Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Marceau Cormery

Global trade-linked nickel cycle

A Material Flow Analysis (MFA) study considering production and trade of nickel at the global and the country level

Master's thesis in Industrial Ecology
Supervisor: Daniel Müller (NTNU)
Co-supervisor: Romain Billy (NTNU), Mark Mistry (Nickel Institute),
Barbara Reck (Yale University)
June 2022

NTNU
Norwegian University of
Science and Technology

Marceau Cormery

Global trade-linked nickel cycle

A Material Flow Analysis (MFA) study considering production and trade of nickel at the global and the country level

Master's thesis in Industrial Ecology
Supervisor: Daniel Müller (NTNU)
Co-supervisor: Romain Billy (NTNU), Mark Mistry (Nickel Institute),
Barbara Reck (Yale University)
June 2022

Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Norwegian University of
Science and Technology

Preface

This master's thesis work, carried out and written in the spring semester of 2022, concludes my two years Master of Science in Industrial Ecology at the Norwegian University of Science and Technology (NTNU) in Trondheim. This work builds on a semester project carried out in the fall semester of 2021.

I would like to express my heartfelt thanks to my supervisor, Dr Daniel B. Müller, who, with his enthusiastic teaching, gave me an interest in Material Flow Analysis from my first semester at NTNU, offered me the opportunity to work on this topic, and trusted my capacities and judgements. I would also like to thank my NTNU co-supervisor Romain Billy for his time and regular help this year. His feedbacks were always insightful, and he, more than once, helped me keep my feet on the ground and focus on the important things. I would like to thank my external co-supervisors Dr Mark Mistry from the Nickel Institute and Dr Barbara Reck from Yale University, for their previous work on the topic, their insights, and the access to data they provided me with and without which I could not have developed my model as much as I wanted.

After spending the last five months in the IndEcol study room, it would not be fair to forget giving my classmates a warm thank you for the good moments spent there and my congratulations for their work, with a special mention to Anna Eide Lunde and Brent McNeil, my MFA partners in crime, as well as my good friends Nils Dittrich, Maxime Malbranque and Samuel Voorwalt. Moreover, I would like to thank my family, particularly my parents, Séverine and Fabrice, and my brothers and sister, Lou, Hugo and Tom, who, even remotely, never failed to give me moral support and remind me of what really matters. Finally, I am particularly grateful to my girlfriend, Tila van der Sluis who, just as always, expressed genuine interest in what I was working on and helped me go the extra mile.

Trondheim, June 2022

M Cormery

Marceau Cormery

Abstract

Nickel (Ni) is a popular alloying element for stainless steel (70% of the use today). Driven by urbanization in emerging economies, its demand will keep increasing. In addition, Ni is a key element in the production of lithium-ion batteries (5% of the use today but the fastest-growing application), necessary to the electrification of the vehicle fleet. This rapid increase in Ni demand, with new geographical markets and competition for feedstocks in a context of more stringent socio-environmental regulations, could drive a burden shift of adverse impacts to less regulated locations, increase geopolitical supply risks and international tensions, but could also incentivize the use of scrap in more recently developed countries. Advising decision-makers and industrial stakeholders best on these topics requires a systemic approach, such as Material Flow Analysis. Because Ni crosses national borders many times in its lifecycle, the trade flows of the Ni cycle are an essential aspect of systemic thinking and motivate the development of a global trade-linked model. The system was analyzed at the global level, illustrating the two main supply routes, sulphide and laterite, which yield class I metal (high purity) and ferronickel/nickel pig iron (low grade). The dominance of the laterite route was emphasized. The country-level analysis revealed that a few countries dominate the total imports and exports of Ni around the world. The production and trade of laterite ore are dominated by Indonesia, the Philippines and New Caledonia, which do not retain high value-added from the operations as ores are mainly processed elsewhere in East Asia (Japan, Korea, China). The production and export of class I metal are dominated by Australia, Canada and Russia. They have plants to produce class I metal and they retain more value-added. Overall, the analysis demonstrated that none could claim itself independent among the major countries mobilizing Ni. Some countries are predominant exporters due to massive resources or important infrastructures, but they are dependent on market fluctuations. China and the EU28 are the most dependent since they combine significant Ni consumption and low domestic mining resources. Recent events such as the Indonesian export ban on Ni ore and the Russian invasion of Ukraine show that geopolitical supply risks could impact them the most. Finally, the limitations of the work were emphasized, and the study calls for better modelling of the scrap generation at the country level, increased attention on trade double-counting issues, and refining the HS code for lithium-ion batteries. Hopefully, this guidance can reduce the gaps between production and trade, strengthen the results and better support the studies on specific commodities (e.g. batteries), recycling opportunities or local socio-environmental impacts at the country level.

Table of contents

List of figures

List of tables

1. Introduction

1.1. Context

1.1.1. Stainless steel, the historical driver of the anthropogenic nickel cycle

Nickel (Ni) is a metal widely used in the industry and present in many objects encountered daily. Mixed with other elements, nickel offers many beneficial properties, including the enhancement of strength, toughness, corrosion resistance, malleability and ductility (Nickel Institute 2021a). These attractive properties made it a popular alloying element for many applications, such as stainless steel, which accounts for around 70% of the 2.4 million tons of nickel produced in 2019 (Roskill 2019).

Nickel is found in two types of mine deposits worldwide: sulphides and laterites. Historically, sulphide deposits represented most of nickel mine production due to their location in politically stable countries where the important consumption markets were and because the ore can be concentrated before processing, resulting in lower energy costs than for laterites (Kerfoot 2000). Over the last two decades, however, the trend has evolved. Since 2005, China has played a significant role in the accelerated growth of the stainless steel sector, driven by the demand for more industrial machinery, buildings, vehicles and other metal goods (Backeberg, Bedder, and Sardain 2021). This has driven up the traditional production of class I metal (a high-purity form of nickel, over 99,8% Ni) made from sulphide ores smelting. However, because stainless steel production does not necessarily require high Ni content in its feedstock, Chinese development has reshaped the nickel industry by incentivizing the rapid expansion of nickel pig iron (NPI) production, a low-grade form of ferronickel (FeNi) obtained from laterite ores, and which has today overcome the sulphide route in volume.

By capturing the most significant amounts of nickel produced annually, the stainless steel sector in China is today one of the main driving forces of the nickel industry. However, experts forecast that China’s economy should follow the patterns of developed countries and see its overall steel production peak as its economic activity shifts towards more services. Even if the production of alloy steel (including stainless) will most likely keep growing in China, this could create opportunities for growth in countries in economic development with large demographics like India, Indonesia, Vietnam, Turkey, Iran or Brazil (Backeberg et al. 2021). This could, to a certain extent, redistribute the cards of the industry of alloy steels and, with it, the magnitude and final destination of important nickel flows.

1.1.2. The role of nickel in the mitigation of emissions in the transport sector

If it is clear that the stainless steel sector will keep playing a pivotal role in the future evolutions of the nickel industry, it is important to understand that major changes could also come from the massive deployment of one of its more recent applications, batteries.

With 15% of global greenhouse gas (GHG) emissions in 2019, the transport sector has a crucial role in mitigating climate change (Shukla et al. 2022). Road transportation is responsible for three quarters of these emissions, and substantial mitigation could come from the electrification of the vehicle fleet, today mostly running on fossil fuels (Lamb et al. 2021; Talantsev 2017). However, electric vehicles (EVs) are no silver bullet. With the soar of EV sales, the production of lithium-ion batteries (LIBs) used to store the electricity that powers them increases sharply. In turn, this amplifies the mobilization of mineral raw materials. Among NMC batteries (Lithium Nickel Manganese Cobalt Oxide), a shift is observed towards more nickel inclusion, with NMC532, NMC622 and NMC811 (where each digit refers to the ratio of the element) getting more popular. The reasons behind this trend are:

- Since 60% of cobalt originates from the politically unstable Democratic Republic of Congo, which is notoriously known for child labor, there is a willingness to phase out cobalt from chemistries (Azevedo et al. 2018; Helbig et al. 2018; Olivetti et al. 2017);
- Nickel has the advantage of storing a lot of energy in a small mass (high energy density) and being able to deliver it quickly (high power delivery), generally at a lower cost than other alternative materials (Armand et al. 2020; Ding et al. 2019);
- Nickel benefits from a more stable industry with more experience and is spread over multiple countries with solid participation from OECD countries (Santillán-Saldivar et al. 2021)

Today, batteries only weigh about 5% of nickel production but are also the fastest-growing application (Roskill 2019). In the many applications where nickel is used its substitution by other materials is challenging (Cusano et al. 2017). Essentially, it means that the growing demand for LIBs will compete with the other traditional uses of nickel, especially stainless steel. In particular, LIBs require a high-purity chemical form of nickel, called nickel sulphate, which can technically be made from many feedstocks, including battery scrap, class I metal, leaching intermediates, and sulphidized FeNi or NPI. In practice, FeNi and NPI are not commercially used today, and there is a possibility that these products will not be tolerated by the environmental regulations framing the battery and EV industries in the future. For this reason, previous work on the topic has shown that bottlenecks in the battery supply chain could arise because the nickel production route that could develop the fastest to meet the rapid increase in demand, NPI smelting, is also the one that produces the highest GHG emissions (Young 2021). Anticipating these policy developments, EV makers collaborate very actively with government officials and companies to strike deals and secure sufficient feedstocks of nickel with satisfactory sustainable requirements (BBC 2022; Teslarati 2022). However, even if the EV battery industry may not directly drive up environmental impacts in the nickel value chain, the low availability of battery scrap and the slow pace at which the capacity of producing class I metal can ramp up, combined with a high demand of nickel for batteries, could indirectly encourage even further the development of NPI smelting for use in stainless steel production instead of class I metal (Roskill 2021). Therefore, the burden-shifting of GHG emissions towards the stainless steel industry is a strong concern (Young 2021). This demonstrates that the development of the battery industry could impact the current nickel cycle significantly, even beyond the production of battery-grade feedstocks.

1.2. The relevance of mapping the nickel cycle and its trade flows

The previous subsection has shown some fundamental changes that will impact the nickel industry, namely a rapid increase in the material demand for both traditional and new industrial sectors, with new geographical markets and possible competition for feedstocks in a context of more stringent socio-environmental regulations. These drivers and their interactions affect society in many ways, and their analysis requires a systemic approach. Therefore, a thorough understanding of how nickel is being produced, used, and its fate at the end-of-life, in other words, a mapping of the global nickel cycle is needed to advise decision-makers and industrial stakeholders best.

Because nickel crosses national borders many times from its mining to its end-of-life management, the trade flows of the nickel cycle are an essential aspect of systemic thinking on this topic. Human intervention through industrialization and trade has radically changed the map of nickel (Sen and Peucker-Ehrenbrink 2012). It redistributed resources geographically in a manner previously unseen, contributing -or not- to local development and affecting power relationships between states and regions. As a consequence, like most strategic metals, nickel is not exempt from geopolitical supply risks. Two recent examples can be mentioned to illustrate this:

- In 2020, Indonesia, the first supplier of nickel ore in the world, implemented a ban on exports of nickel ore with the inner motivation of capturing more value-added, securing supplies for its stainless steel industry and attracting the investors of the battery industry (Pandyaswargo et al. 2021). The export ban led the European Union (EU) to file a complaint to the World Trade Organization (WTO) to denounce illegal actions that were impeding the development of the European steel industry (Foster 2022; Gupta 2022). Such market intervention is risky as it disrupts the global nickel cycle and could cause trade conflicts.
- In 2022, the instability and the high prices caused by the Russian invasion of Ukraine led the London Metal Exchange (LME) to suspend nickel trading for a week (Jolly 2022). Russian resources and refining capacity for high-purity nickel are crucial for the battery industry and the transition to cleaner energy production (Erickson 2022; Stone 2022; Sullivan 2022). This could explain why the dependent Western economies currently impose no import ban on Russian metals (Holzmann 2022; Hyatt 2022). However, the situation could evolve and make shipments more difficult in the future.

These examples of geopolitical sensitivity and supply insecurities show that precise knowledge of the magnitude of nickel flows through their trade between countries must be developed to support decision-making in downstream sectors. In particular, a trade-linked model can help quantify the reliance on imports or the exporting power of individual countries.

Moreover, the expected development in environmental policies towards a more efficient and sustainable primary production is more generally accompanied by an increased focus on reuse and recycling (UNEP and Reuter 2013). In this context, countries are trying to better monitor inefficiencies in the material supply chain and reduce energy use, resource depletion, and waste in processing(UNFCCC 2017). In addition, with time, as more metal will become available at the end-of-life, the opportunities and the incentives to recycle will multiply, especially as governments define targets regarding the inclusion of scrap in new products and the recovery rates in waste products (Peiró et al. 2018). This motivates more transparency and monitoring in the supply chain, including identifying the location of the waste streams and the local availability of scrap for use as a secondary source of nickel. Because the final destination of nickel is likely different from where it originated, these reflections can be supported by a trade-linked model with resolution at the country level.

Finally, trade and country-level analysis can be instrumental in understanding where socio-environmental impacts occur. Indeed, although mining and smelting activities are often encouraged by local governments, particularly in the Global South, they are often accountable for the endangerment of hotspots of biodiversity via land degradation, inadequate tailings management, and construction of facilities (Jaffré, Munzinger, and Lowry 2010; Moran, Petersone, and Verones 2016), acids spills (Lefort and Burton 2014), the release of heavy metals to surrounding water bodies (Gunkel-Grillon et al. 2014), or the emissions of toxic pollutants such as sulfur dioxide (Mudd 2010). From a social perspective, these operations are also associated with impacts on human health, human rights infringements, disrespect of indigenous territories and cultures, and impacts on local agriculture and tourism (Firdaus and Levitt 2022; Sawal 2022). These socio-environmental impacts have local consequences and thus encourage further the development of a model quantifying the nickel cycle at the country level.

1.3. Overview of existent literature on the topic and research gap

1.3.1. Knowledge of the nickel value chain

Nickel metallurgy is complex due to its many processing routes. Reference work on the topic describes the main operations to refine nickel, including mining, pyro- and hydro-metallurgical treatments, with clear chapters including flowcharts and estimates of the efficiencies for each operation based on real facilities (Crundwell et al. 2011). Kerfoot (2000) provides additional information on the chemical reactions, material inputs, waste flows, and by-products. Despite their publishing dates, both works remain relevant as most plants chosen for illustration are still running. However, they do not cover the industry's most recent developments, namely NPI smelting and nickel sulphate production. A report of the Joint Research Centre also covers nickel with similar information for the EU, with guidance to reduce emissions in the production (Cusano et al. 2017). The scope of these sources is limited to the supply of refined nickel, and they do not cover further use in stainless steel or other applications.

Technological steps in the nickel value chain are well covered in the literature. Still, it is argued that a systemic view is necessary to understand better nickel flows around the world and along its value chain. The Material Flow Analysis (MFA) methodology can help establish a framework of analysis where nickel flows are not considered in isolation, where resources are limited and must be balanced from one process to another, and which would cover the entire lifecycle. MFA is especially relevant to support the discussion of competition between uses (e.g. batteries, stainless steel) based on the feedstocks available to produce them and emphasizes that the optimization of a single process is not equivalent to an optimized system.

1.3.2. Mapping and quantification of nickel flows at the global or country level.

MFA has been used in a few studies over the last fifteen years to study nickel. Reck et al. (2008) have quantified the global nickel cycle and 52 country-level cycles for the year 2000, using production and trade data to quantify flows between processes aggregated to mining, smelting, refining, fabrication, manufacturing and waste management. Another work used a simplified MFA system of nickel mining, production of intermediates and refining to high purity metal to discuss the key locations and flows that were becoming relevant for the growing LIB industry (Schmidt, Buchert, and Schebek 2016). The trade flows of nickel in products were calculated by Nakajima et al. (2018), but the study was not specific to nickel, and no system definition was given. Trade data was used but aggregated based on the total nickel content in products, which prevents a precise analysis depending on the step of the value chain or the type of product concerned by the transaction. As a battery raw material, nickel was also studied in a static MFA project commissioned by the EU called Material System Analysis, with an assessment of the import dependencies of the region at each step of the value chain from 2012 to 2020 (Ciacci et al. 2022; Matos et al. 2020). Finally, a previous master thesis at NTNU was dedicated to the anthropogenic flows of nickel. With a dynamic MFA model, the author assessed the factors that could hinder the development of the LIBs (Young 2021).

With MFA, the cited studies have taken a holistic view to map nickel flows and analyze related concerns. Methodological details of their work show that there are trade-offs between the resolution of the processes they define for the system and the geographical resolution. Only a few of these studies considered trade data analysis to understand better the locations of the different processes and the power relationships between the regions involved. As seen in a previous subsection, the analysis of trade flows has high relevance for understanding the nickel cycle. Therefore a trade-linked MFA model could help incorporate trade analysis in a high resolution and systemic study of material flows.

1.3.3. The use of trade statistics and trade-linked models

Building a global nickel trade-linked MFA model requires understanding how trade reporting works. Trade statistics are reported yearly to the United Nations International Trade Statistics Database (UN Comtrade). In theory, every country reports its trade of commodities according to their classification in the Harmonized System (HS), both in value (USD) and in net weight (kg). The latter makes it particularly interesting for trade-linked MFA models as it is not influenced by price fluctuations (UNCTAD 2012). In practice, Comtrade statistics are known for their mismatch problem between the values reported by a country A trading with a country B and the "mirror statistics" reported by B for the same trade flow. The UN Statistics department explains these issues by missing values, different definitions both for the monetary value and the partner attribution between imports and exports, different times of reporting, confidential data, human errors, or falsified data, but do not deal with them (UN Statistics n.d.-a, n.d.-b). Only two independent projects (not MFA) have tried to reconcile unbalanced trade data. A pioneering study on the topic was the Global Trade Analysis Project (GTAP), which developed an index of reliability for each country based on the frequency of accurate transactions (i.e. when the value that country A reports is "close" to that reported by B) (Gehlhar 1996). Only monetary trade values were considered, however. The research institute in international economics CEPII also developed a new database called BACI, which relies on Comtrade data and applies a complex algorithm to reconcile mirror statistics both in monetary value and in mass (Gaulier and Zignago 2010). However, the methodology relies on heavy mathematical modelling and is opaque. In addition, the algorithm deals with data in bulk. Therefore, it could neglect important issues specific to the nickel industry.

A recent study of EU cobalt flows, which are intertwined with nickel, by *Godoy Léon et al.* has displayed significant gaps between reporting sources. They warn that since MFA finds its specificity in the respect of the mass balance conservation, these discrepancies have to be dealt with by studies introducing global trade-linked models and that researchers should be transparent about the high uncertainties related to trade flows (Godoy León, Blengini, and Dewulf 2021). Despite this, among the few trade-linked MFA models in the literature, the treatment of raw trade statistics is barely discussed, as shown by work done on lithium (Sun et al. 2017) and phosphorus (Lun et al. 2021), which do not mention data treatment or quality, or a study of cobalt (Sun et al. 2019), which arbitrarily chooses export values over import values. An analysis of the global trade-linked aluminium cycle used the average of the export and the import values but added outlier detection steps in the algorithm (Liu and Müller 2013). Among the MFA studies on nickel previously cited, Reck et al. (2008) treat raw data with the assumption that imports are more reliable than export values since this is where taxation occurs and Nakajima et al. (2018) used the BACI database without further discussing its limitations.

From a methodological standpoint, trade-linked MFA models on various metals have generally not been combined with other approaches to deal with trade data coherently and reasonably. The discussion of its limitations has often been overlooked or examined superficially. Among the MFA studies reviewed, only the work by Reck et al. (2008) looked at the nickel cycle from ore to waste while considering trade for many countries across all continents. However, it had trade-offs regarding the aggregation of the system processes. Moreover, the study calculates flows in the year 2000. This is becoming obsolete today as the industry has profoundly changed with a shift in the preferred ore type at the global level, the sharp increase in NPI production, and the growing demand for nickel for use in LIB production.

As a result, a gap is observed in the current literature that this master thesis tries to bridge. The study, therefore, focuses on the definition and quantification of a global trade-linked nickel cycle that could (1) update the work referred to previously, (2) increase the resolution of the model, especially regarding different production technologies and end-uses, (3) contribute to increased knowledge on the treatment of trade statistics within MFA models, and (4) support the discussions related to geopolitical issues and competition in the nickel value chain.

1.4. Research questions

The thesis will address the knowledge gap by answering the following research questions:

1) How is the anthropogenic Ni cycle organized, and how are the different Ni-containing commodities traded between individual countries?
2) What is the magnitude of the flows of Ni contained in products and commodities, which are transformed and traded by individual countries in the global Ni cycle?
3) At which stages of the anthropogenic Ni cycle are individual countries contributing the most to the production and the global exports? At which stage are they most reliant on imports?
4) What are the limitations of building a tracking system for the nickel cycle based on trade data, and how to address them? What are the critical points for automatizing the data collection and processing in the future?

2. Methodology

Material Flow Analysis (MFA) is the main approach used to answer the research questions of this work. MFA aims to quantify the resource stocks and flows of a system, which is delimited in space and time (Brunner and Rechberger 2016). In this methodological framework, transformations (e.g. ore extraction, smelting) and other operations (e.g. storage, shipments) are modelled by *processes*. These processes are connected in a network by *material flows*, which can eventually accumulate in some location, therefore leading to the formation of a *stock*. The principle that differentiates MFA from other methodologies is material balance. Respecting the law of the conservation of matter, the "*mass balance principle*" ensures that the difference between all inputs and outputs linked to a process equals the stock variation.

MFA studies are generally organized around the following steps:

- Defining a system to model reality, with a description of the processes, flows, potential stocks, and the choice of system boundaries. These descriptions explain the main assumptions made to simplify the complex relations of the real-world network.
- Collecting data and making sound estimates for the parameters of the system.
- Quantifying the system while respecting the mass balance principle and displaying them in a diagram.
- Analyzing uncertainties associated with the results.
- Interpreting the results and making the limitations of the work transparent.

2.1. System definition

The nickel cycle was analyzed and modelled using two different perspectives:

- A *global system* that gives a snapshot of the flows of nickel on the planet as a whole, without regard to the location of the processes. The usefulness of quantifying such a system is to understand each technological route's weight in a global context. With this perspective, only production is considered, and trade is excluded.
- A *global trade-linked system,* which is a combination of *country-level systems* connected by trade flows via trading markets. With this framework, material flows were analyzed based on their sources and destinations in both the geographical and the technological world.

According to the mass balance principle, at the global level, the sum of all the imports for a given category of commodities must be equal to the sum of all the exports. In addition, the flows at the global level are equal to the sum of all the domestic flows in the country-level systems. The approach is illustrated in Figure 1.

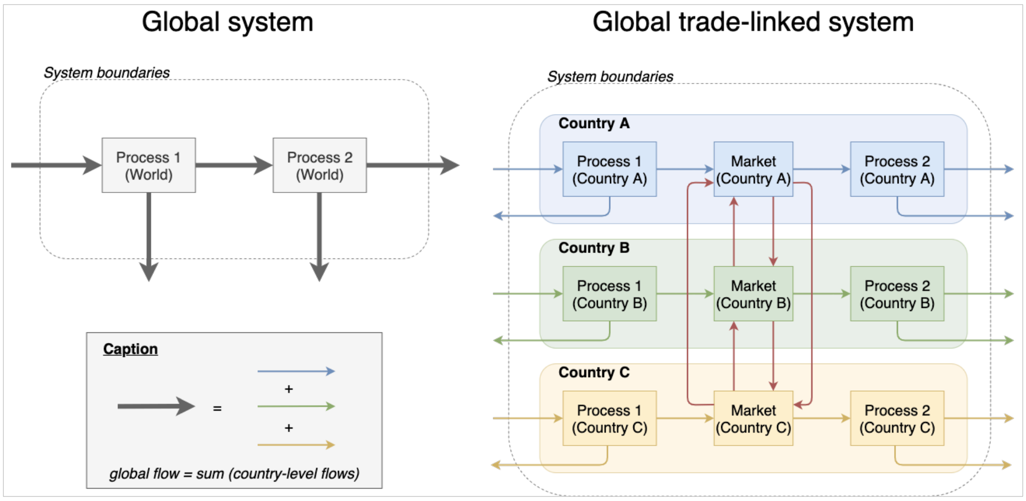


Figure 1 - Illustration of the systems defined for the study (trade flows are represented in red)

In this work, every country-level system is organized like the global system in terms of domestic production routes and processes, except that products are exchanged via trade markets and flows between countries, and thus in and out of the country-level system. Therefore, for a question of simplicity, only a generic country-level system is defined in the following. The system models the nickel value chain from its extraction as ore, to its end-of-life handling, through a complex network of flows and processes. For clarity, a simplified system definition is first shown in Figure 2.

