted during an operations is critical to understanding the susceptibility of nickel supply relative to alternative metals.

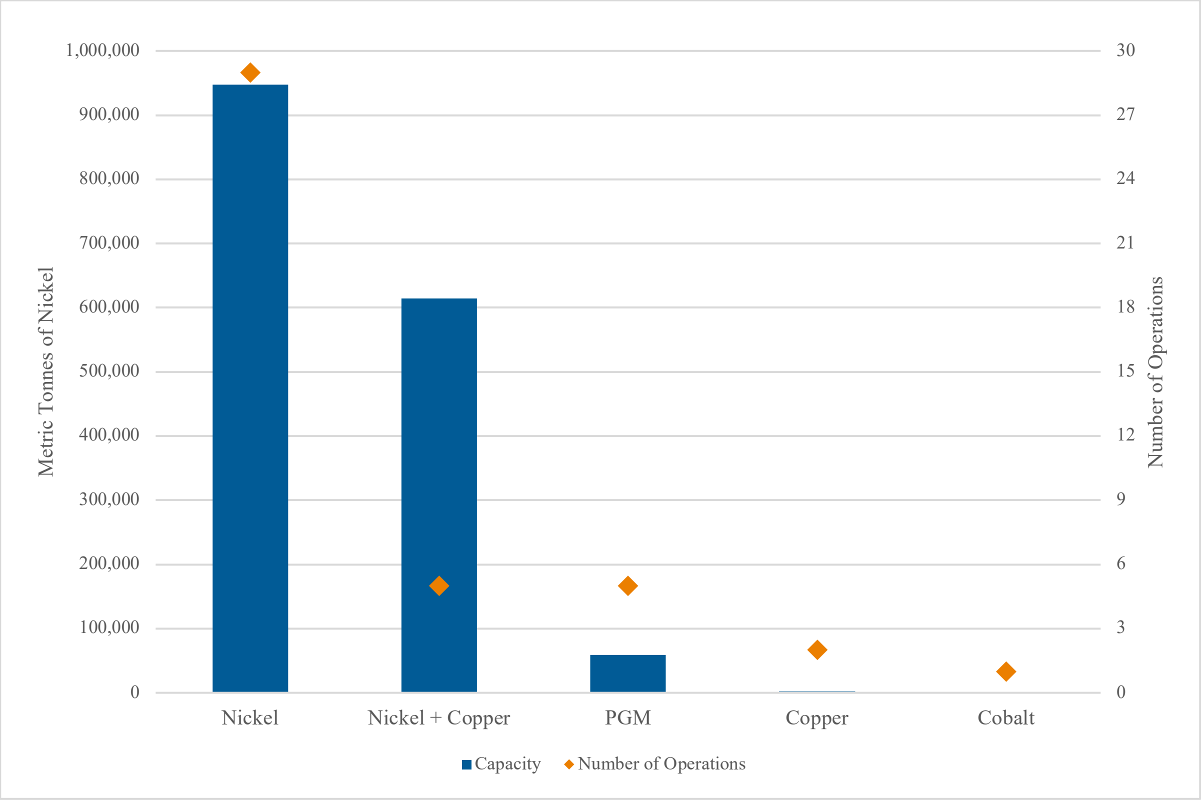


Figure 4-19: Metallurgical Capacity and Number of Operations by Targeted Metal

As can be seen from Figure 4-19, the majority of operations target either exclusively nickel or nickel and copper in tandem. A limited number of metallurgical capacity is associated with operations targeting alternative metals. The most prominent being operations targeting PGMs. Such operations are relatively small due to the lower concentration of nickel in the ore. In contrast, a nearly equivalent number of operations target nickel and copper but account for a disproportionately larger share of metallurgical capacity, suggesting greater concentration of nickel in processed feedstocks.

4.2.14 Nickel Products

Midstream metallurgical operations commonly produce several products of a given metal differentiable by disparities in characteristics such as form factor and chemical composition. While the capacity to produce a given metal is critical, understanding the characteristics of the products produced is equally as important when identifying supply chain bottleneck risks. This is exemplified by constraints imposed by processing requirements of downstream manufactures, specifically manufactures of highly technical applications, which limit the expanse of procurable products suitable to their respective operations.

4.2.14.1 Product Class

Industry adoption of an informal classification system for nickel products, as discussed in Section 1.5.5, gives rise to a highly fractured representation of available products. While historically such classification had aligned with the needs of a large fraction of downstream nickel consumers, such as those utilizing nickel for metallurgical applications, it potentially misaligns with the growing needs of burgeoning downstream consumers, namely battery consumers. Therefore, understanding the share of products produced by midstream metallurgical operations according to historical classifications standards can support the identification of potential supply chain bottleneck risks.

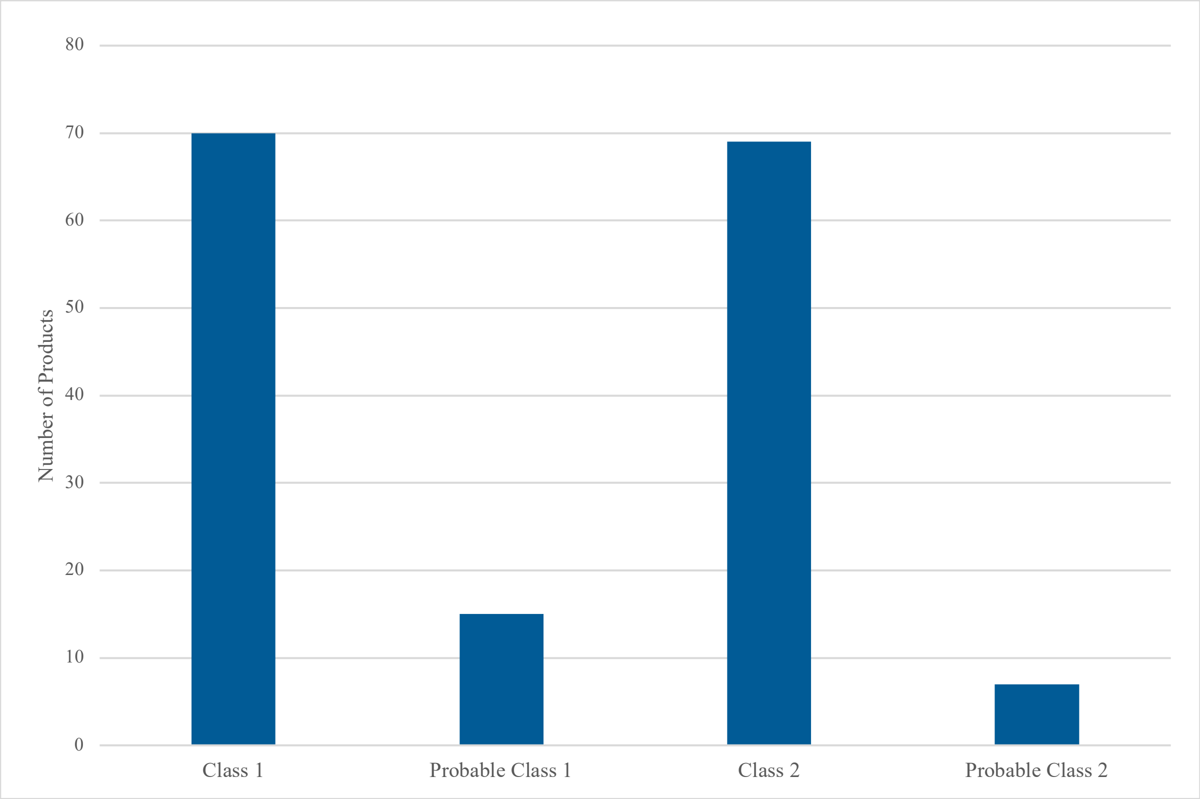
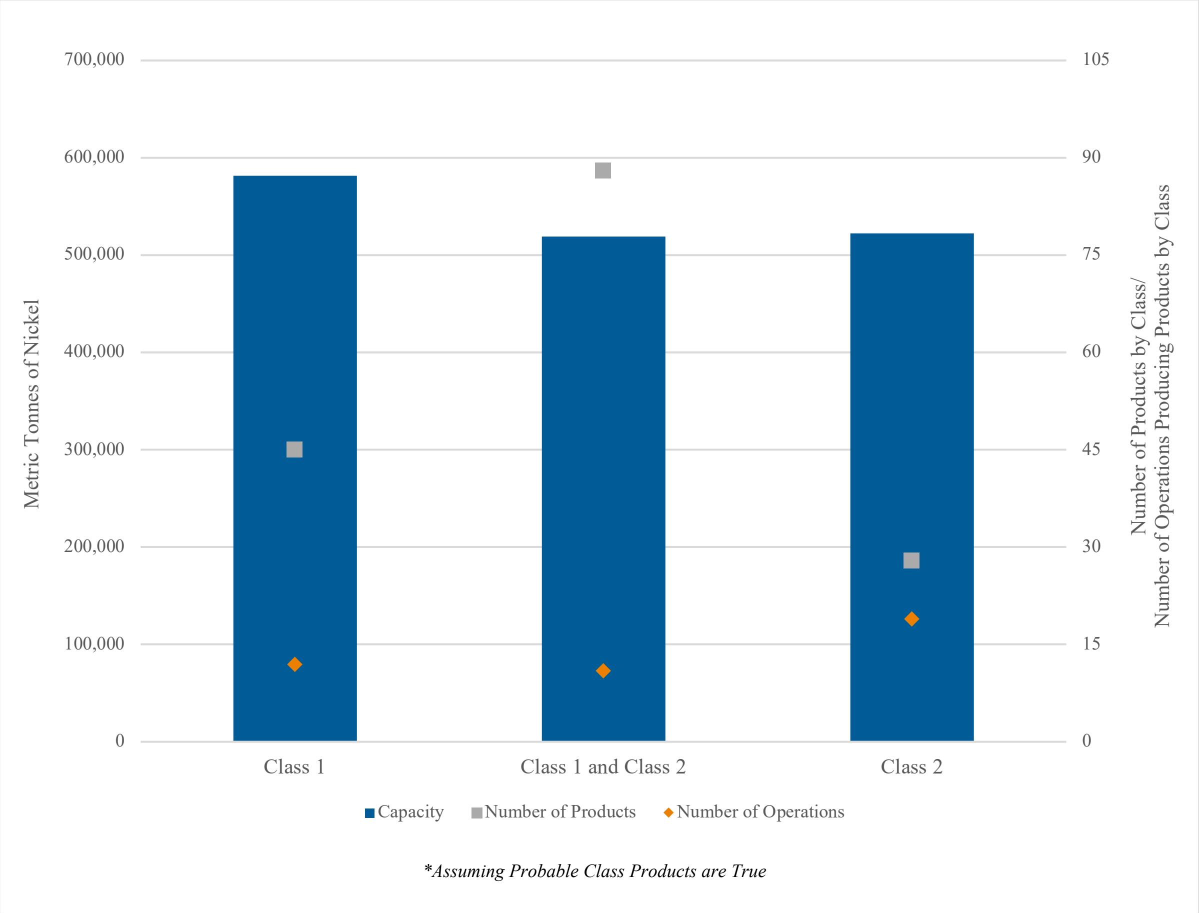


Figure 4-20: Number of Products by Class

Figure 4-20 demonstrates that a nearly equivalent number of products are attributed to each product Class. While such symmetry suggests a diversified downstream consumer base, the inability to associate production capacity to each individual product inhibits the ability to conclude the market share by Class. Assuming probable product classifications are valid, it is possible to equate the metallurgical capacity of each facility to a respective Class, or a combination thereof, given the output products of the facility.



**Assuming Probable Class Products are True*

Figure 4-21: Metallurgical Capacity, Number of Operations, and Number of Products by Product Class

Figure 4-21 demonstrates that a uniform distribution across categories and a combination thereof persist, suggesting considerable variation in product Class capacity. Nevertheless, the persistent inability to associate metallurgical capacity with specific products could lead to significant skewness in the available supply of products across distinct product categories.

4.2.14.2 Product Nickel Content

The range of nickel products produced across midstream metallurgical operations, specifically as it relates to product class, form factor, and chemical composition, gives rise to products with varying degrees of nickel content. For downstream applications, the nickel content of a product is of critical importance, most notably for high-value applications such as non-ferrous alloys and plating, as discussed in Section 1.5.5. Therefore, assessing products in relation to their respective nickel content can provide valuable insight for downstream users.

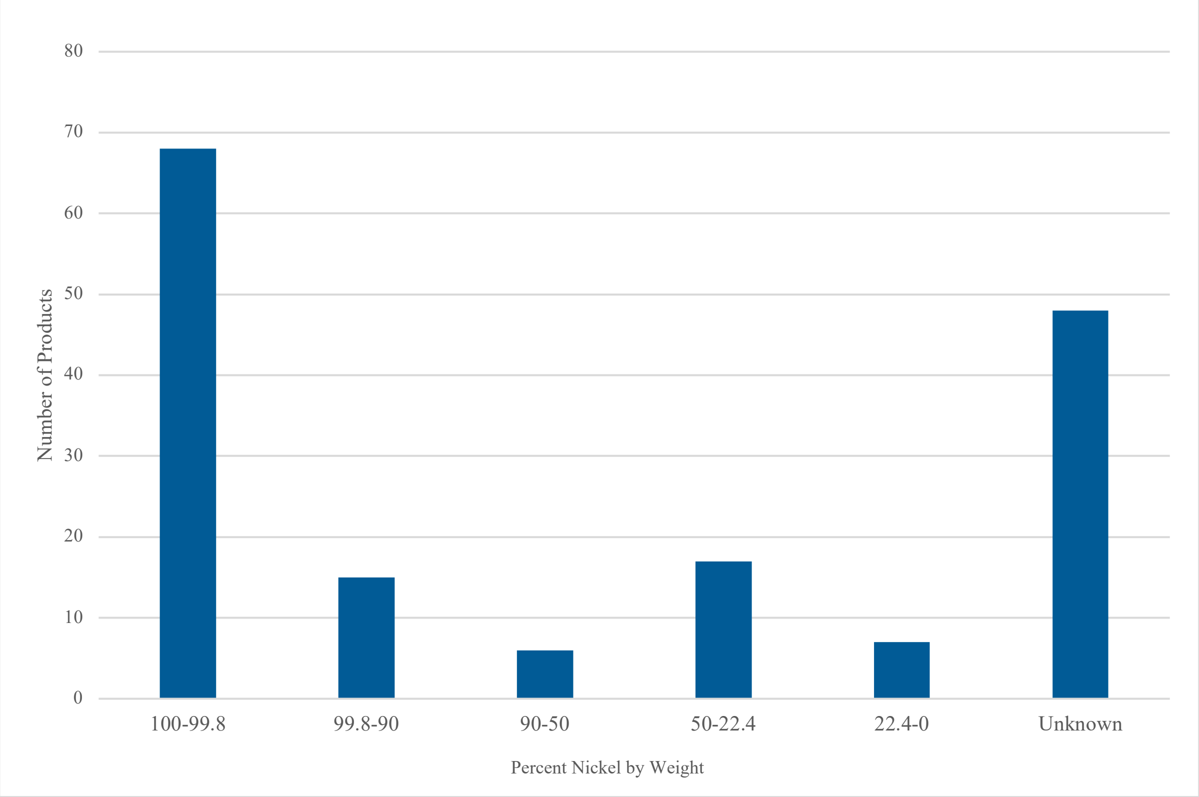
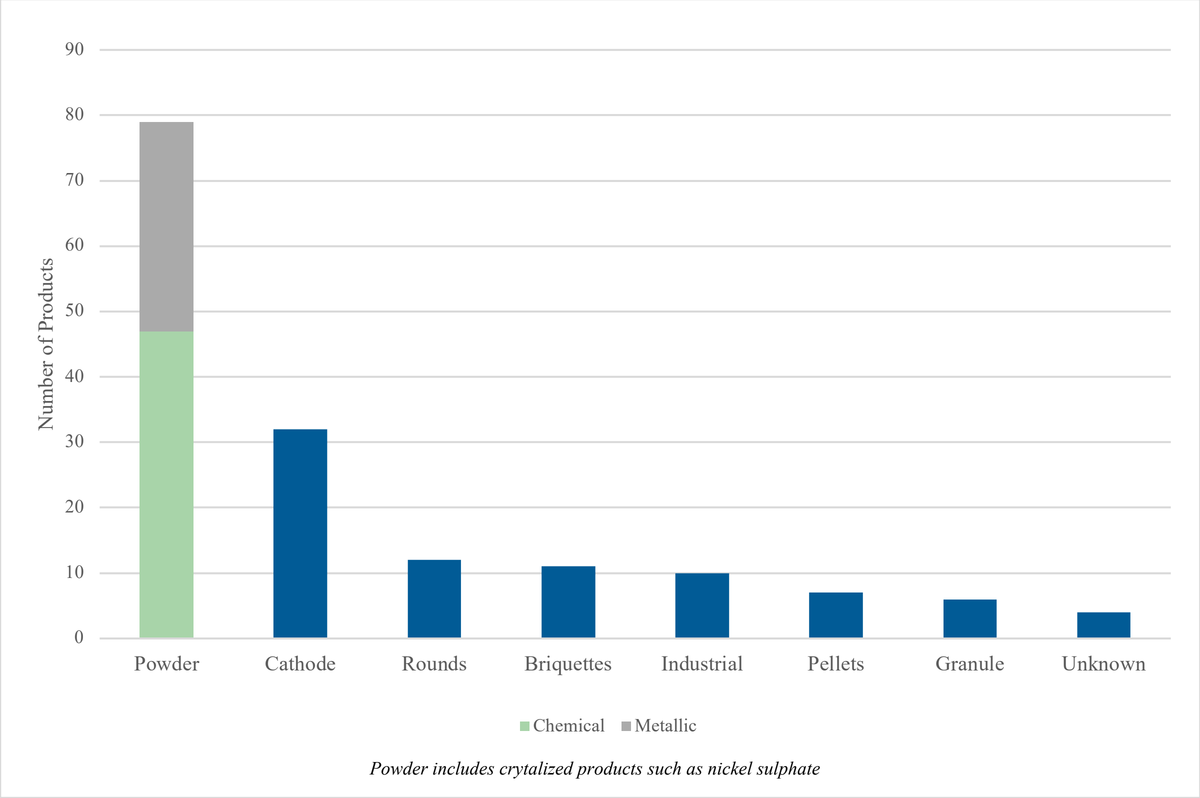


Figure 4-22: Number of Products by Nickel Content per Stratum

Of the 161 products evaluated, the nickel content of 113 could reasonably be determined. As demonstrated in Figure 4-22, the majority of nickel products for which nickel content is reported contain greater than 99.8% nickel by weight. This can largely be attributed to historical industry classification methods and LME specifications for deliverable nickel products, as discussed in Section 2.2.4 and outlined in Appendix A. Of products with reported nickel content below Class 1 thresholds, the range with the highest number of products is 50-22.4%. This category broadly includes products with chemicals such as nickel chloride or nickel hydroxide.

4.2.14.3 Product Form Factor

A critical consideration for downstream metals consumers relates to the form factor in which metal products are available. Downstream process constraints can significantly limit acceptable form factors of distinct metal products. This matter is particularly acute for nickel products, as products with equivalent or nearly equivalent chemical compositions can readily be procured in several distinct product form factors. Nickel products of equivalent quality but distinct form factors are potentially unique to a given downstream process and readily substitutable. For example, superalloy manufacturing processes often require high-purity nickel products; however, vacuum induction melting processes utilize master ingots and powder form factors, while additive manufacturing processes are restricted to powder form factors (Akca & Gürsel, 2015; P. Davies et al., 2003; deBARBADILLO, 1983; Holt & Wallace, 1976). Thus, careful consideration of the product form factor is necessary to ensure compliance with downstream processes.



Powder includes crytalized products such as nickel sulphate

Figure 4-23: Number of Products by Form Factor

Figure 4-23 demonstrated that many nickel products are available as powders, which includes products advertised as crystals. Nevertheless, when further analyzing powder products, many powder products are chemicals, such as nickel sulphates and nickel chlorides, while a smaller fraction are metallic powders. When further assessing nickel metal powders, a significant fraction of the sub-group comprises numerous carbonyl powders exhibiting nearly identical chemical compositions and particle size distributions with minimal variability between product characteristics. Such similarity amongst carbonyl-derived powder nickel products inflates the form factors market share. More specifically, 122,400 metric tonnes of nickel carbonyl capacity was identified across the supply chain[5], accounting for approximately 7% of metallurgical capacity.

Alternatively, several products are in the form of cathode or cathode cuts, highlighting the importance of electrowinning refining technology. In contrast, a limited number of operations produce briquettes and granules, which are preferred form factors amongst stainless steel manufactures.

4.2.14.4 Product Chemical Composition

Downstream demand requirements coupled with metallurgical processing technologies employed by midstream operations give rise to a variety of metal products with unique chemical compositions. While numerous metals are transformed into products proclaiming near purity, countless products are equally created with distinct chemical compositions. This is particularly true for nickel as Class 1 thresholds necessitate products be refined to their respective metallic state. However, alternative downstream applications have expanded demand for nickel products with specific metal compositions. This is particularly true for battery applications as they generally require nickel sulphate products, as discussed in Section 2.2.5.

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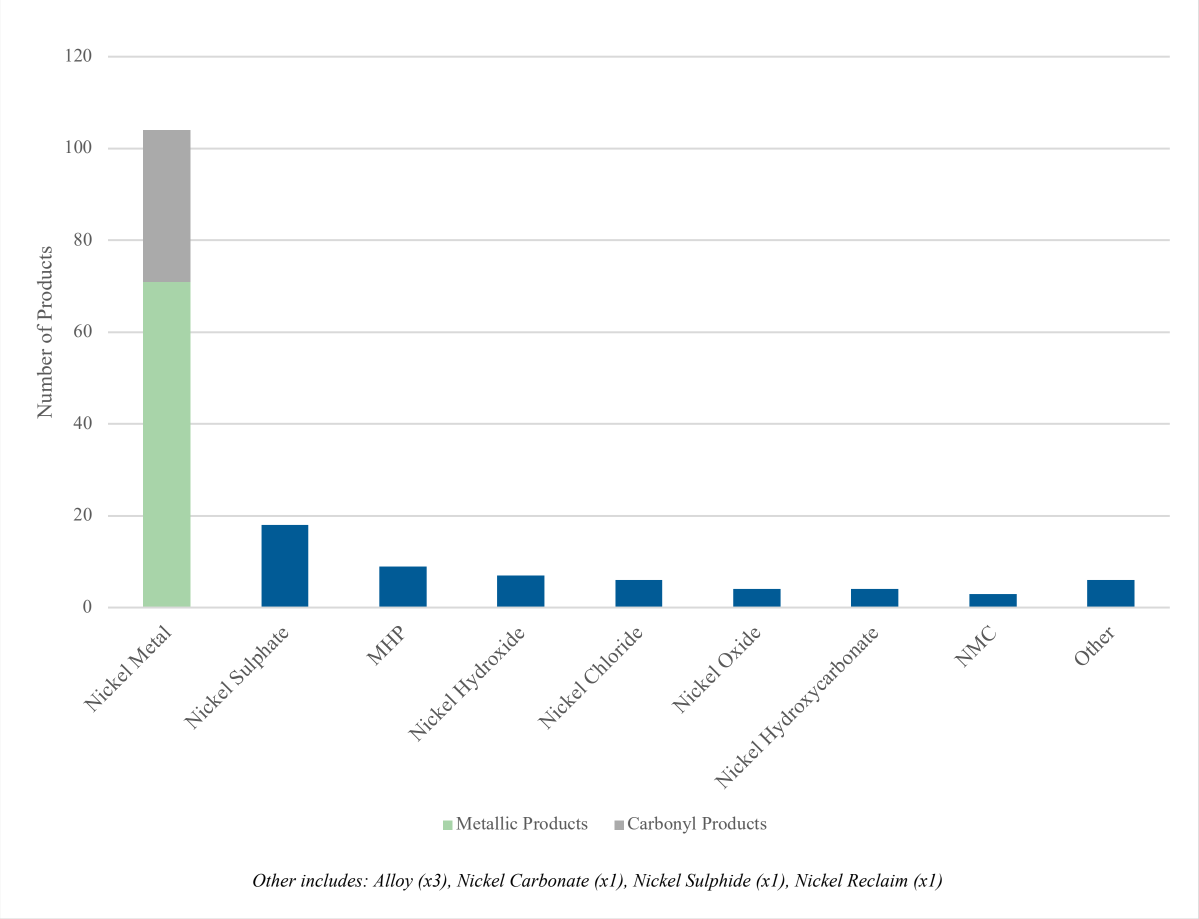
[5] Five operations possess carbonyl refining capabilities: (1) Vale’s Copper Cliff Nickel Refinery operation with 66,000 tpa (Vale, 2022e), (2) Vale’s Clydach Refinery operation with 40,000 tpa (Vale, 2022e), (3) Jinchuan’s operation with 10,000 tpa (Jinchuan Group, 2022c), (4) Nornickel’s Kola Peninsula operation with 4,400 tpa (Nornickel, 2020), and (5) Jilin Jien’s operation with 2,000 tpa (Koehler, 2015).



Other includes: Alloy (x3), Nickel Carbonate (x1), Nickel Sulphide (x1), Nickel Reclaim (x1)

Figure 4-24: Number of Products by Chemistry

Figure 4-24 illustrates that most products are in metallic form. Of the 104 metallic products, 33 are derived from carbonyl processes and exhibit minor deviations in chemical compositions and particle size distribution. The insignificance of the deviations once more exaggerates the prominence of the category. In contrast, 71 products are metallic, primarily in cathode, rounds, briquettes, pellets, and granule form factors. Of chemical products, the majority are in the form of nickel sulphate, extending to the chemical's utility in plating and battery applications.

4.2.14.5 Product Application

The unique supply and demand relationship amongst midstream operators and downstream consumers supports efforts to maximize the efficient production of particular metal products. Considering the numerous nickel products produced across midstream metallurgical operations, each with distinct characteristics, it can be reasonably assumed that each product is produced for a unique application or amenable to a limited number of applications. Analysing the primary advertised application of nickel products by midstream metallurgical operations is critical to understanding the available supply for discrete downstream demand applications.

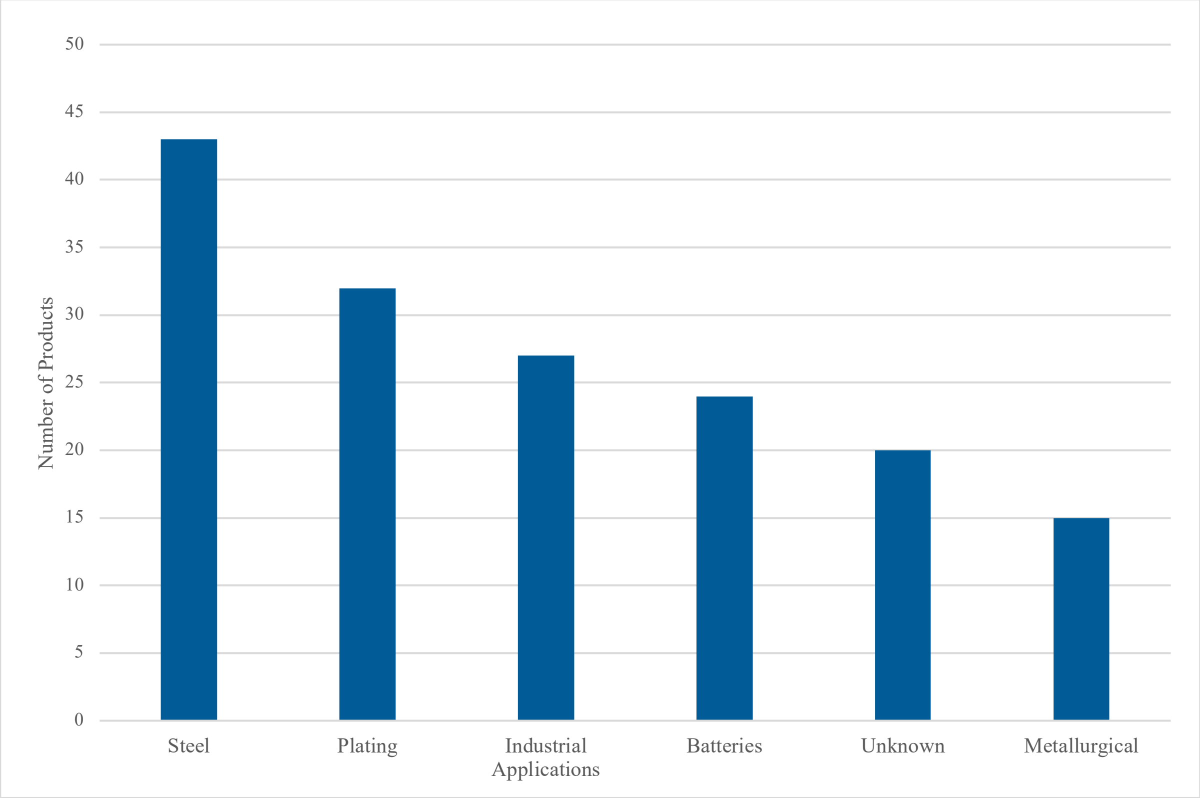


Figure 4-25: Number of Products by Advertised Application

As can be seen in Figure 4-25, the majority of products are advertised toward steel applications. This is likely the result of the application being the primary demand driver of nickel. Alternatively, products advertised for plating and metallurgical applications account for a sizeable fraction of available products. Similar to products advertised for steel, this can be attributed to the application's historical demand for nickel. In addition, a sizeable fraction of nickel products are intended for battery applications suggesting a novel response to predict growth in demand for nickel from the segment, as discussed in Section 4.3.2.

4.2.15 Battery Potential

Predicted growth in demand for nickel stemming from battery applications coupled with the application's stringent requirements for deleterious elements, form factor, and composition gives rise to unique challenges when assessing available supply. While assessing the number of products advertised towards battery applications provides insight into the potential availability of products assumed to be compatible with battery processes, numerous alternative products possess the underlying characteristic necessary for battery processes. These products can, in turn, be converted into the requisite form with minimal subsequent processing requirements, predominantly using established technologies. Most notably, this is achieved by the ability to dissolve Class 1 nickel products into nickel sulphate (Haegel, 2018; Vale, 2022d).

Figure 4-26: Metallurgical Capacity by Battery Potential

As can be seen in Figure 4-26, a significant fraction of metallurgical capacity can reasonably be applied to battery applications, as defined in Section 3.5.16. Facilities included in the category produce either exclusively nickel products advertised towards battery applications, such as nickel sulphates and MHP products, or LME-grade nickel products. A considerable portion of metallurgical capacity could partly be compatible with battery processes. Included facilities generate an array of nickel products with variable characteristics, whereby a fraction of produced products are compatible with battery applications.

The lack of data regarding the characteristics of nickel products produced at a limited number of assessed facilities restricts the ability to conclude their aptitude to satiate battery applications. As such, a small fraction of metallurgical capacity was determined to be potentially compatible with battery applications. Facilities included in this category exhibit limited capacity as nickel is generally produced as a by-product. Alternatively, the products produced at six facilities do not exhibit suitable characteristics for battery applications as they generally produce lower-quality nickel products intended for stainless steel applications.

4.2.16 Cobalt and Copper By-Product

Multi-metal ores are endemic to nearly every mineable metal deposit. The extent to which metals co-occur within a given ore body varies significantly. Similarly, the extent to which metals are extracted and transformed into functional products from multi-metal ores is directly related to the economic and technical viability of upstream and midstream metallurgical operations. Such relationships are eminently acute to both lateritic and sulphide nickel ores, as discussed in Appendix A. Understanding the extent to which metals are co-produced as part of nickel midstream metallurgical operations can further clarify the complexity of historically nuanced and opaque supply chains. A lack of reporting concerning the production of other metals in relation to nickel, most notably the production of minor metals, impeded the comprehensiveness of the metals assessed.

Two metals produced and readily reported on by nickel midstream metallurgical operations are cobalt and copper. While cobalt is produced in substantial volumes from both lateritic and sulphide deposits, copper, is nearly exclusively produced from sulphide deposits.

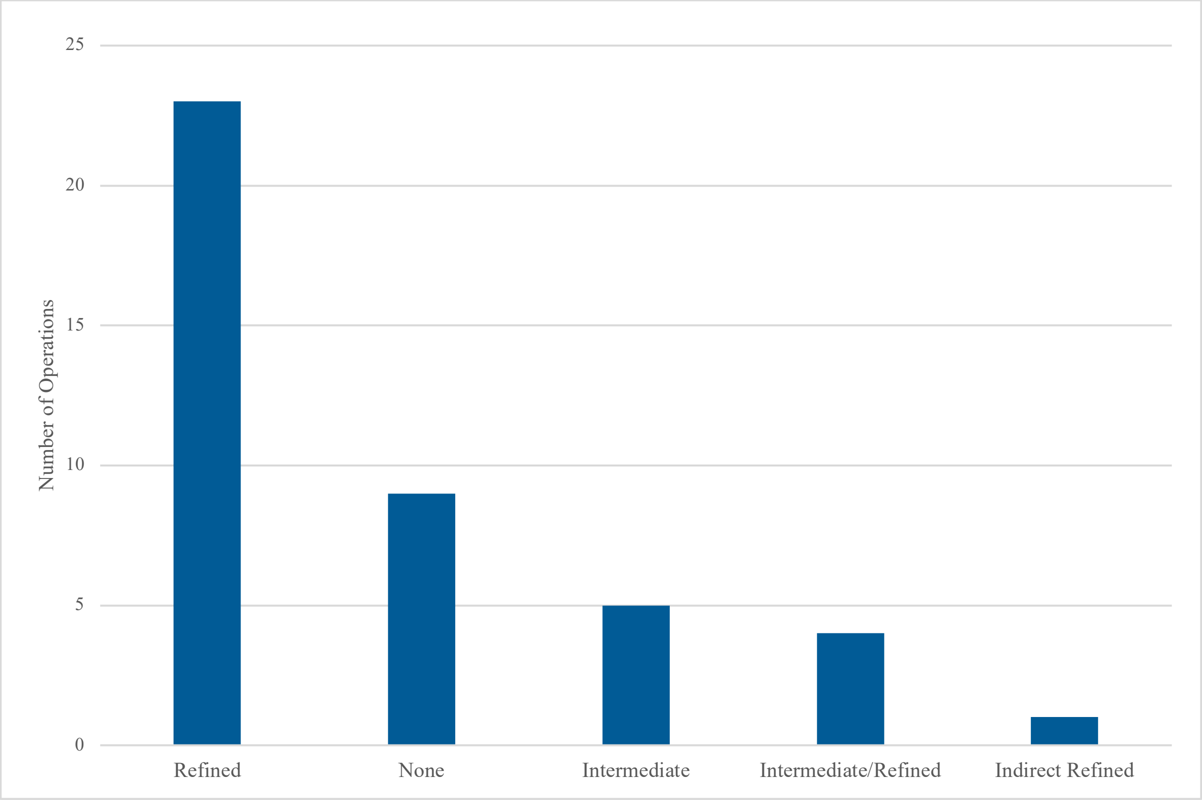


Figure 4-27: Number of Operations Producing Cobalt By-Products

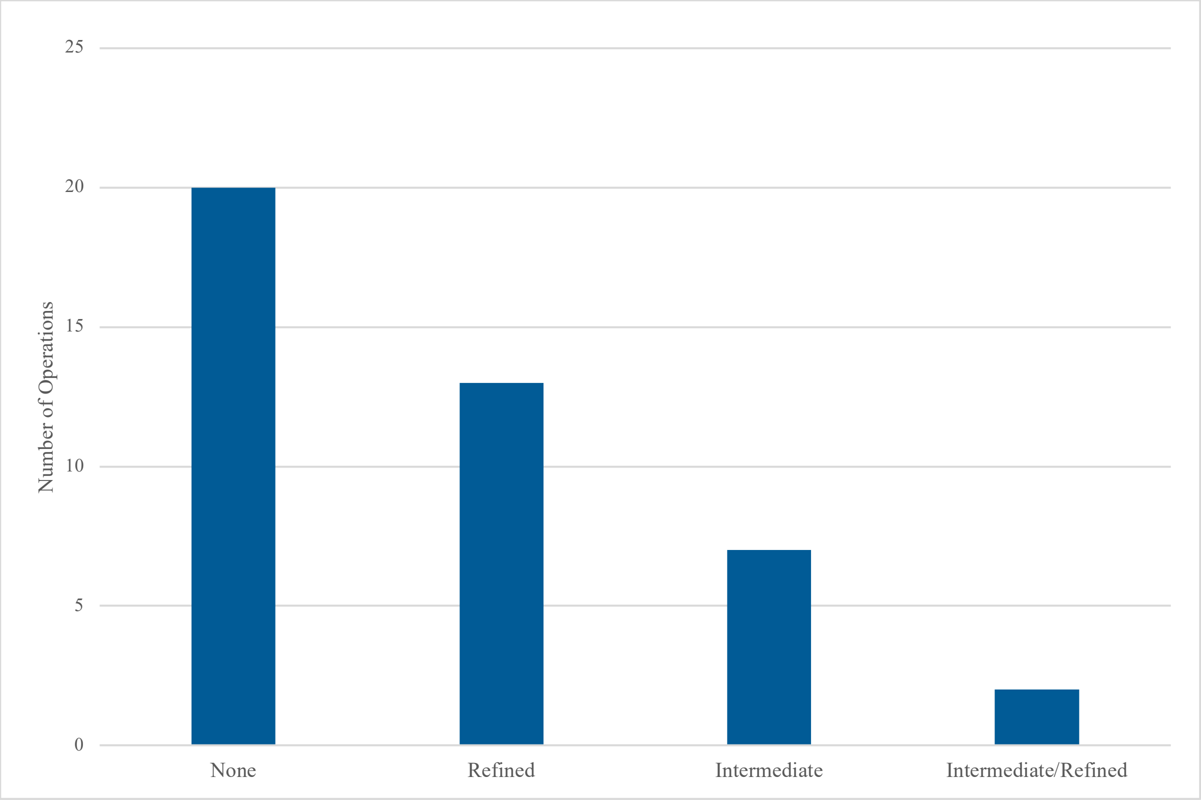


Figure 4-28: Number of Operations Producing Copper By-Products

Figure 4-27 demonstrates a count of nickel midstream metallurgical operations reporting cobalt production across their midstream value chains, while Figure 4-28 demonstrates a count of nickel midstream metallurgical operations reporting copper production across their midstream value chains. As can be seen in Figure 4-27, the majority of nickel midstream metallurgical operations produce cobalt products in some capacity. Such phenomena is primarily owed to the occurrence of cobalt in laterite and sulphide deposits. In contrast, a smaller fraction of nickel midstream metallurgical operations produce copper products in some capacity. The discrepancy between the production of cobalt and copper amongst operations lends to insufficient occurrences, or lack thereof, of copper in laterite deposits (Crundwell et al., 2011).

While the discrepancy in the number of operations producing cobalt and copper is notable, an equally, albeit inverse, discrepancy is exhibited when assessing the production capacity associated with each metal for the given operations and their value chains.

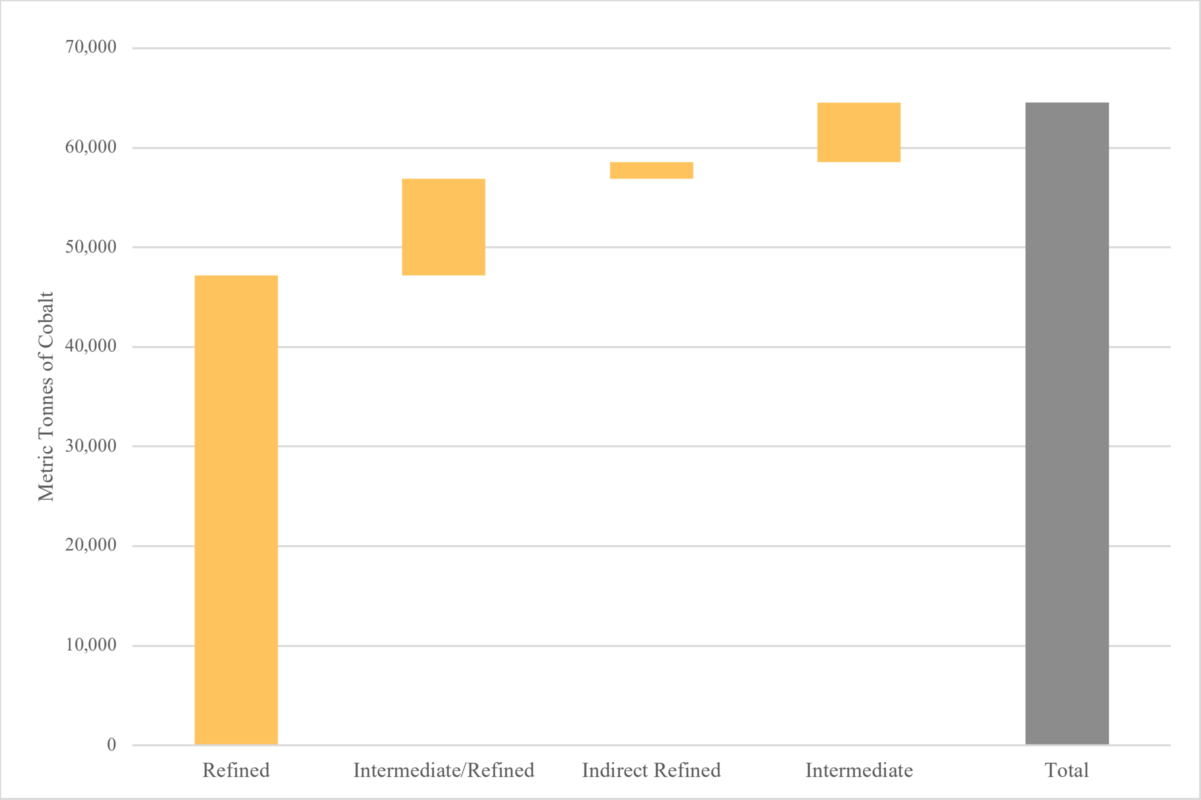


Figure 4-29: Reported Annual Capacity of Cobalt By-Products Among Reporting Producers

Figure 4-29 presents the reported cobalt production capacity of across the midstream value chains of nickel operations. Of the 33 facilities with midstream value chains producing cobalt, the cobalt production capacity of 20 facilities could reasonably be determined across their value chains. Of included reporting value chains, 64,555 tonnes of cobalt production capacity in the form of refined or intermediate products was identified. The figure represents a lower bound of available production capacity associated with nickel midstream value chains, as facilities withholding cobalt capacity figures are likely to contribute significant quantities. Additionally, it should be noted that for intermediate producers, recovery rates incurred during refining processes are not accounted, likely reducing, albeit marginally, extractable quantities of cobalt (Dehaine et al., 2021). The significance of cobalt production in relation to nickel is best exemplified by Indonesia's rise as the second largest producer of cobalt in 2022, in part due to novel nickel HPAL operations (Cobalt Institute, 2023).

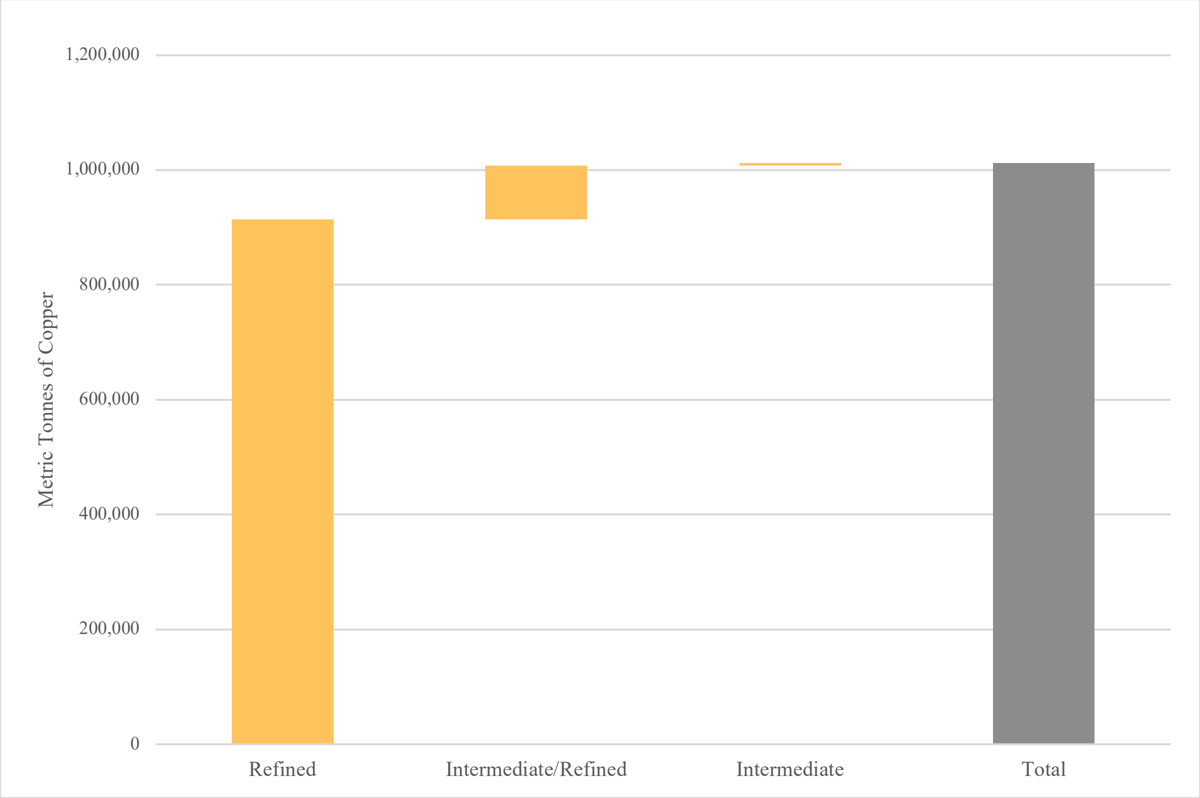


Figure 4-30: Reported Annual Capacity of Copper By-Products Among Reporting Producers

Figure 4-30 presents the reported copper production capacity across the midstream value chains of nickel operations. In contrast to cobalt, the number of facilities reporting copper production is smaller, although associated production capacity is greater than that of cobalt. Of the 22 facilities with midstream value chains reporting copper production, the production capacity of 11 could reasonably be determined. In all, the 11 facilities account for 1,012,125 tonnes of copper production capacity. Such disproportional production capacity can largely be attributed to operations processing sulphide ores with significant concentrations of both copper and nickel.

4.2.17 Carbon Neutrality Commitments

Reducing the environmental footprint of products and services is significant to an increasing number of stakeholders. Given the notable environmental impacts associated with midstream metallurgical operations and their importance in supplying critical materials for clean technologies, concerns regarding the influence of associated impacts on the sustainability of downstream applications have been of significant concern (London Metal Exchange, 2020). As a result, carbon-neutral commitments by owners of midstream operations, to reduce the impact of their operations, are tallied, as illustrated in Figure 4-31.

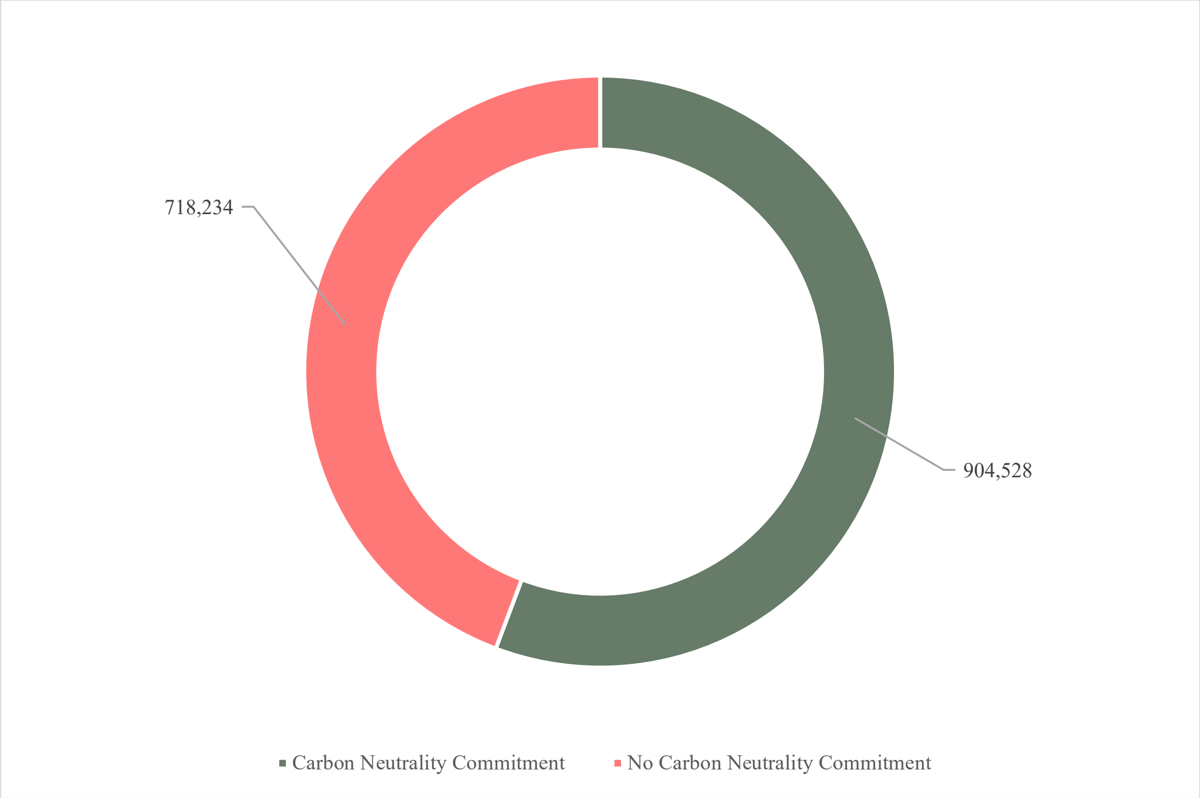


Figure 4-31: Metallurgical Capacity by Carbon Neutrality Commitments

As can be seen, the majority of companies with metallurgical capacity have established carbon neutrality targets. The expected timeline for to achieve these carbon neutral targets is relevant when modeling future impacts of nickel products, as illustrated in Figure 4-32.

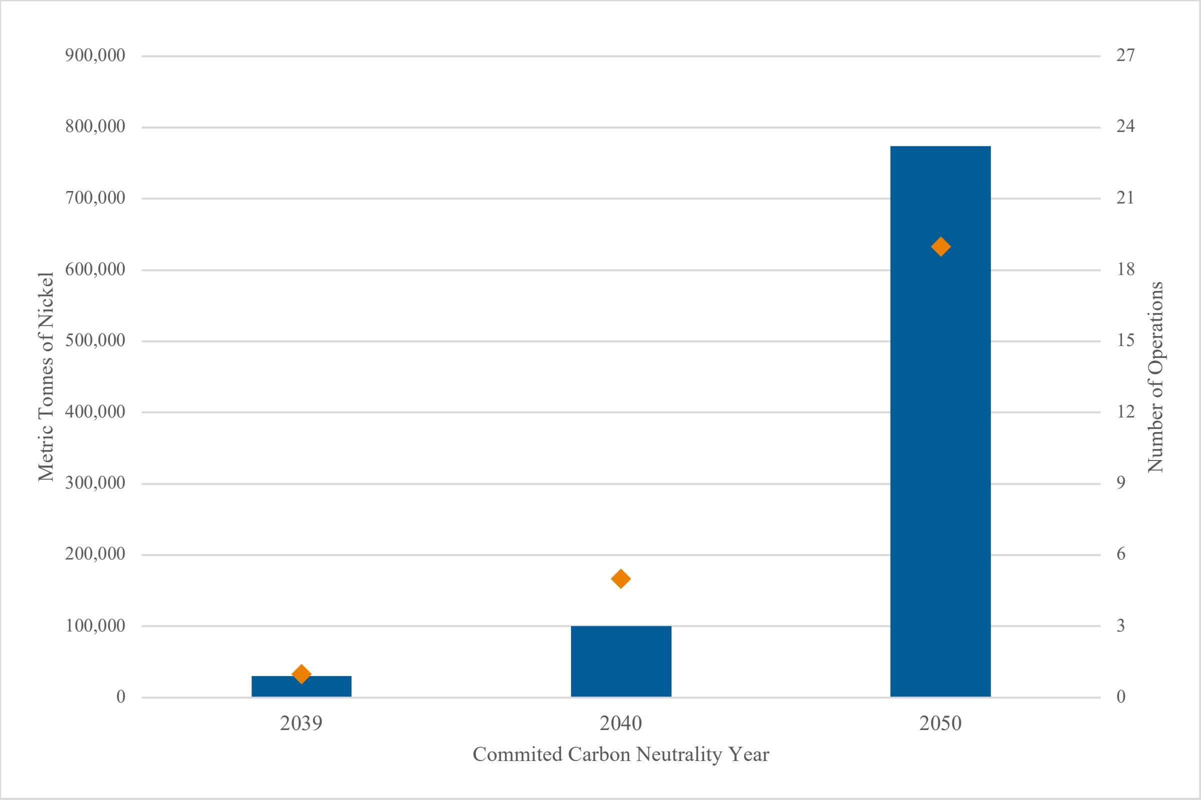


Figure 4-32: Metallurgical Capacity and Number of Operations by Carbon Neutrality Commitments

Most companies target 2050 as the year to achieve carbon neutrality, which aligns with international sustainability accords, such as the 2015 United Nation's Paris Agreement (United Nations, 2015). In contrast, a small fraction of commitments have more condensed timeframes, with operations intending to reach their goals by 2039 or 2040.

4.3 Case Study Questions

The following section addresses the case study questions outlined in Section 1.7.

4.3.1 Primary Question – Metallurgical Capacity and Bottlenecks

Primary Question: *What is the current primary global nickel processing capacity for the production of non-ferrous nickel products, and what bottlenecks exist to expanding capacity?*

Answer: The primary global nickel processing capacity was assessed through the metallurgical capacity and determined to be 1,622,762 metric tonnes of nickel production capacity in 2021. While the metallurgical capacity provides valuable insight into the annual production capacity, it provides marginal insights into bottlenecks prohibiting capacity expansion. In contrast, through detailed assessment of midstream operations, it was conceivable to identify potential bottlenecks to expanding capacity. Potential bottlenecks to burgeoning capacity are further explored throughout Section 5.4.

4.3.2 Sub-Question 1 – Current State of the Market

Question: *What is the current state of non-ferrous nickel products in terms of production capacity, composition, quality, form factor, and indented end-use application?*

Answer: A significant shortfall of the case study was the inability to associate production capacity with specific output products for a given operation. The aggregated nature of reported production capacity necessitated generalized associations of product output and production capacity, as discussed in Section 4.2.14. As evidenced, the majority of capacity is oriented towards metallurgical applications, including stainless steel, non-ferrous alloys, and plating. This includes products with characteristics suitable for downstream metallurgical applications, such as Class 1 nickel cathodes, briquettes, rounds, and carbonyl powders.

While most of the products, and likely in turn capacity, are oriented towards metallurgical applications, a notable trend in operations targeting battery applications persists, likely in response to the predicted growth in demand from battery applications. The trend is particularly acute amongst operations established since 2007.

Table 4-1: Operations Established Since CY2007

Operation	Country	Capacity (Tonnes of Nickel)	Year of Establishment	Process	Product Type	Primary Application
Ravensthorpe Nickel Operation	Australia	30,000	2007	HPAL	MP	Batteries
Dalian	China	32,000	2008	Pyro	Granule	Steel
Goro	New Caledonia	44,000	2009	HPAL	MP	Batteries
Ambatovy	Madagascar	48,000	2011	HPAL	Briquettes	Steel
Ramu	Papua New Guinea	32,601	2012	HPAL	MP	Unknown
Long Harbour	Canada	50,000	2013	PAL	Rounds	Steel
					Rounds	Steel
					Rounds	Plating
Harima Refinery	Japan	10,780	2014	HPAL, SX	Nickel Sulphate	Batteries
Terrafame	Finland	30,000	2008	Bio	MP	Unknown
					Nickel Sulphate	Batteries
Gordes Meta Nickel Cobalt Facility	Turkey	20,000	2016	HPAL	MP	Unknown
Huayue Nickel and Cobalt	Indonesia	60,000	2021	HPAL	MP	Batteries
PT Halmahera Persada Lygend	Indonesia	35,500	2021	HPAL	MP	Unknown
					Nickel Sulphate	Batteries
Skouriotissa	Cyprus	10,000	2021	HPAL	MP	Unknown
					Nickel Sulphate	Batteries

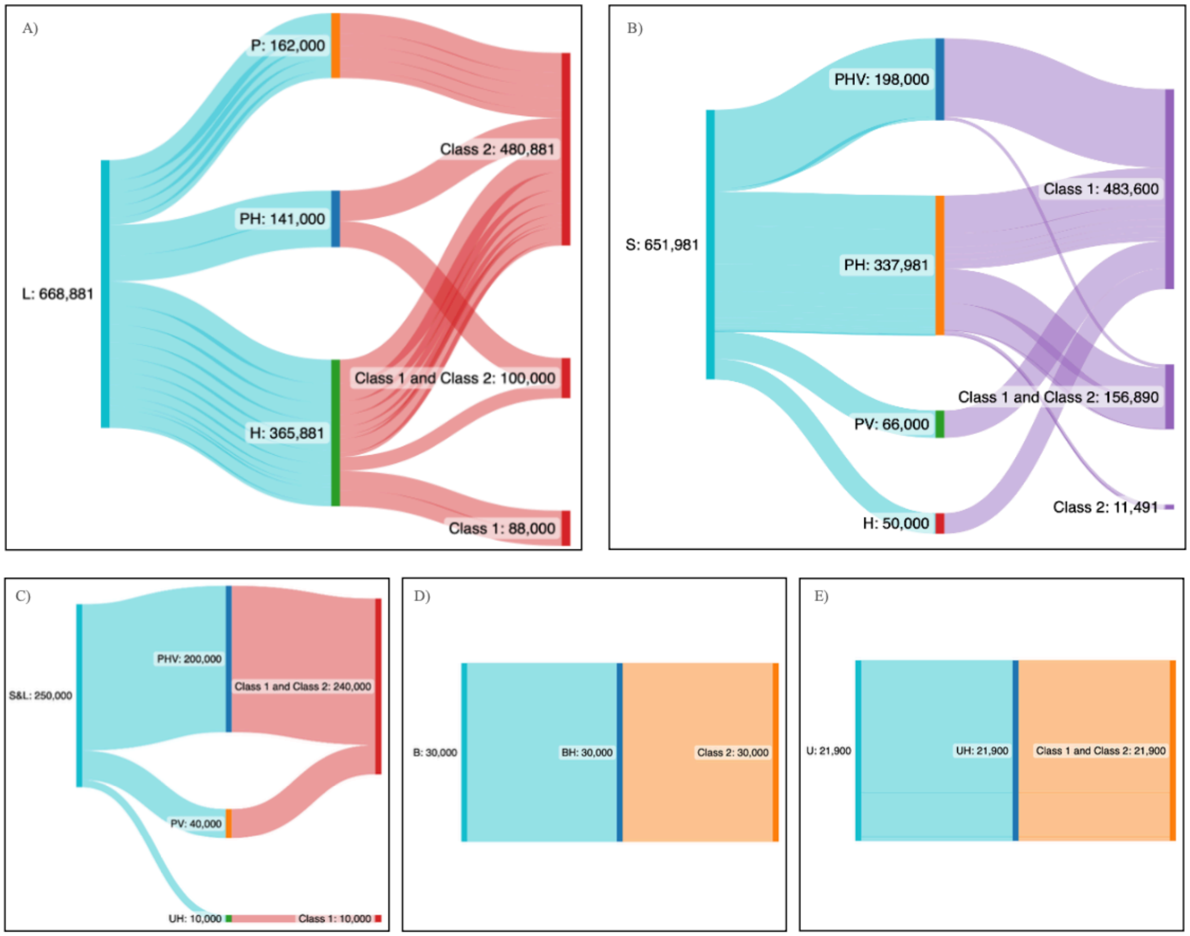
As seen in the Table 4-1, the majority of production capacity established during the period is oriented toward products marketed for battery applications. This amounts to approximately 55% of established capacity since 2007 oriented toward battery applications. The figure rises to 68% when considering Ramu and Gordes, which produce MP intermediate products that can readily be converted to battery precursor materials such as nickel sulphate.

In addition to recently established operations expanding into battery-suitable products, a similar trend has emerged amongst historic operations, which have added the capabilities to produce battery-oriented products. For example, BHP's Nickel West-Kwinana Refinery added a conversion plant designed to convert refined nickel powders into battery-grade nickel sulphate (BHP, 2021c). Alternatively, Sumitomo Metal and Mining's (SMM) Harima Refinery, which was initially established in 1966, was converted from a zinc refinery in 2014 to a nickel sulphate refinery (Sumitomo Metal Mining, 2015). Such conversions and expansions can reasonably be attributed to the predicted future demand for nickel sulphate.

4.3.3 Sub-Question 2 – Supply Chain Correlations

Question: *What is the correlation between ore type, processing technology, and product quality?*

Answer: The partitioned nature of nickel ores, processing routes, and product quality give rise to unique relationships amongst operational attributes. Understanding systemic relationships of these relevant attributes is vital to identifying potential bottlenecks. The correlations are particularly vital to understand given the discrepancy amongst outcomes of different pathways. For example, disparities in the relative abundance of laterite and sulphide ores, incongruities of processing technologies, and scarce ability to substitute nickel products with dissimilar qualities.



A) Laterite Feedstocks; B) Sulphide Feedstocks; C) Sulphide and Laterite Feedstocks; D) Black-Shale Feedstocks; E) Unknown Feedstocks

L: Laterite
S: Sulphide
S&L: Sulphide and Laterite
B: Black-Shale
U: Unknown

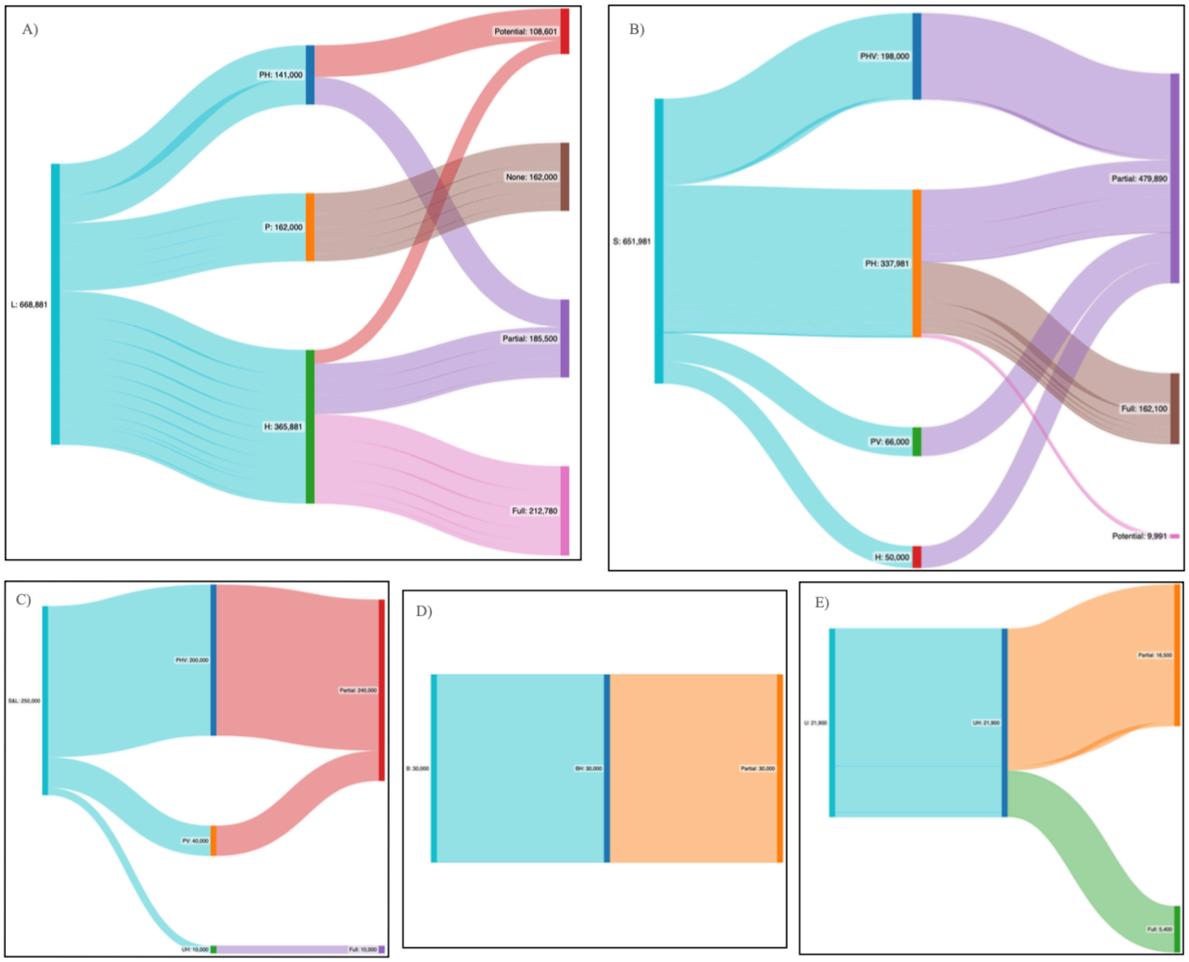
PH = Pyrometallurgical+Hydrometallurgical
PHV = Pyrometallurgical+Hydrometallurgical+Vapor Metallurgical
BH = Bio-Metallurgical+Hydrometallurgical
P = Pyrometallurgical
PV = Pyrometallurgical+Vapor Metallurgical
H = Hydrometallurgical
UH = Unknown+Hydrometallurgical

Figure 4-33: Metallurgical Capacity Correlated by Feedstock Ore Type, Metallurgical Technology, and Product Class

As can be seen in Figure 4-33, notable differences amongst ore type and product class persist. When comparing operations processing sulphide and laterite ore feedstocks, sulphide operations largely produce Class 1 products, whereas laterite operations primarily produce Class 2 products. This is likely attributed to the historical focus of sulphide operations on the production of LME deliverable nickel, as illustrated in Appendix C. In contrast, laterite operations, for which non-ferrous operations are a novel phenomenon, as illustrated in Figure 5-1 and Appendix C, primarily produce nickel chemicals, such as nickel sulphate or intermediate products, such as MP's.

An uneven dependence on specific processing technologies persists when assessing the correlations amongst processing routes and ore type. Operations processing sulphide ores demonstrate a high degree of reliance on the sequential combination of pyrometallurgical and hydrometallurgical technologies. This can be attributed to the historical dominance of smelting, electrowinning, and hydrogen-reducing technologies (Crundwell et al., 2011). In contrast, there is a nearly exclusive dependence on hydrometallurgical technology amongst laterite operations. This can be attributed to advancements in HPAL technology and its subsequent adoption amongst laterite operations (Gultom & Sianipar, 2020). This is further amplified by the decline of pyrometallurgical processes such as the Caron process, which exhibited high operating costs (Dalvi et al., 2004). Alternatively, operations producing nickel-ferrous products from laterite ores nearly exclusively rely upon pyrometallurgical processes, as described in Appendix A.

Considering the predicted growth in demand for nickel products sufficient for battery applications, understanding similar relationships as it relates to the ability of an operation to produce battery-suitable products is vital to identifying potential supply chain bottlenecks specific to the application. Particularly given the notable financial, technical, environmental, and social trade-offs between distinct processing routes.



A) Laterite Feedstocks; B) Sulphide Feedstocks; C) Sulphide and Laterite Feedstocks; D) Black-Shale Feedstocks; E) Unknown Feedstocks

L: Laterite
S: Sulphide
S&L: Sulphide and Laterite
B: Black-Shale
U: Unknown

PH = Pyrometallurgical+Hydrometallurgical
PHV = Pyrometallurgical+Hydrometallurgical+Vapor Metallurgical
BH = Bio-Metallurgical+Hydrometallurgical
P = Pyrometallurgical
PV = Pyrometallurgical+Vapor Metallurgical
H = Hydrometallurgical
UH = Unknown+Hydrometallurgical

Figure 4-34: Metallurgical Capacity Correlated by Feedstock Ore Type, Metallurgical Technology, and Battery Potential

As seen in Figure 4-34, lateritic operations producing products suitable for battery applications rely exclusively on hydrometallurgical technologies. This can be attributed to advancements in HPAL processes and their ability to produce products amenable to battery applications. In contrast, sulphide operations, for which the entirety of their production capacity could be attributed to battery applications, primarily rely upon the sequential combinations of pyrometallurgical and hydrometallurgical processes. A similar dependency on the technologies persists amongst sulphide operations for which a fraction of their products are suitable for battery applications.