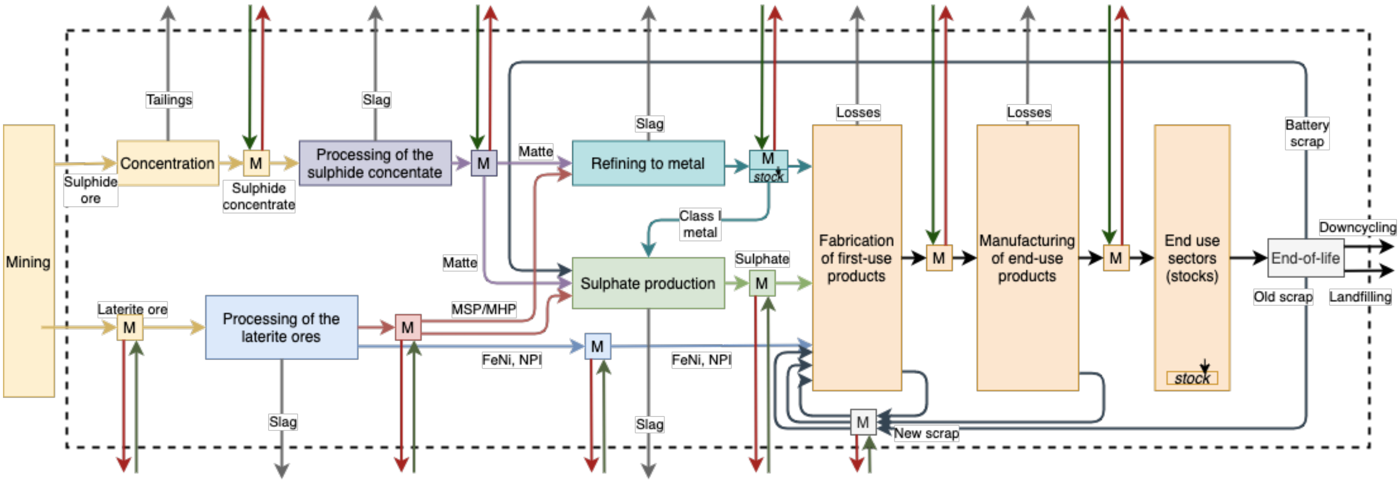


Figure 2 - Simplified MFA system of the global nickel cycle (trade markets are symbolized by an "M", imports are represented with green arrows, and exports are represented with red arrows)

It can be read from left to right, starting with the ore extraction in the mines. Two types of ores exist, sulphides and laterites, and the former can be concentrated after mining. Both ore types are processed into various intermediate products. In the majority, these are matte for sulphide concentrate and mixed sulphides or hydroxides precipitates (MSP/MHP), ferronickel (FeNi) and nickel pig iron (NPI) for the laterite ores. In turn, some of these intermediate products can be refined to a higher purity form of nickel named class I metal (> 99,8% Ni), to chemicals, such as nickel sulphate, or used directly in the fabrication of first-use products. First-use products are, for example, stainless steel and batteries. They are used to manufacture end-use products such as automotives or buildings. Along the way, some of the scrap generated (called “new scrap”) is recycled within the fabrication of first-use sectors. The end-use products accumulate in the society stock (referred to as end-use sectors stocks) before being eventually discarded. Three options are possible at the end-of-life: functional recycling in the fabrication of first-use products, downcycling in carbon steel and landfilling. At all steps of the cycle, Ni-containing products can be traded in and out of the country.

In this study, stocks were considered at two levels. Firstly, there is a physical stock of nickel in various warehouses around the world that are affiliated with the London Metal Exchange (LME) or the Shanghai Future Exchange (SHFE). Among others, these entities regulate the trade of class I Ni metal, which is why a stock is added to the class I market. Secondly, stock variations are considered in the society’s in-use stocks such as automotives or industrial machinery (end-use sector stocks). Some government strategic stocks exist in the USA, Japan, the Russian Federation and possibly other countries. Still, they were not considered as they are either negligible (for the USA) or the quantity is unknown. According to the International Nickel Study Group (INSG), in the last fifteen years, the variation of producers’ stocks represents under 0.2% of the annual production of nickel (< 5 kt) (INSG 2020b), and producers’ stocks were therefore disregarded in this study.

The generic country-level system is displayed in Figure 3 in its highest resolution. In Table 1, the correspondence between the processes of the two figures is established, and the process descriptions and modelling assumptions are presented.

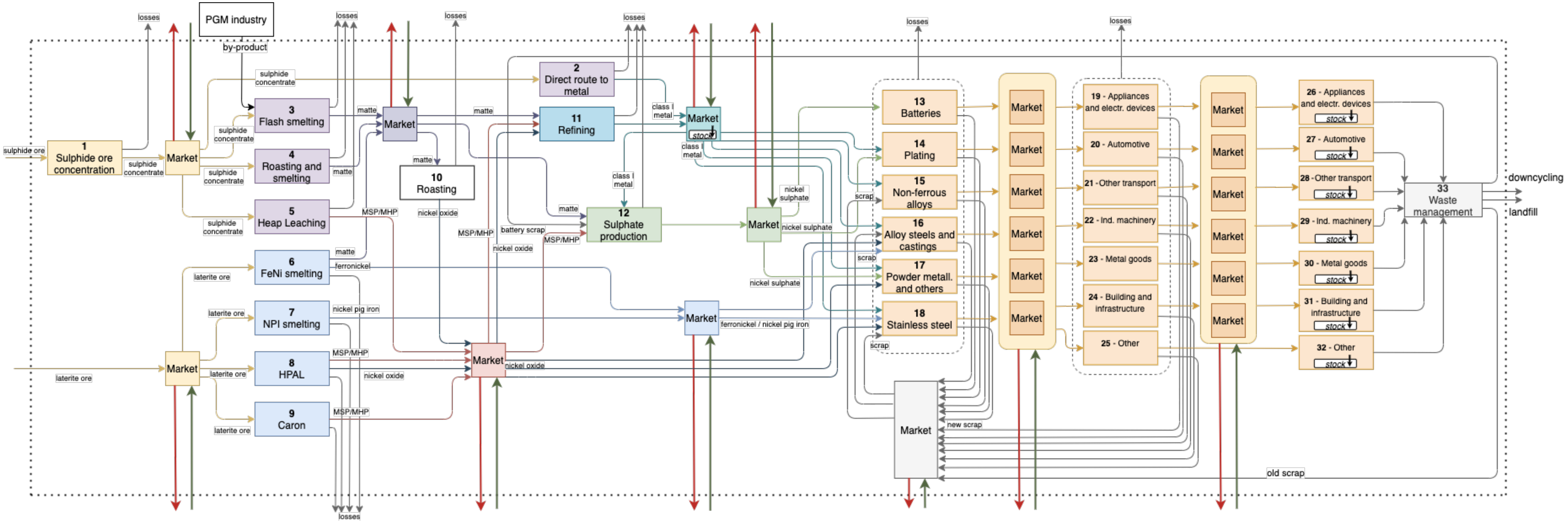


Figure 3 – Detailed country-level model of the nickel value chain (red arrows are export; green arrows are import)

Table 1 - Correspondence between the processes of Figure 2 and Figure 3, description and modelling assumptions

Simplified system	Global system	Description and modelling assumptions
Mining	*Not included*	Nickel is mined in deposits of sulphide and laterite ores (Crundwell et al. 2011; Cusano et al. 2017; Mudd and Jowitt 2022). Geological deposits are hard to represent with the MFA nomenclature. The concepts of reserves and resources used by geologists are dynamic quantities that depend on whether the extraction is economically viable and change with market prices and technological progress (Wellmer 2008). The extraction of ores from the ground is also set outside the system boundaries. The main consequence is that nickel contained in tailings, which may be significant, is not considered.
Concentration	1 – Sulphide ore concentration	Unlike laterite ores, sulphide ores can be concentrated. In this process, the metal content is increased by physical treatment (e.g. grinding, crushing) and separation from undesired rock matter by using magnetic or hydrophobic properties (Ozberk and Marcuson 1986).
Processing of the sulphide concentrate	2 – Direct route to metal	Sulphide concentrate can be treated by direct hydrometallurgical refining to produce class I metal. In 2019, only Vale's Long Harbour facility in Canada used such a process (INSG 2020a).
	3 – Flash smelting, and 4 – Roasting and smelting	These two processes are pyrometallurgical treatments which lead to the production of nickel matte. Their main difference is that traditional smelting in an electric arc furnace has higher recovery rates of nickel and valuable by-products but consumes more electricity than flash smelting (Crundwell et al. 2011). The conversion step that follows these types of treatments to reduce the iron content of the matte is also included. In addition, some nickel is recovered as a by-product of Ni-Cu-PGM (Platinum Group Metals) concentrate (INSG 2020a). In practice, it is smelted to matte, separated magnetically from PGM, and leached to produce crude nickel sulphate. In the system of this study, this outflow is here represented as matte and further as nickel sulphate.
	5 – Heap leaching	A mixed sulphide precipitate (MSP) can be produced from sulphide concentrate by successive crushing, screening, mixing with sulphuric acid and leaching operations. This technology is only used in Terrafame's Talvivaara mine in Finland (INSG 2020a; Riekkola-Vanhanen 2013; Saari and Riekkola-Vanhanen 2012).
Processing of the laterites ores	6 – FeNi smelting, and 7 – NPI smelting	Laterite ores can be treated pyrometallurgically. The ores are smelted in a rotary kiln electric furnace to make ferronickel. In the Sorowako smelter (Indonesia), sulphur is added to the kiln to produce a matte similar to the sulphide route, but this remains an exception (Kyle 2010). Since 2005, the production of low-grade FeNi, called "nickel pig iron" (NPI), has become very popular in China, encouraged by the high prices of class I metal and easy access to many small and old iron blast furnaces. More recently, the discussions of the ban on ores export in Indonesia that started in 2014 incentivized Chinese firms to invest in NPI smelters in Indonesia (Keskinkilic 2019).
	8 – HPAL	High-Pressure Acid Leaching (HPAL) is a hydrometallurgical treatment of laterite ores that consists in leaching the ore with sulphuric acid under pressure above 5.4 MPa and temperatures around 245-270°C, followed by decantation (Mudd 2008). HPAL plants can produce class I metal if a refinery is integrated into the same facility or products such as MSP, mixed hydroxide precipitate (MHP) and nickel hydroxide cake (NHC). In this work, these three products are not differentiated because data does not always allow their separation, their nickel content is similar, and they are all used either as feedstock for refining to class I metal (process 11) or nickel sulphate (process 12).
	9 – Caron	Caron is a hybrid process that roasts the laterite ore before leaching it with ammonia. It produces nickel oxide (Crundwell et al. 2011; Moskalyk and Alfantazi 2002; Mudd 2008). In 2019, it was only used in Cuba (INSG 2020a)).
Not represented	10 – Roasting	Matte can be roasted by oxidization to produce granules of nickel oxide with a higher nickel content (Crundwell et al. 2011; INSG 2020a). It is used exclusively in the Matsusaka plant owned by Vale in Japan. Still, in this study, it also represents the downstream production of nickel oxide in the Sudbury flash smelter owned by Vale in Canada (INSG 2020).

Refining to metal	11 – Refining	If FeNi, NPI and some Ni oxide can be used directly as an alloying element in stainless steel fabrication, other applications necessitate a high nickel content. During refining, impurities such as iron, copper, lead or phosphorus are taken away from intermediates (MSP/MHP, matte or Ni oxide) and some are sold to other markets (e.g. cobalt, platinum) (Kerfoot 2000). If "refining" is a term used broadly in the literature for "increasing the metal content" (e.g. smelting falls under this definition), in this study, it only designates downstream Ni recovery via the following technologies: (a) the carbonyl process, (b) the leaching, solvent extraction and precipitation techniques, and (c) electrowinning and hydrogen reduction (Kerfoot 2000). This process yields class I metal, which nickel can take the form of cathodes, pellets, briquettes and electrolytic nickel with a purity above 99,8% Ni.
Sulphate production	12 – Sulphate production	Nickel sulphate ($NiSO_4$) is a chemical that can be produced from MSP/MHP, matte, crude nickel sulphate obtained as a by-product of the PGM industry (represented by the matte route in this study), battery scrap, and by dissolution of class I metal (Larsen and Tyle 2008; Roskill 2021). In this work, other salts and chemicals with much lower production than $NiSO_4$ (e.g. nickel chloride, nickel hydroxide) are also categorized under the term "nickel sulphate".
Fabrication of first-use products	13 – Batteries	This process represents the fabrication of Ni-containing batteries namely NMC, NCA, NiMH (nickel metal hydride) and NiCd (nickel-cadmium). The fabrication of the cathodes, the cells and the assembly in modules and packs are covered. The input is nickel sulphate (Roskill 2021).
	14 – Plating	Class I metal and nickel sulphate can be used for electroplating, which consists in adding a thin layer of Ni on metal items to increase their corrosion and wear resistance or for aesthetic purposes (Nickel Institute 2014).
	15 – Non-ferrous alloys	Class I metal and stainless steel scrap can be used to make nickel-base alloys and copper-base alloys (Nickel Institute 2021b).
	16 – Alloy steels and castings	Class I metal, FeNi, Ni oxide and stainless steel scrap can be used to make ferrous alloys that benefit from the properties of Ni in terms of strength and corrosion resistance for instance. Stainless steel is excluded from this process.
	17 – Powder metallurgy and others	Nickel is used for many other applications that capture a minor share of the annual production including powder metallurgy, catalysts or dyes (Roskill 2019).
	18 – Stainless steel	Stainless steel is the main application of nickel. The possible feedstocks are class I metal, FeNi, NPI, Ni oxide and stainless steel scrap. The process represents here the fabrication of Ni-containing stainless steels: austenitic 300-series, ferritic and martensitic 400-series, and CR-Mn 200-series (Nickel Institute 2021d)
Manufacturing of end-use products & End-use sectors stocks	19 to 25 (manufacturing) and 26 to 32 (stocks)	Ni-containing first-use products are then used in the manufacturing of end-use products, identified by the various processes. During the manufacturing, losses are generated and some of the scrap (called "new scrap") joins the nickel scrap market to be functionally recycled (Reuter and Kojo 2012). These end-use products are then purchased and accumulate in the stock of the society.
End-of-life	33 – Waste management	When end-use products are not used anymore, they become waste products and are collected, dismantled and sorted by various chemical and mechanical processes. The majority of nickel scrap is functionally recycled. Some battery scrap can be used in sulphate production, while most of the post-consumer scrap (called "old scrap"), especially stainless steel scrap, joins the nickel scrap market to be used as a secondary source in the production of steels. However, Reuter's Metal Wheel demonstrates that some stainless steel scrap may be directed to the incorrect waste stream and not recycled (Reuter, Schaik, and Ballester 2018; UNEP and Reuter 2013). Instead it often joins the carbon steel or copper scrap cycles. This phenomenon is called "downcycling" because nickel is "recycled" in applications where the benefits of nickel are not desired, and where it can even be considered an impurity (Henckens 2021; Reck et al. 2008). The rest of nickel scrap that is not recovered for economical or technical reasons (e.g. metal goods, electronics waste) goes to landfills (Nickel Institute 2021c).

It should be emphasized that the country-level system is a generic system made for a single country but can be adapted quickly for an aggregation of countries like the EU by ignoring the trade flows within this aggregation.

To be complete, the system definition of a trade-linked MFA system also requires identifying all the Ni-containing commodities, how they are described in the HS system, and how they identify with the system's flows. A list of Ni-containing products, their HS codes and their related trade markets in the system is shown in appendix 1. It should be pointed out here that since MSP/MHP and Ni oxide are covered with a single commodity code (7501.20), but that data at the country level does not allow for splitting the trade values between the two markets, it was decided to group them in a single market. Similarly, NPI and FeNi are designated by a single trade code (7202.60) and thus were grouped into a single market. Finally, no trade was attributed to the "other end-use products", which is a buffer process for products with very small Ni content that are not covered by Processes 19 to 24. The trade of sulphide ore, sulphide concentrate and laterite ore is designated under the same trade code (2604.00). However, sulphide ores are rarely traded as they are usually concentrated close to the mines. Australia is the only country in the world that has operating mines extracting both types of ores in a non-negligible amount. Therefore, trade data associated with this code could easily be split with knowledge of the exporting country (depending on the local ore type) and the importing country (depending on the facilities available to process them).

2.2. Data sources

In this study, many data sources were used to estimate nickel production in various forms, the consumption of Ni-containing products, the transfer coefficients of the system (e.g. process efficiencies), the trade flows or the nickel content of the traded commodities. They are described in this subsection.

2.2.1. Domestic flows

The MFA study was conducted for the year 2019. This year was chosen based on the most complete and recent data available for production, consumption and trade during the study while avoiding irregular industrial activity during the COVID-19 pandemic.

For the year 2019, production statistics were available by country for:

- The total mining volume (sulphide concentrate and laterite ore) (INSG 2020b).
- The total production of “intermediates” encompassing matte, MSP/MHP, Ni oxide, and FeNi and NPI (Anderson et al. 2021).
- The total production of “finished nickel”, which captures class I metal, sulphate (only the share made from intermediates to avoid double counting), FeNi, NPI, and Ni oxide to be used in the fabrication of first-use products (INSG 2020b).

The production of nickel sulphate, including the amount from the dissolution of class I metal and battery scrap, was estimated from market research (Nornickel 2020). The distribution of the sulphate production from these two feedstocks worldwide was derived from discussions with industry experts. The figures are displayed in appendix 2. To help understand and adapt the production statistics aforementioned to the system’s flows, reported company and governmental data was used (see subsection 2.3 for the quantification method, and appendix 3 for a detailed list of the reports used). The stock variations of class I metal in SHFE/LME warehouses in 2019 were available by country from the INSG (2020b).

The total consumption of primary nickel to be used as a feedstock in the fabrication of first-use products was estimated for each first-use application and selected countries by Roskill and the Nickel Institute (Roskill 2019). The list of countries available is detailed in appendix 4. The same report estimated the allocation of the consumption of finished nickel to the different feedstocks -class I metal, sulphate, FeNi, NPI and Ni oxide- (Roskill 2019). At the country level, this data was not available, and the global estimates were used as a first proxy and refined at a later stage based on the type of local finished nickel production and the country's imports. The consumption of secondary sources of nickel for the fabrication of first-use products was estimated to be zero for Processes 14 (Plating) and 17 (Powder metallurgy and others) based on previous research done on the topic (Reck et al. 2008). As mentioned, battery scrap recycling was attributed to nickel sulphate production, and there is, therefore, no additional input of scrap in Process 13 (Batteries). Scrap inclusion rates in Processes 15 (Non-ferrous alloys) and 16 (Alloy steels and castings) were estimated to be 14% and 17%, respectively (Reck et al. 2008). These coefficients were assumed to be the same for individual countries. Finally, the recycled content of stainless steel was estimated for 2015 (the most recent year available) to be 44% as a global average (Reck et al. 2020). At the country level, the same source estimates the recycled content for China, the USA, and EU countries with stainless steel production (e.g. Finland, Belgium, Germany) and some key producers in Asia (India, Republic of Korea and Japan). Details are given in appendix 5. The global average value was used for the other countries.

For the consumption of nickel in first-use products by the manufacturing of end-use products, some estimates were available (Roskill 2019). However, these were not used directly as they only account for primary data, not all categories seem to be corrected for trade (imports and exports of first-use products before manufacturing), and the authors are not transparent on the methodology used. Instead, transfer coefficients (in the form of ratios) were derived from these estimates for the countries available. For other countries not covered by the report, estimated coefficients at the global level were used.

The amount of Ni in waste products out of the end-use sectors was calculated based on ratios of outflows/inflows – for Processes 20 (Appliances and electronics), 24 (Metal goods), 25 (Buildings and infrastructure) and 26 (Other) – or based on the lifetime of end-use products and the growth rate of the respective sector during the same period – for Process 21 (Automotive), 22 (Other transport), 23 (Industrial machinery). Ratios and lifetime estimates were collected from the literature (Reck et al. 2008). Growth rates of end-use sectors were estimated from figures of (Roskill 2019) and linearly extrapolated if needed to capture the entire period. Details are shown in appendix 6. According to the Nickel Institute (2021c), waste management distributes post-consumer scrap between functional recycling (68%), non-functional recycling or downcycling (15%), and landfilling (17%). Without country-specific data, these ratios were assumed to be the same across individual countries.

Many domestic flows at the country level could be derived from other quantified flows. This required knowledge of the efficiency of the system's processes, which was collected from the literature (Andika et al. 2019; Crundwell et al. 2011; Kerfoot 2000; Khan, Manjong, and Strømann 2021; Khoo et al. 2017; Rao et al. 2013; Reck et al. 2008; Riekkola-Vanhanen 2013). The range of efficiency, the sources and the value chosen for this study are detailed for each process in appendix 7 of this report.

2.2.2. Trade flows

Trade statistics were extracted from UN Comtrade. An algorithm developed for this study and presented in subsection 2.3.2 cleaned the data from outliers, estimated missing mass flows, and reconciled mirror statistics between reporting countries. After that, trade flows were available for all commodity codes and countries in net weight. To convert this mass into nickel content, the values needed to be multiplied by a coefficient which attributed a share of the commodity code to the trade flows (in case the code refers to an aggregation of products containing nickel and others not containing nickel) and applied the right nickel concentration. Generally, these were summed up in a single coefficient. For the trade related to ores and concentrate, matte, MSP/MHP and Ni oxide, class I metal, FeNi/NPI, and nickel sulphate, as much as possible, the nickel content used was country-specific (based on the exporter):

- For laterite ores, average country concentrations were collected from extensive geological reviews of current deposits (Mudd and Jowitt 2022).
- The INSG directory and yearbook are expert documents listing all the facilities intervening in the primary nickel supply chain worldwide (INSG 2020b, 2020a). If the nickel content was known for a facility in the country (e.g. mine, smelter, refinery) and listed in these documents, then the value was used as a proxy for the country as a whole.
- When the value could not be estimated at the country level, default values were used. These values were estimated from literature (Crundwell et al. 2011; Cusano et al. 2017; Kerfoot 2000). The range of nickel concentration, the sources and the value chosen for this study are displayed in appendix 8.

The nickel content of trade flows of first-use and end-use products was derived from data from Dr Barbara Reck of Yale University (Reck et al. 2008 and personal communication, April 2022). Batteries were not covered in the study previously cited. The nickel content was estimated at 10% for LIB as the result of the average of Ni-containing commodities possibly covered by the LIB trade code (precursor Cathode Active Material -PCAM-, CAM, cell, module, pack), according to the market share of nickel-containing battery chemistries in 2018 (BGS 2021) and the mass ratio of nickel for these chemistries (Skare, Wind, and Flåten Andersen 2019). The calculations that led to this estimate are given in appendix 9. It was estimated at 28% for nickel-metal hydride batteries from the literature (Lu et al. 2016). For nickel scrap, the concentration was estimated at 2,1% based on a weighted average of the nickel content of each end-use sector generating scrap. The nickel content of the respective product was used for stainless and other alloy steel scrap.

2.3. Quantification method

2.3.1. Domestic flows

For a given country, the mining production statistics could be attributed to the flow of sulphide concentrate or laterite ore based on the local type of ore, which was known by reviewing the mines of the countries one by one in the INSG Nickel Directory (INSG 2020a). The total intermediate production and finished nickel production statistics by country were split between the different technologies by applying the following procedure:

- Review all the facility (e.g. smelters, refineries) types in the country operating in 2019 from INSG (2020a) Identify the form of nickel they produce.
- Search company reports for that given plant's displayed production in that year.
- If the production could be found for all the plants in the country, the total was corrected by normalization to match the total intermediate production from Anderson et al. (2021) or the total finished nickel production from (INSG 2020a).
- If the production was missing for one facility, it was deduced by subtracting the total production in the country and the sum of the others.
- If the production was missing for two facilities or more, or if data was not refined enough that it could not be split between different intermediates, the difference between the total production in the country and the sum of the known production was allocated to the various forms of nickel-based on the nominal capacity of each facility, which could be collected from INSG (2020a).

The stocks of class I metal, and sulphate production were directly taken from data sources detailed in subsection 2.2.1. The feedstocks of ores and concentrate in Processes 3 to 9 were calculated with the respective process efficiency. So were the matte, MSP/MHP and Ni oxide feedstocks in Processes 10 to 12. Losses of nickel in tailings and slag were deduced from mass balance. At the level of the markets of sulphide concentrate, laterite ore, and matte, and after quantification of the imports and exports (see further for the algorithm treating trade data), the inputs could be confronted with the outputs. Since all the flows were calculated from independent methods, this leads to a mass balance inconsistency (MBI) – the smaller the best - which is displayed in the results for transparency.

Regarding the quantification of the flows of class I metal, FeNi/NPI, sulphate and Ni oxide to the fabrication of first-use products:

- If estimates were available for the country under study in the Roskill report (2019), the values were used and initially split according to global transfer coefficients. This split ould be manually refined to minimize mass balance inconsistency at the class I, FeNi/NPI, sulphate and MSP/MHP/Ni oxide markets (in case there is no local production or imports of the product).
- If estimates were not available for the country, the markets of finished nickel were initially considered balanced, and the total flow was deduced. Once this was done for all the countries not detailed in the report, each value was normalized over the total "rest of the world" value, and the split was done the same way as in the previous paragraph. The difference between the normalized and pre-normalized values was reported as a mass balance inconsistency.

The mass balance inconsistency was calculated for the markets of class I metal, FeNi/NPI, sulphate and MSP/MHP/Ni oxide.

The scrap inputs in first-use products were derived via the scrap inclusion rates. The efficiencies of Processes 13 to 18 yielded the amount of first-use products fabricated and the scrap generated for recovery. The losses were deduced from mass balance. After quantifying the imports and exports of first-use commodities, the total net outflow of first-use products going to local end-use manufacturing was calculated from mass balance (these markets are considered balanced due to lack of additional statistics). It was attributed to each end-use sector via transfer coefficients described in subsection 2.2.1. Then, the efficiency of Processes 19 to 25 gave the amount of end-use products manufactured, the scrap generated for recovery, and the mass balance principle yielded the waste flow. These products could be traded after manufacturing, and the net value deduced by mass balance entered Processes 26 to 32.

After quantifying the waste outflows of the end-use sectors via transfer coefficients presented in subsection 2.2.1, the stock changes were deduced from mass balance. The flows of recycling and downcycling were calculated via transfer coefficients and the landfilling by mass balance. Finally, the sum of all the new and old scrap, corrected for imports and exports, could be confronted with the use of scrap in the fabrication of first-use products.

An illustrated overview of a given country's quantification strategy is shown in Figure 4.

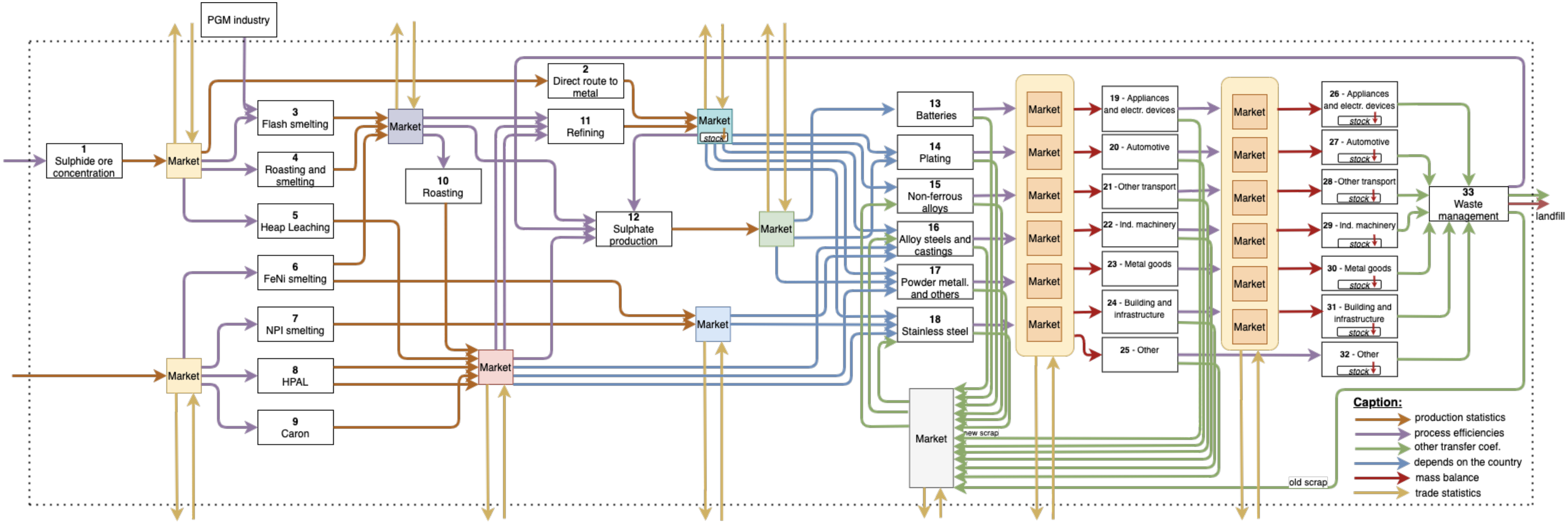


Figure 4 - Overview of the quantification strategy for a given country. For clarity, unrecovered losses are not shown (they are all calculated from mass balance)

2.3.2. Trade flows

As stated previously, trade statistics were flawed and had to be processed before use in an MFA system. The main issues to solve were:

- Filling the missing mass data to quantify all the system's flows.
- Screening data for outliers, to avoid generating wrong quantifications.
- Reconciling mirror statistics to ensure mass balance.

The study defined an algorithm to treat trade data and solve these issues. It is illustrated in Figure 5. When initial unprocessed data was available both in monetary value and net weight, it was used to estimate an average price per kg by linear regression. This was done for each 6-digits commodity code and independently for both the importer and exporter because import monetary values include transportation and insurance costs. In contrast, the export monetary values do not. For the commodity codes of ores and concentrate, matte, MSP/MHP/Ni oxide, and FeNi/NPI, the linear regression was done by considering the metal content and not the entire weight because it is argued that the metal content drives the price of these products. The correlation coefficients r^2 were collected at that point to keep track of the reliability of this average price estimate.

Then, trade flows were connected to their mirror statistics and could be split into nine categories, depending on whether monetary values and mass are reported by a country A and its partner B. The case where mass was registered but not the monetary value does not exist, which is why it does not appear in Figure 5.

The relative difference between the reported mass and the one reported by the trading partner was calculated for each country. If this value was under 20%, the flow was considered an "accurate" trade report. A reliability indicator for each country, both as an importer and exporter, was defined as the frequency of accurate reported flows relative to all the reported flows.

To fill the missing information, different methods were used:

- Cases 2 and 3: the missing mass information was estimated with the average price estimate per kg for the country where the monetary value is reported. The mass of the trading partner was assumed to be equal.

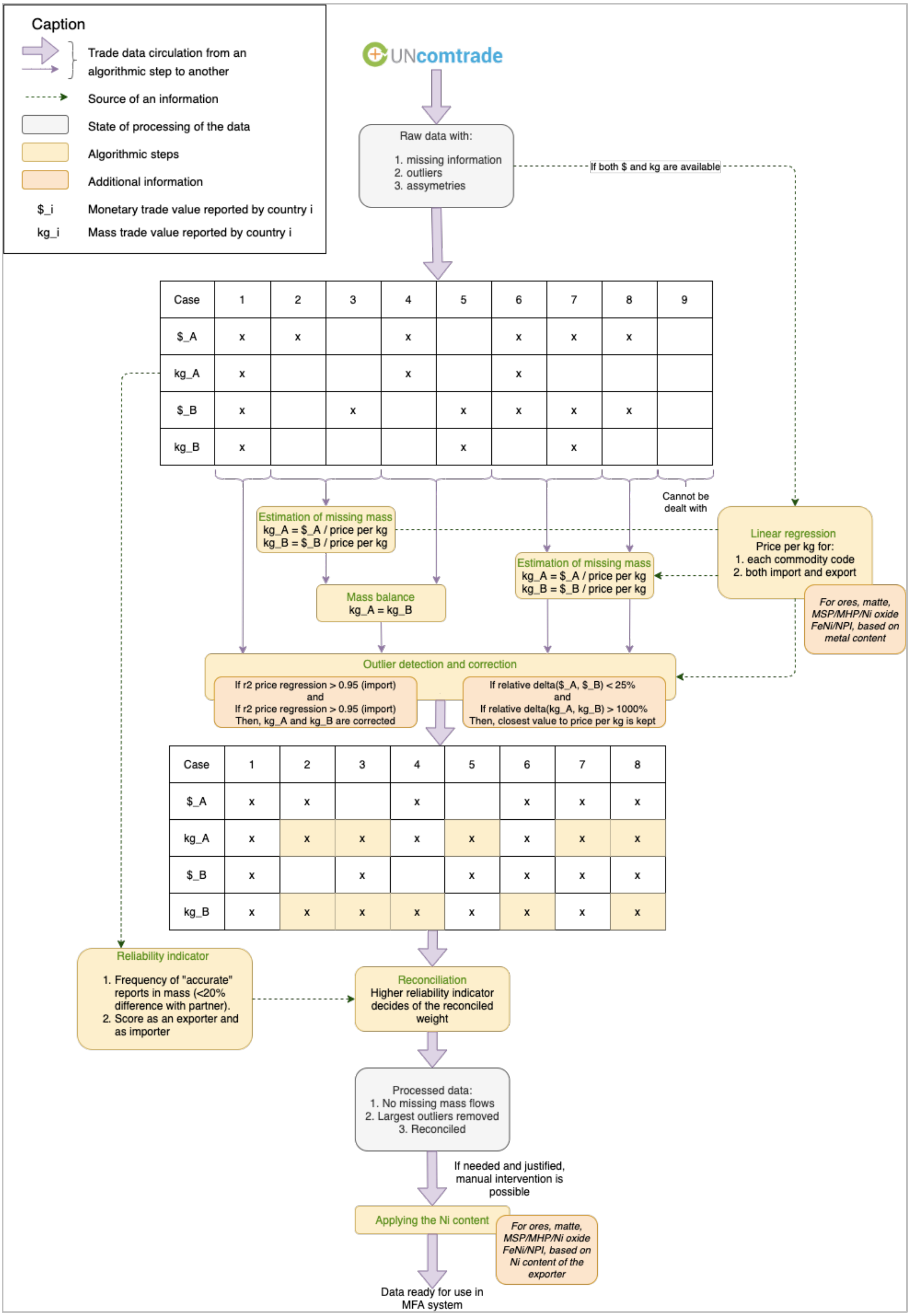
- Cases 4 and 5: the missing mass information was assumed to equal the mass reported by the trading partner.
- Cases 6, 7 and 8: the missing information of the exporter and/or importer were estimated independently from the monetary value with the average price per kg estimate.
- Case 9 is a hypothetical case where neither country reports the trade flow, but it cannot be detected in the Comtrade data; it was therefore not dealt with.

In terms of outlier detection and correction, two main control steps were operated:

- If the average price per kg was considered very stable and reliable for a given commodity code ($r^2 > 0{,}95$), they were used to correct the mass values reported. The idea is to correct mass flows that are initially reported but are outliers. This step was beneficial for values of case 1 but even more for cases 2 to 5, which were already reconciled and therefore almost ready to be used directly in the MFA system.
- If the relative difference between monetary values of a reporter and its partner was relatively "small" (< 25%), but the relative difference of mass was huge (> 1000%), then the closest value to the average price per kg was kept. This was done to ensure that obvious mass outliers were also dealt with if the average price was not highly reliable.

Once these steps were applied, missing mass information was completed, and important outliers were detected and corrected. Not all the monetary information was filled in, but it was not necessary because they were not used in the MFA system.

To ensure mass balance, imports and exports were reconciled. The reliability indicator was used for that, and the value of the more reliable country under that criteria became the reconciled net weight trade flow. Due to previous algorithm steps, the reconciliation could only affect trade flows from cases 1 and 6 to 8. Once all issues related to trade flows were reported, some manual interventions could be operated, for instance, in case obvious errors were observed during the quantification of important flows of the system. Finally, the reconciled net weight trade value was converted to nickel content by multiplying the trade flow with the appropriate concentration. When possible, exporter-specific concentrations for ores and concentrate, matte, MSP/MHP/Ni oxide, and FeNi/NPI were used.



Case	1	2	3	4	5	6	7	8	9
$_A	x	x		x		x	x	x	
kg_A	x			x		x			
$_B	x		x		x	x	x	x	
kg_B	x				x		x		

Case	1	2	3	4	5	6	7	8
$_A	x	x		x		x	x	x
kg_A	x	x	x	x	x	x	x	x
$_B	x		x		x	x	x	x
kg_B	x	x	x	x	x	x	x	x

Figure 5 - Illustration of the algorithm processing trade data before use in the MFA systems

2.4. Uncertainties

Systemic errors are dealt with with a thorough discussion of the system's modelling, and the assumptions were presented in a previous subsection. Regarding random errors, quantifying uncertainties for each system's flow is unmanageable in the time available for the master's thesis work. However, understanding the source and the relative extent of these errors associated with the input parameters is crucial to emphasize the limitations of the work. Therefore, each category of data used in this work and cited in subsection 2.2 is reviewed and given a qualitative uncertainty spread over three possible levels: low, medium and high uncertainty.

Factors taken into consideration for assessing the level of uncertainty are, for instance: the type and quality of the source (e.g. internationally renowned organization, government, company, literature), the range of values, the year data was published, the country-specificity, the variability in time, the assumptions required to use the data for the study, the validation by an independent source, the number of the steps needed to estimate the parameter or the transparency of the methodology.

The review of the uncertainty levels is summarized in Table 2.

Table 2 - Uncertainty level of the parameters used in the quantification of the system

Category	Parameter	Uncertainty level	Comment
Production	Mining production	High for Albania, Burma, China, Dominican Republic, Guatemala, Indonesia, Kosovo, Russia, Serbia and Turkey	For the countries cited, the production is either based on estimates (indicated in the source) and/or varies a lot across sources (INSG, US Geological Survey, British Geological Survey).
		Low for the other countries	For the other countries, supported by company data and governmental agencies, and is consistent between different institutes.
	Intermediate production	Medium	For the overlapping categories (FeNi/NPI), the production is consistent with that of finished nickel production. However, the methodology is not shown, which prevents from reviewing the credibility of the estimates/assumptions.
	Finished nickel production	Low	Relies on company data, which is generally published as Ni content in finished form. The INSG is a highly credible and specialized association of experts of the nickel industry.

	Nickel sulphate production from class I conversion and from battery scrap	High	Only one source available: market research from a company (Nornickel). Class I conversion occurs mostly in China, which is notoriously known for the low quality of its published statistics. No methodology is mentioned. The risk of double-counting is higher because finished nickel is used as a feedstock. Country-level split is not supported by written publications.
Consumption	Total primary nickel to first-use applications, by country	Medium/High for the countries covered by the Roskill report (2019)	Roskill and the Nickel Institute have published the "End-use of Nickel" report yearly for many years and are a credible source, but the methodology is not transparent, and sources are not cited.
		High for other countries	Only the total is available for the "rest of the world", and is split between the remaining countries based on a weighted average of country-level calculations, with cascading assumptions and uncertainties (see subsection 2.3.1).
	Scrap inclusion rates in the fabrication of first-use products	Medium for stainless steel scrap for the countries covered by Reck et al. (2020)	Based on the study of country-level cycles of stainless steel by an expert researcher on the topic. Even if the value cannot change very fast and very significantly, the study is based on 2015 data.
		High for the other countries, and the other first-use products	Based on a global average value, for studies done for 2015 (stainless steel) or 2000 (other first-use sectors).
	Distribution matrix of nickel in first-use products to the manufacturing of end-use products (derived transfer coefficients)	Medium/High for the countries covered by the Roskill report (2019)	Roskill and the Nickel Institute have published the "End-use of Nickel" report yearly and are a credible source, but the methodology is not transparent, and sources are not cited.
		High for other countries	Based on a global split, which itself is not supported by transparent methodology.
Stock	Class I metal stock	Low	Based on data collected by the INSG, LME and SHFE yearly, at each warehouse around the world.
End-of-life	Lifetimes of end-use products	High	Based on dated estimates (Reck et al. 2008), but arguably did not vary too much since then. Lifetime estimates are always debatable, especially as end-use sectors encompass a wide variety of products.
	Growth rate of end-use sectors	High	Read on a graph of the Roskill report (2019), whose methodology is not transparent, and extrapolated outside the displayed time period by linear regression.
End-of-life	Ratio outflow/inflow end-use sectors	High	Based on dated information from (Reck et al. 2008). The source mentioned is "informed estimate".
	End-of-life recycling	High	There is a consensus on the value in the literature, but the reference year is 2010 and the value is not country-specific, and can have large variability at country-level depending on the quality of the waste management there.
	Downcycling	High	It ranges from 10 to 20% in the literature, and is not country-specific.
Process efficiencies	Processes 2 to 5 (Direct route to metal, flash smelting, roasting and smelting, heap leaching), 10 (Roasting) and 11 (Refining)	Low	The sources are (a) company data and validated by governmental sources (heap-leaching, direct route to metal), (b) well-known traditional techniques (sulphide smelting) covered by extensive literature, (c) refining steps with low variability across sources
	Processes 6 to 9 (FeNi/NPI smelting, HPAL, Caron), and 12 (Sulphate production)	Medium	Supported by literature, but more variability across sources and supported by a limited number of examples of facilities
	Processes 13 to 33	High	Based on estimates from (Reck et al. 2008). Not supported by additional literature.
Trade statistics	Difference between mirror statistics is under 5% in mass	Low	Data in mass is validated independently by the trading partner.

	Difference between mirror statistics is between 5% and 25% in mass	Medium	There might be over- or under- estimations, or small errors in the reporting. Factors like different time of reporting, and measurement methods can be responsible.
	Difference between mirror statistics is above 25% in mass, or no mirror statistics is available in mass	High	Larger discrepancies between a country's report and that of its partner. Incorrect partner attribution, errors, illegal activity, poor statistics, value reported in a different unit than expected (e.g. metal content instead of total weight)
Nickel content	Class I metal, nickel sulphate	Low	Products sold on international markets, and regulated to meet specific purity requirements.
	Laterite ore, sulphide concentrate, matte, MSP/MHP, FeNi/NPI (country specific)	Medium	If the value is known for the exporter specifically, it is supported either by highly credible literature or organizations.
	Laterite ore, sulphides concentrate, matte, MSP/MHP, FeNi/NPI (default values)	High	If the value is not known specifically for the exporter, the default value is used. The variability is higher
	Batteries	Medium	Multiple assumptions, but not high variability possible.
	Stainless steel	Low	Under 10% uncertainty estimated by (Reck et al. 2008). The stainless steel industry is well-covered in the literature.
	Other first-use products	High	Based on informed estimates
	End-use products	High	Based on informed estimates. Small amounts of nickel, which means that it is not well-studied in the literature.
	Nickel scrap, stainless scrap, alloy steel scrap	High	Strong assumptions, not supported by literature.

3. Results

In this section, the results of the quantification of the global trade-linked model are presented. First, the global quantified system is displayed, showing the main production routes and types of products that contain nickel at the planetary level. Then, the production and trade of nickel are shown from a product category perspective, which helps to understand at what step of its value chain nickel is the most traded and the key country actors' contributions to these operations. Finally, the production and trade of nickel are presented from a country-level perspective. The aim is to understand the overall trade balance of the major countries intervening in the nickel cycle and show their exporting power and import reliance in various product categories.

To structure the results, six product categories are defined: “ores and concentrate” (laterite ore and sulphide concentrate), “intermediates” (matte and MSP/MHP/Ni oxide[1]), “finished nickel” (FeNi/NPI[2], class I metal and sulphate), “first-use products”, “end-use products” and “scrap” (recovered old and new scrap for use in the fabrication of first-use products). To illustrate the results at the country level, the most important actors in the production and trade of nickel have been identified. These are Australia, Canada, China, the EU28[3], India, Indonesia, Japan, New Caledonia, Norway, the Philippines, the Republic of Korea, the Russian Federation, and the USA. The total coverage of these countries in each category is detailed in appendix 10.

3.1. Global system

The global quantified system is shown in Figure 6 and represented as a Sankey diagram. This means that the size of the flows is proportional to the mass of nickel they stand for, according to a scale displayed in the bottom left corner of the figure. In addition, the values of the stock changes (“SC”) and the mass balance inconsistencies (“MBI”) are explicitly written.

---

[1] Ni oxide is here only considered an intermediate because (a) it is difficult to split the trade of Ni oxide from that of MSP/MHP, and (b) the volume of Ni oxide used in the first-use sectors is low (see subsection 3.1).

[2] To avoid misinterpreting the production and trade of matte and MSP/MHP/Ni oxide, FeNi/NPI is here excluded from the “intermediates” denomination, despite being produced directly from the smelting of ores.

[3] For the rest of the work, the term “country-level” is also used to refer to the EU28.

Sulphide concentrate and laterite ore production at the global level represent 27-32% and 68-73% of the total mining production. Most sulphide concentrate produced undergoes pyrometallurgical treatments in flash smelters (70%) or electric arc furnaces (20%). On the laterite side, NPI and FeNi smelting capture 70% and 20% of the processing, and the HPAL (hydrometallurgy) comes in the third position with close to 10% of the laterite ore production.

In 2019, the finished nickel production is mainly NPI/FeNi (1332 kt Ni, 56%). Class I metal is the second form of finished nickel by weight. The production is estimated at 841 kt Ni, with 92 kt Ni converted to nickel sulphate. Most of the class I metal is produced from sulphide ores by refining matte (80% of the total feedstock), and the connection with the laterite ores is made by the refining of MSP/MHP produced from HPAL plants (129 kt Ni). A net stock change of -31 kt Ni is calculated for class I metal, which means an additional 31 kt Ni of class I metal (-53 kt Ni in LME; +22 kt Ni in SHFE) is removed from the warehouses and consumed in the fabrication of first-use products. Sulphate production is estimated at 207 kt Ni, and nickel oxide production is minor at the global level.

About 70% of primary nickel production is used to fabricate stainless steel, with 80% as NPI/FeNi. Alloy steels and castings, and non-ferrous alloys are the following first-use applications by weight, with each a consumption of 190 kt Ni in primary form. These three applications are also supplied by old and new scrap: 1263 kt Ni, 39 kt Ni and 31 kt Ni, respectively. Batteries consume 125 kt Ni in the form of nickel sulphate. The first-use products are then used in the manufacture of end-use products. Driven by their high consumption of stainless steel, the manufacturing of industrial machinery, metal goods, and buildings and infrastructure capture the most significant amount of nickel, with 1182 kt Ni, 791 kt Ni and 639 kt Ni consumed, respectively. The end-use products join the in-use stocks, with the most considerable accumulation occurring in the same sectors.

Most post-consumer scrap is functionally recycled, back in stainless steel production (811 kt Ni). 179 kt Ni is downcycled in carbon steel production, and 203 kt Ni is landfilled.

Throughout the nickel value chain, the losses in the processing are estimated at 497 kt Ni, with the most significant sources being NPI smelting (219 kt Ni) and sulphide ore concentration (123 kt Ni).