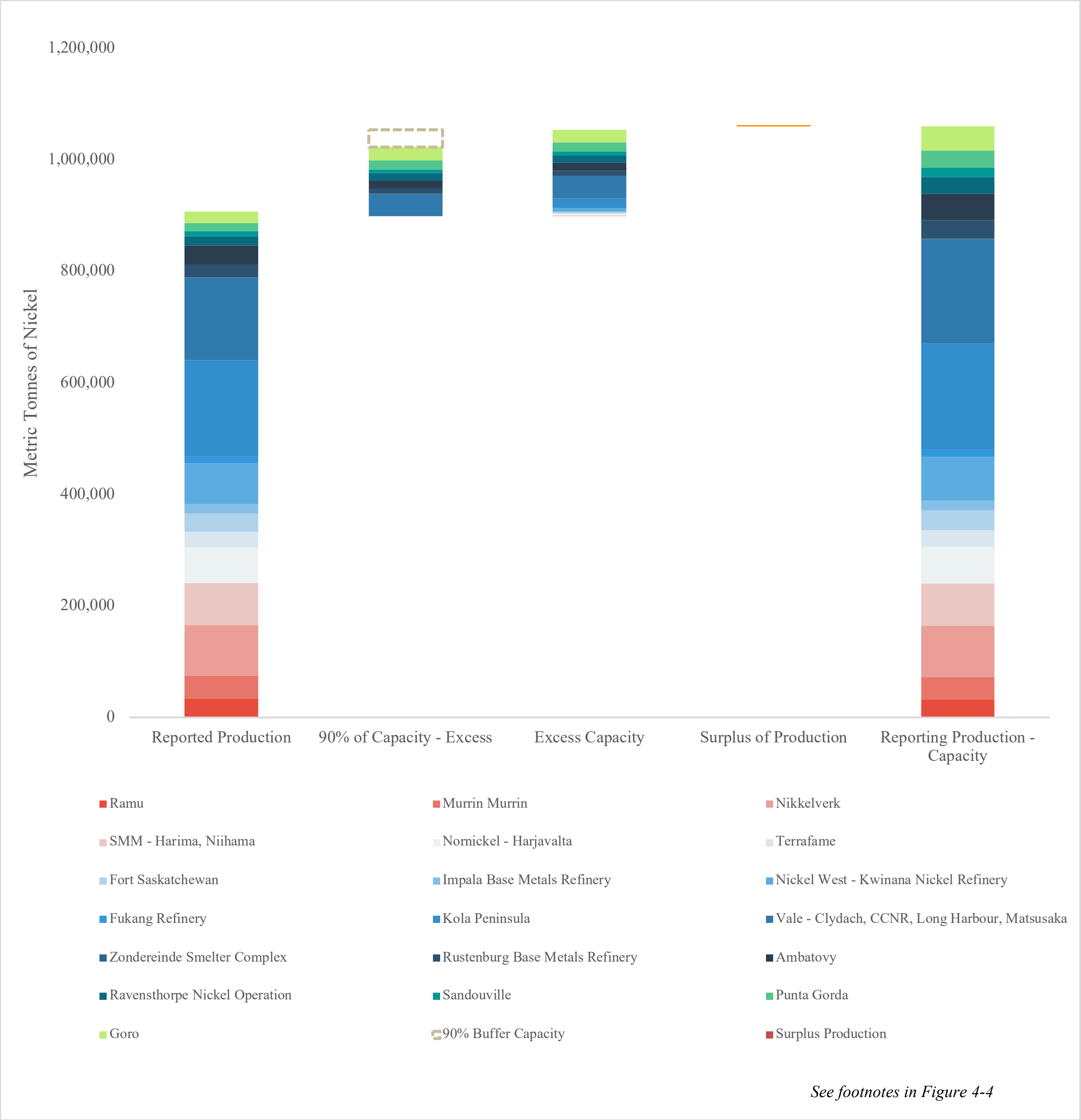
4.3.4 Sub-Question 3 – Available Spare Capacity

Question: *How much spare capacity remains dormant across operations?*

Answer: As demonstrated in Figure 4-4, of operating facilities reporting production volumes in 2021, approximately 155,000 metric tonnes of capacity remained undercapitalized. A nuanced assessment of such excess capacity is needed to assess the potential prospect of exploiting the dormant capacity.

An array of exogenous and endogenous factors can lead to a facility operating below nameplate capacity, as described in Section 4.2.4. As such, a facility's ability to process additional feedstock to operate at its nameplate capacity is contingent upon the operation's capabilities. This matter is further complicated when considering processing third-party feedstocks, as technical limitations of processing technologies could limit the substitutability of alternative feedstocks.

When analyzing excess capacity, the extent to which a facility operates at or near its nameplate capacity must be considered. For example, a facility operating at 98% of its nameplate capacity may be less disposed to process additional feedstock in contrast to a facility of equivalent size operating at 50% of its nameplate capacity. Additionally, operations with marginal nominal capacities, notably operations which produce nickel as a by-product, are likely less reluctant to process additional feedstock. In either case, the reluctance to process additional feedstock can result from the limited upside risk incurred from processing auxiliary feedstocks. Potential risks can be attributed to economic, environmental, or operational challenges in operating the necessary unit operations (Ndlovu, 2014). Thus, consideration of an individual facility's conditions is necessary when assessing the excess capacity amongst operational facilities operating below nameplate capacity.



See footnotes in Figure 4-4

Figure 4-35: Breakdown of Excess Capacity by Operation

As can be seen in Figure 4-35, when considering operations operating below 90% of their respective nameplate capacities, assumed to be a conservative estimate of an operation's willingness to process additional feedstocks, a considerable reduction in the portion of dormant capacity emerges. Of the 23 operations with reported production volumes below their nameplate capacity, 11 operated below the 90% threshold. When analyzing such facilities, the likelihood of leveraging the capacity is further reduced. Vale's operations, which required amalgamating due to the company's reporting methods, as discussed in Section 4.2.4, exhibited the largest relative excess capacity. While the efficiency of each operation is unknown, Long Harbour had still not yet achieved nameplate capacity and was still ramping up as of 2021 (Vale, 2021). Similarly, Vale's Copper Cliff Nickel Refinery has reported a lack of feedstock due to depleting mine production from local mines and labour disputes impacting its operation (Vale, 2020, 2022c). Further, the ability to assess the efficiency of Matsusaka and Clydach is limited, given their respective positions in the value chain and the company's aggregated reporting structure.

Of the remaining seven operations, three employ HPAL technologies. Of which one, Goro, had undergone ownership changes during the assessed period (Vale, 2022b), while another, Ravensthorpe, was recommissioned in 2020 (First Quantum, 2021a). Additionally, two operations rely on PGM feedstocks and have relatively marginal capacities. One facility, Punta Gorda, which is owned by the Cuban government, has been subject to considerable operational setbacks (R. Ferreira & Pinto, 2021). Finally, Sandouville, which possesses nominal capacity, underwent a change in ownership during the assessed period, likely impacting its production capability (Sibanye-Stillwater, 2021b). As such, exploiting undercapitalized capacity at the facilities is unlikely, with Sandouville exhibiting the most potential.

While limited excess capacity persists amongst operating facilities reporting production, limited excess capacity likely endures amongst non-reporting operating facilities. Notably, the largest operational non-reporting facility, Jinchuan's Nickel Operation, recently completed an expansion project increasing its nameplate capacity (Jinchuan Group, 2022d). As a result, it can be assumed that the facility had historically operated near its nameplate capacity, and the expansion indicates it expects to continue to operate near nameplate capacity. Nevertheless, a significant source of uncertainty regarding Jinchuan's operating potential is its ability to process and access third-party feedstocks as well as the share that third-party feedstocks account to production volumes relative to the company's mined production.

Of the six remaining operating non-reporting facilities established prior to 2021, they possess a cumulative metallurgical capacity of approximately 38,000 metric tonnes. The largest operation, Gordes Meta Nickel Cobalt, with a capacity of 20,000 metric tonnes, leverages HPAL technology and does not claim to process third-party feedstocks. The second largest operation of the group, Jilin Jien, has a capacity of 8,000 metric tonnes and, similar to Jinchuan, has announced plans to construct an expansion capable of producing 60,000 metric tonnes of nickel sulphate per year, or 13,200 metric tonnes of nickel assuming 22wt% Ni nickel sulphate, indicating limited excess capacity (Zhongze Group, 2023). The remaining four facilities produce nickel as a by-product and in relatively limited quantities, further limiting the ability to utilize excess processing capacity.

4.3.5 Sub-Question 4 – Supply Chain Monopolization

Question: *Are operations or product production capacity geographically concentrated or monopolized?*

Answer: The geographic concentration of metal deposits coupled with the capital, operational, and environmental barriers to building and operating midstream metallurgical facilities can yield geographically concentrated and monopolized supply chains. As demonstrated in Figure 4-5, midstream production capacity is relatively distributed amongst regions. Nevertheless, it is necessary to understand the geographic concentration and monopolization of capacity related to specific nickel products to identify potential supply bottlenecks more accurately.

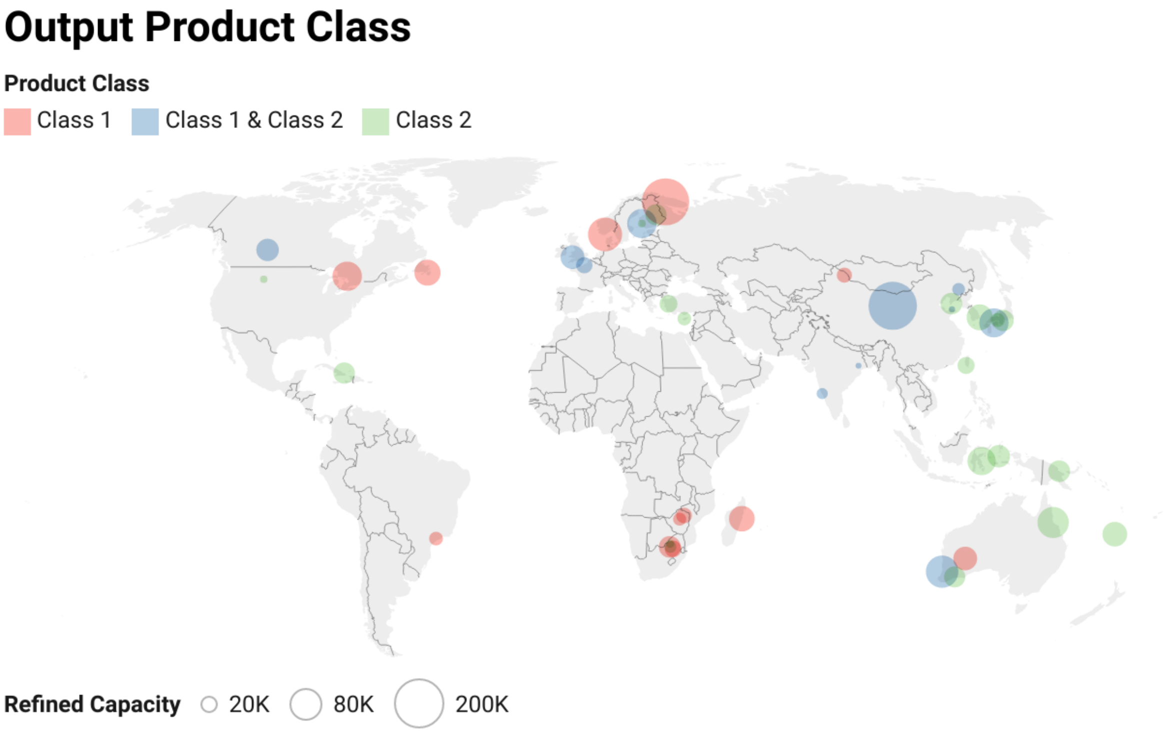


Figure 4-36: Geographic Distribution of Metallurgical Capacity Relative to Product Output Class

As evidenced in Figure 4-36, the production of Class 1 nickel products is concentrated in Australia, Canada, southern Africa, northeast Asia, and northern Europe. This is primarily attributed to the abundance of sulphide deposits in the regions, with few exceptions, and the historical adoption of processes tailored to high-value products amongst operations in the respective regions. In contrast, most producers exclusively producing Class 2 products are located in southeast Asia, northeast Asia, and central Europe. This can be attributed to the relative abundance of laterite nickel deposits in the regions and operations adopting processes producing products intended for battery production, namely MP and nickel sulphate products.

While established product classifications provide limited insight into the characteristics of nickel products beyond their respective nickel contents, the classification system remains a valuable proxy for assessing the supply of high-quality nickel products, given the outstanding share of Class 1 production capacity. Additionally, the ability to transform Class 1 products into alternative products, such as high-purity nickel sulphate, albeit at additional cost, lends to the product class's relevance.

Given the predicted rise in demand for nickel stemming from battery applications, the geographic concentration of battery production capacity is vital to identifying potential geographic supply chain susceptibilities. When considering the ability of an operation to produce nickel products adequate for battery applications, considerable geographic shifts occur relative to the geographic distribution of capacity concerning product Class.

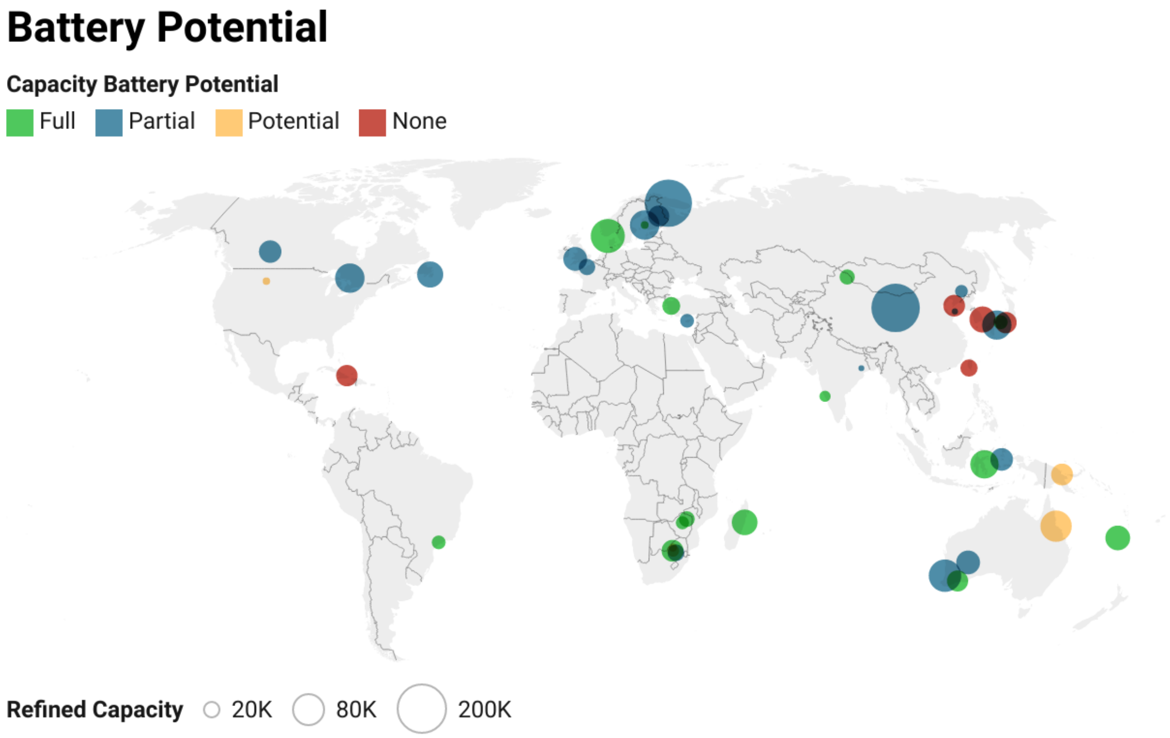


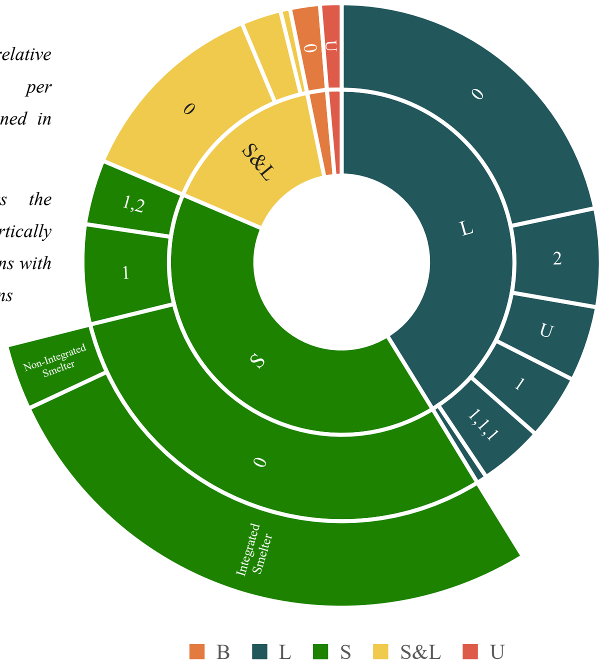
Figure 4-37: Geographic Distribution of Metallurgical Capacity Relative to Battery Potential

Figure 4-37 represents the distribution of nickel operations in relation to their ability to satiate battery applications, as defined in Section 3.5.16 and demonstrated in Figure 4-26 and Figure 4-34. As can be seen, operations for which their total production capacity can be attributed to battery applications are primarily located in southeast Asia, Oceania, southern Africa, and central and northern Europe. This is attributed to several factors. For many operations, the limited number of products produced theoretically allows for the entirety of their capacity to be attributed to battery applications. Similarly, operations in Southeast Asia and Central Europe were recently established and adopted HPAL processes specifically intended to produce products suitable for battery applications, as demonstrated in Table 4-1.

Alternatively, operations for which an unknown fraction of capacity can be attributed to battery applications, as a result of the array of products produced and lack of product production capacity data, are generally geographically distributed and exhibit remarkable capacity. In contrast, facilities with no potential to supply batteries are primarily located in northeast Asia. This is likely attributed to their focus on lower-quality products intended for stainless steel applications and their proximity to the largest stainless steel producing and consuming region globally (WorldStainless, 2022).

It is further necessary to consider the degrees of integration of facilities when assessing their geographic concentration. Vertically integrated facilities, while less flexible in regard to suitable feedstocks and asset longevity, are endowed with consistent and reliable feedstocks as a result of their integration with upstream operations. In contrast, operations with complex midstream value chains, which exhibit prolonged asset lifetimes, are far more susceptible to feedstock supply disruptions as they rely solely on imported feedstocks or are marginally supported by accompanying integrated upstream operations.

This is particularly relevant for non-integrated laterite operations as they exhibit complex value chains. The complexity of their value chains is likely explained by the prolonged operational lifetimes of terminal operations, depletion of regional deposits, and ability to readily import feedstock. Alternatively, integrated laterite operations are predominantly novel and employ HPAL processes tailored to the deposit, suggesting limited ability of HPAL processes to adjust to alternative feedstocks.



**Inner ring represents relative capacity by feedstock ore type, as defined in Section 3.5.1*

***Center ring represents relative capacity by integration per feedstock ore type, as defined in Section 3.5.12*

****Outer ring represents the relative capacity for vertically integrated sulphide operations with integrated smelting operations*

Feedstock Ore Type

B: Black-Shale

L: Laterite

S: Sulphide

S&L: Sulphide and Laterite

U: Unknown

Figure 4-38: Metallurgical Capacity by Ore Type Relative to Value Chain Integration

As demonstrated in Figure 4-38, the majority of lateritic capacity includes vertically integrated operations. Nonetheless, several operations produce intermediate products for which final refining operations could not be reasonably identified. While sulphide operations are predominantly integrated, they often include preceding smelting operations that are often adjacent to refining unit operations or within proximity.

While geographic concentration is vital to assessing a supply chain's dependence on particular countries or regions, asset monopolization can play an equally important role in the supply of products. As discussed in Section 4.2.6, a select number of companies own the majority of production capacity. Consequently, such monopolization of production capacity can notably impact prices and supply.

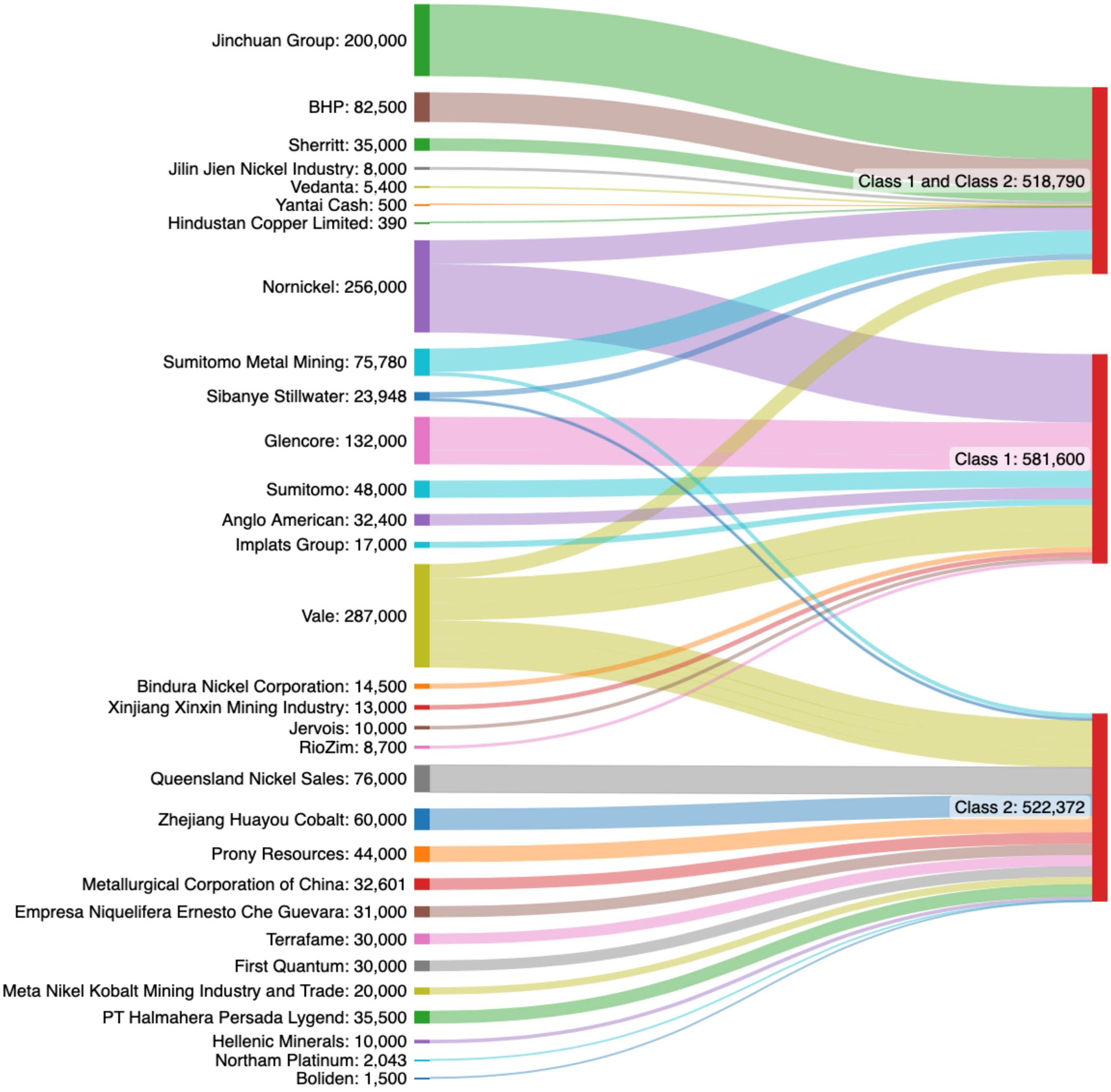


Figure 4-39: Ownership of Metallurgical Capacity Relative to Product Class

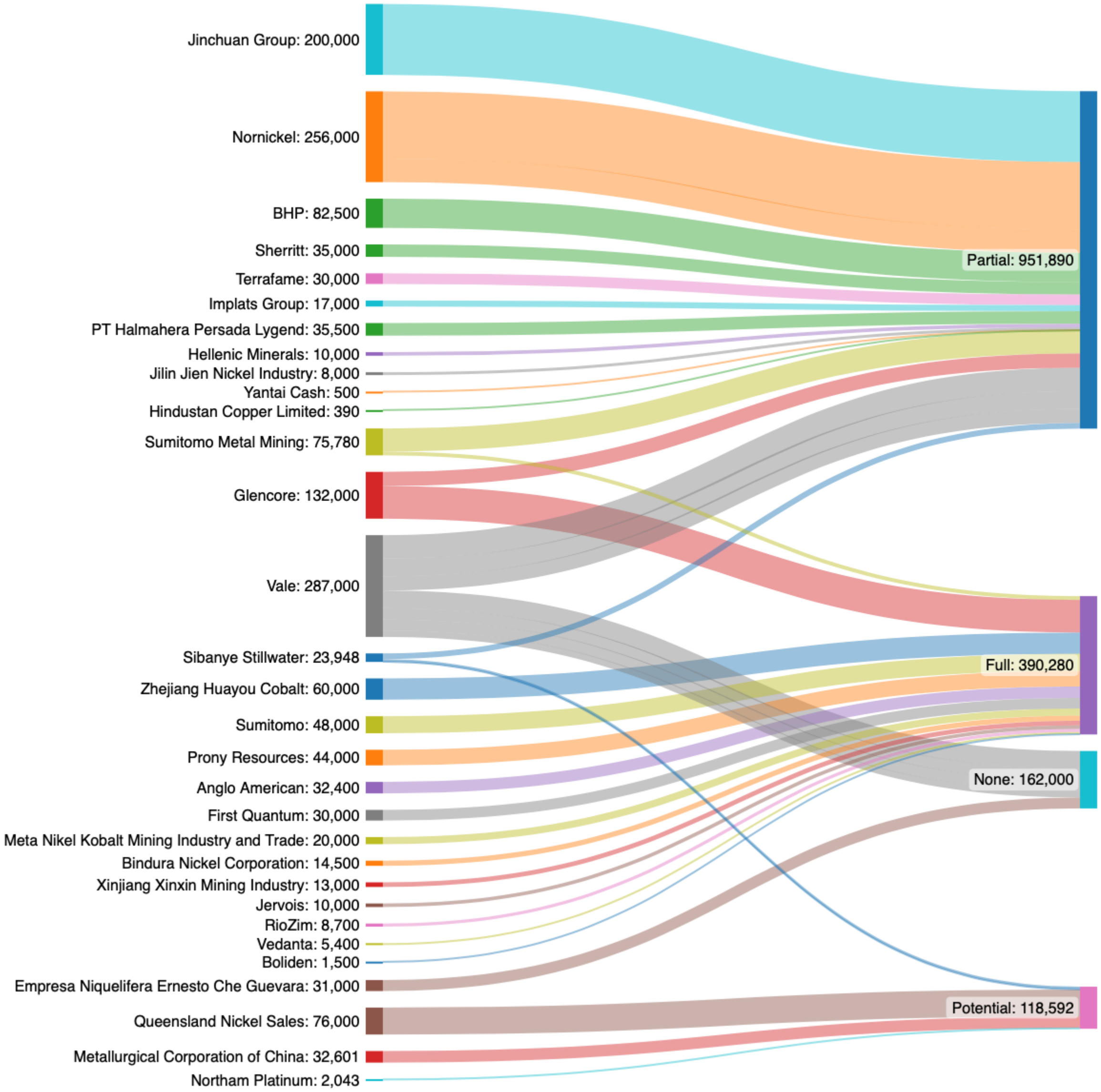
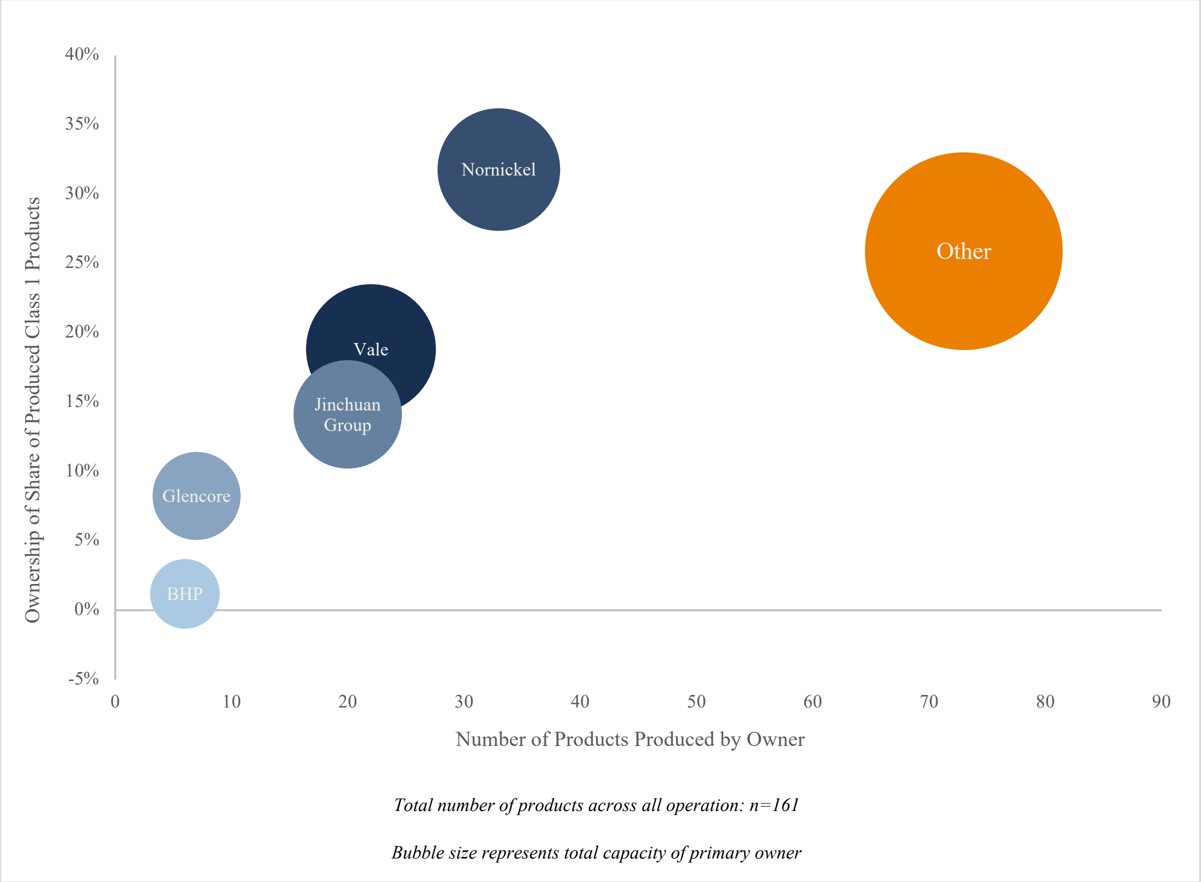


Figure 4-40: Ownership of Metallurgical Capacity Relative to Battery Potential

As seen in Figure 4-39, the majority of Class 1 production capacity is controlled by a limited number of companies, likely owing to the considerable size of the company's operations. In contrast, Class 2 production is substantially more disturbed, likely owing to the relatively small size of laterite operations. A similar trend persists to that of Class 2 production when assessing control of capacity relative its potential for battery applications, as described in Section 3.5.16 and demonstrated in Figure

4-40. It can be seen that production is distributed amongst a range of companies, likely due to the influence of laterite operations. Nevertheless, the lack of data surrounding the production capacity of individual products limits the results derived as the share of production among companies with partial operations could likely a have significant impact on the true share of products suitable for battery applications.



Total number of products across all operation: n=161

Bubble size represents total capacity of primary owner

Figure 4-41: Share of Produced Products and Class 1 Product Market Share by Top Five Owners of Metallurgical Capacity Relative to Remaining Owners

When assessing operations governed by companies controlling a substantial share of metallurgical capacity, it can be seen that their operations produce a number of products, as demonstrated in Figure 4-41. Additionally, it can be seen that the top five owners of metallurgical capacity account for 74% of produced Class 1 products by count. Such market concentration is particularly concerning given their ability to influence product markets with minimal supply liquidity. This matter is further compounded for specialty nickel products such as nickel chloride or carbonyl nickel powders which have smaller markets.

4.3.6 Sub-Question 5 – Carbon-Neutrality Goals

Question: *What are the carbon neutrality goals of operations?*

Answer: The outstanding impact associated with the extraction and transformation of metals is of critical concern to numerous downstream stakeholders. Chief among the impacts relates to the greenhouse gas emissions, referred to as carbon footprint, of metals. As such, a growing trend of carbon neutrality commitments has been made by companies extracting and transforming metals. Understanding the extent to which nickel midstream operations have established commitments towards carbon neutrality is vital to identifying potential supply bottlenecks for low-impact nickel products. Similarly, the assessment can support efforts in assessing the future impacts associated with nickel used in applications, most notably, batteries for electric vehicles or stationary storage applications.

As discussed in Section 4.2.17, the majority of metallurgical capacity has stated commitments towards carbon neutrality. Additionally, as illustrated in Figure 4-32, the bulk of the capacity targets achieving their respective commitments by 2050. Understanding the geographic distributions of operations with carbon-neutral commitments is vital to constructing procurement policies with geographic and environmental elements, as insufficient consideration could generate a bottleneck to achieving proposed policies. This is particularly relevant to policies proposed for LIBs, as further discussed in Section 5.4.6.2.

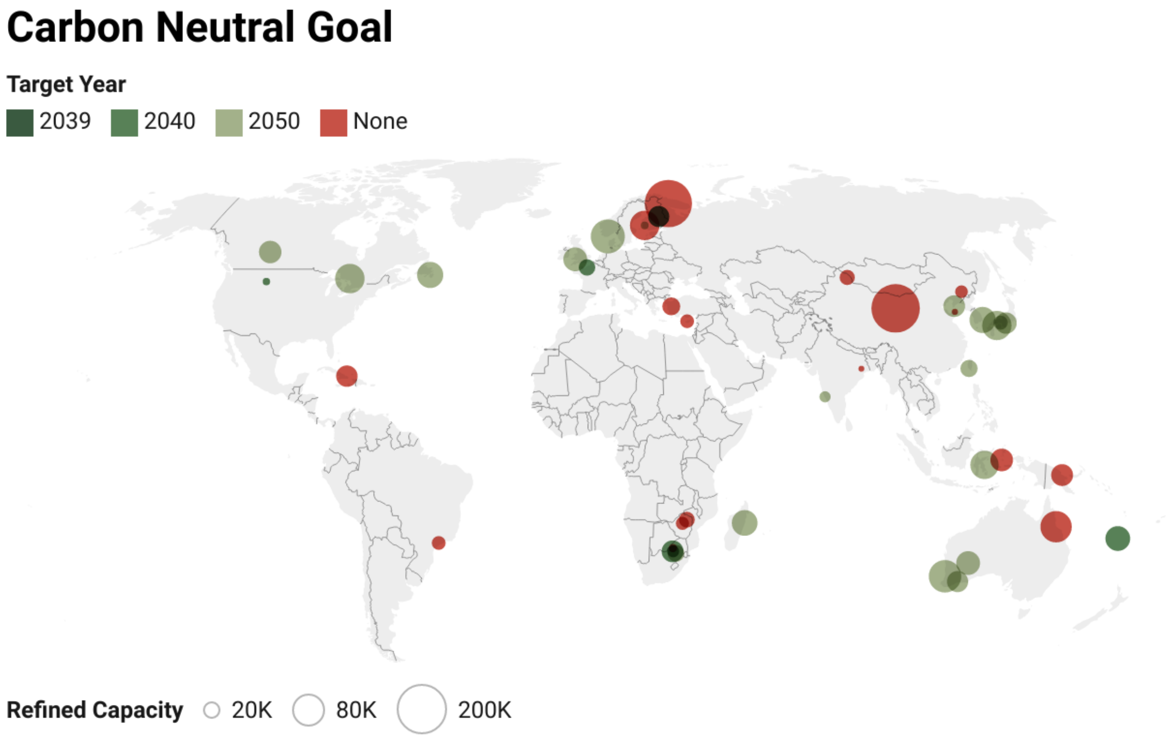


Figure 4-42: Geographic Distribution of Metallurgical Capacity by Carbon Neutrality Target Year

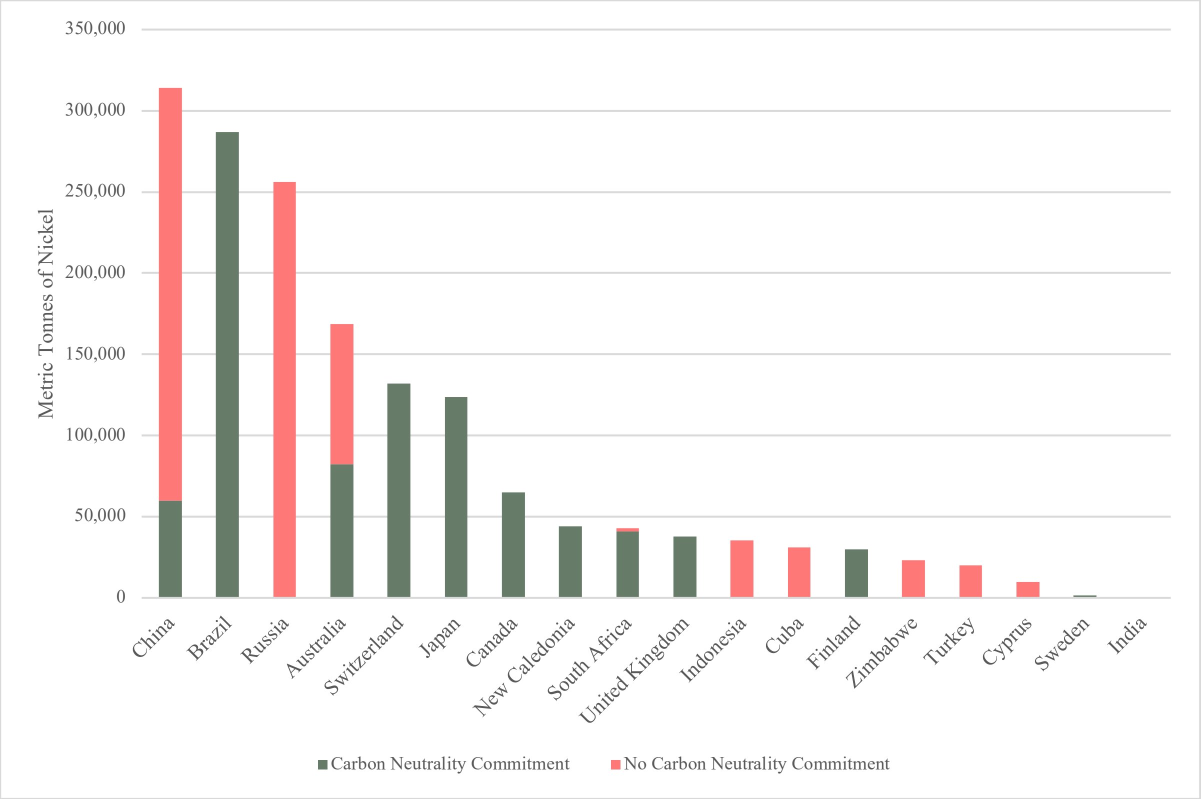


Figure 4-43: Metallurgical Capacity According to Carbon Neutrality Commitments by Headquartered Country of Primary Owner

As can be seen in the Figure 4-42 and Figure 4-43, the majority of operations, and in turn, capacity, with carbon neutrality commitments are primarily located or owned by companies headquartered in jurisdictions with stringent environmental goals. While operations without carbon neutrality commitments are primarily located in regions with lower environmental requirements, many operations support efforts to reduce their impacts, albeit without stated commitments. For example, Nornickel, based in Russia, has multiple ongoing initiatives to reduce the impact of its nickel products and actively promote low-carbon nickel products (Nornickel, 2021a). Heightened awareness towards sustainability among non-committed operations likely indicates the effect of a broader market pull toward sustainable sourcing practices.

Although carbon neutrality commitments and their respective timelines can provide valuable insight into potential future impacts of nickel production, careful consideration must be practiced when employing the data. Notably, the assessment does not consider the breadth of the commitment, particularly as it relates to the committed scopes. This is primarily due to the lack of available data and transparency surrounding the commitments.

Further, the lack of deliberation towards temporal evolutions of the commitments, in exact, the rate at which commitment will be achieved, limits the adaptability of the analysis. This matter is particularly relevant for vertically integrated operations. When considering the finite nature of upstream deposits and the potential inability of dependant midstream operations to adapt to alternative feedstock sources, the operations could conceivably be decommissioned prior to the commitment date. As a result, it is necessary to consider the lifetime of the upstream operations supplying the midstream operations in conjunction with data represented herein when adopting the data.

4.3.7 Sub-Question 6 – Expansion and Recycling

Question: *Are operations investing in expansion or battery recycling capacity?*

Answer: Anticipated growth in demand for nickel stemming from battery applications, in addition to continued growth, albeit to a lesser extent, from traditional downstream nickel applications, will require significant expansions in primary production capacity to meet forecasted demand growth. While sufficient nickel resources and reserves to meet expected demand remain unexploited, as discussed in Section 1.5.1, the ability to extract and convert the resources and reserves into suitable products, specifically battery-suitable products, within the required timeframes to meet broader economic and sustainability goals remains uncertain. Growth in midstream supply capacity from primary sources can be achieved by expanding brownfield operations or developing novel greenfield operations.

Given the historical challenge associated with developing midstream greenfield operations, specifically those producing high-value Class 1 nickel products from laterite ores, as demonstrated in Table 5-1, coupled with the abrupt growth in demand, a notable supply and demand imbalance will likely occur due to timeline discrepancies in onboarding novel supply and downstream demand requirements. While recent greenfield developments demonstrate considerable promise in challenging historical trends, substantial risks must be addressed before the operations are considered successful, as further discussed in Section 5.4.1.1. Similarly, the lack of recent greenfield sulphide midstream operations, coupled with the prolonged development timelines of recent greenfield sulphide midstream operations, as demonstrated in Table 5-1, will likely further exacerbate the dislocation.

Quantifying the predicted expansion in metallurgical capacity stemming from midstream operations is challenging due to the fluidity of developments. Additionally, highly volatile exogenous factors, such as macroeconomic conditions, political influence, and technological advancements, can further exacerbate the fluidity of development plans and timelines (Leonida, 2020). As a result, it was not possible to accurately assess future metallurgical capacity resulting from expansion. Nevertheless, several notable examples of brownfield expansions provide valuable reference points for broader industry trends.

Successful contemporary brownfield expansions comprise two categories, capacity expansion and an expansion of product offerings. Often, the categories are not mutually exclusive and have been adopted in tandem as part of recent expansions. When considering capacity expansion, Jinchuan, Nornickel, and SMM each recently completed expansion projects (Jinchuan Group, 2022d; Nornickel, 2022; Sumitomo Metal Mining, 2021). Alternatively, BHP's Nickel West – Kwinana Nickel Refinery and Sibanye Stillwater's Marikana Base Metal Refinery, in conjunction with Thakadu Group, completed the addition of battery-grade nickel sulphate unit operations at their respective facilities (BHP, 2021c; Marleny Arnoldi, 2021). Similar announcements for battery-grade nickel sulphate operations have been made by Vale (Vale, 2022d), Jilin Jien (Zhongze Group, 2023), Yantai Cash (Yantai Cash, 2019), Jinchuan (Jinchuan Group, 2022b), First Quantum, in partnership with POSCO (First Quantum, 2021b). The focus on brownfield expansion, specifically expanding capacity for battery-grade nickel sulphate, is likely endemic to the growing demand for nickel in battery applications.

An alternative point of interest to expanding primary capacity is the faculty of operations to recycle batteries. The ability to exploit synergies between metallurgical technologies utilized for processing primary feedstocks and those used for battery recycling, as further explored in Section 5.4.4, yields considerable potential. Similar to quantifying primary capacity expansion objectives, quantifying investment in battery recycling amongst established facilities is limited, given the variable nature of the investments. Nevertheless, historical data points, as well as recent announcements, provide adequate data points for identifying potential broader industry trends.

Glencore's Sudbury Integrated Nickel Operations, and coincidentally Nikkelverk operation, first began recycling waste material, including battery materials, in 1990. Additionally, the company has announced further plans to expand its battery recycling capabilities (Glencore Canada, 2021; Glencore, n.d.). Similarly, Jinchuan currently recycles waste battery material and expects to expand its capabilities (Jinchuan Group, 2022a). Several announcements regarding investment in battery recycling have occurred among established operations. Notably, BHP's Nickel West – Kwinana Nickel Refinery (BHP, 2021d), SMM's Niihama Refinery (Sumitomo Metal Mining, n.d., 2021), Nornickel's Harjavalta Refinery (Nornickel, 2021b), Jervoi's São Miguel Paulista Refinery (Jervois, 2021) and Vale's proposed nickel sulphate refinery (Vale, 2022f), have all announced investments and, or, research efforts regarding battery recycling opportunities.

Chapter 5
Discussion

This chapter begins by revisiting the research objective and addressing the research outcome. A comparison with existing literature relative to the research objective and case study is then followed. Thereafter, a comprehensive discussion of supply chain bottleneck risks specific to the evaluated case study with a focus on emerging trends and their potential ramifications is presented. Research applicability related to the metallurgical capacity then proceeds. Finally, the limitations of the metric and opportunities to improve the metric are discussed.

5.1 Research Objective

Motivation for the conception of metallurgical capacity emanated from the need for a novel metric and an adequate approach sufficient to represent the complexity and nuances of mineral and metal supply chains and their ability to satiate discrete downstream applications. As described in Section 2.1, established metrics that quantify the availability of minerals and metals are broadly relegated to geological abundance and upstream operations. As such, they provide valuable but limited insight for downstream stakeholders, specifically when considering their stringent procurement requirements. Therefore, the premise of this research was to develop a metric and suitable approach sufficient to assess midstream operations within a given mineral or metal supply chain to illustrate the intricacies of the supply chain stage while also addressing the concerns of downstream stakeholders more effectively.

As discussed in Section 2.1, previous studies assessing midstream operations of mineral and metal supply chains principally relied on aggregated global trade data and utilized generalized system boundaries. The lack of granularity inherent to the studies, due to the employed data and system boundaries, limited the dissemination of their respective results, particularly amongst downstream stakeholders. Adopting an approach capable of providing highly granular and segregated data was required to achieve the desired provisions for the metric.

A bottom-up facility-by-facility methodology provided the requisite conditions for assessing midstream operations in line with established preconditions for the metric. The approach permitted the ability to identify the production capacity of midstream operations within a given metal supply chain and, ultimately, quantify the metallurgical capacity of apt midstream operations. Derivates of the metric in relation to characteristics of the output products produced at each operation demonstrate the ability to conceive highly targeted assessments of procurable products and their respective capacities within a given metal supply chain. Additionally, derivates of the metric concerning operational attributes allowed for subsequent analysis of the metric tailored to pertinent criteria of relevant stakeholders. Combined, the metric and its derivates addressed the proficiency of metal supply chains to satiate the needs of downstream users.

The utility of the metric was validated through the case study whereby the metallurgical capacity of primary non-ferrous nickel was determined. Additionally, numerous derivates of the metric supporting the needs of supply chain participants were contrived. The case study demonstrated notable trends and insights regarding the evaluated supply chain partly due to the metric and its underlying approach, as evidenced throughout the report. As such, the case study highlighted the benefits and utility of the metallurgical capacity metric. However, it also provided awareness of the metric's potential shortcomings in its adoption within the case study and the broader conceptual framework. Nevertheless, it was determined that the research objective was achieved.

5.2 Case Study

Validating the utility of the metallurgical capacity metric required a critical assessment of a mineral or metal supply chain in which application of the adopted approach and quantification of the metric could be achieved. Additionally, the case study supplemented the validation of the metric by developing pertinent derivates, identifying broader industry trends, fundamental market dynamics, and recognizing potential supply chain bottlenecks. This was achieved through an extensive case study on the global primary non-ferrous nickel supply chain in 2021. In addition to meeting the requisite selection criteria, as explained in Section 3.3.2, utilizing the metal for demonstrating the utility of metallurgical capacity had supplemental consequences. Particularly, assessing a critical metal vital to numerous clean energy technologies while subsequently supporting a more comprehensive understanding of a metal vital to numerous economic sectors.

While the case study conducted was constrained to primary non-ferrous nickel, a considerable amount of data was collected. As a result, countless insights and trends were derived as they related to the nickel supply chain. Adoption of a bottom-up facility-by-facility methodology allowed for the collection of highly granular and segregated data pertinent to acute attributes of individual operations. Similarly, the global scope of the case study provided the ability to contrast operations across geographic locales.

In total, 42 operations were assessed as part of the case study. Data related to operational, technological, environmental, and investment aspects was collected for each operation, resulting in over 5,000 unique data points. In addition, data and accompanying references were compiled in an accessible and open-source database for improved transparency.

5.3 Comparison with Literature

Inspiration for a novel metric to assess the supply potential of midstream metallurgical operations is rooted in previously established literature, gaps within the literature, and industry materiality. Analogously, investigating nickel and identifying relevant supply chain bottlenecks potentially limiting its utility in the clean energy transition were similar provocations. Therefore, comparing the outcome of the metric and methodology developed herein, as well as the results of the case study conducted, to the literature is necessary to determine the relevant contributions of the research. Nevertheless, given the lack of literature on the topic, specifically publicly accessible literature, comparing the metric, its underlying methodology, and the results of the case study to analogous studies is limited.

As mentioned in Section 2.1, a narrow body of academic literature on the supply potential of midstream metallurgical operations has been published. Relevant research, specifically work conducted by Mudd and Jowitt (2014) as well as Heijlen et al. (2021), focused on the geological availability of nickel and applicable upstream operations. Nevertheless, the bottom-up facility-by-facility methodology employed by the authors provided a sufficiently adaptable methodological framework for the metric developed herein. As such, the developed metric is an extension of the work conducted by the authors and can be used in conjunction with established literature on the topic.

Similarly, a notable lack of academic literature assessing midstream metallurgical operations, specifically nickel midstream operations, persists. As discussed in Section 2.3.2, pertinent research on the topic, such as those conducted by Warner et al. (2007, 2006), Dalvi et al. (2004), and Eckelman (2010), employed limited scope as they primarily focused on technical aspects of operations within the midstream value chain, the value chain of a given feedstock, or the environmental impacts of operations. Additionally, given the fluidity of the nickel market and, in turn, midstream value chains, data from the studies does not accurately reflect the present state of the midstream supply chain. While limited in scope and dated, the studies supported the conceptual framework for the metric and the subsequent case study conducted. The metric and case study can be seen as a revised and more comprehensive extensions of the studies.

While a considerable lack of academic literature exists related to the supply potential of nickel midstream operations, several notable studies have been published outside the realm of academia, as discussed in Section 2.3. Nevertheless, a significant challenge in assessing the validity and compatibility of the studies relative to the metric and case study conducted herein lies in the inability to access their underlying methodologies and data. As such, comparing the outcome of the study with related existing grey literature is not possible due to a lack of transparency, thus prohibiting the ability to ensure comparable scope and resolution. Regardless, as mentioned in Section 3.6.3, when comparing the results of the study to similar industry assessments (Berlin et al., 2022), they are within reasonable margins of errors, suggesting the study's outcome is reasonably representative of the supply chain.

5.4 Discussion of Nickel Supply Chain Bottleneck Risks

The complex nature of mineral and metal supply chains and their predisposition to supply and demand shocks induces a considerable amount of risk to upstream and downstream stakeholders. In turn, dependent midstream operations are highly susceptible to supply chain bottlenecks. A plethora of factors, acting in unison or coalescences, can act as the genesis of a supply bottleneck. Therefore, identifying bottleneck risks related to established supply chain dynamics and future supply chain dynamics is critical to developing actionable solutions to remedy such risks.

This matter is particularly relevant to the midstream nickel supply chain. Factors such as predicted growth in nickel demand stemming from battery applications, increased geopolitical and trade tensions, and heightened awareness towards environmental impacts of products and services are among a subset of factors with substantial risk to spur supply chain bottlenecks. However, the extent of such potential bottleneck risks and their subsequent impacts are not equally distributed amongst supply chain stakeholders.

Leveraging the adopted methodology, namely a bottom-up facility-by-facility assessment, the case study allowed for a comprehensive assessment of the nickel midstream metallurgical supply chain. The granularity and scope provided by the methodology yielded the requisite conditions for identifying systemic and discrete supply chain bottlenecks relevant to individual stakeholder groups as well as broader industry risks. In all, the supply risk identified are predicated upon the condensed timelines for which growth in demand for nickel is expected to materialize, the ability to economically achieve diverging outcomes, and the sustainability profile of midstream outputs.

5.4.1 Laterite vs. Sulphide – Who will supply what?

The bifurcated nature of nickel deposits, into laterites and sulphides, results in unique relationships across the midstream supply chain, as previously explained in Section 2.2 and Appendix A. Attributes related to each deposit, including but not limited to geographic distribution, geologic formation, and environmental impact of extracting and processing known deposits, result in diverging risk profiles. While the extent of the risks requires detailed evaluations of their respective supply chains, broader risks emerge when assessing and comparing the supply chains as a whole.

One of the most significant supply risks relates to the product quality that can be produced from a given ore type. As demonstrated in Section 4.3.2, a notable discrepancy exists when evaluating the capacity potential of operations utilizing feedstocks derived from distinct ores to produce Class 1 and Class 2 products. By in large, sulphide operations produce Class 1 products, while laterite operations produce Class 2 products. The discrepancy is likely further exacerbated when including ferrous nickel products as they are inherently Class 2 products and nearly exclusively produced from lateritic ores using pyrometallurgical processes, as described in Appendix A.

Bifurcation amongst nickel ore feedstocks and product classes is particularly relevant when considering future growth areas and demand constraints. Given the predicted demand in growth stemming from battery applications and assuming that existing rigorous impurities requirements and chemistry requirements for battery-grade nickel sulphate persist, the ability of laterite ores to satisfy growth in demand from batteries remains uncertain. This is particularly consequential given the geological abundance of laterite ores relative to sulphide ores, as discussed in Section 1.5.3. While lateritic ores are more abundant, their limited ability to be converted into high-grade nickel products at cost-competitive rates could limit the ability of downstream applications requiring high-quality nickel products to exploit what is widely considered an abundant source of nickel (Azevedo et al., 2020; Kevin Murphy, 2020; Shunyu Yao, 2022).

Further, while not explored in the study, additional analysis of the specific lateritic minerals being converted into high-quality products could further reduce the geological supply of lateritic ores suitable for high-quality nickel products. For example, established operations processing laterite ores into high-quality nickel products primarily rely on limonite minerals, suggesting that potential lateritic resources amenable for high-quality nickel products is lower than the commonly cited laterite resource figures suggest. Nevertheless, several lateritic operations producing high-quality nickel products have begun blending saprolite and limonite minerals in their feedstocks (Gabb, 2018). Further, proposed NPI-to-Matte routes primarily utilize saprolite minerals for their respective feedstocks (Sherritt, 2021a). Such technological advancements suggest that the burden could be alleviated, albeit to an unknown extent and cost.

The dichotomy amongst ore types further presents a risk when considering recent midstream metallurgical capacity growth, as demonstrated in Figure 5-1 and Appendix C. As discussed in Section 4.2.9, the bulk of recent growth in metallurgical capacity has been driven by lateritic operations.

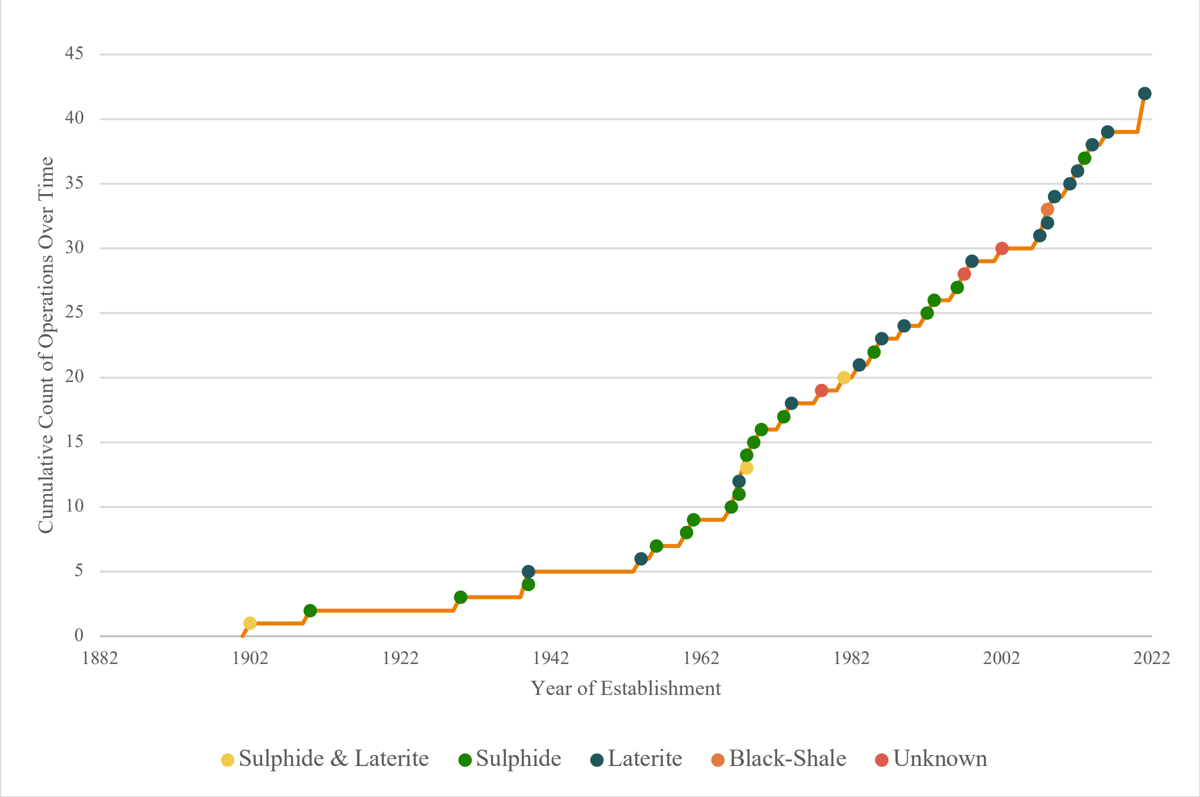


Figure 5-1: Cumulative Count of Operations by Year of Establishment According to Feedstock Type

While it remains technically feasible to produce Class 1 nickel from laterite ores, as evidenced by Sumitomo Metal’s Ambatovy operation in Madagascar, Glencore’s Murrin Murrin operation in Australia, SMM’s Taganio and Coral Bay operations in the Philippines via its Niihama Refinery operation in Japan, and Sherritt's Moa joint venture operation in Cuba via its Fort Saskatchewan operation in Canada, operational, financial, and environmental challenges associated with the projects present considerable risks, as further considered in the following sections. To accurately assess the ability of lateritic operations to produce high-quality nickel products with requisite impurity levels, specifically for battery applications, considerable technical and financial evaluations are required.

While technical and financial challenges present substantial uncertainty for lateritic developments, an equivalent source of uncertainty to lateritic developments stems from political influences. This is most notable when considering export restrictions put in place by Indonesia aimed at increasing the share of the midstream supply chain within the country (IEA, 2022). Therefore, the uncertainties regarding political factors in developing midstream operations in lateritic resource-rich jurisdictions could potentially engross supply chain bottlenecks.

In contrast to the ability of lateritic ores to supply high-purity nickel products efficiently and economically, the ability of sulphide operations to produce lower-quality Class 2 products, particularly ferrous nickel products, remains uncertain. While Class 1 products yield greater flexibility regarding downstream applications, Class 2 products focus primarily on metallurgical applications, notably stainless steel. Given the historical focus of sulphide operations on Class 1 products, primarily used in metallurgical applications as well as applications with stringent impurity requirements, the ability to produce Class 2 products competitively from sulphide ores presents a unique risk. The risk is further compounded when considering increased nickel demand from batteries, geopolitical risk, and diverging market economics. Additionally, the associated risk profile is geographically constrained. These issues are further explored in the following sections.

Overarching supply chain risks in relation to both upstream ore supply and midstream capacity are highly variable and situational. As stated above, the extent of the risk will likely be predicated upon temporal demand expectations, economic viability, and sustainability tolerances of discrete downstream users.

5.4.1.1 Laterites – Supply Growth and Buffer

Laterite deposits are endowed with several favourable qualities. Most notably, their abundance, proximity to the surface allowing for open pit mining, ability to be upgraded into products with varying degrees of quality, and their geographic concentration in jurisdictions keen on developing their respective deposits (Dalvi et al., 2004; Huber, 2021; G. M. Mudd & Jowitt, 2014). As such, exploiting laterites deposits is seen as a promising solution to meet predicted growth in demand. Nevertheless, the ore is equally endowed with adverse qualities. Most pertinent are the environmental impact of exploiting lateritic ores, their complex ore bodies, which include significant deleterious elements, and exploitable deposits in predominately tropical regions with inconvenient operating environments (Elias, 2002). Challenges in overcoming related shortcomings have historically plagued the exploitation of laterite deposits. Albeit novel technological advancements and favourable development conditions have aided in elevated exploration interest as well as a surge in contemporary developments. As such, two notable, non-environmental related, trends have emerged regarding lateritic deposits producing non-ferrous nickel products. Understanding the trends and their associated trade-offs is necessary for evaluating potential supply bottlenecks. Environmental trade-offs related to laterites operations are further discussed in Section 5.4.6.1.

Advancements in HPAL technologies have resulted in the proliferation of the process in recent years, as evidenced in Table 4-1. While the technology offers a promising solution for producing high-quality non-ferrous nickel products, historical challenges in ramping and achieving nameplate capacity could inhibit their performance (Gabb, 2018). Recently established HPAL operations, produce intermediate MP products requiring additional midstream processing, as discussed in Appendix A. This is in contrast to previously established HPAL operations that produce Class 1 nickel products, such as Ambatovy and Murrin Murrin, which each experienced operational challenges during ramp-up. Analogously, there has been a shift to MHP intermediate products that are more amenable to battery applications as opposed to traditional MSP intermediate products common amongst HPAL operations producing Class 1 products (Milewski, 2021). The focus of novel HPAL operations on intermediate products coupled with their recent success suggests converting intermediate products into high-quality products could be a limiting factor and, in turn, a bottleneck. While SMM's Coral Bay and Taganito HPAL operations supply intermediate products for subsequent conversion at the company's Niihama and Harima operations, the extent to which alternative converting facilities can achieve equivalent success in converting intermediate MPs into high-quality nickel products remains unclear.

Conversion of NPI to matte is an alternative processing pathway to produce high-quality nickel products from lateritic ores, as discussed in Appendix A. The proposed process for converting saprolite minerals into high-quality nickel products involves utilizing a combination of existing technologies. This pathway is estimated to have significant associated costs, which could limit its proliferation (Sherritt, 2021a). Additionally, as discussed in Section 5.4.6, associated environmental impacts could decrease demand for products produced from the process. Nevertheless, the pathway provides considerable market flexibility, specifically when considering the preliminary stages of the process. The ability of the processes to produce both NPI and matte products grants the process superior marketable flexibility during volatile economic conditions. The capability to supply alternative downstream applications, namely stainless steel and battery applications, each with unique underlying market economic influences, could benefit the process. However, the flexibility and success of the process in supplying multiple discrete downstream applications in such a scenario is predicated upon the ability to finance and sustain terminal unit operations, namely matte conversion unit operations required for producing high-quality nickel products, during periods of low demand for the products.

In all, HPAL and NPI-to-Matte processes present valuable opportunities to meet the growing demand for high-quality nickel products and alleviate supply deficits. However, associated financial risks remain intangible and require additional analysis to determine their respective supply potential of high-quality nickel products in variable market conditions.

5.4.1.2 Sulphides – Quality Products, Absent Growth

A myriad of factors influenced the historical supply dominance of sulphide ores. Their relative abundance, ease of processing, lack of equivalent product competition from laterite ores, geographic proximity to historical downstream demand regions, and relatively low environmental impact are among the leading factors. Sulphide processing technologies have historically and continue to focus on producing high-quality nickel products, as evidenced in Figure 4-33. As a result of their quality, in regard to their low concentration of impurities, high-grade nickel products derived from sulphide ores could readily be adapted to nearly any downstream demand application. This matter is further compounded when considering the ability to readily transform Class 1 products into Class 2 products. Such capabilities are likely to be leveraged by battery applications due to the application's stringent requirements for impurities in precursor nickel materials, as discussed in Section 5.4.2.

Nevertheless, several notable trends present considerable bottleneck risks related to the ability of sulphide ores to meet expected demand. When evaluating the development trends of midstream metallurgical operations, as demonstrated in Figure 5-1, only seven midstream operations known to process sulphide ores have been established since 1981, of which one processes both sulphide and laterite ores. The seven operations, in turn, account for 15% of established capacity during the period. A lack of novel sulphide midstream capacity is further exacerbated when considering that Long

Harbour accounts for 55% of such capacity, indicating a lack of sizeable new developments. Further, of the seven operations, one is currently placed on Care and Maintenance, while of the remaining six operating, three produce nickel as a by-product of PGM. The lack of novel sulphide midstream with sufficient capacity could significantly reduce the supply of high-quality nickel products.

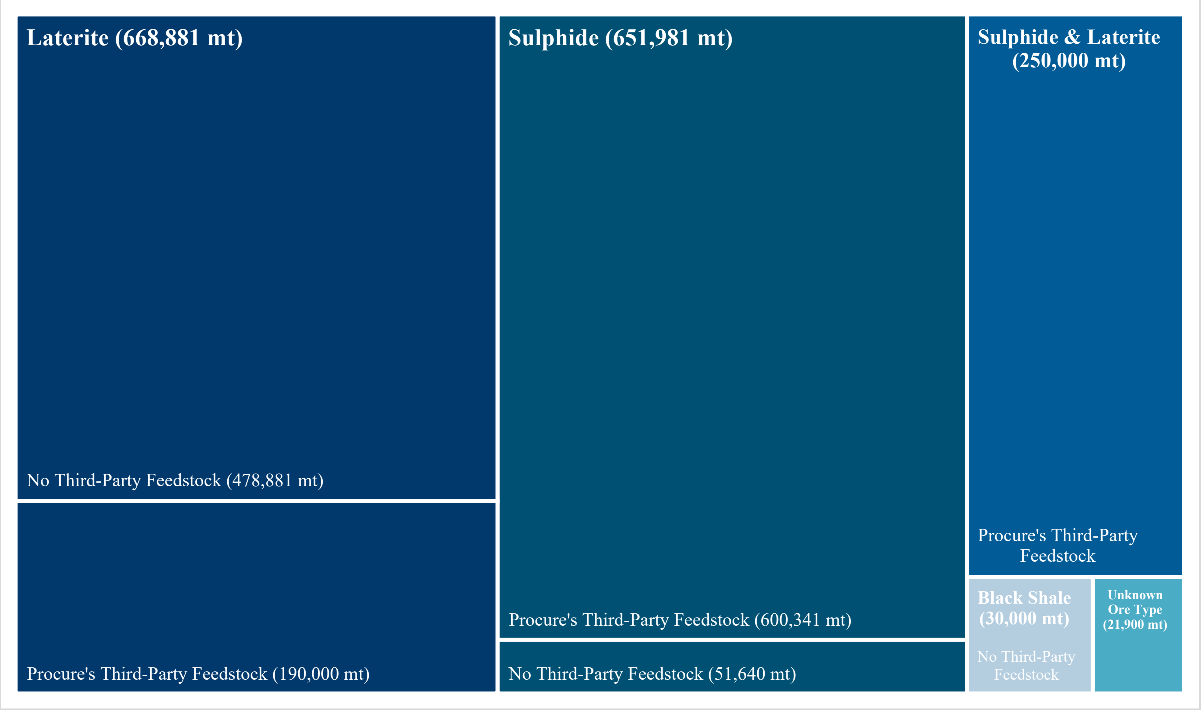


Figure 5-2: Metallurgical Capacity by Ore Type and Third-Party Capabilities

While there remains a lack of new midstream sulphide processing capacity, the relative flexibility and adaptability of the processing technologies employed amongst established sulphide operations has profited those operations. This is best evidenced when considering the degree of integration and reliance on third-party feedstocks amongst sulphide operations, as demonstrated in Figure 4-38, and Figure 5-2. Further, many sulphide operations have undergone significant expansions over time highlighting the value of adopted processes. Additionally, the recent expansion in battery-grade nickel sulphate unit operations amongst primarily sulphide operations, as described in Section 4.3.7, suggests that sulphide midstream operations possess the requisite processing technologies to achieve battery-grade material. Such conditions provide a unique opportunity for established operations to meet future demand, as further explored in Section 5.4.5.

One of the limiting factors in expanding sulphide midstream capacity relates to the geographic distribution of reserves in jurisdictions resistant to development, specifically as it relates to deposits in Europe and North America. When evaluating the distribution of reserves of sulphide ores in Appendix A, it can be seen that the majority of sulphide deposits are situated in developed countries. This is particularly problematic given the increased resistance to resource exploitation and processing in the regions. Such resistance is likely grounded in the historical environmental and social impact induced by historic operations in the region. Notably, the high associated sulphur dioxide emissions from smelting operations, and lack of local and indigenous community consultations are likely a subset of precedent-setting justifications for resistance to novel exploitation amongst affected communities (Fioletov et al., 2016; Gibson, 2006; Whitby et al., 1976). While significant efforts have been made to address the environmental and community impact of midstream operations, considerable trust amongst stakeholders will likely need to be established prior to any significant development of sulphide deposits in developed regions.

5.4.2 Class 1 and Nickel Sulphate – One without the other?

Historical classification of nickel products, and more broadly established metal exchange standards for nickel products, have had a considerable impact on non-ferrous midstream operations product output. The superior quality of Class 1 products, regarding the negligible concentrations of impurities, and their ability to be readily transformed into alternate nickel products provided the requisite conditions for their adoption amongst downstream consumers. While historically, the flexibility benefited producers necessitating high-quality products, recent market shifts, as well as predicted market shifts, put into question the utility of the historical classification.

The growing share of stainless steel production in China, coupled with regional producers preference's for NPI percussor feedstocks, has resulted in significant geographic shifts in market influence (Pariser et al., 2018; Rao et al., 2013). This is compounded when considering the reliance of stainless steel producers outside of China on high quality nickel products for alloying purposes due to high scrap feedstock ratio’s (Johnson et al., 2008; Rao et al., 2013; Reck & Rotter, 2012; Team Stainless, 2021). Further, the declining share of stainless steel production from Western regions exacerbates the geographic shifts in market influence (WorldStainless, 2022). The geographic proximity, relative abundance, and discounted prices of FeNi and NPI products derived from laterite operations in Southeast Asia, as discussed in Appendix A, affords a considerable advantages to amenable primary stainless steel producers, namely Chinese producers, relative to their secondary reliant counterparts (Campagnol et al., 2017; G. M. Mudd & Jowitt, 2014; WorldStainless, 2022). These events, in turn, have had significant implications on lateritic and sulphide midstream operations.

Nevertheless, predicted growth in demand for battery-grade nickel products could further shift markets, assuming underlying fundamental conditions persist. Stringent impurity requirements for battery-grade nickel sulphate necessitate additional refining unit operations to reduce the concentration of deleterious elements. This is illustrated with BHP's current use of Class 1 nickel to produce battery-grade nickel sulphate, as well as Vale's proposal to use Class 1 nickel to produce battery-grade nickel sulphate (Haegel, 2018; Vale, 2022d). This trend suggests that Class 1 nickel is necessary to meet downstream requirements for battery-grade nickel sulphate. While the lack of industry standards for battery-grade nickel sulphate prohibits the realization of such requirement, the established off-take agreements for nickel sulphate produced from the operations, namely between BHP and Tesla (BHP, 2021b), Ford (BHP, 2022), and Toyota (BHP, 2021d), as well as Vale and GM (Vale, 2022f), suggest that Western automotive manufactures require Class 1 quality.