Global nickel cycle in 2019

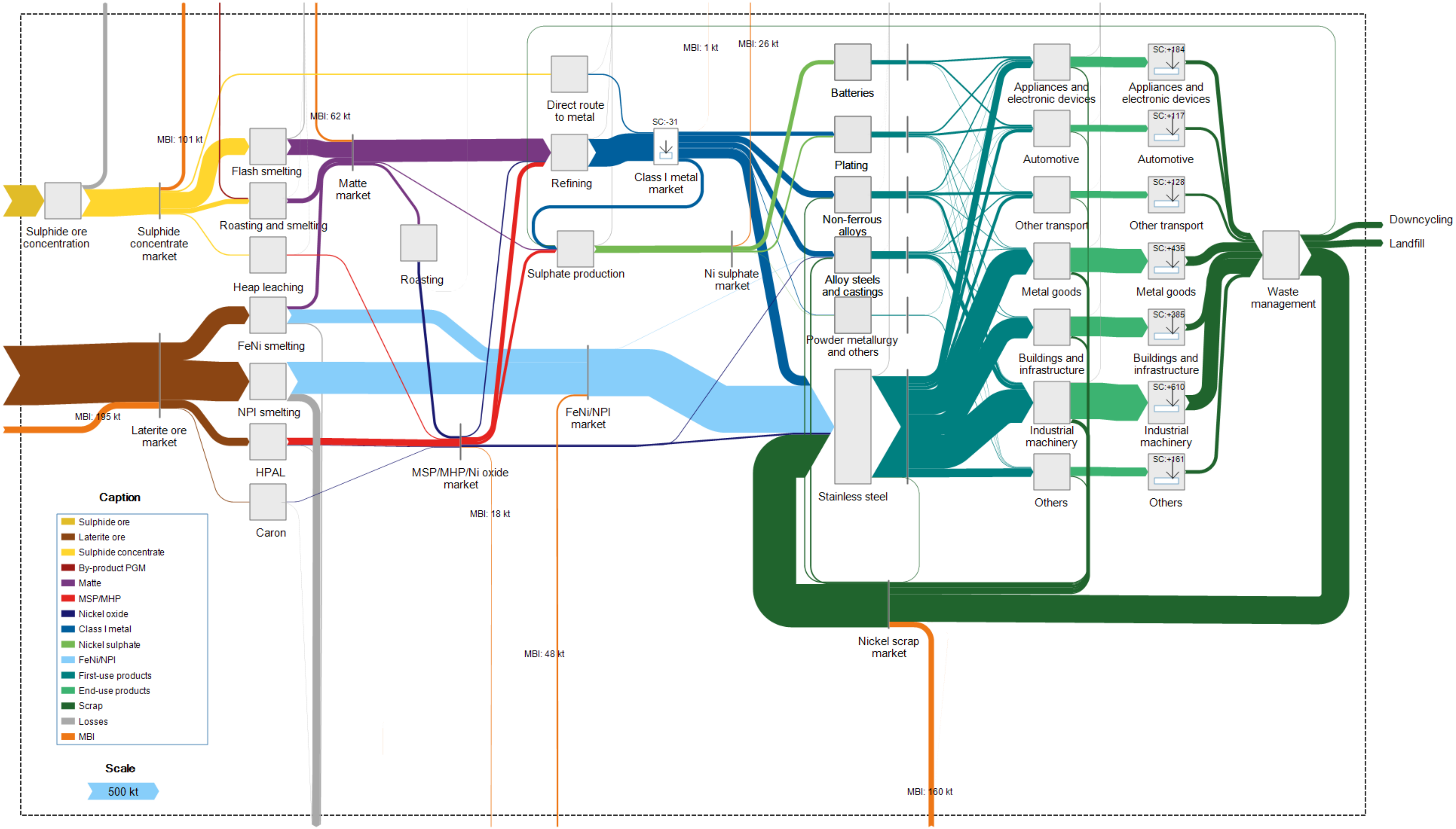


Figure 6 - Quantified MFA system for the global nickel cycle in 2019

3.2. Production and trade of Ni by product category in the value chain

The amounts of nickel being produced and traded at different levels of the supply chain are displayed in Figure 7. The contribution of the key countries identified is also indicated. Concerning the mass balance principle, it can be observed that total imports and exports of each category are equal at the global level.

Figure 8 shows the trade flows of nickel in the six product categories between the different countries. They are represented in a circular diagram where the countries are attributed a share of the circumference based on the sum of their imports and exports for a given product category. The color of the flows corresponds to the exporters' color and is kept consistent with the palette used in Figure 7.

Figure 9 gives complementary information on the production and trade of nickel by breaking down the main product categories into the products they cover.

3.2.1. Ores and concentrate

The production of ores and concentrate is estimated at 2534 kt Ni in 2019. According to Figure 7, Indonesia is the first mining producer in the world with 853 kt Ni, followed by the Philippines (323 kt Ni), the Russian Federation (223 kt Ni), New Caledonia (208 kt Ni), Canada (187 kt Ni), Australia (159 kt Ni) and China (105 kt Ni). Together these seven countries account for about 81% of the total mining production. About 40% of the category “ores and concentrate” is being traded, but they are predominantly (80%) imported by China only. The leading exporters in this category are Indonesia (407 kt Ni), the Philippines (334 kt Ni) and New Caledonia (107 kt Ni). Figure 8 shows that most Indonesian and Filipino exports go to China, while New Caledonia exports primarily to the Republic of Korea and Japan.

3.2.2. Intermediates (matte, MSP/MHP/Ni oxide)

The production volume of intermediates is lower (1029 kt Ni) because not all routes processing ores and concentrate go through the “intermediate” form, as was defined for this work. The difference with the total production volume of laterite ore and sulphide concentrate is, therefore, to be attributed to FeNi and NPI smelting and, to a much smaller extent, to losses during the processing. The main countries producing these kinds of intermediates are the

Russian Federation (214 kt Ni), Canada (157 kt Ni), Australia (127 kt Ni) and China (127 kt Ni). These countries all intervene in the sulphide route and produce matte, which accounts for two thirds of the intermediate production, based on Figure 9. Intermediates are the least traded category in absolute terms, with 490 kt Ni. The main trade flows in this category are imports to China coming from countries in the “others” category (Papua New Guinea, Cuba), exports from Indonesia to Japan, exports from Canada to Norway, and exports from the Russian Federation to the EU28 (Finland).

3.2.3. Finished nickel (FeNi/NPI, class I metal, sulphate)

The total production volume is estimated at 2289 kt Ni. To avoid double-counting in the combined finished nickel production of Figure 7, the production of sulphate from class I conversion (about 92 kt Ni at the global level, see subsection 3.1) is removed. The difference with the total production of ores and concentrate is explained by Ni oxide used directly in first-use applications (about 70 kt Ni, see global system) and losses during processing and refining (about 328 kt Ni in total). Within the finished nickel category, Figure 9 shows that FeNi/NPI is the most produced form (58% of finished nickel), followed by class I metal (33%). Note that in Figure 9, class I metal being converted to sulphate at a later stage is not discounted. This choice is because class I metal can be traded before being converted to sulphate, and the graph aims at comparing production and trade for individual categories. Despite this, the trade of class I metal is calculated to be higher than the annual production, which may seem incoherent at first sight. This point is being further discussed in subsection 4.1.2. Overall, if more FeNi/NPI is being produced than class I metal, the trend is reversed in trade, with some of the main producers of class I metal (Russian Federation, Canada, Australia and Japan) exporting significant amounts of their production to China, the EU28 and the USA. In comparison, nickel sulphate has much lower production volumes (207 kt Ni) and low trade volumes (about a quarter of the production). The detail of the trade flows in Figure 8 shows that the main transfers of finished nickel are going to China, which is a significant absorber of exports from Indonesia, the Russian Federation, Australia, New Caledonia, and other countries (Brazil, Myanmar, Colombia, Dominican Republic, North Macedonia). Apart from the ones connected to China, the main trade flows are from Norway to the EU28 and Canada to the USA.

3.2.4. First-use products

The total production of first-use products is calculated to be 3711 kt Ni. This is higher than the total finished nickel production mainly because significant volumes of scrap (1332 kt Ni) are used in the fabrication of first-use products in addition to nickel of primary source. The remaining difference is to be attributed to the abovementioned Ni oxide feedstocks and losses (19 kt Ni unrecovered in the fabrication of first-use products and 19 kt recovered scrap). Based on Figure 9, stainless steel is the most produced (82%) and traded (73%) first-use product. The largest producers of first-use products are, therefore, the major stainless steel producers, with China in the lead (1710 kt Ni), followed by the EU28 (654 kt Ni), Indonesia (301 kt Ni), Japan (287 kt Ni), the USA (239 kt Ni) and the Republic of Korea (225 kt Ni).

Regarding trade, most first-use commodities producers are exporters and importers. If most are net exporters, both the USA and the EU28 are net importers of first-use commodities. It can also be noticed that intra-EU trade is significant (532 kt Ni, one third of the total trade volume). The combined export of EU28 with both EU and non-EU members is estimated to be higher than the annual production by this region, which is another example of double-counting that is discussed further in subsection 4.1.2. Some of the imports are also reported by other countries not represented in Figure 2, such as Viet Nam, Turkey, Malaysia, Thailand, the United Arab Emirates, Switzerland, and many countries with imports under 10 kt Ni. It can be observed in Figure 8 that the transfers of first-use products are more numerous but smaller (the visually largest ones are aggregated flows going to the "others" category) and operate in both directions (imports of some products and exports of others depending on the domestic industry).

3.2.5. End-use products

End-use production is estimated at 3316 kt Ni. The difference with first-use production is 343 kt Ni of recovered scrap ("new scrap") and minor losses. Figure 9 shows the distribution of production and trade of nickel in the end-use product categories. About one third of the total end-use production is related to the industrial machinery sector, namely due to its considerable stainless steel input. Other important sectors are metal goods and buildings and infrastructure, representing 21% and 17% of the total production, respectively. The other categories account each for 6-9% of the total. Trade follows a relatively similar distribution in relative terms compared to the total trade volume. Industrial machinery is also the first trading end-use sector, followed by buildings and infrastructure, and metal goods, with the latter being a little less traded than the former. Smaller applications such as automotive and other transport are more traded relative to their production (32% and 45% respectively, compared to 15% for buildings and infrastructure or 18% for metal goods). As expected, no trade is attributed to the “others” categories due to the way the system was defined. Overall, end-use products are the least traded of all the categories discussed in this part compared to production (23%). Out of the 760 kt, Ni traded, 202 kt Ni occurs inside the EU28. China is the most important single-country exporter with 180 kt Ni, and the USA is the most important single-country importer with 128 kt Ni. Similarly to first-use products, it can be observed in Figure 8 that the transfers of end-use products are more numerous but smaller and operate in both directions, except for China which is a much more significant exporter than an importer.

3.2.6. Scrap

Finally, the scrap generation corresponds to the recovered Ni in scrap from first-use fabrication, end-use manufacturing and end-of-life management for use in first-use applications. The main sources are China (473 kt Ni) and the EU28 (216 kt Ni). Other non-negligible producers are the USA, Japan, the Republic of Korea and India. More than half of the total trade volume is intra-EU, but as this value is higher than the quantity of scrap recovered in the region, it is also discussed in subsection 4.1.2. Again, the trade of Ni scrap involves more actors, but apart from intra-EU trade, Figure 8 shows that the main trade flows are going from the EU28 and the USA to India.

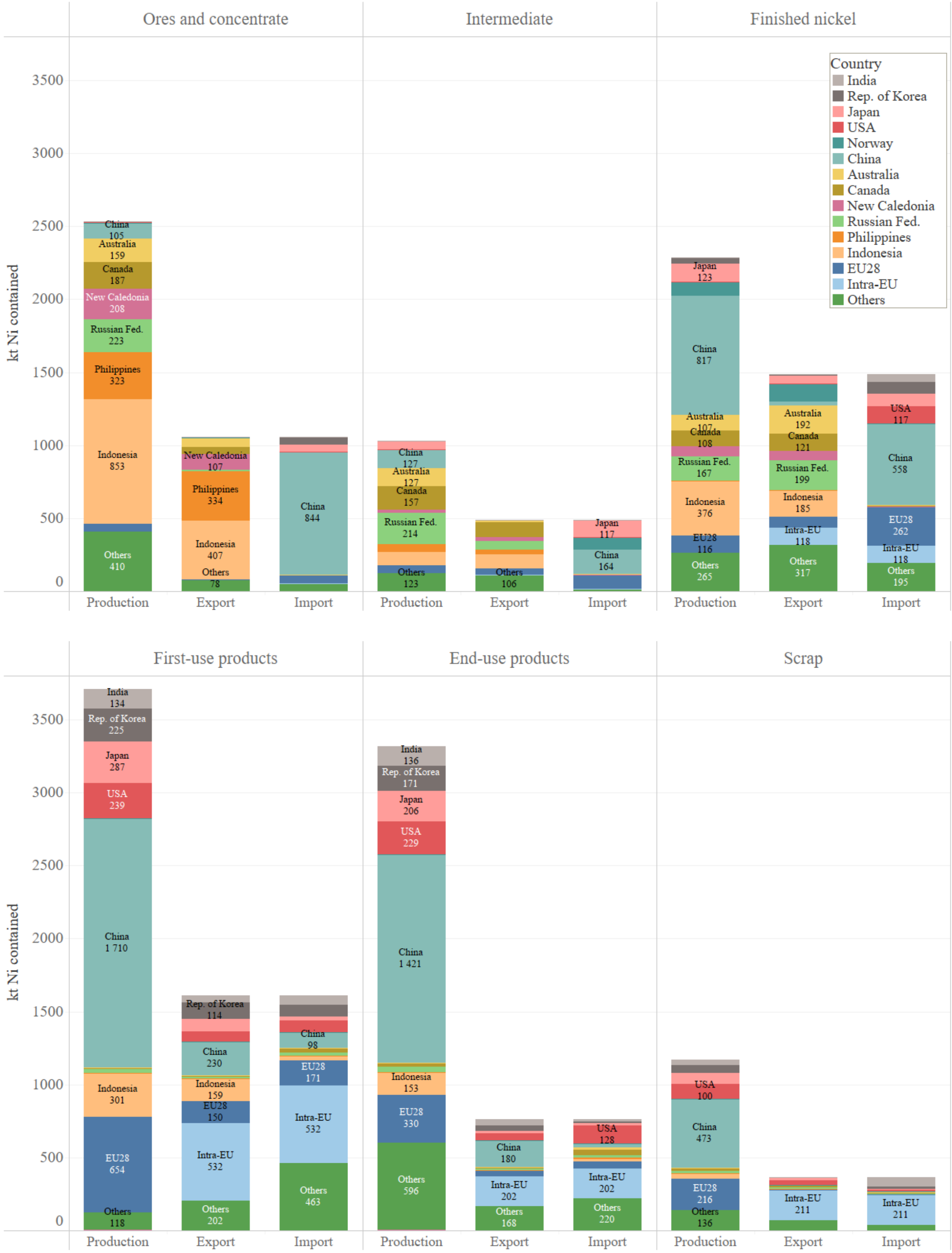


Figure 7 - Total production and trade volumes of nickel in each product category with the contributions of the major countries identified

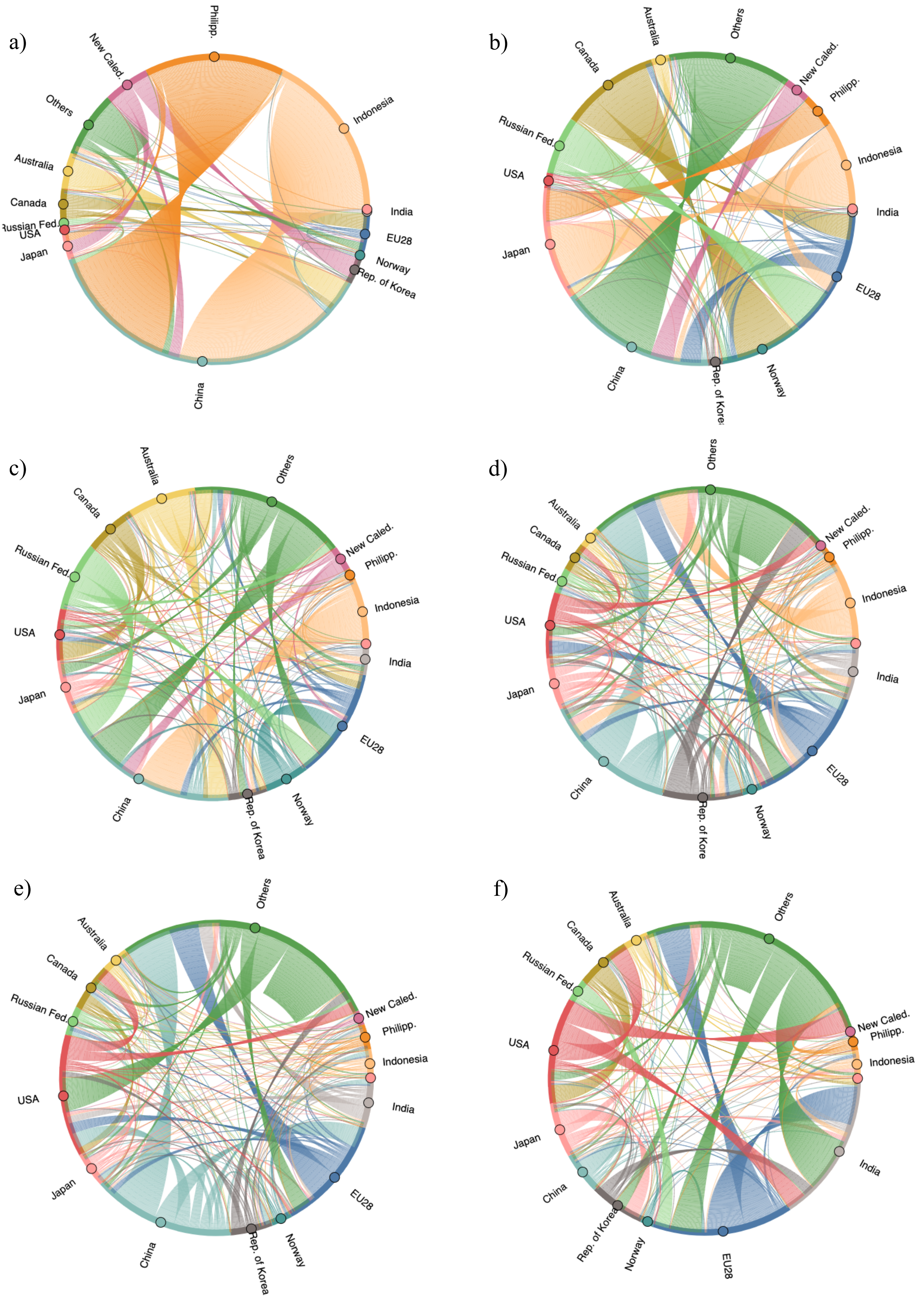


Figure 8 - Trade of nickel in various forms between selected countries: (a) ores and concentrate, (b) intermediates, (c) finished nickel, (d) first-use products, (e) end-use products, and (f) scrap. Intra-EU trade is not represented.

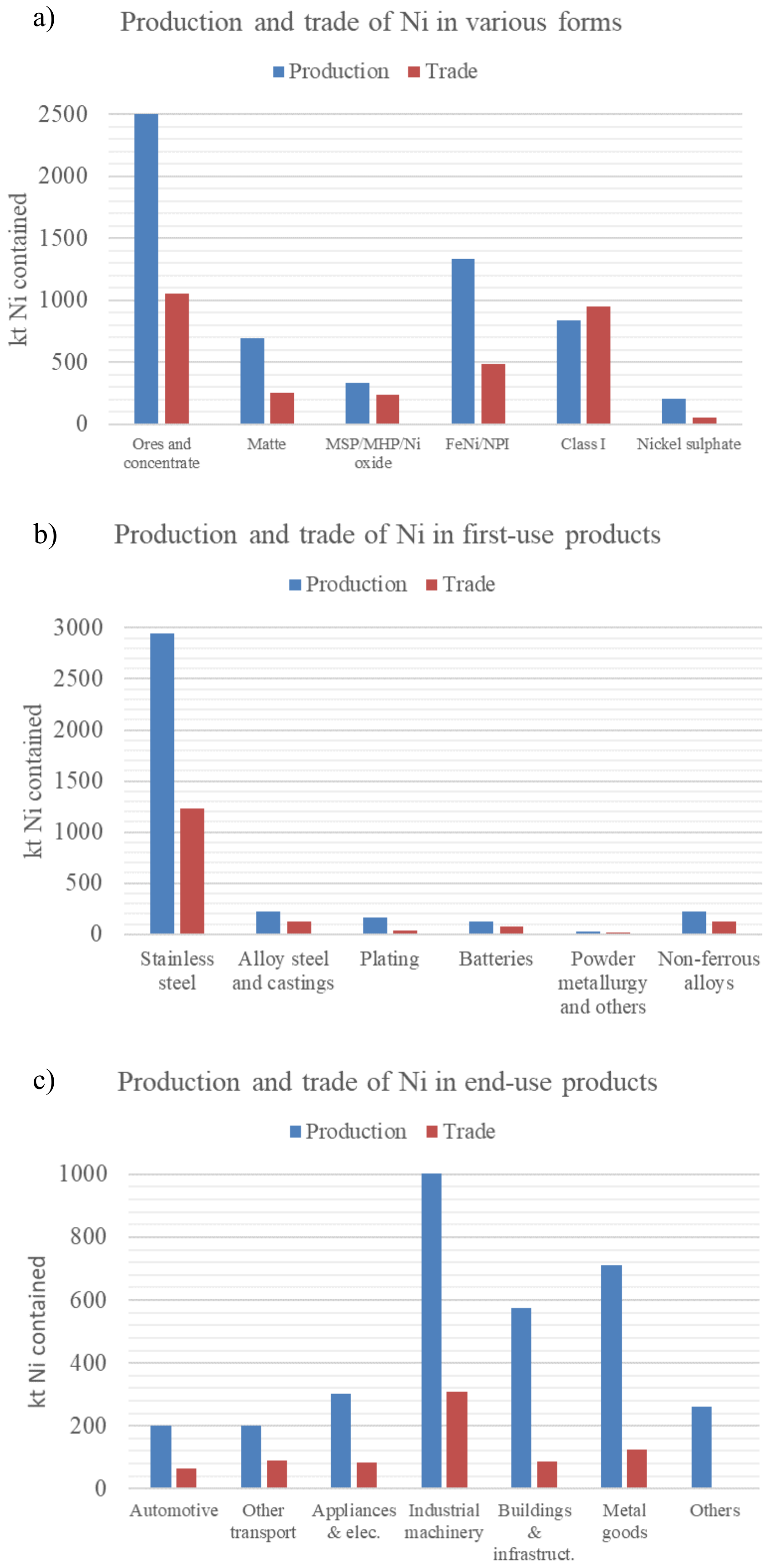


Figure 9 - Breakdown of the production and trade of nickel based on the products covered by the product categories: (a) ores and concentrate, intermediates and finished nickel, (b) first-use products, and (c) end-use products.

3.3. Country-level perspective on the production and trade of nickel

After being presented with a focus on the product categories at the global level, the quantification of the global trade-linked cycle results is shown in this subsection from an individual country perspective.

Figure 10 displays the net trade balance for each product category and the overall net nickel balance for the main countries identified to illustrate section 0. A positive trade balance means that exports are more prominent than imports and vice versa.

In addition, country-level Sankey diagrams of the selected countries give a complementary outlook and show the quantification of the system, including domestic flows, losses, trade flows, and stock changes (SC), while making mass balance inconsistencies (MBI) transparent to the reader. The diagrams of Indonesia, the EU28 and China are displayed in Figure 11, Figure 12 and Figure 13, respectively. The other country-level diagrams are presented in appendix 11. For comparison, all diagrams are represented at the same scale. This scale is 2:1 compared to the one used for the global system in Figure 6.

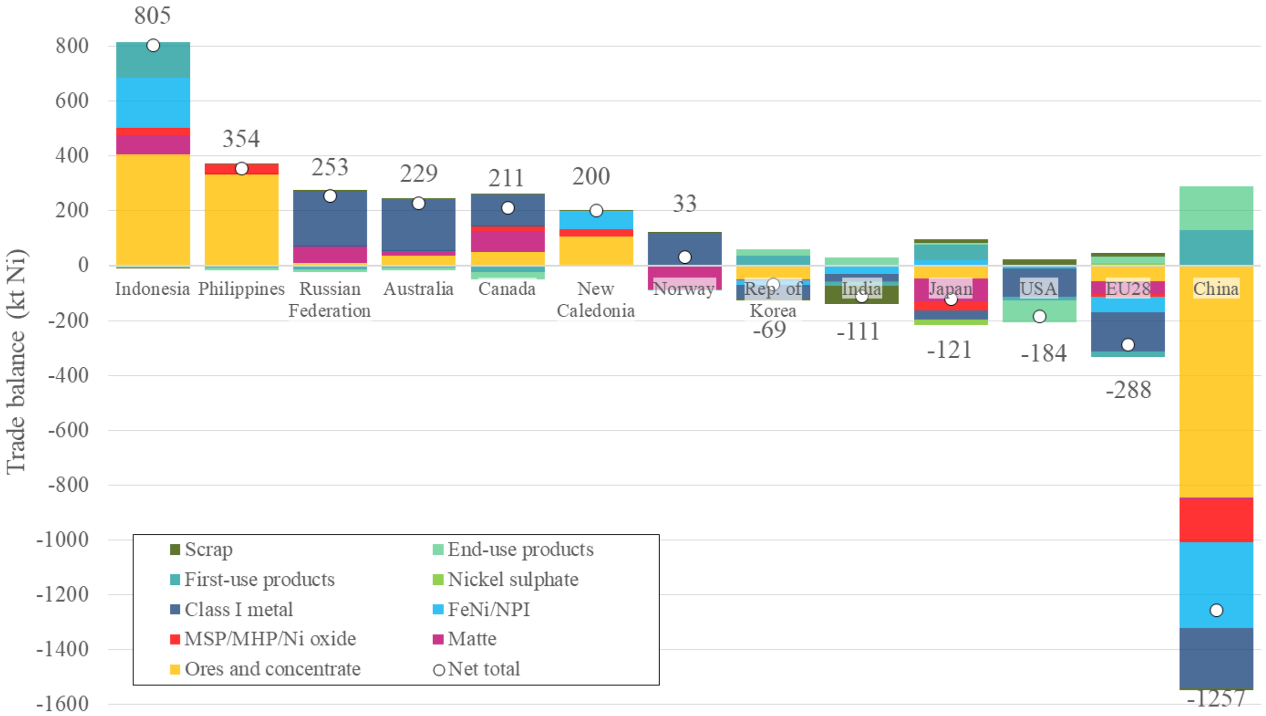


Figure 10 - Nickel trade balance of selected countries

3.3.1. Indonesia, Philippines and New Caledonia

In 2019, Indonesia was the largest net exporter of nickel globally. With a positive balance estimated at 805 kt Ni, it is a net exporter in almost all the categories and dominates the net exports of ores and concentrate, FeNi/NPI, while ranking second in first-use products closely behind China. The Philippines is the second net exporter of ores and concentrate globally. The gap with Indonesia is much smaller for net exports (53 kt Ni) than for production (645 kt Ni). Unlike Indonesia, the Philippines has a minimal capacity to process its laterite ore. Also, it does not have any refining capacity, so its small consumption of first- and end-use products is supplied by imports, which are negligible compared to its exports of ores. Therefore, the overall net trade balance is largely positive (354 kt Ni). New Caledonia shares a similarity with Indonesia because it exports about half its laterite ore production but still processes the rest inside the country to make FeNi. However, New Caledonia has barely any stainless steel production, so its FeNi is entirely exported.

3.3.2. Russian Federation, Australia and Canada

The Russian Federation, Australia and Canada have similar profiles with a comparable net trade balance and breakdown by categories. The three countries benefit from significant sulphide concentrate production (and laterite ore production for Australia), local processing facilities enabling them to produce intermediates (especially matte), and local refining capacities that yield class I metal intended in a large majority for exports. These three countries are also net importers of both first- and end-use products. The main difference is that the Russian Federation contributes five to six times less to the exports of ores and concentrate than Canada and Australia but more to the exports of matte and class I metal due to more important smelting and refining capacities.

3.3.3. Norway, the Republic of Korea and Japan

Norway is a particular case. It has no local mining or intermediate production. It only intervenes in the cycle with its local refining capacity of fully imported matte to class I metal, which is entirely exported. Thus, its net trade balance should be lower than displayed in Figure 10 and even slightly negative, but the reasons behind this issue are discussed in greater detail in subsection 4.1.2. The Republic of Korea does not have local mining but has domestic FeNi smelting of imported laterite ore. Therefore the imports are primarily ores and the class I metal to supply the fabrication of first-use products. However, the country is a net exporter of first-and end-use products, especially stainless steel and industrial machinery. Japan is overall a net importer of nickel, with a trade balance of -121 kt Ni. Its production and trade profile is a hybrid version of Norway and the Republic of Korea because it does not have local mines but imports laterite ore for FeNi smelting and intermediates for refining to class I metal or to produce sulphate. Like the Republic of Korea, it is a net exporter of stainless steel. However, its exports of end-use products are lower.

3.3.4. India

The specificity of India in the selected countries is that it does not have any mining, processing, or refining capacities. It essentially relies on imports of class I metal and FeNi/NPI, but most importantly, scrap to supply its domestic stainless steel production.

3.3.5. USA

The USA have a net trade balance of -184 kt Ni. It has a very low mining capacity and no processing or refining facilities. The majority of its net imports are class I metal to supply its production of non-ferrous alloys and end-use products, especially metal goods and appliances and electronic devices, to meet domestic demand. It exports 31 kt Ni in scrap.

3.3.6. EU28

The EU28 is a net importer of nickel, with a trade balance of -288 kt. It benefits from small domestic mining, smelting and refining capacities, especially in Greece for the laterite route and Finland for the sulphide route. It relies mainly on imports at all steps of the nickel supply chain: sulphide concentrate, matte, FeNi, and most importantly, class I metal. Part of Finland's class I metal production is exported or accumulated temporarily in LME warehouses in the Netherlands. Still, it is primarily used in the domestic production of alloy steels and castings, and non-ferrous alloys. The significant stainless steel production in the EU28 is supplied with an important scrap input from the region itself. Additional net imports of first-use commodities supply the domestic manufacture of end-use products. The EU28 is a slight net exporter of end-use products.

3.3.7. China

China is the largest net importer of nickel in the world. Its total net trade balance is estimated at -1257 kt Ni. It benefits from important local sulphide mining, but it is insufficient to meet the country's very high demand. Therefore, the class I metal production from domestic matte refining is complemented with significant class I imports. Likewise, the sulphate production from class I conversion is supplemented by imports of MSP/MHP. In addition, the stainless steel production in China requires massive amounts of FeNi/NPI, either smelted from imported laterite ore (about two thirds) or directly imported. China is also a net exporter of first-use products, especially stainless steel (95 kt Ni), alloy steels and castings (27 kt Ni), and batteries (18 kt Ni). Finally, China is a net exporter of end-use products, particularly industrial machinery (59 kt Ni), appliances and electronic devices (35 kt Ni), and metal goods (30 kt Ni). However, the majority of end-use products enter in-use stocks.

Indonesia - nickel cycle in 2019

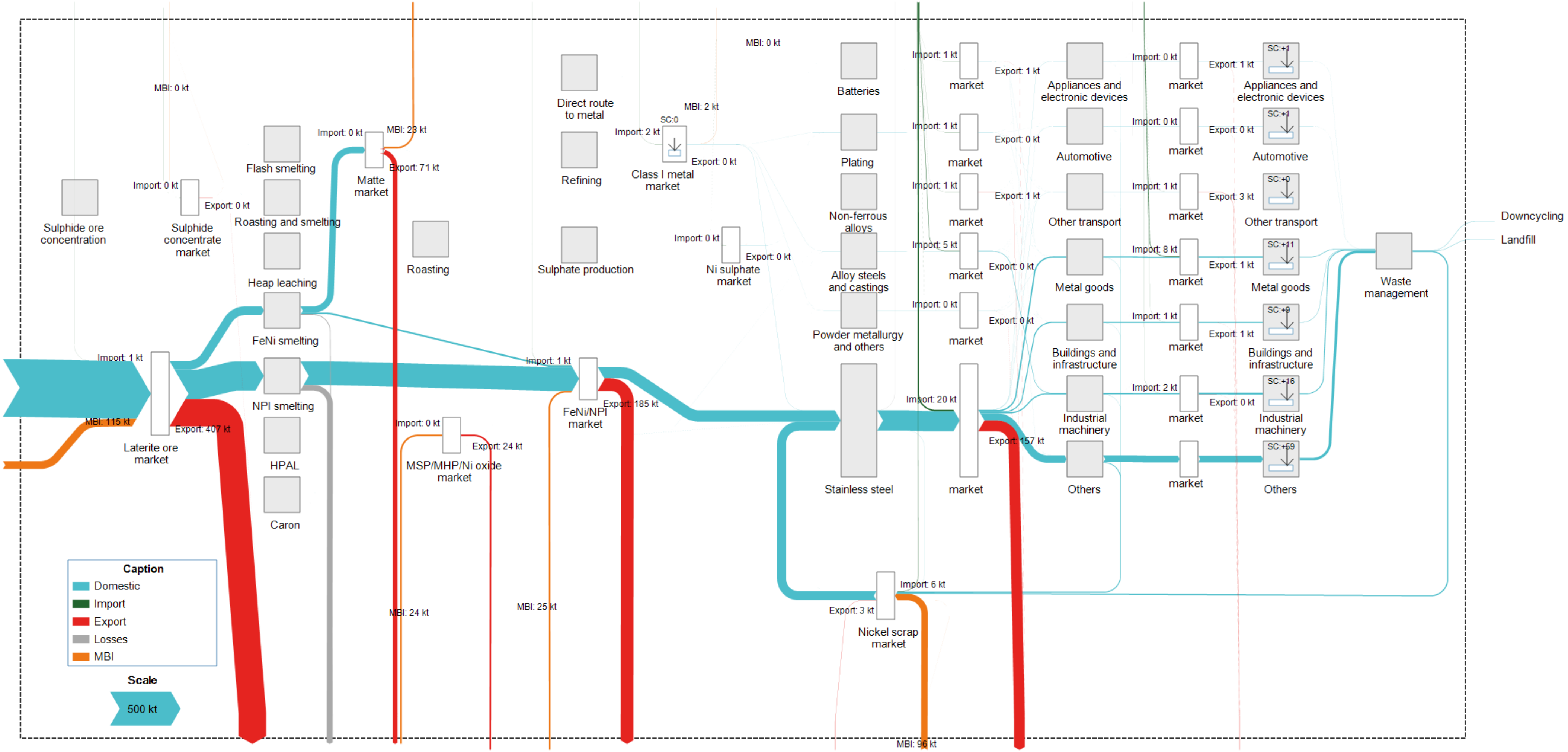


Figure 11 - Quantified MFA system for the nickel cycle in Indonesia in 2019

EU28 - nickel cycle in 2019

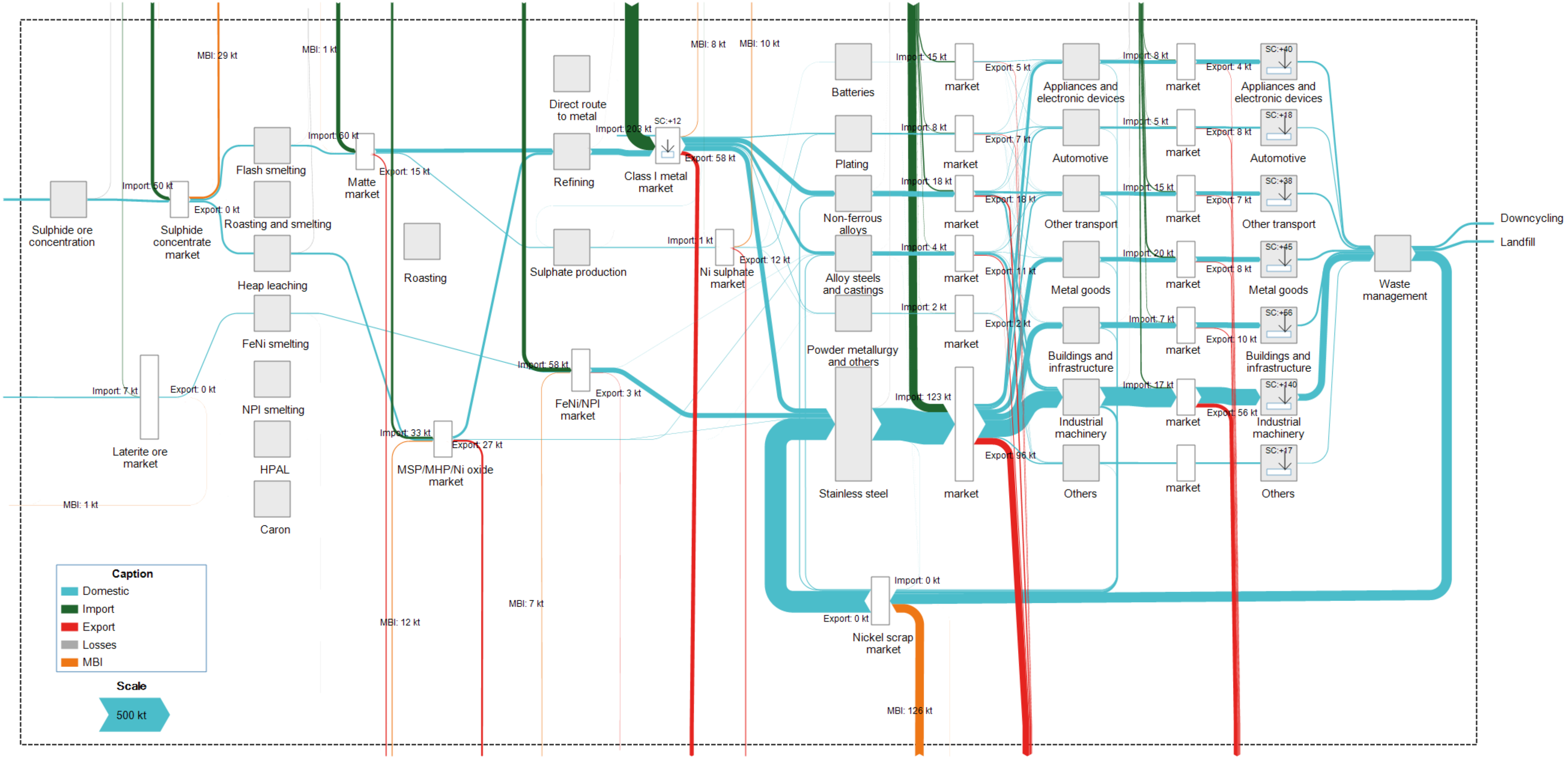


Figure 12 - Quantified MFA system for the nickel cycle in the EU28 in 2019

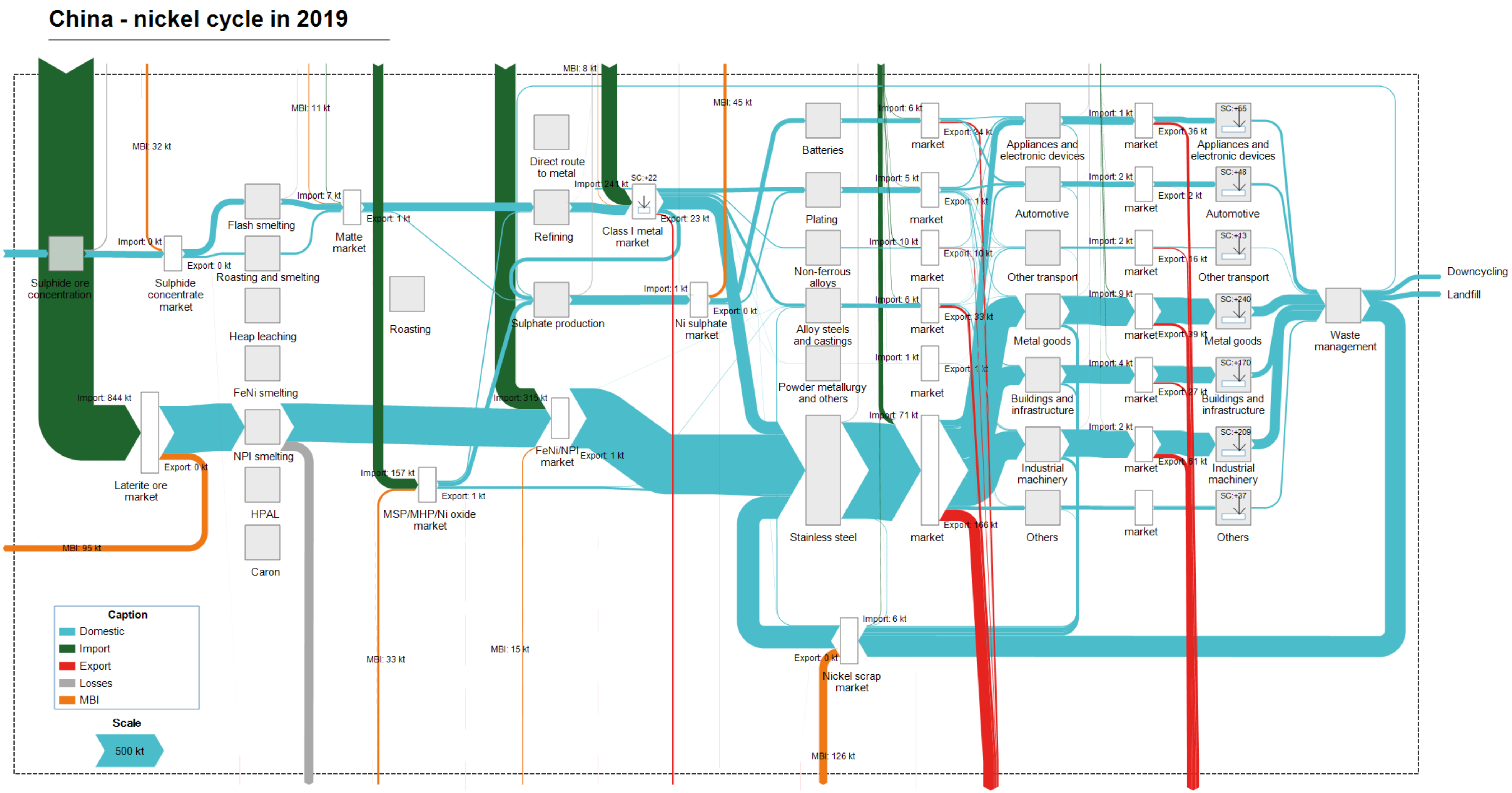


Figure 13 - Quantified MFA system for the nickel cycle in China in 2019

4. Discussion

4.1. Accuracy of the results and limitations of the study

4.1.1. Mass balance inconsistencies

In the results of section 3, mass balance inconsistencies were explicitly indicated. The MBI are gaps that may appear when the system is quantified with more independent equations than necessary. The idea is that instead of deducing some flows by the mass balance of a process or a market, they are calculated from an independent source or calculation. Confronting different sources and figuring the MBI helps to understand the origins of the uncertainties of the work, possible limitations in the system definition or the calculation methodology, and, to a certain extent, to validate some results. This work calculated MBIs at eight markets: sulphide concentrate, laterite ore, matte, MSP/MHP/Ni oxide, class I metal, FeNi/NPI, sulphate, and scrap. It can be highlighted that, due to the calculation methodology detailed in subsection 2.3.1, the markets of first- and end-use products are balanced. For this part of the system, the data sources were too few to calculate the inflows and the outflows independently from each other.

At the global level, the flows in Figure 6 are calculated as the sum of the generic country-level cycles calculated for all the countries reporting production or trade of nickel in any form. Since the total mass of imports and exports is the same (mass balance forced by the reconciliation of trade data), the contributions of the trade flows to the MBI at the global level cancel each other out. The only exception is for the ores and concentrate. Indeed, it is the only case where one HS code (2604.00) designates two different markets (sulphide concentrate market and laterite market), which means that the choice of attribution to either market or partly to both can contribute to the MBI at the global level. The INSG covers the mining countries with production above 0,1 kt Ni, and the type of ore is known because usually only one type is mined in a country. Some countries not covered by the INSG report some trade of ores and concentrate, and a split of 50-50% is arbitrarily used. However, even if these flows theoretically contribute to the MBI at the global level, their contributions are negligible. The main contribution of trade flows to the MBI of ores and concentrate at the global level is due to two countries: China, which has sulphide mining but processing facilities for both types of ores, and Australia, which has the two types of mining and processing. These are two key actors of the nickel industry, and the split of import data between the two markets requires some assumptions. Manual adjustments were made to try and minimize the MBI. However, one must be cautious with such intervention because it must be done equally in the partner countries to ensure that the mass balance is respected. An idea for future improvement of the algorithmic model would be to track for each trade flow the share attributed to each type of ore, to stay consistent between exporters and importers, and thus only make assumptions for the exporter, which is generally more straightforward.

Having established that MBIs at the global level are independent of trade flows' contributions, with some exceptions for ores and concentrate, the datasets and parameters used to compute the markets' domestic inflows, and outflows are discussed. For the mining and finished nickel productions, other datasets than those cited in subsection 2.2.1 were available, particularly from the British Geological Survey (2020) and the United States Geological Survey ((U.S. Geological Survey 2021). The detail of these datasets is presented in appendix 12. The range between the lowest and highest value estimated for each country can sometimes be significant: the ranges of the Russian Federation (25% for mining, 35% for finished nickel), Indonesia (18% for mining, 9% for finished nickel) and China (15% for mining) are particularly important to mention due to their high contribution to global and finished nickel mining, as demonstrated in subsection 3.2.1. The sources may differ due to:

- Different estimates for countries with low-quality statistics (e.g. Indonesia).
- Different publication dates, with access to updated data for the reports published more recently.
- Different relations between the institutions (BGS, USGS, INSG), local companies, and statistical institutes can mean access to better data or insights for better assumptions.
- Different scopes, particularly the inclusion of the production from secondary sources and of nickel sulphate.
- Different methodologies to translate company data into published datasets. Suppose companies are involved in both mining and processing. In that case, they may only report the production of nickel contained in the product they sell, which can be a concentrate, an intermediate or a form of finished nickel. Also, some companies prefer to report their production in net weight and not in metal content. This means that some assumptions (efficiencies, ore grade) are necessary to derive mining production, and they can differ from one institution to another. Assumptions are also required to deal with double-

counting issues (e.g. class I conversion to sulphate, refining matte to nickel oxide and then to class I metal).

MBIs result from many positive and negative contributions, making it difficult to point out that a specific flow is either over- or under-estimated. For instance, for sulphide concentrate, the MBI of 101 kt Ni could mean an over-estimation of the mining production or an under-estimation of the feedstocks of flash smelting, roasting and smelting, and heap leaching due to a too low estimate for efficiencies or the intermediate production. Each is a sum of positive and negative contributions from production parameters at the country level, which can add up or compensate.

However, the net MBI calculated at the global level can indicate where the system shows weaknesses because it can result from an error that occurs systematically at the country level. The results of subsection 3.1 show that the largest MBIs in the system are in the laterite ore market and the scrap market. For laterite ores, some reasons have already been mentioned in the previous paragraphs, and country-level diagrams show a “missing inflow” for some of the most critical laterite ore producers (Indonesia, Philippines). The MBI of the scrap market is easier to read. At the global level, the “missing inflow” of 160 kt Ni can be explained either by an over-estimation of the scrap input in stainless steel production or the under-estimation of the new and old scrap. Based on the uncertainties discussed in subsection 2.4, the scrap inclusion rate has a lower uncertainty, at least for some specific countries, and at the global level, compared to the scrap generation, which is the result of cascading assumptions even at the global level. This shows even more at the country level, as the parameters used for scrap generation were global averages and not country-specific, and the trade of scrap is relatively small in general:

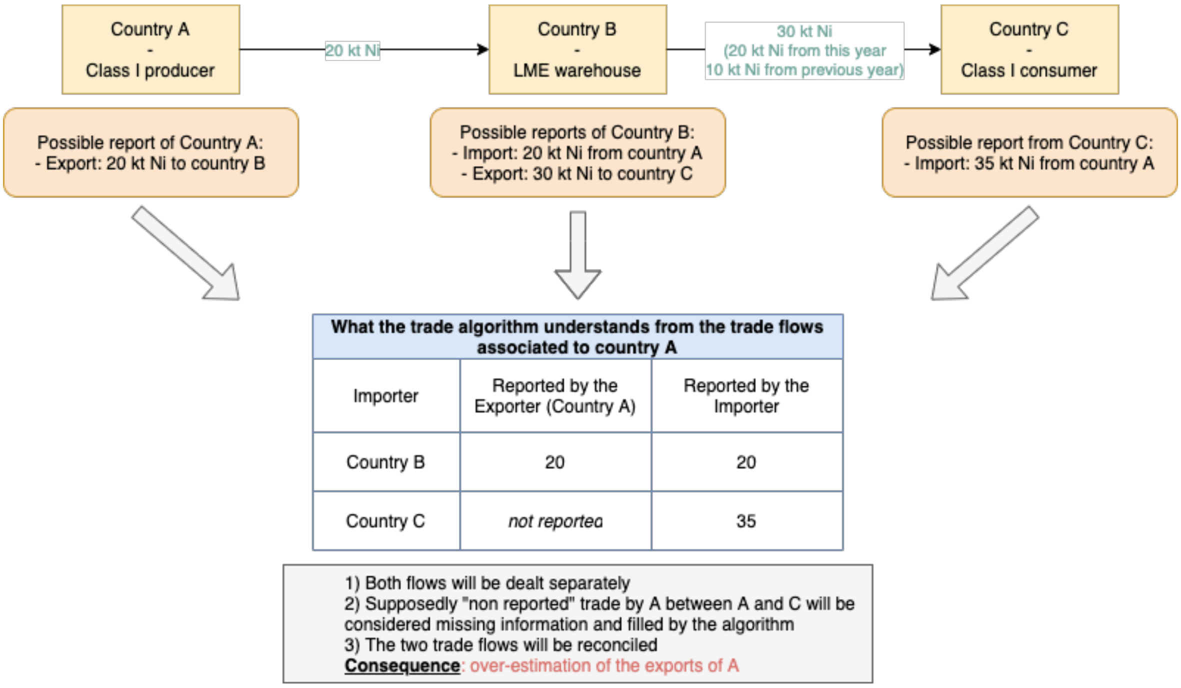
- Countries like China and India have a “missing outflow”, which could be explained by an over-estimation of the post-consumer scrap generated, as their economic development is more recent and their consumption of goods over the lifetime of the end-use products has been lower than the global average.
- Countries like the USA, the EU28, Canada, Japan, and the Republic of Korea all have a “missing inflow”, which could be explained by an under-estimation of the scrap generated, as they are developed economies, which have had higher levels of consumption than the global average over the last two decades.