The ability of sulphide operations to produce Class 1 nickel, coupled with limited established lateritic Class 1 capacity, and historical challenges in producing Class 1 products from lateritic operations, result in sulphide midstream operations being the dominant supplier of batteries in 2021. However, the scenario is predicated on the assumption that sulphide operations can achieve the required quality at a lower marginal cost relative to laterite operations, equivalent quality requirements for battery-grade nickel sulphate persist across the industry, and a continued reliance on high-purity nickel sulphate for batteries.

While the current research suggests that a considerable portion of established lateritic capacity can be leveraged for battery application, the analysis is primarily predicated on the advertised ability of the products produced by operations to satiate battery applications. Therefore, an analysis of the quality of the output product from midstream operations, specifically in relations to their impurities, is necessary to assess the impact of such a scenario.

Such an analysis is particularly relevant given the emerging trend amongst lateritic operations positioned to supply battery consumers, namely HPAL operations, with intermediate products, such as

MPs. The ability of the operations to supply battery consumers will likely be predicated upon the quality, cost, provenance, and environmental impact of the products produced. Given that a significant degree of uncertainty relates to the ability of subsequent midstream converting facilities to transform intermediate products into battery-grade nickel sulphate at a competitive cost, the risk of capacity shortfall is further exacerbated.

As with established nickel standards, such as ASTM B39-79 (2013) and GB/T 6516-2010 used by the LME, an industry standard for battery-grade nickel sulphate could likely benefit the broader industry in identifying metallurgically adequate capacity for battery applications (London Metal Exchange, 2022).

5.4.3 Stainless Steel – Not to be forgotten

Historically, stainless steel applications accounted for the largest share of nickel consumption. While battery growth is anticipated to account for the majority of new growth in demand, demand from stainless steel applications is also predicted to grow, albeit to a lesser extent, all the while remaining a dominant application of nickel (IEA, 2021a; Nickel Institute, n.d.). While FeNi and NPI influence nickel and stainless steel market dynamics considerably, as explored in Section 5.4.1, secondary stainless steel feedstocks equally affect market dynamics (Pariser et al., 2018). Given the uncertainty regarding the supply potential of nickel for battery applications and the market dynamics resultant from the array of feedstock sources amenable to stainless steel producers, the sector is highly susceptible to supply bottlenecks. This is amplified when considering specific stakeholders.

As mentioned in Section 5.4.1.2, stainless steel consumers exhibit highly fragmented procurement practices in relation to nickel. Most notably concerning discrepancies in operational practices and quality of primary feedstocks. For example, stainless steel producers outside of China utilize higher ratios of scrap feedstocks and, in turn, Class 1 nickel for alloying (Johnson et al., 2008; Reck & Rotter, 2012; Team Stainless, 2021). In contrast, Chinese producers, which predominantly produce stainless steel from primary sources, utilize FeNi and NPI products (Rao et al., 2013; Team Stainless, 2021). Such regional discrepancy results in considerable market dislocations. The dislocations are further exacerbated when considering the discrepancies amongst regional producers regarding their environmental goals. The impact associated with such conditions, as well as evolving market dynamics, could potentially result in notable nickel and stainless steel supply chain bottlenecks, each with varying degrees of impact.

5.4.3.1 Class 1 vs. Class 2 – The real trade-offs

Variation in Class 1 and Class 2 nickel products, specifically Class 2 FeNi and NPI products relative to Class 1 products, have significant implications for stainless steel producers. Compositional variability amongst the product classes limits the applicability of stainless steel producers to leverage the products interchangeably due to downstream quality requirements. Similarly, the variability in nickel concentrations considerably impacts stainless steel producers utilizing secondary feedstocks. The superior nickel concentration in Class 1 products allows stainless steel producers to utilize elevated ratios of secondary feedstocks to achieve the requisite nickel concentration (Reck & Rotter, 2012). In contrast, the lower concentration of nickel in Class 2 products and higher concentration of impurities limit their ability to achieve the requisite compositions for stainless steels (Reck & Rotter, 2012; Wang et al., 2021). As such, Class 1 products can be seen as more amenable to a more extensive array of producers relative to Class 2 ferrous products. However, the superior qualities of Class 1 products are reflective of their higher relative prices comparative to Class 2 products, as demonstrated in Appendix A.

Given the predicted demand for high-grade nickel products from battery applications, the lack of relevant supply can significantly affect stainless steel producers reliant on Class 1 products. The price premium for battery-grade nickel sulphate relative to that of LME prices and Vale's reported premium for 'Upper Class 1' nickel (Jesline Tang & Leah Chen, 2022; Vale, 2019), suggests that midstream producers could be incentivized to produce battery-grade nickel sulphate as opposed to Class 1 products such as cathodes or briquettes. Similarly, battery manufacturers, in an effort to ensure a sufficient supply of nickel for their operations, may enter long-term off-take agreements with midstream producers, thus further constraining the available supply of Class 1 products. Alternatively, battery manufacturers may integrate converting operations with their existing manufacturing processes, potentially limiting the quantity of feedstock converted to Class 1. The strong demand for high-quality nickel stemming from battery applications and the lack of novel supply to support sufficient market liquidity can significantly impact stainless steel producers reliant on the product.

In such a scenario, several trade-offs would likely take place, all of which require subsequent analysis to determine the extent of the impact. Stainless steel producers utilizing higher ratios of secondary feedstocks will either be forced to procure lower quality nickel products, such as NPI and FeNi, or capitulate to the elevated prices for Class 1 products. The ability of stainless steel producers reliant on higher ratios of secondary feedstocks to adapt to alternative feedstocks remains unknown. Additionally, the economic impact of higher nickel feedstock cost on stainless steel producers remains unknown. A potential lack of supply and inability to adapt to alternative feedstocks could be detrimental to operations lacking sufficient financial resources.

Environmental regulations and policies could further exacerbate the situation, specifically those related to responsibly produced steel and expectations for lower carbon emissions. As further explored in Section 5.4.6.2, complying with relevant policies could be challenging to achieve, even in the likelihood that stainless steel producers can adopt alternative nickel products, as limited supply of high quality, low-carbon, in relation to green-house-gas emissions, nickel products persist. In a similar manner, given the emission reductions incurred when leveraging higher ratios of recycled feedstock, stainless steel producers pursuant of such operational practices in order to abide with agreed policies, would further necessitate high quality, low-carbon nickel products (ISSF, 2022).

The substantial carbon emissions from the production of FeNi and NPI products present considerable challenges given the dominance of RKEF processes in producing the products. The process's reliance on carbo-thermic reductions contributes to the product's associated carbon emission (Mistry et al., 2016). While possible to utilize hydrogen as a reductant (Kawahara et al., 1988; Utigard & Bergman, 1993), a lack of established commercially viable operations limits the near-term proliferation of the technology and, in turn, emission reductions. Further, while possible to utilize low-carbon energy for electric furnaces (Bartzas & Komnitsas, 2015), the energy intensity of the furnaces presents unique operational challenges to the adoption of intermittent renewable sources of energy.

As such, sulphide operations are the most likely source for low-carbon nickel products amenable to stainless steel applications. As stated in Section 5.4.1, it is unclear the extent to which sulphide midstream operations can economically produce Class 2 products suitable for stainless steel application, nonetheless, suitable low-carbon Class 2 products. Developing pathways for suitable products would further support efforts to diversify the nickel supply. Investigation of these implications should be considered when developing relevant policies.

While the above-stated situation was framed within the context of stainless steel, an equivalent argument could reasonably be conceived for alternative applications competing against battery applications for high-quality nickel battery products or applications competing for sustainable nickel products. For several applications dependent on high-purity nickel products, namely non-ferrous alloys, plating and specialty chemicals, increased demand for high-purity nickel products from batteries could have devastating impacts when considering their inability to substitute with lower-quality nickel products. Comprehensive policies are needed to support non-battery applications and avoid market disruptions.

5.4.3.2 Chromium – An exercise in problem shifting

A potential, albeit limited, substitute for nickel in producing stainless steel is chromium (U.S. Geological Survey, 2022). The extent to which chromium can be substituted is constrained to the end-use requirements of stainless steel applications (Oshima et al., 2007). While historically 300 series stainless steels have been the dominant stainless steel grade, alternative grades, such as 200 and 400 series stainless steel which requires little or no nickel, have been gradually growing in terms of their respective share of stainless steel production (WorldStainless, 2022). The exact motive for this trend is driven by the sizeable cost to which nickel contributes in the production of stainless steel and its volatile prices (Lo et al., 2009; Omura et al., 2010; Rick & Engholm, 2010). Nevertheless, leveraging low-nickel or nickel-deficient stainless steels can alleviate potential supply bottlenecks induced by supply and demand disparities.

Shifting to chromium-dominant stainless steel due to insufficient nickel supply or elevated prices presents unique challenges and potentially unintended bottleneck risks. The geographic concentration of chromium deposits in South Africa, and the geographic concentration of ferrochromium processing in China, present a notable supply risk for countries and companies intending to diversify their raw material supply (ICDA, n.d.). Without adequate regional chromium exploitation and processing capacity, countries and stainless steel producers would remain susceptible to supply disruptions.

Further, while the carbon emissions of ferrochromium are relatively lower than that of ferronickel among established production routes, albeit in each case, the influence of Chinese production was not considered (ICDA, 2022; Sphera, 2023), the potential to reduce the carbon emissions of ferrochromium is likely more challenging than those of ferronickel (Holappa, 2010). When considering the suitability of hydrogen as reductant in place of carbon in the production of ferrochromium, within the context of established processes, limited opportunity persist (J. Davies et al., 2022). In contrast, hydrogen is a viable reductant replacement in established ferronickel production processes (Kawahara et al., 1988; Utigard & Bergman, 1993). The lack of sufficient low-carbon reductants for the production of ferrochromium production could limit its ability to be a suitable substitute for nickel in stainless steel, specifically when considering carbon emissions.

Another sustainability implication of chromium as a replacement for nickel in stainless steel arises when considering end-of-life recyclability. As a result of their magnetic properties, ferritic stainless steels are often downgraded and mixed with carbon steels when recycled thus decrease the recycling rate of chromium. In contrast, the absence of magnetic properties in austenitic stainless steel allows for the metal to be recycled at a higher rate (Daigo et al., 2010). As such, low-nickel chromium based stainless steels require continuous streams of primary feedstocks when recycled. In all, constrained nickel supply could have outsized impact on chromium markets if adopted as a viable substitute.

5.4.4 Battery Recycling – A Potential Bridge Gap

The increasing demand for nickel in battery applications are intended to support climate solutions in electricity and transportation sectors. However, the realization of such an outcome is largely contingent on the impacts of the materials used in production and the end-of-life (EOL) management of batteries (Porzio & Scown, 2021). As explored in Section 4.2.17, 4.3.6, and Appendix C, low-carbon nickel for battery applications can be attainted. Further, while not explored in detail, companies are continuing to reduce the impact of their respective nickel products on alternative environmental and social dimensions, such as water intensity, land reclamation, and labour practices (Glencore, 2022b; Nornickel, 2021a; Sumitomo Metal Mining, 2021; Vale, 2022b). As a result, it is achievable to produce batteries with responsibly sourced nickel. Furthermore, novel industry efforts indicate that the available capacity of responsibly produced nickel will continue to rise.

An additional aspect related to the sustainability of batteries is EOL management. Irrespective of proposed solutions to extend the useful lifetime of batteries, they will inevitably reach their EOL (Ahmadi et al., 2017). To ensure the sustainable management of EOL batteries, recycling has been widely proposed as a viable solution (Mayyas et al., 2019). Given the projected growth in batteries, a flurry of activity related to recycling EOL batteries has been undertaken, most prominently in regions with large automotive sectors as well as jurisdictions with stringent environmental requirements (Pinegar & Smith, 2019).

Most of the proposed battery recycling processes have adopted metallurgical technologies from primary midstream operations due to the relative compositional similarity between EOL batteries and primary feedstocks (Sommerville et al., 2021). This is best exemplified by Glencore’s Sudbury INO, which currently recycles EOL batteries alongside primary feedstock, as discussed in Section 4.3.7. Further, proposed battery recycling processes can accept scrap material generated during the manufacturing of batteries, thus further improving the sustainability of batteries. However, the lack of EOL battery supply until 2040, improved manufacturing processing efficiencies decreasing the availability of scrap, and the competitive EOL battery market landscape could hamper the financial sustainability of battery recyclers (J. Burton, 2022; Circular Energy Storage, 2022; IEA, 2021a).

The inherent synergies between battery recycling processes and midstream operations, coupled with insufficient primary midstream processing capacity, present a unique opportunity. Such synergies can be leveraged to alleviate the potential lack of primary midstream capacity while also generating countless positive externalities.

A significant trend amongst North American junior mining companies developing nickel deposits relates to a lack of planned midstream operations to process feedstocks generated from prospective upstream operations, as demonstrated in Appendix C. In short, while the companies plan to produce concentrates, they will likely be sold on the open market for subsequent processing, given the lack of planned midstream capacity and excess capacity among established operations, as explored in Sections 4.2.4 and 4.3.4. While the presence of upstream operations in North America alleviates reliance on foreign ores, the lack of excess midstream capacity likely implies that the concentrates will be upgraded into relevant products in foreign markets willing to expand to midstream capacity. This, in turn, continues the reliance on imported material for critical supply chains, albeit at the expense of locally sourced ore.

Leveraging the metallurgical technology synergies between battery recycling processes and primary midstream operations can provide enumerable benefits. Most notably, the presence of battery recyclers in proximity to upstream operations producing concentrates can act as a substitute for midstream operations. Such a relationship would ensure localized supply chains from ore to product reducing supply chain risk. Additionally, the ability for battery recyclers to act as tolling operations, akin to precious metal refineries, provides added flexibility to their operations while providing necessary financial support until sufficient EOL battery stock is realized. Finally, and arguably most relevant, developing battery recycling facilities in communities adjacent to upstream operations can support the community by providing long-term solutions beyond the life of the mine as the operational life of midstream assets can be expanded. This could likely support efforts to gain social licenses to operate in the community with upstream deposits, thus increasing the supply of primary production.

5.4.5 Expanding Existing Operations: Supply to Meet Short-to-Medium Term Demand and A Hedge Against Uncertainty

A lack of novel nickel midstream capacity growth sufficient to meet predicted growth in demand for nickel can result in notable negative externalities. This matter is particularly acute when considering the expansion of capacity sufficient to meet growing demand sectors, such as batteries. A lack of nickel capacity appropriate for battery applications could significantly constrain the deployment of clean energy technologies (IEA, 2021a). Given the need to rapidly deploy clean energy technologies coupled with prolonged greenfield development timelines, novel solutions to expand capacity are needed.

Table 5-1: Operational Challenges Amongst Facilities Established Since 2000

Operation	Country of Operation	Year of Establishment	Ore Type	Capacity	Integration	Metallurgical Technology	Product Class	Year Construction Started	Year Construction Completed	Year of First Production	Year Nameplate Capacity Achieved
Huayue Nickel and Cobalt	Indonesia	2021	L	60,000	0	HPAL	Class 2	2020	2021	2021	Ramping
PT Halmahera Persada Lygend	Indonesia	2021	L	35,500	0	HPAL	Class 2	2018	2021	2021	Ramping
Skouriotissa	Cyprus	2021	L	10,000	0	HPAL	Class 2	2019	2021	2021	Ramping
Gordes Meta Nickel Cobalt Facility	Turkey	2016	L	20,000	0	HPAL	Class 2	2012	2014	2016	Nearing Nameplate
Harima Refinery	Japan	2014	L	10,780	1,1	HPAL Dependent	Class 2	2012	2013	2014	2017
Long Harbour	Canada	2013	S	50,000	0	Hydro	Class 1	2010	2013	2014	Nearing Nameplate
Ramu	Papua New Guinea	2012	L	32,601	0	HPAL	Class 2	2008	2012	2012	2017
Ambatovy	Madagascar	2011	L	48,000	0	HPAL	Class 1	2007	2011	2012	Not Reached
Goro	New Caledonia	2009	L	44,000	0	HPAL	Class 2	2005	2009	2011	Not Reached
Dalian	China	2008	L	32,000	2	Pyro	Class 2	2006	2008	2008	Unknown
Terrafame	Finland	2008	B	30,000	0	Bio-Hydro	Class 2	2007	2008	2008	Nearing Nameplate
Ravensthorpe Nickel Operation	Australia	2007	L	30,000	0	HPAL	Class 2	2004	2007	2008	Nearing Nameplate
Yantai Cash	China	2002	U	500	U	Unknown-Hydro	Class 1 & Class 2	Unknown	2002	Unknown	Unknown

When assessing development timelines of midstream operations established since 2000, as outlined in Table 5-1, several concerning trends persist. Most notable is the lack of novel sulphide operations. Only one sulphide operations, Vale's Long Harbour, has been commissioned since 2000. While the operation achieved first production in 2014, when examining the development timeline of the operation, it can be seen that preliminary efforts, namely feasibility studies and testing, took eight years while construction and commissioning were an additional nine years (Vale, 2012, 2015). In contrast, construction and commissioning of recent laterite operations were completed in as short as 18 months (Huayou Cobalt, 2021; Nickel Industries, 2023). The exact reasons for such dichotomies between development timelines for laterite and sulphide operations is unknown. However, likely sources include, permitting challenges, technical and economic requirements, and governance influence.

The extent to which the condensed development timelines of novel lateritic operations can be replicated remains to be seen, specifically in jurisdictions with higher ESG requirements. Further, the lack of insight regarding the capabilities of subsequent converting operations limits the ability to extrapolate the supply impact of the operations on discrete segments of the nickel market, particularly their impact on high-purity nickel products. Nevertheless, novel sulphide capacity will likely be required, specifically in the context of mitigating supply risk among particular countries and regions.

The lack of novel greenfield sulphide capacity and their prolonged development timelines implies that the ability to expand sulphide supply through greenfield developments is unlikely to support short to medium-term growth. In contrast, the relatively condensed timelines of sulphide brownfield expansions for nickel sulphate products, as evidenced by BHP's expansion and Vale's proposed expansion, presents a unique opportunity for operations to expand capacity through brownfield development to meet growing demand, primarily short to medium-term demand growth.

Recent sulphide brownfield capacity expansions have been relatively modest in size. This is likely the result of economic, regulatory, and technical constraints. A likely reason for their reduced timelines relative to greenfield operations is the established accreditation of a social license to operate by local communities. This is likely due to the accepted environmental impact, economic benefits, and established community relations. Such implications are significantly advantageous to established operations relative to proposed greenfield operations. Therefore, expanding brownfield operations can reasonably be achieved within the required timelines to meet demand growth and, in turn, broader climate goals.

To further accelerate capacity through brownfield operations, the potential of larger expansions of brownfield operations should be explored. Doubling or tripling capacity amongst established operations through expansion would significantly contribute to capacity and alleviate supply bottleneck risk. While such a proposition would accelerate the depletion of upstream operations and, in turn, reduce the lifetime of the mine, it can also provide a hedge against several risks. For example, it can be argued that the inherent uncertainty in demand projections, as further explored in Section 5.4.8, could equally impact the prospect of local communities. Therefore, exploiting resources as rapidly as possible would hedge against the risk of future demand destruction. Numerous negative externalities can be conceived beyond the aforementioned scenarios, including scenarios related to environmental, financial, and social outcomes.

The development of novel battery technologies, increased secondary supply, and rapidly expanding nickel capacity in several jurisdictions pose considerable risks to future nickel demand. It could be reasonably assumed that novel battery technologies which are not reliant on nickel, as discussed in Section 5.4.8, could rapidly decrease demand for nickel (IEA, 2021a). Further, the rapid expansion of novel capacity in competing jurisdictions could result in a significant oversupply of nickel if alternative technologies are adopted which would likely have economic implications for established operations. Scenarios in which the lack of policies aimed at countering such risks arise, the inability to rapidly expand supply could, in turn, have equally damaging implications on local communities. Economic and technical evaluations to expand existing operations would be needed before implementing such a policy. While it is recognized that the proposed solution is naive and lacking in sufficient evidence, given the repercussions of inaction, audacious solutions such as this are trivial to the alternative.

5.4.6 Environmental Considerations

The championing of clean energy technologies as viable solutions to reducing global warming emissions from critical economic sectors is promising. However, the substantial metal intensity of viable technologies relative to fossil fuel alternatives presents considerable environmental trade-offs beyond global warming emissions. Therefore, identifying and managing the extent of the impacts is vital to ensuring and maximizing the sustainability of the technologies.

Considering the predicted growth in demand for minerals and metals due to the widespread adoption of clean energy technologies, a considerable expansion in primary supply is required. With the lack of metal commonality between fossil fuel and clean energy technologies, marginal displacement of existing supply will likely transpire, as discussed in Section 1.5.1. Further, the continued demand and growth of traditional applications will require additional novel supply.

While recycling is a viable solution to limit the need for novel supply, projected demand exceeds projected secondary supply (IEA, 2021a). Additionally, when considering the availability of secondary sources amenable to novel supply requirements, the ability of recycling to act as a viable solution to meeting novel demand is limited, thus further solidifying the need for novel primary supply. Identifying and managing the environmental impacts of novel supply concerning all downstream applications is necessary to avoid problem shifting. This matter is particularly acute in relation to nickel.

5.4.6.1 Environmental Trade-offs – Ore, Process, and Product Quality

As demonstrated in Section 4.3.3, a significant relationship exists between ore type, processing technology, and output product quality. Such correlations can, in turn, be extended to linked environmental impact. Considerable variation in the environmental impact persists across products, processes, and geographies, as stated in Appendix A. Further, the impacts vary considerably across distinct environmental categories. The variability presents considerable trade-offs between products originating and processed under distinct conditions. For example, the impacts of tailings generated from lateritic HPAL operations, both MP and Class 1 operations, present substantial risk (Durrant, 2023). In contrast, sulphur dioxide emissions from sulphide smelting operations are of considerably concern (Fioletov et al., 2016; Whitby et al., 1976).

While countless equivalent examples can be considered, adopting technologies aimed at addressing and reducing associated environmental impacts, such as dry stack tailings or flue-gas desulphurization, can considerably reduce the impact of an operation (Eri Silva, 2023; Plant & Mathay, 1999). Nevertheless, the prohibitive cost of implementing such technologies can limit their proliferation (Erik White, 2018; Rodrigo Gouveia, 2020). This gives rise to a limited subset of capacity for which their environmental impact across all categories is negligible. As such, companies or governments requiring nickel products with specific environmental characteristics can consequently generate a considerable supply chain bottleneck. Therefore, considering the supply potential of products with the requisite characteristics is necessary in developing applicable policies.

5.4.6.2 Regional Requirements and Industry Goals

Increased awareness of the associated environmental impacts of products and services has resulted in governments and industry stakeholders considering and implementing policies to reduce associated environmental impacts. The adoption of related policies is primarily concentrated in developed countries or amongst industry participants present in such jurisdictions. While several policies intend to utilize their corresponding market force to influence regions beyond their respective control, it remains to be seen the extent to which the totality of non-compliant supply chain actors conform. The lack of broader industry participation can generate a bifurcated market in which compliant stakeholders compete with non-compliant stakeholders. Two prominent examples of competing environmental policies influencing nickel, for which considerable bifurcated markets could arise, are the European Commission Green Deal proposed regulation on batteries and ResponsibleSteel's International Standard V2.0 (European Commission, 2020b; ResponsibleSteel, 2022).

The European Commission's proposed policy aims at reducing the environmental impact of batteries used within the region, while ResponsibleSteel's standard aims to improve the sustainability of steel products. While the policy and standard aim to address multiple ESG considerations, a key pillar of each strategy relates to carbon emissions. Given the presence of nickel in both batteries and steel, the strategies are inherently in competition with one another for low-carbon or carbon-neutral nickel products.

For example, while steel producers can leverage nickel products that do not compete with battery applications, namely FeNi and NPI products, the considerable environmental impacts of such products, as discussed in Appendix A, limits the ability of stainless steel producers to adopt such products while attempting to achieve the overarching standard. Therefore, to meet the standard, steel producers will emphasize the procurement of available low-carbon nickel products, which, as demonstrated in Appendix C, are equally suitable for battery applications. Similarly, battery producers operating in the European market will equally aim to procure available low-carbon nickel products to meet regional requirements, thus generating competing interest for products with limited supply.

The restricted availability of low-carbon nickel products and their compatibility in steel and battery applications presents a considerable bottleneck to producers impacted by such regulations or standards. A lack of consideration towards the availability of low-carbon feedstocks in the design of such policies could result in contradictory outcomes to the overarching objectives of the policies and in considerable problem shifts. For example, the competition could induce a premium for low-carbon nickel products. In turn, operations unable to economically adopt such price premiums and comply with requisite policies could be displaced to alternative jurisdictions lacking equivalent policies. Alternatively, operations accepting the elevated cost must compete with producers in regions without relevant policies, albeit at a disadvantageous due to elevated cost, thus generating further bifurcate market.

5.4.7 Supply Independence Requires Supply Chain Independence

Along with heightened attention toward the environmental impacts of products and services, an equally growing trend has emerged as it relates to the geographic concentration of supply chains. Such attention has been particularly acute as it relates to the production of critical metals and minerals used in clean and emerging technologies. In an effort to reduce their reliance on critical minerals and metals from foreign countries, several countries have enacted policies to support efforts to ensure localized supply or ensure supply from allied sources (European Commission, 2023; South Korean Government, 2022; U.S. Department of State, 2022). While such efforts could reduce a given country's reliance on foreign supply, the limited scope of the policies does not alleviate supply susceptibility from foreign influence. Such susceptibility can take two forms: midstream operations reliant on imported feedstocks and imported processing components. While the following examples shed light on such matters in relation to nickel, the vulnerabilities apply to alternative critical mineral and metal supply chains.

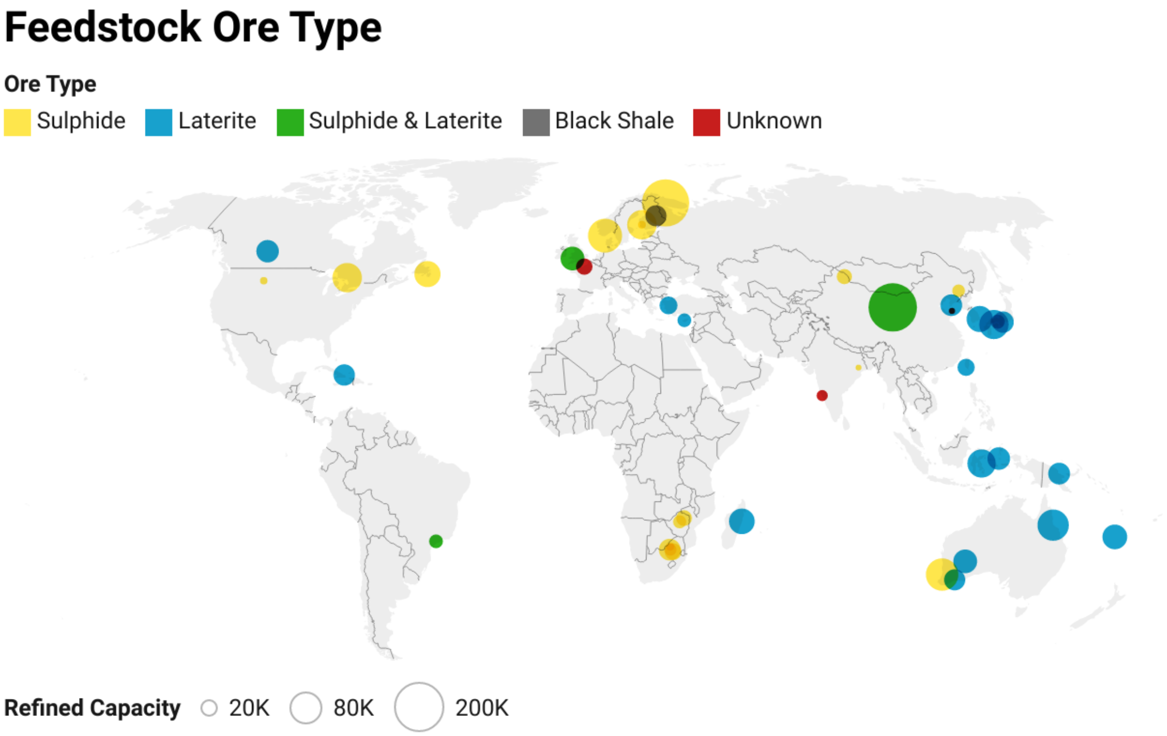


Figure 5-3: Geographic Distribution of Metallurgical Capacity by Feedstock Ore Type

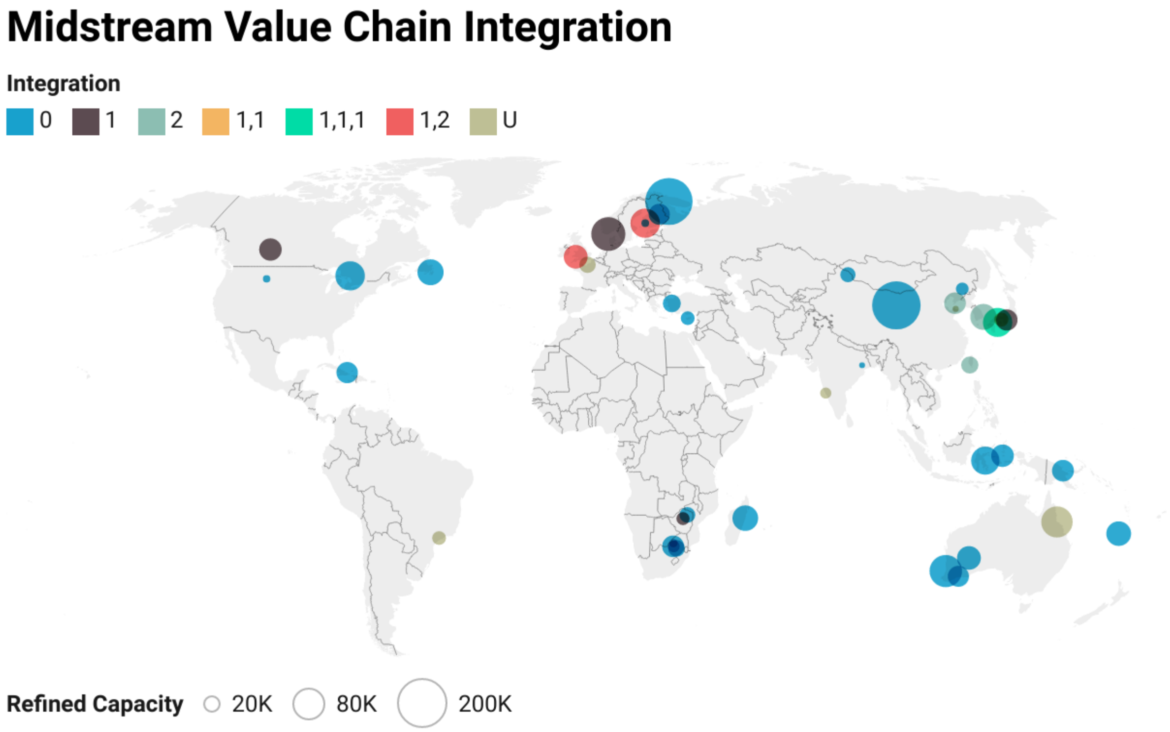


Figure 5-4: Geographic Distribution of Metallurgical Capacity According to Integration of Midstream Value Chains

As discussed in Section 4.3.5, the majority of sulphide operations, particularly Northern European operations, as demonstrated in Figure 5-3, are not vertically integrated and rely on imported feedstocks, as illustrated in Figure 5-4. While the localization of midstream operations within countries provides a localized source of nickel products for their respective downstream demand, the reliance on imported upstream feedstocks does not alleviate their susceptibility to foreign influence. As such, the level of integration of midstream operations could cause bottlenecks for particular countries or regions.

The alternative bottleneck risk related to supply chain independence, albeit seldom considered, relates to the reliance of upstream and midstream operations on imported processing components and services. Notable examples of processing components include metallurgical technologies, such as furnaces or reactor vessels; and reagents, such as lixiviants or sulphur. Alternatively, examples of services include engineering, financing, and logistics. The lack of domestic processing components and services can result in midstream operations, including vertically integrated operations, susceptible to foreign influence. A notable example includes the reliance of solvent-extracting unit operations on specialized lixiviants for which a limited number of producers globally can readily supply. Without the necessary lixiviants, midstream operations with solvent extraction operations would be unable to operate. In turn, the lack of domestic processing components and services can result in considerable bottlenecks for countries looking to alleviate foreign supply risk.

5.4.8 Demand Risk

The development of novel battery technologies and manufacturing processes presents considerable risk regarding the materialization of future demand projections. Additionally, social pressures stemming from substandard extraction practices for particular minerals and metals could expedite manufacturers' adoption of alternative technologies and processes (IEA, 2021a) or by seeking responsible sourcing and sustainability certification (S. B. Young, 2018; S. Young & Dias, 2011; S. B. Young et al., 2010, 2014). These matters are best exemplified by the battery manufacturers decreasing the use of cobalt in their batteries as well as adopting chemistries without cobalt primarily due to consumer pressure stemming from poor labour conditions in artisanal cobalt mining operations in the Democratic Republic of the Congo (Faber et al., 2017; Van den Brink et al., 2020).

Decreased cobalt content has resulted in manufacturers adopting formulations with higher nickel content to compensate for the effects of reduced cobalt content, thus further increasing demand for nickel (Li, Erickson, et al., 2020; IEA, 2023b). Given the presence of cobalt in nickel deposits, as discussed in Section 2.2.1, it remains valuable to evaluate the potential of nickel operations to produce cobalt, as discussed in Section 3.4.2.3.2 and demonstrated in Section 4.2.16.

In addition to adopting formulations with lower cobalt content, manufacturers have also explored chemistries absent cobalt (Gourley et al., 2020; Li, Lee, et al., 2020; Y. Kim et al., 2021). Lithium-Iron-Phosphate (LFP) is the most prominent chemistry exhibiting widespread commercialization and adoption, which does not require cobalt or nickel (IEA, 2021a). Adopting LFP chemistries is anticipated to reduce demand for cobalt and nickel (IEA, 2023b).

Such radical and rapid technological shifts present substantial risks to companies developing deposits and upgrading operations, including stakeholders involved in nickel. The prolonged lifespan of deposits and transforming operations require long-term financing due to the high barriers to entry (IEA, 2023b). Therefore, it remains possible that the assets could become economically infeasible prior to achieving any positive financial outcome. While the effects of such matters are not explored in detail as part of this research, they remain relevant to future discussions related to this subject. Further, research and discussions are needed on required policies to bridge the gap between the long development and financial payback periods incurred by commodity producers and the relatively abrupt shifts in material demand endemic to technology manufacturers.

5.5 Metallurgical Capacity – Research Applicability

Developing a metric to assess the production capacity of mineral or metal products with sufficient resolution to highlight the intricacies of the supply chain stage and address the needs of relevant stakeholders was the primary motivation for developing metallurgical capacity. While the case study conducted herein demonstrated the utility of the metric, the pertinence of the metric to alternative applications was revealed in conjunction. While the most logical applicability of the metric is its ability to be extended to alternative minerals and metals, several other applications could benefit from the metric. They include criticality assessments, geopolitical risk, and environmental assessment.

5.5.1 Other Minerals and Metals

The applicability of metallurgical capacity as a metric in assessing the availability of specific minerals and metals was demonstrated as part of the case study conducted. The success of the metric gives rise to its broader applicability. Given the malleability of the underlying methodology used to determine the metric, its applicability to minerals and metals beyond nickel is indefinite. While possible to extend the metric to any mineral or metal, the metric is most effective for minerals or metals exhibiting fragmented supply chains with respect to their ore sources, processing routes, or product output. Additionally, the metric's focus on capacity as opposed to production is highly valuable in assessing minerals or metals with highly elastic supply responses. For example, specific unit operations can be placed on care and maintenance while the remainder of the operation continues to operate to reduce operating cost during periods of market oversupply. Such considerations are particularly acute among minor metals (McNulty & Jowitt, 2021).

When considering the importance of critical minerals and metals to the energy transition and the dynamics of their respective supply chains, the metric can play a pivotal role in further evaluating and communicating the availability of critical minerals and metals. This is especially true of critical minerals and metals suitable for battery applications. A few notable examples of critical minerals and metals vital to battery applications for which expeditious adoption of metallurgical capacity could meaningfully support the adoption of the technology include lithium, phosphorus, and manganese. Similarly, the metric presents considerable potential when considering metals commonly produced as ferroalloys, given the diverging nature of their midstream value chains.

Similar to nickel, lithium exhibits bifurcation with respect to its geological sources, processing routes, and output products. The presence of lithium in hard rock and brines presents two distinct supply chains, each requiring distinct processing routes for conversion into relevant products (Vikström et al., 2013). The historical demand for technical-grade lithium products coupled with novel demand for battery-grade lithium products and their further sub-bifurcation into lithium carbonate and lithium hydroxide products exacerbates the fragmented nature of the metals supply chain (Egbue & Long, 2012).

As discussed in Section 5.4.8, phosphorous has gained interest amongst battery manufacturers as an alternative cathode chemistry due to its perceived relative abundance and relatively low cost. However, phosphorus similarly exhibits a fragmented supply chain due to its geological sources, processing routes, and output products. When considering purified phosphoric acid, which is the only suitable phosphorus product for battery applications, can be derived from igneous feedstocks, of which only account accounts 5% of global reserves, the abundance of phosphorus in the context of batteries is significantly diminished (Hotter, 2023). Similarly, the array of phosphorus chemicals produced, which are primarily oriented towards agricultural applications, and distinct processing routes, further exacerbates the complexity of the metal's supply chain (Mew et al., 2018).

Finally, manganese presents a valuable case study for metallurgical capacity. While produced in significant quantities, it is primarily processed into ferromanganese products for metallurgical applications. In contrast, a small fraction of manganese is refined into electrolytic metal manganese (EMM), for which is suitable for battery applications (IMnI, 2022). Further, a limited number of manufacturers possess the refining technology suitable to produce EMM deprived of selenium, a highly toxic element (Creamer, 2022).

A subset of metals for which metallurgical capacity could benefit their broader understanding of their respective supply chains includes metals for which the primary output product is ferroalloys. Similar to nickel and manganese, metals such as chromium, molybdenum, and vanadium are commonly transformed into ferrous products, while a smaller fraction of mined production is transformed into purified refined products (Gasik, 2013; Gao et al., 2022; Lee et al., 2021; National Research Council, 1995; U.S. Geological Survey, 2022). Such supply chain bifurcations are vital to understand given the skewed distribution amongst the produced output products. Detailed understanding of their respective supply chains and the supply capacity for distinct products produced can support countless stakeholders, including researchers, policy planners, and manufactures.

While not explored, additional examples of critical minerals and metals for which timely adoption of the metallurgical capacity would be beneficial include rare earth elements (Castor & Hedrick, 2006), fluorspar (Simandl, 2009), silicon (Simandl et al., 2023), and graphite (Jara et al., 2019). Alternatively, the adoption of the metric for minerals and metals not deemed critical that would benefit from the metric include iron (Vittori et al., 2021), sulphur (Maslin et al., 2022), and sodium (Vaalma et al., 2018).

5.5.2 Criticality

As previously mentioned, governments and companies are increasingly assessing the geographic concentration of mineral and metal supply chains, particularly those related to critical applications. This has resulted in numerous evaluations on the criticality of countless minerals and metals (J. Burton, 2022; European Commission, 2020a; Government of Canada, 2022). The scope of the evaluations varies considerably amongst studies. However, by in large, assessments utilize metrics such as reserves and resources or mined production (Graedel & Reck, 2016). While more recent assessment have expanded the breadth of metrics used to evaluate criticality, the aggregation of employed data likely misrepresents suitable production. Further, given the fragmented nature of mineral and metal supply chains, by utilizing such metrics, the applicability of the assessments is significantly reduced.

A more nuanced and targeted assessment of criticality can be achieved by utilizing metallurgical capacity as a substitute for prevalent metrics. Such subtlety is granted through the metric’s increased granularity and improved data quality, which remains a considerable limitation to current criticality assessments (Schrijvers et al., 2020). For example, when assessing a country’s criticality in relation to nickel for battery applications, utilizing the metallurgical capacity of the country in question to produce battery-suitable nickel products would best represent its independence. In contrast, using mined production, which does not account for product quality, would, in many cases, overestimate a country's degree of independence.

5.5.3 Geopolitical Risk

Similar to criticality, the geopolitical risk of mineral and metal supply chains has been of significant concern to countries lacking exploitable resources or value chain assets (Cimprich et al., 2017). Ensuring adequate supply from allied countries with sufficient exploitable resources or production capacity is critical to ensuring accessible supply for domestic industries during potential conflicts. While metallurgical capacity can support in evaluating allied countries with sufficient capacity to meet necessary domestic demand requirements, the metric can further support in evaluating specific geopolitical risks for countries lacking both established upstream and midstream operations. A notable example includes the degree to which midstream operations are integrated. Non-integrated operations are highly susceptible to supply disruptions. Thus, understanding the degree of integration is vital to assessing geopolitical risk. While supply disruption for non-integrated operations can commonly take the form of import or export restrictions by governments, they can similarly result from foreign companies operating facilities within a given country and acting on behalf of their respective government. As such, understanding the sovereignty of capacity is critical to assessing geopolitical risk.

5.5.4 Supply Chain Environmental Assessments

Metallurgical Capacity demonstrates tremendous potential in supporting the environmental impact assessments of products and services. In a similar regard to criticality, the granularity and resolution of the data afforded by the metric can considerably improve the applicability of an assessment. The ability to account for specific attributes of mineral or metal products, notably product quality, processing pathways and product carbon footprint, can considerably improve the resolution of assessments. Further, the metric grants the ability to develop alternative scenarios and more accurate sensitivity analysis, providing a more accurate representation of practical upper and lower bound limits. For example, when modelling the environmental impact of nickel in superalloys under different demand scenarios, the metric permits the ability to account for the path and impact dependency of the nickel, or other raw materials, used in the product. More specifically, it is possible to model a scenario in which a superalloy is produced using Class 1 nickel procured from Vale's Long Harbour operation, with the lowest reported carbon footprint of 4.4 kg $CO_{2\text{-eq}}$/kg Ni, relative to nickel procured from Vale's Clydach operation, with a carbon footprint of 33 kg $CO_{2\text{-eq}}$/kg Ni. By modeling scenarios with such data resolution, a more accurate representation of feasible outcomes can be achieved.

5.6 Research Limitations and Future Research Opportunities

Developing a metric to assess the supply potential of mineral and metal supply chains is intrinsically challenging, given their exceedingly opaque nature. The metric and methodology developed herein permit the ability to amass considerable data on assessed supply chains. However, an enumerable number of limitations persist, restricting the utility of collected data. Limitations of collected data within the case study were previously outlined in Section 3.6. Broader structural limitations related to both the case study, as well as the metric and methodology are discussed in the following section. Additionally, future research opportunities to improve upon the utility of the metric and methodology are presented.

5.6.1 Fluid Market

The volatile nature of commodity markets results in considerable temporal variations in market dynamics. Given that the scope of the study conducted herein accounts for market dynamics in 2021, collected data predates changes in market dynamics incurred in the ensuing years. This matter is particularly acute regarding nickel. When considering the unprecedented growth of greenfield midstream operations in Indonesia commissioned after 2021, metallurgical capacity is likely considerably higher, specifically MP and NPI-to-Matte capacity (McKay, 2023). As such, accounting for the variability in market dynamics and providing a contemporary representation of the supply chain is challenging. Further, the size and opacity of the market present unique challenges in ensuring an exhaustive scope.

Alternatively, the time lag between production and production disclosures presents further challenges when illustrating market dynamics. For example, annual corporate reports summarizing annual production are typically published towards the end of the first fiscal quarter, generally between February and May of the subsequent year for companies with January 1st fiscal calendars. While it remains possible to update production figures on a quarterly basis, the sparsity of the data inhibits its utility. To ensure the metric is representative of the most recent market dynamic, annual updates of the metric are necessary to account for incurred changes.

To address these shortcomings, several viable solutions are presented. Most notably, open-sourcing data collection can support efforts to update data regularly and address existing data gaps. As mentioned, the scale of mineral and metal supply chains and their opacity remains a challenge to assess in a comprehensive manner. By developing an open-source data collection system, a larger subset of contributors with relevant regional or industry knowledge can participate, ensuring more representative data. Alterative solutions include conducting periodic industry surveys, as further discussed in Section 5.6.3, and annual government geological surveys, as further discussed in Section 5.6.6.

5.6.2 Economic Attributes

A significant weakness of the case study conducted is a lack of consideration for the economic attributes of midstream operations. When considering the importance of economics on the feasibility of an operation, incorporating such data into the metric would significantly improve its utility. In addition, a lack of economic data, notably regarding revenues, realized metal prices, operating costs, and profit margins, considerably limits the depth of the analysis. Inclusion of such attributes to both the case study conducted as well as subsequent case studies would support efforts to understand the impacts of variable metal prices on production or operable capacity.

Further, including economic data would highlight the economic discrepancies amongst operations, which could be related to ore type, processing technology, product quality, and environmental performance. While economic data is generally limited to publicly owned operations, it could be reasonably extended to privately owned operations with equivalent attributes and operability. However, the ability to extend economic data and realize broader industry trends could likely be limited due to inconsistent reporting standards amongst companies, as further explored in Section 5.6.6.

5.6.3 Processing Comparability

A further limitation of the case study is the aggregation of midstream value chains and evaluated operations. In particular, a lack of detailed considerations toward preceding midstream operations. For example, smelters within the value chain of assessed terminal midstream operations, more specifically regarding their respective operational attributes, limits the scope of the study. In a similar regard, evaluating midstream operations in aggregated manners, whereby individual unit operations of a facility are not considered, further limits the scope of the study. Assessing both trailing operations within midstream value chains as well as the unit operations of a given facility would significantly improve the exhaustiveness of the study.

A proposed solution to address this shortcoming includes developing an analogous index to that used to assess the complexity of petroleum refineries. The Nelson Complexity Index, initially conceptualized in the 1960s by W.L. Nelson and since further expanded upon, measures the complexity and cost of each unit operation within a given petroleum refinery (Kaiser, 2017). As such, the index allows for more apt comparisons of refineries in relation to their respective capabilities. Additionally, the index can provide a relative approximation for key operational attributes, such as production cost, product output, and environmental controls, for particular operations. While developing a surrogate index for midstream metallurgical operations would require notable adaptations, the index provides a sufficiently malleable methodology and framework reasonably suitable for metallurgical midstream operations. Further, developing such an index would require vast quantities of accessible data. The requisite data could be collected through periodic industry surveys, similar to surveys conducted by the TMS (Battle, 2004; Jones, 2004; Kapusta, 2004; Warner et al., 2006, 2007), for which technical data of individual operations were collected, as discussed in Section 2.3.2.

A noteworthy application of such an index includes the proficiency to compare the qualification of dissimilar operations to exchange feedstocks. The ability of a midstream operation to accept intermediate third-party feedstocks from a relevant counterparty could significantly improve the efficiency of installed capacity. A notable example is Jinchuan's and Nornickel's refusal of Anglo American's Rustenburg Base Metal Refinery matte. According to Anglo America, their feedstock, which was derived from sulphide-poor ores, is incompatible with the majority of nickel operations, specifically those primarily processing sulphide-rich ore feedstocks. This is due economic challenges as well as technical challenges such as the presence of elevated concentrations of magnesium oxide and chromite, and necessitating operating temperatures above 1400 degrees Celsius (Ndlovu, 2014). A metric demonstrating the ability of operations to exchange feedstock would benefit the broader industry in maximizing capital resources. Further, it would support operations in extending the useful lifetime of their assets beyond the depletion of dependent deposits.

5.6.4 Upstream and Midstream Synergies

A considerable opportunity to expand the utility of the metric lies in further investigating the interface between upstream and midstream operations. As part of the case study, adopted system boundaries primarily focus on the interface between midstream and downstream operations. The inclusion of data related to the quality of output products from midstream operations primarily supports the downstream operations in evaluating the availability of suitable nickel products and functional capacity. Expanding the assessment to include the quality of input feedstock necessary for midstream operations would further improve the utility of the analysis. Such an analysis, in tandem with an analogous Nelson

Complexity Index, would support efforts to correlate midstream processing requirements to a given ore body. As such, reserve and resource estimates could then be reasonably segregated to include consideration for output product quality and other relevant attributes.

This matter is particularly acute when considering iron ore. While relatively abundant, deleterious elements in iron ores, notably silica, aluminum, and phosphorus, necessitate additional upstream and midstream unit operations to purge the elements and achieve the requisite final output product quality requirements (Dub et al., 2006). Further, technological limits of the unit operations constrain the ability of established midstream operations to process iron ores with concentrations of deleterious elements in excess of established thresholds. The ability to assess an iron ore body in relation to appropriate processing operations would significantly improve a broader understanding of available resources and reserves and potentially expedite their development.

5.6.5 Other Limitations

A number of additional limitations can reasonably be deduced in relation to both the methodology and the metric. A notable limitation includes the influence of non-majority owners on the operability of an operation. This matter is particularly relevant in relation to feedstock procurement, product marketing, capacity fixed to off-take agreements, environmental goals, and geopolitics.

Similarly, a lack of deliberation regarding upstream feedstock, as it relates to feedstock quality and volume, limits the depth of the analysis. As previously mentioned, the ability to correlate upstream and midstream operations would considerably expand the scope of the analysis or any subsequent analysis.

Analogously, insufficient consideration for downstream off-take agreements could lead to a misrepresentation of accessible capacity. This is particularly relevant for critical minerals and metals as companies and governments aim to secure future supplies. For example, the BHP has multiple nickel supply agreements with various automotive manufactures including Ford (BHP, 2022), Tesla (BHP, 2021b), and Toyota, via Toyota Tsusho Corporation and Prime Planet Energy & Solutions (BHP, 2021d). Accounting for both upstream and downstream off-take agreements can further shed light on accessible production capacity for a given supply chain.

5.6.6 Recommendation and Improvements

Enhancing the scope, granularity, utility, and applicability of the metallurgical capacity metric could be achieved through a number of recommendations enacted by industry participants. A viable solution to expand the metric to alternative minerals and metals includes expanding annual government statistics and reporting to include metallurgical capacity, analogous to established reporting on reserves, resources, and mined production. While such reports lack equivalent degrees of transparency and granularity in relation to the metric presented herein, such efforts would support providing a credible data source.

Although the aggregation prohibits detailed analysis, it would likely support in collecting data on privately owned operations for which limited publicly available data exist. An alternative method to collecting data on privately owned operations includes a continuation of industry surveys, as previously discussed in Section 5.6.3. The surveys would further benefit in collecting pertinent primary data compared to secondary data, as relied upon in the case study conducted herein.

The most applicable recommendation relates to company reporting practices. The lack of industry standards for metallurgical accounting and reporting results in considerable uncertainty. This is in contrast to established national standards, namely National Instrument 43-101 (NI 43-101) (Canadian Securities Administrators, 2012), Joint Ore Reserves Committee Code (JORC) (JORC, 2012), and South African Code for the Reporting of Mineral Resources and Mineral Reserves (SAMREC) (SAMREC, 2016), which set strict reserve and resource reporting requirements. The prominence of the standards is achieved through government requirements and the need to conform to such standards in order to be publicly listed amongst several exchanges. Extending the standards to include metallurgical accounting would benefit policymakers, researchers, as well as investors by providing a consistent means of comparing operations. In addition, such an extension would benefit from disaggregated reporting on operational performance. In turn, segregated reporting on the performance of individual operations, as well as of individual products, would further improve the efficiency of the market.

Additional transparency regarding off-take agreements for feedstocks, output products, and marketed products would be beneficial. Transparency regarding such aspects would greatly benefit downstream stakeholders in ensuring the provenance of the material within a given product. While such efforts to increase operational transparency pose a considerable commercial risk, the increased transparency could induce substantial positive externalities, most notably in the form of broader public confidence and support for the industry. This could ultimately support efforts to gain critical social licenses to operate.

Chapter 6
Conclusion

6.1 Research Gap

Minerals and metals are vital to modern society. Their advantageous properties and a lack of equivalent substitutable materials have rendered them indispensable to nearly every facet of life. Absent any revolutionary material advancements, minerals and metals will remain a foundational component of society. However, given the need to address climate change, their societal relevance will conceivably ascend.

Rapidly reducing global consumption of fossil fuels is vital to minimizing further impacts of climate change. Countless technologies have demonstrated technical and economic viability to replace fossil fuels. However, while the technologies reduce the consumption of fossil fuels, they inherently present novel problems. The mineral and metal intensity of the technologies will necessitate unprecedented consumption of countless mineral and metal resources (IEA, 2021a). Increasing deployment of the technologies will, in turn, shift the global economy from a fossil fuel-based economy to a mineral and metal-intensive economy.

Countless studies have demonstrated the required scale of deployment of available technologies to meet global climate change commitments. In turn, studies have correlated the necessary supply of minerals and metals to meet required demand (Hund et al., 2020; IEA, 2021a; World Bank Group, 2017). Results indicate that unprecedented expansion in the supply of numerous minerals and metals is required. With minimal demand displacement from fossil fuel technologies and insufficient supply from secondary sources, primary supply will be required to attain climate goals (M. Burton & Biesheuvel, 2022; Ghenai & Janajreh, 2013; Hund et al., 2020; IEA, 2021a; Petavratzi & Gunn, 2022). Moreover, in addition to clean technologies, growth in demand from conventional applications of minerals and metals is further expected to increase, thus exacerbating the need for novel primary supply.

Fortunately, it has been demonstrated that sufficient resources of crucial minerals and metals remain unexploited (IEA, 2021a). However, a considerable challenge persists in exploiting the resources within the necessary timelines to meet predicted demand and, ultimately, climate targets. Historical development timelines for novel primary supply present a considerable bottleneck in ensuring sufficient future supply (Keen, 2022; Khan et al., 2016). Further, ensuring that the exploitation is conducted sustainably is vital to minimizing problem shifting.

The complexity, scale, and opacity of mineral and metal supply chains present a considerable challenge for downstream stakeholders aspiring to procure vital resources for their products expeditiously. This matter is further engrossed when considering ESG requirements. Established metrics to assess the geological availability and annual production of minerals and metals provide insufficient insight into the complexity and intricacies of mineral and metal supply chains. This presents a considerable challenge to stakeholders within the mineral and metal supply chain with a deficient understanding of the associated nuances. A considerable need and opportunity remains to develop metrics with sufficient representation of the intricacy of mineral and metal supply chains to support relevant chain stakeholders.

When considering mineral and metal supply chains, it can be seen that extensive and accessible assessments of upstream and downstream operations have been conducted. Such assessments primarily focus on resources, reserves, annual mined production, and demand from downstream applications. In contrast, a limited number of assessments of midstream stages have been conducted. The lack of midstream evaluation is substantial when considering the diverging nature of mineral and metal supply chains, explicitly as it relates to upstream inputs and downstream outputs.

Supply chain divergences result in distinct relationships amongst operational attributes. Specifically, the array of products produced by midstream operations, in relation to product composition, chemistry and form factor, require distinct processing pathways and significantly impacts downstream procurement capabilities. Therefore, understanding the correlation amongst the distribution of products produced, attributes, and their associated capacity can considerably support downstream procurements efforts. This is particularly relevant for downstream producers of clean technologies requiring prompt procurement of distinct mineral and metal products.

6.2 Metallurgical Capacity

Assessing the extent to which mineral and metal midstream operations can supply discrete downstream demand sectors is vital. As such, a novel metric, metallurgical capacity, was developed to quantify the production capacity of mineral and metal midstream operations. The metric was developed using a bottom-up facility-by-facility methodology, analogous to the methodology applied by Mudd to assess upstream operations (G. M. Mudd et al., 2013; G. M. Mudd & Jowitt, 2014; Weng et al., 2015). The methodology was selected due to its demonstrated ability to afford highly granular data of distinct attributes of mineral and metal operations.

6.3 Nickel Case Study

The utility of the metric was determined through a case study of primary non-ferrous nickel. The supply chain was chosen as the inaugural supply chain due to its diverging ore supply, processing pathway, and product output. Further, the supply chain's relevance in clean technologies, namely for electric vehicles and grid storage batteries, provided supplementary bearing to its selection (IEA, 2021a).

Adopted methodology granted the compilation of considerable supply chain data. Data on critical attributes, including ownership, development, operational, technological, investment, and environment, was collected for each terminal midstream operation in the supply chain. Secondary data was exclusively used, which was primarily derived from company reports and disclosures. Operational data was collected in reference to 2021, while product data was collected in reference to 2023 capabilities. In all, 42 operations, for which produced 161 products, were assessed.

The metallurgical capacity of primary non-ferrous nickel in 2021 was determined to be 1.6 million metric tonnes. The metallurgical capacity was found to be in close approximation to reported industry figures using an undisclosed methodology and database, suggesting that the case study was successful in evaluating the supply chain. Furthermore, due to the expanse of data collected, courtesy of the adopted methodology, several unique insights on the assessed supply chain were divulged which are not considered in similar reports. Such details further supported the assessment of the proposed case study questions.

Several notable findings concerning the proposed case study question were determined. First, it was determined that the majority of metallurgical capacity was operating in 2021 with limited capacity under care and maintenance. Similarly, it was determined that, of operations reporting production volumes between 2019-2021, most operated near their respective nameplate capacity suggesting limited underutilized capacity persists. When assessing the products produced across the value chain, it was shown that products are predominantly advertised for metallurgical applications. In contrast, a limited number of products are primarily advertised for battery applications. However, novel midstream operations have demonstrated a trend toward products directly advertised for battery applications.

Regarding novel midstream operations, a disproportionate number of operations established since 2000 predominately process laterite ores and employ HPAL processes. Over the same period, only one novel sulphide operation was established and exhibited considerable development challenges. When considering geographic concentration and monopolization, it was shown that capacity is reasonably geographically distributed, with few regions lacking capacity. Nevertheless, a limited number of companies controlled a considerable portion of capacity. Concerning carbon neutrality commitments, over half of the capacity is tied to commitments, with the majority intended to be realized by 2050. While a comprehensive evaluation of intended expansion and recycling investments amongst established operations was not achieved due to a lack of meaningful data, a notable trends towards battery materials and battery recycling amongst established operations was highlighted.

In addition to addressing stated research questions, the methodology and data permitted the identification of several supply chain bottleneck risks. Identified risks were considered for both current supply chain dynamics as well as predicted future supply chain dynamics. The most prevalent bottleneck risk identified is the considerable disruption potential absent novel supply. While the effects of the disruption will likely impact the entirety of the supply chain, downstream metallurgical stakeholders reliant on non-ferrous nickel products, namely stainless steel, plating, and non-ferrous alloy manufacturers, are likely to be disproportionately impacted. Likewise, without adequate novel capacity sufficient for battery applications or changes in material requirements for battery applications, the deployment of the technology and, in turn, climate goals will likely falter.

While the timelines of recent laterite developments present considerable promise to expanding supply, it remains unclear the extent to which the developments can be replicated, given the historical precedent of similar laterite developments. Further, increased awareness of the environmental impacts of laterite operations could limit the extent to which such development could contribute to novel supply, specifically amongst concerned consumers. Additionally, the geopolitical risk of novel laterite supply presents considerable risk. In all, novel primary laterite and sulphide midstream capacity will be required to meet future demand scenarios and proposed provenance requirements.

6.4 Outcome, Outlook, and Obstacles

The research objective of developing a novel metric and accompanying approach to assessing the production capacity of midstream operations was successfully achieved, as demonstrated by the success of the case study. Specifically, the main case study question and five sub-questions were successfully answered, while one sub-question was partially answered. Moreover, the case study conducted demonstrated innumerable novel insights regarding the primary non-ferrous nickel supply chain and its dependent stakeholders. While the insights demonstrated herein represent a subset of relevant categories, accompanying data can readably be adapted and tailored to the needs and considerations of individual stakeholders.

Although the metric provides valuable insights, countless opportunities remain to expand upon the case study and metric. Specific to the case study, expanding the parameters to include ferrous products, secondary sources, and preceding midstream value chain operations would benefit a broader understanding of market and supply chain dynamics. As it relates to the metric, the inclusion of economic attributes, upstream feedstock characteristics, and consideration of capacity fixed to off-take agreements would considerably expand the utility of the metric.

The success of the case study and the methodology's malleability suggest that the metric can be reasonably extended to other minerals and metals. In particular, adoption amongst critical minerals and metals such as lithium, manganese, and phosphorus would considerably support the deployment and development of battery technologies. Alternatively, the metric would benefit mineral and metal supply chains for which multiple products of the metal are produced; for example, metals that are predominately transformed into ferroalloys. Adoption of the metric in periodic government commodity surveys would benefit countless stakeholders. Alternatively, an open-sourced framework for collecting data would further improve the resolution of the data collected by leveraging expert and regional knowledge of facilities.

While the metric and case study proved resourceful, several obstacles were encountered specific to the case study as well as to the metric that requires further deliberation to improve the quality of the metric. Most criticality was overcoming the sparsity of the data. Establishing industry standards for reporting would considerably improve the transparency and consistency of the data. Alternatively, the fluidity of commodity markets presents a considerable challenge in illustrating a representative characterization of supply chains. Periodic updates of the metric would ensure contemporary dynamics are depicted while simultaneously monitoring market trends.

6.5 Reflection

While the adopted method provided critical insights into the supply chain of a singular critical metal based on defined parameters, the methodology highlighted the broader systematic and multi-variable nature of supply chains, as demonstrated by the potential indirectly induced chromium supply chain bottleneck risk from future nickel demand. As such, it remains relevant to ensure that adequate systematic considerations are deliberated when developing pertinent policies directed at addressing explicit supply chain attributes. Such a matter is further exacerbated when attempting to concurrently address and maximize multiple attributes. This is best reflected in the need to rapidly deploy clean technologies while simultaneously addressing and maximizing environmental, social, financial, and political elements. Given the systematic and multi-variable nature of supply chains, maximizing for multiple criteria will inherently require innumerable concessions. Absent adequate consideration and deliberation of relevant concessions, policies will inevitably continue to falter from their objectives. Therefore, when attempting to alter a multi-variable system, it remains imperative to recall that, to optimize is to compromise.