At the country level, the MBIs can potentially be more significant than at the global level because trade flows also contribute to inconsistencies related to domestic production. MBIs at the country level are particularly noticeable for the top class I exporters (the Russian Federation, Australia, Canada and Norway) and are discussed in a dedicated subsection (4.1.2). With FeNi/NPI being less traded than class I metal, the risks of incoherent trade data are lower. In addition, FeNi/NPI are not connected to any further refining step to class I metal or sulphate as of today, which means that the only uncertainty associated with the domestic production route is the one of the INSG dataset (used for finished nickel production), which is arguably not independent of data from Roskill and the Nickel Institute (used for the consumption of finished nickel in first-use products), hence the low MBI at the FeNi/NPI market both at global and country levels. Nickel sulphate MBIs are not significant in absolute terms, but they can be high compared to production. In particular, China and Japan have a "missing outflow" of 45 kt Ni and 22 kt Ni, respectively, compared to a production of 144 kt Ni and 41 kt Ni. In these countries, there is a possibility that the share of sulphate in plating relative to class I metal is higher than the global average, so a manual intervention could be possible to adjust this split and reduce the MBI of sulphate, but this would, in turn, affect the MBI of class I metal, which would need to be adapted with the MBI of the FeNi/NPI market (sulphate and FeNi/NPI do not have any first-use sector in common, but class I metal has, with both of them). This example shows that manual interventions are possible, and the system can technically be optimized. Still, the author of this report preferred to only intervene in the model's output if it was highly justified with industry knowledge, which was not the case here. Instead, MBIs are made transparent to the reader and discussed.

4.1.2. Double-counting issues

The results of subsection 3.2 demonstrate that for some categories such as class I metal, first-use products, or scrap, the trade computed by the model was higher than the production, either at the global level or the country level. It is argued in this subsection that this phenomenon may, to a certain extent, be caused by double-counting issues, which may lead to the over-estimation of trade flows connected to some countries.

To illustrate this, the example of the trade of class I metal is very evocative. Indeed, it was emphasized in subsection 3.2.3 that all the major producers of class I metal are attributed exports larger than their domestic production. As was explained previously in this report, this commodity is highly traded, and the LME and the SHFE regulate the transactions. Therefore, important class I quantities transit through warehouses in countries such as Malaysia, the Netherlands, Singapore, Taiwan or China, where they can be stored for multiple months depending on the market demand and logistics. Usually, the country with the warehouse will report it both as an import when it comes in and as an export when it comes out, leading to double-counting. According to the concepts and definitions of the International Merchandise Trade Statistics of the United Nations (United Nations. Statistical Division. 2011), it is recommended that these "re-exports" are not only reported as exports but also in a separate category for analytical purposes. However, during the study, it was observed that this reporting category is barely used in the UN Comtrade database and thus does not help deal with this issue. In addition, when the class I metal is being shipped further to a country where it is used in first-use sectors, it must be reported as an import according to the Rules of Origin, which means that the trade partner will be reported as the country where the class I metal was refined, and not the intermediate warehouse. This misleads the algorithm into believing that the producer of class I trades with more countries than in reality since the exporter reports the last known destination (arguably the warehouse), and the importers will be both the warehouse and the actual consumer.



What the trade algorithm understands from the trade flows associated to country A

Importer	Reported by the Exporter (Country A)	Reported by the Importer
Country B	20	20
Country C	*not reported*	35

1) Both flows will be dealt separately
2) Supposedly "non reported" trade by A between A and C will be considered missing information and filled by the algorithm
3) The two trade flows will be reconciled
Consequence: over-estimation of the exports of A

Figure 14 - Fictional example illustrating the issue of double-counting in class I metal trade reporting.

An illustration of this issue is shown in Figure 14. The problem with this attribution of the partner country is that it is very complex and usually even impossible (at least with objective and reasonable assumptions) to reattribute the "right" partner and the "right" amount because, unlike in Figure 14, (1) there are many more producer and consumer countries involved, (2) the intermediate countries can also be consumers at the same time, and (3) the intermediate countries are difficult to identify accurately: if the IMTS highly recommends that goods simply being transported through a country, in transit or transhipment are excluded from the reported data, no country is obligated to follow this guideline, and therefore other countries can play the role of an intermediate country, without having an LME or an SHFE warehouse. This seems especially frequent inside the EU28, where intra-firm or inter-country trade is not systematically reported.

Figure 15 shows an example of trade data reported by the Russian Federation and Norway and their trading partners. Even though the report of imports by the Netherlands shows a large discrepancy with the exporters, they cannot be corrected easily without making strong assumptions since there are many unknowns regarding (1) the Dutch imports for its own use, (2) the inventory in the LME warehouse, and (3) the destination of Dutch exports. These questions are not simple to answer, mainly because the Netherlands did not report any class I export in 2019. There is always a possibility to suggest an algorithm to try and solve this problem. Still, one must remember that class I metal is only one commodity amongst many analyzed in this study. Generalizing an algorithmic rule from a specific example can be tricky and possibly cause the opposite effects by "worsening the data" in another part of the system. For instance, in the trade data reported by the Russian Federation, a partner is Switzerland, which does not have any LME warehouse storing nickel to the author's knowledge. Therefore an algorithm treating only LME warehouses would overlook this issue and possibly mask it entirely by changing the value.

In addition, double-counting issues are hard to process because they are not the only source of discrepancy and thus cannot be isolated to solve them. The example of the LME warehouse in Malaysia is relevant to show this.

Reported by the Russian Federation

Importer	Amount (kt Ni)
Netherlands	95
Switzerland	38

Reported by the partners of the Russian Fed.

Importer	Amount (kt Ni)
China	88
Germany	31
Netherlands	11
Other Asia	8
Singapore	6

Reported by Norway

Importer	Amount (kt Ni)
Netherlands	38
China	8
USA	8
Japan	6
India	6
Sweden	6

Reported by the partners of Norway

Importer	Amount (kt Ni)
China	10
France	10
USA	9
Germany	8
Japan	7
India	6
Sweden	6

Figure 15 - Example of reports of trade for class I metal by Norway, the Russian Federation and their partners. Only flows above 5 kt Ni are indicated. Source: UN Comtrade.

Figure 16 shows the stock and stock variation of class I metal in the LME warehouse of Malaysia. There is no metal use in the country. If the overall trade over the years is coherent between the one calculated from trade data and LME inventories, it should be noticed that there is an important mismatch for specific years that are compensated by report at a later date. For example, in 2015 and 2016, the stock variation was considered positive from trade statistics, whereas the LME inventory, which is much more reliable, shows a negative value. In 2017, the over-report of class I import or under-report of class I export was compensated by a negative trade balance, and the stock matched again. For 2019, it can be observed that there is likewise a mismatch between the stock and stock change estimated from the two sources. This could be due to a delayed trade report, but in the meantime, this causes the over-estimation of the net imports of class I metal of Malaysia in 2019. The issue is that Malaysia is the destination of about a quarter of Australia's exports of class I metal. Simultaneously, the Australian Bureau of Statistics has issued confidentiality restrictions on the reporting of exports of nickel products (Australian Government 2019). Because only a few firms produce such products as the ones of the nickel industry in a country (usually less than three producers), trade data often coincides with private intel. Thus, governments are allowed to only report their trade under the first two digits of the code (UNCTAD 2012), which makes its use impossible in a study like the one described in this report. Therefore, Malaysian data had to be used, causing an over-estimation of Australian exports and increasing the mass balance inconsistency. Again, this issue, once in many, can be modified by manual intervention. Still, this subsection shows that this requires strong industry knowledge and independent sources to correct the issue, in addition to strong assumptions (here attributing the net balance which was positive in the LME inventory partly to more exports and partly to fewer imports than reported by trade data).

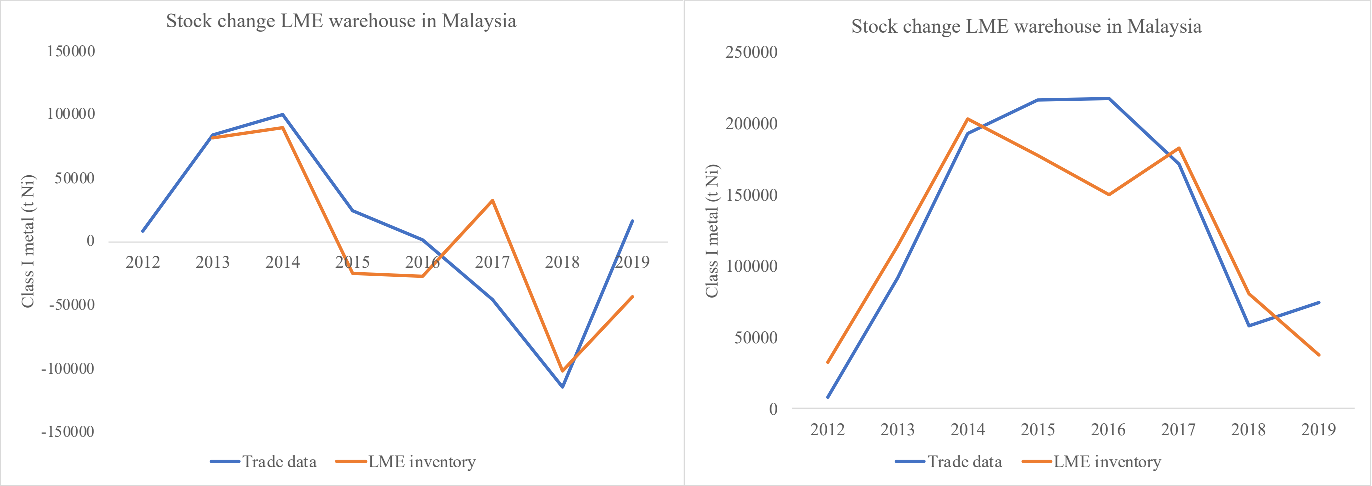


Figure 16 - Stock and stock variation as calculated from trade data and LME inventories. Source: Comtrade, INSG (2020)

4.1.3. The necessity of a more refined HS code for lithium-ion batteries

The results of 3.2.4, particularly Figure 9, have shown that the mass of nickel associated with the production and trade of lithium-ion batteries in 2019 is low compared to the most significant flows of the nickel cycle at the global and the country level. However, LIBs are expected to become critical commodities soon. The two main reasons are the fast-growing demand for the EV industry and the current concentration of the production in a few countries: this study estimates that 58% of the Ni-containing batteries are produced in China, followed by Japan (27%) and the Republic of Korea (9%). The European Union is currently strengthening its regulations on sourcing sustainable raw materials for batteries and calls for more transparency in the battery supply chain through initiatives like “battery passports”. Driven by similar motivations, collecting and managing representative and accurate trade statistics could be an additional helpful tool to support decision-making and increase the knowledge of the battery supply chain. However, tracking materials such as nickel in the battery supply chain is impossible with the system currently in place for monitoring the trade of commodities.

At the international level, the Harmonized System is only revised every five years by the World Commodities Organization (WCO). With the last update in 2022, the commodity code associated with lithium-ion batteries 8507.60, created in 2017, has not been revised. This code designates LIB pack for all applications (EV, energy storage systems, portable devices) simultaneously but also many components that make them: battery modules, battery cells, and possibly the cathode active materials (CAM), or even the precursor cathode active materials (pCAM). Since these products have not been traded a lot historically, explanatory notes of the HS system are not explicit about how to attribute these products to a trade code, which leaves room for interpretation and inconsistency in their attribution by reporting countries. In addition, if many commodities are identified with a single code, there is a high risk of double-counting. For example, cells produced in country A can be exported to country B to be assembled in modules, then to country C to be assembled in packs, and used in country D to manufacture an EV. In this theoretical example, the product could be reported up to three times (if reported from A to B, B to C, and C to D). A low resolution of the HS system is problematic for studies like the one described in this report because it can lead to an overestimation of the total trade associated with a category and increase the already high uncertainties related to trade data in general (e.g. missing values, partner country attribution, reporting errors).

Furthermore, the components above under the HS code 8507.60 have different nickel content because nickel is almost exclusively present in the cathode. In this work, the nickel content in Ni-containing batteries (for a virtual battery item weighting the various NMC and the NCA chemistries by their market shares) is estimated to range from 7,9% (in battery packs) to 36,9% (in pCAM). When considering the market shares of all the battery chemistries (including the ones that do not contain nickel but are anyway identified under the same code), the nickel content in batteries is estimated to range from 3,9% (in battery packs) to 18,5% (in pCAM). For this study, a strong assumption was made to attribute the same weight to each nickel content (pCAM, CAM, cell, module, pack), leading to an average nickel content of 10% for this commodity code. Weighting each component differently would require better market knowledge, especially in knowing at which step most trade occurs, which seems unrealistic to tell with data publicly available as of today.

These issues make it harder to move from an analysis of the nickel cycle to a more precise but accurate analysis of a single product category like batteries. Therefore, this study calls for better refining trade codes associated with LIBs in the HS system and revising the explanatory notes produced by the WCO.

4.2. Insights into the production and trade of nickel around the world

In this study, the anthropogenic nickel cycle was studied in its entirety for most of the countries in the world. The results of section 3 show some important patterns in the production and trade of nickel along its anthropogenic cycle.

4.2.1. Production and trading patterns in the sulphide and laterite routes

The global system of Figure 6 shows that from the mines to the finished nickel, there are two main routes that start with the two types of ores. These run in parallel and barely interact: sulphide concentrate is mostly smelted to matte and refined to class I metal, while laterite ores are smelted to FeNi/NPI. There are connection points between the two paths, mostly refining MSP/MHP from HPAL production to class I metal or sulphate production, but in 2019, these flows were of a lower magnitude. This "isolation" of the two routes is also present at the country level, with countries generally specializing in one type of ores, even if they do not have local mining. For instance, Norway, Canada, or the Russian Federation only intervene in the sulphide route, while Indonesia or New Caledonia only intervene in the laterite route. This can be explained by the advantages of having smelting and refining capacities in the proximity of the deposits, which are generally of the sulphide type in the northern hemisphere and the laterite type in the southern hemisphere, with some exceptions (e.g. Australia).

In terms of trade, from ores and concentrate to finished nickel, the main trade flows show distinct patterns based on the type of ore involved. It can be observed in Figure 8 a) and b) that there are strong regional transfers of laterite ores and intermediates from Oceania to East Asia. Transfers of laterite ore are considerable from Indonesia and the Philippines to China, mainly to be smelted to NPI and used in stainless steel production. For the same reasons, China is also involved in NPI trade with Indonesia. The only upgrade of intermediates such as matte made from laterite ore by sulphidization, or MSP/MHP/Ni oxide from HPAL plants, to high-purity forms of nickel (class I metal and sulphate) is not done in countries with mining resources like Indonesia or the Philippines, but by exporting them to Japan and the Republic of Korea, which have refining facilities. These two countries also receive ores from New Caledonia to smelt the mined production, which cannot be processed locally due to a lack of refining capacities. Figure 8 shows a second distinct pattern of trading relations linked to the sulphide route: the trade of concentrate and matte occurs mainly from Canada to Norway and the EU28 or from the Russian

Federation to the EU28. However, as seen in Figure 9, sulphide ores, concentrate and matte are traded in much lower volumes than laterite ores and MSP/MHP/Ni oxide.

Finished nickel, however, is a lot more traded in the form of class I metal than FeNi/NPI. Most of the class I metal is exported by the Russian Federation, Canada, Australia and Norway, which have been identified as the main producers, to the most significant consumptions market, namely China (218 kt Ni net import), the EU28 (145 kt Ni net import), the USA (101 kt Ni net import), the Republic of Korea (51 kt Ni net import), and Japan (23 kt Ni net import). Meanwhile, FeNi/NPI smelted domestically is either consumed in the same country or traded in smaller amounts to minor countries to be used as a cheaper feedstock than class I metal in the production of stainless steel.

The trade patterns in the sulphide and laterite route reveal the profile of the countries involved and the extent to which they benefit from added value. In the laterite route, the role of resource countries such as the Philippines and New Caledonia shrinks considerably as the ore, and the few intermediates are exported to be smelted to China, Japan or the Republic of Korea. Indonesia's role is different because if a large number of its ores were exported to China in 2019, it is also involved in NPI smelting and stainless steel production, and the government tries to change the situation to better leverage the vast local resources and retain more value-added in the country (see subsection 4.2.3 for more details). On the contrary, the countries involved in the sulphide supply route are all developed countries, and the trade is limited in ore, concentrate or intermediate form because these countries have domestic refining capacities, which enable them to retain more value-added from the operations: during refining, some valuable by-products like copper, cobalt or platinum can be recovered (Kerfoot 2000).

This difference in the processing and the relative trade of commodities in the early stages of the sulphide and laterite route is also embedded in physical facilities. It is important not to be misled by the system defined for this study and the visualizations that show smelting and refining as separate technological processes. In many situations, the sulphide smelting and refining steps are integrated into the same facility, and the matte production is "locked-in" and cannot be exported. On the contrary, MSP/MHP produced from HPAL plants that could produce high purity forms of nickel are rarely associated with a refining facility in the same country, as was seen with the exports of MSP/MHP from New Caledonia to Japan and the

Republic of Korea, for instance. This phenomenon is clearly shown in Figure 9, as 70% of MSP/MHP/Ni oxide production is traded, compared to only 37% for matte.

Finally, if this study has analyzed the production and trade of nickel from individual country perspectives, it should not be forgotten that private corporations own most mines and facilities. States can influence production and trade through regulations, taxes or subsidies. Still, some trade flows of ores and intermediates are well-established via agreements between companies or even often intra-firm, making it challenging to orientate flows in a coordinated way. Some examples can be cited:

- The export of matte from Canada to Norway, which occurs inside the organizational boundaries of Glencore.
- The export of matte from the Russian Federation to Finland, which occurs inside the organizational boundaries of Norilsk.
- Most of the export of matte from Indonesia to Japan (80%), which occurs inside the organizational boundaries of Vale.

4.2.2. Consumption, production and trade patterns in the first- and end-use sectors

Consumption patterns of finished nickel by the first-use sectors in the EU28 and China are different, as shown in Figure 12 and Figure 13. These countries import and produce the same order of magnitude of class I metal. However, China relies on considerable NPI for its stainless steel production. In contrast, the EU28 uses about 70% of scrap as feedstock and limits the consumption of FeNi to a minimum. This is not possible for China because industrialization in the country has happened in the last decades. Therefore, scrap availability is much lower than in historically developed economies such as the EU28 or the USA.

The types of feedstock consumed by the first-use sectors of the key countries at this step (China, the EU28, the USA) resonate with some of the patterns described in the previous subsection on the supply of nickel. Historically, sulphide deposits were a favorite because of the countries' political stability and proximity to the consumption markets. It was also cheaper because it used less energy for its processing and the metal content of the products was higher than in the laterite route. However, this trend changed in the mid-2000s with the development of emerging economies in East Asia, particularly China, which has driven up the contributions of new actors in the nickel industry in Oceania in the production and trade of ores and concentrate, and to a smaller extent, intermediates in the last fifteen to twenty years.

The trade flows of nickel in first- and end-use products in Figure 8 d) and e) show that the number of partners involved downstream of the cycle increases as nickel becomes an element among others in products used by all modern societies. Especially, the category “others” grows, and the trade flows are more intricate and represent smaller amounts. The production of first- and end-use products are for half in China. However, the trade in these categories is smaller, as these products are primarily used to meet the domestic demand and join the in-use stocks. The trade flows do not show clustering effects. Still, they are also more difficult to analyze since many products are covered, and many countries are involved, contrary to the supply of nickel, where each commodity could be analyzed separately, and the number of actors was reduced.

It is relevant to point out that virtually no country in the world can consider itself autonomous in the nickel cycle as of today. China is one of the most critical countries in the cycle and is involved at all steps of the value chain, but, as was seen in subsection 3.3.7, its local mining is negligible compared to its consumption, which means that it is heavily reliant on imports of all forms (ores, intermediates and finished nickel). In addition, it was shown that most of the countries involved in the class I route (Russian Federation, Canada, Australia, Norway) have no domestic consumption of their refined nickel production. They are, therefore, just as reliant as their importers on volatile nickel prices.

4.2.3. Recent events and potential impacts on the global nickel cycle

4.2.3.1. Indonesian ban on ore exports

In 2014, the Indonesian government unexpectedly announced a mineral export ban, preventing nickel ore exports. Two years later, it was relaxed because revenues were dropping too much for Indonesian companies, and the government gave a five-year delay for companies to invest in local smelting and refining capacities to treat the ore domestically. In addition, this was an incentive for Chinese companies – the main importers of nickel ore – to invest in NPI smelting plants in Indonesia (Keskinkilic 2019). However, the export ban of ore with Ni content under 1,7% became effective two years ahead of schedule. This amendment was issued to try and retain more value-added from the local resources, especially by pushing forward the country's involvement in the battery supply chain and possibly developing the domestic EV industry.

The outcomes of such a strong market intervention by the Indonesian government on the trade of nickel products cannot be predicted. Such a situation has had too few precedents to be sure of the effects on LME nickel prices (Lim, Kim, and Park 2021) or if the strengths that Indonesia has to offer to the EV industry will outweigh its weaknesses (Pandyaswargo et al. 2021). However, it can be expected that in the short term, the results of 3.3.1 will change according to the following:

- Prevented by the export ban, the trade of ores and concentrate will decrease significantly between Indonesia and China. Filipino mining production and exports may increase to compensate for that loss, but since most of the output is already exported to China, this should remain limited. Therefore, the trade of ores and concentrate at the global level should diminish;
- The trade of finished nickel, especially NPI, should continue to increase between Indonesia and China, as nickel will be more exported in this processed form than before;
- In the longer term, the nickel needed for LIBs could be increasingly coming from HPAL plants that would be implemented in Indonesia to upgrade laterite ore to feedstocks suitable for sulphate production (MSP/MHP). Companies such as the German BASF, the Japanese Sumitomo Metal Mining and the French Eramet have considered refining activities in Indonesia by the mid-2020s (Pandyaswargo et al. 2021). In any case, Indonesia should become a hotspot for developing the HPAL technology since it is estimated that 70% of the world's 220 kt Ni project production capacities for HPAL are planned to be built in Indonesia (Bloomberg 2022).

4.2.3.1. The Russian invasion of Ukraine

Currently, Russian metals are not subject to import bans by the international community. However, as the war continues, stricter sanctions are being imposed. The relations between Western economies and the Russian Federation remain very tense and plans to decrease the dependency on Russian commodities are being designed. Therefore, the nickel industry could undergo important changes in the coming years.

As was seen in 3.3.2, the Russian Federation is heavily involved in the sulphide route and is the first producer of class I metal in the world. It is understandable that Russian resources and refining capacity for high-purity nickel are crucial for the battery industry and the transition to cleaner energy production. Figure 17 shows the trade flows of class I metal in a circular diagram where countries are aggregated according to their vote at the United Nations to condemn or not the Russian invasion of Ukraine. Among the "pro-Ukraine", the nations are further split between the members of the North Atlantic Treaty Organization (NATO) - separated by countries that are also members of the EU28 and the others -, members of the EU28 that are not part of NATO, and the other countries. Due to its pivotal role in the nickel industry, China, which voted "Abstain" on this vote, is also shown separately. For clarity, intra-EU28 trade is not shown, except between NATO and non-NATO members, to try and reduce the visual effects of the double-counting issues of class I metal described in subsection 4.1.2.

This graph shows that the Russian Federation, as a single country, exports a large quantity of class I metal to the rest of the world. Notably, these exports are sent to China, a country which has remained in a neutral position since the beginning of the conflict due to its economic ties with Russia. Other significant importers of Russian class I metal are the EU28 members that are part of NATO. If other NATO countries like the USA or Canada are largely independent of Russian nickel, the EU members see almost one third of their class I feedstock coming from the Russian Federation. It should be noted that all the exports of the EU28 NATO members are coming from the refineries in the United Kingdom, which get their Ni oxide feedstock from Vale's operations in Canada and Japan. Therefore, since the Brexit, the UK would join the "other NATO" category in orange in the graph, and the rest of the EU27 NATO members would only be absorbers of class I metal. In addition, it should be highlighted that most of the import of EU28 NATO members from EU28 non-NATO members (in purple on the figure) is from Finland. This reveals another indirect dependency on the Russian Federation because the Finnish Harjavalta refinery is owned by the Russian company Norilsk, which supplies matte to the refinery from its operations in the Russian Federation.

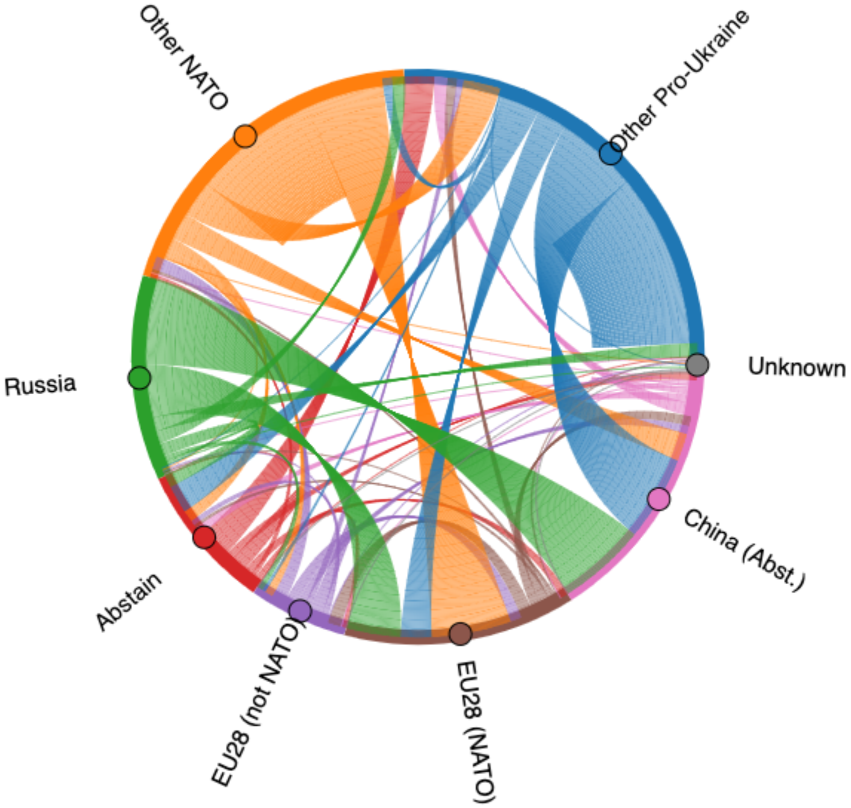


Figure 17 - Trade of class I metal in 2019 considering the countries' standpoint on the Russian invasion of Ukraine in 2022

Thus, depending on the evolutions of the situation in Ukraine, and if sanctions were to be imposed by Western economies on the import of Russian metals, the European Union especially could put itself in a complicated situation, which may partly explain why there is no such ban on minerals today. With reduced access to class I feedstocks, and considering the strong ties between the USA and Canada, such a situation could hinder the development of the battery industry in Europe or incentivize industrial stakeholders to turn to other types of feedstocks for sulphate production, such as MSP/MHP produced from the leaching of laterite ore. Since HPAL technology has higher GHG emissions than sulphide smelting, this could ultimately lower the beneficial effects of the energy transition by the electrification of the vehicle fleet.

4.3. Replicability of the study and opportunities for further work

When developing a global trade-linked model that studies the anthropogenic cycle of a metal for a given year, there is always interest in understanding what is required to update this work in the future. This is even more important for a material like nickel, whose consumption globally is increasing very quickly and which has gotten a lot more attention in research and the media due to its use in the production of cathodes for lithium-ion batteries.

Following the quantification strategy described in subsection 2.3, it can be noticed that the extraction of trade data and its pre-treatment by the algorithm designed for this study is done in isolation of production data, except for the use of the nickel content in products such as ores or intermediates, which can be updated with new sources at country-level, while global averages remain constant, at least in the short term. This means that the algorithm and the Python supporting files that have been programmed during the time of the master's thesis work can be adapted quickly to retrieve and process trade data for later years, and explains why the code was saved on Github to be accessible for the MFA research group of the Industrial Ecology program at a later date. The code can also be adapted easily for commodities containing other materials, as long as these are identified by their HS code. Naturally, it takes about two years for the majority of trade statistics to be reported and added to the UN Comtrade database, which forces a delay before updating the work.

However, if trade data can be retrieved in isolation from production data, this work has shown that confronting production and trade is what made the discussion of the nickel cycle at the global and country level more insightful in terms of power relations, import dependency and export power, but also because it helped significantly in making the results more accurate. Indeed, if the trading algorithm has shown helpful in detecting and removing significant outliers, filling missing data, and reconciling trade statistics, significant corrections were made, and issues were identified that were sometimes specific to the nickel industry and that an algorithm could not have detected. Examples were mentioned in previous sections: double-counting, especially for the trade of class I metal, the use of an average price per kg considering the metal content instead of the entire mass for ores, intermediates and FeNi/NPI in the algorithm, or the issue that some flows were reported in metal content in UN Comtrade.

Thus, if the procedure can always be automated for later years, it will also be essential to update production datasets, which are updated yearly for the most important ones by the INSG and the Nickel Institute. In addition, because some issues require manual intervention, knowing production is essential to make reasonable decisions. This can only be done if the work is performed at a refined level. Ideally, it is better if this is done per trade code, as it was seen that first- and end-use commodities, which represent many commodities, are hard to deconstruct and analyze. In addition, the procedure will always require knowledge of the topic and the industry. Not all problems can be dealt with by algorithms. Sometimes, the risk may be to alter good data because the country would algorithmically have a poor reliability indicator or would benefit from an unusual price. This is precisely the use of databases like BACI which deals with problems in bulk, which was avoided for this study.

There are many opportunities to develop further the model. The quantification of the scrap generation at the country level must be particularly refined. In addition, there will be a need to refine the flows and processes connected to the production of LIBs, but this will only be possible with a more refined tracking with new HS codes. An important improvement could be better quantifying the uncertainties, which have been mostly discussed qualitatively in this report. An uncertainty score for each flow depending on the step undergone in the algorithm could, for example, be designed. Finally, the model could support a more precise analysis of topics requiring knowledge of a refined nickel cycle at the country level related to recycling opportunities or socio-environmental impacts.

Conclusion

During this study, Material Flow Analysis was used to model the processes of the anthropogenic nickel cycle and their connections at the global and the country level. At the international level, it illustrated the two main supply routes starting with sulphide and laterite ore and leading to the production of class I metal and FeNi/NPI, which until now are not interconnected much. The growing dominance of the laterite route, supplying FeNi/NPI to the stainless steel production will carry on, driven by higher demand for stainless steel in emerging economies, the competition with LIBs for high-purity nickel, and the development of the HPAL technology to produce intermediates suitable for battery production.

The country-level analysis, which considered trade between countries, revealed that a few countries dominate the total imports and exports of nickel around the world at all stages of the value chain. The production and trade of laterite ore were shown to be dominated by Indonesia, the Philippines and New Caledonia, who mainly exported their ores to China in 2019. The general trend observed was that these countries do not retain high value-added from the operations and that the ores are mostly processed in more developed countries in East Asia (Japan, Korea, China). Barely connected to the laterite cluster between Oceania and East Asia, the production of sulphide concentrate, matte and class I metal is dominated by Australia, Canada and the Russian Federation, who have smelting and refining capacities to produce class I metal and therefore retain more value-added from the operations. Since they do not have a large consumption of high purity metal, the production is mainly exported.

Overall, the analysis demonstrated that none could claim itself independent among the major countries mobilizing nickel the most around the world. Some countries are predominant exporters due to massive resources or important smelting and refining capacities, but they are dependent on market and price fluctuations. China and the EU28 were shown to be the most dependent since they combined both significant nickel consumption and low domestic mining resources, which means that they require substantial imports of ore (for China), and class I metal (for both, but relative to the total consumption more for the EU28). At the same time, recent events such as the Indonesian export ban on nickel ore and the Russian invasion of Ukraine show that geopolitical supply risks will impact them the most.

Finally, the limitations of the work were emphasized, and the study particularly called for better modelling of the scrap generation at the country level, increased attention on double-counting issues, especially for class I metal, and the refining of the HS tracking system for lithium-ion batteries. Hopefully, this guidance can reduce the gaps observed between production and trade, strengthen the accuracy of the results and support the studies on specific commodities (e.g. batteries), recycling opportunities or local socio-environmental impacts at the country level.

References

Alvarez, Simon. 2022. "Tesla's Elon Musk Meets with Delegation from Indonesia at Giga Texas to Discuss Potential Nickel Deal." Retrieved June 11, 2022 (https://www.teslarati.com/tesla-elon-musk-indonesia-nickel-deal-giga-texas-pictures/).

Anderson, Corby G., Graeme Goodall, Sumedh Gostu, Dean Gregurek, Mari Lundström, Christina Meskers, Stuart Nicol, Esa Peuraniemi, Fiseha Tesfaye, Prabhat Tripathy, Shijie Wang, and Yuanbo Zhang. 2021. *Ni-Co 2021: The 5th International Symposium on Nickel and Cobalt*.

Andika, R., W. Astuti, Syafriadi, and F. Nurjaman. 2019. "Effect of Flux Addition and Reductant Type in Smelting Process of Indonesian Limonite Ore in Electric Arc Furnace." *IOP Conference Series: Materials Science and Engineering* 478(1). doi: 10.1088/1757-899X/478/1/012007.

Anon. 2021. "Global Material Flows of Lithium i Global Material Flows of Lithium for the Lithium-Ion and Lithium Iron Phosphate Battery Markets ENERGY CATALYST ROUND 7 UPSCALING LITHIUM IRON PHOSPHATE (LFP) BATTERY PRODUCTION FOR BOLIVIA."

Anon. n.d.-a. "New Study Shows Life Cycle of Stainless Steels - RECYCLING Magazine." Retrieved June 11, 2022 (https://www.recycling-magazine.com/2020/10/01/new-study-shows-life-cycle-of-stainless-steels/).

Erickson, Camille. 2022b. "Nickel Price Spike during Russia-Ukraine Conflict Could Drive up EV Costs | S&P Global Market Intelligence." Retrieved June 11, 2022 (https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/nickel-price-spike-during-russia-ukraine-conflict-could-drive-up-ev-costs-69130867).

Sullivan, Arthur. 2022c. “Russian Nickel, Palladium, Chromium Exports a Headache for Germany | Business | Economy and Finance News from a German Perspective | DW | 11.04.2022.” Retrieved June 11, 2022 (https://www.dw.com/en/russian-nickel-palladium-chromium-exports-a-headache-for-germany/a-61429132).

Armand, Michel, Peter Axmann, Dominic Bresser, Mark Copley, Kristina Edström, Christian Ekberg, Dominique Guyomard, Bernard Lestriez, Petr Novák, Martina Petranikova, Willy Porcher, Sigita Trabesinger, Margret Wohlfahrt-Mehrens, and Heng Zhang. 2020. “Lithium-Ion Batteries – Current State of the Art and Anticipated Developments.” *Journal of Power Sources* 479:228708. doi: https://doi.org/10.1016/j.jpowsour.2020.228708.

Australian Government. 2019. *Impact of ABS Confidential Restrictions on Exports of Nickel*.

Azevedo, M., N. Campagnol, T. Hagenbruch, K. Hoffman, A. Lala, and O. Ramsbottom. 2018. “Lithium and Cobalt-a Tale of Two Commodities.” *McKinsey&Company Metals and Mining* (June):p1-25.

Backeberg, Nils R., J. C. M. Bedder, and Erik Sardain. 2021. “Bulk and Stainless Ferroalloys Markets: Fundamentals, Trends and Forecasts.” *SSRN Electronic Journal* (September):27–29. doi: 10.2139/ssrn.3927686.

BBC News. 2022. “Tesla Partners with Nickel Mine amid Shortage Fears - BBC News.”

Bloomberg. 2022. “Battery Metals Outlook.” Retrieved June 11, 2022 (https://spotlight.bloomberg.com/story/battery-metals-outlook/page/6/1).

British Geological Survey. 2020. *World Mineral Production 2015–2019*.

Brunner, Paul H., and Helmut Rechberger. 2016. “Handbook of Material Flow Analysis : For Environmental, Resource, and Waste Engineers, Second Edition.” doi: 10.1201/9781315313450.

Ciacci, Luca, Cristina T. de Matos, Barbara K. Reck, Dominic Wittmer, Elena Bernardi, Fabrice Mathieux, and Fabrizio Passarini. 2022. “Material System Analysis: Characterization of Flows, Stocks, and Performance Indicators of Manganese, Nickel, and Natural Graphite in the EU, 2012–2016.” *Journal of Industrial Ecology*. doi: 10.1111/JIEC.13226.

Crundwell, Frank, Michael Moats, Venkoba Ramachandran, Timothy Robinson, and W. G. Davenport. 2011. “Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals.” *Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals*. doi: 10.1016/C2009-0-63541-8.

Cusano, Gianluca, Miguel Rodrigo Gonzalo, Frank Farrell, Rainer Remus, Serge Roudier, and Luis Delgado Sancho. 2017. *Best Available Techniques (BAT) Reference Document for the Non-Ferrous Metals Industries*.

Ding, Yuanli, Zachary P. Cano, Aiping Yu, Jun Lu, and Zhongwei Chen. 2019. “Automotive Li-Ion Batteries: Current Status and Future Perspectives.” *Electrochemical Energy Reviews* 2(1):1–28.

Firdaus, Febriana, and Tom Levitt. 2022. “‘We Are Afraid’: Erin Brockovich Pollutant Linked to Global Electric Car Boom | Pollution | The Guardian.” Retrieved June 11, 2022 (https://www.theguardian.com/global-development/2022/feb/19/we-are-afraid-erin-brockovich-pollutant-linked-to-global-electric-car-boom).

Foster, Scott. 2022. “Indonesia Bans Mineral Exports to Move up Value Chain - Asia Times.”

Gaulier, Guillaume, and Soledad Zignago. 2010. *BACI: International Trade Database at the Product-Level The 1994-2007 Version*.

Gehlhar, Mark J. 1996. *Reconciling Bilateral Trade Data for Use in GTAP*.

Godoy León, María Fernanda, Gian Andrea Blengini, and Jo Dewulf. 2021. “Analysis of Long-Term Statistical Data of Cobalt Flows in the EU.” *Resources, Conservation and Recycling* 173:105690. doi: 10.1016/J.RESCONREC.2021.105690.

Gunkel-Grillon, Peggy, Christine Laporte-Magoni, Monika Lemestre, and Nicolas Bazire. 2014. “Toxic Chromium Release from Nickel Mining Sediments in Surface Waters, New Caledonia.”

Gupta, Krisna. 2022. “Indonesia’s Claim That Banning Nickel Exports Spurs Downstreaming Is Questionable.” Retrieved June 11, 2022 (https://theconversation.com/indonesias-claim-that-banning-nickel-exports-spurs-downstreaming-is-questionable-180229).

Helbig, Christoph, Alex M. Bradshaw, Lars Wietschel, Andrea Thorenz, and Axel Tuma. 2018. “Supply Risks Associated with Lithium-Ion Battery Materials.” *Journal of Cleaner Production* 172:274–86. doi: 10.1016/J.JCLEPRO.2017.10.122.

Henckens, Theo. 2021. “Scarce Mineral Resources: Extraction, Consumption and Limits of Sustainability.” *Resources, Conservation and Recycling* 169:105511. doi: 10.1016/J.RESCONREC.2021.105511.

Holzmann, Jael. 2022. “Could Russian Sanctions Hobble U.S. Clean Energy Push? - E&E News.” Retrieved June 11, 2022 (https://www.eenews.net/articles/could-russian-sanctions-hobble-u-s-clean-energy-push/).

Hyatt, John. 2022. “How Russia’s Wealthiest Oligarch Is Expanding His Financial Empire Free From Sanctions.” Retrieved June 11, 2022 (https://www.forbes.com/sites/johnhyatt/2022/05/05/how-russias-wealthiest-oligarch-is-expanding-his-financial-empire-free-from-sanctions/?sh=455c93007613).

INSG. 2020a. *World Directory of Nickel Production*.

INSG. 2020b. *World Nickel Yearbook*. Vol. XXIX.

Jaffré, Tanguy, Jérôme Munzinger, and Porter P. Lowry. 2010. "Threats to the Conifer Species Found on New Caledonia's Ultramafic Massifs and Proposals for Urgently Needed Measures to Improve Their Protection." *Biodiversity and Conservation* 19(5):1485–1502. doi: 10.1007/S10531-010-9780-6.

Jolly, Jasper. 2022. "London Metal Exchange Faces Review over Nickel Trading Chaos | Commodities | The Guardian."

Kerfoot, Derek G. E. 2000. "Nickel." *Ullmann's Encyclopedia of Industrial Chemistry*.

Keskinkilic, Ender. 2019. "Nickel Laterite Smelting Processes and Some Examples of Recent Possible Modifications to the Conventional Route."

Khan, Sara, Nelson Manjong, and Anders Hammer Strømann. 2021. "Parametric Life Cycle Modelling of Nickel Sulphate - Master's Thesis." Norwegian University of Science and Technology.

Khoo, Janelle Zhiyun, Nawshad Haque, Geoff Woodbridge, Robbie McDonald, and Sankar Bhattacharya. 2017. "A Life Cycle Assessment of a New Laterite Processing Technology." *Journal of Cleaner Production* 142:1765–77. doi: 10.1016/J.JCLEPRO.2016.11.111.

Kyle, Jim. 2010. "Nickel Laterite Processing Technologies – Where to Next?" in *ALTA Nickel/Cobalt/Copper Conference*. Perth, Western Australia.

Lamb, William F., Thomas Wiedmann, Julia Pongratz, Robbie Andrew, Monica Crippa, Jos G. J. Olivier, Dominik Wiedenhofer, Giulio Mattioli, Alaa al Khourdajie, Jo House, Shonali Pachauri, Maria Figueroa, Yamina Saheb, Raphael Slade, Klaus Hubacek, Laixiang Sun, Suzana Kahn Ribeiro, Smail Khennas, Stephane de La Rue Du Can, Lazarus Chapungu, Steven J. Davis, Igor Bashmakov, Hancheng Dai, Shobhakar Dhakal, Xianchun Tan, Yong Geng, Baihe Gu, and Jan Minx. 2021. "A Review of Trends and Drivers of Greenhouse Gas Emissions by Sector from 1990 to 2018." *Environmental Research Letters* 16(7):073005. doi: 10.1088/1748-9326/ABEE4E.

Larsen, Poul Bo, and Henrik Tyle. 2008. *Nickel and Nickel Compounds. RISK ASSESSMENT.*

Lefort, Cecile, and Melanie Burton. 2014. "Protesters Burn Vehicles, Buildings at New Caledonia Nickel Mine | Reuters." Retrieved June 11, 2022 (https://www.reuters.com/article/us-vale-sa-newcaledonia-spill-idINKBN0E70IT20140527).

Lim, Byungkwon, Hyeon Sook Kim, and Jaehwan Park. 2021. “Implicit Interpretation of Indonesian Export Bans on Lme Nickel Prices: Evidence from the Announcement Effect.” *Risks* 9(5). doi: 10.3390/risks9050093.

Liu, Gang, and Daniel B. Müller. 2013. “Mapping the Global Journey of Anthropogenic Aluminum: A Trade-Linked Multilevel Material Flow Analysis.” *Environmental Science & Technology* 47(20):11873–81. doi: 10.1021/es4024404.

Lu, Qiang, Pengfei Wu, Wanxia Shen, Xuechao Wang, Bo Zhang, and Cheng Wang. 2016. “Life Cycle Assessment of Electric Vehicle Power Battery.” *Materials Science Forum* 847:403–10. doi: 10.4028/WWW.SCIENTIFIC.NET/MSF.847.403.

Lun, Fei, Jordi Sardans, Danfeng Sun, Xiao Xiao, Ming Liu, Zhuo Li, Chongyang Wang, Qiyuan Hu, Jiayue Tang, Philippe Ciais, Ivan A. Janssens, Michael Obersteiner, and Josep Peñuelas. 2021. “Influences of International Agricultural Trade on the Global Phosphorus Cycle and Its Associated Issues.” *Global Environmental Change* 69:102282. doi: 10.1016/J.GLOENVCHA.2021.102282.

Matos, C. T., L. Ciacci, M. F. Godoy León, M. Lundhaug, J. Dewulf, D. B. Müller, K. Georgitzikis, D. Wittmer, and F. Mathieux. 2020. *Material System Analysis of Five Battery-Related Raw Materials: Cobalt, Lithium, Manganese, Natural Graphite, Nickel*. doi: 10.2760/519827.

Moran, Daniel, Milda Petersone, and Francesca Verones. 2016. “On the Suitability of Input–Output Analysis for Calculating Product-Specific Biodiversity Footprints.” *Ecological Indicators* 60:192–201. doi: 10.1016/J.ECOLIND.2015.06.015.

Moskalyk, R. R., and A. M. Alfantazi. 2002. “Nickel Laterite Processing and Electrowinning Practice.” *Minerals Engineering* 15(8):593–605. doi: 10.1016/S0892-6875(02)00083-3.

Mudd, Gavin. 2008. “Environmental Sustainability Metrics for Nickel Sulphide Versus Nickel Laterite CSIRO’s Wealth from Waste Flagship Research Custer View Project Critical Minerals Assessment View Project NICKEL SULFIDE VERSUS LATERITE : THE HARD SUSTAINABILITY CHALLENGE RE.”

Mudd, Gavin M. 2010. “Global Trends and Environmental Issues in Nickel Mining: Sulfides versus Laterites.” *Ore Geology Reviews* 38(1–2):9–26. doi: 10.1016/j.oregeorev.2010.05.003.

Mudd, Gavin M., and Simon M. Jowitt. 2022. “The New Century for Nickel Resources, Reserves, and Mining: Reassessing the Sustainability of the Devil’s Metal.” *Economic Geology*. doi: 10.5382/ECONGEO.4950.

Nakajima, Kenichi, Ichiro Daigo, Keisuke Nansai, Kazuyo Matsubae, Wataru Takayanagi, Makoto Tomita, and Yasunari Matsuno. 2018. “Global Distribution of Material Consumption: Nickel, Copper, and Iron.” *Resources, Conservation and Recycling* 133:369–74. doi: 10.1016/J.RESCONREC.2017.08.029.

Nickel Institute. 2014. *Nickel Plating Handbook*.

Nickel Institute. 2021a. “About Nickel.” Retrieved December 22, 2021 (https://nickelinstitute.org/about-nickel-and-its-applications/#01-nickel-properties).

Nickel Institute. 2021b. “Copper-Nickel Alloys.” Retrieved December 22, 2021 (https://nickelinstitute.org/about-nickel-and-its-applications/copper-nickel-alloys/).

Nickel Institute. 2021c. “Nickel Recycling.” Retrieved December 22, 2021 (https://nickelinstitute.org/policy/nickel-life-cycle-management/nickel-recycling/).

Nickel Institute. 2021d. “Stainless Steel: The Role of Nickel.” Retrieved December 22, 2021 (https://nickelinstitute.org/about-nickel-and-its-applications/stainless-steel/).

Nornickel. 2020. *Quintessentially Nickel*.

Olivetti, Elsa A., Gerbrand Ceder, Gabrielle G. Gaustad, and Xinkai Fu. 2017. “Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals.” *Joule* 1(2):229–43. doi: 10.1016/j.joule.2017.08.019.

Ozberk, E., and S. W. Marcuson. 1986. “25th Annual Conference of Metallurgists.” in *Nickel Metallurgy - Volume I: Extraction and Refining of Nickel*. Vol. 1. Montreal: Canadian Institute of Mining and Metallurgy.

Pandyaswargo, Andante Hadi, Alan Dwi Wibowo, Meilinda Fitriani Nur Maghfiroh, Arlavinda Rezqita, and Hiroshi Onoda. 2021. “The Emerging Electric Vehicle and Battery Industry in Indonesia: Actions around the Nickel Ore Export Ban and a SWOT Analysis.” *Batteries* 7(4):80. doi: 10.3390/batteries7040080.