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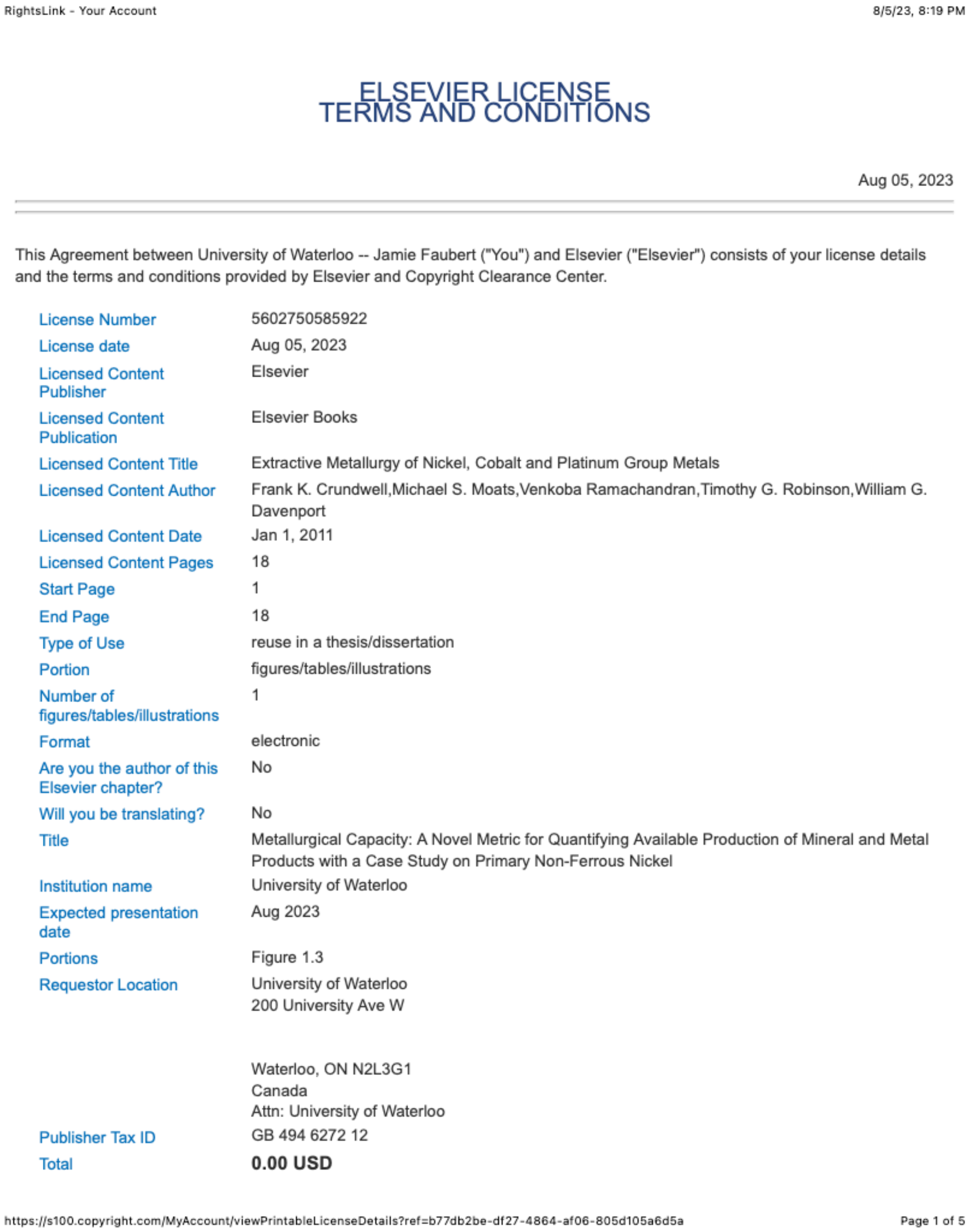

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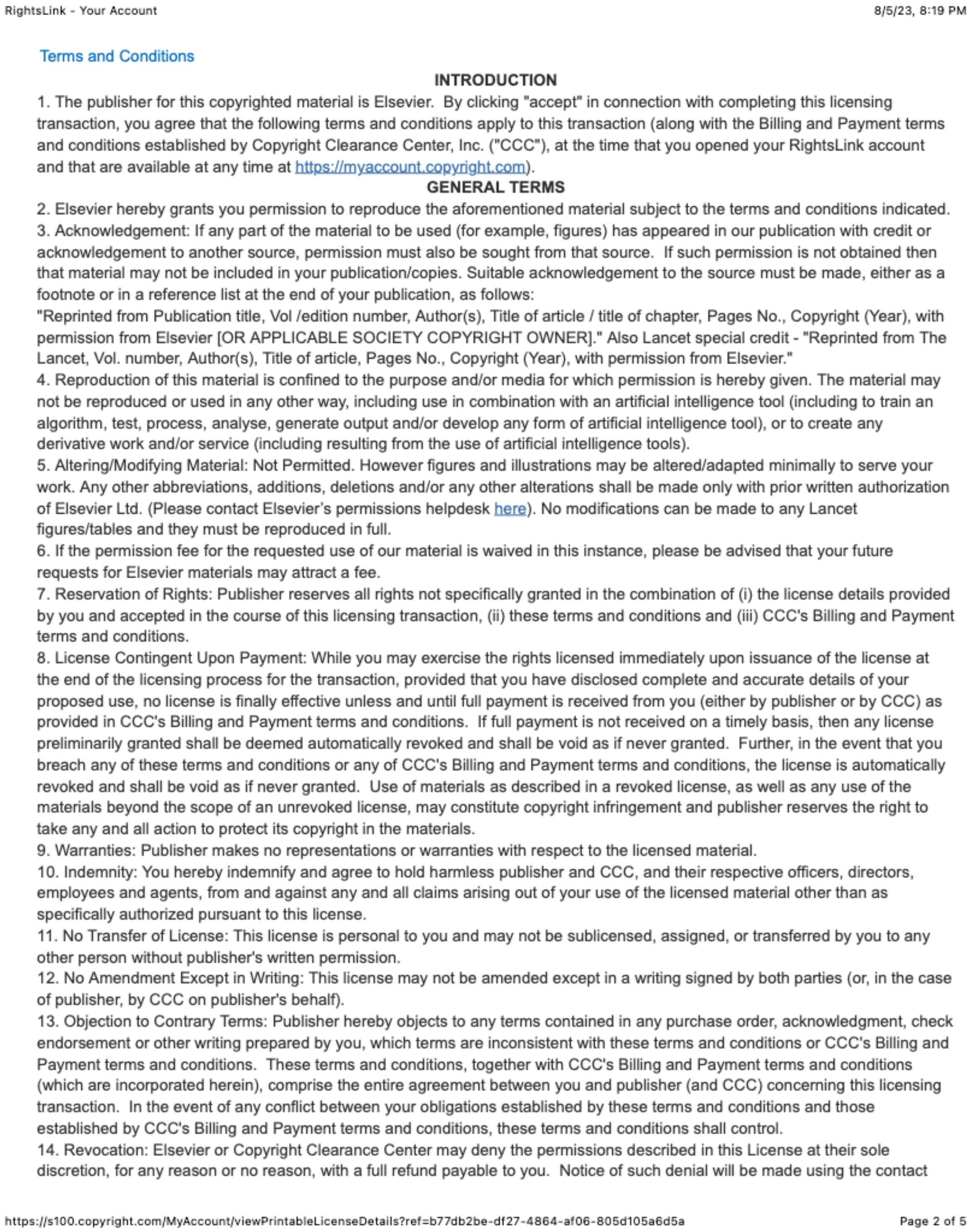

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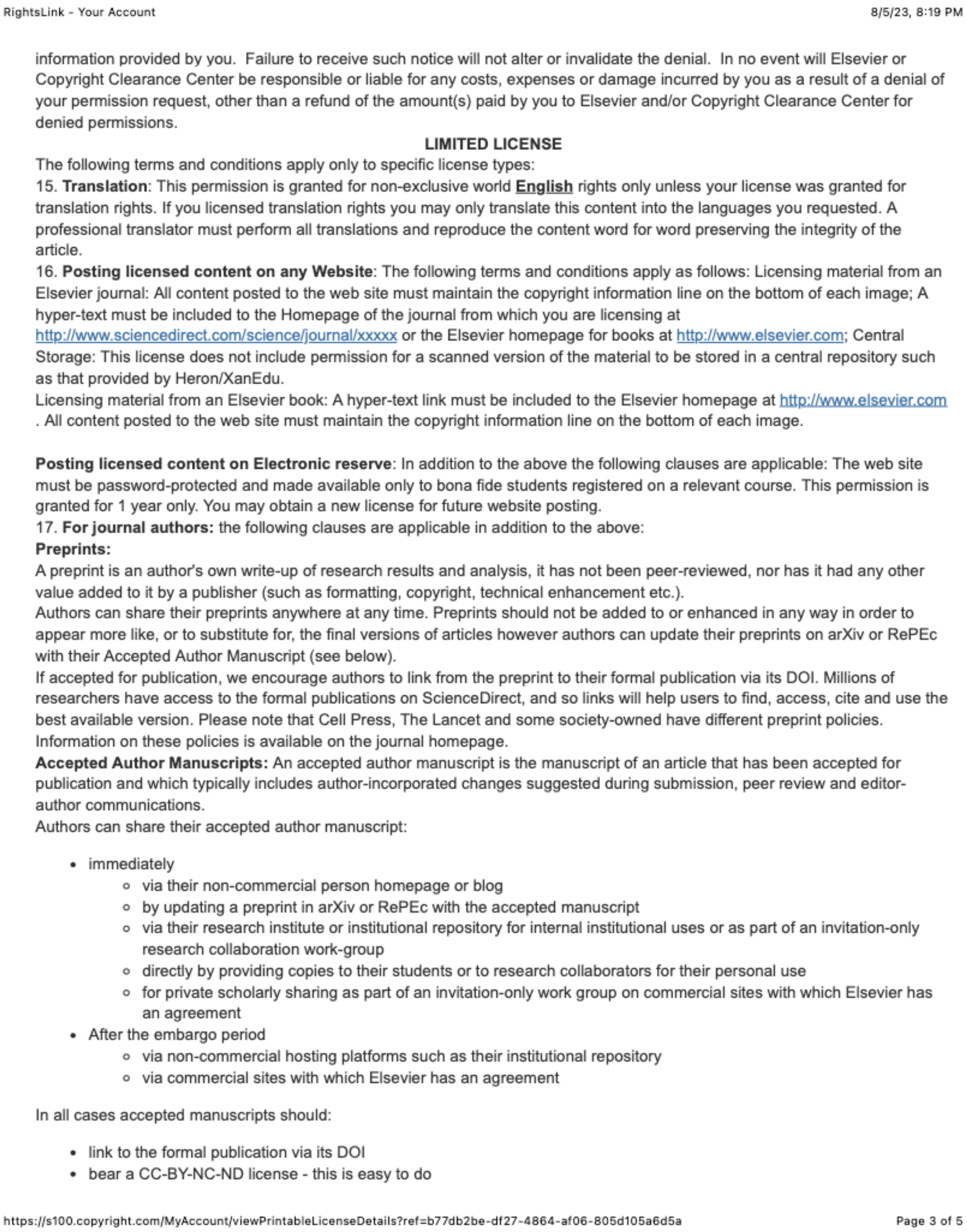

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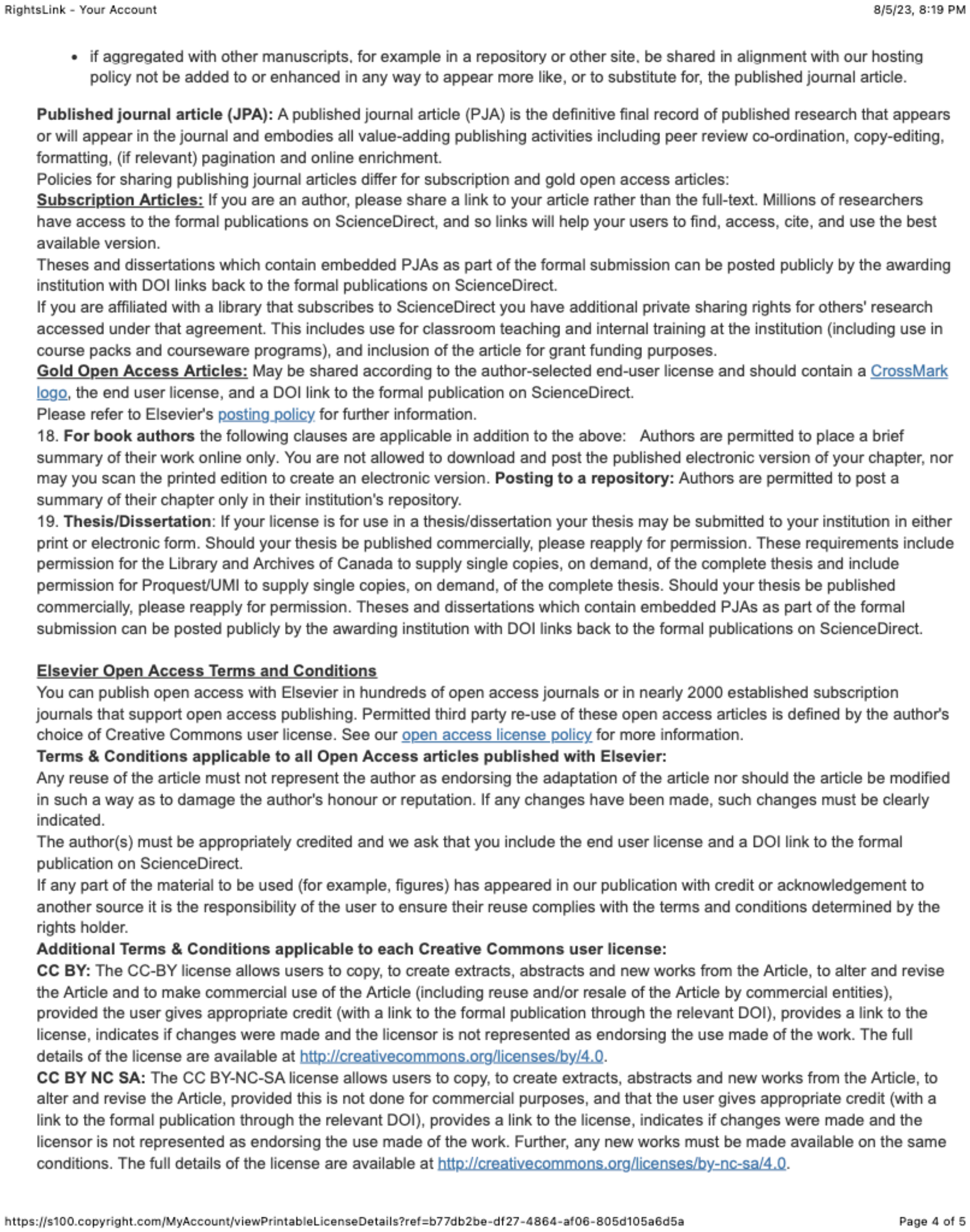

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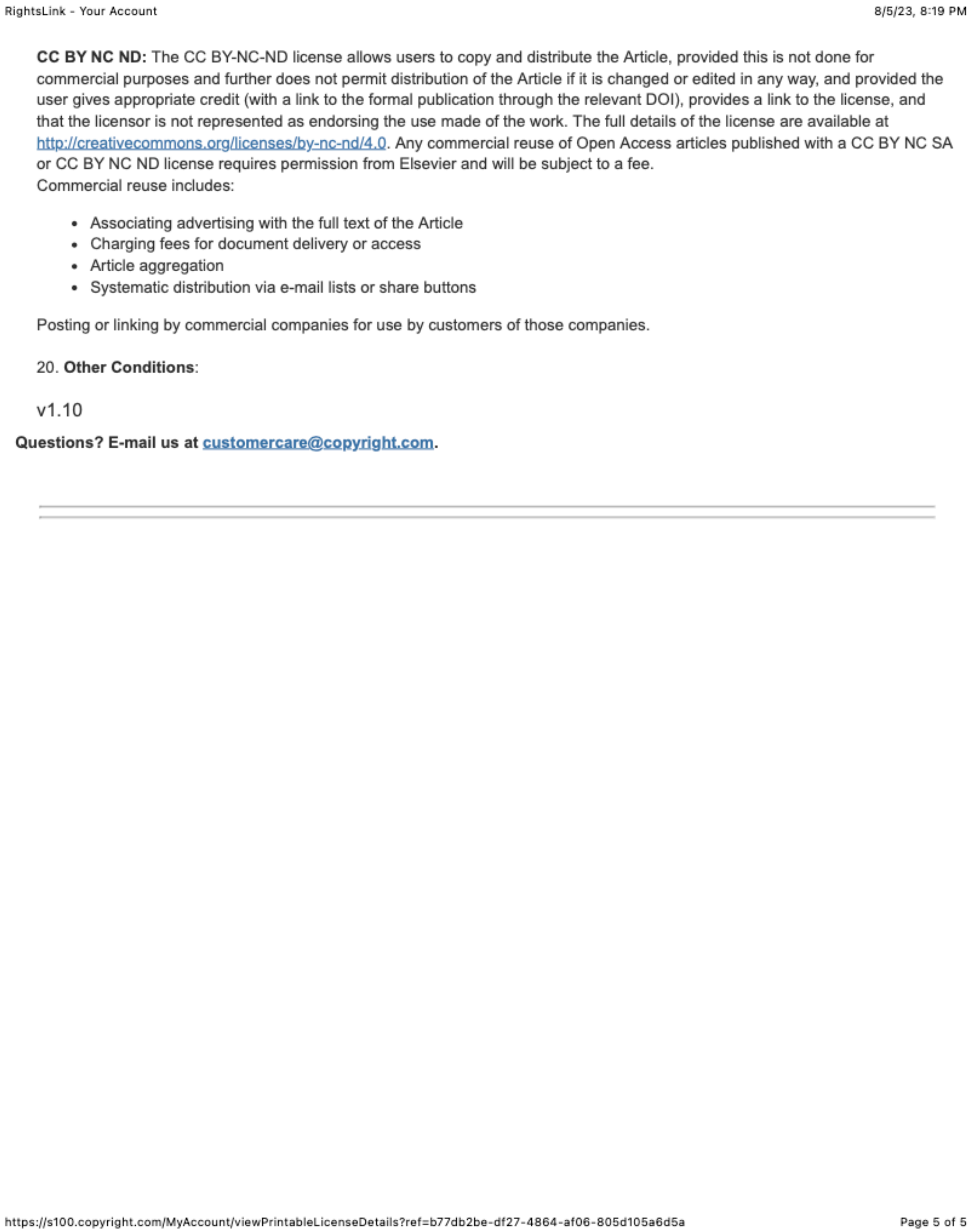

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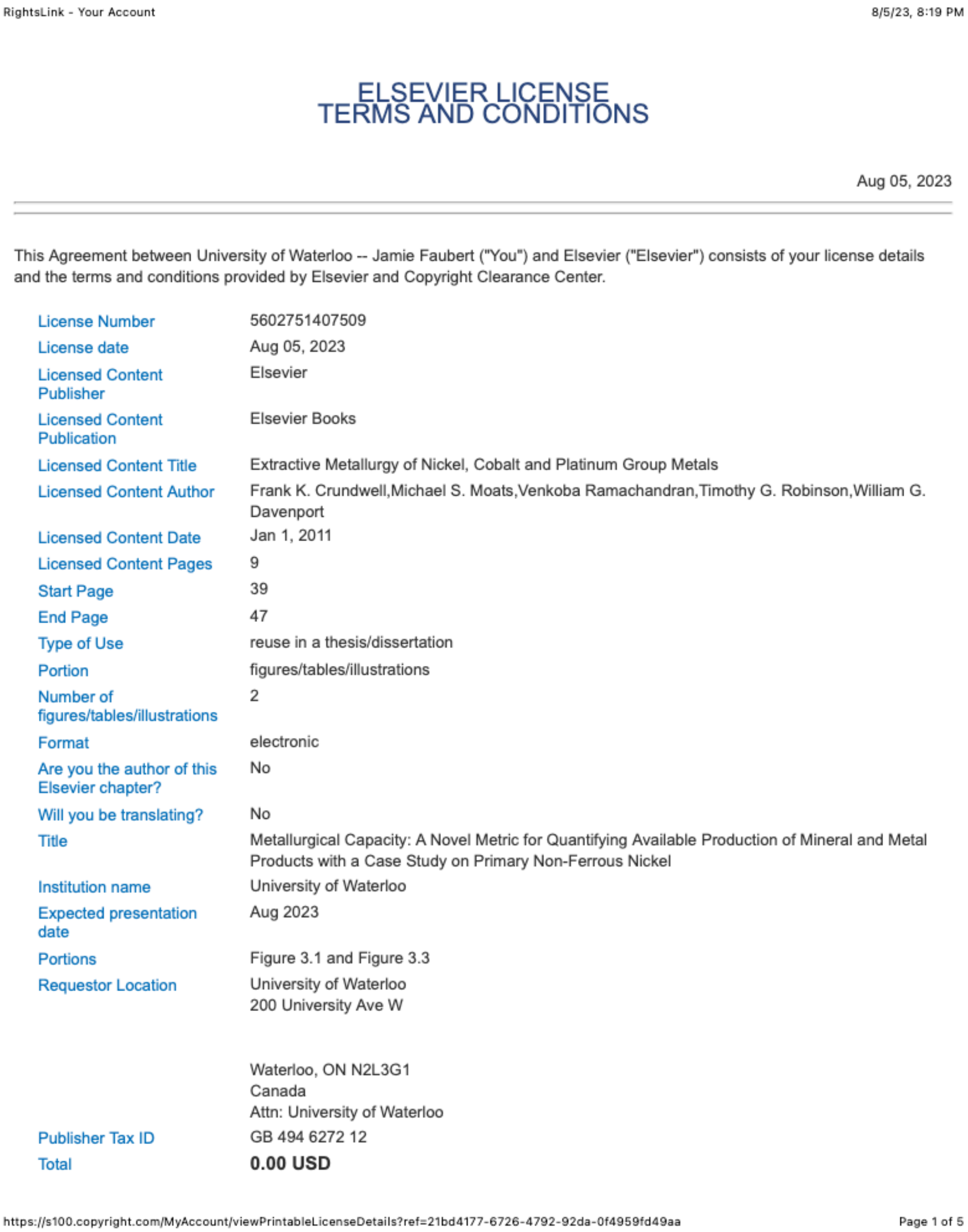

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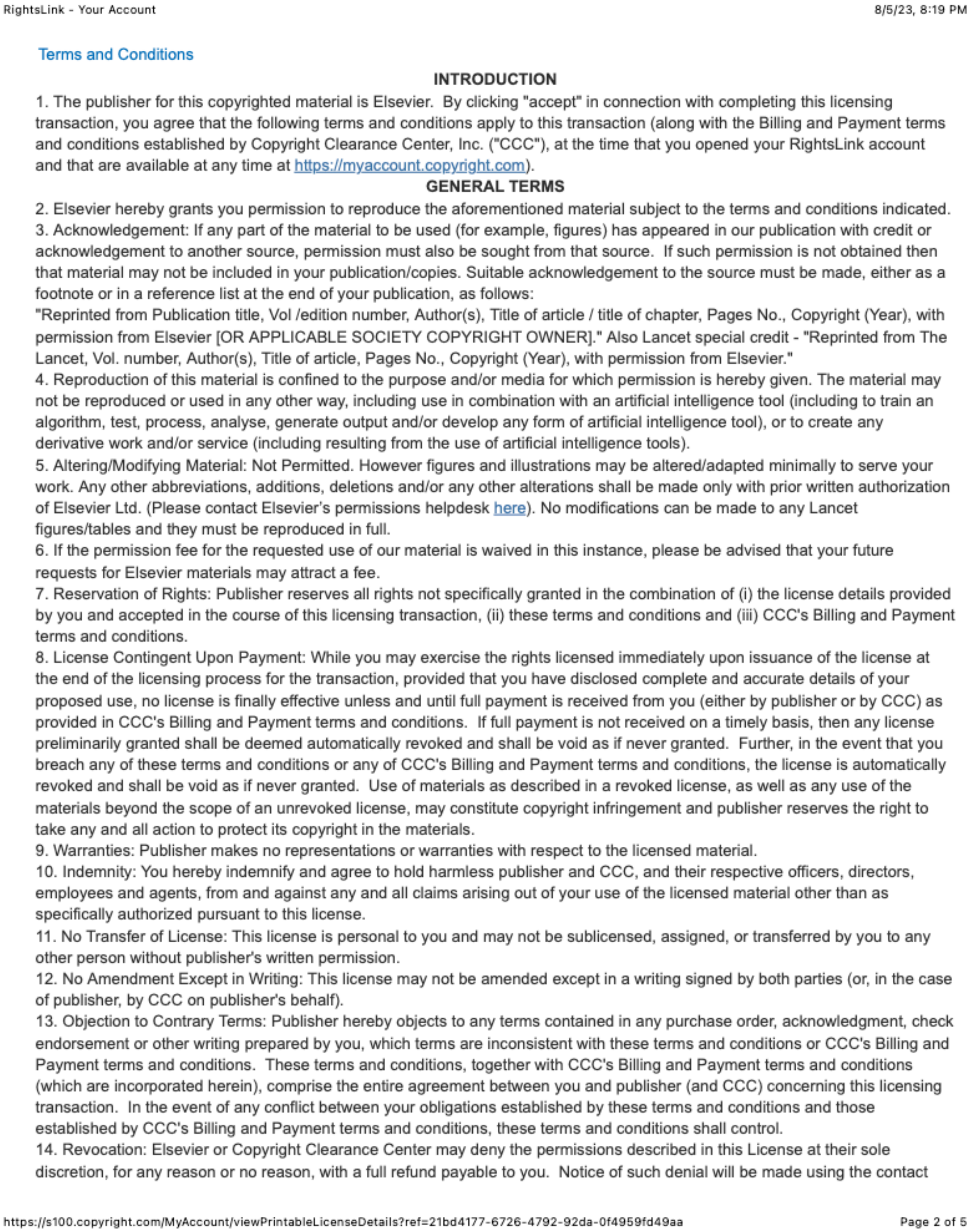

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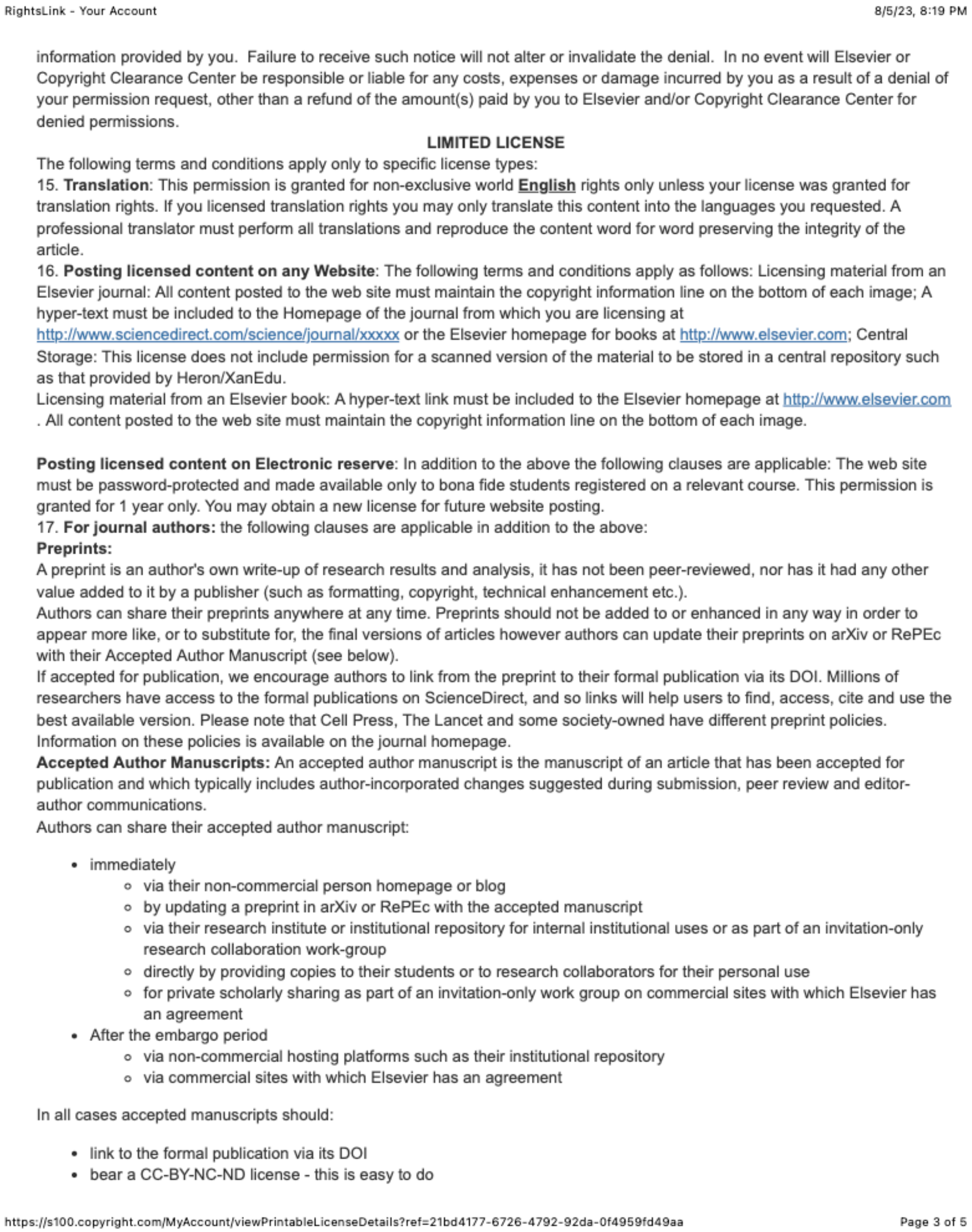

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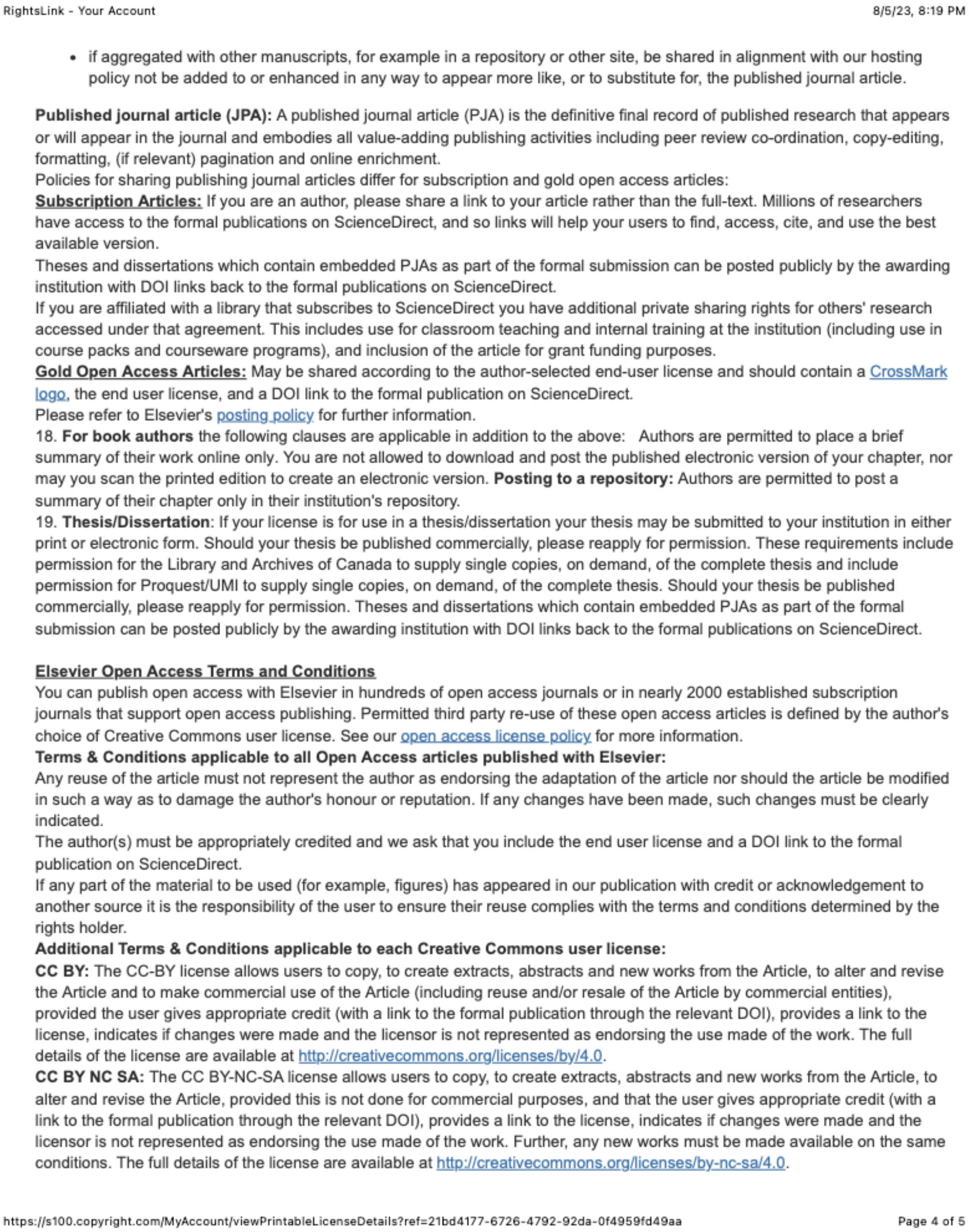

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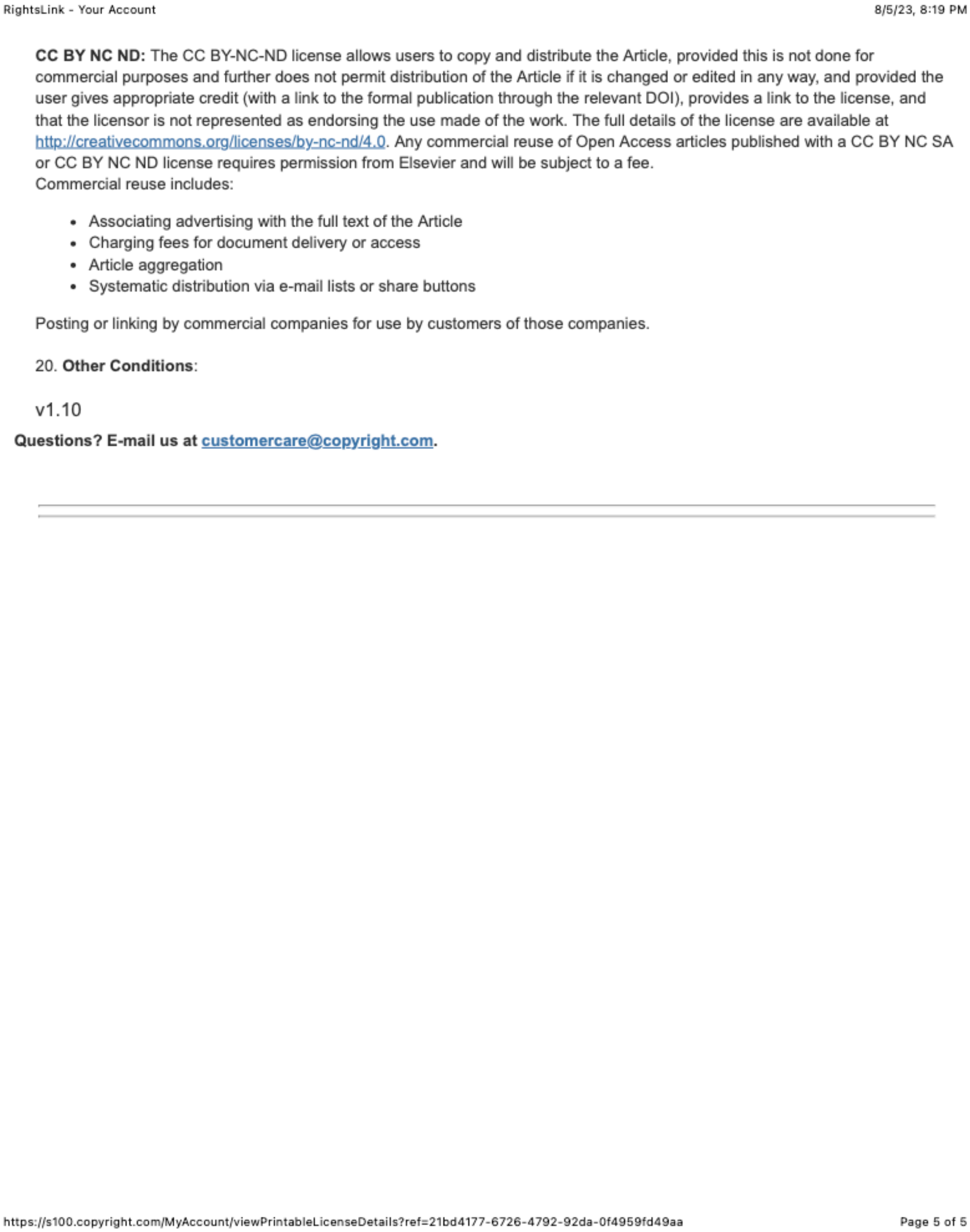

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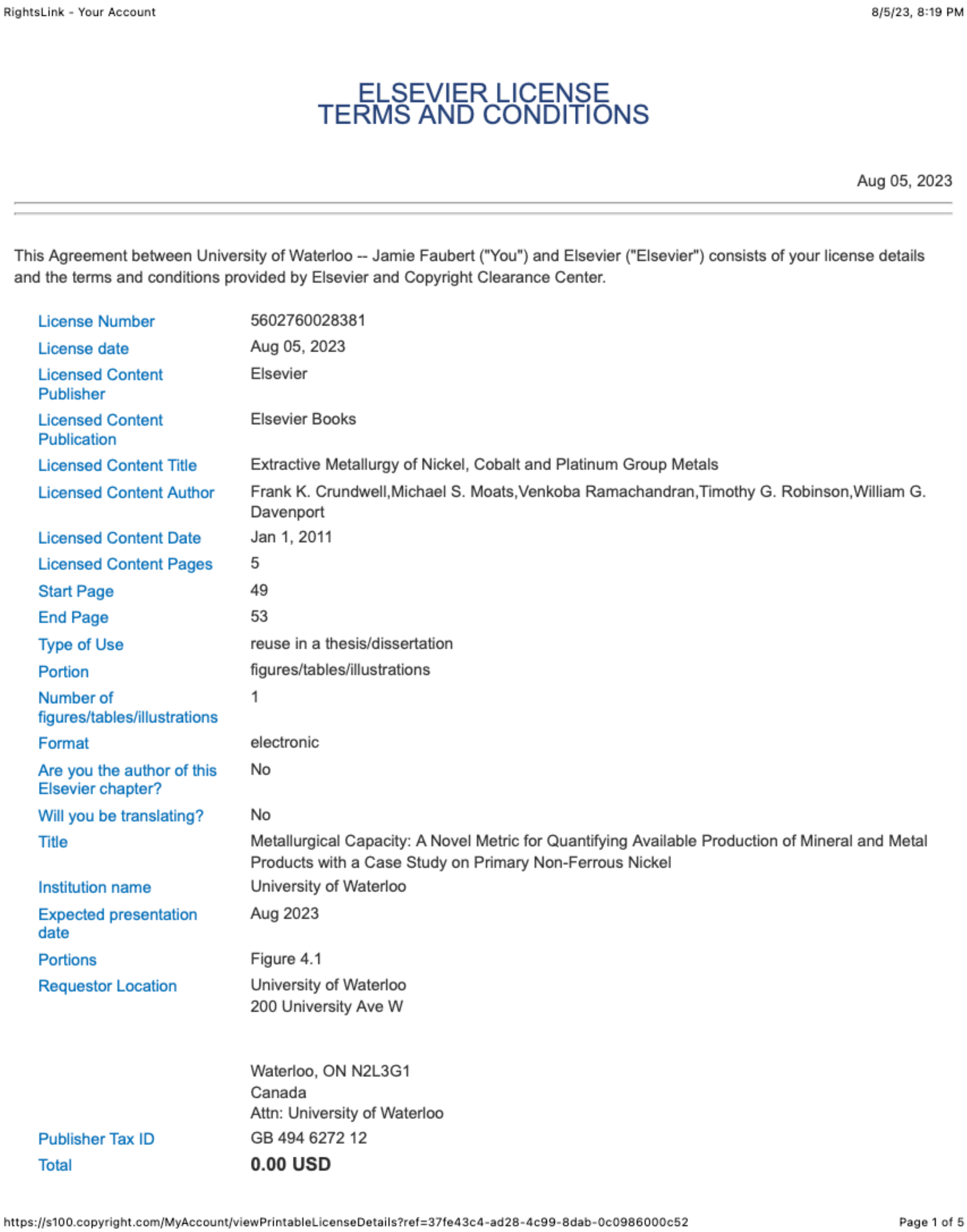

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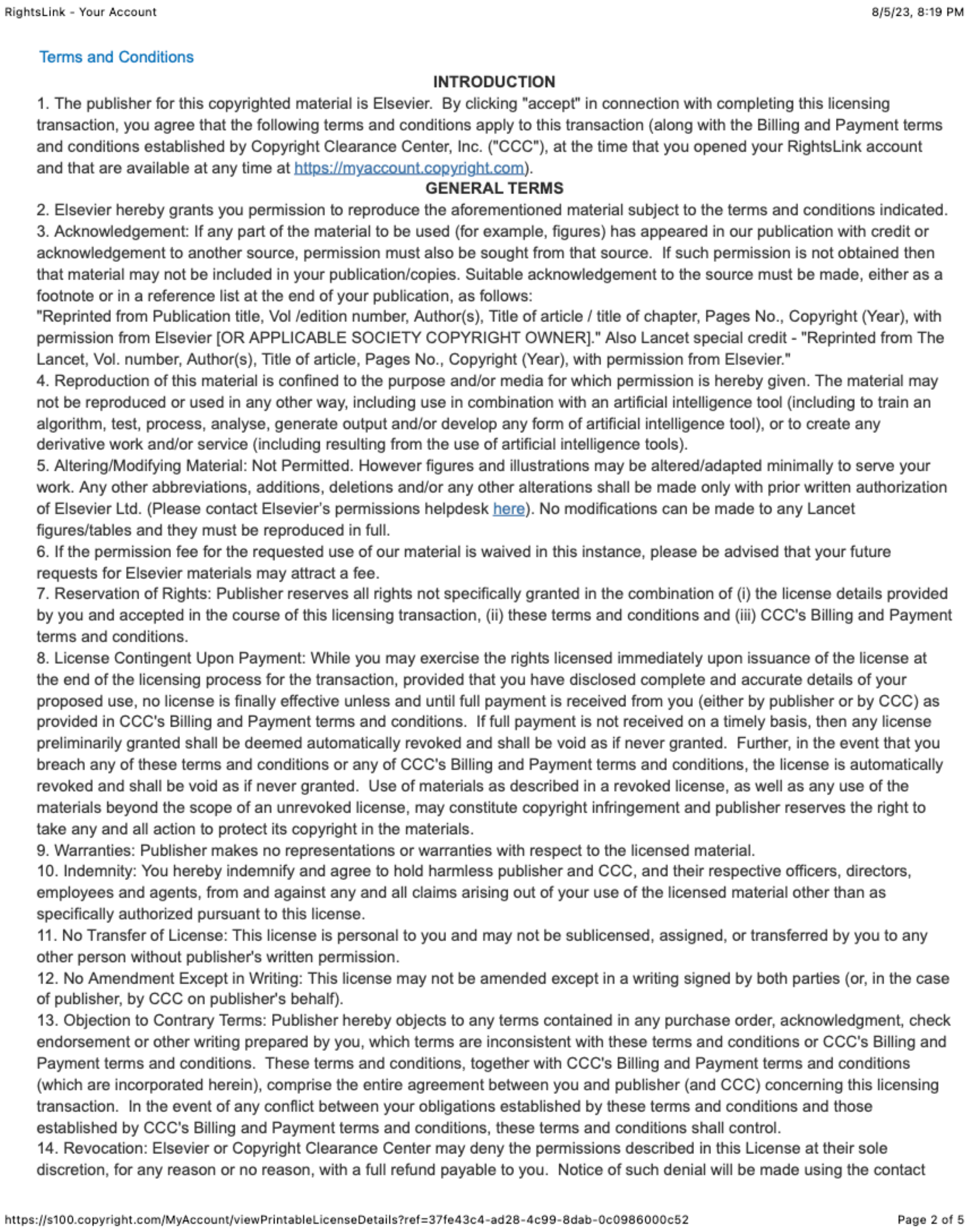

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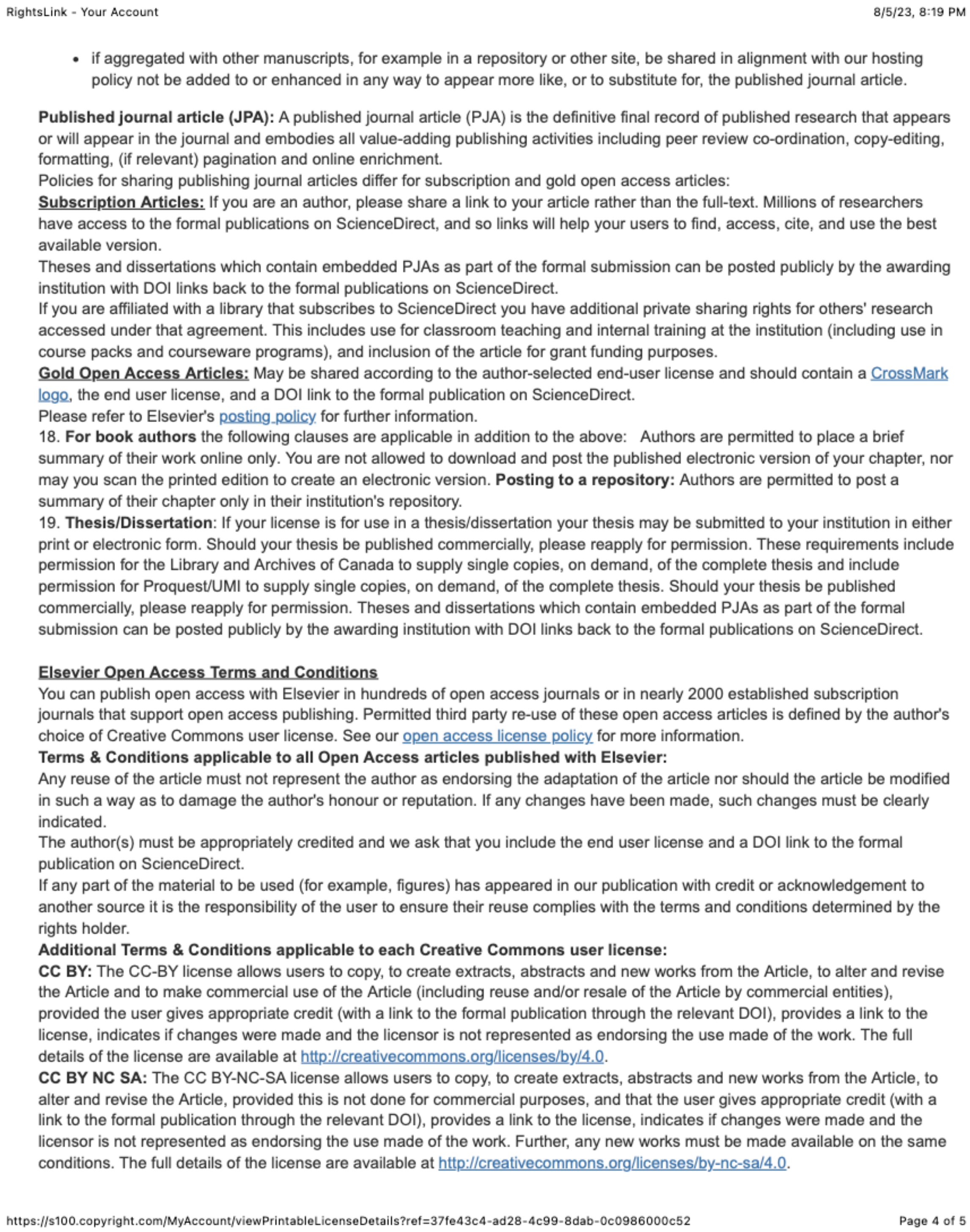

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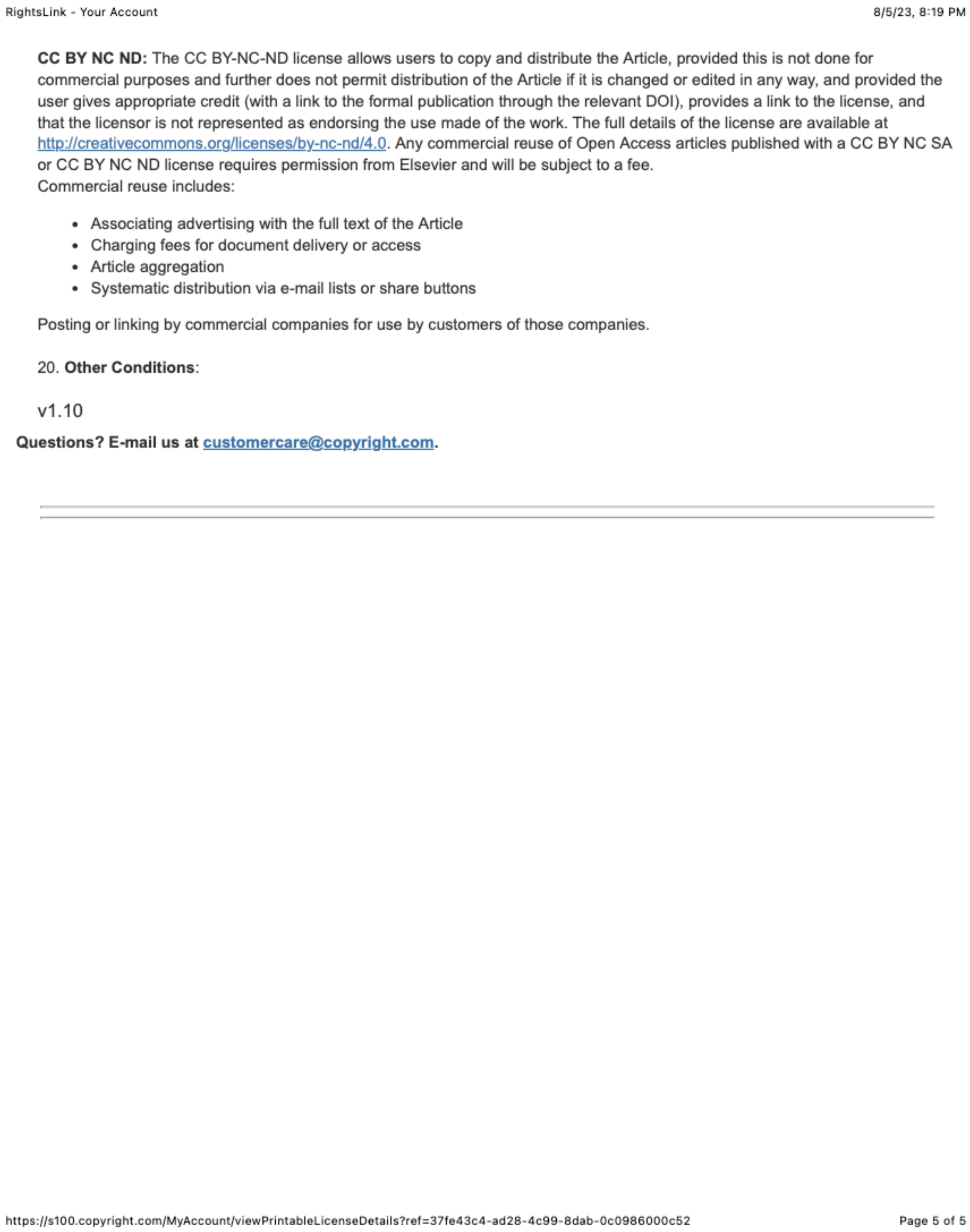

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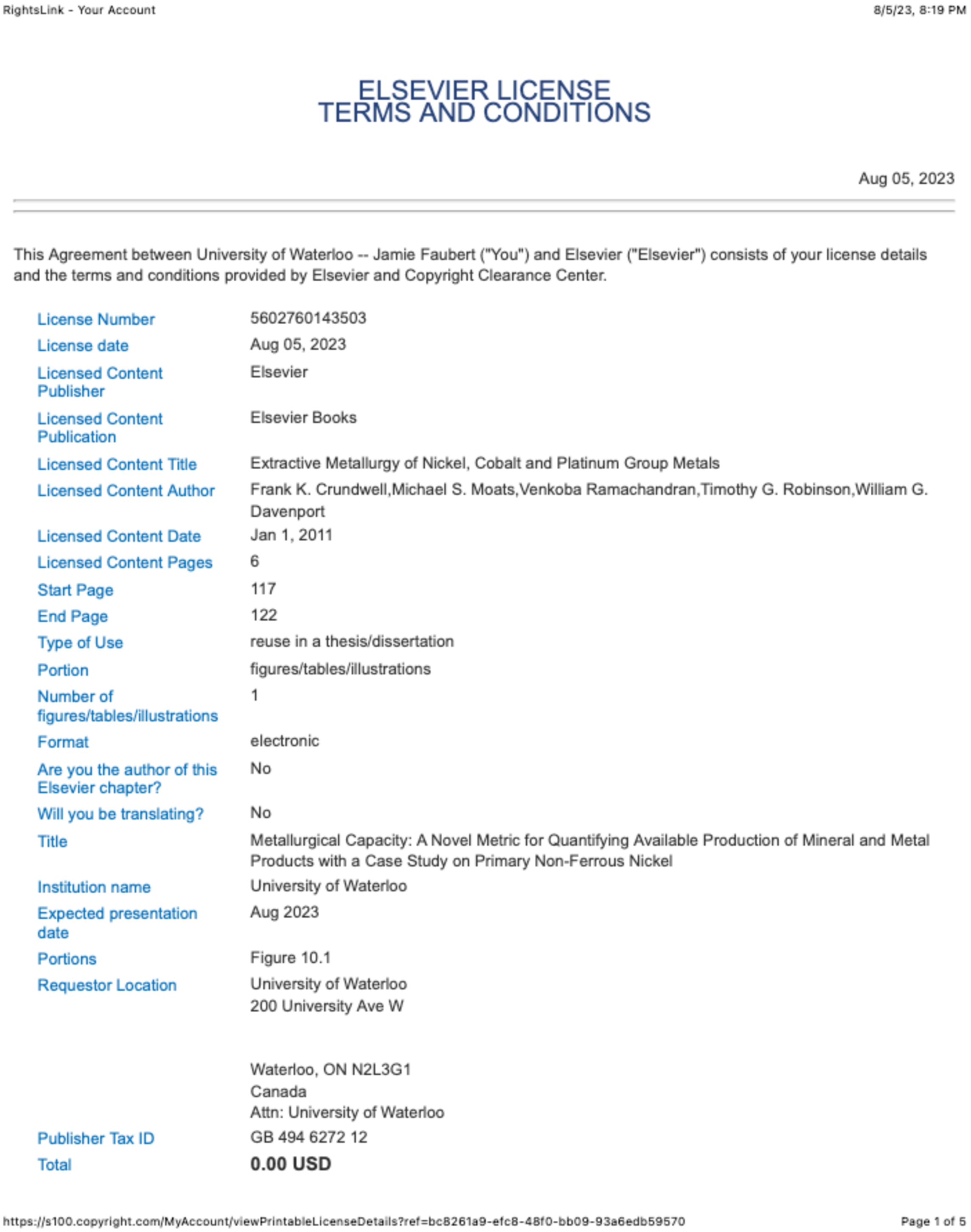

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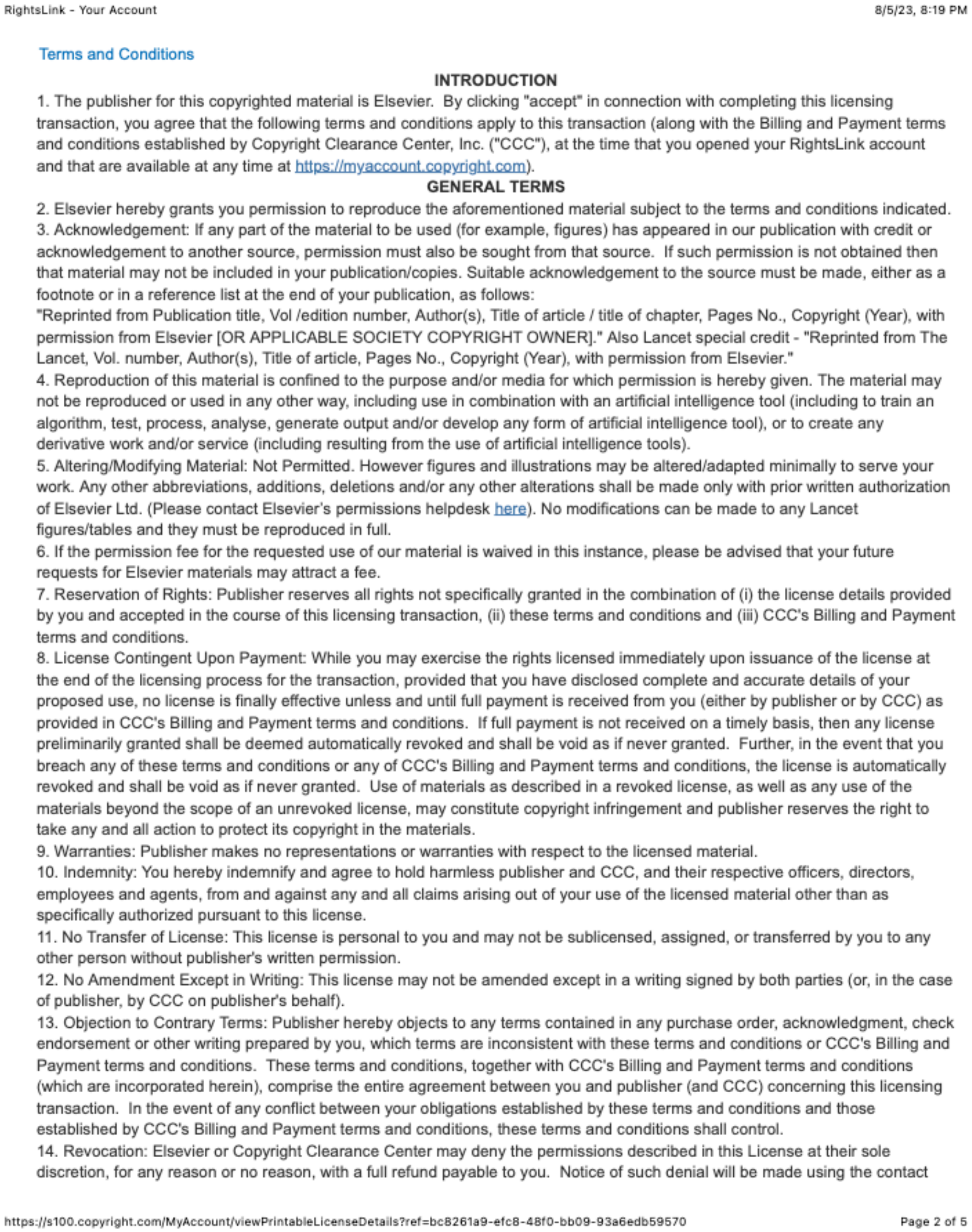

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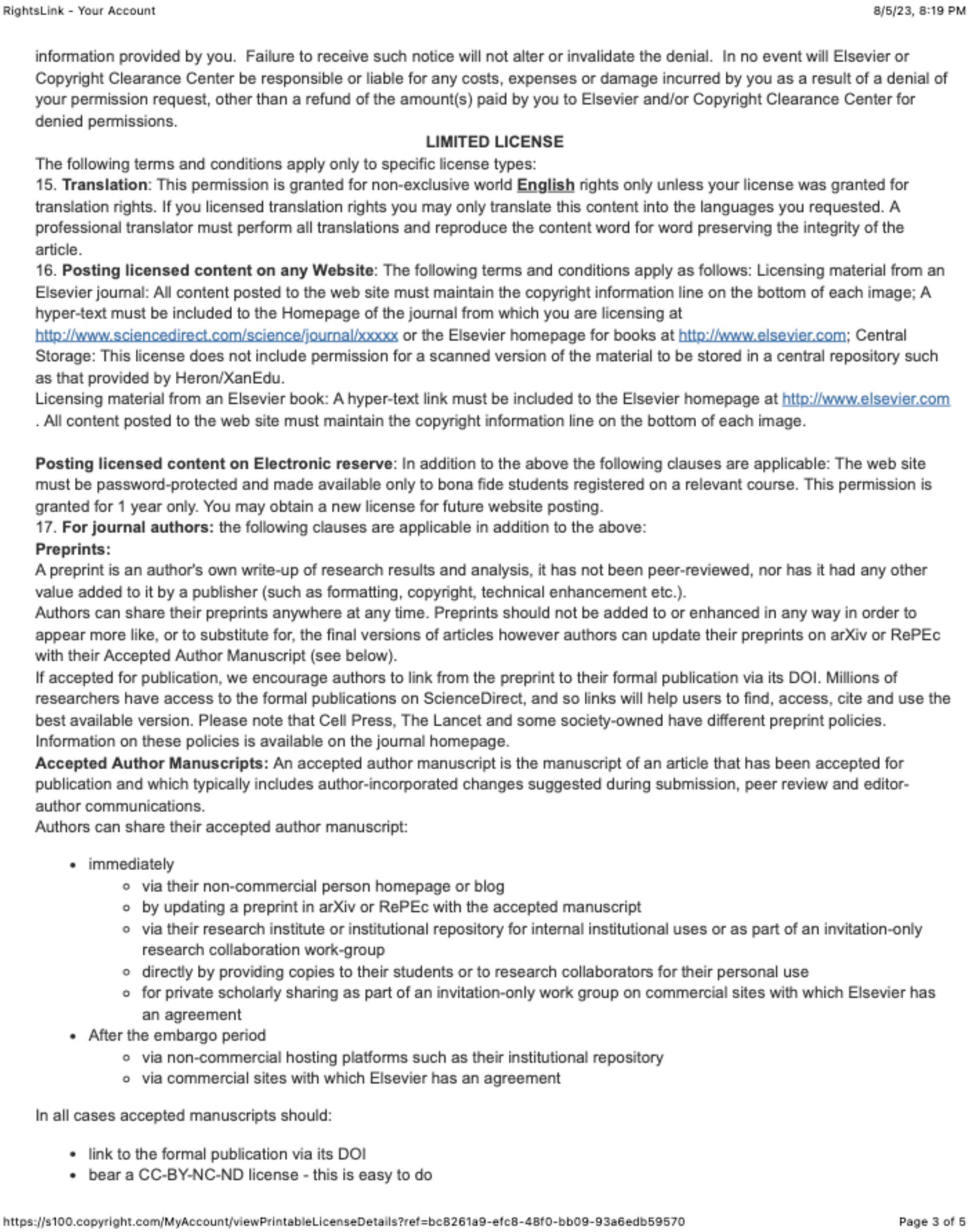

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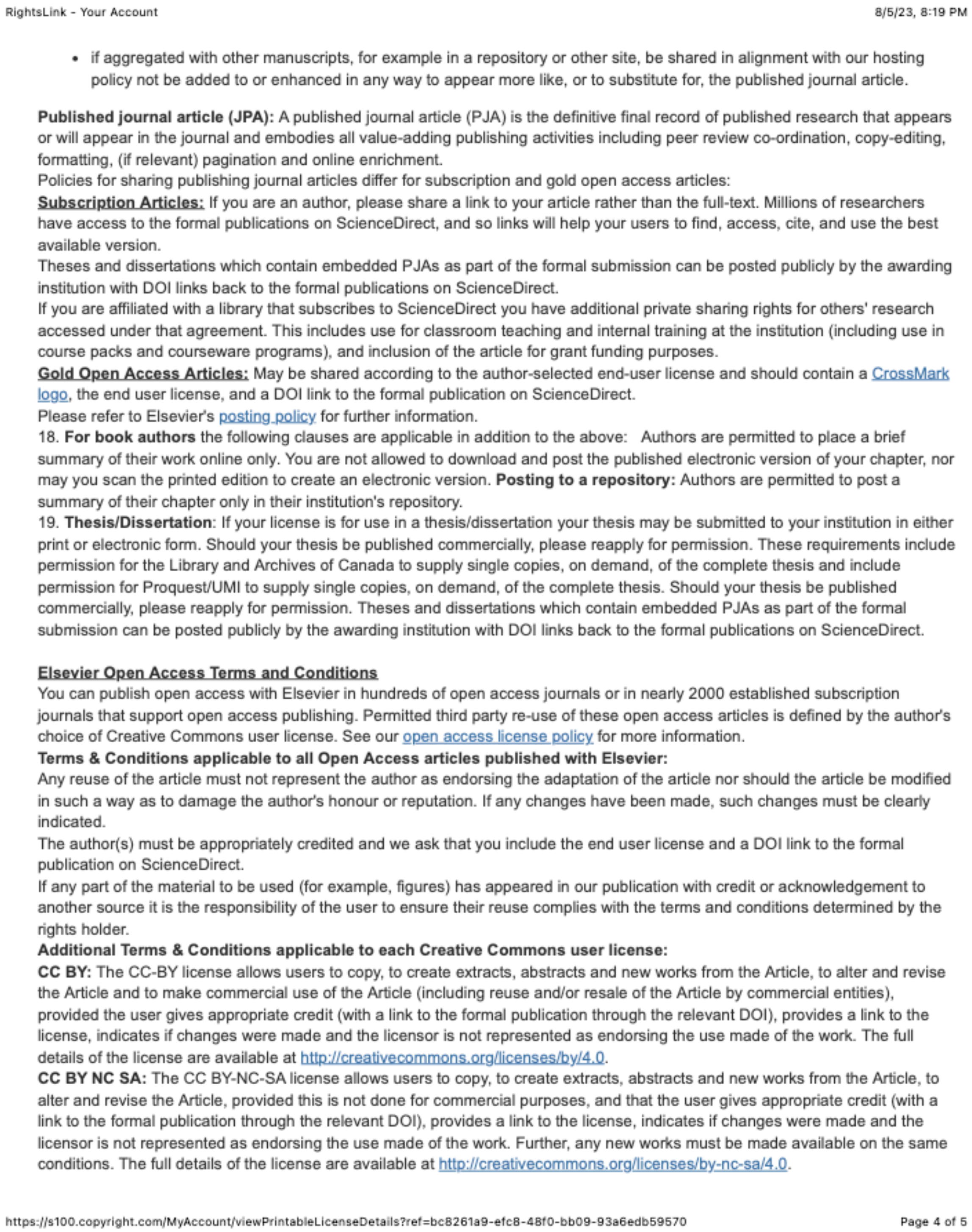

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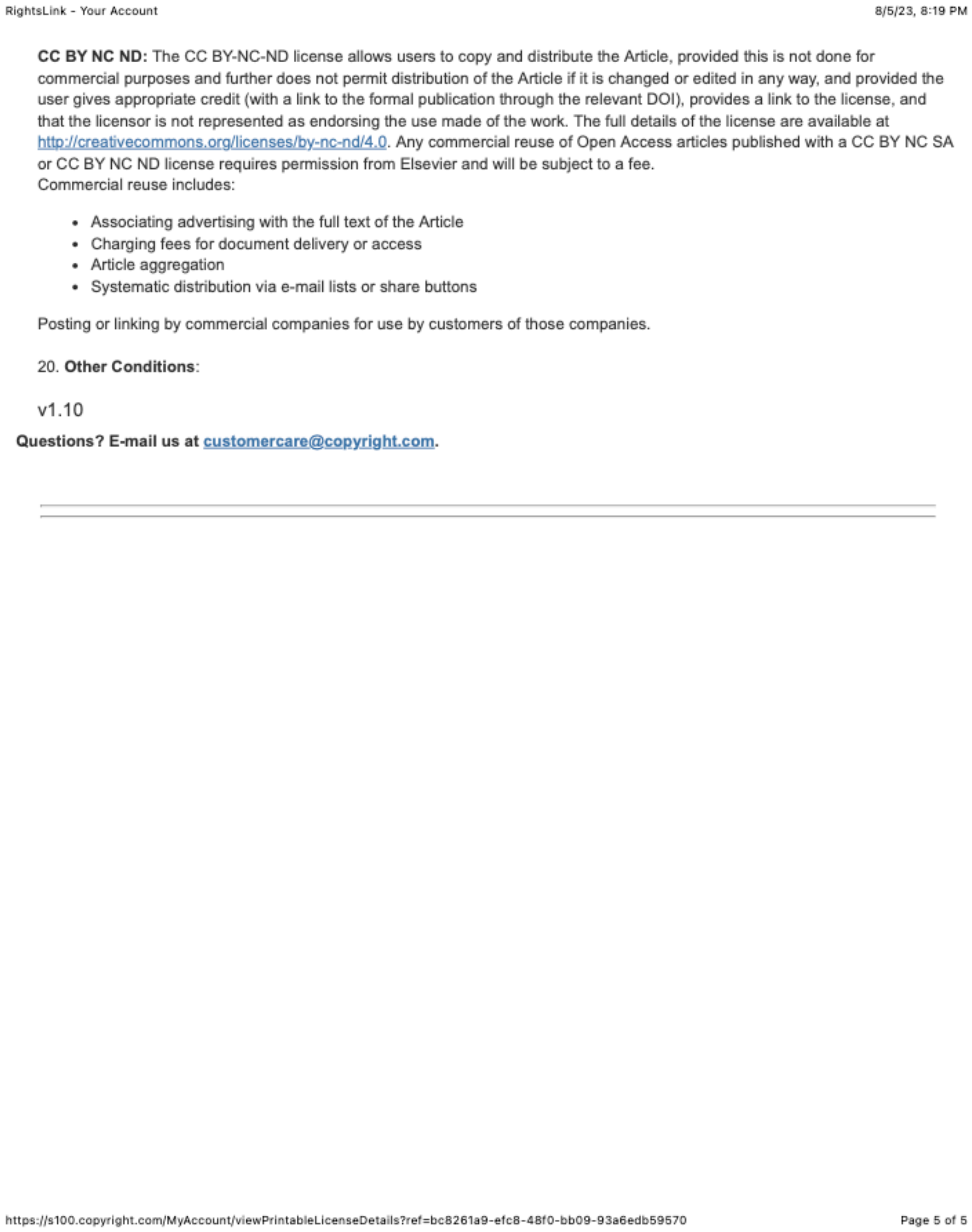

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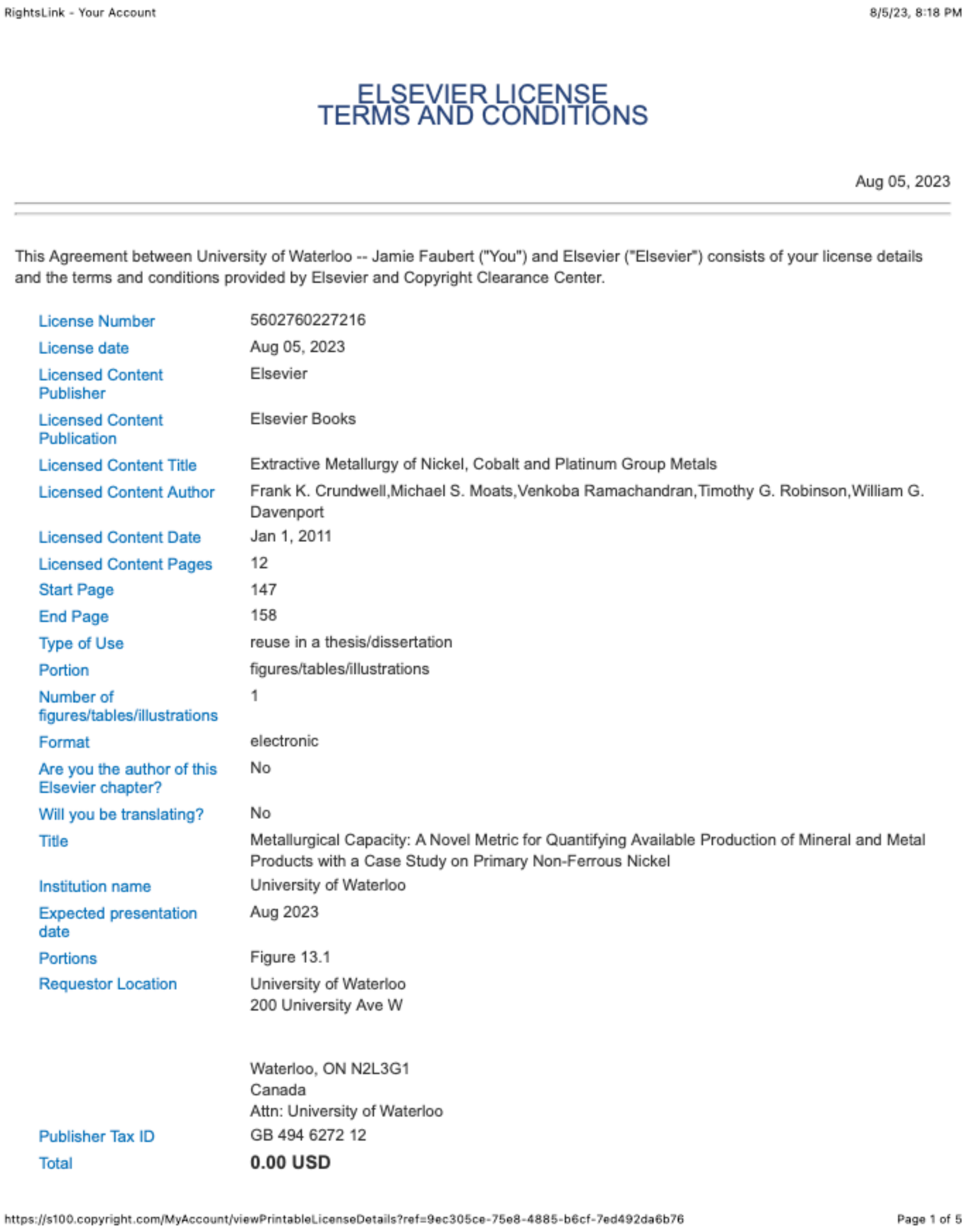

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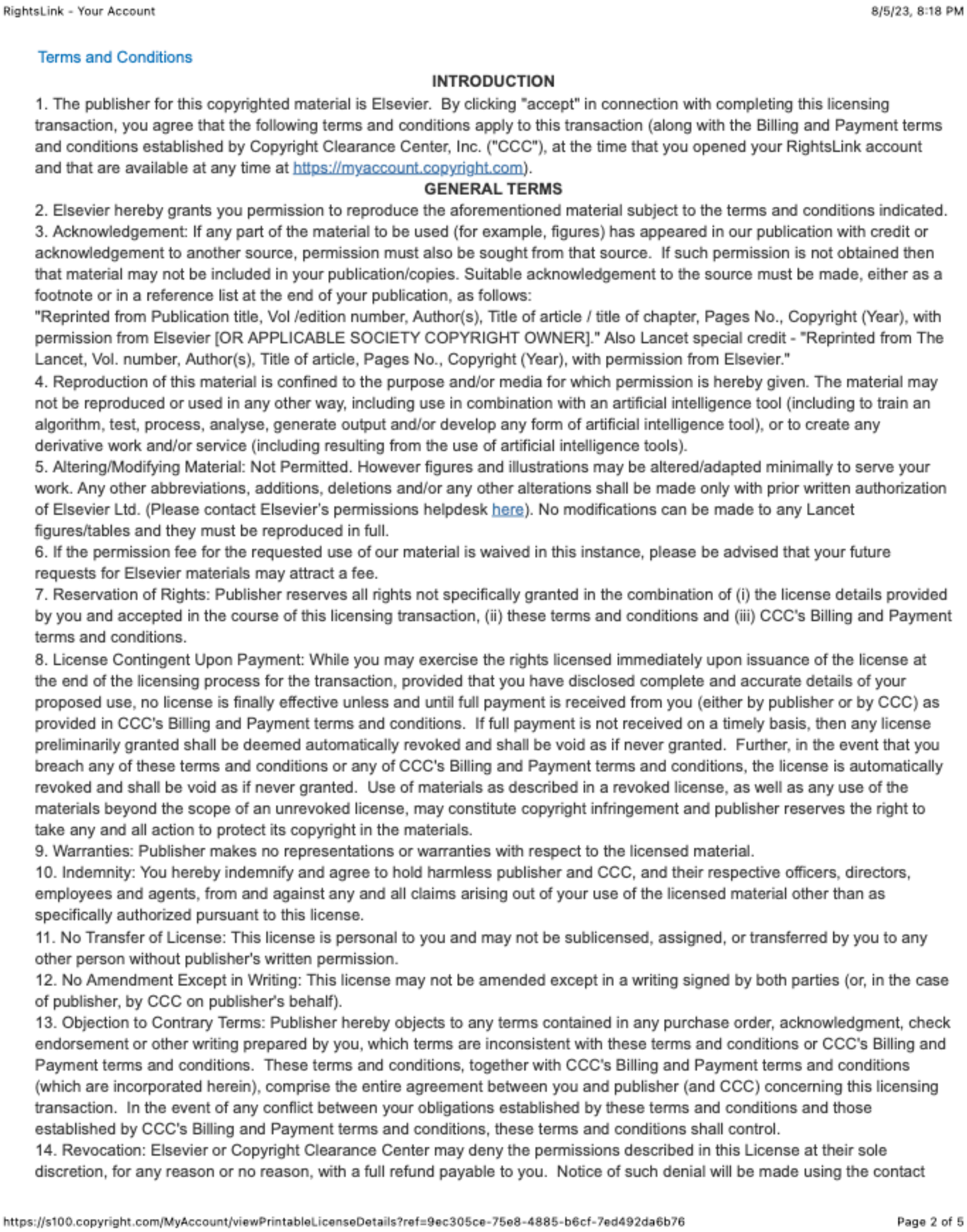

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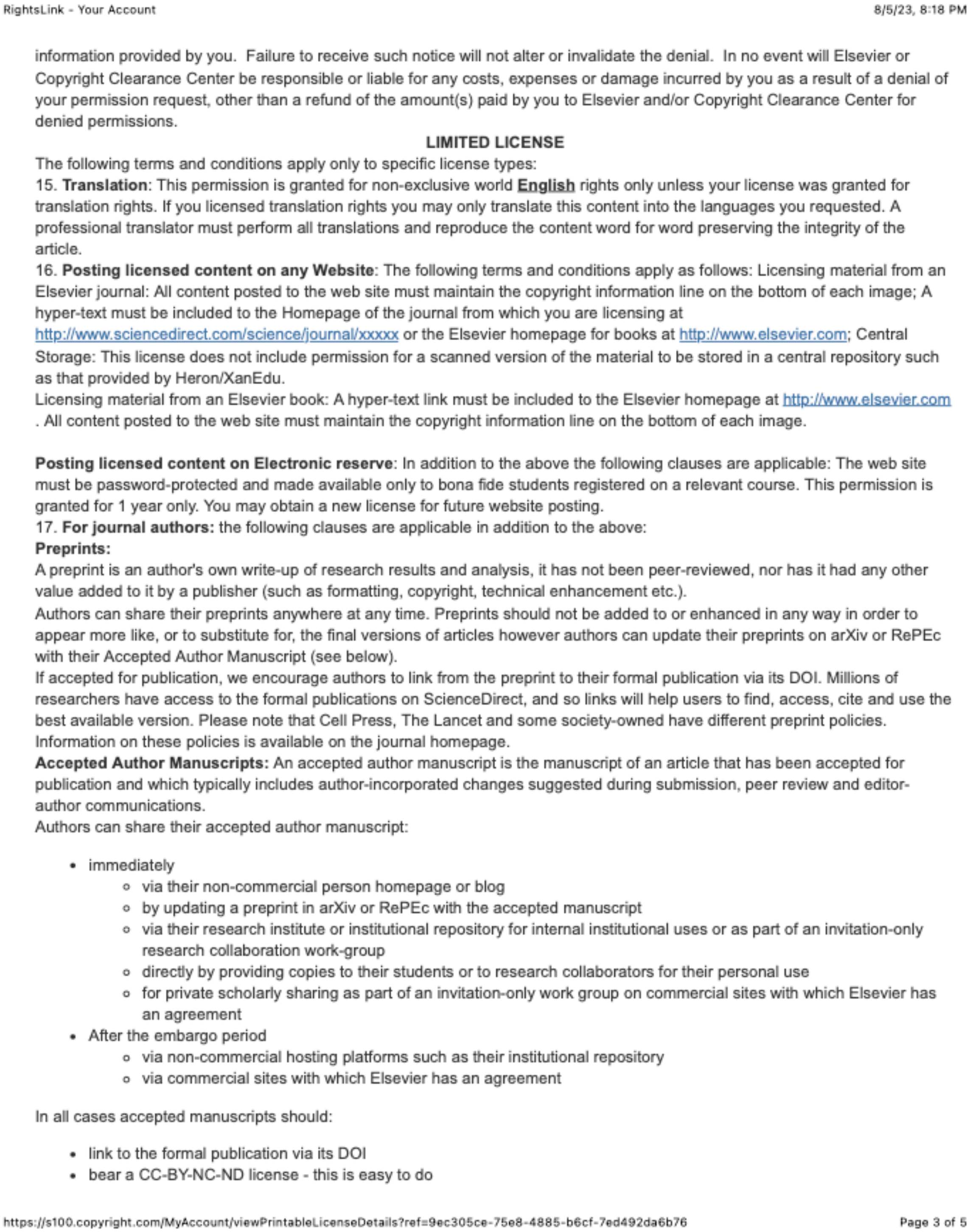

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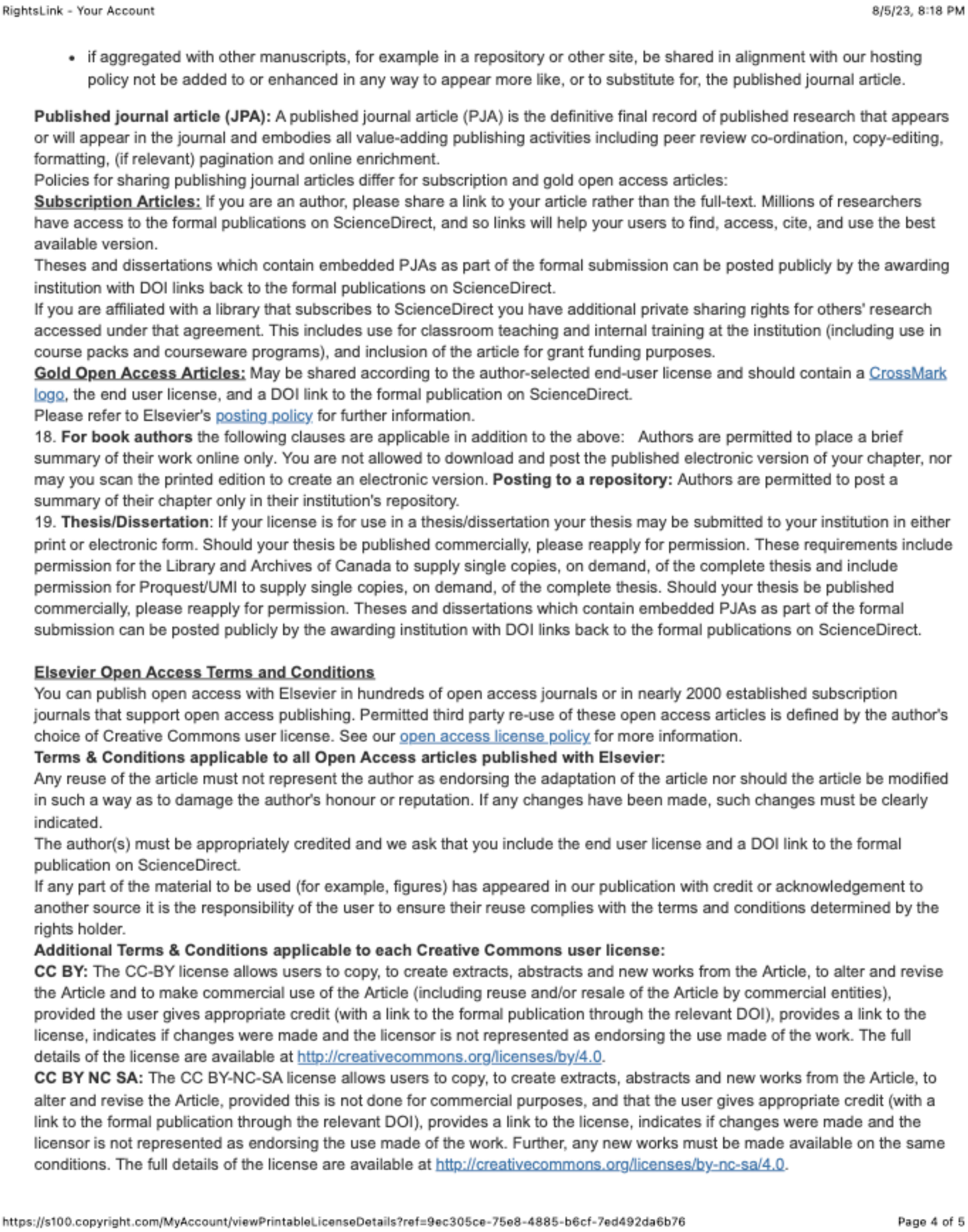

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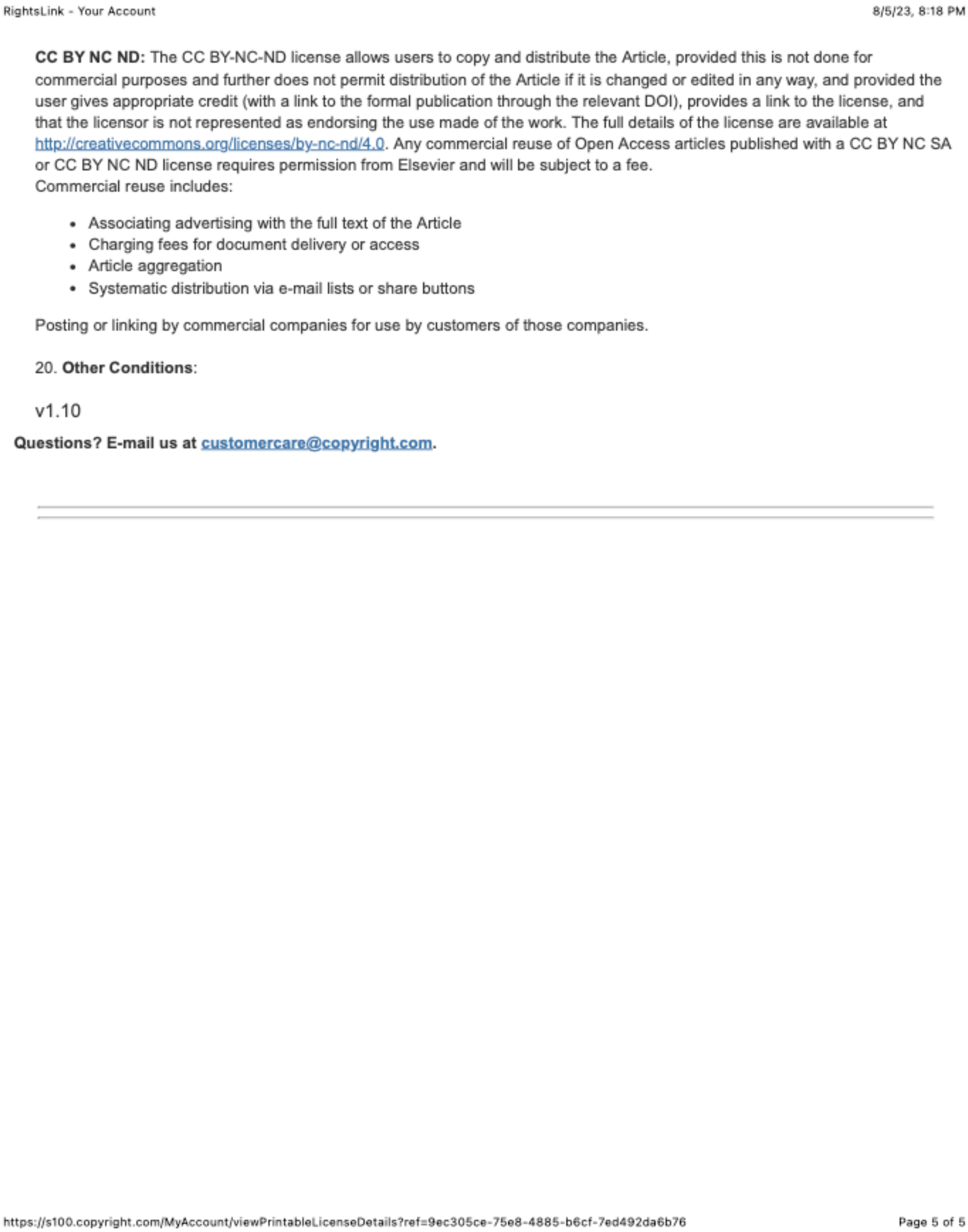

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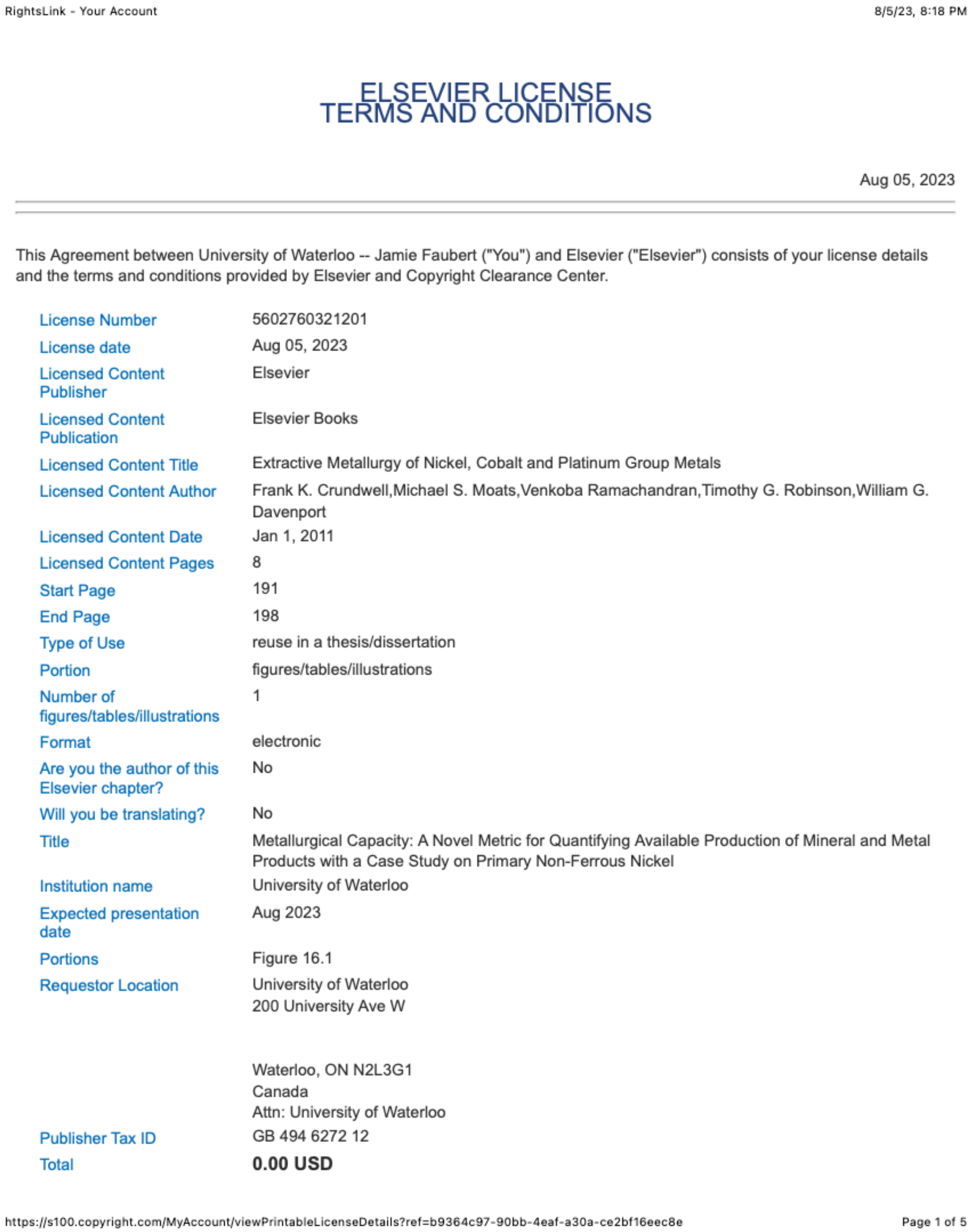

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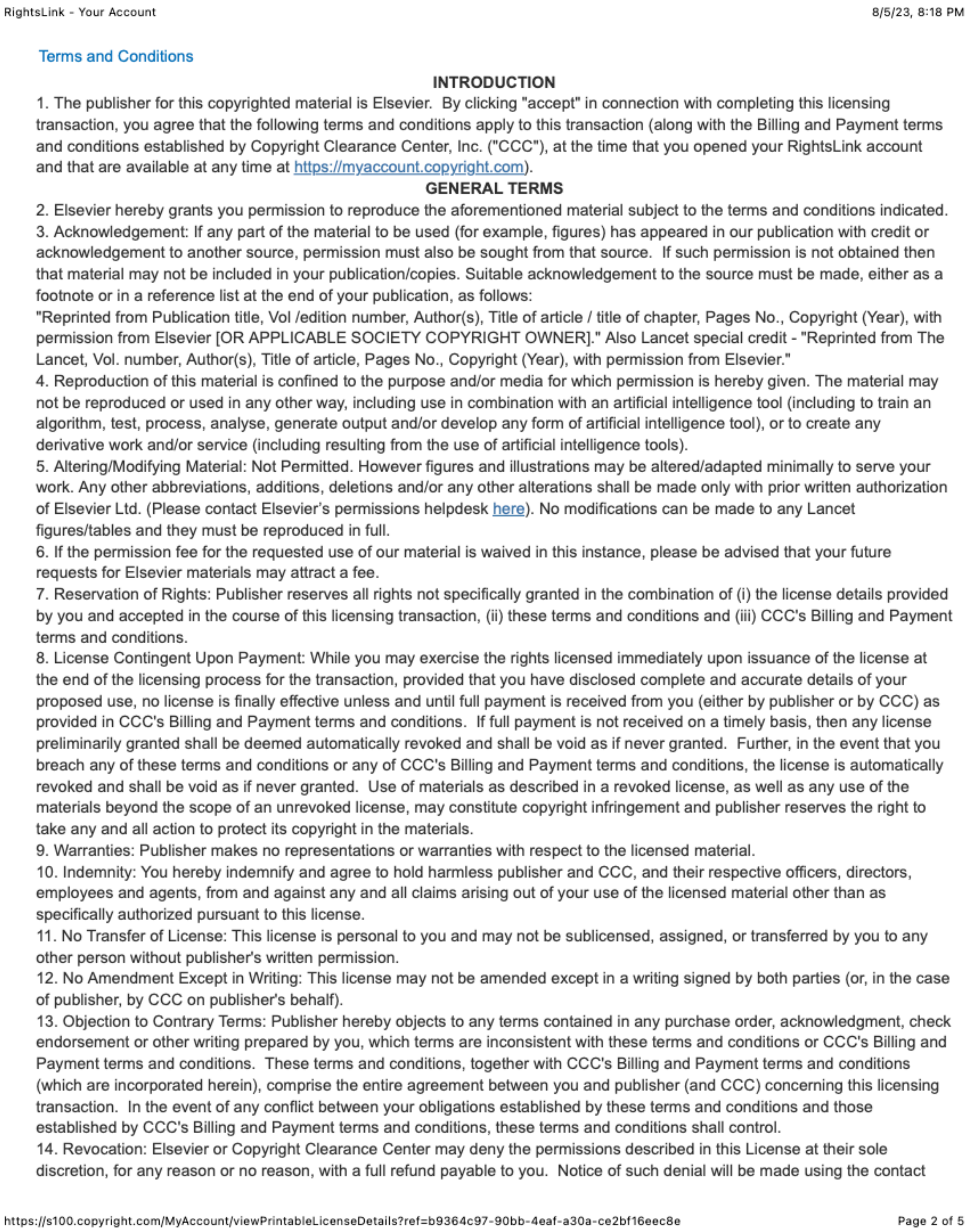

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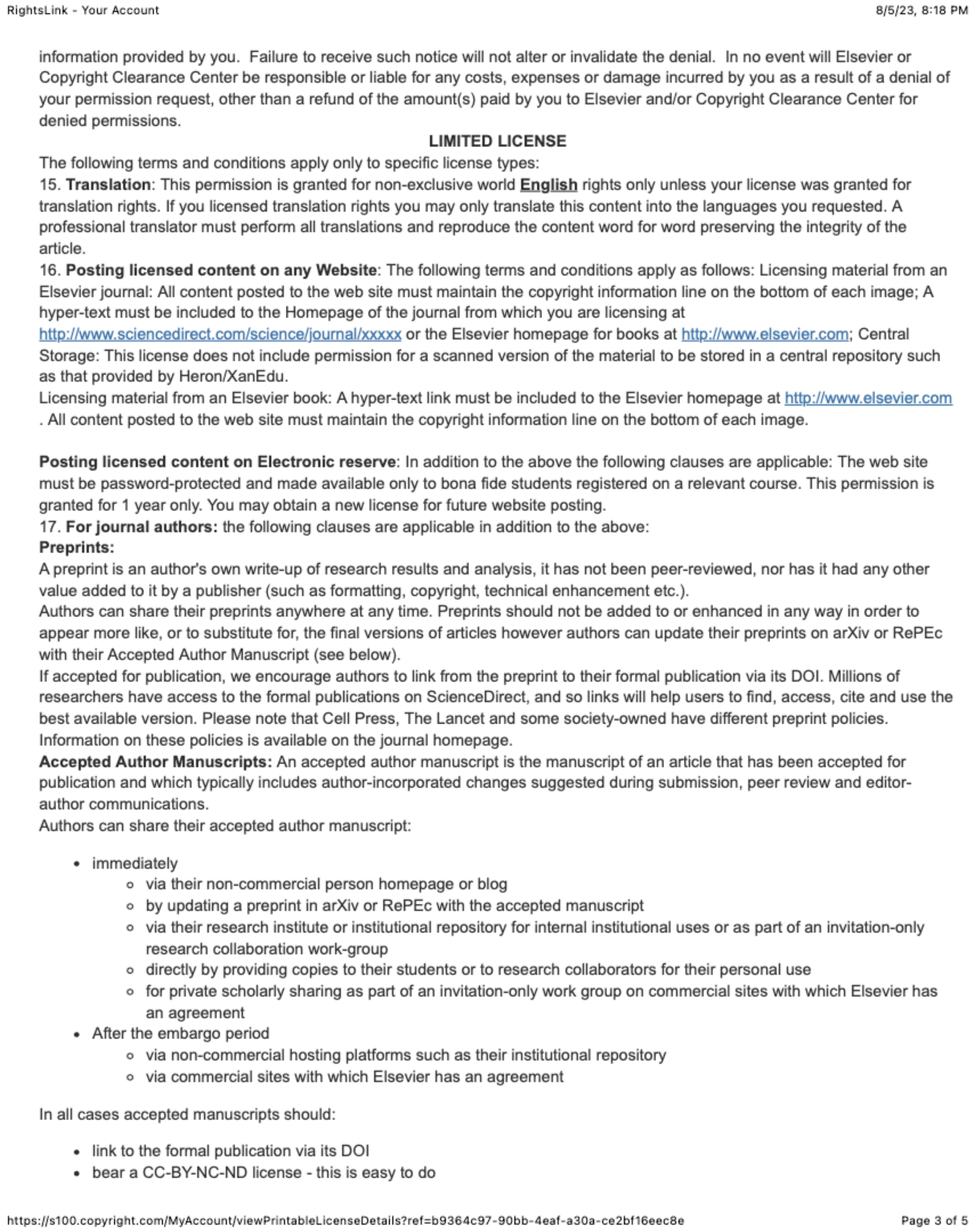

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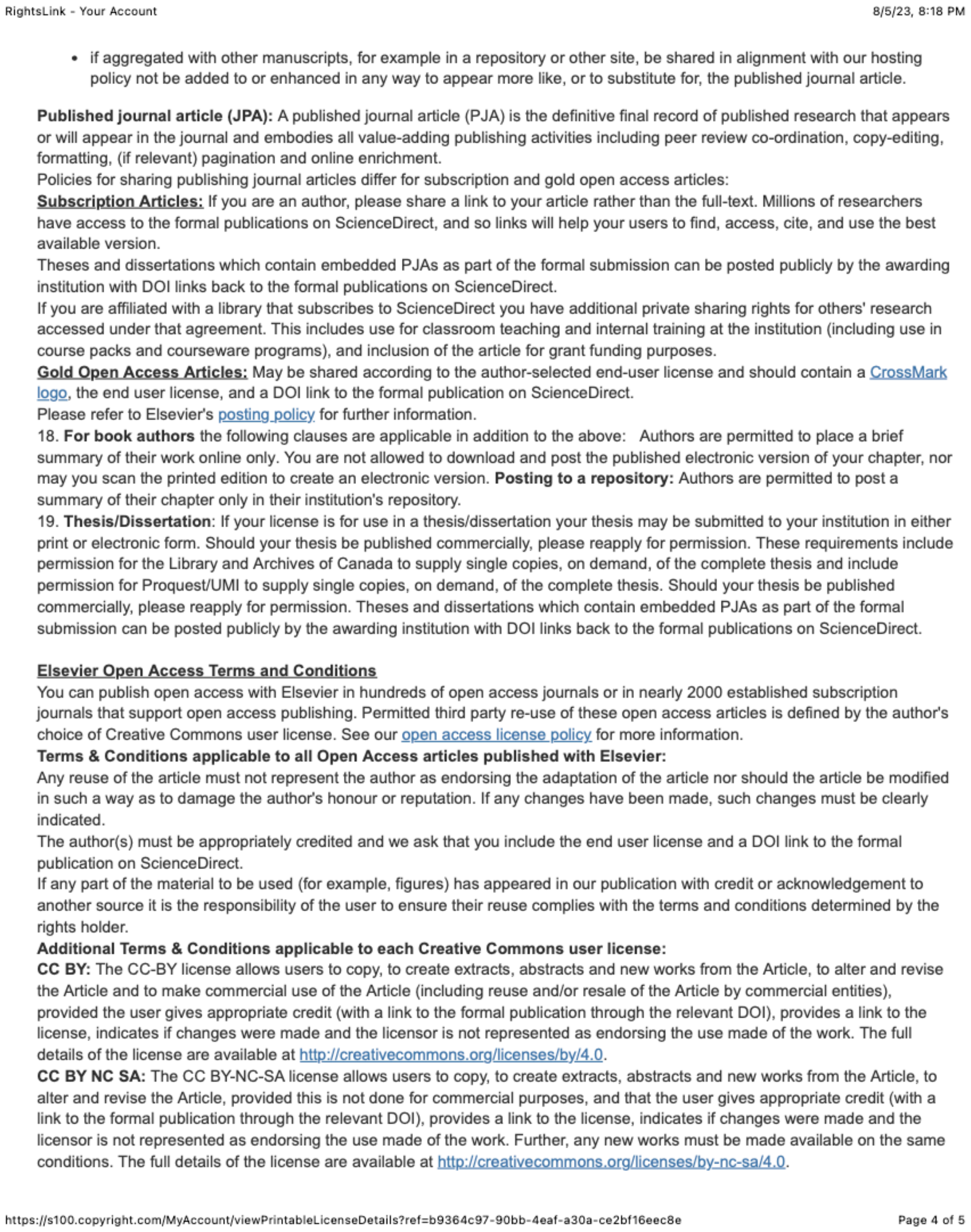

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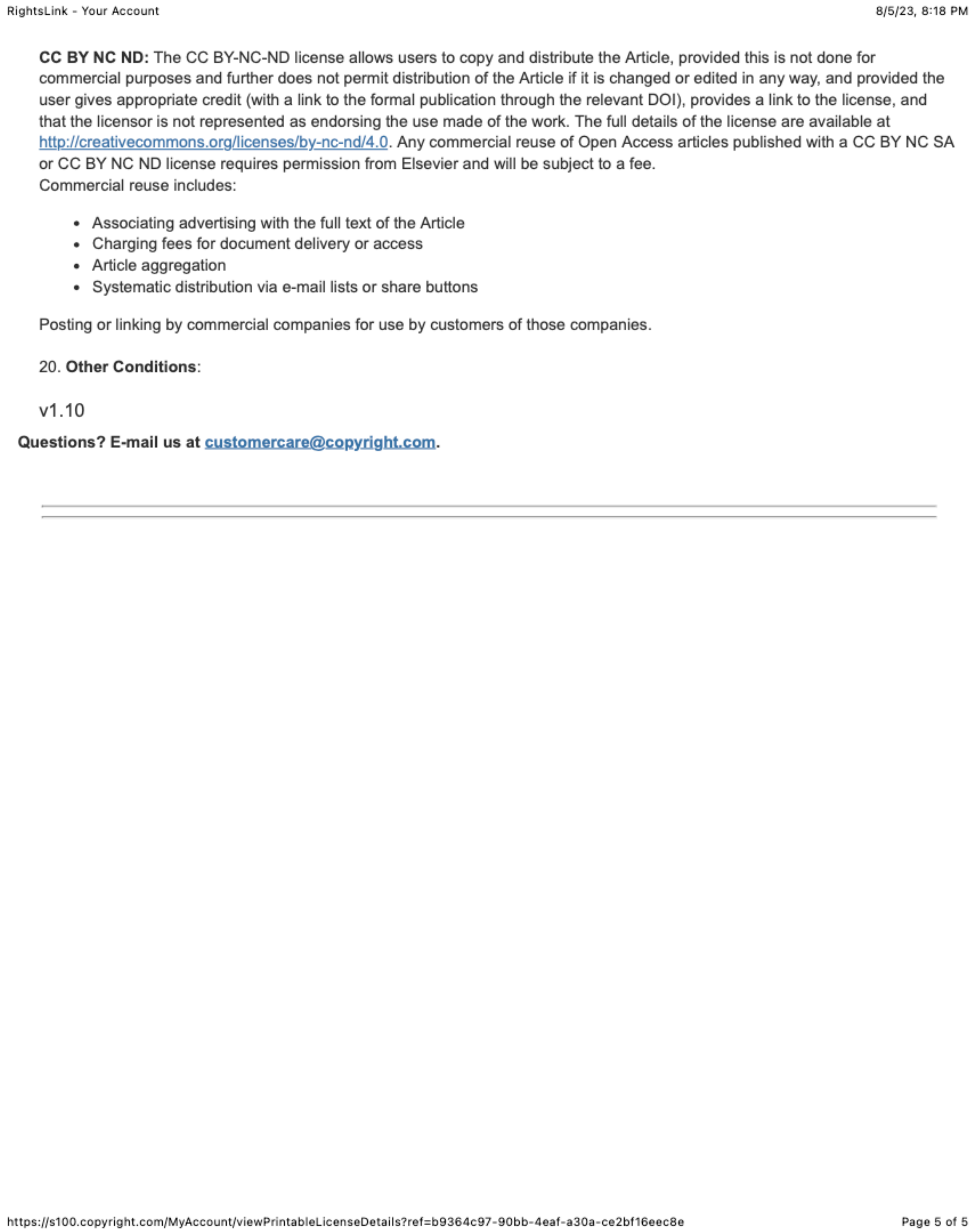

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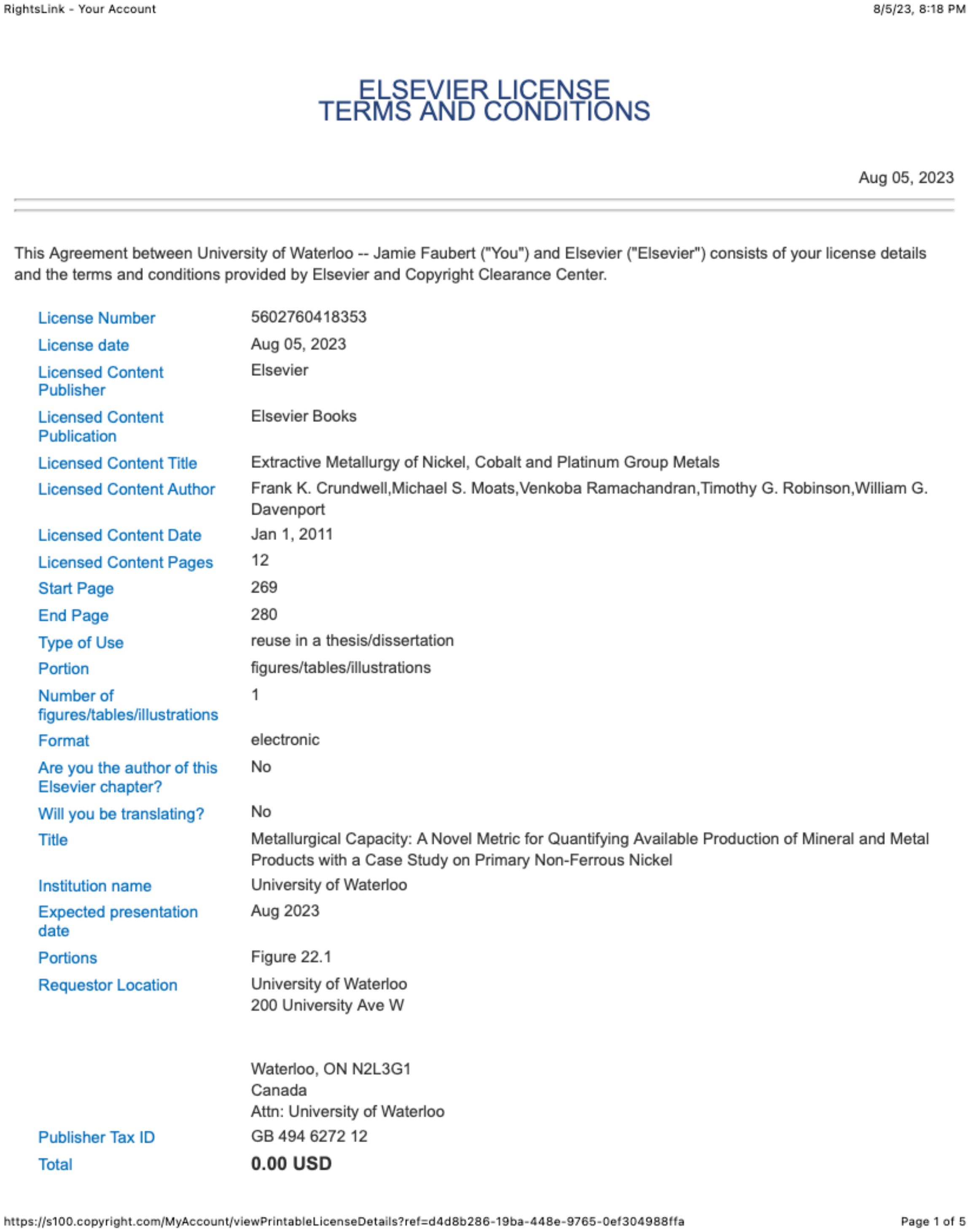

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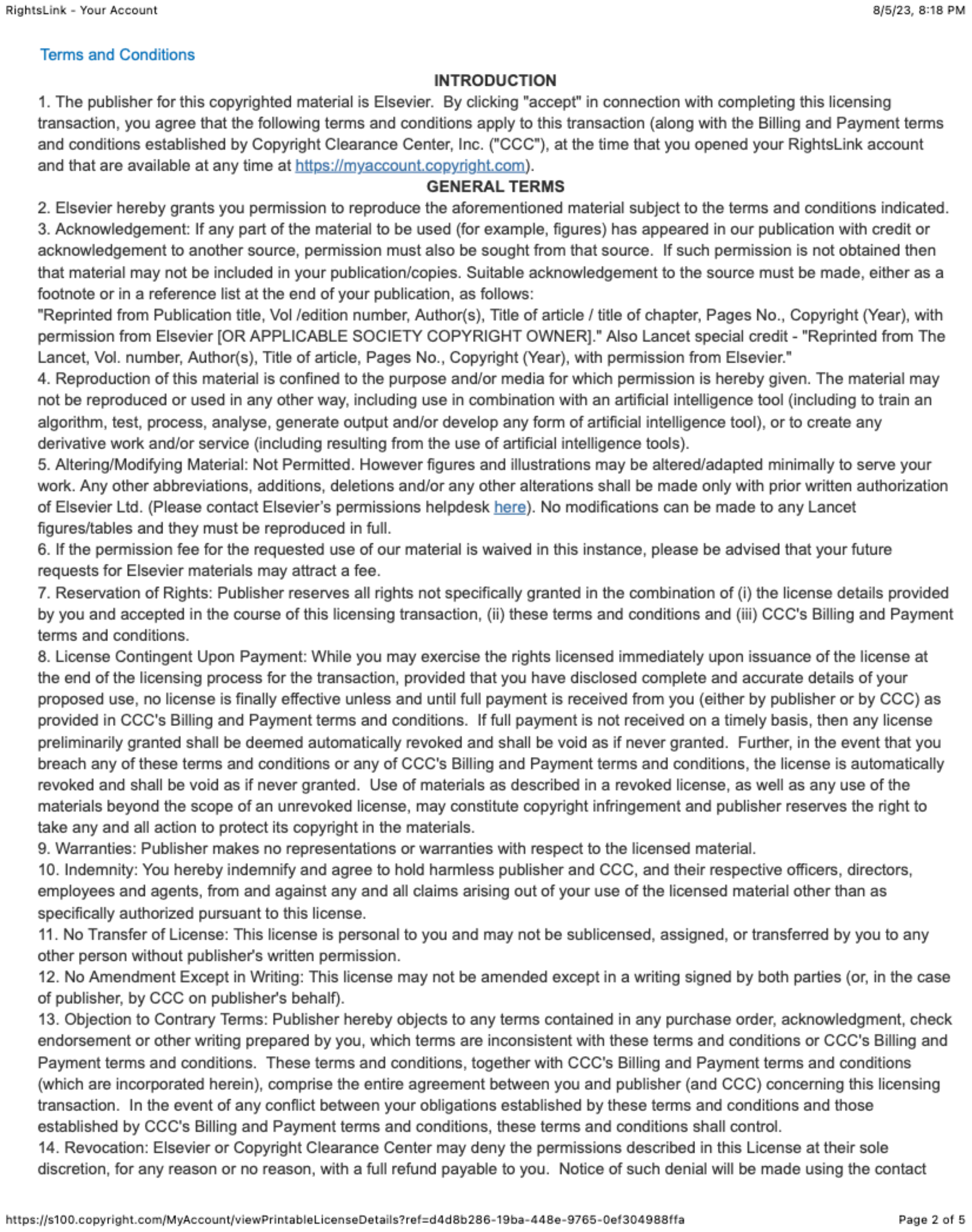

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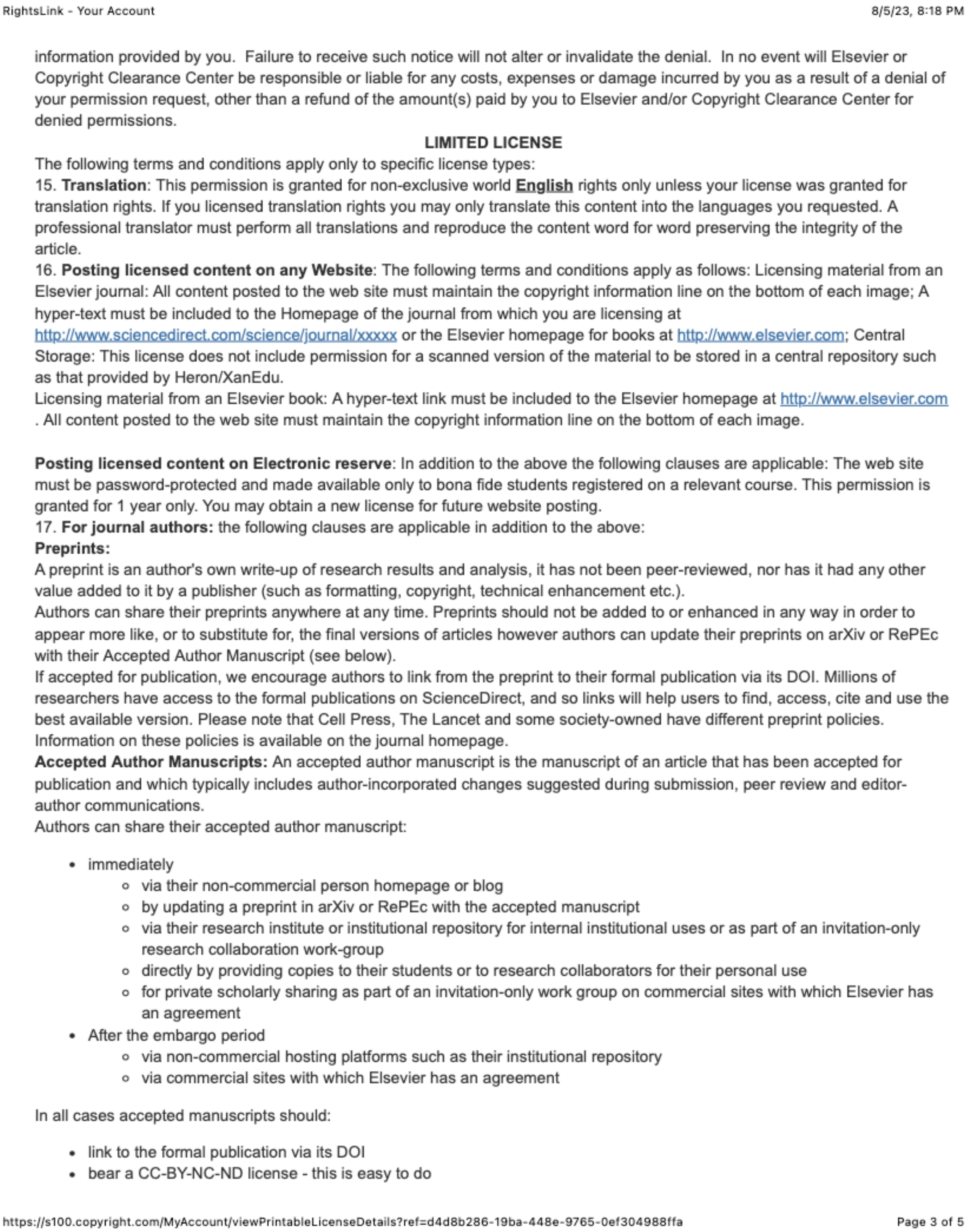

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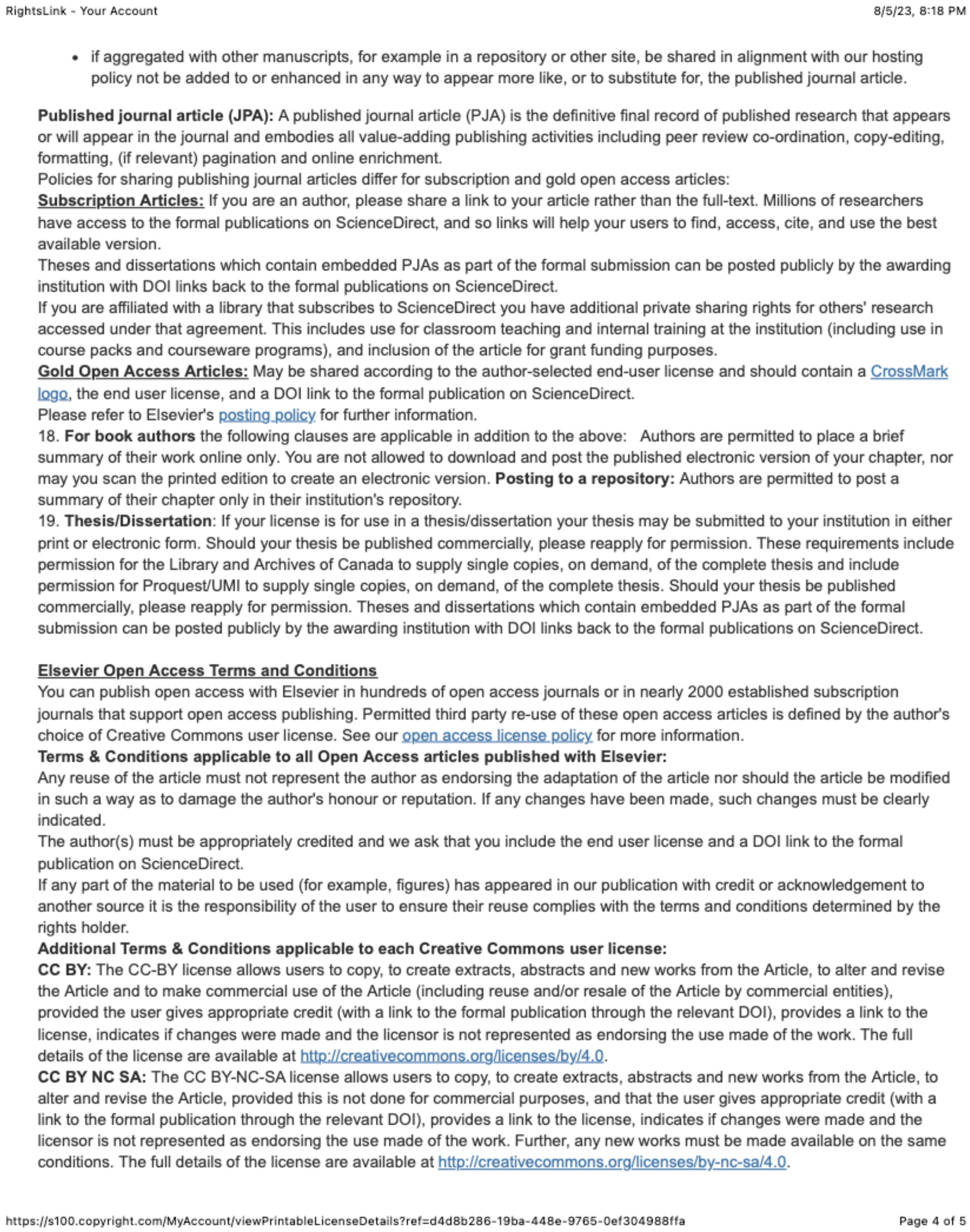

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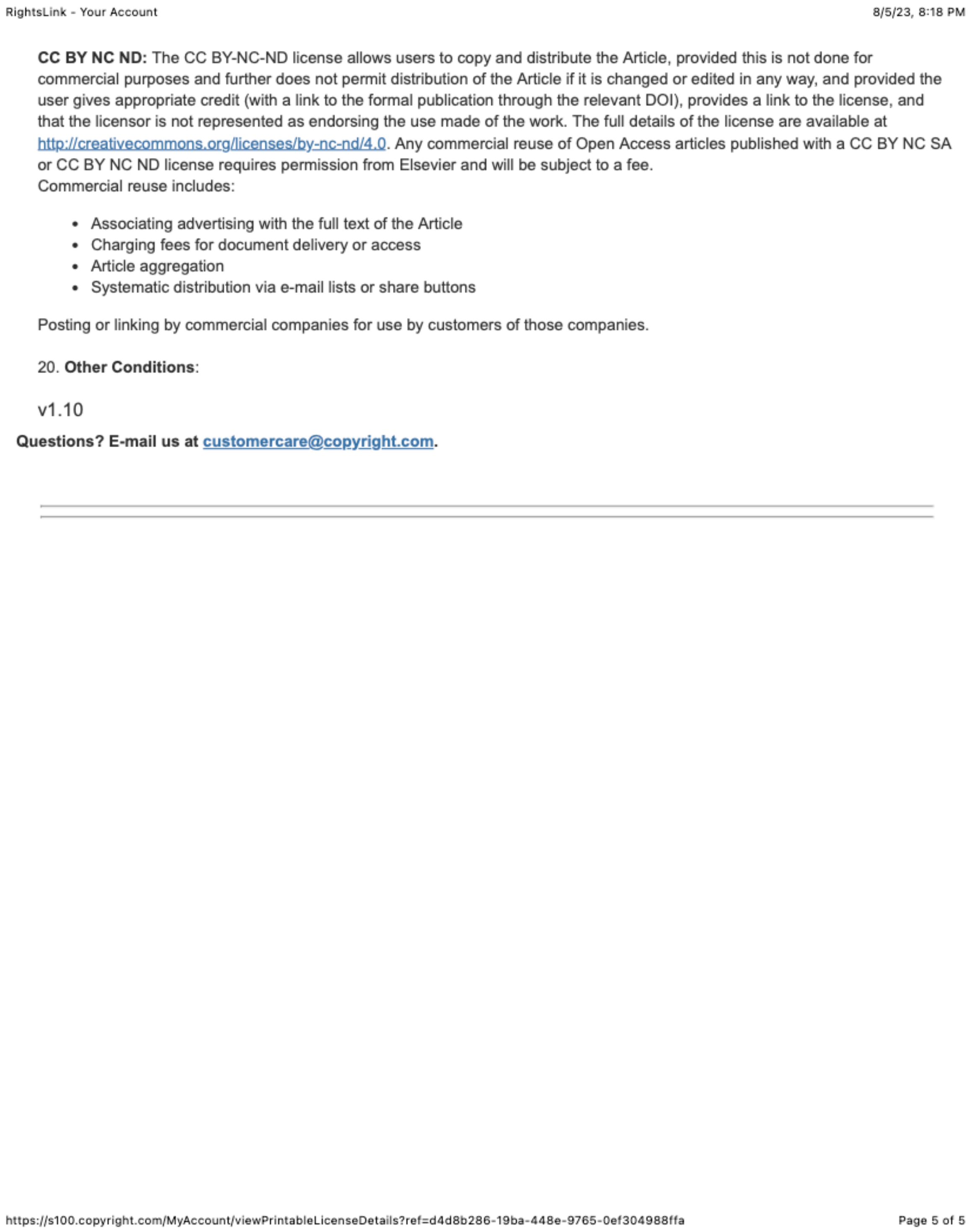

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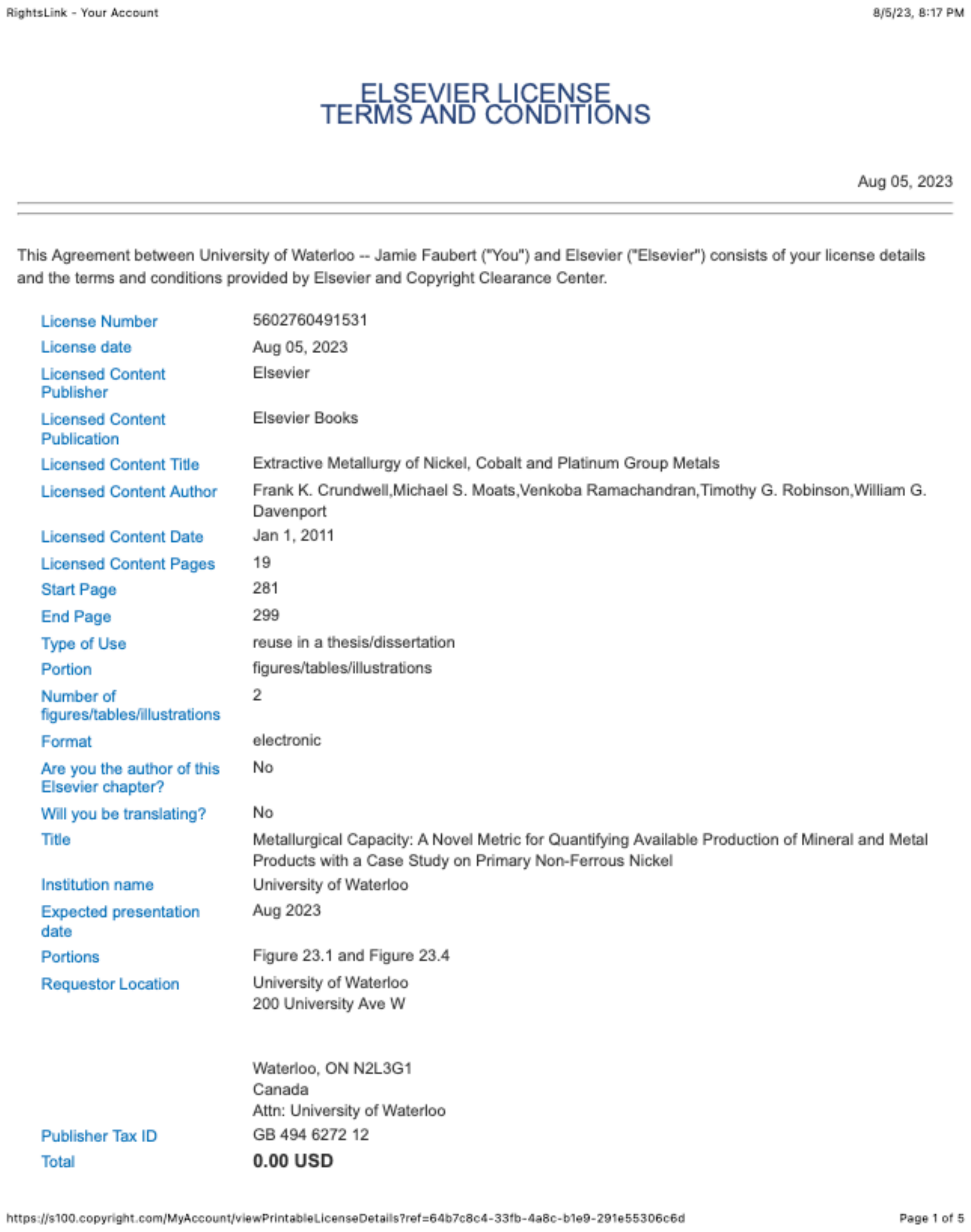

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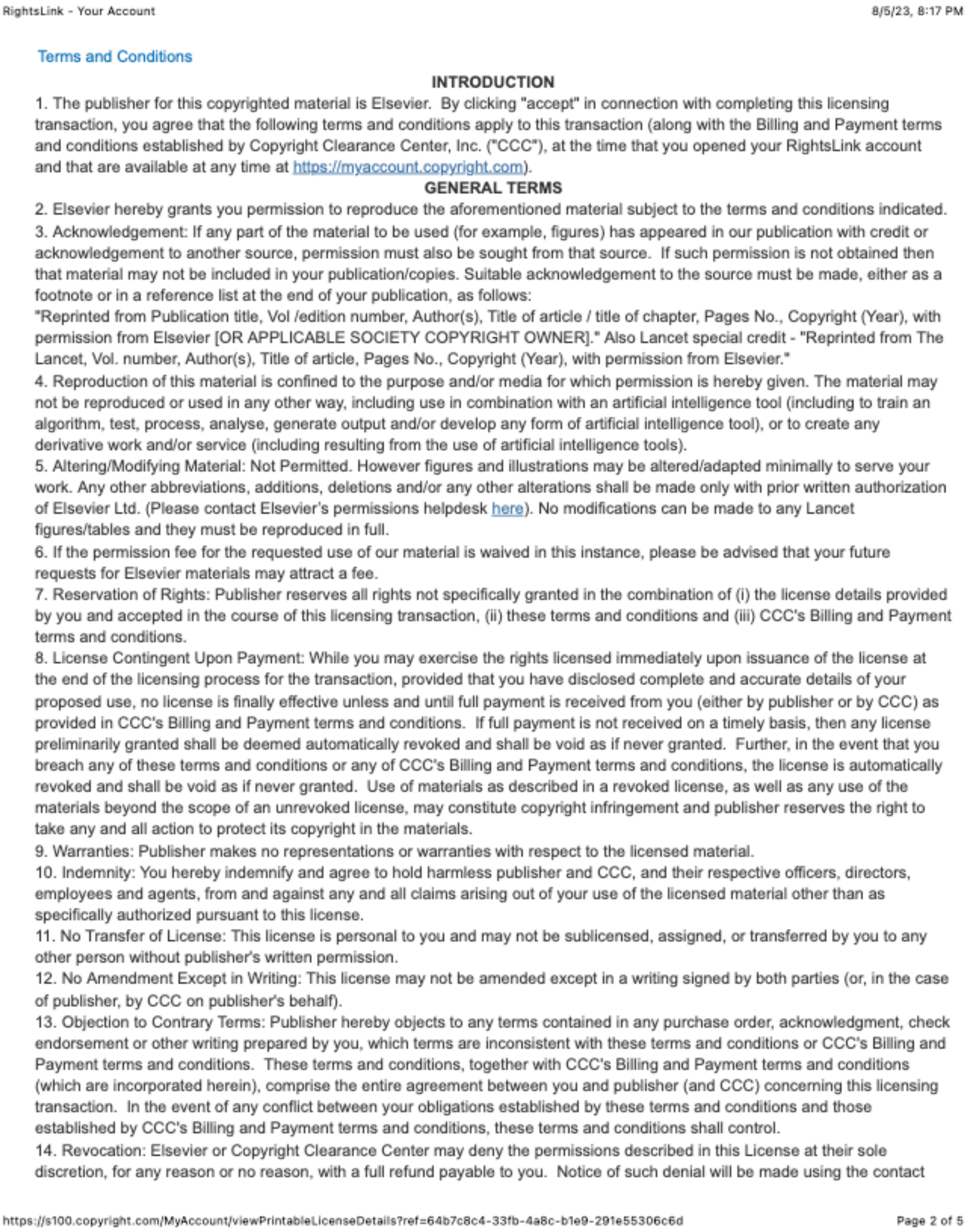

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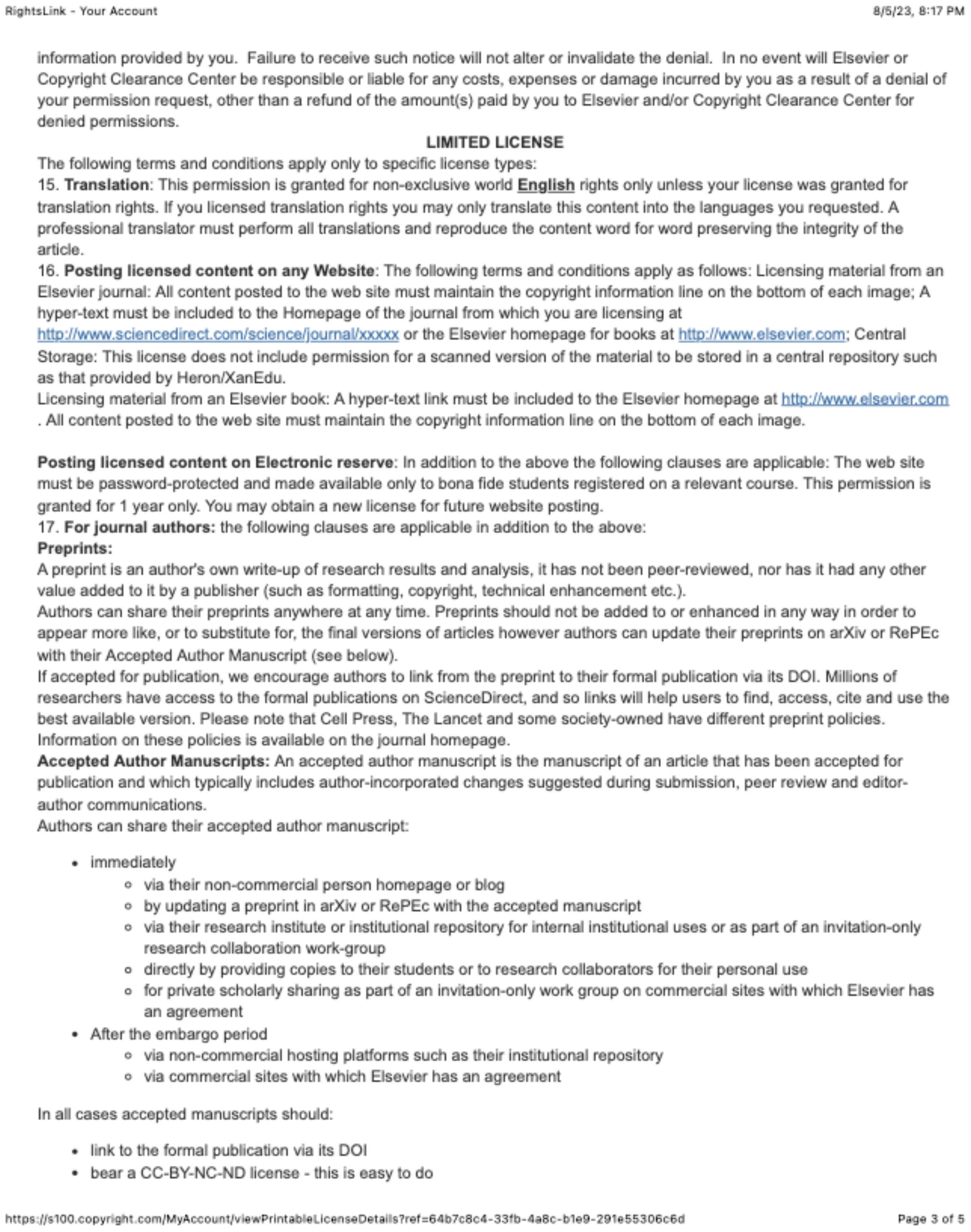

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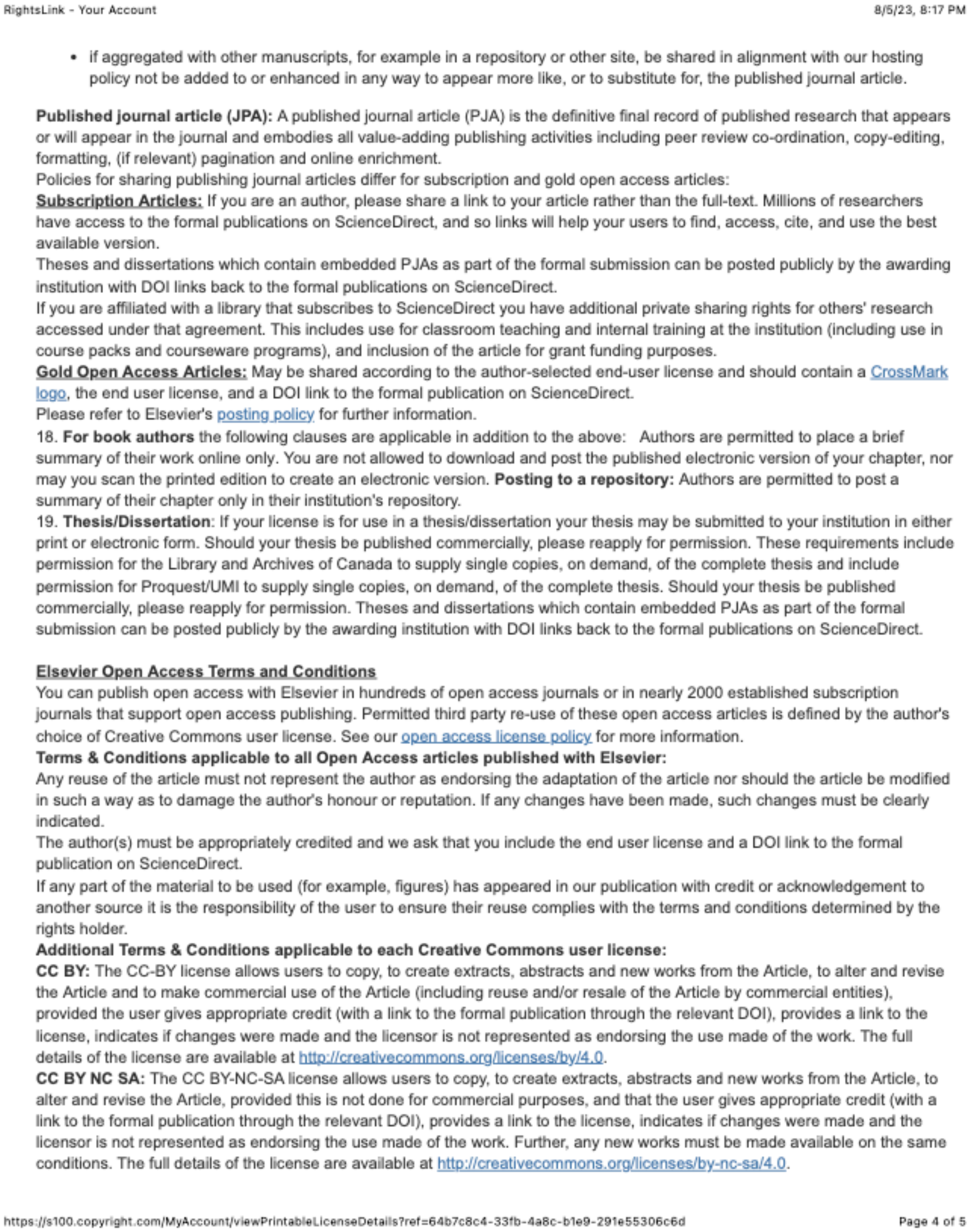

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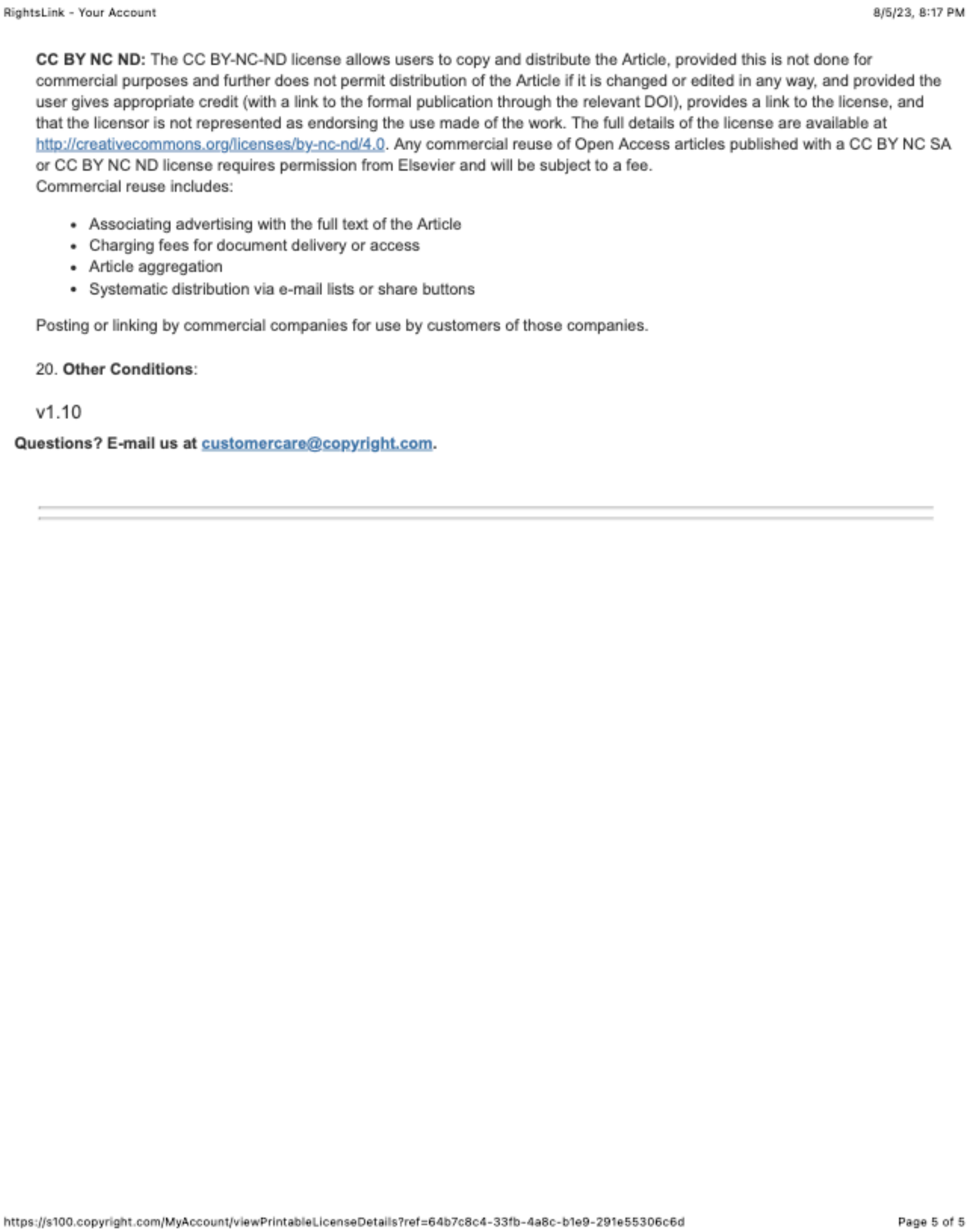

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Appendix A

Background

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Background

A-1. Nickel Overview

Metals are vital elements of modern society. Their superior material properties are exploited and applied in nearly every sector of the economy. The importance of metals such as iron, aluminum, and copper to the economy is well understood. However, lesser-known metallic elements play an equally vital role but remain largely unknown. A notable example is nickel. A transition metal, nickel is known for its ductility, high metal point, ferromagnetism, corrosion resistance, and silver-like appearance. These properties have been exploited in various applications, including metallic alloying, plating, and batteries. Its utility in foundational goods, notably stainless steel, has made it a vital commodity for the global economy.

A-1.1 Nickel Discovery and Application History

Nickel has played a critical role in the advancement of human society. Historical artifacts containing nickel dating back to 3500 BCE have been found throughout Asia and Europe. The metal has been found in low concentration in various metal alloys, chiefly used for military armament. Commercial nickel mines were first developed in Germany during the 15th century. Although efforts were made to exploit the metal, the inability to transform the material into valuable products limited its exploitation. German miners at the time had named the metal 'Kupfernickel' – roughly translating to "Devils' Copper" – after "Old Nick" due to difficulties extracting the metal. Superstitions about the ore and a lack of known applications resulted in limited ore extraction.

Swedish chemist Axel Fredrick Cronstedt first isolated nickel in 1751, although broad scientific acceptance of the discovery lagged several years. Recognition of the element subsequently led to considerable research and development into discerning critical properties of the metal. Initial applications of the metal were chiefly centred on producing a copper-zinc-nickel alloy referred to as "nickel-silver." Although the alloy did not contain silver, the white appearance of the alloy prompted many to associate the metal with silver.

Early commercial applications of nickel were limited due to challenges in processing nickel-containing ores. The invention of electroplating in the 19th century spawned newfound applications for nickel. The initial implementation of nickel electroplating largely centred on plating monetary coins. The metal rose to prominence during the late 19th and early 20th century, as numerous countries forged pure or plated monetary coins of various denominations using the metal.

Applications of nickel involving iron and steel were first discovered in the late 19th century through the pioneering of nickel-clad steel. The discovery of sizeable nickel deposits in the early 20th century, coupled with advances in nickel extraction and processing technologies, considerably expanded the supply of nickel, allowing for the broader proliferation of the metal. Metallurgical applications, specifically plaiting and alloying, were the primary use of nickel throughout the 20th century. In the late 20th century, the invention of lithium-ion batteries using nickel cathode material further expanded the potential applications of nickel.

A-1.2 Nickel Mining and Processing History

Early uses of nickel predominately relied on nickel sourced as a by-product of arsenic-bearing ores. The first commercial nickel mine, established in 1848 in Norway, exploited sulphide ores. In 1875, the first laterite deposits were successfully developed in New Caledonia. The abundant supply of laterite ores and favourable economic processing conditions resulted in rapid growth in nickel supply from lateritic ores, lasting until the early 20th century. Rising demand for nickel in the early 20th century and the expansion of infrastructure provided favourable economic conditions for exploiting sulphide deposits in Canada and Russia. The expansion in supply from sulphide ores shifted the supply balance away from laterite sources and toward sulphide sources. Sulphide ores remained the dominant source of nickel until the early 21st century due to their ability to be transformed into high-quality products.

Pyrometallurgical processing technologies dominated early processing pathways of both sulphide and laterite ores. Demand for high-purity nickel products in the early 20th century spurred the development of novel processing technologies. Due to economic and technological challenges of refining lateritic ores to higher purity products, limited processing advancements of lateritic ores were realized, and processing remained limited to smelting. Notable advancements in refining sulphide ores were made at the time, including the Mond process, which could produce high-purity nickel products. A combination of hydrometallurgical, pyrometallurgical, and vapour metallurgical processing technologies have since remained the dominant processing pathway for nickel sulphide ores.

The period following WWII saw further advancements in nickel processing technology. The development of the Sherritt Gordon process in 1948 allowed for the production of high-purity nickel from lateritic ores. The novel process utilized sulphuric acid to leach nickel and cobalt from the ore at elevated temperatures and pressures. The metals were then recovered and refined into higher-quality products using ammonia hydroxide. The technology was first applied to lateritic ores in Cuba and has since been adopted at various lateritic deposits globally. Growing demand for nickel for use in stainless steel applications in the early 21st century spurred further advancements in processing. The production of low-quality ferronickel products, commonly referred to as nickel pig iron, from lateritic ores using blast furnace smelting technology rapidly expanded the supply of nickel. The initial adoption of the technology was limited to China, which has since evolved to utilizing rotary-kiln electric furnaces (RKEF).

A-2. Nickel Uses

The superior properties of nickel have resulted in its proliferation across various applications. Developments and advancements in cost-effective methods of extracting nickel, coupled with an improved understanding of nickel properties, have expanded the scope of potential applications. In turn, the demand for nickel has expanded considerably over time. Innovations in battery technologies and the transitions to low-carbon energy sources are anticipated to expand the demand for nickel in the coming decades. Understanding the historical evolution of nickel demand and future demand relative to its downstream applications is critical for identifying supply chain bottlenecks.

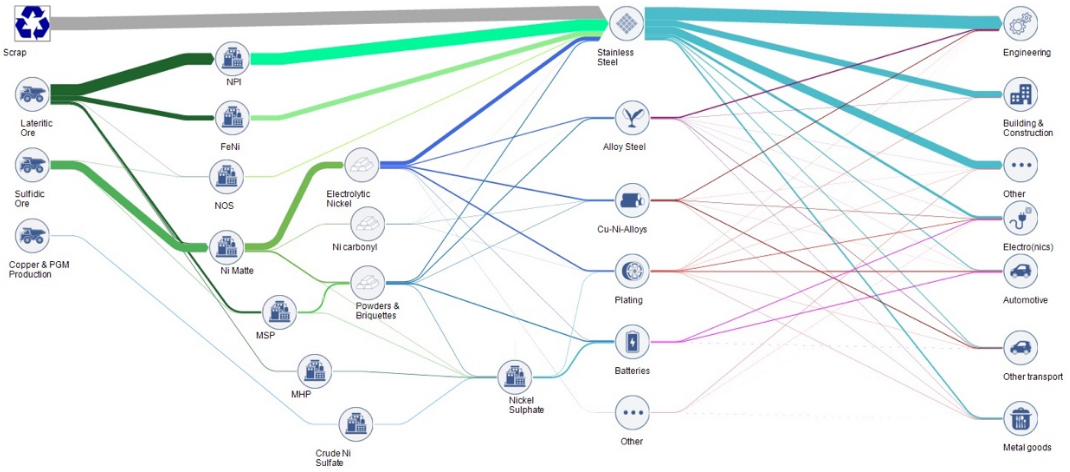


Figure A-2-1: Sankey Diagram of Nickel Material Flow (2020 Data) (Nickel Institute, n.d.)

A-2.1 Historical Applications and Demand

Throughout the 21st century, nickel has primarily been used in metallurgical applications. Consumption from metallurgical applications has primarily stemmed from three first-use applications: stainless steel, non-ferrous alloys, and plating. In turn, such first-use applications of nickel have been leveraged by a variety of end-use applications spanning multiple industries.

A-2.1.1 Stainless Steel

Historically, stainless steel has been the dominant first-use application of nickel. While stainless steels are iron-chromium alloys that must contain a minimum of 10.5% chromium by weight, an assortment of alloying elements are commonly added to achieve unique performances. Chief amongst such alloying elements is nickel. Several recognized grades of stainless steel contain substantial quantities of nickel. Stainless steels are known for superior corrosion resistance to crude carbon steel. The formation of a passive, tenacious and self-renewing chromium oxide layer forms on the surface of the steel and protects the underlying steel from a range of environmental conditions. The first stainless steel alloys containing nickel were developed between 1904-1911. Since its introduction, many nickel-containing stainless-steel alloys with varying alloy compositions have been developed.

Adding nickel as an alloying element drastically improves many properties, including enhanced corrosion resistance, formability, weldability, and ductility. The extent of the properties can be adjusted based on the composition of the alloying elements. Variations in composition also result in various microstructures, further influencing their properties. The most common nickel-containing stainless steel grade, industrially referred to as 300-series, accounts for 55% of total stainless steel production. This grade of stainless steel contains 6-20% nickel by weight. Other common nickel grades include 200 and 400-series stainless steel, which contain anywhere from 0.5-6.0% nickel by weight.

Stainless steel is generally produced using pyrometallurgical processes, including electric arc furnaces (EAF), where nickel is combined and melted down with crude steel and other alloying elements. The resulting output product is then solidified and processed before achieving the desired microstructure and form factor. Nickel is added to the process using a variety of form factors depending on the operation and quality of the output product. Typical nickel products include ferronickel (FeNi) granules, Nickel-Pig Iron (NPI) granules, briquettes, nickel cathode, and nickel oxide (NiO) granules. Nickel is also indirectly added by adding scrap stainless steel into the furnace.

The favourable properties of stainless steel have led to its use in many end-use applications that are, in turn, utilized in sectors such as healthcare, transportation, and chemical.

Appreciable volumes of stainless-steel waste are generated due to varying in-use lifespans of end-use applications. Beneficially, waste stainless steel can be infinitely recycled without degradation to its properties. Stainless steel recycling leverages identical processing pathways to those employed in producing virgin stainless steel where in place of primary nickel products, scrap stainless steel is used as feedstock.

The quality of the final product from recycled sources largely depends on the scrap feedstock's homogeneity.

According to the Nickel Institute, approximately 69% of primary nickel production is used in stainless steel applications. Historically, stainless steel has accounted for the majority of nickel consumption. Anticipated growth in the stainless steel market stemming from continued development in emerging markets is expected to sustain marginal growth for nickel. Considering the bulk of global stainless steel production and consumption is primarily concentrated in China and, to a greater extent, Asia, nickel consumption for stainless steel is concentrated within Asia.

A-2.1.2 Plating Applications

Plating is a well-known first-use application of nickel due to its historical use in plating financial coins. The first successful electroplating of nickel was achieved in 1843. Nickel rapidly displaced silver as the preferred plating metal for industrial and low-cost applications due to its favourable economics, corrosion resistance, and reflective surface finishing, which did not require polishing.

Nickel plating provides numerous cosmetic and engineering advantages over alternative coatings. The resulting nickel coating exhibits a bright surface finish. Additives can be included in plating solutions to enhance the brightness or alter the surface colour of the coatings. The coatings can also maintain their surface finish without additional polishing. From a technical perspective, nickel plating exhibits favourable wear, corrosion, and heat resistance. These advantages are attributed to the thin nickel oxide layer on the plating surface's exterior. Further, nickel plating is beneficial due to its ability to adhere to various surfaces, including metals, plastics, and ceramics. As a result, nickel is commonly used as an undercoating in many plating applications.

Three nickel plating processes exist electroplating, electroless plating, and electroforming. Numerous configurations of each process have been developed and are employed based on the technical requirements of the coating and the geometric features of the objects plated. Electroplating is the most common process deployed. In principle, high-quality nickel metal, commonly in sheets or rounds, is submerged in the aqueous solution along with the plating object. Current is applied to the submerged plating object and nickel metal. The resulting potential difference dissolves the nickel into the solution, which migrates to the object's surface, where it is deposited layer by layer. Various parameters can be adjusted to control the quality and thickness of the nickel plate.

Plated nickel is used in various end-use applications due to its superior properties and appearance. One of the most prominent end-use applications of nickel plating includes financial coins. Various countries over time have used nickel-platted currencies. Nickel plating has also seen extensive use in the transportation sector, including the automotive and aviation industry, where it is used to plate components to improve their performance and longevity. Similarly, nickel plating has played a critical role in the electronics industry, where it is used for connectors, microprocessors, and integrated circuits. Nickel plating has also been used extensively in the jewelry industry as an undercoating for plating metals such as gold.

According to the Nickel Institute, approximately 6% of nickel produced globally is used in plating applications. Historically, plating applications have been a significant consumer of high-purity nickel products. It is anticipated that the consumption of nickel for plating applications will grow with global economic growth.

A-2.1.3 Non-Ferrous Alloys applications

Non-ferrous alloys, also referred to as superalloys, are broadly categorized as alloys in which the bulk of the constituent metal is not iron. Several metals comprise the primary constituent, including cobalt, nickel, and chromium. The history of non-ferrous alloys dates back to 1907 with the patenting of Nickel-Chromium and Cobalt-Chromium alloys. Early alloys were limited in capabilities. Commercially available alloys became readily available in the 1950s. Numerous nickel-based non-ferrous alloys have been developed and seen adoption in various end-use applications. Similarly, nickel has been used as an alloying element in other non-ferrous alloys, primarily in cobalt and chromium based non-ferrous alloys.

Non-ferrous alloys were initially favoured for their superior heat resistance. With advancements in metallurgy and processing technologies, nickel-based non-ferrous alloys gained notoriety for their superior mechanical strength, creep resistance, corrosion resistance, and density. Modern nickel-based non-ferrous alloys contain 30-99wt% nickel and are alloyed with varying levels of chromium, iron, molybdenum, copper, and cobalt, depending on the application. Exotic elements such as titanium, niobium, tungsten, and tantalum are also used in minor amounts. Non-nickel based non-ferrous alloys contain a range of nickel content from 0.5wt% to 30wt%. The combination of elements in non-ferrous based alloys is highly dependent on the desired properties and end-use application.

A variety of processing techniques are employed in the production of nickel-based non-ferrous alloys. Two processes commonly exist: casting and forging, and powder metallurgy. The type of process used is highly dependent on the properties required and the end-use application. Due to the high cost and difficulty in processing and refining non-ferrous alloys, along with a small subset of end-use applications, the recycling rate of non-ferrous alloys is relatively high. In either process, high-quality nickel products, such as powders, rounds, and cathodes, are utilized due to their concentrations of impurities.

Thanks to their superior properties, non-ferrous alloys are most commonly used in specialized, high-performance end-use applications. The most notable use of non-ferrous alloys includes turbine blades in gas power turbines and jet engines. Nickel-based non-ferrous alloys are favoured due to the high-temperature requirement needed to maximize combustion efficiency. Non-ferrous alloys are also widely used in chemical and industrial applications, nuclear energy generation, and space exploration.

According to the Nickel Institute, approximately 7% of nickel produced globally is used in non-ferrous alloy applications. Non-ferrous alloys are relatively novel applications of nickel. The future outlook for nickel in non-ferrous alloy applications is anticipated to increase due to elevated demand for non-ferrous alloys in energy, transportation, and military sectors. Consumption of non-ferrous alloys is primarily concentrated in developed nations and emerging Asian markets.

A-2.1.4 Other Applications

According to the Nickel Institute, trivial amounts of nickel are used for alloy steel, foundry, and other distributed applications accounting for approximately 3%, 2%, and 1% of total first-use applications. Alloy steel applications include iron-based materials with a low nickel content ranging from 0.3-20wt% nickel. They are manufactured using processes similar to those used in the fabrication of stainless steels and require similar nickel products, including briquettes, nickel oxides, and cathodes. Alloy steels exhibit superior properties to plain carbon steels, including higher strength, hardness, wear resistance, and toughness. They are commonly used in energy, industrial equipment, infrastructure, tooling, and transportation end-use applications. Limited information is available on nickel used in foundry and other applications.

A-2.2 Future Uses and Demand

The advent of climate change has required governments and organizations to assess their environmental impact and develop abatement strategies for addressing their respective impacts. Nickel is expected to play a critical role in numerous reduction strategies, specifically those related to energy, transportation, and infrastructure sectors. As a result, demand for nickel is expected to increase drastically in the coming decades.

A-2.2.1 Batteries

Countless advancements in battery technologies have been realized since their inception in 1799 by Alessandro Volta. Nickel-based batteries were first conceived in 1899 with the development of Nickel-Cadmium (Ni-Cd) batteries which were closely followed by Nickel-Iron (NiFe) and Nickel-Zinc (NiZn) batteries in 1901. The batteries gained commercial prominence at the time due to their utility in industrial and consumer applications, including batteries in early electric vehicles. A significant leap in nickel-based battery technology came in 1967 with the invention of the Nickel-metal hydride (NiMH) battery which saw widespread utility in consumer electronics. Lithium-ion batteries (LIB) were developed in 1979 by John Goodenough, although the initial formulation did not include nickel. The use of nickel in LIB cathodes followed shortly after.

The commercialization of nickel-based batteries has primarily centred on Ni-Cd, Ni-Fe, Ni-Zn, NiMH, and LIB chemistries. In all cases, nickel plays a critical role in the cathode material. However, nickel is also used in non-cathode components to varying degrees. Ni-Cd, Ni-Fe, Ni-Zn, and NiMH batteries require nickel hydroxide as a precursor material in cathode production.

Several nickel-based LIB cathode materials have been developed, each exhibiting varying capabilities. In general, nickel is used in the cathode material due to its cost-effective means of enhancing energy density, storage capacity, and stability. The most widely used LIB cathode chemistries include nickel-cobalt-aluminum (NCA) and nickel-manganese-cobalt (NMC). The nickel content in each cathode material varies significantly and can range from 30-80% of the weight of the cathode material. In either instance, nickel sulphate is the favoured precursor cathode material.

Various battery manufacturing processes have been developed. The process is unique to manufacturers, battery chemistries, form factors, and end-use applications. The material requirements and processing operations used by manufacturers for nearly all battery types are highly proprietary. Given the high concentration of nickel in batteries, the ability to recover valuable metals, including nickel, through recycling processes is feasible.

Nickel-containing batteries are used in a wide range of end-use applications. Historically, Ni-Cd, Ni-Fe, and Ni-Zn batteries were extensively used in small portable electronics due to their ability to be recharged and assembled at relatively low cost. Similarly, they found utility in transportation and standby power applications. NiFe batteries were initially developed for electric vehicles but were quickly overtaken by internal combustion engines. In contrast, NiMH batteries partially replaced Ni-Cd batteries in consumer electronic applications. The battery chemistry was also widely used in electric and hybrid vehicles introduced in the later part of the 20th century, but due to end-of-life toxicity concerns, they were quickly phased out.

Since their introduction, LIBs have become the dominant battery of choice in numerous end-use applications. The most notable examples of end-use applications for nickel-based LIB include electric vehicles. These battery chemistries have also seen applications in consumer electronics and grid energy storage applications. The type of nickel-based cathode material used depends on the requirements of the intended end-use applications.

According to the Nickel Institute, approximately 7% of nickel produced globally is used in battery applications. Historically, the application has accounted for a small fraction of overall demand and was primarily concentrated in Asia. However, battery applications are predicted to account for over 40% of all nickel demand by 2040.

A-2.2.2 Other Novel Applications

A wide range of applications has historically profited from nickel's advantageous properties. While the applications will remain relevant and require appreciable quantities of nickel, new novel applications employing nickel are anticipated to see considerable growth in the coming decades. A notable application includes fuel cells. Recent research has shown that nickel can significantly improve the economics and performance of fuel cells. The extent to which this technology will materialize remains to be seen.

A-2.3 Critical Mineral

The scarcity of nickel and its anticipated increase in demand stemming from the energy transition has raised concerns among various stakeholders. In response, numerous companies and governments have deemed nickel a critical metal. Various definitions of what constitutes a critical metal exist and are typically tailored to the specific needs and interests of the stakeholder. Factors include geological scarcity, economic importance, geopolitical supply constraints, and national security risk. Countries, including Canada and the USA, have listed nickel as a critical metal. Alternatively, the European Union has stated they are motoring nickel but does not consider it a critical metal. Canada lists nickel as a critical mineral due to its importance in stainless steel, solar panels, and batteries. The United States of America list nickel for its importance in stainless steel, superalloys, and rechargeable batteries. The European Union states that it is monitoring nickel due to its importance in battery applications. The criteria and weighting of factors used in determining critical metals are periodically updated, and as such, the importance of nickel could increase and expand beyond the current number of governments deeming it critical.

A-3. Geology, Extracting, and Processing

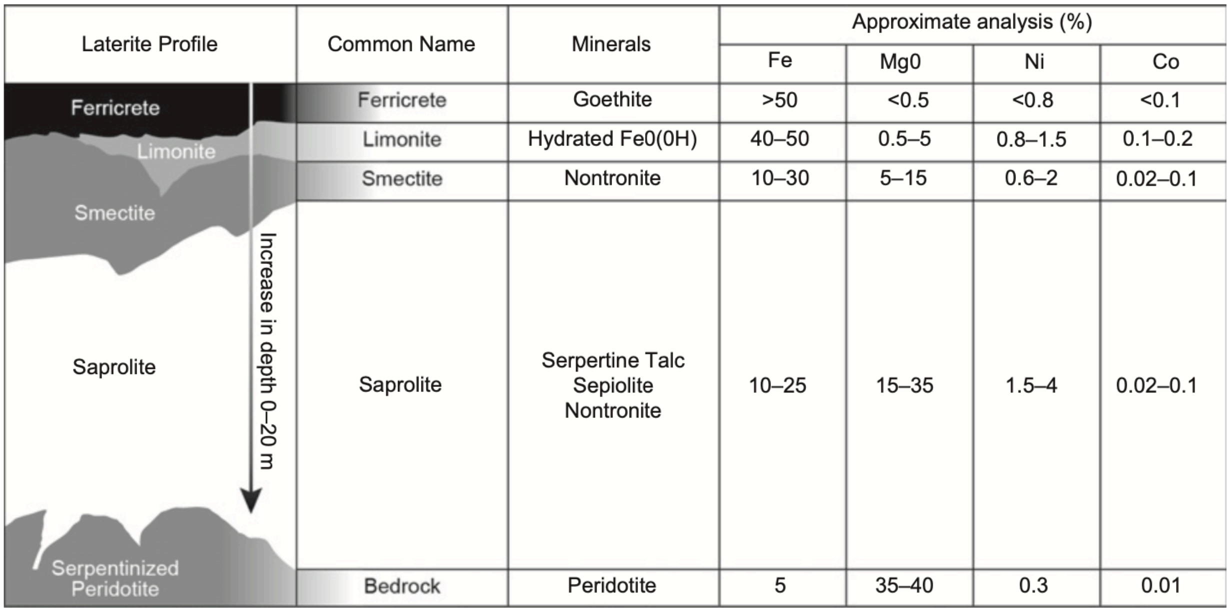
Transforming primary nickel into functional products suitable for commercial applications depends on myriad factors, most notably, the geology of a deposit, the extraction method utilized, and the processing technology employed. These factors are essential to decipher when assessing the potential availability of nickel as they further influence economic, environmental, and social elements.

A-3.1 Geology and Primary Sources

Nickel is the 23rd most abundant element within the earth's continental crust, with an average content of 84 parts per million. Although nickel is relatively abundant compared to other critical minerals, deposits with sufficient concentrations to be economically extracted are limited and geographically constrained. Notable nickel deposits are located along the ocean floor but remain unexploited. Terrestrial nickel deposits are hosted by two distinct mineral groups: laterites and sulphides. Various characteristics segregate the minerals, which in turn impact downstream processing. The mineralogy of a deposit is also critical to producing other valuable metals such as cobalt, copper, and PGMs.

A-3.1.1 Laterite Ore

Laterite ores are a critical source of nickel and have been a significant production source since they were first mined in 1886. Laterite deposits form from prolonged tropical weathering in which extensive chemical and mechanical interactions generate a stratified ore profile. Laterite nickel deposits are situated in regions that have experienced or are currently experiencing prolonged weathering. Notable deposits are in Australia, Brazil, Cuba, New Caledonia, Indonesia, the Philippines, and other predominantly tropical regions.



Common Name	Minerals	Approximate analysis (%)			
		Fe	Mg0	Ni	Co
Ferricrete	Goethite	>50	<0.5	<0.8	<0.1
Limonite	Hydrated Fe0(0H)	40–50	0.5–5	0.8–1.5	0.1–0.2
Smectite	Nontronite	10–30	5–15	0.6–2	0.02–0.1
Saprolite	Serpertine Talc Sepiolite Nontronite	10–25	15–35	1.5–4	0.02–0.1
Bedrock	Peridotite	5	35–40	0.3	0.01

Figure A-3-1: Laterite Deposit Profile (Crundwell et al., 2011)

Laterite deposits exhibit three distinct subtypes: (I) clay silicate, (II) Magnesium hydrous silicate and (III) Iron Oxide. Each layer displays unique depth, chemical composition, and occurrence characteristics. The clay silicate layer forms the top layer and is generally considered overburdened, containing insignificant quantities of extractable nickel. The magnesium hydrous silicate layer lies below and is often referred to as limonite. The composition of the layer varies drastically but contains between 1.2-1.7wt% Ni, 0.1-0.2wt% Co, 1-4wt% Mg, and approximately 45wt% Fe. The iron oxide layer, referred to as saprolite, lies below the limonite ore and is the deepest layer containing nickel. Like limonite layers, the composition of saprolite layers varies significantly. Generally, saprolite layers contain approximately 0.4-3wt% Ni, 0.02-0.1wt% Co, 10-30wt% Mg and 9-25wt% Fe.

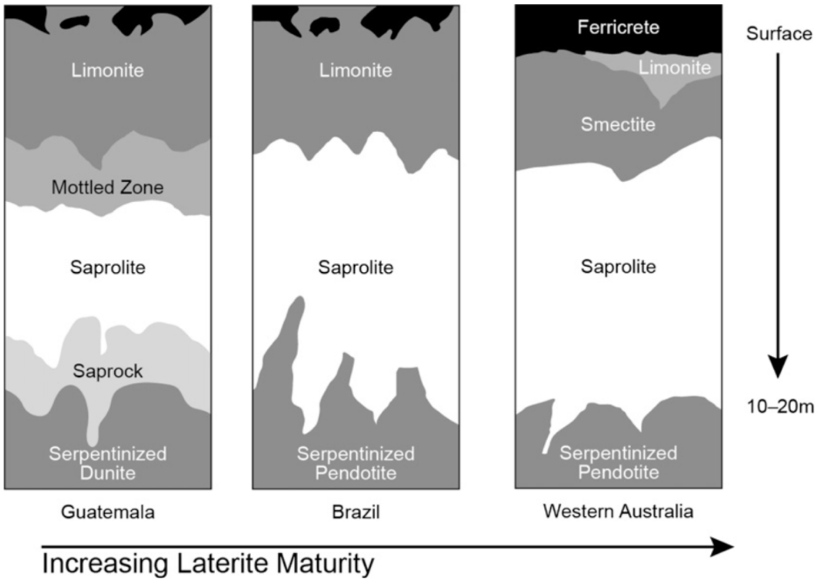


Figure A-3-2: Spatial and Temporal Variation of Select Laterite Deposit Profiles (Crundwell et al., 2011)

The composition and quality of each layer varies drastically between regions due to variations in climatic conditions over time. The depth of the laterite ore deposits is relatively shallow and within a few meters from the surface. The economic viability of a deposit and the quality of the output product is related mainly to the composition of each layer. In general, cobalt is a dominant by-product extracted from laterite ores. However, deposits also contain considerable quantities of PGMs, Cu, and Mg.

A-3.1.2 Sulphide Ore

Nickel sulphide ores were the leading source of nickel throughout the 20th century. The ores are classified as magmatic sulphide deposits. The ores contain Group VIII transition metals (Fe, Co, Ni, Pd, Pt, Rh, Ru, Ir and Os), copper, and gold. Deposits are divided into two distinct groups: sulphide-poor and sulphide-rich. The groups further exhibit notable differences in the concentration of other valuable metals, which is critical in the quality of nickel that can be produced from the ore. Historically deposits have been located at a range of depths. However, modern deposits have been discovered at increasingly greater depths.

Sulphide-poor deposits contain between 0.5-5wt% sulphides. The primary product recovered from these ores is generally PGMs, while nickel and copper are recovered as by-products. The composition of the ores can vary significantly but generally contain between 0.05-.5wt% Ni, 0.02-0.2wt% Cu, and 1.5-25 g/t PGM. Minimal cobalt is associated with these deposits. Such ore deposits are predominately found in South Africa, Zimbabwe, and Russia, with smaller deposits in the United States, Canada, and Australia.

In contrast, sulphide-rich containing deposits contain between 20-90% sulphides and higher concentrations of nickel and copper relative to sulphide-poor deposits. PGMs are hosted within the deposits, albeit at lower concentrations. Sulphide-rich ores contain between 0.2-1.9wt% Ni, 0.16-3.57wt% Cu, and 0-9.5 g/t PGMs. Further, these deposits generally contain appreciable amounts of cobalt ranging between 0.01-0.2wt%. Deposits are predominately found in Russia, China, Canada, and Australia, with smaller deposits in northern Europe, Brazil, and the USA.

A-3.1.3 Other Deposits and Minerals

Beyond laterites and sulphides, nickel is found in various minerals. The deposits generally contain lower concentrations of nickel and are seldom commercially exploited. The most prominent include hydrothermal deposits, which contain appreciable concentrations of nickel and manganese in crusts and nodules found along the seafloor and lakes. They are generally present as distributed tracts of partially buried concretions along the body of water's floor. The composition of the nodules varies significantly. Iron and manganese in the form of hydroxides are the most abundant metals, typically containing 29wt% and 6wt%, respectively. The nodules also host other valuable elements, including appreciable nickel, copper, and cobalt concentrations containing 1.4wt%, 1.3wt%, and 0.25wt%, respectively. Extraction of the deposits has thus far been limited, while future commercial operations face a range of uncertainty due to legal, environmental, and social challenges.

Declining nickel ore grades across existing and newly discovered deposits have prompted interest in unconventional sources of nickel. Forefront to these efforts includes reprocessing tailings from retired mining operations. Tailings discarded from the retired operations contain sufficiently high nickel concentrations for economic recovery, albeit with lower net resources.

Other novel sources of nickel include vegetation. Several tropical species of vegetation grown in regions with lateritic deposits are known to contain appreciable nickel concentrations. Attempts to recover the nickel have been successful. However, numerous economic, environmental, and social issues need to be addressed prior to commercialization.

A-3.2 Resources and Reserves

The geological availability of extractable nickel is critical to understanding potential future supply. The most common indicators for assessing the geological availability of metals and minerals include resources and reserves. The United States Geological Survey (USGS) is the most widely cited source of the indicators. Although the definitions adopted by the USGS are used broadly throughout the mining industry, various definitions of reserves and resources have been established. Various stakeholders have adopted dissimilar definitions, including companies, organizations, and government agencies, to describe the availability of metals. The nuances between definitions create uncertainty when estimating the availability of metals and minerals. Inconsistencies and narrow scope of endorsed terms are pervasive in estimating nickel resources and reserves, limiting the potential for adequate assessment of future supply potential.

According to the USGS, in 2021, 300 million metric tonnes of terrestrial nickel resources, averaging approximately 0.5% nickel or greater, remained unexploited globally. Of which, it is estimated that approximately 60% of resources are in the form of laterite deposits, while 40% are in the form of sulphide deposits. While excluded from resource estimates, it is further estimated that 350 million metric tonnes of nickel are located offshore in manganese crusts and nodules along the sea floor. Global nickel reserves are estimated to be greater than 95 million metric tonnes.

Table A-3-1: USGS Country-level Reserves and 2021 Mine Production (U.S. Geological Survey, 2022)

	2021 Mine production *(metric tonnes)*	**Reserves** *(metric tonnes)*
United States	18,000	340,000
Australia	160,000	21,000,000
Brazil	100,000	16,000,000
Canada	130,000	2,000,000

China	120,000	2,800,000
Indonesia	1,000,000	21,000,000
New Caledonia	190,000	NA
Philippines	370,000	4,800,000
Russia	250,000	7,500,000
Other countries	410,000	20,000,000
World total (rounded)	2,700,000	>95,000,000

The geographic distribution of resources and reserves varies considerably. Sulphide deposits are predominately in Australia, Canada, China, South Africa, and Russia. In contrast, laterite deposits are in Australia, Brazil, Indonesia, and the Philippines.

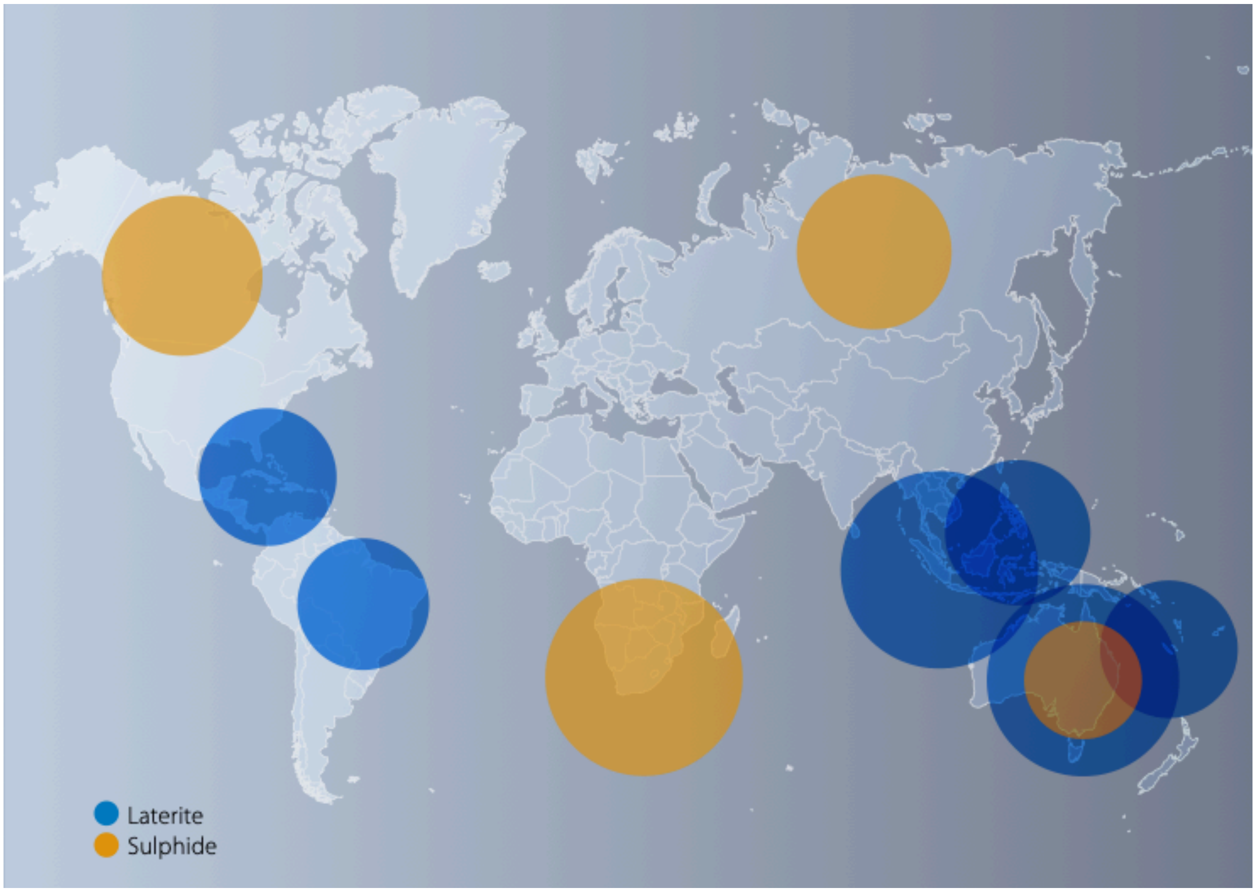


Figure A-3-3: Geographic Distribution of Major Sulphide and Laterite Reserves (Nickel Institute, 2016)

Historical analysis of nickel reserves and resources has demonstrated that global nickel reserves estimates have remained stable in recent decades, all the while mined production has increased nearly exponentially over the same period. The analysis indicates that resources have been successfully converted to reserves due to technological advancements and evolving economic conditions. While reserves have remained flat, ore head grades have declined drastically, specifically among sulphide ores. Nevertheless, given current production levels, sufficient terrestrial geological availability of nickel remains unexploited.

The finite nature of nickel resources coupled with projected increases in demand has raised concerns regarding the future availability of nickel leading to proclamations of peak nickel. Inquiry into alternative nickel sources has resulted in considering non-terrestrial sources. The presence of nickel in manganese crusts and nodules along the sea-bed floor is an attractive alternative source. Research appraising the availability of nickel from known deposits has demonstrated extractable nickel from the deposits to be greater than the sum of known terrestrial resources. Additional research suggests that the total potential nickel contained on the seafloor significantly exceeds projected increases in demand.

A-3.3 Mining

Mining methods employed to extract nickel depend highly on the geology of the deposit, ore body, environmental factors, and downstream processing requirements. Generally, two mining methods are employed: open pit mining and underground mining. In some circumstances, a combination of the two methods is employed.

Open pit mining is the dominant mining practice employed in extracting laterite ores. The proximity of the deposits to the surface and distribution across a broad area render them ideal for open pit operations. Lateritic mining operations utilize a combination of heavy machinery (e.g., hauling trucks and excavators) and conveying equipment (e.g., conveying belts and slurry pipelines) to transport ore around sites. The geographic concentration of lateritic deposits in tropical climates inadvertently affects the performance of mining operations. Climatic weather events, such as typhoons, monsoons, and prolonged rains, create challenging mining conditions and can limit mined production.

Historically, open pit mining has been favoured for sulphide deposits as deposits were located within reasonable proximity to the surface. The depletion of these deposits required exploration at greater depths. Advancements in underground mining practices resulted in converting open pit mines to underground mines. At present, both open pit and underground mining are used to extract sulphide ores. The variations in mining techniques require unique and distinct technologies. Underground operations leverage smaller equipment and large shafts to transport the ore. More recently, underground operations have begun adopting electric machinery to reduce harmful emissions. In contrast, open pit operations utilize large equipment to extract and transport ore. Climatic weather events at open pit operations are primarily limited to seasonal changes in temperatures and precipitation. Alternatively, climatic weather events have minimal impact on underground operations, increased risk of potential cave-in requires high safety tolerances.

A-3.4 Beneficiation

Beneficiation is a critical stage in the extraction and processing of nickel. The unit operations are responsible for pulverizing, classifying, and isolating the nickel-containing mineral. The sequence of operations varies drastically among operations and depends on the ore type, downstream processing capabilities, and final product requirements.

The beneficiation processes employed for lateritic ores differ among operations and are highly dependent on downstream processing capabilities. For example, limonite ores intended for non-ferrous products, such as mixed precipitates and Class 1 products, the mined feedstock is treated using an assortment of unit operations due to the high processing requirements of downstream operations. Variability in chemical composition, granularity, and moisture content across deposits yield a diverse range of employed technologies. Unit operations include crushing, grinding, sizing, drying, magnetic separation, and flotation. Generally, the granular size of the minerals requires minimal comminution efforts. A select number of operations exercise the mixing of limonite and saprolite ores depending on the ore quality and the downstream operations' flexibility. In either instance, beneficiation stages are carried out adjacent to or near mining operations.

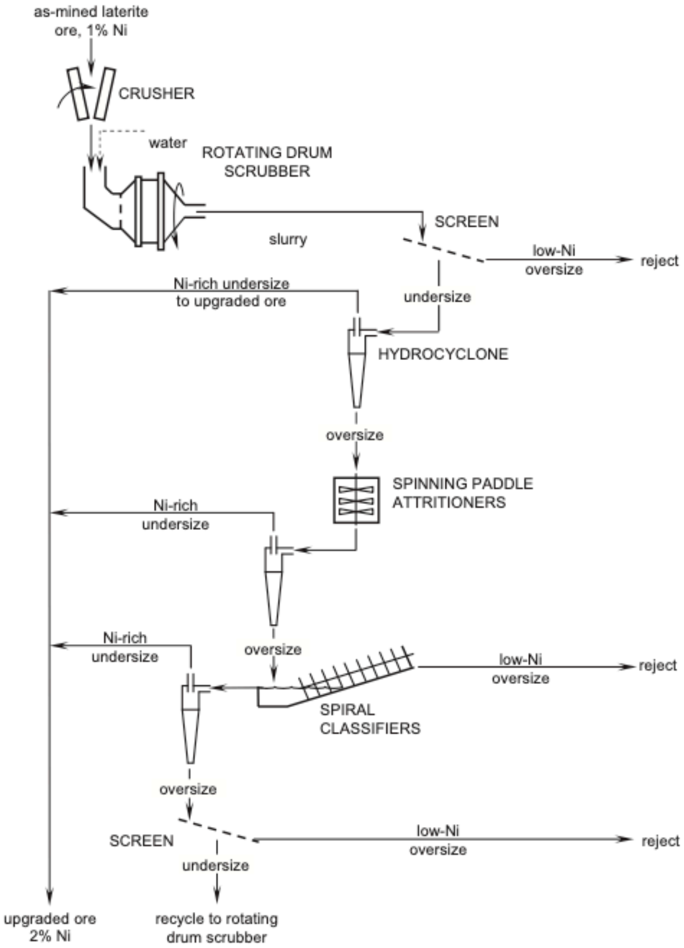


Figure A-3-4: Generalized Laterite Beneficiation Flow Sheet (Crundwell et al., 2011)

In contrast, limonite ores and saprolite ores intended for ferrous nickel products, such as FeNi and NPi, typically employ fewer unit operations due to flexibility in downstream processing. Standard unit operations include crushing, drying, and classification. Saprolite ores destined for ferrous nickel products broadly do not enact any beneficiation as mined ore can be used as a direct feedstock in downstream operations. In some instances, size reduction, separation, and classification are carried out to improve processing. Beneficiation of laterite ores intended for ferrous products is performed adjacent or within proximity to mining operations as well as adjacent to downstream operations. Many lateritic feedstocks intended for ferrous applications do not employ beneficiation and produce direct shipping ore (DSO) used unprocessed by downstream operations.

Sulphide ores require extensive beneficiation due to the high concentration of economically valuable metals associated with the ores, each with dissimilar downstream processing pathways. Significant differences in beneficiation stages exist among sulphide-rich and sulphide-poor ores. For sulphide-poor ores, mined ores are first crushed, ground, slurried, and sized. The ores are then subjected to flotation stages to remove the waste material and separate valuable minerals. The output of the process is a copper-nickel-precious metal-containing concentrate with a superior concentration of valuable metals. Tailings containing low concentrations of valuable metals, gangue material, and chemical reagents are generated as a by-product of the operations and are disposed of in tailing ponds.

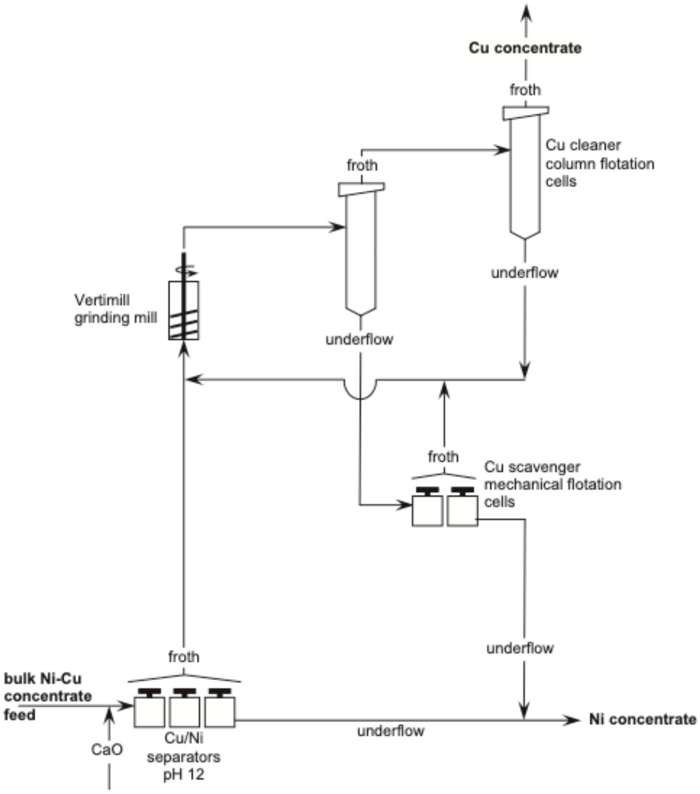


Figure A-3-5: Generalized Sulphide-Rich Flotation Flow Sheet (Crundwell et al., 2011)

Sulphide-rich ores, where copper and nickel are the target metals, utilize similar unit operations to sulphide-poor ores. Mined ores are first crushed, ground, slurried, and sized. The ores are then floated, producing three outputs: nickel concentrate, copper concentrate, and tailings. The nickel and copper concentrate both contain varying concentrations of PGMs and low concentrations of each metal (i.e. low concentrations of nickel in the copper fraction and low concentrations of copper in the nickel fraction). The two streams are further processed using dissimilar pathways to recover contained metals. The tailing generated exhibits a similar content profile to those produced from sulphide-poor ores and is treated similarly. The technical requirements of the beneficiation stages vary between sulphide operations due to variations in ore body composition and downstream processing. Generally, beneficiation operations of sulphide ores occur adjacent to or within proximity to mining operations.

A-3.5 Processing

Following beneficiation, nickel ores and concentrates are further converted to produce a range of products suitable for downstream applications. Variations in the chemical composition of nickel feedstocks, coupled with the economic, technical, and product specification requirements, have resulted in an assortment of processing pathways. Distinct pathways have been commercially adopted for nickel feedstocks from lateritic and sulfidic deposits. Blending the two ore types seldom occurs in practice, with few facilities adept at simultaneously employing lateritic and sulfidic ore feedstocks. The processes primarily rely on hydrometallurgical and pyrometallurgical processing technologies, with more novel alternative processes also commercially prevalent, albeit to a lesser extent.

A-3.5.1 Laterite

Variability in the chemical composition of lateritic ores, specifically amongst limonite and saprolite layers, has resulted in several distinct processing pathways. Technical and economic constraints of the processes have resulted in a wide range of products. Two general processing routes are commercially deployed to convert lateritic ores, each with distinct feedstock, unit operations, and product outputs. The following sections describe the general stages involved in each processing route.

A-3.5.1.1 Rotary Kiln- Electric Furnace: Ferronickel and Nickel Pig Iron

Rotary kiln-electric furnace (RKEF) is the leading processing route for producing FeNi and NPI. Beneficiated lateritic ores, typically saprolite ores due to their lower iron content, are first fed into rotating dryers to reduce the ore's moisture content. Limonite ores are similarly used as feedstock but are mainly limited to operations with high-quality standards. The dry ore is then loaded into a rotary kiln with coal, which is subjected to higher temperatures from the combustion of carbon fuels. The elevated temperatures calcine the ore, producing nickel and iron oxide. Additionally, oxides of impurities such as magnesium and silicon are formed. The presence of coal and reducing gases within the kiln generate a reducing environment in which nickel is partially reduced to nickel. The output of the rotary kiln is then fed into an electric furnace. The furnace utilizes an electrical current and carbon electrodes to generate temperatures sufficient to melt the calcine feed material. The presence of carbon in the furnace results in the near-complete reduction of nickel and iron, producing a molten metal mix. Impurities such as magnesium and silicon report to the slag layer formed above the molten nickel and iron layer. The molten nickel and iron are then tapped from the furnace, commonly yielding ingots or granules form factors. RKEF facilities are commonly integrated with mining operations as well as with steel mills in which beneficiated ore is shipped to the facility.

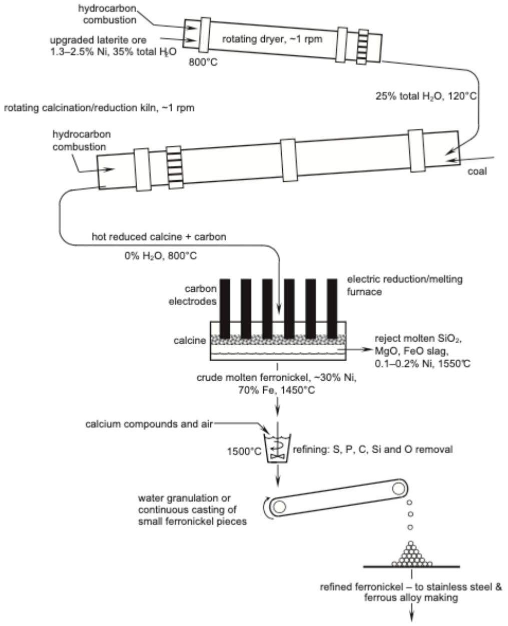


Figure A-3-6: Generalized RKEF Flow Sheet (Crundwell et al., 2011)

A-3.5.1.2 High Pressure Acid Leach: Mixed Metal Precipitates

Increased demand for high-quality nickel products and decreasing sulphide grades have led to significant research and development into pathways capable of generating high-grade nickel products from lateritic ores. The development of the Sherritt-Gordon process in the late 1940s demonstrated the ability to produce high-quality nickel products from lateritic ores using hydrometallurgical processing technology. The commercial success of the process has since spurred the development of numerous facilities globally. Variations in laterite ore bodies have resulted in facilities adopting a range of unit operations necessary for treating specific ores.

Generally, high-pressure acid leach (HPAL) processes rely on limonite ores from specific ore bodies. Recent advancements have allowed facilities to utilize blended feedstocks of saprolite and limonite ores. Although no two HPAL processing pathways are identical, several similarities exist between processes.

Beneficiated ore is first slurried and pre-heated to the desired condition. The slurried ore is then pumped into autoclaves and mixed with acid, typically sulphuric acid. Elevated temperatures and pressures within the autoclave drives the desired reactions to leach nickel and cobalt from the ores. The abrasive environment also leaches other deleterious metals from the ore. The solution is then neutralized and separated from residual unreacted gangue material. A series of purification stages are then employed to treat the solution and remove any further remove impurities.

Several precipitation phases are then carried out to precipitate nickel and cobalt from the solution. The precipitate products are mixed hydroxide precipitates (MHP) or mixed sulphide precipitates (MSP). MHP is precipitated using magnesium oxide, while MSP is precipitated using hydrogen sulphide gas. The precipitated products contain approximately 40-50% nickel and 2-5% cobalt, and other impurities such as manganese, magnesium, and copper.

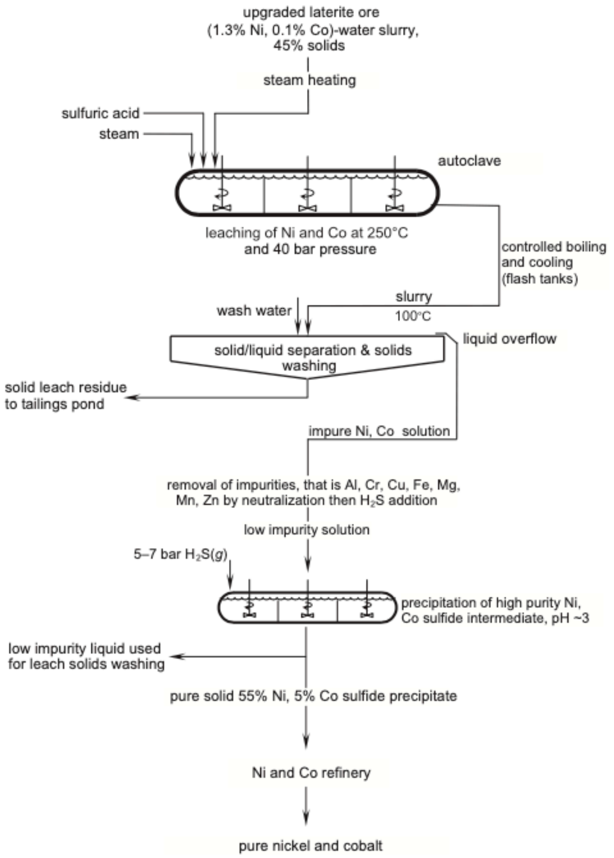


Figure A-3-7: Generalized HPAL Flow Sheet (Crundwell et al., 2011)

Precipitated products from HPAL circuits are shipped to a dedicated refining facility or further refined on-site. Refining MHP and MSP products is highly variable and specific to operations. Generally, a series of hydrometallurgical processes are employed, including additional HPAL operations, solvent extraction, hydrogen reduction, chloride leaching, and electrowinning. The output products range from nickel sulphate to nickel briquettes. Cobalt is also frequently recovered, generally in the form of high-grade products. HPAL circuits producing MHP and MSP are generally integrated with mining operations. Refining circuits can equally be integrated into mining operations as well as separate, distinct dedicated facilities distant from the mining operation.

A-3.5.1.3 NPI-to-Matte

Predicted growth in demand for nickel has spurred interest in unconventional processing routes. The renewed interest in the NPI-to-Matte processing pathway best reflects this phenomenon. Similar to NPI processes, saprolite ores are converted into an NPI product using an RKEF process. The NPI product and elemental sulphur are added to a ladle furnace to liquefy the products. The resulting output is then added to a converter, analogous to the Pierce-Smith converter used for treating sulphide ores, as described below, where air is injected to oxidize and separate iron resulting in a high-grade matte product. The matte product is then treated through an HPAL process to produce a mixed precipitate product, albeit with lower cobalt content, as cobalt primarily reports to the slag during the RKEF process. The mixed precipitate product is then refined using solvent extraction or similar to hydrometallurgical processes to recover the nickel.

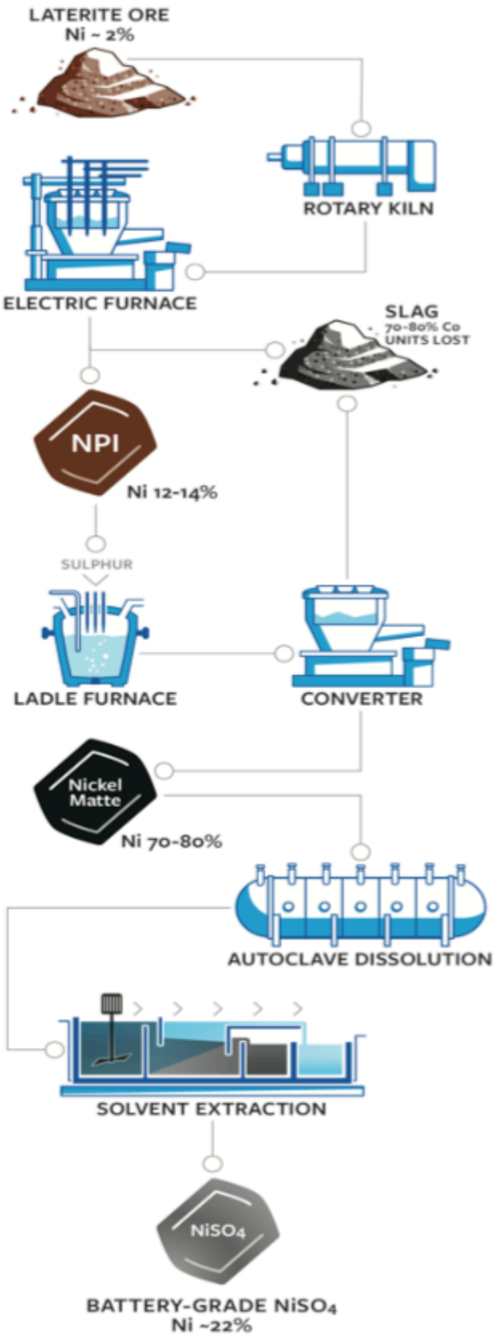


Figure A-3-8: Simplified NPI-to-Matte Flowsheet (Sherritt, 2021)

The pathway has seen varying degrees of commercialization to date. Most notably, Eramet employed the process at its New Caledonia operation, where NPI was converted to matte and refined at the company's refinery in France. Vale operates a similar processing pathway at its Indonesia operation, where the matte is produced within the RKEF unit operations, as opposed to producing an intermediate NPI product. While the operation is less flexible, it is more efficient, allowing for the lower-quality coal with high sulphur content to be used as a reductant.

A-3.5.1.4 Other

The above sections describe the most prevalent processing pathways for lateritic ores in service. Several other pathways have been proposed for treating laterite ores, including atmospheric leaching, heap leaching, carbonyl refining, the caron process, blast furnace, and bioleaching.

A-3.5.2 Sulphide

Processing of nickel sulphide ores generally relies on pathways established in the early 20th century. The most common processing pathway involves two sequential stages: pyrometallurgical smelting and hydrometallurgical refining. Numerous advancements have been implemented over time to improve several aspects of the process, including material recovery, environmental impact, and energy efficiency. The pathway generally applies to sulphide-rich and sulphide-poor ores, with differences primarily relevant during refining stages. More novel processing pathways have been established and employed, albeit less common.

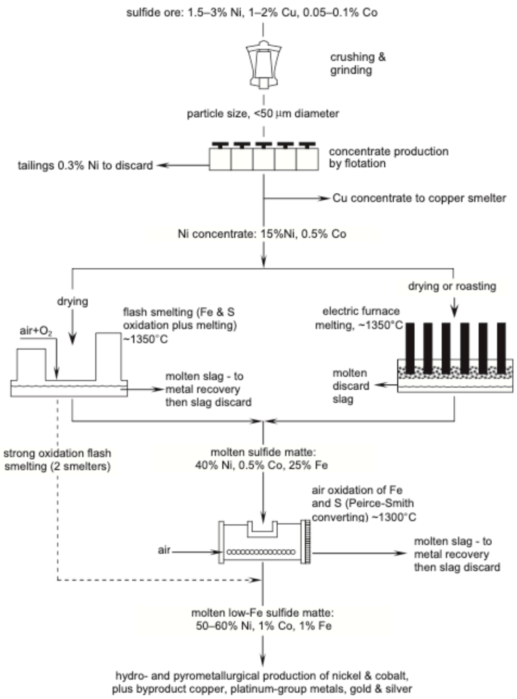


Figure A-3-9: Generalized Sulphide Flowsheet (Crundwell et al., 2011)

A-3.5.2.1 Smelting

Due to the complexity of processing nickel sulphide ores, smelting was initially conceived as the only viable pathway to liberate nickel from sulphide ores. The primary objective of the smelting is to enrich the nickel further. This is achieved by subjecting the mineral to elevated temperatures, typically in excess of 1350 degrees Celsius.

Two smelting technologies commonly treat sulphide ores: flash smelting and fluidized bed roaster with an electric furnace. In each instance, they are combined with pierce smith converters to achieve the necessary chemical composition. The primary output product from the converter is a matte containing variable amounts of nickel, iron, and sulphur. Generally, smelting operations are integrated with individual or regional mining operations and are located relative to upstream feedstock operations. Feeds from dissimilar mining operations can be treated using smelters providing greater operational flexibility. Substitutability of sulphide-poor and sulphide-rich ores is limited due to technical constraints.

Flash furnaces are commonly used to treat sulphide-poor ores. The concentrate, oxygen, air, and silica flux are first charged into the furnace. Elevated temperatures resulting from the exothermic oxidation of iron and sulphur liquify the concentrate creating a nickel-rich layer. A slag layer of iron and other impurities forms above the nickel-rich layer. The slag is periodically tapped and reprocessed to recover any entrapped metals that inadvertently departed from the matte. The oxidized sulphur reacts with oxygen to form sulphur dioxide gas. The sulphur dioxide, as well as other gases, are commonly captured and reprocessed prior to being discharged into the atmosphere. Generally, capture sulphur dioxide gas is reprocessed to generate sulphuric acid, which is subsequently used in refining operations, as described in the following section.

In contrast, operations treating sulphide-rich ores commonly employ fluidized bed roasters with electric furnaces. Nevertheless, they have historically been favoured, and continue to be prevalent, in processing sulphide-poor ores. The concentrate is charged into the roaster at elevated temperatures along with air to oxidize the concentrate partially. The reaction produces a calcine of nickel oxide and iron oxide. Sulphur dioxide gas is generated and captured along with other off-gasses. They are treated in a similar manner as described above. The calcined products are then fed into the electric furnace along with silica flux and subjected to elevated temperatures. The iron and any remaining sulphur are oxidized to their elemental state, forming a molten nickel layer. A slag layer similar to that described above forms above the matte and is handled similarly.

For either pathway, the molten nickel, iron, and sulphur layer are tapped and converted to purge residual iron and other entrapped impurities. This is achieved using Pierce-Smith converters in which the molten matte is injected with air, or a combination of air and oxygen, as well as silica to oxidize iron to iron silicate. The iron silicate forms a slag layer above the molten nickel and is periodically tapped and reprocessed to recover entrapped metals. The molten nickel layer primarily consists of nickel, sulphur, copper, cobalt, PGM's, and residual iron levels. The matte is then tapped, solidified, and sent for further refining.

A-3.5.2.2 Refining

Various refining processes are used to treat nickel mattes derived from nickel sulphide ores. Similar processing technologies are employed for material originating from sulphide-rich and sulphide-poor ores. The assortment of processing pathways has resulted in a range of nickel products suitable for multiple or niche applications. Refining processes primarily rely on hydrometallurgical technologies. The technology permits superior recovery of metals beyond nickel, including copper, cobalt, and PGMs.

Cooled and solidified mattes with low concentrations of PGM, primarily derived from sulphide-rich deposits, are first crushed, ground, and classified. The ground matte product is then subjected to a series of leaching, precipitation, and solvent extraction processes to liberate further and separate contained metals. Highly homogenous streams of metals in solution are generated. Given the final product requirements – namely purity and form factor – the purified streams are subjected to additional processing stages. For example, electrowinning is employed to produce high-purity nickel cathodes, while the production of nickel briquettes employs hydrogen reduction.

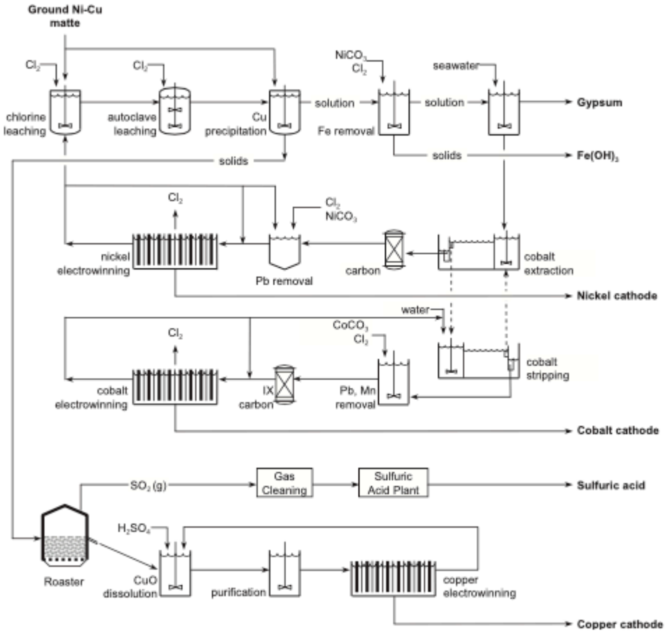


Figure A-3-10: Generalized Flowsheet of Nikkelverk (Crundwell et al., 2011)

Material originating from sulphide-poor deposits, where PGMs are the primary target material, employ similar processing technologies. The primary difference lies in the separation of base metals from PGMs. In contrast to processing sulphide-rich materials, nickel and copper are contained in the bulk material through smelting. This contrasts with sulphide-rich ore, where the metals are separated during beneficiation. As such, the matte product, in addition to containing elevated concentrations of PGMs, further contains appreciable concentrations of nickel and copper. Therefore, after crushing, grinding, and sorting the matte, contained base metals are separated from PGMs by a series of leaching and precipitations unit operations. Separated PGMs are captured and sent for additional refining at dedicated refining facilities. The base metal stream is then further processed, typically on-site, employing similar refining technologies to those used to treat materials derived from sulphide-rich ores. Generally, nickel is transformed into crude nickel sulphate utilizing precipitation and crystallization operations.

Refining facilities are commonly collocated adjacent to smelters. Third-party feeds are frequently processed at refining facilities, most commonly through off-take tolling agreements amongst feed derived from sulphide-poor deposits. Refining operations are highly sensitive to impurities and can limit the substitutability of feeds.

A-3.5.2.3 Other

Although the most common processing pathways for treating sulphide ores include a sequential combination of smelting and refining operations, alternative processes have been adopted. A prominent example includes direct leaching, in which hydrometallurgical technologies are uniquely applied. The pathway substitutes smelting for a series of leaching and precipitation operations. The resulting solution can then be electrowon.

Similarly, two noteworthy refining processing pathways are employed to recover nickel and other valuable base metals. The Sherritt Process, initially developed for lateritic ores, is extensively utilized by refining facilities treating mattes derived from sulphide-poor material. The process leverages ammonia to liberate and recover valuable metals from the matte. Nickel is then recovered utilizing copper boils and hydrogen reduction.

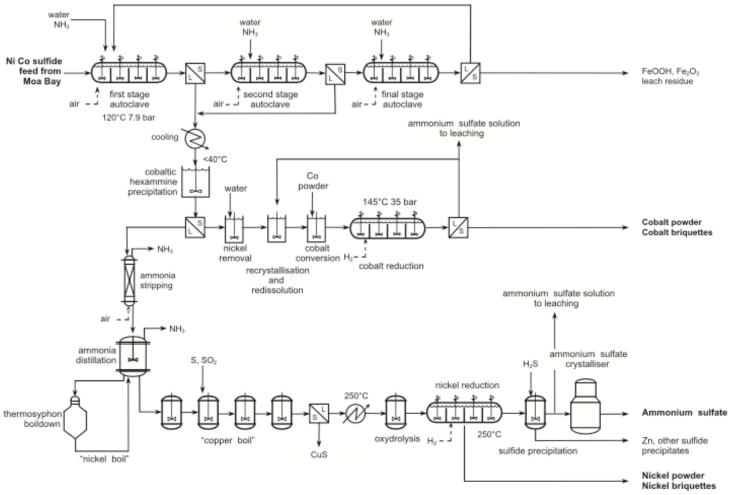


Figure A-3-11: Generalized Flowsheet of Fort Saskatchewan (Crundwell et al., 2011)

Another notable process includes carbonyl refining. The process is commercially used to refine sulphide-rich ores. The process is unique in that it utilizes vapour metallurgical processes to recover nickel. Granulated nickel matte is charged into a low-temperature rotating kiln and purged with carbon monoxide gas. The nickel in the matte reacts with the carbon monoxide forming gaseous nickel carbonyl. The gas is then captured and transferred to a decomposer, where it is subjected to moderately high temperature allowing for the decomposition of the nickel and carbon monoxide gas. Nickel is then continuously deposited onto the surface of high-purity nickel pellets within the decomposer. The process is favoured for its ability to produce high-purity nickel. However, the intermediate gas product produced is extremely lethal at low dosages, thus limiting the technologies adoption.

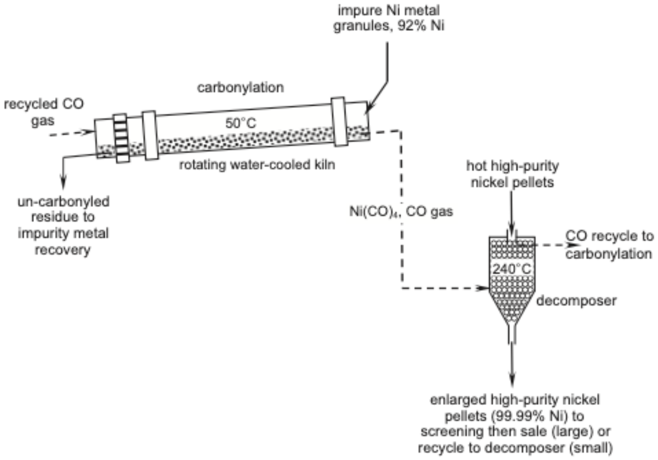


Figure A-3-12: Generalized Flowsheet of Carbonyl Refining (Crundwell et al., 2011)

A-3.5.3 Other Processing Pathways

Few operations currently process feedstocks derived from sulphide and laterite ores concurrently. Amongst current operations, they often process intermediate products generated by a complex value chain, typically producing either matte or mixed precipitate products. The most prominent example includes Vale's Clydach operation. The operation processes a nickel oxide intermediate product from a matte derived from laterite ores. Additionally, the facility processes matte derived from sulphide ores.

Beyond laterite and sulphide ores, novel processing pathways have been proposed and, in certain instances, commercialized. Most notably, the successful adoption of bio-heap leaching to treat black-shale ore. The process produces a mixed nickel precipitate product which is then converted using hydrometallurgical processes. Alternative pathways not yet commercialized include agro metallurgy, where nickel naturally absorbed in plants is recovered. However, this process has not yet been commercially adopted.

A-4. Nickel Products

Various nickel products are produced globally, serving an array of downstream applications. As a result, nickel products exhibit unique form factors and chemical compositions. The characteristics of these products are critical to downstream operations. Processing limitations and established industry standards serve to organize nickel products. An informal industry classification segregated nickel products into two distinct groups. The origin of the classification remains opaque; however, they largely align with standards utilized by prominent commodity exchanges.

A-4.1 Product Class

An informal categorization of nickel products has been adopted across the industry based on the nickel content of products. The threshold aligns with the LME requirement for minimum nickel content. Products with nickel content greater or equal to 99.8% by weight are considered “Class 1,” while products with nickel content less than 99.8% by weight are considered “Class 2”. The classification method for nickel products has propagated throughout the broader industry and serves as guidelines for unapproved brands.

A-4.1.1 Class 1

Class 1 products are near pure nickel due to the elevated requirements; therefore, they often contain minimal concentrations of impurities. A limited number of form factors are often produced, including powders, briquettes, cathodes, rounds, and pellets. Products are known to be derived from laterite and sulphide ores; however, they have historically been produced by sulphide operations. Class 1 products are suitable for various applications, given their low impurities. Applications often include stainless steel, non-ferrous alloys, and plating. Further, Class 1 products can often be converted into Class 2 products; for example, Class 1 nickel powder can be transformed into Class 2 nickel sulphate.

A-4.1.2 Class 2

Many produced nickel products contain nickel contents within the Class 2 range. The broad nickel content range results in various products with distinct chemical compositions and form factors, including FeNi, NPI, nickel sulphate, and nickel oxide. Class 2 products are generally produced from laterite ores using hydrometallurgical processes. Nevertheless, they are also derived from sulphide ores using a range of metallurgical technologies. The range of products included in Class 2 often leads to confusion regarding suitable products and their availability. This is especially relevant given the variety of industries the products service, including batteries and stainless steel.

A-4.2 London Metals Exchange

The London Metals Exchange (LME) is a critical stakeholder in the nickel industry. A brief outline of the supply and financial mechanisms of the exchange is discussed in the following sections. The exchange allows for the sale of primary nickel conforming to specified rules from approved brands. Rules for approved brands are periodically reviewed and updated to reflect industry constraints. Similarly, third-party auditing firms regularly update and review approved brands to ensure compliance.

A-4.2.1 LME Nickel Requirements

LME rules for primary nickel cover a variety of product attributes, including composition, form factor, and verification. As of June 1st, 2022, the exchange states that primary nickel must conform to one of two quality standards: ASTM B39-79 (2013) or GB/T 6516-2010. The ASTM standards require a minimum purity of 99.80% nickel by weight, while the GB/T standard sets a minimum content of 99.90% nickel and cobalt by weight, where cobalt cannot be greater than 0.08wt%. Approved products require analytical testing to ensure they conform to the standards. The standard sets no requirements on the ore mineralogy, or the processing pathway used for production.

Table A-4-1: LME Composition of Approved LME Standards (London Metal Exchange, n.d., 2022b)

Standard: ASTM B39-79 (2013)

Element	Composition (wt%)	Specification
Nickel	99.8	minimum
Cobalt	0.15	maximum
Copper	0.02	maximum
Carbon	0.03	maximum
Iron	0.02	maximum
Sulphur	0.01	maximum
Phosphorus	0.005	less than
Manganese	0.005	less than
Silicon	0.005	less than
Arsenic	0.005	less than
Lead	0.005	less than
Antimony	0.005	less than
Bismuth	0.005	less than
Tin	0.005	less than
Zinc	0.005	less than

Standard: GB/T 6516-2010 - Ni9990 grade

Element	Composition	Specification
Ni+Co	99.90	%min
Cobalt	0.08	%max
Carbon	0.01	%max
Silicon	0.002	%max
Phosphorus	0.001	%max
Sulphur	0.001	%max
Iron	0.02	%max
Copper	0.02	%max
Zinc	0.002	%max
Arsenic	0.001	%max
Cadmium	0.0008	%max
Tin	0.0008	%max
Antimony	0.0008	%max
Lead	0.0015	%max
Bismuth	0.0008	%max
Magnesium	0.002	%max

The table above outlines the compositional requirements as defined by the standards. The LME requires nickel sold under contract to comply with standardized form factors. Acceptable form factors include cathodes (full plate or cut), briquettes, pellets, and rounds. The exchange outlines additional requirements regarding the shapes, weights, and packaging for each form factor. The exchange allows for a select number of approved brands. A series of requirements much be achieved for a producer's product to be eligible as an approved brand.

Table A-4-2: LME Approved Nickel Brands Prior to 2022 (London Metal Exchange, 2022a)

Country/ Region	Brand	Producer	Deliverable Shape	Warrant Issuance
Australia	BHP BILLITON NICKEL BRIQUETTES	BHP Billiton Nickel West Pty Ltd	Briquettes, Bagged briquettes	NEW WARRANTS CANNOT BE ISSUED FROM THE DEFINED DATE
Australia	BHP NICKEL BRIQUETTES	BHP Nickel West Pty Ltd	Bagged briquettes	WARRANTABLE
Australia	MINARA HIGH GRADE NICKEL BRIQUETTES	Minara Resources Pty Ltd	Briquettes, Bagged briquettes	WARRANTABLE
Brazil	TOCANTINS	Votorantim Metais S.A.	Cut cathodes, Full plate cathodes	NO NEW WARRANTS CAN BE ISSUED
Canada	SHERRITT NICKEL BRIQUETTES	The Cobalt Refinery Company Inc	Briquettes, Bagged briquettes	WARRANTABLE
Canada	VALE MELT ROUNDS	Vale Canada Limited	Rounds bagged	WARRANTABLE
Canada	VALE NICKEL PELLETS	Vale Canada Limited	Pellets, Bagged pellets	WARRANTABLE
Canada	VALE PLATING ROUNDS	Vale Canada Limited	Rounds bagged	WARRANTABLE
China	CASH	Yantai Cash Industrial Co., Ltd.	Full plate cathodes	WARRANTABLE
China	JINTUO GRADE 1	Jinchuan Group Co., Ltd.	Cut cathodes, Full plate cathodes	WARRANTABLE
Finland	NORILSK NICKEL HARJAVALTA CATHODES	Norilsk Nickel Harjavalta Oy	Cut cathodes, Full plate cathodes	WARRANTABLE
Finland	NORILSK NICKEL HARJAVALTA BRIQUETTES	Norilsk Nickel Harjavalta Oy	Briquettes	WARRANTABLE
France	NICKEL HP	Sibanye-Stillwater Sandouville Refinery	Cut cathodes, Full plate cathodes	WARRANTABLE
Japan	SUMITOMO METAL MINING CO. LTD	Sumitomo Metal Mining Co., Ltd.	Cut cathodes	WARRANTABLE
Japan	SMM	Sumitomo Metal Mining Co., Ltd.	Full plate cathodes	WARRANTABLE
Madagascar	AMBATOVY NICKEL BRIQUETTES	Dynatec Madagascar S.A. a "société anonyme"	Briquettes, Bagged briquettes	WARRANTABLE
Norway	NIKKELVERK NICKEL	Glencore Nikkelverk AS	Cut cathodes, Full plate cathodes	WARRANTABLE
Russia	NORILSK COMBINE H-1	PJSC “MMC “Norilsk Nickel”	Cut cathodes, Full plate cathodes	NO NEW WARRANTS CAN BE ISSUED
Russia	NORNICKEL	JSC "Kola GMK"	Full plate cathodes	WARRANTABLE
Russia	SEVERONICKEL COMBINE H-1	JSC "Kola GMK"	Cut cathodes, Full plate cathodes	WARRANTABLE
Russia	SEVERONICKEL COMBINE H-1Y	JSC "Kola GMK"	Cut cathodes, Full plate cathodes	WARRANTABLE
South Africa	IMPALA NICKEL	Impala Platinum Ltd	Briquettes	WARRANTABLE
South Africa	RPM NICKEL	Rustenburg Platinum Mines Limited	Full plate cathodes, Cut cathodes	WARRANTABLE
UK	VALE NICKEL PELLETS	Vale Canada Limited produced by Vale Europe Limited	Pellets, Bagged pellets	WARRANTABLE
Zimbabwe	BCL EMPRESS	RioZim Limited	Cut cathodes, Full plate cathodes	NO NEW WARRANTS CAN BE ISSUED

The above table outlines approved brands as well as former approved brands prior to 2022. The requirements and standards are broadly used as guidelines and have seen widespread adoption throughout the industry amongst unapproved brands. Buyer further uses the standards to ensure product quality.

A-4.3 Important Nickel Products

Various nickel products with distinct chemical compositions and form factors are commercially produced. Midstream operations generally produce several products concurrently with a range of characteristics. Chemical composition and product form factor are critical determinants for companies procuring nickel products as they must conform to established processing requirements. Although the LME has set standards for chemical compositions and form factors, a range of nickel products that do not conform to the standards are produced throughout the nickel supply chain and constitute a large portion of the nickel market. More specifically, they include refined products intended for use in downstream applications as well as intermediate products requiring additional processing. Many products lack formal definitions outlining their characteristics and are generally informally defined by industry stakeholders.

A-4.3.1 Cathode

Cathodes are a common form among nickel products. They constitute large sheets of nickel with low concentrations of impurities. They are produced using electrowinning operations and can be produced from laterite or sulphide ores. The exact dimensions of the sheets depend on the configuration of the electrowinning cells and are often cut into smaller pieces to improve shipping and handling. Nickel cathodes are high purity and generally meet the Class 1 requirement of 99.8 wt% nickel. Various impurities are entrapped within the cathode sheets. The concentration and exact elements vary by facility and ore deposit. Tramp elements generally include arsenic, cobalt, copper, iron, and lead. The superior purity of nickel cathodes extends its use in a broad range of applications, including specialty alloys, stainless steel, plating, and batteries.

A-4.3.2 Briquettes and Powders

Alternative to cathodes, Class 1 products are commonly produced in briquette or powder form factors. Powders are commonly produced using hydrogen reduction processes which are often further transformed into briquettes by sintering. Alternatively, nickel powders can be produced using carbonyl refining processes, albeit in lesser quantities. They exhibit similar composition profiles to cathodes as they are typically refined to Class 1 grade. Briquettes are favourable amongst stainless steel and non-ferrous alloy producers due to their ease of handling. In contrast, powders are favoured amongst specialty applications or in conversion processes.

A-4.3.3 Nickel Sulphate

Due to its importance as a precursor-cathode material for lithium-ion batteries, nickel sulphate has emerged as a crucial product. It is generally marketed as crystalized nickel sulphate hexahydrate. Processing routes have been developed for ore derived from lateritic or sulfidic sources. Production from lateritic ores typically relies on HPAL processing technology, where MHP or MSP is produced as an intermediate product. Production from sulphidic ores varies considerably between operations but is generally produced from purified leaching solutions during refining stages. Alternatively, nickel sulphate can be produced by converting refined nickel products, notably Class 1 products, such as powders, briquettes, and cathodes. Nickel content generally ranges between 20-22wt% with marginal cobalt, copper, and iron impurities. Beyond battery applications, it is also extensively used in chemical, industrial, and plating applications.

A-4.3.4 MHP and MSP

Mixed hydroxide precipitates (MHP) and mixed sulphide precipitates (MSP) are noteworthy intermediate products that have gained significant prominence in recent years. MHP and MSP products are exclusively produced from lateritic ores, primarily limonitic ores, using HPAL processing technologies. The primary difference lies in the precipitation method employed. MHP pathways precipitate utilizing an oxide, such as magnesium oxide, while MSP processes utilize hydrogen sulphide gas. They are commonly marketed as a powder or wet cake. Products contain 40-60wt% nickel and notable concentrations of cobalt. Precipitates also contain impurities such as iron, magnesium, and manganese. MHP and MSP are commonly used in the production of nickel sulphate as well as other chemical salts. However, they can be further refined to produce high-purity products such as cathodes, briquettes, or powders.

A-4.3.5 Matte

Nickel matte is a common intermediate product in nickel value chains. It is derived mainly from smelting sulphide ores but is also produced in small quantities from lateritic ores. Mattes are generally formed into ingots and granules. They contain between 35-60wt% nickel along with variable concentrations of copper, iron, sulphur, cobalt, and precious metals. Nickel mattes are further refined to produce high-grade nickel products such as cathodes, pellets, nickel sulphate, and rounds.

A-4.3.6 Ferronickel

Ferronickel is a crucial nickel feedstock for stainless steel production. It is predominantly produced from lateritic ores, specifically saprolite ores. Rotary-kiln electric furnace (RKEF) is the most prominent processing pathway. Ferronickel is commonly transformed into either shot or granular form factors and contains between 20-40wt% nickel. It further comprises significant concentrations of iron and nominal concentrations of impurities, such as cobalt, manganese, and silicon. Ferronickel is nearly exclusively used in the production of stainless steel.

A-4.3.7 Nickel Pig Iron

Nickel pig iron (NPI) has emerged as a notable nickel product in recent years. It is produced exclusively from lateritic ores, specifically saprolite ores. Several processing pathways exist, including RKEF, blast furnace, and electric furnace. NPI is marketed in a variety of forms factors including ingots, shots, and granules. Nickel content ranges between 5-15wt%. It contains high concentrations of iron and notable concentrations of impurities, such as cobalt, manganese, carbon, and silicon. NPI is used primarily in low-quality stainless steel mills and for low-nickel crude steels.

A-4.3.8 Direct Shipping Ore

Direct shipping ore (DSO) is a vital feedstock for several midstream producers, specifically FeNi and NPI. It is critical to midstream operations geographically distant from mining operations or regions with insufficient geological resources. DSO is generally derived from lateritic ores. However, DSO from sulfidic ores is common, albeit to a lesser extent. They include extracted ores that have undergone little comminution and are distinct from concentrates. Nickel content typically ranges between 1-2wt% and contains variable iron, cobalt, manganese, and silicon concentrations.

A-4.3.9 Others

In addition to the products listed, an array of end-use and intermediate products with distinct chemical compositions and form factors are commonly produced throughout the nickel supply chain. Other notable nickel products include concentrates, briquettes, pellets, powders, and nickel oxide. The market share for each product is unclear as product capacity and production are not commonly reported.

A-5. Nickel Market

Nickel is a globally traded commodity servicing an array of markets. Complex economic and financial systems underpin the exchange of nickel. As with any commodity, the nickel market is susceptible to regional and global economic, political, and social shifts. These factors directly influence the supply, demand, and pricing of nickel products. Economic factors and market conditions related to nickel are severally understudied in academia. Analysis of economic and market factors has primarily been relegated to private institutions. The highly opaque nature of nickel supply chains provides limited insight into economic and market details. Available information on economic and market conditions is inferred mainly from available information.

A-5.1 Pricing and Exchanges

The nickel market is highly convoluted and intricate, with diverse stakeholders and products disseminated globally. Such conditions result in numerous, largely disconnected markets. In spite, the commonality between the markets lies in their indirect bond to the most prevalent nickel exchange, the LME. The LME provides liquidity and pricing transparency to the nickel market. As mentioned above, the LME is restricted to a limited number of products and suppliers that the exchange has approved. In addition to products approved by the exchange, certified suppliers generally produce numerous not approved. Unapproved products from approved brands often meet or exceed LME standards. Similarly, unapproved brands generally produce various products, including LME-eligible products, not transacted through the LME. These circumstances culminate in only a minute fraction of globally produced nickel transacting through the exchange.

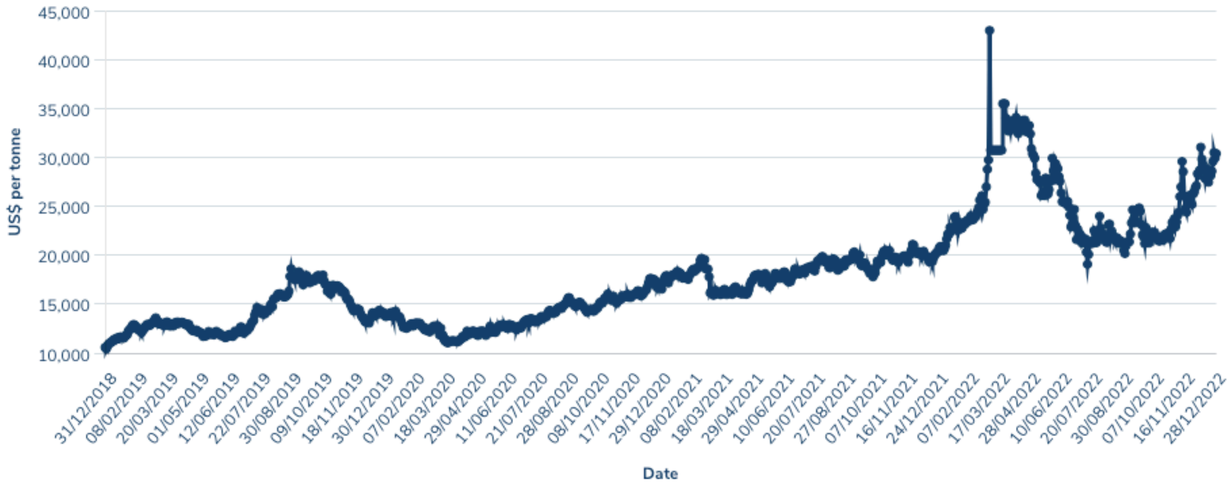
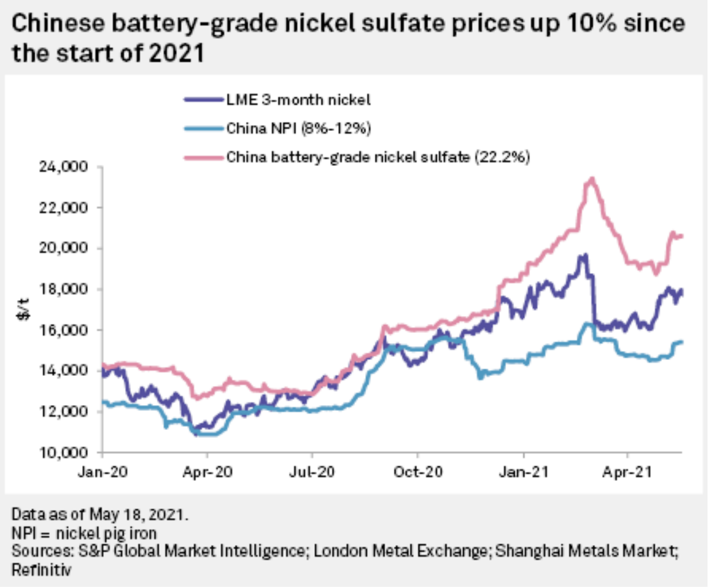


Figure A-5-1: 2019-2022 LME Nickel Cash Price

Stakeholders purchasing through the exchange range from commodity traders to end-users. The LME operates a global network of warehouses that physically store approved nickel products from approved brands providing liquidity to the market. The exchange lists a variety of pricing arrangements. Limited information is provided on the specific terms and conditions of transactions conducted through the exchange leading. During the spring of 2022, nickel prices experienced considerable volatility resulting in unprecedented market turmoil. Alternative nickel products are similarly transacted on dissimilar exchanges, most notably the SME, with their unique product portfolio and supplier list.



Chinese battery-grade nickel sulfate prices up 10% since the start of 2021

Data as of May 18, 2021.
NPI = nickel pig iron
Sources: S&P Global Market Intelligence; London Metal Exchange; Shanghai Metals Market; Refinitiv

Figure A-5-2: Variation in Nickel Prices (Sappor, 2021)

Various mechanisms are used to transact available products for products not transacted through exchanges. Notable products outside the LME include nickel ores, concentrates, intermediates, and specialized refined products. A significant lack of transparency exists for products transacted outside the exchanges. Channels for procuring and selling products on the closed market vary from long-term off-take agreements between parties to one-time purchasing agreements. Generally, product prices are indexed to LME prices and vary significantly between products. Products with nickel content equivalent to or greater than Class 1 nickel are generally priced at a premium to LME. However, products such as intermediates, ferronickel, and nickel-pig iron are sold at a discount to LME. Geographic, time, and technical arbitrages largely reflect the price discrepancies. The broad spectrum of arrangements for nickel products and the complexity of their supply chains result in difficulties in tracking the providence of nickel across operations.

A-5.2 Commodity Cycles

The supply and demand of nickel are correlated to various factors, including political, social, environmental, and legal variables. Fluctuations in the supply and demand of nickel are reflected in the price of nickel. The price of nickel has oscillated considerably over the past century. Significant, prolonged price variations have been linked with major global economic shocks.

Similar to other commodities, nickel prices sustain periodic fluctuations. The underlying mechanisms responsible for the harmonic nature of prices are complex and ill-defined. A prevailing reasoning states that rapid increases in demand stemming from exogenous shocks to global commodities markets coupled with lagging supply responses due to prolonged development cycles results in sharp supply and demand imbalances leading to elevated prices. The lagging supply response gives way to delayed oversupply, which declining prices reciprocate. Lower prices induce financial pressure on operations, leading to decreased supply caused by lower profitability. The cycle then resets from new demand shocks. Cycles play a critical role in investments and development.

The anticipated increase in demand for nickel coupled with sustained underinvestment in new developments is predicted to result in significant supply and demand in balance. While it is assumed that the entirety of the nickel market will be impacted, specific market segments will likely be disproportionately impacted.

A-5.3 Geographic Distribution

The uneven distribution of nickel deposits and global demand for nickel products have resulted in complex value chains, often spanning several continents. Many factors influence the need to distribute value chains across multiple regions. These factors influence the availability of processed nickel products. As a result, supply chain bottleneck risks are not exclusively limited to regions endowed with abundant nickel deposits.

The regional disconnect between operations supplying feedstock and midstream processing facilities converting feedstock into refined products is most prevalent among FeNi and NPI supply chains. This effect is further compounded when considering the regional concentrations of the supply chains. Most FeNi and NPI production occurs in China, Japan, and South Korea. In contrast, ore supplied to the facilities is primarily sourced from Indonesia, the Philippines, and New Caledonia.

In a similar vein, regional differences in deposit mineralogy have culminated in the geographic concentration of the production of several nickel products. High-quality nickel products are derived mainly from sulphide ores. In contrast to FeNi and NPI supply chains, downstream processing operation transforming the ore into high-quality products is often conducted near the mining operations. This is exemplified by the bulk of Class 1 production concentrated in Russia, Canada, Australia, and China, which host vast sulphide deposits.

Factors such as production cost, government policies, and historical precedent have also influenced supply chains. Developing countries typically have lower operational costs. The adoption of government policies has required the localization of production, forcing companies to import ore or establish facilities in mining jurisdiction. This is most evident in Indonesia, where export controls on ores have expanded the country's midstream production capacity. Prolonged development timelines and elevated capital requirements for new midstream facilities have resulted in established facilities adapting to imported sources following the depletion of local deposits. This is most evident in European operations.

A-5.4 Operating Status

As mentioned above, variability in the price of nickel products stemming from supply and demand in-balances has a direct impact on the financial performance of an operation. Sustained nickel prices inferior to an operations cost of production can result in long-term financial stress. To alleviate the financial burden, facilities enter care and maintenance status. The state of care and maintenance status varies by facility and conditions. Facilities generally cease operations or operate at minimum capacity to sustain outstanding financial obligations. Depending on market conditions, facilities can remain in care and maintenance for short or prolonged periods. Generally, the operability of the facility is maintained over the period. Upon emerging from care and maintenance, facilities can continue to process material. However, facilities typically undergo a series of upgrades to reduce operating costs and improve their financial viability. Additionally, facilities may enter care and maintenance due to endogenous and exogenous factors—for example, system failures, unit operation overhauls, supply disputes, or climatic events.

Alternatively, operations may curtail production and operate below their nameplate capacity. Factors influencing brownfield operations to operate at reduced capacity often include labour disruptions, maintenance and improvements, and new regulatory requirements. Such production disruptions are often short-lived leading to rapid returns to operating capacity. However, prolonged disruptions can lead to long-term reductions in capacity or increases in capacity in the case of expansions or improvements. Facilities with excess production capacity and insufficient feedstocks can supplement their production by processing third-party feeds. In contrast, for greenfield operations, factors such as inadequate design, supply disruptions, and financial liabilities can lead to deviation in production from nameplate capacity. Often for greenfield facilities experiencing curtailment, impacts are long-lived, leading to long-term reductions in production capacity.

Operations reaching the end of their operational lifecycles or those no longer economically feasible often seize operating and are mothballed. Mothballed operations enter prolonged decommission periods in which equipment and facilities are removed and sold.

A-6. Sustainability

Sustainability topics, particularly environmental, social, and governance (ESG), have been of critical concern across the commodities industry in recent years. Poor historic ESG performance across the industry has resulted in increased resentment towards the industry. Nickel supply chains have not been immune to demands for ESG reform primarily due to their poor track record. Drivers underpinning the associated impacts of each topic are complex and nuanced. Improving upon such aspects is critical to maintaining a social license to operate.

A-6.1 Environmental

The environmental impact of nickel production from primary sources has been extensively documented across several impact categories. The extent of the impacts varies significantly between operations. Such variability can be attributed to differences in processing technologies, regional governance, and corporate standards.

One of the most notable environmental impacts from the extraction of nickel relates to sulphur dioxide emissions stemming from the smelting of nickel sulphide ores. Regions with extensive smelting of sulphide ores have historically exhibited pervasive sulphur dioxide emissions that have resulted in acid rain pollution. Several efforts to abet sulphur dioxide emissions from smelting operations have decreased emissions by 90%; nevertheless, emissions from operations located in jurisdictions with lower environmental standards persist. Other notable environmental impacts endemic to both laterite and sulphide operations include tailings that contain high concentrations of toxic pollutants. Challenges associated with managing the waste material are of serious concern due to numerous tailing pond failures at non-nickel mining operations. The high potential for failure leading to detrimental ecological impact persists.

Studies quantifying the environmental impact of nickel products across multiple indicators have provided critical insight into environmental hotspots throughout the product's lifecycle. Significant variability in the environmental impact persists due to a myriad of factors, most notably the range of processing pathways, complex supply chains, and geographically dispersed operations. An LCA commissioned by the Nickel Institute in 2017 compares the environmental impact of three distinct product systems.

Table A-6-1: LCA Data Comparison (Nickel Institute, 2020b, 2020a, 2021; Sphera, 2023)

	Nickel Metal *(1 kg Ni)*	**Nickel Sulphate** *(1 kg $NiSO_4 \bullet H_2O$)*	**Ferronickel** *(1 kg Ni in FeNi)*
Global Warming Potential *(kg CO_2 eq.)*	**13**	**4**	**45**
Mining	*13%*	*9%*	*4%*
Beneficiation and Ore Preparation	*15%*	*8%*	*8%*
Primary Extraction	*55%*	*57%*	*87%*
Refining	*13%*	*18%*	-
Water and Waste Treatment	-	*1%*	-
Transportation	*4%*	*7%*	*1%*
Primary Energy Demand *(MJ)*	**236**	**68**	**592**
Mining	*10%*	*7%*	*5%*
Beneficiation and Ore Preparation	*13%*	*10%*	*6%*
Primary Extraction	*56%*	*53%*	*88%*
Refining	*19%*	*24%*	-
Water and Waste Treatment	-	*1%*	-
Transportation	*2%*	*5%*	*1%*
Blue Water Consumption *(kg)*	**106**	**49**	**924**
Mining	*11%*	*2%*	*39%*
Beneficiation and Ore Preparation	*13%*	*4%*	-
Primary Extraction	*63%*	*57%*	*61%*
Refining	*13%*	*33%*	-
Water and Waste Treatment	-	*4%*	-
Transportation	-	-	-
Scope 1-3 Emissions *(kg CO_2 eq.)*	**13**	**4**	**45**
Scope 1	*61%*	*62%*	*72%*
Scope 2	*14%*	*10%*	*17%*
Scope 3	*25%*	*28%*	*11%*
Energy Sources	-	-	-
Non-renewable energy sources	*88%*	*90%*	*88%*
Renewable energy sources	*12%*	*10%*	*12%*
Acidification Potential *(kg SO_2 eq.)*	**1.4**	**0.17**	**0.49**
Eutrophication Potential *(kg Phosphate eq.)*	**5.2E-03**	**0.016**	**1.5E-03**
Photochemical Ozone Creation Potential *(kg Ethene eq.)*	**0.055**	**0.01**	**0.02**
Product Quality (wt% Ni)	>99.8	22	27
2017 Total Production Covered	52%	100%	47%
Total Production Covered	550,000	700,000	734,000
Number of Producing Countries Covered	9	All	4
Process Types Covered	All	6	All

As evidenced in the table above, among products and impact categories assessed, distinct outcomes emerge. FeNi accounts for the highest GWP, primary energy demand, and blue water consumption across the three product systems. This is attributed to the vast quantities of electricity and carbon needed to produce FeNi. Further, the geographic concentration of operations in developing regions with carbon-intensive electricity exacerbates the impacts. Similarly, nickel metal leads in terms of acidification potential primarily due to the majority of production being derived from sulphide ores.

System boundaries considered in the assessment vary considerably due to the copious number of feasible processing pathways. Similarly, the scope and coverage of the assessment are limited and do not provide comprehensive coverage. As a result, the environmental impact of products varies considerably.

A-6.2 Social

Social impacts from the extraction of nickel have been long documented and are often detrimental. Impacts are primarily concentrated in mining stages, with fewer related to midstream processing stages, although still common. The extent of social impacts of midstream operations is highly variable and often unique to facilities, geographies, and operating companies. The basis of the incidents ranges considerably. They often include matters related to labour practices and lack of community engagement. Poor social impact has raised concerns regarding the impact of the social license to operate on future operations.

A-6.3 Governance

Governance issues related to the processing of nickel vary significantly. A notable concern relates to supply chain transparency. The opaque nature of the nickel supply chains limits downstream operations' ability to validate the nickel products' provenance. The opacity inhibits downstream operations from guaranteeing that their products are sourced from operations aligned with their standards. The lack of transparency increases the risk of corruption. Other noteworthy governance issues relate to operational governance and disclosures. Nickel extraction companies have varying degrees of corporate governance practices and disclosure mandates. Governance concerns are highly dependent on the company and regional regulatory requirements.

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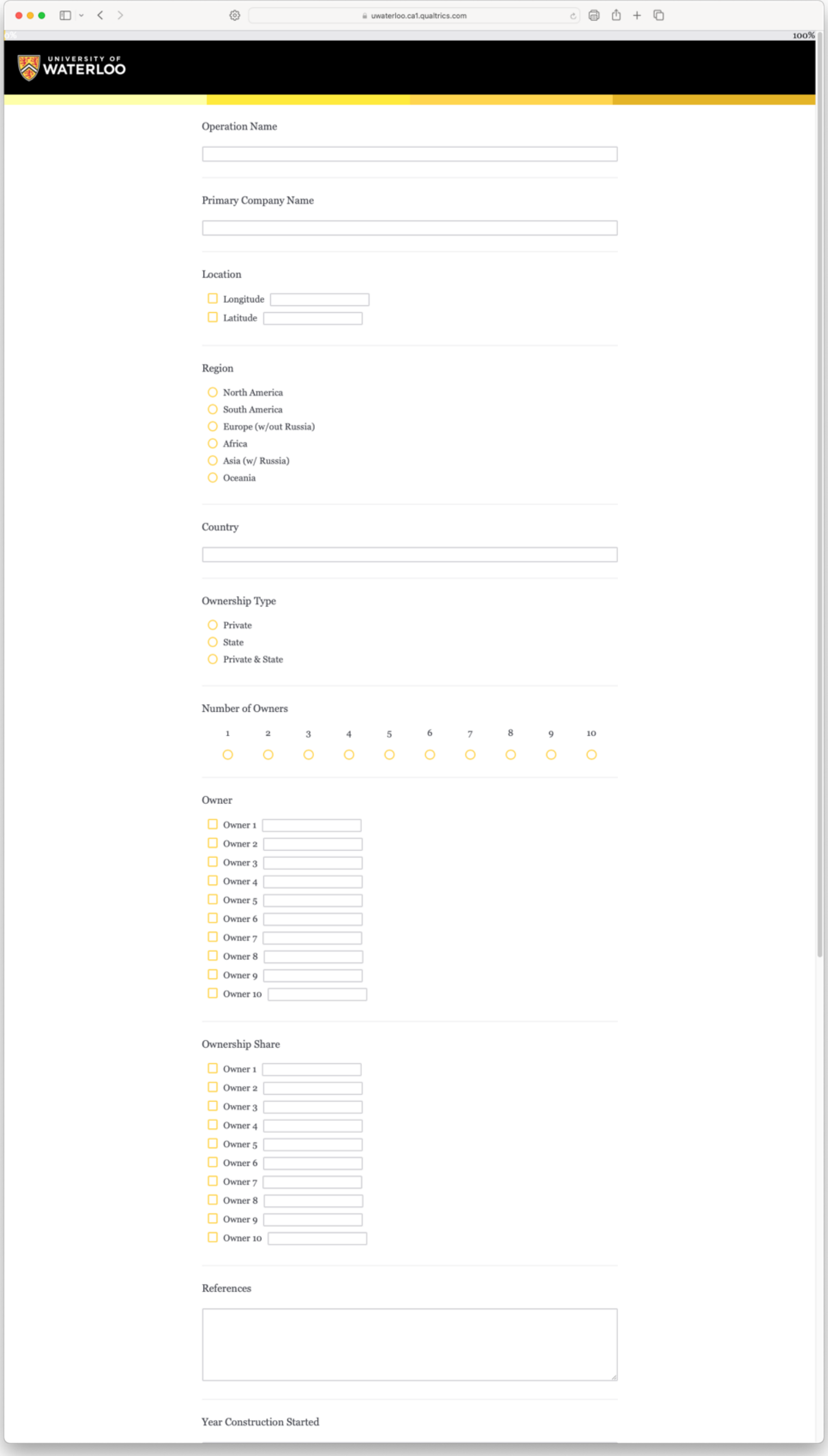
Appendix B
Data Terms

Sections 1.7, 3.4.1, 3.4.3.2

Link to WEIG Database: https://uwaterloo.ca/industrial-ecology/publications

Link to Qualtrics Survey: https://uwaterloo.ca1.qualtrics.com/jfe/form/SV_bNKhNkGOwcZqjpY

Section 3.4.2 Screen shots of Qualtrics Survey:



Operation Name

Primary Company Name

Location

☐ Longitude
☐ Latitude

Region

○ North America
○ South America
○ Europe (w/out Russia)
○ Africa
○ Asia (w/ Russia)
○ Oceania

Country

Ownership Type

○ Private
○ State
○ Private & State

Number of Owners

1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○

Owner

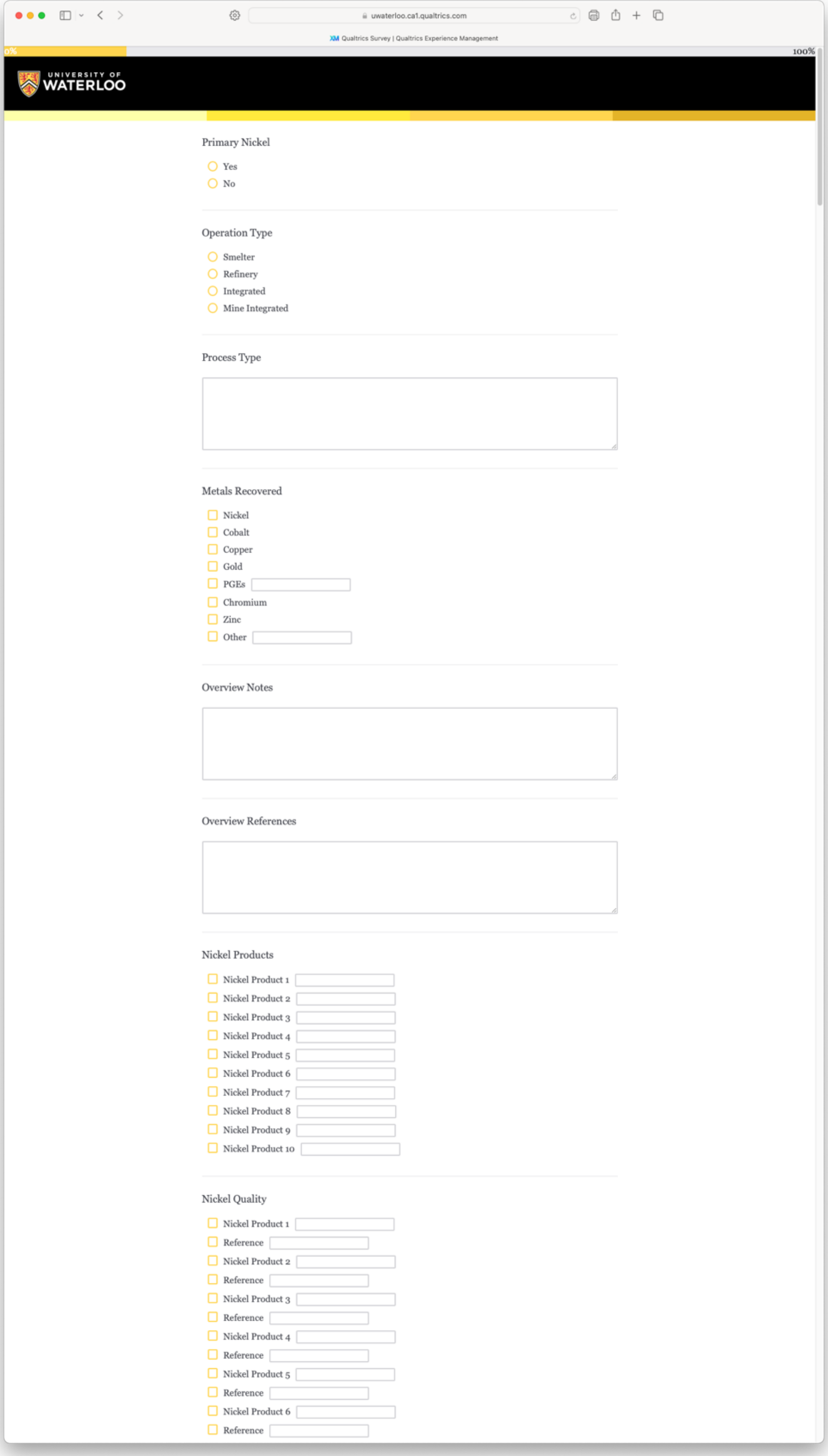
☐ Owner 1
☐ Owner 2
☐ Owner 3
☐ Owner 4
☐ Owner 5
☐ Owner 6
☐ Owner 7
☐ Owner 8
☐ Owner 9
☐ Owner 10

Ownership Share

☐ Owner 1
☐ Owner 2
☐ Owner 3
☐ Owner 4
☐ Owner 5
☐ Owner 6
☐ Owner 7
☐ Owner 8
☐ Owner 9
☐ Owner 10

References

Year Construction Started



Primary Nickel

○ Yes
○ No

Operation Type

○ Smelter
○ Refinery
○ Integrated
○ Mine Integrated

Process Type

Metals Recovered

☐ Nickel
☐ Cobalt
☐ Copper
☐ Gold
☐ PGEs
☐ Chromium
☐ Zinc
☐ Other

Overview Notes

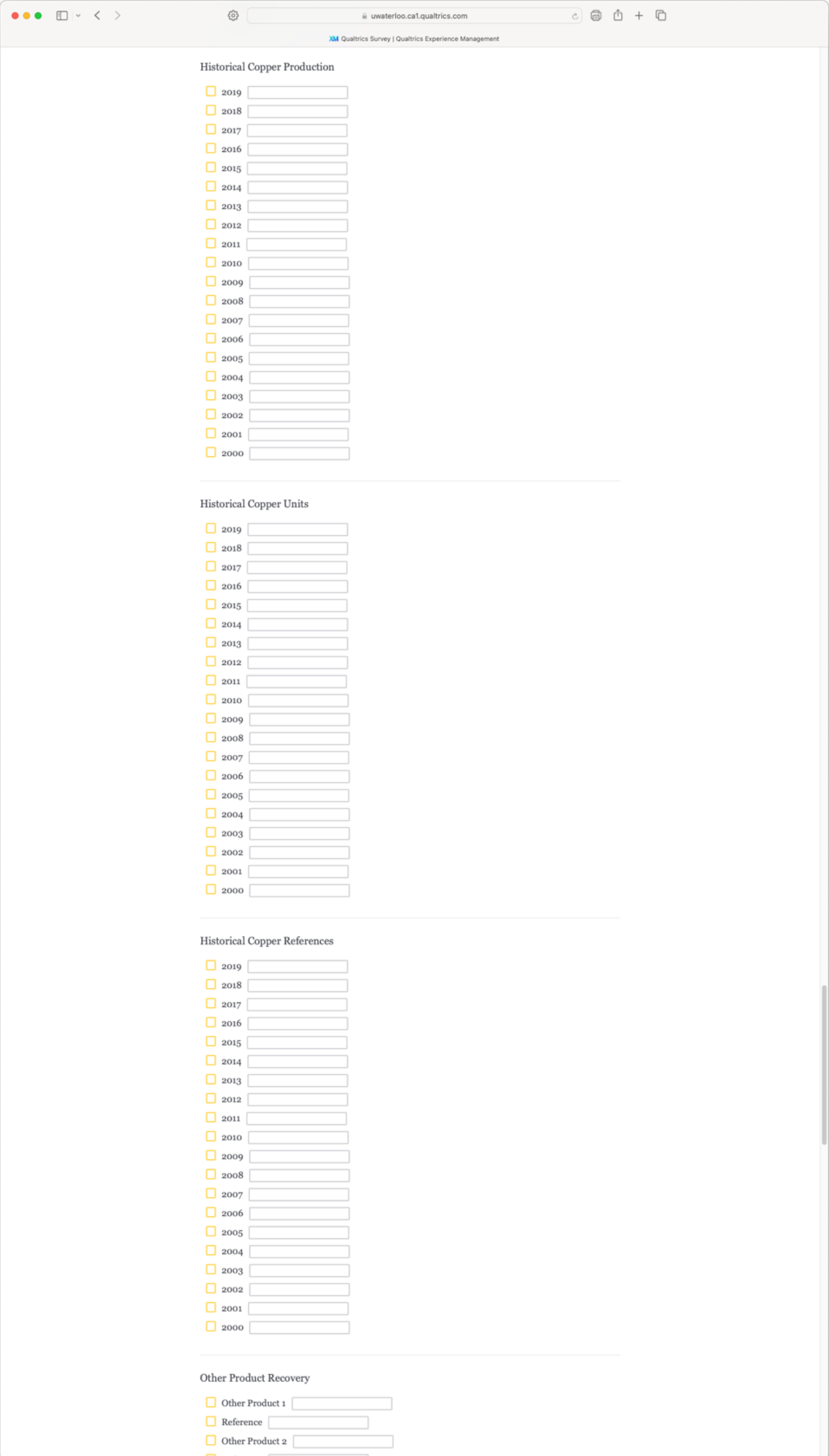
Overview References

Nickel Products

☐ Nickel Product 1
☐ Nickel Product 2
☐ Nickel Product 3
☐ Nickel Product 4
☐ Nickel Product 5
☐ Nickel Product 6
☐ Nickel Product 7
☐ Nickel Product 8
☐ Nickel Product 9
☐ Nickel Product 10

Nickel Quality

☐ Nickel Product 1
☐ Reference
☐ Nickel Product 2
☐ Reference
☐ Nickel Product 3
☐ Reference
☐ Nickel Product 4
☐ Reference
☐ Nickel Product 5
☐ Reference
☐ Nickel Product 6
☐ Reference



Historical Copper Production

☐ 2019
☐ 2018
☐ 2017
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Historical Copper Units

☐ 2019
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Historical Copper References

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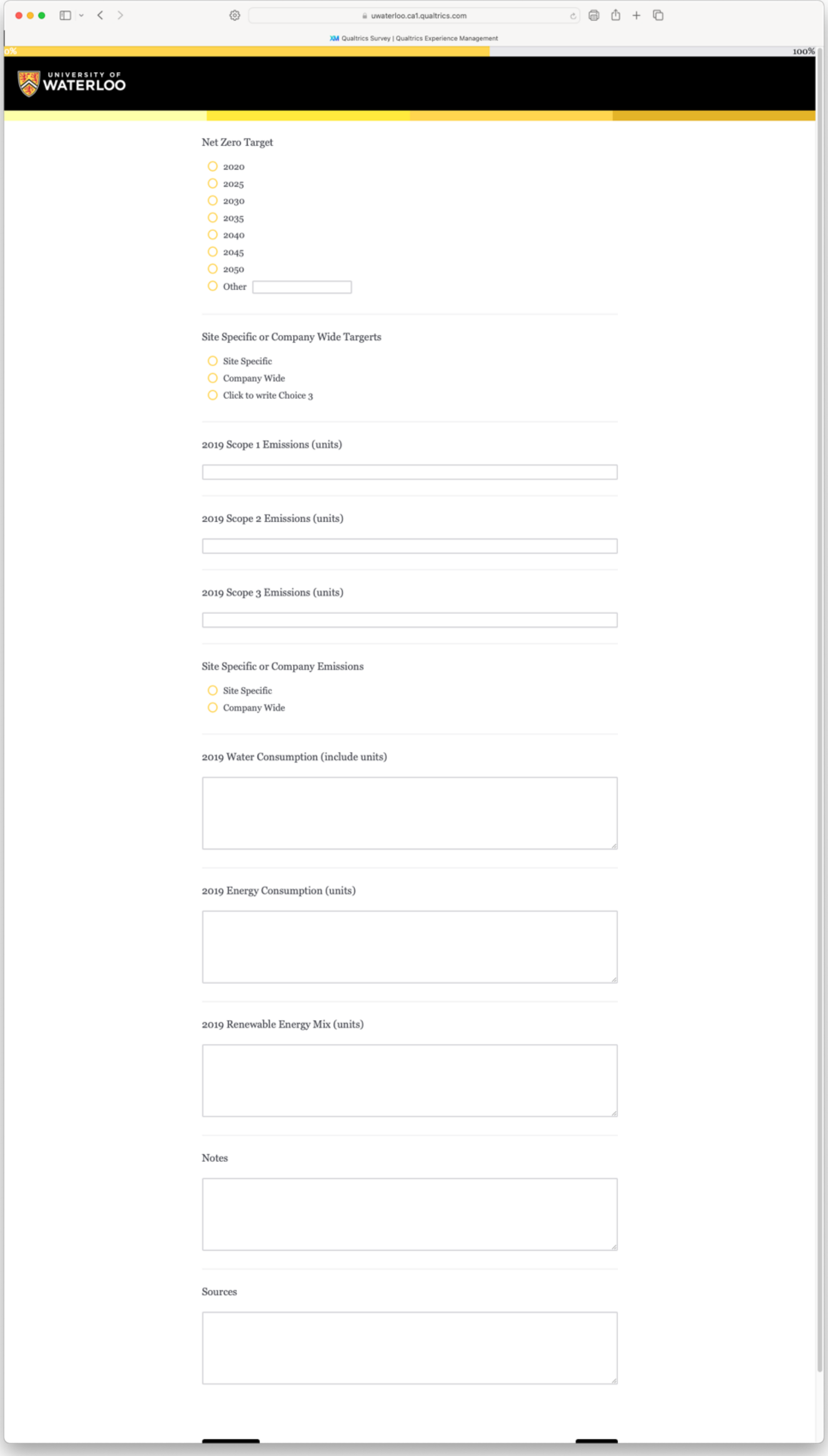
☐ 2001
☐ 2000

Other Product Recovery

☐ Other Product 1
☐ Reference
☐ Other Product 2
☐ Reference



Net Zero Target

○ 2020
○ 2025
○ 2030
○ 2035
○ 2040
○ 2045
○ 2050
○ Other

Site Specific or Company Wide Targerts

○ Site Specific
○ Company Wide
○ Click to write Choice 3

2019 Scope 1 Emissions (units)

2019 Scope 2 Emissions (units)

2019 Scope 3 Emissions (units)

Site Specific or Company Emissions

○ Site Specific
○ Company Wide

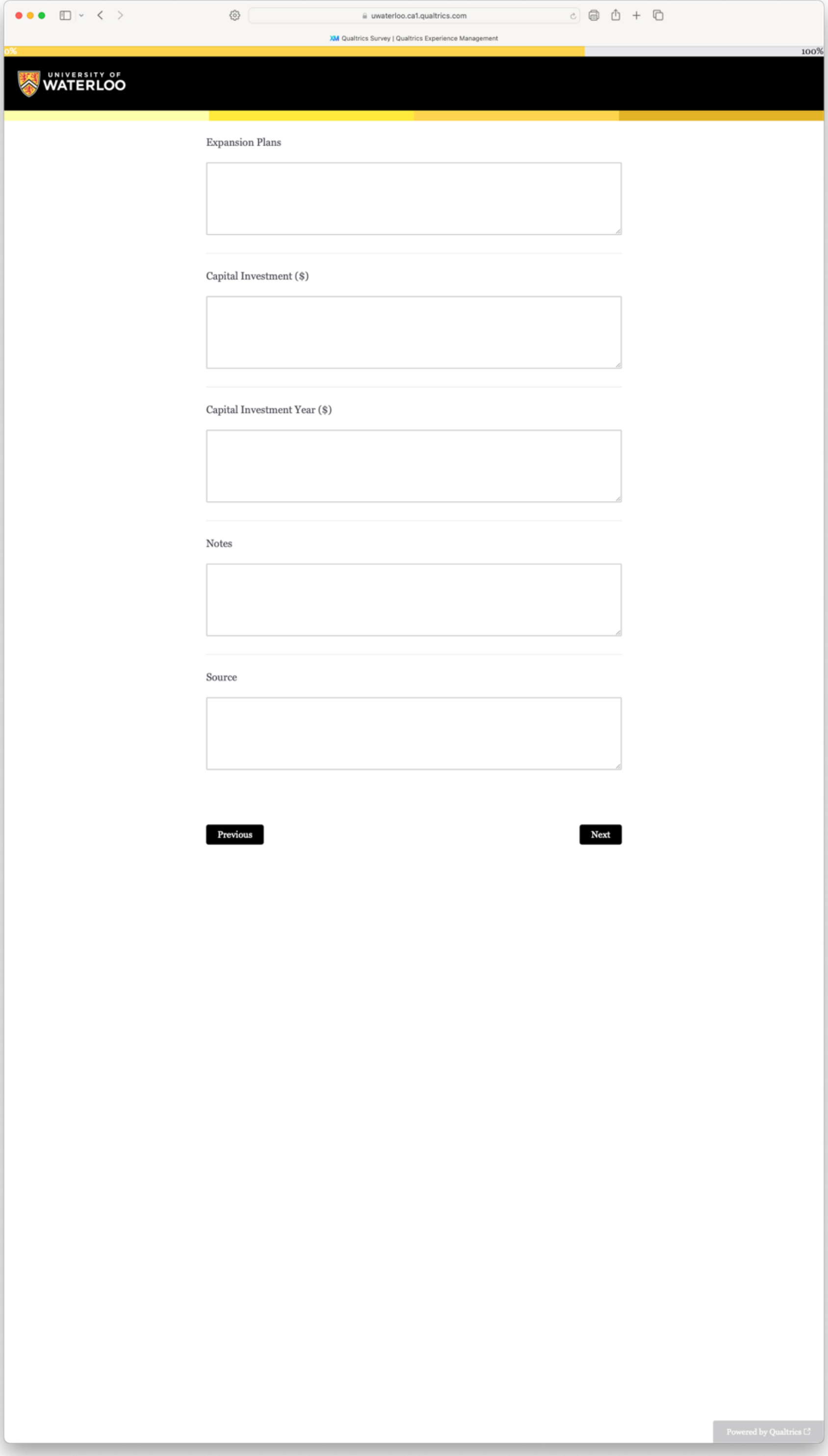
2019 Water Consumption (include units)

2019 Energy Consumption (units)

2019 Renewable Energy Mix (units)

Notes

Sources



Expansion Plans

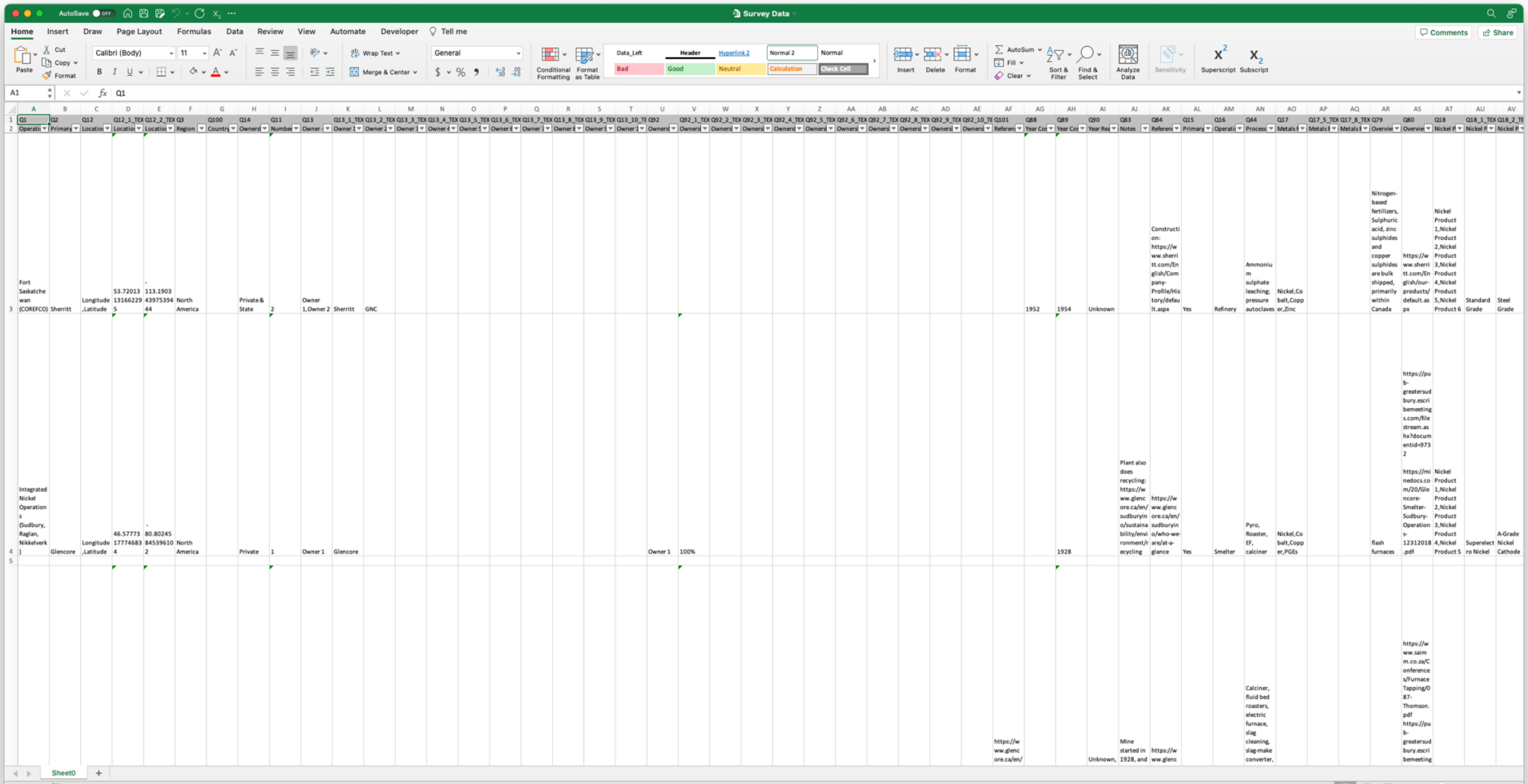
Capital Investment ($)

Capital Investment Year ($)

Notes

Source

Screen shots of Qualtrics Survey Data



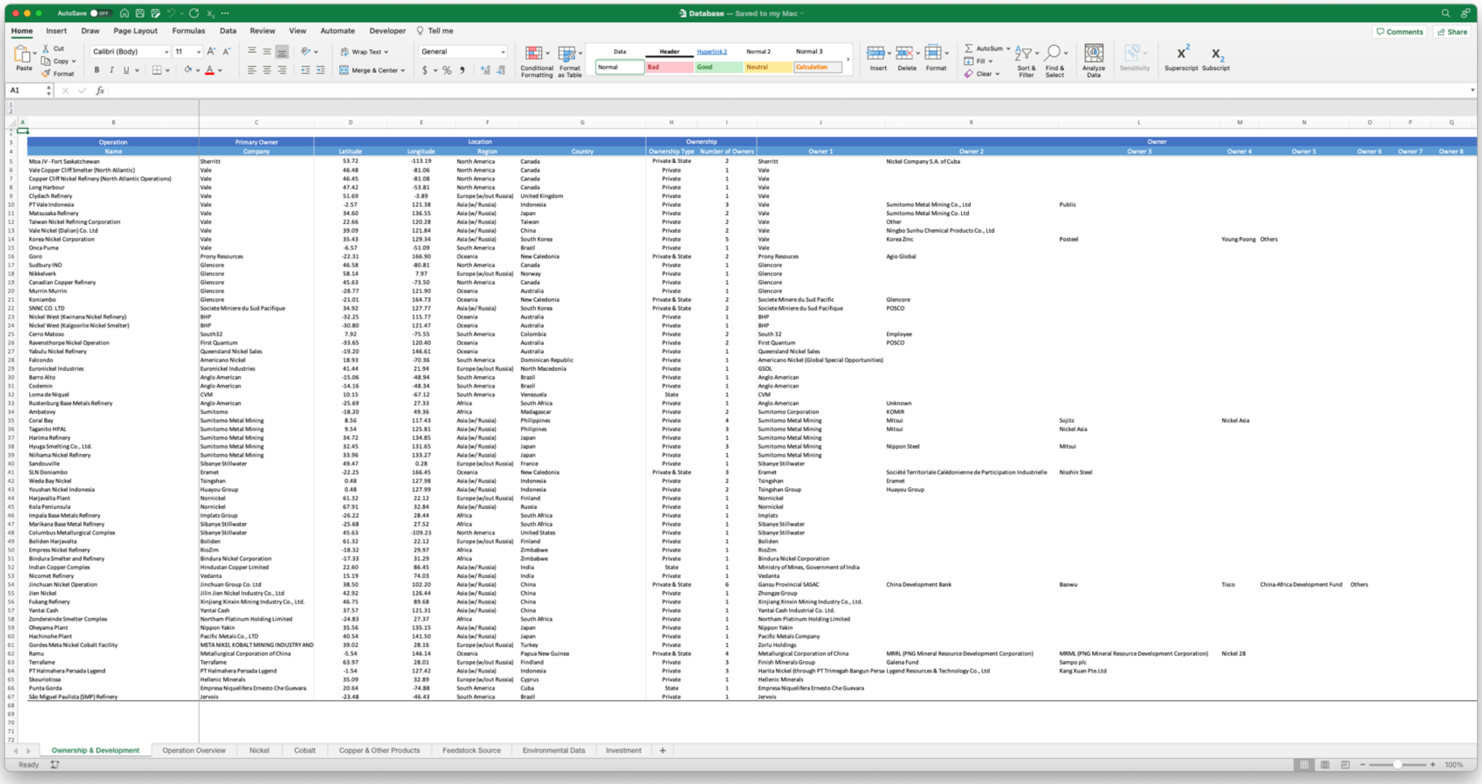
A1 | fx Q1

	A	B	C	D	E	F	G	H	I	J	K	L
1	Q1	Q2	Q12	Q12_1_TEX	Q12_2_TEX	Q3	Q100	Q14	Q11	Q13	Q13_1_TEX	Q13_2_TEX
2	Operati	Primary	Locatio	Locatio	Locatio	Region	Country	Owners	Number	Owner -	Owner 1	Owner 2
3	Fort Saskatchewan (COREFCO)	Sherritt	Longitude ,Latitude	53.72013131662295	-113.19034397539444	North America		Private & State	2	Owner 1,Owner 2	Sherritt	GNC
4	Integrated Nickel Operations (Sudbury, Raglan, Nikkelverk)	Glencore	Longitude ,Latitude	46.57773177746834	-80.80245845396102	North America		Private	1	Owner 1	Glencore	
5												

	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE
1	Q13_3_TEX	Q13_4_TEX	Q13_5_TEX	Q13_6_TEX	Q13_7_TEX	Q13_8_TEX	Q13_9_TEX	Q13_10_TE	Q92	Q92_1_TEX	Q92_2_TEX	Q92_3_TEX	Q92_4_TEX	Q92_5_TEX	Q92_6_TEX	Q92_7_TEX	Q92_8_TEX	Q92_9_TEX	Q92_10_TE
2	Owner 3	Owner 4	Owner 5	Owner 6	Owner 7	Owner 8	Owner 9	Owner 1	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners
3																			
4									Owner 1	100%									
5																			

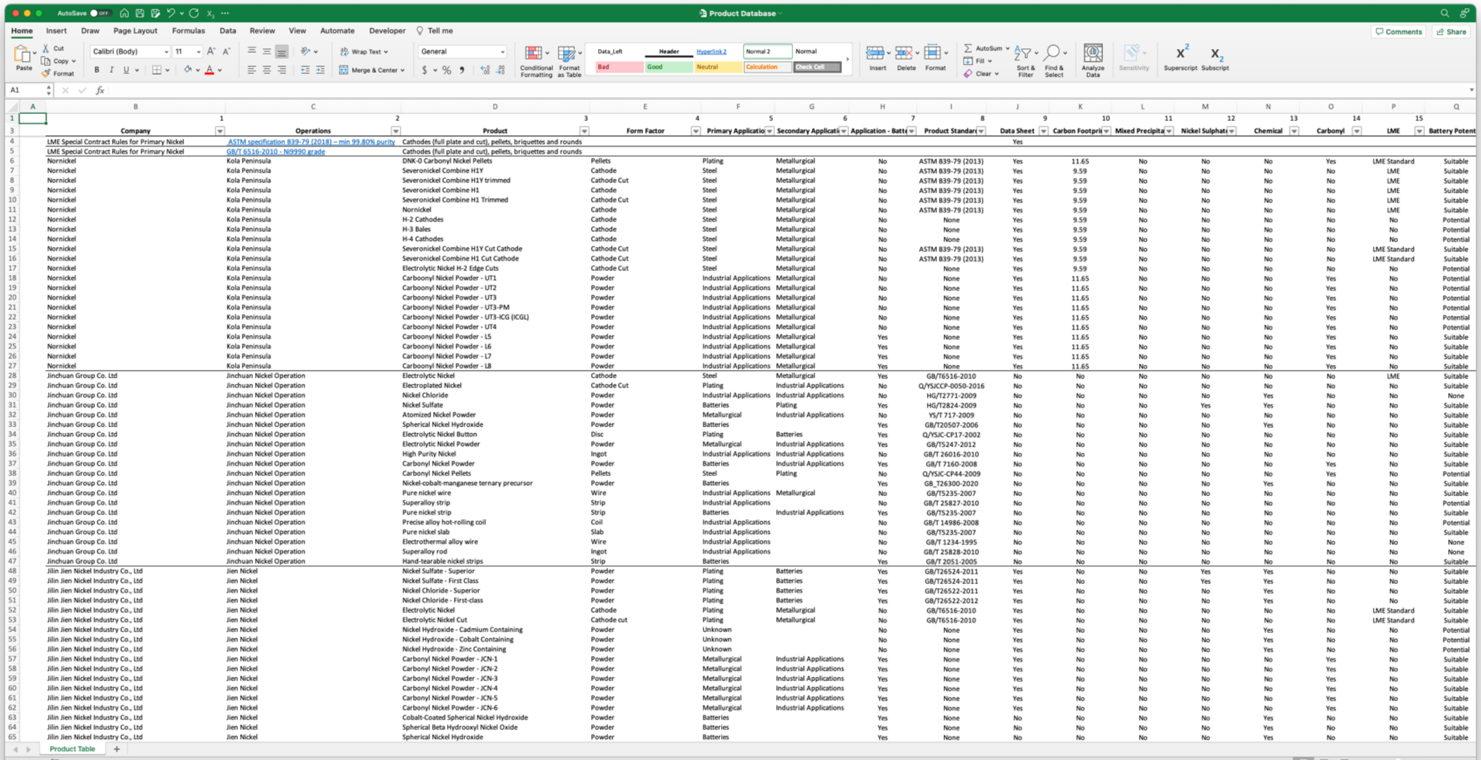
	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV
1	Q101	Q88	Q89	Q90	Q83	Q84	Q15	Q16	Q44	Q17	Q17_5_TEX	Q17_8_TEX	Q79	Q80	Q18	Q18_1_TEX	Q18_2_TE
2	Referen	Year Co	Year Co	Year Rea	Notes	Referen	Primary	Operati	Process	Metals	Metals	Metals	Overvie	Overvie	Nickel P	Nickel P	Nickel P
3		1952	1954	Unknown		Construction: https://www.sherritt.com/English/Company-Profile/History/default.aspx	Yes	Refinery	Ammonium sulphate leaching; pressure autoclaves	Nickel,Cobalt,Copper,Zinc			Nitrogen-based fertilizers, Sulphuric acid, zinc sulphides and copper sulphides are bulk shipped, primarily within Canada	https://www.sherritt.com/English/our-products/default.aspx	Nickel Product 1,Nickel Product 2,Nickel Product 3,Nickel Product 4,Nickel Product 5,Nickel Product 6	Standard Grade	Steel Grade
4			1928		Plant also does recycling: https://www.glencore.ca/en/sudburyino/sustainability/environment/recycling	https://www.glencore.ca/en/sudburyino/who-we-are/at-a-glance	Yes	Smelter	Pyro, Roaster, EF, calciner	Nickel,Cobalt,Copper,PGEs			flash furnaces	https://pub-greatersudbury.escribemeetings.com/filestream.ashx?documentid=9732 https://minedocs.com/20/Glencore-Smelter-Sudbury-Operations-12312018.pdf	Nickel Product 1,Nickel Product 2,Nickel Product 3,Nickel Product 4,Nickel Product 5	Superelectro Nickel	A-Grade Nickel Cathode
5																	
	https://www.glencore.ca/en/			Unknown,	Mine started in 1928, and	https://www.glenc			Calciner, fluid bed roasters, electric furnace, slag cleaning, slag-make converter,					https://www.saimm.co.za/Conferences/FurnaceTapping/087-Thomson.pdf https://pub-greatersudbury.escribemeeting			

Screen shot of Database



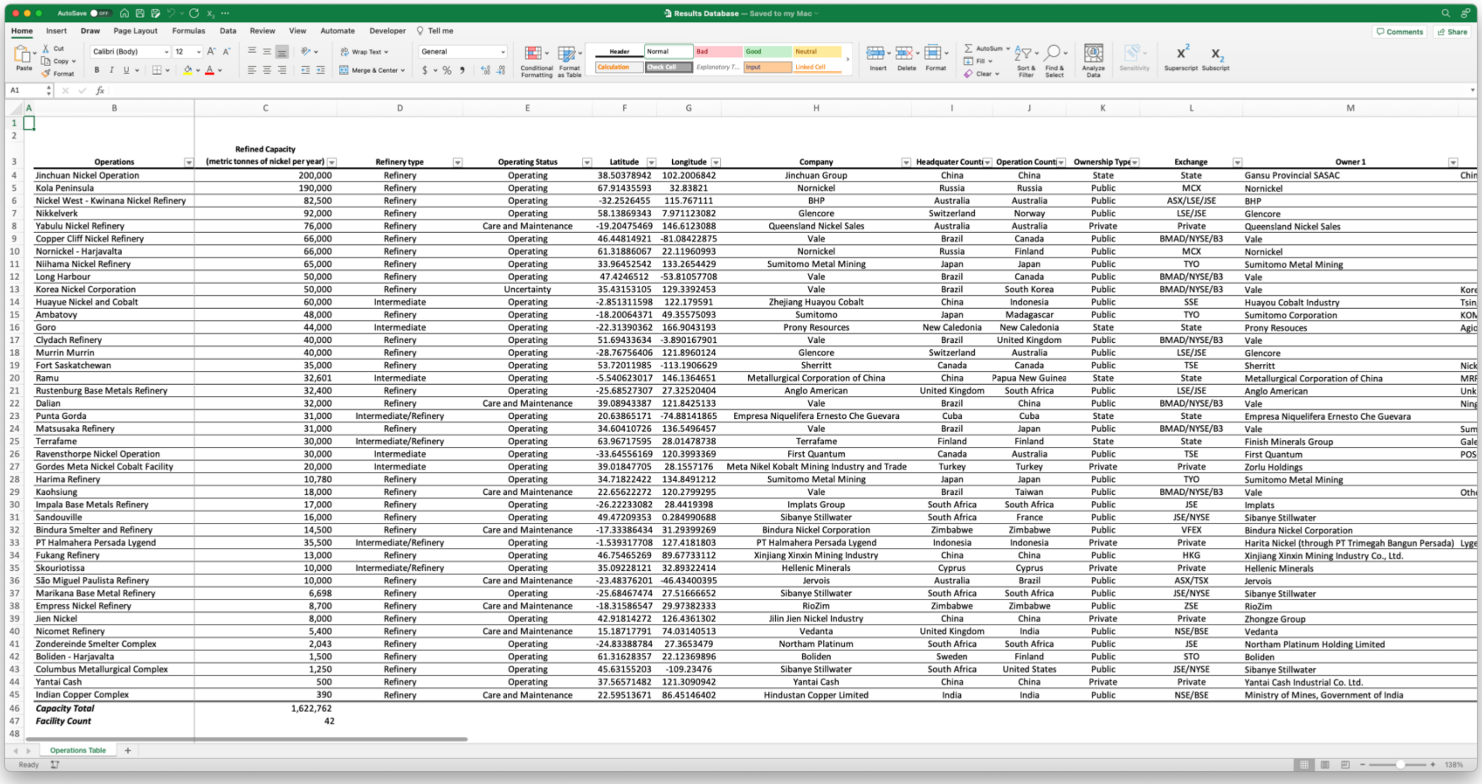
	Operation	Primary Owner	Location				Ownership		Owner							
	Name	Company	Latitude	Longitude	Region	Country	Ownership Type	Number of Owners	Owner 1	Owner 2	Owner 3	Owner 4	Owner 5	Owner 6	Owner 7	Owner 8
5	Moa JV - Fort Saskatchewan	Sherritt	53.72	-113.19	North America	Canada	Private & State	2	Sherritt	Nickel Company S.A. of Cuba						
6	Vale Copper Cliff Smelter (North Atlantic)	Vale	46.48	-81.06	North America	Canada	Private	1	Vale							
7	Copper Cliff Nickel Refinery (North Atlantic Operations)	Vale	46.45	-81.08	North America	Canada	Private	1	Vale							
8	Long Harbour	Vale	47.42	-53.81	North America	Canada	Private	1	Vale							
9	Clydach Refinery	Vale	51.69	-3.89	Europe (w/out Russia)	United Kingdom	Private	1	Vale							
10	PT Vale Indonesia	Vale	-2.57	121.38	Asia (w/ Russia)	Indonesia	Private	3	Vale	Sumitomo Metal Mining Co., Ltd	Public					
11	Matsusaka Refinery	Vale	34.60	136.55	Asia (w/ Russia)	Japan	Private	2	Vale	Sumitomo Metal Mining Co. Ltd						
12	Taiwan Nickel Refining Corporation	Vale	22.66	120.28	Asia (w/ Russia)	Taiwan	Private	2	Vale	Other						
13	Vale Nickel (Dalian) Co. Ltd	Vale	39.09	121.84	Asia (w/ Russia)	China	Private	2	Vale	Ningbo Sunhu Chemical Products Co., Ltd						
14	Korea Nickel Corporation	Vale	35.43	129.34	Asia (w/ Russia)	South Korea	Private	5	Vale	Korea Zinc	Posteel	Young Poong	Others			
15	Onca Puma	Vale	-6.57	-51.09	South America	Brazil	Private	1	Vale							
16	Goro	Prony Resources	-22.31	166.90	Oceania	New Caledonia	Private & State	2	Prony Resouces	Agio Global						
17	Sudbury INO	Glencore	46.58	-80.81	North America	Canada	Private	1	Glencore							
18	Nikkelverk	Glencore	58.14	7.97	Europe (w/out Russia)	Norway	Private	1	Glencore							
19	Canadian Copper Refinery	Glencore	45.63	-73.50	North America	Canada	Private	1	Glencore							
20	Murrin Murrin	Glencore	-28.77	121.90	Oceania	Australia	Private	1	Glencore							
21	Koniambo	Glencore	-21.01	164.73	Oceania	New Caledonia	Private & State	2	Societe Minere du Sud Pacific	Glencore						
22	SNNC CO. LTD	Societe Miniere du Sud Pacifique	34.92	127.77	Asia (w/ Russia)	South Korea	Private & State	2	Societe Miniere du Sud Pacifique	POSCO						
23	Nickel West (Kwinana Nickel Refinery)	BHP	-32.25	115.77	Oceania	Australia	Private	1	BHP							
24	Nickel West (Kalgoorlie Nickel Smelter)	BHP	-30.80	121.47	Oceania	Australia	Private	1	BHP							
25	Cerro Matoso	South32	7.92	-75.55	South America	Colombia	Private	2	South 32	Employee						
26	Ravensthorpe Nickel Operation	First Quantum	-33.65	120.40	Oceania	Australia	Private	2	First Quantum	POSCO						
27	Yabulu Nickel Refinery	Queensland Nickel Sales	-19.20	146.61	Oceania	Australia	Private	1	Queensland Nickel Sales							
28	Falcondo	Americano Nickel	18.93	-70.36	South America	Dominican Republic	Private	1	Americano Nickel (Global Special Opportunities)							
29	Euronickel Industries	Euronickel Industries	41.44	21.94	Europe (w/out Russia)	North Macedonia	Private	1	GSOL							
30	Barro Alto	Anglo American	-15.06	-48.94	South America	Brazil	Private	1	Anglo American							
31	Codemin	Anglo American	-14.16	-48.34	South America	Brazil	Private	1	Anglo American							
32	Loma de Niquel	CVM	10.15	-67.12	South America	Venezuela	State	1	CVM							
33	Rustenburg Base Metals Refinery	Anglo American	-25.69	27.33	Africa	South Africa	Private	1	Anglo American	Unknown						
34	Ambatovy	Sumitomo	-18.20	49.36	Africa	Madagascar	Private	2	Sumitomo Corporation	KOMIR						
35	Coral Bay	Sumitomo Metal Mining	8.56	117.43	Asia (w/ Russia)	Philippines	Private	4	Sumitomo Metal Mining	Mitsui	Sojitz	Nickel Asia				
36	Taganito HPAL	Sumitomo Metal Mining	9.54	125.81	Asia (w/ Russia)	Philipines	Private	3	Sumitomo Metal Mining	Mitsui	Nickel Asia					
37	Harima Refinery	Sumitomo Metal Mining	34.72	134.85	Asia (w/ Russia)	Japan	Private	1	Sumitomo Metal Mining							
38	Hyuga Smelting Co., Ltd.	Sumitomo Metal Mining	32.45	131.65	Asia (w/ Russia)	Japan	Private	3	Sumitomo Metal Mining	Nippon Steel	Mitsui					
39	Niihama Nickel Refinery	Sumitomo Metal Mining	33.96	133.27	Asia (w/ Russia)	Japan	Private	1	Sumitomo Metal Mining							
40	Sandouville	Sibanye Stillwater	49.47	0.28	Europe (w/out Russia)	France	Private	1	Sibanye Stillwater							
41	SLN Doniambo	Eramet	-22.25	166.45	Oceania	New Caledonia	Private & State	3	Eramet	Société Territoriale Calédonienne de Participation Industrielle	Nisshin Steel					
42	Weda Bay Nickel	Tsingshan	0.48	127.98	Asia (w/ Russia)	Indonesia	Private	2	Tsingshan	Eramet						
43	Youshan Nickel Indonesia	Huayou Group	0.48	127.99	Asia (w/ Russia)	Indonesia	Private	2	Tsingshan Group	Huayou Group						
44	Harjavalta Plant	Nornickel	61.32	22.12	Europe (w/out Russia)	Finland	Private	1	Nornickel							
45	Kola Peniunsula	Nornickel	67.91	32.84	Asia (w/ Russia)	Russia	Private	1	Nornickel							
46	Impala Base Metals Refinery	Implats Group	-26.22	28.44	Africa	South Africa	Private	1	Implats							
47	Marikana Base Metal Refinery	Sibanye Stillwater	-25.68	27.52	Africa	South Africa	Private	1	Sibanye Stillwater							
48	Columbus Metallurgical Complex	Sibanye Stillwater	45.63	-109.23	North America	United States	Private	1	Sibanye Stillwater							
49	Boliden Harjavalta	Boliden	61.32	22.12	Europe (w/out Russia)	Finland	Private	1	Boliden							
50	Empress Nickel Refinery	RioZim	-18.32	29.97	Africa	Zimbabwe	Private	1	RioZim							
51	Bindura Smelter and Refinery	Bindura Nickel Corporation	-17.33	31.29	Africa	Zimbabwe	Private	1	Bindura Nickel Corporation							
52	Indian Copper Complex	Hindustan Copper Limited	22.60	86.45	Asia (w/ Russia)	India	State	1	Ministry of Mines, Government of India							
53	Nicomet Refinery	Vedanta	15.19	74.03	Asia (w/ Russia)	India	Private	1	Vedanta							
54	Jinchuan Nickel Operation	Jinchuan Group Co. Ltd	38.50	102.20	Asia (w/ Russia)	China	Private & State	6	Gansu Provincial SASAC	China Development Bank	Baowu	Tisco	China-Africa Development Fund	Others		
55	Jien Nickel	Jilin Jien Nickel Industry Co., Ltd	42.92	126.44	Asia (w/ Russia)	China	Private	1	Zhongze Group							
56	Fukang Refinery	Xinjiang Xinxin Mining Industry Co., Ltd.	46.75	89.68	Asia (w/ Russia)	China	Private	1	Xinjiang Xinxin Mining Industry Co., Ltd.							
57	Yantai Cash	Yantai Cash	37.57	121.31	Asia (w/ Russia)	China	Private	1	Yantai Cash Industrial Co. Ltd.							
58	Zondereinde Smelter Complex	Northam Platinum Holding Limited	-24.83	27.37	Africa	South Africa	Private	1	Northam Platinum Holding Limited							
59	Oheyama Plant	Nippon Yakin	35.56	135.15	Asia (w/ Russia)	Japan	Private	1	Nippon Yakin							
60	Hachinohe Plant	Pacific Metals Co., LTD	40.54	141.50	Asia (w/ Russia)	Japan	Private	1	Pacific Metals Company							
61	Gordes Meta Nickel Cobalt Facility	META NIKEL KOBALT MINING INDUSTRY AND	39.02	28.16	Europe (w/out Russia)	Turkey	Private	1	Zorlu Holdings							
62	Ramu	Metallurgical Corporation of China	-5.54	146.14	Oceania	Papua New Guinea	Private & State	4	Metallurgical Corporation of China	MRRL (PNG Mineral Resource Development Corporation)	MRML (PNG Mineral Resource Development Corporation)	Nickel 28				
63	Terrafame	Terrafame	63.97	28.01	Europe (w/out Russia)	Findland	Private	3	Finish Minerals Group	Galena Fund	Sampo plc					
64	PT Halmahera Persada Lygend	PT Halmahera Persada Lygend	-1.54	127.42	Asia (w/ Russia)	Indonesia	Private	3	Harita Nickel (through PT Trimegah Bangun Persa	Lygend Resources & Technology Co., Ltd	Kang Xuan Pte.Ltd					
65	Skouriotissa	Hellenic Minerals	35.09	32.89	Europe (w/out Russia)	Cyprus	Private	1	Hellenic Minerals							
66	Punta Gorda	Empresa Niquelifera Ernesto Che Guevara	20.64	-74.88	South America	Cuba	State	1	Empresa Niquelifera Ernesto Che Guevara							
67	São Miguel Paulista (SMP) Refinery	Jervois	-23.48	-46.43	South America	Brazil	Private	1	Jervois							

Screen shot of Product Database



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
3		Company	Operations	Product	Form Factor	Primary Applicatio	Secondary Applicati	Application - Batte	Product Standar	Data Sheet	Carbon Footpri	Mixed Precipita	Nickel Sulphat	Chemical	Carbonyl	LME	Battery Potent
4		LME Special Contract Rules for Primary Nickel	ASTM specification B39-79 (2018) – min 99.80% purity	Cathodes (full plate and cut), pellets, briquettes and rounds						Yes							
5		LME Special Contract Rules for Primary Nickel	GB/T 6516-2010 - Ni9990 grade	Cathodes (full plate and cut), pellets, briquettes and rounds													
6		Nornickel	Kola Peninsula	DNK-0 Carbonyl Nickel Pellets	Pellets	Plating	Metallurgical	No	ASTM B39-79 (2013)	Yes	11.65	No	No	No	Yes	LME Standard	Suitable
7		Nornickel	Kola Peninsula	Severonickel Combine H1Y	Cathode	Steel	Metallurgical	No	ASTM B39-79 (2013)	Yes	9.59	No	No	No	No	LME	Suitable
8		Nornickel	Kola Peninsula	Severonickel Combine H1Y trimmed	Cathode Cut	Steel	Metallurgical	No	ASTM B39-79 (2013)	Yes	9.59	No	No	No	No	LME	Suitable
9		Nornickel	Kola Peninsula	Severonickel Combine H1	Cathode	Steel	Metallurgical	No	ASTM B39-79 (2013)	Yes	9.59	No	No	No	No	LME	Suitable
10		Nornickel	Kola Peninsula	Severonickel Combine H1 Trimmed	Cathode Cut	Steel	Metallurgical	No	ASTM B39-79 (2013)	Yes	9.59	No	No	No	No	LME	Suitable
11		Nornickel	Kola Peninsula	Nornickel	Cathode	Steel	Metallurgical	No	ASTM B39-79 (2013)	Yes	9.59	No	No	No	No	LME	Suitable
12		Nornickel	Kola Peninsula	H-2 Cathodes	Cathode	Steel	Metallurgical	No	None	Yes	9.59	No	No	No	No	No	Potential
13		Nornickel	Kola Peninsula	H-3 Bales	Cathode	Steel	Metallurgical	No	None	Yes	9.59	No	No	No	No	No	Potential
14		Nornickel	Kola Peninsula	H-4 Cathodes	Cathode	Steel	Metallurgical	No	None	Yes	9.59	No	No	No	No	No	Potential
15		Nornickel	Kola Peninsula	Severonickel Combine H1Y Cut Cathode	Cathode Cut	Steel	Metallurgical	No	ASTM B39-79 (2013)	Yes	9.59	No	No	No	No	LME Standard	Suitable
16		Nornickel	Kola Peninsula	Severonickel Combine H1 Cut Cathode	Cathode Cut	Steel	Metallurgical	No	ASTM B39-79 (2013)	Yes	9.59	No	No	No	No	LME Standard	Suitable
17		Nornickel	Kola Peninsula	Electrolytic Nickel H-2 Edge Cuts	Cathode Cut	Steel	Metallurgical	No	None	Yes	9.59	No	No	No	No	No	Potential
18		Nornickel	Kola Peninsula	Carboonyl Nickel Powder - UT1	Powder	Industrial Applications	Metallurgical	No	None	Yes	11.65	No	No	No	Yes	No	Potential
19		Nornickel	Kola Peninsula	Carboonyl Nickel Powder - UT2	Powder	Industrial Applications	Metallurgical	No	None	Yes	11.65	No	No	No	Yes	No	Potential
20		Nornickel	Kola Peninsula	Carboonyl Nickel Powder - UT3	Powder	Industrial Applications	Metallurgical	No	None	Yes	11.65	No	No	No	Yes	No	Potential
21		Nornickel	Kola Peninsula	Carboonyl Nickel Powder - UT3-PM	Powder	Industrial Applications	Metallurgical	No	None	Yes	11.65	No	No	No	Yes	No	Potential
22		Nornickel	Kola Peninsula	Carboonyl Nickel Powder - UT3-ICG (ICGL)	Powder	Industrial Applications	Metallurgical	No	None	Yes	11.65	No	No	No	Yes	No	Potential
23		Nornickel	Kola Peninsula	Carboonyl Nickel Powder - UT4	Powder	Industrial Applications	Metallurgical	No	None	Yes	11.65	No	No	No	Yes	No	Potential
24		Nornickel	Kola Peninsula	Carboonyl Nickel Powder - L5	Powder	Industrial Applications	Metallurgical	Yes	None	Yes	11.65	No	No	No	Yes	No	Suitable
25		Nornickel	Kola Peninsula	Carboonyl Nickel Powder - L6	Powder	Industrial Applications	Metallurgical	Yes	None	Yes	11.65	No	No	No	Yes	No	Suitable
26		Nornickel	Kola Peninsula	Carboonyl Nickel Powder - L7	Powder	Industrial Applications	Metallurgical	Yes	None	Yes	11.65	No	No	No	Yes	No	Suitable
27		Nornickel	Kola Peninsula	Carboonyl Nickel Powder - L8	Powder	Industrial Applications	Metallurgical	Yes	None	Yes	11.65	No	No	No	Yes	No	Suitable
28		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Electrolytic Nickel	Cathode	Steel	Metallurgical	Yes	GB/T6516-2010	No	No	No	No	No	No	LME	Suitable
29		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Electroplated Nickel	Cathode Cut	Plating	Industrial Applications	No	Q/YSJCCP-0050-2016	No	No	No	No	No	No	No	Suitable
30		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Nickel Chloride	Powder	Industrial Applications	Industrial Applications	No	HG/T2771-2009	No	No	No	No	Yes	No	No	None
31		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Nickel Sulfate	Powder	Batteries	Plating	Yes	HG/T2824-2009	No	No	No	Yes	Yes	No	No	Suitable
32		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Atomized Nickel Powder	Powder	Metallurgical	Industrial Applications	No	YS/T 717-2009	No	No	No	No	No	No	No	Suitable
33		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Spherical Nickel Hydroxide	Powder	Batteries		Yes	GB/T20507-2006	No	No	No	No	Yes	No	No	Suitable
34		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Electrolytic Nickel Button	Disc	Plating	Batteries	Yes	Q/YSJC-CP17-2002	No	No	No	No	No	No	No	Suitable
35		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Electrolytic Nickel Powder	Powder	Metallurgical	Industrial Applications	Yes	GB/T5247-2012	No	No	No	No	No	No	No	Suitable
36		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	High Purity Nickel	Ingot	Industrial Applications	Industrial Applications	No	GB/T 26016-2010	No	No	No	No	No	No	No	Suitable
37		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Carbonyl Nickel Powder	Powder	Batteries	Industrial Applications	Yes	GB/T 7160-2008	No	No	No	No	No	Yes	No	Suitable
38		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Carbonyl Nickel Pellets	Pellets	Steel	Plating	No	Q/YSJC-CP44-2009	No	No	No	No	No	Yes	No	Potential
39		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Nickel-cobalt-manganese ternary precursor	Powder	Batteries		Yes	GB_T26300-2020	No	No	No	No	Yes	No	No	Suitable
40		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Pure nickel wire	Wire	Industrial Applications	Metallurgical	No	GB/T5235-2007	No	No	No	No	No	No	No	Suitable
41		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Superalloy strip	Strip	Industrial Applications		No	GB/T 25827-2010	No	No	No	No	No	No	No	Potential
42		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Pure nickel strip	Strip	Batteries	Industrial Applications	Yes	GB/T5235-2007	No	No	No	No	No	No	No	Suitable
43		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Precise alloy hot-rolling coil	Coil	Industrial Applications		No	GB/T 14986-2008	No	No	No	No	No	No	No	Potential
44		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Pure nickel slab	Slab	Industrial Applications		No	GB/T5235-2007	No	No	No	No	No	No	No	Suitable
45		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Electrothermal alloy wire	Wire	Industrial Applications		No	GB/T 1234-1995	No	No	No	No	No	No	No	None
46		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Superalloy rod	Ingot	Industrial Applications		No	GB/T 25828-2010	No	No	No	No	No	No	No	None
47		Jinchuan Group Co. Ltd	Jinchuan Nickel Operation	Hand-tearable nickel strips	Strip	Batteries		Yes	GB/T 2051-2005	No	No	No	No	No	No	No	Suitable
48		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Nickel Sulfate - Superior	Powder	Plating	Batteries	Yes	GB/T26524-2011	Yes	No	No	Yes	Yes	No	No	Suitable
49		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Nickel Sulfate - First Class	Powder	Plating	Batteries	Yes	GB/T26524-2011	Yes	No	No	Yes	Yes	No	No	Suitable
50		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Nickel Chloride - Superior	Powder	Plating	Batteries	Yes	GB/T26522-2011	Yes	No	No	No	Yes	No	No	Suitable
51		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Nickel Chloride - First-class	Powder	Plating	Batteries	Yes	GB/T26522-2012	Yes	No	No	No	Yes	No	No	Suitable
52		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Electrolytic Nickel	Cathode	Plating	Metallurgical	No	GB/T6516-2010	Yes	No	No	No	No	No	LME Standard	Suitable
53		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Electrolytic Nickel Cut	Cathode cut	Plating	Metallurgical	No	GB/T6516-2010	Yes	No	No	No	No	No	LME Standard	Suitable
54		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Nickel Hydroxide - Cadmium Containing	Powder	Unknown		No	None	Yes	No	No	No	Yes	No	No	Potential
55		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Nickel Hydroxide - Cobalt Containing	Powder	Unknown		No	None	Yes	No	No	No	Yes	No	No	Potential
56		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Nickel Hydroxide - Zinc Containing	Powder	Unknown		No	None	Yes	No	No	No	Yes	No	No	Potential
57		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Carbonyl Nickel Powder - JCN-1	Powder	Metallurgical	Industrial Applications	Yes	None	Yes	No	No	No	No	Yes	No	Suitable
58		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Carbonyl Nickel Powder - JCN-2	Powder	Metallurgical	Industrial Applications	Yes	None	Yes	No	No	No	No	Yes	No	Suitable
59		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Carbonyl Nickel Powder - JCN-3	Powder	Metallurgical	Industrial Applications	Yes	None	Yes	No	No	No	No	Yes	No	Suitable
60		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Carbonyl Nickel Powder - JCN-4	Powder	Metallurgical	Industrial Applications	Yes	None	Yes	No	No	No	No	Yes	No	Suitable
61		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Carbonyl Nickel Powder - JCN-5	Powder	Metallurgical	Industrial Applications	Yes	None	Yes	No	No	No	No	Yes	No	Suitable
62		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Carbonyl Nickel Powder - JCN-6	Powder	Metallurgical	Industrial Applications	Yes	None	Yes	No	No	No	No	Yes	No	Suitable
63		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Cobalt-Coated Spherical Nickel Hydroxide	Powder	Batteries		Yes	None	No	No	No	No	Yes	No	No	Suitable
64		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Spherical Beta Hydrooxyl Nickel Oxide	Powder	Batteries		Yes	None	No	No	No	No	Yes	No	No	Suitable
65		Jilin Jien Nickel Industry Co., Ltd	Jien Nickel	Spherical Nickel Hydroxide	Powder	Batteries		Yes	None	No	No	No	No	Yes	No	No	Suitable

Screen shot of Results



	Operations	Refined Capacity (metric tonnes of nickel per year)	Refinery type	Operating Status	Latitude	Longitude	Company	Headquater Countr	Operation Countr	Ownership Type	Exchange	Owner 1	
4	Jinchuan Nickel Operation	200,000	Refinery	Operating	38.50378942	102.2006842	Jinchuan Group	China	China	State	State	Gansu Provincial SASAC	Chin
5	Kola Peninsula	190,000	Refinery	Operating	67.91435593	32.83821	Nornickel	Russia	Russia	Public	MCX	Nornickel	
6	Nickel West - Kwinana Nickel Refinery	82,500	Refinery	Operating	-32.2526455	115.767111	BHP	Australia	Australia	Public	ASX/LSE/JSE	BHP	
7	Nikkelverk	92,000	Refinery	Operating	58.13869343	7.971123082	Glencore	Switzerland	Norway	Public	LSE/JSE	Glencore	
8	Yabulu Nickel Refinery	76,000	Refinery	Care and Maintenance	-19.20475469	146.6123088	Queensland Nickel Sales	Australia	Australia	Private	Private	Queensland Nickel Sales	
9	Copper Cliff Nickel Refinery	66,000	Refinery	Operating	46.44814921	-81.08422875	Vale	Brazil	Canada	Public	BMAD/NYSE/B3	Vale	
10	Nornickel - Harjavalta	66,000	Refinery	Operating	61.31886067	22.11960993	Nornickel	Russia	Finland	Public	MCX	Nornickel	
11	Niihama Nickel Refinery	65,000	Refinery	Operating	33.96452542	133.2654429	Sumitomo Metal Mining	Japan	Japan	Public	TYO	Sumitomo Metal Mining	
12	Long Harbour	50,000	Refinery	Operating	47.4246512	-53.81057708	Vale	Brazil	Canada	Public	BMAD/NYSE/B3	Vale	
13	Korea Nickel Corporation	50,000	Refinery	Uncertainty	35.43153105	129.3392453	Vale	Brazil	South Korea	Public	BMAD/NYSE/B3	Vale	Kore
14	Huayue Nickel and Cobalt	60,000	Intermediate	Operating	-2.851311598	122.179591	Zhejiang Huayou Cobalt	China	Indonesia	Public	SSE	Huayou Cobalt Industry	Tsin
15	Ambatovy	48,000	Refinery	Operating	-18.20064371	49.35575093	Sumitomo	Japan	Madagascar	Public	TYO	Sumitomo Corporation	KOM
16	Goro	44,000	Intermediate	Operating	-22.31390362	166.9043193	Prony Resources	New Caledonia	New Caledonia	State	State	Prony Resouces	Agic
17	Clydach Refinery	40,000	Refinery	Operating	51.69433634	-3.890167901	Vale	Brazil	United Kingdom	Public	BMAD/NYSE/B3	Vale	
18	Murrin Murrin	40,000	Refinery	Operating	-28.76756406	121.8960124	Glencore	Switzerland	Australia	Public	LSE/JSE	Glencore	
19	Fort Saskatchewan	35,000	Refinery	Operating	53.72011985	-113.1906629	Sherritt	Canada	Canada	Public	TSE	Sherritt	Nick
20	Ramu	32,601	Intermediate	Operating	-5.540623017	146.1364651	Metallurgical Corporation of China	China	Papua New Guinea	State	State	Metallurgical Corporation of China	MRF
21	Rustenburg Base Metals Refinery	32,400	Refinery	Operating	-25.68527307	27.32520404	Anglo American	United Kingdom	South Africa	Public	LSE/JSE	Anglo American	Unk
22	Dalian	32,000	Refinery	Care and Maintenance	39.08943387	121.8425133	Vale	Brazil	China	Public	BMAD/NYSE/B3	Vale	Ning
23	Punta Gorda	31,000	Intermediate/Refinery	Operating	20.63865171	-74.88141865	Empresa Niquelifera Ernesto Che Guevara	Cuba	Cuba	State	State	Empresa Niquelifera Ernesto Che Guevara	
24	Matsusaka Refinery	31,000	Refinery	Operating	34.60410726	136.5496457	Vale	Brazil	Japan	Public	BMAD/NYSE/B3	Vale	Sum
25	Terrafame	30,000	Intermediate/Refinery	Operating	63.96717595	28.01478738	Terrafame	Finland	Finland	State	State	Finish Minerals Group	Gale
26	Ravensthorpe Nickel Operation	30,000	Intermediate	Operating	-33.64556169	120.3993369	First Quantum	Canada	Australia	Public	TSE	First Quantum	POS
27	Gordes Meta Nickel Cobalt Facility	20,000	Intermediate	Operating	39.01847705	28.1557176	Meta Nikel Kobalt Mining Industry and Trade	Turkey	Turkey	Private	Private	Zorlu Holdings	
28	Harima Refinery	10,780	Refinery	Operating	34.71822422	134.8491212	Sumitomo Metal Mining	Japan	Japan	Public	TYO	Sumitomo Metal Mining	
29	Kaohsiung	18,000	Refinery	Care and Maintenance	22.65622272	120.2799295	Vale	Brazil	Taiwan	Public	BMAD/NYSE/B3	Vale	Othe
30	Impala Base Metals Refinery	17,000	Refinery	Operating	-26.22233082	28.4419398	Implats Group	South Africa	South Africa	Public	JSE	Implats	
31	Sandouville	16,000	Refinery	Operating	49.47209353	0.284990688	Sibanye Stillwater	South Africa	France	Public	JSE/NYSE	Sibanye Stillwater	
32	Bindura Smelter and Refinery	14,500	Refinery	Care and Maintenance	-17.33386434	31.29399269	Bindura Nickel Corporation	Zimbabwe	Zimbabwe	Public	VFEX	Bindura Nickel Corporation	
33	PT Halmahera Persada Lygend	35,500	Intermediate/Refinery	Operating	-1.539317708	127.4181803	PT Halmahera Persada Lygend	Indonesia	Indonesia	Private	Private	Harita Nickel (through PT Trimegah Bangun Persada)	Lyge
34	Fukang Refinery	13,000	Refinery	Operating	46.75465269	89.67733112	Xinjiang Xinxin Mining Industry	China	China	Public	HKG	Xinjiang Xinxin Mining Industry Co., Ltd.	
35	Skouriotissa	10,000	Intermediate/Refinery	Operating	35.09228121	32.89322414	Hellenic Minerals	Cyprus	Cyprus	Private	Private	Hellenic Minerals	
36	São Miguel Paulista Refinery	10,000	Refinery	Care and Maintenance	-23.48376201	-46.43400395	Jervois	Australia	Brazil	Public	ASX/TSX	Jervois	
37	Marikana Base Metal Refinery	6,698	Refinery	Operating	-25.68467474	27.51666652	Sibanye Stillwater	South Africa	South Africa	Public	JSE/NYSE	Sibanye Stillwater	
38	Empress Nickel Refinery	8,700	Refinery	Care and Maintenance	-18.31586547	29.97382333	RioZim	Zimbabwe	Zimbabwe	Public	ZSE	RioZim	
39	Jien Nickel	8,000	Refinery	Operating	42.91814272	126.4361302	Jilin Jien Nickel Industry	China	China	Private	Private	Zhongze Group	
40	Nicomet Refinery	5,400	Refinery	Care and Maintenance	15.18717791	74.03140513	Vedanta	United Kingdom	India	Public	NSE/BSE	Vedanta	
41	Zondereinde Smelter Complex	2,043	Refinery	Operating	-24.83388784	27.3653479	Northam Platinum	South Africa	South Africa	Public	JSE	Northam Platinum Holding Limited	
42	Boliden - Harjavalta	1,500	Refinery	Operating	61.31628357	22.12369896	Boliden	Sweden	Finland	Public	STO	Boliden	
43	Columbus Metallurgical Complex	1,250	Refinery	Operating	45.63155203	-109.23476	Sibanye Stillwater	South Africa	United States	Public	JSE/NYSE	Sibanye Stillwater	
44	Yantai Cash	500	Refinery	Operating	37.56571482	121.3090942	Yantai Cash	China	China	Private	Private	Yantai Cash Industrial Co. Ltd.	
45	Indian Copper Complex	390	Refinery	Care and Maintenance	22.59513671	86.45146402	Hindustan Copper Limited	India	India	Public	NSE/BSE	Ministry of Mines, Government of India	
46	***Capacity Total***	1,622,762											
47	***Facility Count***	42											

Sections 3.4.2 and 3.4.2.2: Database Terms and Definitions

Part 1

Section	Sub-Section	Field	Options	Definition
Ownership & Development	Operation Name	Name		As reported by primary owner. For facilities by the same name, the name of the primary owner was prefixed to the operation's name.
	Primary Owner	Company		Majority owner of the asset.
	Location	Latitude		Data retrieved from Google Maps. Data reported in Decimal Degrees.
		Longitude		Data retrieved from Google Maps. Data reported in Decimal Degrees.
		Region	North America	Includes Canada, Mexico, USA, and Caribbean countries.
			South America	Includes continental countries south of Mexico.
			Europe (w/out Russia)	Includes continental countries west of Russia, excluded, and Turkey, included.
			Africa	Includes African continental countries.
			Asia (w/ Russia)	Includes Asian continental countries, including Russia and excluding Turkey.
			Oceania	Includes Oceania continental countries.
		Country		Country in which operation is located.
	Ownership	Ownership Type	Private	Owner is a private enterprise, includes publicly traded and private companies.
			State	Primary owner is controlled by a state entity.
			Private and State	Operation is controlled by both state and private enterprises.
		Number of Owners		Total number of enterprises included in joint-venture operations.
	Owner	Owner #n		List of owners, 1 through n.
	Ownership Share	Owner #n		Ownership share of owner n, 1 through n, in %.
	Primary Owner	Headquarter Country		Country which the primary owner is headquartered in.

		Ownership Type	Primary owner ownership structure. Includes, Public, Private, and State.
		Exchange	For public companies, exchanges in which the company is listed.
	Development	Year Construction Started	Year in which construction of the facility first started.
		Year Construction Completed	Year in which construction of the facility completed.
		Year Started Production	Year in which commercial production started.
		Year Reached Max Capacity	Year in which operation reached nameplate capacity. Accounting for changes in nameplate capacity.
		Year of Establishment	Year in which operation was established, as defined in thesis.
	Operating Status	2021 Status	Operating status in calendar year 2021. Includes, Operating, Care and Maintenance, and Uncertainty.

Part 2

Section	Sub-Section	Field	Options	Definition
Operation Overview	Primary Nickel			Yes or No response. Based on reported statements of facility owner. For operations in which nickel and copper are co-produced, the facility was considered as primary nickel.
	Operation Overview	Operation Type	Smelter	An operation which the majority of produced products are equivalent to an intermediate product requiring additional refining.
			Refinery	An operation which the majority of produced nickel products are suitable for downstream applications.
			Integrated	An operation which transforms upstream feedstocks directly into nickel products suitable for downstream applications.
			Mine Integrated	An integrated operation which adjacent to the upstream feedstock source.
		Refinery Type	Refinery	Operation produces nickel products suitable for downstream applications.
			Intermediate	Operation produces nickel products requiring additional midstream transformation prior to being suitable for downstream applications.

		Intermediate/ Refinery	Operation produces nickel products that are both refined and intermediate.
	Process Type		List of key processing technologies employed by the operation.
Material Recovery	Metals Recovered	Nickel	Operation produces a nickel product, either intermediate or refined product.
		Cobalt	Operation produces a cobalt product, either intermediate or refined product.
		Copper	Operation produces a copper product, either intermediate or refined product.
		Gold	Operation produces a gold product, either intermediate or refined product.
		PGEs	Operation produces a PGE product, either intermediate or refined product.
		Chromium	Operation produces a chromium product, either intermediate or refined product.
		Zinc	Operation produces a zinc product, either intermediate or refined product.
	Other Materials Recovered		List of other products produced by the operation.
Operation Analysis	Operation Process Category	Pyrometallurgical	Utilizes pyrometallurgical technologies to transform feedstocks.
		Hydrometallurgical	Utilizes hydrometallurgical technologies to transform feedstocks.
		Vapor Metallurgical	Utilizes vapour metallurgical technologies to transform feedstocks.
		Bio Metallurgical	Utilizes biometallurgical technologies to transform feedstocks.
		Unknown	Unknown processing technology employed.
	Smelting Operations Included	Yes	Smelting operation included as part of the operation. Applicable to value chains which upstream feedstock is smelted using pyrometallurgical process to produce an intermediate product.
		No	Smelting operation not included as part of the operation.

	N/A	Not applicable. Operation which do not employ smelting.
	Unknown	Unknown in smelting operations are utilized.
Process		Generalized process employed.
Auxiliar Refining Process #n		Major unit operations employed by the operation, 1 through 5.
Metallurgical Technology		Includes one, or a combination of operation process category's utilized to transform upstream feedstock throughout the value chain.
HPAL Processing Technology		Operation employs high-pressure acid leach unit operation.

Part 3

Section	Sub-Section	Field	Options	Definition
Nickel	Nickel Products	Product #n		Nickel products produced at the operation. Based on advertised products. Products 1 through n, where n is the total number of nickel products produced at the facility.
	LME Nickel Approved Brand			Operation includes a minimum of one product listed as an approved LME brand.
	Quality	Nickel Product #n		Nickel content in product as reported. Typically, in weight percentage. Products 1 through n, relative to Product #n.
	Capacity	Nickel Product #n		Production capacity of nickel Product #n. Unless unit reported, data is in tonnes per annum.
	2019 Product Production	Nickel Product #n		2019 production of nickel Product #n. Unless unit reported, data is in tonnes per annum.
	Reported Nickel Capacity			Reported total annual nickel production capacity.

	Historical Production	Year	Historical annual nickel production from 2021 to 2000, includes all products.
	Historical Production Units	Year	Units which historical annual nickel production figures are reported.
	Recovery Rates		Operation's nickel recovery rate, as percentage.

Part 4

Section	Sub-Section	Field	Options	Definition
Cobalt	Cobalt By-Product			Operation produces cobalt products. Includes Refined, intermediate, intermediate/refined products, and none.
	Cobalt Products	Product #n		Cobalt products produced at the operation. Based on advertised products. Products 1 through n, where n is the total number of cobalt products produced at the facility.
	Cobalt Product Quality	Cobalt Product #n		Cobalt content in product as reported. Typically, in weight percentage. Products 1 through n, relative to Product #n.
	Cobalt Product Capacity	Cobalt Product #n		Production capacity of cobalt Product #n. Unless unit reported, data is in tonnes per annum.
	Reported Cobalt Capacity			Reported total annual cobalt production capacity.
	2019 Product Production	Cobalt Product #n		2019 production of cobalt Product #n. Unless unit reported, data is in tonnes per annum.
	Historical Production	Year		Historical annual cobalt production from 2021 to 2000, includes all products.
	Historical Production Units	Year		Units which historical annual nickel production figures are reported.

	Recovery Rates			Operation's cobalt recovery rate, as percentage.

Part 5

Section	Sub-Section	Field	Options	Definition
Other Product	Other Products	Product #n		Other products produced at the operation. Based on advertised products. Products 1 through n, where n is the total number of other products produced at the facility.
	Other Product Quality	Product #n		Quality of other products as reported. Typically, in weight percentage. Products 1 through n, relative to Product #n.
	Other Product Capacity	Product #n		Production capacity of other product's related to Product #n. Unless unit reported, data is in tonnes per annum.
	Other Product 2019 Production	Product #n		2019 production of other product Product #n. Unless unit reported, data is in tonnes per annum.
	Copper Co-Production			Operation produces copper products. Includes Refined, intermediate, intermediate/refined products, and none.
	Reported Copper Capacity			Reported total annual copper production capacity.
	Historical Copper Production	Year		Historical annual copper production from 2021 to 2000, includes all products.
	Historical Copper Production Units	Year		Units which historical annual nickel production figures are reported.
	Other Product Recovery Rates	Product #n		Operation's recovery rate for other products, as percentage. Listed for each product.

Part 6

Section	Sub-Section	Field	Options	Definition
Source	Feed Source Location	Source #n		Origin of feedstock material. When possible associated with upstream operations. Source 1 through n.
	Feed Source Type	Source #n		Descriptive term of feedstock. When possible, based on mineral type. Relative to source n.
	Ore Type			Based on processed ore type. Includes, sulphide, laterite, sulphide and laterite, black-shale and unknown.
	Third-Party			Reported to utilize feedstock from third-party sources. Includes tolling.
	Integration			Based on midstream value chain. See Thesis for explanation.

Integration Type		Includes name of preceding midstream operations or for integrated facilities, mine. Undefined values chains listed as unknown.
Source Volume	Source #n	Volume of feedstock material procured from given source. Relative to source n.
Source Nickel Content	Source #n	Content of nickel in feedstock material. Unless unit reported, data is in weight percent. Relative to source n.
Source Cobalt Content	Source #n	Content of cobalt in feedstock material. Unless unit reported, data is in weight percent. Relative to source n.
Source Sulphur Content	Source #n	Content of sulphur in feedstock material. Unless unit reported, data is in weight percent. Relative to source n.
Source Iron Content	Source #n	Content of iron in feedstock material. Unless unit reported, data is in weight percent. Relative to source n.
Other Elements		List of other elements contained in feedstock material. Unless unit reported, data is in weight percent. Relative to source n.

Part 7

Section	Sub-Section	Field	Options	Definition
Environmental Data	Net Zero	Commitment		Relative to primary owner for year 2021. Explicit statement of carbon neutrality required. Yes or No.
		Date		Stated year which net zero carbon is intended to be realized.
		Site Specific or Company Wide Targets		Site specific implies that other operations controlled by primary owner will be carbon neutral. Companywide includes all operations.
	2019 Carbon Emissions	2019 Scope 1 Emissions		Reported Scope 1 GHG emissions. According to reported units.
		2020 Scope 2 Emissions		Reported Scope 2 GHG emissions. According to reported units.
		2021 Scope 3 Emissions		Reported Scope 3 GHG emissions. According to reported units.
		Site Specific or Company Wide Emissions		Site specific emissions includes Scope 1,2,3 emissions specific to the site. Companywide emissions includes all operations.
	Water	2019 Water Consumption		Water consumption. Specified units and scope.
	Energy	2019 Energy Consumption		Energy consumption. Specified units and scope.
		2019 Renewable Energy Mix		Share of energy derived from renewable energy. Specified units and scope.
	Battery Recycling		Yes	Operation actively recycles batteries.

			No	Operation does not recycle batteries.
			Development	Operation is developing battery recycling capabilities.

Part 8

Section	Sub-Section	Field	Options	Definition
Investment	Investment Plans	Expansion Plans		Description of reported expansion plans in terms of capacity and materials.
		Capital Investment		Capital cost of investment. Specified currency.
		Capital Investment Year		Year which capital for expansion was committed.
	Capacity and Material Expansion Plans	Expansion Plans		Yes or no response to proposed expansion plans in 2021.
		Expected New Capacity		New nameplate capacity for operations with planned capacity expansions.
		Material Expansion Plans		New material offering for operations with material expansion plans.
		Material Type		Description of planned new material offering.

Nickel Product Database

Field	Definition	Notes
Company	Primary owner of operation for which product is produced.	In line with Operation Database
Operation	Name of Operation for which product is produced.	In line with Operation Database
Product	Commercial name of produced product.	In line with Operation Database
Form Factor	Form factor of produced product.	Crystals are considered powders.
Primary Application	Primary advertised application of product according to producer.	
Secondary Application	Second advertised application of product according to producer.	
Application - Battery	Battery advertised application, including and beyond primary and secondary applications.	Yes or No.

Product Standard	Listed product standard.	
Data Sheet	Elemental composition provided.	Yes or No or SDS. Includes composition listed on SDS.
Carbon Footprint	Listed carbon footprint of product.	
Mixed Precipitate Product	Product is a mixed precipitate.	Includes, MHP, MSP. Yes or No.
Nickel Sulphate	Product is nickel sulphate.	Yes or No.
Chemical	Product is non-metallic.	Yes or No.
Carbonyl	Product is produced using carbonyl process.	Yes or No.
LME	Product is listed as approved LME brand, or either meets LME grade, or LME standard.	
Battery Potential	Includes products with advertised battery applications, nickel sulphate products, LME suitable products, and mixed precipitates.	Suitable, Potential, or None
Product Class	Based on reported nickel content.	>=99.8wt% Ni; Class 1, otherwise, Class 2
Elemental Composition	Based on reported elemental composition from data sheets or listed elements.	Data in wt%

Appendix C

Supplementary Results

Section 4.2.4: Year of Max Capacity by Reporting Operations

Operation	Annual Capacity	Year of Max Capacity	Production in Year of Max Capacity	Excess Capacity (Surplus Capacity)	Excess Capacity %
Ramu	32,601	2020	33,659	-1,058	103%
Murrin Murrin	40,000	2020	40,800	-800	102%
Nikkelverk	92,000	2019	91,500	500	99%
SMM - Harima, Niihama	75,780	2019	75,322	458	99%
Nornickel - Harjavalta	66,000	2020	63,352	2,648	96%
Terrafame	30,000	2020	28,740	1,260	96%
Fort Saskatchewan	35,000	2019	33,108	1,892	95%
Impala Base Metals Refinery	17,000	2019	16,000	1,000	94%
Fukang Refinery	13,000	2021	12,103	897	93%
Kola Peninsula	190,000	2020	172,357	17,643	91%
Nickel West - Kwinana Nickel Refinery	79,000	2019	73,600	5,400	93%
Vale - Clydach, CCNR, Long Harbour, Matsusaka	187,000	2021	147,640	39,360	79%

Zondereinde Smelter Complex	2,043	2019	1,563	480	77%
Rustenburg Base Metals Refinery	32,400	2019	23,000	9,400	71%
Ambatovy	48,000	2019	33,736	14,264	70%
Ravensthorpe Nickel Operation	30,000	2021	16,818	13,182	56%
Sandouville	16,000	2021	8,900	7,100	56%
Punta Gorda	31,000	2020	14,800	16,200	48%
Goro	44,000	2021	20,605	23,395	47%

Section 4.2.4: Combined Operation's Reporting Production

Vale	**2021**	**2020**	**2019**
Sudbury Mine	32,180	43,300	50,800
Thompson Mine	5,880	10,600	11,300
Voisey's Bay	38,130	35,700	35,400
Sorowako	65,400	71,600	68,200
New Caledonia	0	31,000	23,400
External	6,050	6,600	7,300
Total Refined Production from Mines	147,640	198,800	196,400
Clydach Refinery	40,000	40,000	40,000
Goro	0	50,000	50,000
Dalian	0	0	32,000
Matsusaka Refinery	31,000	31,000	31,000
Copper Cliff Nickel Refinery	66,000	66,000	66,000
Long Harbour	50,000	50,000	50,000
Total Annual Refining Capacity	187,000	237,000	269,000
% of Refined Capacity	79%	84%	73%
Analysis Values Reflect 2021 due to changes in ownership in Goro			
Excess Capacity (2021)	39,360		

BHP

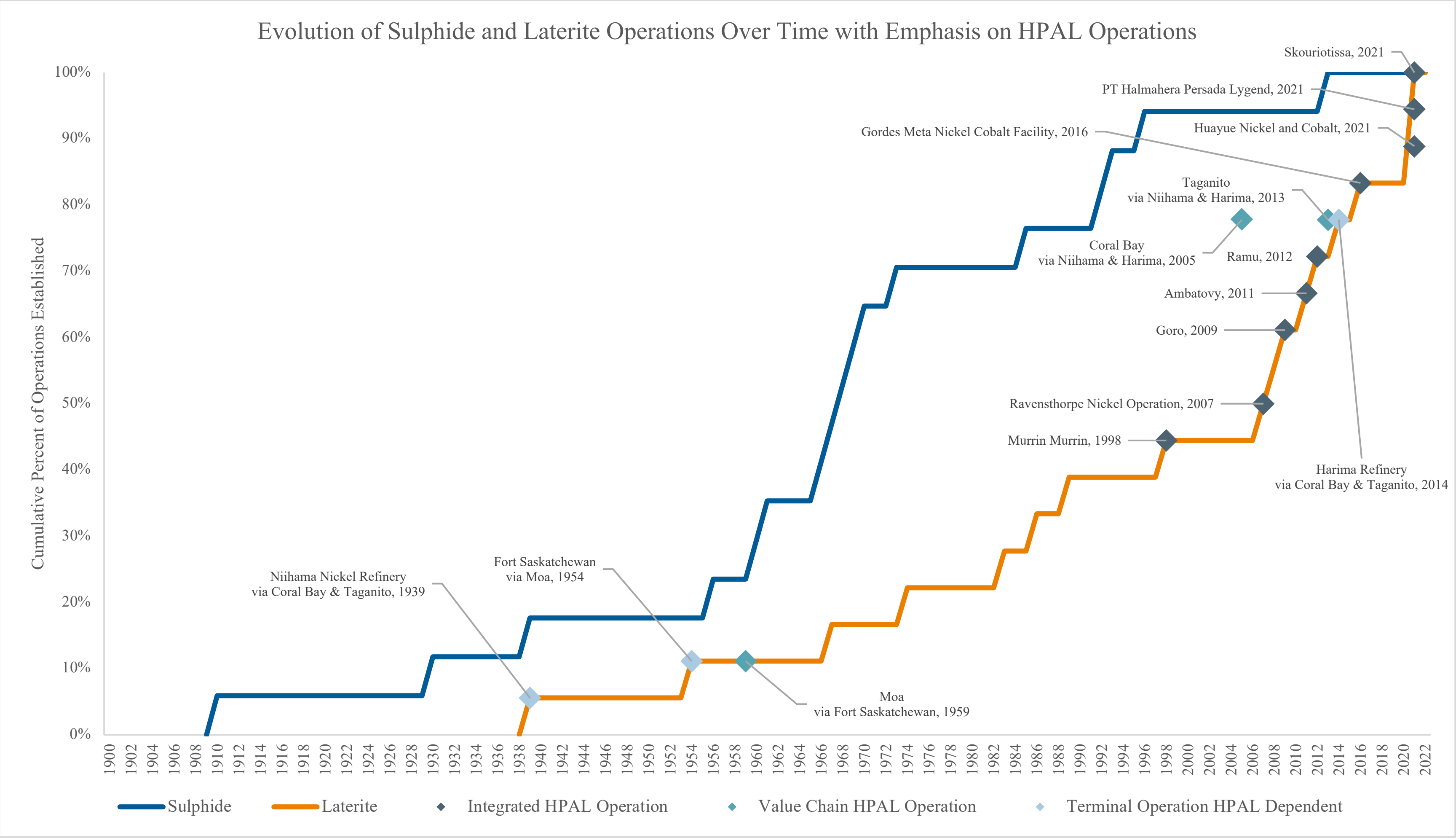
Nickel West - Kwinana Nickel Refinery	**2021**	**2020**	**2019**
Refined Product	70,000	65,600	73,600
Intermediate	19,000	14,500	13,800
Nickel Sulfate	0	0	0
Refined Production	70,000	65,600	73,600
Total Annual Refining Capacity	82,500	82,500	79,000
% of Refined Capacity	85%	80%	93%
Only refined products considered due to output from refinery			
Max Year	2019		
Excess Capacity	5,400		

SMM	**2021**	**2020**	**2019**
Niihama Electrolytic	52,500	55,900	58,800
Harima + Niihama NiSO4 (tonnes of contained nickel)	17,182	17,402	16,522
Total Refined Production (tonnes of contained nickel)	69,682	73,302	75,322
Harima Refinery	10,780	10,780	10,780
Niihama Nickel Refinery	65,000	65,000	65,000
Total Combined Capacity (tonnes of contained nickel)	75,780	75,780	75,780
% of Refined Capacity	92%	97%	99%
Max Year	2019		
Excess Capacity	458		

Section 4.2.4: HPAL Operations based on third party feeds

Operation	Capacity	Year of Establishment	Ore Type	Third-Party Feed Stock	Integration	Battery Potential	Product Class	LME	HPAL
Niihama Nickel Refinery	65,000	1939	L	TP	1,1,1	Partial	Class 1 and Class 2	Partially LME Approved	HPAL Dependent
Huayue Nickel and Cobalt	60,000	2021	L	None	0	Full	Class 2	N/A	HPAL
Ambatovy	48,000	2011	L	None	0	Full	Class 1	Fully LME Approved	HPAL
Goro	44,000	2009	L	None	0	Full	Class 2	N/A	HPAL
Murrin Murrin	40,000	1998	L	TP	0	Partial	Class 1	Partially LME Approved	HPAL
Fort Saskatchewan	35,000	1954	L	TP	1	Partial	Class 1 and Class 2	Partially LME Approved	HPAL Dependent
Ramu	32,601	2012	L	None	0	Potential	Class 2	N/A	HPAL
Ravensthorpe Nickel Operation	30,000	2007	L	None	0	Full	Class 2	N/A	HPAL
Gordes Meta Nickel Cobalt Facility	20,000	2016	L	None	0	Full	Class 2	N/A	HPAL
Harima Refinery	10,780	2014	L	None	1,1	Full	Class 2	N/A	HPAL Dependent
PT Halmahera Persada Lygend	35,500	2021	L	None	0	Partial	Class 2	N/A	HPAL
Skouriotissa	10,000	2021	L	None	0	Partial	Class 2	N/A	HPAL

Section 4.2.4: Evolution of Sulphide and Laterite Operations Over time with Emphasis on HPAL Operations



Section 5.4.4: Junior North American Mining Companies and Midstream Intention as of August 2022 - **Part 1**

Property Name	Operator Owners	Country	Province/Territory	Latitude	Longitude
Dumont	Waterton Global Resource Management	Canada	Quebec	48.64667	-78.4425
Nickel Shaw	Nickel Creek Platinum Corp.	Canada	Yukon	61.46667	-139.53333
Thierry	Braveheart Resources Inc.	Canada	Ontario	51.49667	-90.34694
Onaping Depth	Glencore Canada Corporation	Canada	Ontario	46.632019	-81.383878
Minago	Flying Nickel	Canada	Manitoba	54.1092	-99.21912
Lynn Lake	Corazon Mining Limited	Canada	Manitoba	56.85217	-101.03486
Turnagain	Giga Metals Corporation	Canada	British Columbia	58.47856	-128.86282
Ferguson Lake	Canadian North Resources Inc.	Canada	Nunavut	62.87306	-96.83306
River Valley	New Age Metals Inc.	Canada	Ontario	46.70591	-80.27606
Shakespeare	Magna Mining Inc.	Canada	Ontario	46.33417	-81.85944
Junior Lake	Landore Resources Limited	Canada	Ontario	50.38169	-87.94799
Kenbridge	Tartisan Nickel Corp.	Canada	Ontario	49.48357	-93.6347
Makwa Mayville	Grid Metals Corp.	Canada	Manitoba	50.6298	-95.60953
Hidden Bay	UEX Corporation	Canada	Saskatchewan	58.15333	-103.73639
Eagle’s Nest	Wyloo Metals	Canada	Ontario	52.74202	-86.3038
Decar	FPX Nickel Corp.	Canada	British Columbia	54.894513	-125.359691
Victoria	KGHM Polska Miedź S.A.	Canada	Ontario	46.41667	-81.38333
Crawford	Canada Nickel Company Inc.	Canada	Ontario	48.83972	-81.37309
Battery Material Park	Electra Battery Materials	Canada	Ontario	47.50380609	-79.69653646

Tamarack	Talon Metals/Rio Tinto	United States	Minnesota	46.64429459	-93.12736774
Mesaba	Teck	United States	Minnesota	47.63732392	-91.89937818
NorthMet	PolyMet Mining	United States	Minnesota	47.58787004	-92.14961218

Part 2

Property Name	Commodities	Product	Operation	Development Stage
Dumont	Ni, Co, Pt, Pd, Fe	Concentrate	Mine	Advanced project
Nickel Shaw	Ni, Cu, Pt, Pd, Au, Co	Concentrate	Mine	Advanced project
Thierry	Cu, Ni, Ag, Au, Pt, Pd	Concentrate	Mine	Advanced project
Onaping Depth	Ni, Cu, Co, Pt, Pd, Rh, Au, Ag	Existing Process	Mine	Advanced project
Minago	Ni, Cu, Co, Pd, Au, Pt, Ag, Rh, Other	Concentrate	Mine	Advanced project
Lynn Lake	Ni, Cu, Co, Pb, Ag, Au	Concentrate	Mine	Advanced project
Turnagain	Ni, Co, Cu, Pt, Pd, Au	Concentrate	Mine	Advanced project
Ferguson Lake	Ni, Cu, Pd, Pt, Co, Other	Refined product	Mine, Processing	Advanced project
River Valley	Pd, Pt, Au, Ni, Cu, Rh, Co	Concentrate	Mine	Advanced project
Shakespeare	Ni, Cu, Pd, Pt, Au, Co	Concentrate	Mine	Advanced project
Junior Lake	Ni, Cu, Co, Pt, Pd, Au, Fe, Rh, Other	Concentrate	Mine	Advanced project
Kenbridge	Ni, Cu, Co, Ag, Au, Pt	Unknown	Mine	Advanced project
Makwa Mayville	Ni, Cu, Au, Pt, Pd, Co	Concentrate	Mine	Advanced project
Hidden Bay	U, Co, Ni	Unknown	Mine	Advanced project
Eagle’s Nest	Ni, Cu, Au, Pt, Pd, Ag	Concentrate	Mine	Advanced project

Decar	Ni, Fe, Cr	Nickel-Iron Alloy Concentrate	Mine	Advanced project
Victoria	Ni, Cu, Au, Ag, Co, Pt, Pd	Concentrate	Mine	Advanced project
Crawford	Ni, Fe, Co, Pd, Pt, Au	Concentrate	Mine	Advanced project
Battery Material Park	Co, Cu, Ni, Li, C	Nickel Sulfate	Processing	Advanced project
Tamarack	Ni, Cu, Co, Pt, Pd, Au	Concentrate, Refined?	Mine, Processing?	Advanced project
Mesaba	Ni, Cu, Co, Pt, Pd	Concentrate	Mine	Advanced project
NorthMet	Cu, Ni, Co, Pd, Pt	Concentrate	Mine	Advanced project

Part 3

Property Name	Carbon Goals	Sequestration	Notes	Website
Dumont	Low carbon	Yes		www.dumontnickel.com
Nickel Shaw	Limited	Yes		http://www.nickelcreekplatinum.com
Thierry	None	No		https://braveheartresources.com/
Onaping Depth	Carbon Neutral Operations	No		https://www.glencore.ca
Minago	Low carbon	No		https://www.flynickel.com
Lynn Lake	None	No		https://corazon.com.au
Turnagain	Low carbon	Yes	2.2t/co2	https://www.gigametals.com
Ferguson Lake	None	No	Hydrometallurgical	https://www.cnresources.com
River Valley	None	No		https://newagemetals.com
Shakespeare	Carbon Neutral Operations	No		https://magnamining.com
Junior Lake	None	No		https://www.landore.com

Kenbridge	None	No		http://www.tartisannickel.com
Makwa Mayville	None	No		https://gridmetalscorp.com
Hidden Bay	None	No		https://www.uex-corporation.com
Eagle’s Nest	Net Zero	Yes		https://www.wyloometals.com
Decar	None	No		https://fpxnickel.com
Victoria	2050 Carbon Neutral	No		https://kghm.com
Crawford	Zero-Carbon Footprint	Yes	2.8t/co2	https://canadanickel.com
Battery Material Park	Low carbon	No	Hydrometallurgical	https://electrabmc.com
Tamarack	Low carbon	Yes	Partnership with Tesla	https://talonmetals.com/
Mesaba	Carbon Neutral Goal	No		https://www.teck.com
NorthMet	None	No	Partnership with Teck; tailings	https://polymetmining.com

Section 5.4.4: Products Carbon Footprint

Part 1

Operation	Product	Form Factor	Primary Application	Advertised Battery Application	Nickel Content	Carbon Footprint
Kola Peninsula	DNK-0 Carbonyl Nickel Pellets	Pellets	Plating	No	Class 1	11.65
Kola Peninsula	Severonickel Combine H1Y	Cathode	Steel	No	Class 1	9.59
Kola Peninsula	Severonickel Combine H1Y trimmed	Cathode Cut	Steel	No	Class 1	9.59
Kola Peninsula	Severonickel Combine H1	Cathode	Steel	No	Class 1	9.59
Kola Peninsula	Severonickel Combine H1 Trimmed	Cathode Cut	Steel	No	Class 1	9.59
Kola Peninsula	Nornickel	Cathode	Steel	No	Class 1	9.59
Kola Peninsula	H-2 Cathodes	Cathode	Steel	No	Class 1	9.59
Kola Peninsula	H-3 Bales	Cathode	Steel	No	Class 1	9.59
Kola Peninsula	H-4 Cathodes	Cathode	Steel	No	Class 1	9.59
Kola Peninsula	Severonickel Combine H1Y Cut Cathode	Cathode Cut	Steel	No	Class 1	9.59
Kola Peninsula	Severonickel Combine H1 Cut Cathode	Cathode Cut	Steel	No	Class 1	9.59
Kola Peninsula	Electrolytic Nickel H-2 Edge Cuts	Cathode Cut	Steel	No	Class 1	9.59
Kola Peninsula	Carbonyl Nickel Powder - UT1	Powder	Industrial Applications	No	Class 1	11.65
Kola Peninsula	Carbonyl Nickel Powder - UT2	Powder	Industrial Applications	No	Class 1	11.65
Kola Peninsula	Carbonyl Nickel Powder - UT3	Powder	Industrial Applications	No	Class 1	11.65
Kola Peninsula	Carbonyl Nickel Powder - UT3-PM	Powder	Industrial Applications	No	Class 1	11.65
Kola Peninsula	Carbonyl Nickel Powder - UT3-ICG (ICGL)	Powder	Industrial Applications	No	Class 1	11.65
Kola Peninsula	Carbonyl Nickel Powder - UT4	Powder	Industrial Applications	No	Class 1	11.65
Kola Peninsula	Carbonyl Nickel Powder - L5	Powder	Industrial Applications	Yes	Class 1	11.65
Kola Peninsula	Carbonyl Nickel Powder - L6	Powder	Industrial Applications	Yes	Class 1	11.65
Kola Peninsula	Carbonyl Nickel Powder - L7	Powder	Industrial Applications	Yes	Class 1	11.65

Kola Peninsula	Carbonyl Nickel Powder - L8	Powder	Industrial Applications	Yes	Class 1	11.65

Part 2

Operation	Product	Form Factor	Primary Application	Advertised Battery Application	Nickel Content	Carbon Footprint
Nornickel - Harjavalta	Full Plate Cathodes	Cathode	Steel	No	Class 1	8.95
Nornickel - Harjavalta	Nickel Briquettes	Briquettes	Steel	No	Class 1	10.29
Nornickel - Harjavalta	Nickel Sulphate STD	Powder	Plating	No	Class 2	10.55
Nornickel - Harjavalta	Nickel Hydroxycarbonate Powder	Powder	Plating	No	Class 2	15.96
Nornickel - Harjavalta	Nickel Hydrometallurgical Powder	Powder	Industrial Applications	Yes	Class 2	10.23
Nornickel - Harjavalta	Cut Cathodes	Cathode Cut	Steel	No	Class 1	8.95
Nornickel - Harjavalta	Electrolytic Nickel Edge Strips	Cathode Cut	Plating	No	Class 1	8.95
Nornickel - Harjavalta	Electrolytic Nickel Edge Cuts	Cathode Cut	Plating	No	Class 1	8.95
Nornickel - Harjavalta	Nickel Sulphate EN	Powder	Plating	No	Class 2	10.55
Nornickel - Harjavalta	Nickel Hydroxycarbonate Granules	Granule	Plating	No	Class 2	15.96
Nornickel - Harjavalta	Nickel Hydroxycarbonate Paste	Paste	Plating	No	Class 2	15.96

Part 3

Operation	Product	Form Factor	Primary Application	Advertised Battery Application	Nickel Content	Carbon Footprint
Copper Cliff Nickel Refinery	Nickel Pellets (Canada)	Pellets	Steel	No	Class 1	7.3
Copper Cliff Nickel Refinery	Nickel Discs (Canada)	Disc	Steel	No	Class 1	7.3
Copper Cliff Nickel Refinery	Nickel P-Pellets (CDN)	Pellets	Plating	No	Class 1	7.3
Copper Cliff Nickel Refinery	Nickel Plating Chips (CDN)	Disc	Plating	No	Class 1	7.3

Copper Cliff Nickel Refinery	Chemical Grade Nickel Powder (CDN)	Powder	Plating	Yes	Class 1	7.3

Part 4

Operation	Product	Form Factor	Primary Application	Advertised Battery Application	Nickel Content	Carbon Footprint
Long Harbour	Long Harbour Nickel Melt Rounds	Rounds	Steel	No	Class 1	4.4
Long Harbour	Long Harbour Nickel Assorted Melt Rounds	Rounds	Steel	No	Class 1	4.4
Long Harbour	Plating Rounds	Rounds	Plating	No	Class 1	4.4

Part 5

Operation	Product	Form Factor	Primary Application	Advertised Battery Application	Nickel Content	Carbon Footprint
Clydach Refinery	Nickel Pellets (UK)	Pellets	Steel	No	Class 1	33.1
Clydach Refinery	Nickel Discs	Disc	Steel	No	Class 1	33.1
Clydach Refinery	Nickel S-Pellets	Pellets	Plating	No	Class 1	33.1
Clydach Refinery	Nickel P-Pellets	Pellets	Plating	No	Class 1	33.1
Clydach Refinery	Nickel Plating Chips	Disc	Plating	No	Class 1	33.1
Clydach Refinery	Chemical Grade Nickel Powder (UK Standard Grade)	Powder	Plating	Yes	Class 1	33.1
Clydach Refinery	Chemical Grade Nickel Powder (UK Battery Grade)	Powder	Batteries	Yes	Class 1	33.1
Clydach Refinery	T123 Nickel Powder	Powder	Metallurgical	No	Class 1	33.1
Clydach Refinery	T255 Nickel Powder	Powder	Batteries	Yes	Class 2	33.1

Section 4.3.3 Table 5-1 Accompanying Notes

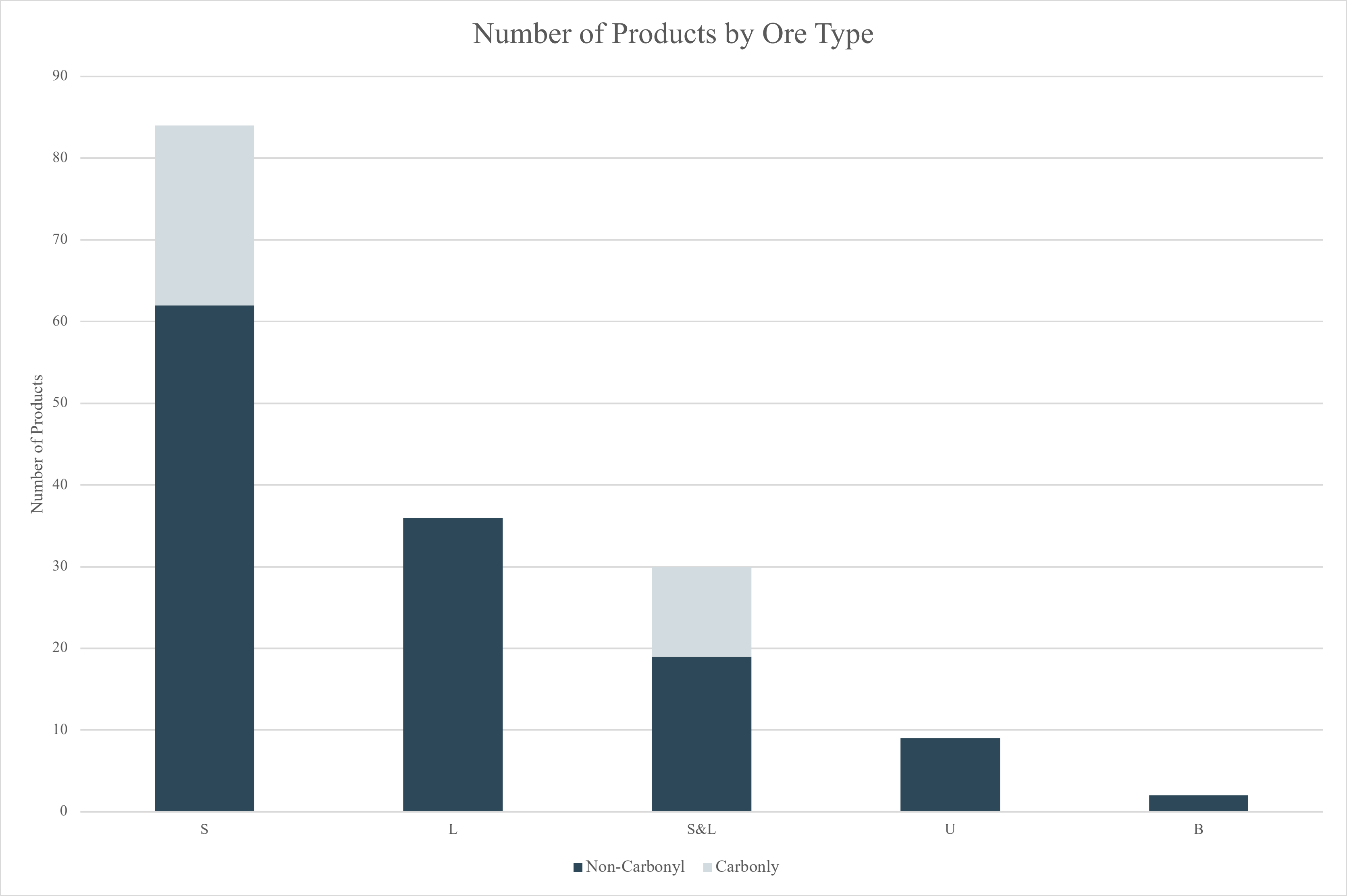
Operation	Notes
Ravensthorpe Nickel Operation	Limited construction began in May 2004. Started production in May 2008. Operation were suspended in January 2009.
Dalian	Originally commissioned by Inco. Construction start in second half of 2006. Began operation in April 2008.
Goro	Significant delays in construction. Originally planned to start up in 2007.
Ambatovy	Exploration began in 1960. Feasibility studies started in 1994 and finished in 1997, Final permits granted in 2006 and 2007.
Ramu	Deposit discovered in 1962. Feasibility Studies started in late 1990's, technical and economic due diligence started in 2003, commissioning started in 2010.
Harima Refinery	Originally built in 1966, stable operations in 2014, 2015 achieved 25kt NiSO4 capacity, second nickel sulphate line launched in 2016.
Gordes Meta Nickel Cobalt Facility	Equipment procurement started in 2011.
Huayue Nickel and Cobalt	Construction completed in 18 months.
PT Halmahera Persada Lygend	Originally target production in 2019.
Skouriotissa	Started construction in 2019 and first production in 2021.
Long Harbour	Laboratory testing and processing took place between 1997-2002. Mini-pilot plant 2003-2004. Demonstration plant 2005-2008. Construction started in April 2009. Construction Completed in second half of 2013. First production July 2014.
Terrafame	First discovered in 1977, construction of bioleaching started in 2007, bioleaching started in July 2008 with first sulphide production by October 2008. Operation was acquired again in 2015. Production restarted in 2017. Permit for battery chemical plant granted in 2021.
Yantai Cash	No information on history.

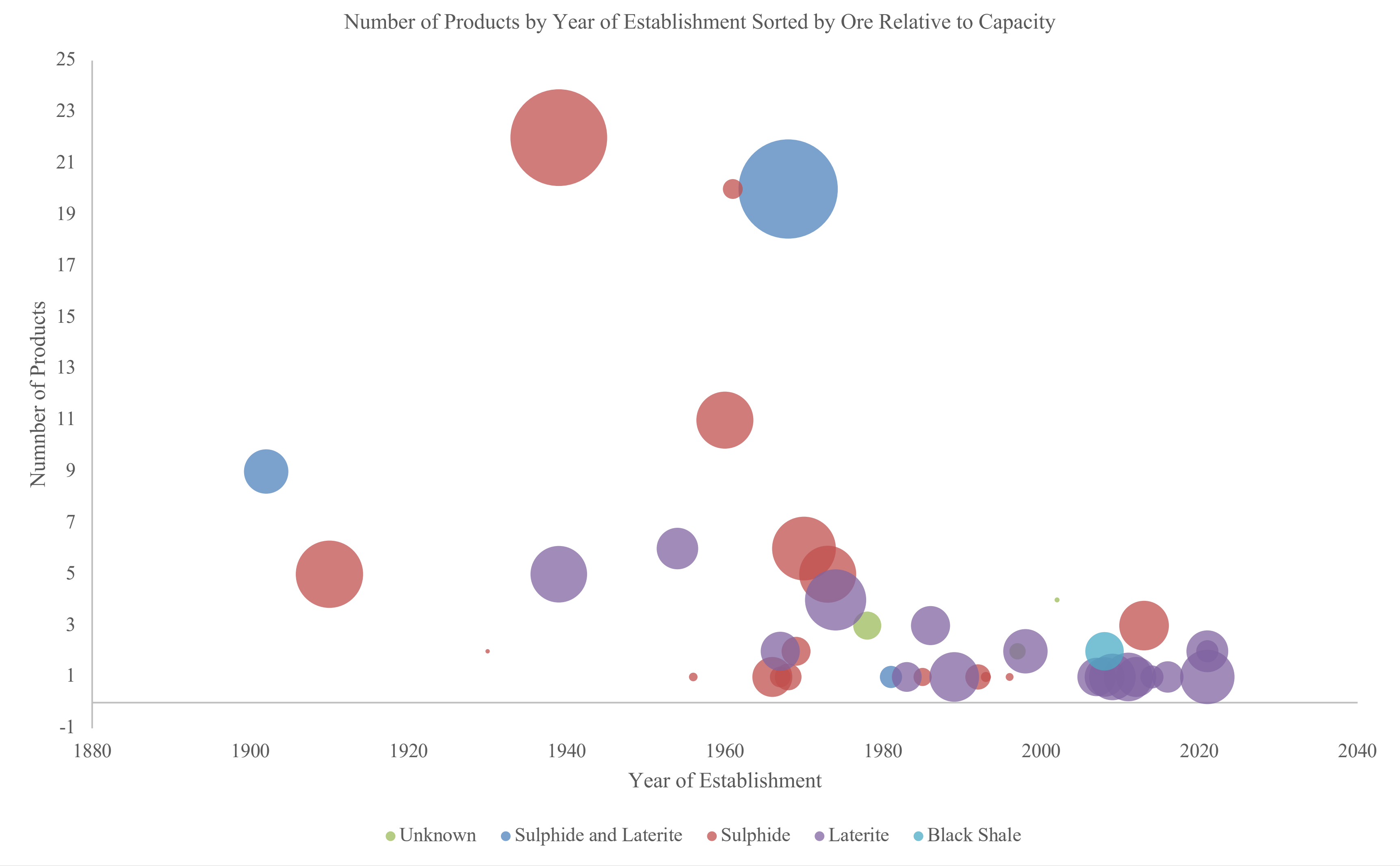
Section 4.3.3: LME Approved Brands by Ore Type

Country/ Region	Brand	Producer	Notes	Operation	Owner	Capacity *(metric tonnes)*	Number of Products Produced	Ore Type	Third-Party
Australia	BHP NICKEL BRIQUETTES	BHP Nickel West Pty Ltd	WARRANTABLE	Nickel West – Kwinana Nickel Refinery	BHP	82,500	6	S	TP
Australia	MINARA HIGH GRADE NICKEL BRIQUETTES	Minara Resources Pty Ltd	WARRANTABLE	Murrin Murrin	Glencore	40,000	2	L	TP
Canada	SHERRITT NICKEL BRIQUETTES	The Cobalt Refinery Company Inc	WARRANTABLE	Fort Saskatchewan	Sherritt	35,000	6	L	TP
Canada	VALE MELT ROUNDS	Vale Canada Limited	WARRANTABLE	Long Harbour	Vale	50,000	3	S	None
Canada	VALE NICKEL PELLETS	Vale Canada Limited	WARRANTABLE	Copper Cliff Nickel Refinery	Vale	66,000	5	S	TP
Canada	VALE PLATING ROUNDS	Vale Canada Limited	WARRANTABLE	Long Harbour	Vale	50,000	3	S	None
China	CASH	Yantai Cash Industrial Co., Ltd.	WARRANTABLE	Yantai Cash	Yantai Cash	500	4	U	U
China	JINTUO GRADE 1	Jinchuan Group Co., Ltd.	WARRANTABLE	Jinchuan Nickel Operation	Jinchuan Group	200,000	20	S&L	TP
Finland	NORILSK NICKEL HARJAVALTA CATHODES	Norilsk Nickel Harjavalta Oy	WARRANTABLE	Nornickel - Harjavalta	Nornickel	66,000	11	S	TP
Finland	NORILSK NICKEL HARJAVALTA BRIQUETTES	Norilsk Nickel Harjavalta Oy	WARRANTABLE	Nornickel - Harjavalta	Nornickel	66,000	11	S	TP
France	NICKEL HP	Sibanye-Stillwater Sandouville Refinery	WARRANTABLE	Sandouville	Sibanye Stillwater	16,000	3	U	U
Japan	SUMITOMO METAL MINING CO. LTD	Sumitomo Metal Mining Co., Ltd.	WARRANTABLE	Niihama Nickel Refinery	Sumitomo Metal Mining	65,000	5	L	TP
Japan	SMM	Sumitomo Metal Mining Co., Ltd.	WARRANTABLE	Niihama Nickel Refinery	Sumitomo Metal Mining	65,000	5	L	TP
Madagascar	AMBATOVY NICKEL BRIQUETTES	Dynatec Madagascar S.A. a "société anonyme"	WARRANTABLE	Ambatovy	Sumitomo	48,000	1	L	None

Norway	NIKKELVERK NICKEL	Glencore Nikkelverk AS	WARRANTABLE	Nikkelverk	Glencore	92,000	5	S	TP
Russia	NORNICKEL	JSC "Kola GMK"	WARRANTABLE	Kola Peninsula	Nornickel	190,000	22	S	TP
Russia	SEVERONICKEL COMBINE H-1	JSC "Kola GMK"	WARRANTABLE	Kola Peninsula	Nornickel	190,000	22	S	TP
Russia	SEVERONICKEL COMBINE H-1Y	JSC "Kola GMK"	WARRANTABLE	Kola Peninsula	Nornickel	190,000	22	S	TP
South Africa	IMPALA NICKEL	Impala Platinum Ltd	WARRANTABLE	Impala Base Metals Refinery	Implats Group	17,000	2	S	TP
South Africa	RPM NICKEL	Rustenburg Platinum Mines Limited	WARRANTABLE	Rustenburg Base Metals Refinery	Anglo American	32,400	1	S	TP
UK	VALE NICKEL PELLETS	Vale Canada Limited produced by Vale Europe Limited	WARRANTABLE	Clydach Refinery	Vale	40,000	9	S&L	TP
Brazil	TOCANTINS	Votorantim Metais S.A.	NO NEW WARRANTS CAN BE ISSUED, Under C&M	São Miguel Paulista Refinery	Jervois	10,000	1	S&L	TP
Zimbabwe	BCL EMPRESS	RioZim Limited	NO NEW WARRANTS CAN BE ISSUED, Under C&M	Empress Nickel Refinery	RioZim	8,700	1	S	TP
Total				18 *Unique Operations*	14 *Unique Owners*	1,059,100	107		
						65% *of Metallurgical Capacity*			

Extra Figures




Number of Products by Year of Establishment Sorted by Ore Relative to Capacity
Nummber of Products
25
23
21
19
17
15
13
11
9
7
5
3
1
-1
1880
1900
1920
1940
1960
1980
2000
2020
2040
Year of Establishment
● Unknown
● Sulphide and Laterite
● Sulphide
● Laterite
● Black Shale