Peiró, Laura Talens, Philip Nuss, Fabrice Mathieux, and Gian Andrea Blengini. 2018. “Towards Recycling Indicators Based on EU Flows and Raw Materials System Analysis Data Supporting the EU-28 Raw Materials and Circular Economy Policies through RMIS.” doi: 10.2760/092885.

Rao, Mingjun, Guanghui Li, Tao Jiang, Jun Luo, Yuanbo Zhang, and Xiaohui Fan. 2013a. “Carbothermic Reduction of Nickeliferous Laterite Ores for Nickel Pig Iron Production in China: A Review.” *JOM* 65(11):1573–83. doi: 10.1007/S11837-013-0760-7/FIGURES/9.

Rao, Mingjun, Guanghui Li, Tao Jiang, Jun Luo, Yuanbo Zhang, and Xiaohui Fan. 2013b. “Carbothermic Reduction of Nickeliferous Laterite Ores for Nickel Pig Iron Production in

China: A Review." *Journal of Minerals* 65(11):1573–83. doi: 10.1007/s11837-013-0760-7.

Reck, Barbara K., Daniel B. Müller, Katherine Rostkowski, and T. E. Graedel. 2008. "Anthropogenic Nickel Cycle: Insights into Use, Trade, and Recycling." *Environmental Science and Technology* 42(9):3394–3400. doi: 10.1021/es072108l.

Reuter, M. A., and Ilkka Veikko Kojo. 2012. "Challenges of Metals Recycling." *Materia* 2(September):50–57.

Reuter, Markus, Antoinette Schaik, and Miquel Ballester. 2018. "Limits of the Circular Economy: Fairphone Modular Design Pushing the Limits." *World of Metallurgy - ERZMETALL* 71.

Riekkola-Vanhanen, Marja. 2013. "Talvivaara Mining Company – From a Project to a Mine." *Minerals Engineering* 48:2–9. doi: 10.1016/j.mineng.2013.04.018.

Roskill. 2019. *Nickel End Use Report 2010-2019*.

Roskill. 2021. *Study on Future Demand and Supply Security of Nickel for Electric Vehicle Batteries*.

Saari, P., and M. Riekkola-Vanhanen. 2012. "Talvivaara Bioheapleaching Process." *Journal of the Southern African Institute of Mining and Metallurgy* 112(12):1013–20.

Santillán-Saldivar, Jair, Tobias Gaugler, Christoph Helbig, Andreas Rathgeber, Guido Sonnemann, Andrea Thorenz, and Axel Tuma. 2021. "Design of an Endpoint Indicator for Mineral Resource Supply Risks in Life Cycle Sustainability Assessment: The Case of Li-Ion Batteries." *Journal of Industrial Ecology* 25(4):1051–62. doi: 10.1111/JIEC.13094.

Sawal, Rabul. 2022. "Red Seas and No Fish: Nickel Mining Takes Its Toll on Indonesia's Spice Islands." Retrieved June 11, 2022 (https://news.mongabay.com/2022/02/red-seas-and-no-fish-nickel-mining-takes-its-toll-on-indonesias-spice-islands/).

Schmidt, Tobias, Matthias Buchert, and Liselotte Schebek. 2016. "Investigation of the Primary Production Routes of Nickel and Cobalt Products Used for Li-Ion Batteries." *Resources, Conservation and Recycling* 112:107–22. doi: 10.1016/J.RESCONREC.2016.04.017.

Sen, Indra S., and Bernhard Peucker-Ehrenbrink. 2012. "Anthropogenic Disturbance of Element Cycles at the Earth's Surface." *Environmental Science and Technology* 46(16):8601–9. doi: 10.1021/ES301261X/SUPPL_FILE/ES301261X_SI_001.PDF.

Shukla, P. R., J. Skea, R. Slade, A. al Khourdajie, R. van Diemen, D. Mccollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley,] Cambridge, M. Grubb, C. Okereke, J. Arima, V. Bosetti, Y. Chen, J. Edmonds, S. Gupta, and A. Köberle. 2022. *Climate Change 2022: Mitigation of Climate Change Working*

Group III Contribution to the IPCC Sixth Assessment Report Citations Full Report Chapter 1. doi: 10.1017/9781009157926.

Skare, Marte O., Julia Wind, and Hanne Flåten Andersen. 2019. *LIB Technology Mapping Report - A BATMAN Report on Current and Future Trends within Lithium-Ion Battery Chemistry*.

Stone, Maddie. 2022. “European Electric Car Makers Have a Russian Nickel Problem | Grist.” Retrieved June 11, 2022 (https://grist.org/international/european-electric-car-makers-have-a-russian-nickel-problem/).

Sun, Xin, Han Hao, Zongwei Liu, Fuquan Zhao, and Junnan Song. 2019. “Tracing Global Cobalt Flow: 1995–2015.” *Resources, Conservation and Recycling* 149:45–55. doi: 10.1016/J.RESCONREC.2019.05.009.

Sun, Xin, Han Hao, Fuquan Zhao, and Zongwei Liu. 2017. “Tracing Global Lithium Flow: A Trade-Linked Material Flow Analysis.” *Resources, Conservation and Recycling* 124:50–61. doi: https://doi.org/10.1016/j.resconrec.2017.04.012.

Talantsev, Anton. 2017. “Who Gains and Who Loses in the Shift to Electric Vehicles: Impact Assessment through Multi-Criteria Multi-Stakeholder Analysis.” *Procedia Environmental Sciences* 37:257–68. doi: 10.1016/J.PROENV.2017.03.057.

UN Statistics. n.d.-a. “Commodity Trade Statistics Database (COMTRADE) Read Me First.” Retrieved December 24, 2021 (https://comtrade.un.org/db/help/uReadMeFirst.aspx).

UN Statistics. n.d.-b. “UN Comtrade Knowledgebase - Comtrade - UN Statistics Wiki.” Retrieved December 24, 2021 (https://unstats.un.org/wiki/display/comtrade).

UNCTAD. 2012. “Lunchtime Seminar and Workshop on the Occasion of the 2012 Meeting of BWC States Parties. UN COMTRADE: Understanding Trade Data.” Retrieved December 22, 2021 (http://www.biological-arms-control.org/projects_trademonitoring/MSP2012 - Markie Muryawan - Understanding trade data.pdf).

UNEP, and Markus Reuter. 2013. *Metal Recycling: Opportunities, Limits, Infrastructure*.

UNFCCC. 2017. *Industrial Energy and Material Efficiency in Emission-Intensive Sectors TECHNOLOGY EXECUTIVE COMMITTEE*.

United Nations. Statistical Division. 2011. *International Merchandise Trade Statistics : Concepts and Definitions 2010*. United Nations.

U.S. Geological Survey. 2021. *Mineral Commodity Summaries 2021*.

Wellmer, Friedrich W. 2008. “Reserven Und Ressourcen Der Geosphäre, Begriffe, Die so Häufig Missverstanden Werden. Ist Die Reichweite Der Reserven von Natürlichen

Ressourcen Ein Hinweis Für Die Zukunft?” *Zeitschrift Der Deutschen Gesellschaft Fur Geowissenschaften* 159(4):575–90. doi: 10.1127/1860-1804/2008/0159-0575.

Young, Eric. 2021. “Battery Nickel Bottlenecks Master’s Thesis.” NTNU.

ZoneBourse. 2022. “La Société Brésilienne Vale Signe Un Accord à Long Terme Pour Fournir Du Nickel à Tesla.”

Appendix

1. Ni-containing commodities

For a question of clarity and to limit the number of pages, the list of Ni-containing, their HS code, and the estimate of their Ni content are joined as a supporting Excel file to this report.

2. Sulphate production from class I by country

The estimates for sulphate production from class I dissolution are:

- China: 54,4 kt Ni
- Japan: 24,7 kt Ni
- Republic of Korea: 7,4 kt Ni
- Belgium: 1,2 kt Ni
- USA: 1,2 kt Ni

3. List of company reports used

The following company reports were used:

- Anglo American. (2020). News Release.
- BHP. (2021). Annual Report 2020 *Bringing people and resources together to build a better world*.
- Boliden. (2019). *A Sustainable Future with Metals*: Annual and Sustainablity Report 2019. 124.
- Finnish Minerals Group. (2019). Annual Report 2019.
- Glencore. (2020). Full Year 2019 Production Report NEWS RELEASE. www.glencore.com
- Nornickel. (2020a). Annual Report 2019.
- Sherritt International Corporation. (n.d.). 2019 Financial results.
- Vale. (2020). PRODUCTION AND SALES IN 4Q19 AND 2019.

4. Countries covered by Roskill (2019)

The countries covered by the End-use of nickel report are the USA, Canada, Mexico, Brazil, Argentina/Chile, Austria, Belgium, the Czech Republic, Finland, France, Germany, Italy, Poland, Slovenia, Spain, Sweden, the UK, Norway, the Russian Federation, Switzerland, Turkey, Ukraine, China, Hong-Kong, Japan, India, the Republic of Korea, Taiwan, Thailand, Indonesia, Iran, Israel, Malaysia, the Philippines, Singapore, the United Arab Emirates, Vietnam, South Africa and Australia.

5. Scrap input in stainless steel production

The estimates for the rates of inclusion of scrap in stainless steel are:

- China: 23%
- USA: 71%
- Japan, India, Republic of Korea: 66%
- Belgium, France, Germany, Finland, Sweden, UK, Italy: 70%
- Global average: 44%

6. Ratio inflow/outflow end-use sectors

Table 3 - Ratio inflow/outflow for end-of-life quantification

End-use sector	Lifetime (years)	Growth rate sector	Ratio outflow/inflow
26 – Appliances and electronic devices	-	-	39%
27 – Automotive	16,8	5,4%	(41%)
28 – Other transport	16 for airplanes, 25 for the rest	5,4%	(37%) considering 40% airplane
29 – Industrial machinery	25	3,5%	42%
30 – Metal goods	-	-	39%
31 – Buildings and infrastructure	-	-(Crundwell et al., 2011; Kerfoot, 2000; Khoo et al., 2017)	39%
31 – Others	-	-(Andika et al., 2019; Rao et al., 2013)	39%

7. Process efficiencies

Table 4 - Process efficiencies

Process	**Range in the literature**	**Literature source**	**Value used**
1 – Sulphide ore concentration	87-90%	(Crundwell et al., 2011)	87,0%
2 – Direct concentrate to metal	-	-	Not used
3 – Flash smelting	95%	(Crundwell et al., 2011)	95,0%
4 – Roasting and smelting	98-99%	(Crundwell et al., 2011)	98,5%
5 – Heap leaching	85%	(Riekkola-Vanhanen, 2013)	85%
6 – FeNi smelting	91-98%	(Crundwell et al., 2011; Kerfoot, 2000; Khoo et al., 2017)	94,8%
7 – NPI smelting	80-82%	(Andika et al., 2019; Rao et al., 2013)	81,0%
8 – HPAL	90-97%	(Crundwell et al. 2011; Kerfoot 2000; Khoo et al. 2017)	93,7%
9 – Caron	60-80%	(Crundwell et al. 2011)	75,0%
10 – Roasting	97-100%	(Crundwell et al. 2011)	99,0%
11 – Refining	99%	(Crundwell et al. 2011)	99,0%
12 – Sulphate production	90-98%	(Khan et al. 2021)	94,0%
13 to 18	99% (0,5% scrap, 0,5% losses)	(Reck et al. 2008)	99% (0,5% scrap, 0,5% losses)
19 to 25	90% (9,3% scrap, 0,7% losses)	(Reck et al. 2008)	90% (9,3% scrap, 0,7% losses)
26 to 33	-	-	Not used

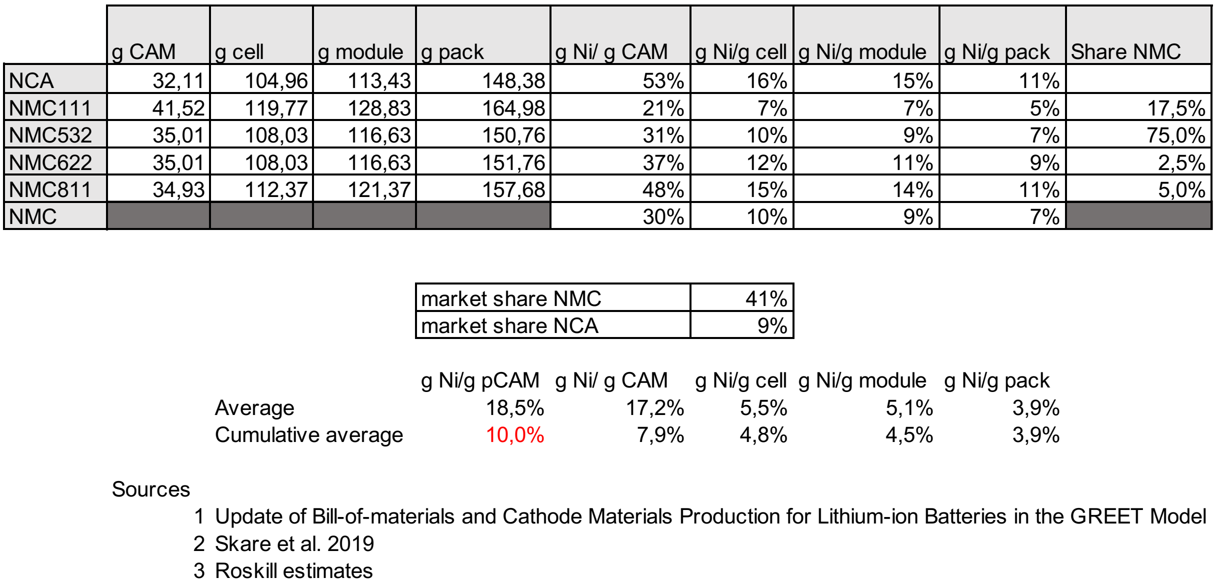
8. Default values for concentrations of the supply system

Table 5 - Default values for the concentrations of the supply products

Commodity	**Crundwell et al. 2011**	**Cusano et al. 2017**	**Kerfoot et al. 2000**	**Value used as default**
Sulphide concentrate	12-20%	7-25%	6,7-13%	15,0%
Laterite ore	1-3%	1-3%	1,02-2,9%	2,0%
Matte	35-66%	35-70%	38-73%	50,0%
Nickel oxide sinter/utility	75-78%	N/A	77%	75,0%
MHP/MSP	55-57%	N/A	30-55%	45,0%
FeNi	20-40%	N/A	14-45%	27,5%
NPI	N/A	N/A	N/A	10,0%
Class I metal	99,8-99,9%	> 99%	99,8%	99,8%
Sulphate	N/A	N/A	N/A	22,1%

9. Calculation details for the Ni content of HS code 8507.60

Table 6 - Calculation details for the Ni content of HS code 8507.60



	g CAM	g cell	g module	g pack	g Ni/ g CAM	g Ni/g cell	g Ni/g module	g Ni/g pack	Share NMC
NCA	32,11	104,96	113,43	148,38	53%	16%	15%	11%	
NMC111	41,52	119,77	128,83	164,98	21%	7%	7%	5%	17,5%
NMC532	35,01	108,03	116,63	150,76	31%	10%	9%	7%	75,0%
NMC622	35,01	108,03	116,63	151,76	37%	12%	11%	9%	2,5%
NMC811	34,93	112,37	121,37	157,68	48%	15%	14%	11%	5,0%
NMC					30%	10%	9%	7%	

market share NMC	41%
market share NCA	9%

	g Ni/g pCAM	g Ni/ g CAM	g Ni/g cell	g Ni/g module	g Ni/g pack
Average	18,5%	17,2%	5,5%	5,1%	3,9%
Cumulative average	10,0%	7,9%	4,8%	4,5%	3,9%

Sources
1 Update of Bill-of-materials and Cathode Materials Production for Lithium-ion Batteries in the GREET Model
2 Skare et al. 2019
3 Roskill estimates

10. Coverage of the selected countries for the product categories

Table 7 - Coverage of the selected countries for the product categories

	Ores & concentrate		Matte		MSP/MHP/Ni ox.		FeNi/NPI		Class I		Nickel sulpate		First-use products		End-use products		Scrap	
	Import	*Export*	*Import*	*Export*	*Import*	*Export*	*Import*	*Export*	*Import*	*Export*	*Import*	*Export*	*Import*	*Export*	*Import*	*Export*	*Import*	*Export*
Indonesia		39%		28%			0%	38%			1%		2%	10%	2%	1%	2%	1%
Philippines		32%				15%					2%				2%			1%
Russian Fed.		1%		23%						21%			1%		2%	1%		2%
Australia		6%		6%		0%				20%	4%				2%		0%	1%
Canada		5%	2%	32%	1%	8%				13%	7%		2%		5%	1%	3%	3%
Norway			33%			0%				13%					1%			
Rep. of Korea					2%	0%	4%	1%	6%		7%	8%	5%	7%	1%	4%	4%	2%
Japan	5%		32%		15%	0%	1%	5%	6%	2%	44%	6%	2%	5%	2%	3%	1%	4%
India						0%	6%		3%		1%		4%	3%	2%	6%	18%	
USA						0%	2%		11%		1%	3%	5%	4%	17%	6%	3%	8%
EU28	5%	0%	27%	9%	14%	10%	15%	4%	31%	16%	20%	43%	44%	42%	29%	32%	54%	58%
China	80%		3%		67%	0%	65%		25%	2%	3%	1%	6%	14%	3%	24%	2%	
Total	90%	82%	97%	98%	99%	34%	94%	48%	82%	87%	89%	61%	70%	86%	66%	77%	86%	80%

11. Country-level diagrams

12. Datasets available for the production

Table 8 - Datasets available for the production: mining, intermediate and finished nickel

		mining			intermediates	finished nickel	
Country	**Region**	**USGS**	**BGS mining**	**INSG yearbook mi**	**Wood MacKenzie**	**INSG yearbook fin**	**BGS production**
Albania	Europe	N/A	2,8	5,4			
Australia	Oceania	159,0	158,8	158,8	127	106,7	106,5
Austria	Europe	N/A			3	1,0	0,7
Botswana	Africa	N/A					
Brazil	Latin America	60,6	55,7	60,4	54	54,3	54,3
Myanmar	Asia	N/A	16,0	20	20	20,0	16,0
Canada	North America	181	180,9	187,1	177	123,9	124,7
China	Asia	120,0	104,7	104,7	711	806,0	806,0
Colombia	Latin America	N/A	40,6	45,0	41	40,5	40,6
Cuba	Latin America	49,2	45,3	48,9	48	15,0	14,8
Dominican Rep.	Latin America	56,9	28,5	31,5	24	28,5	13,4
Finland	Europe	38,5	38,5	38,1	54	62,4	90,2
France	Europe	N/A				6,9	6,9
Germany	Europe	N/A			1		
Greece	Europe	N/A	13,7	13,7	12	12,0	12,0
Guatemala	Latin America	N/A	55,0	36,3	15	20,3	20,3
India	Asia	N/A				0,5	0,1
Indonesia	Asia	853,0	1036,0	853,0	470	375,7	409,0
Côte d'Ivoire	Africa	N/A	9,1	8,6			
Japan	Asia	N/A			50	182,7	182,7
Kosovo	Europe	N/A	3,3		6	6,0	3,6
Madagascar	Africa	N/A	33,7	36,8	34	33,7	33,7
New Caledonia	Oceania	208,0	209,5	208,2	95	87,9	87,9
North Macedonia	Europe	N/A			15	15,3	15,3
Norway	Europe	N/A	0,2	0,2		92,1	92,1
Papua New Guinea	Oceania	N/A	33,1	32,7	35		
Philippines	Asia	323,0	323,3	323,3	52		
Poland	Europe	N/A	0,7				0,7
Russian Federation	Russia and the caspian	279,0	226,0	223,2	214	167,3	226,3
Serbia	Europe	N/A					
Solomon Isds	Oceania	N/A		3,8			
South Africa	Africa	N/A	43,4	43,5	38	39,1	39,1
Rep. of Korea	Asia	N/A			45	46,3	41,1
Turkey	Europe	N/A	11,0	16,6	1		
Ukraine	Europe	N/A			14	14,2	14,2
United Kingdom	Europe	N/A				35,0	39,6
USA	North America	13,5	13,5	13,5			
Zambia	Africa	N/A	2,5	3,0			
Zimbabwe	Africa	N/A	16,3	17,4	5		
		Data is incomplete					
TOTAL (calculated)		*2341,7*	2702,1	2533,7	2361	2393,3	2491,7
TOTAL (announced)		2610,0	2702,0	2539,7	2361	2372,3	2492,0

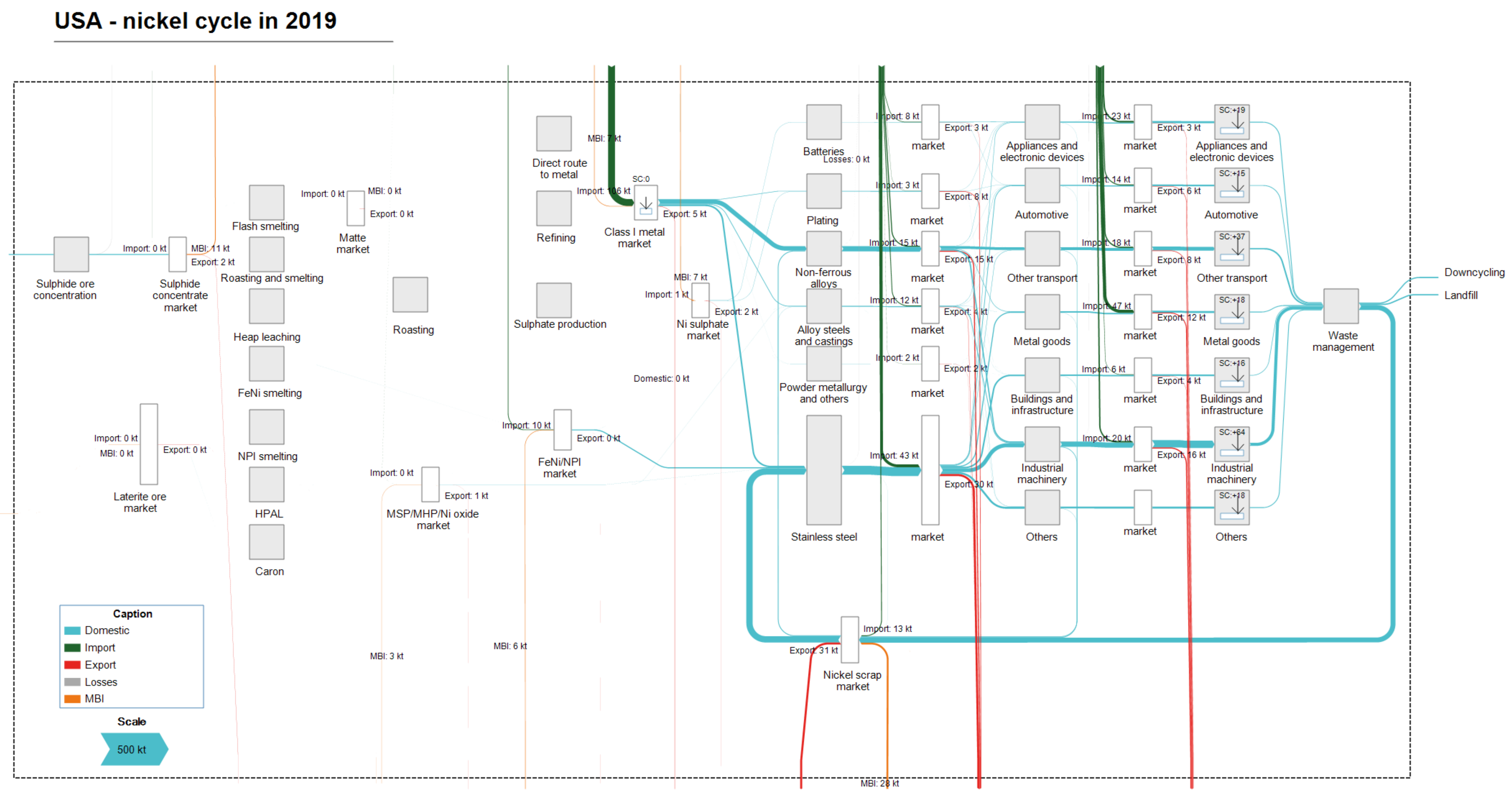


Figure 18 - Quantified nickel cycle for the USA in 2019

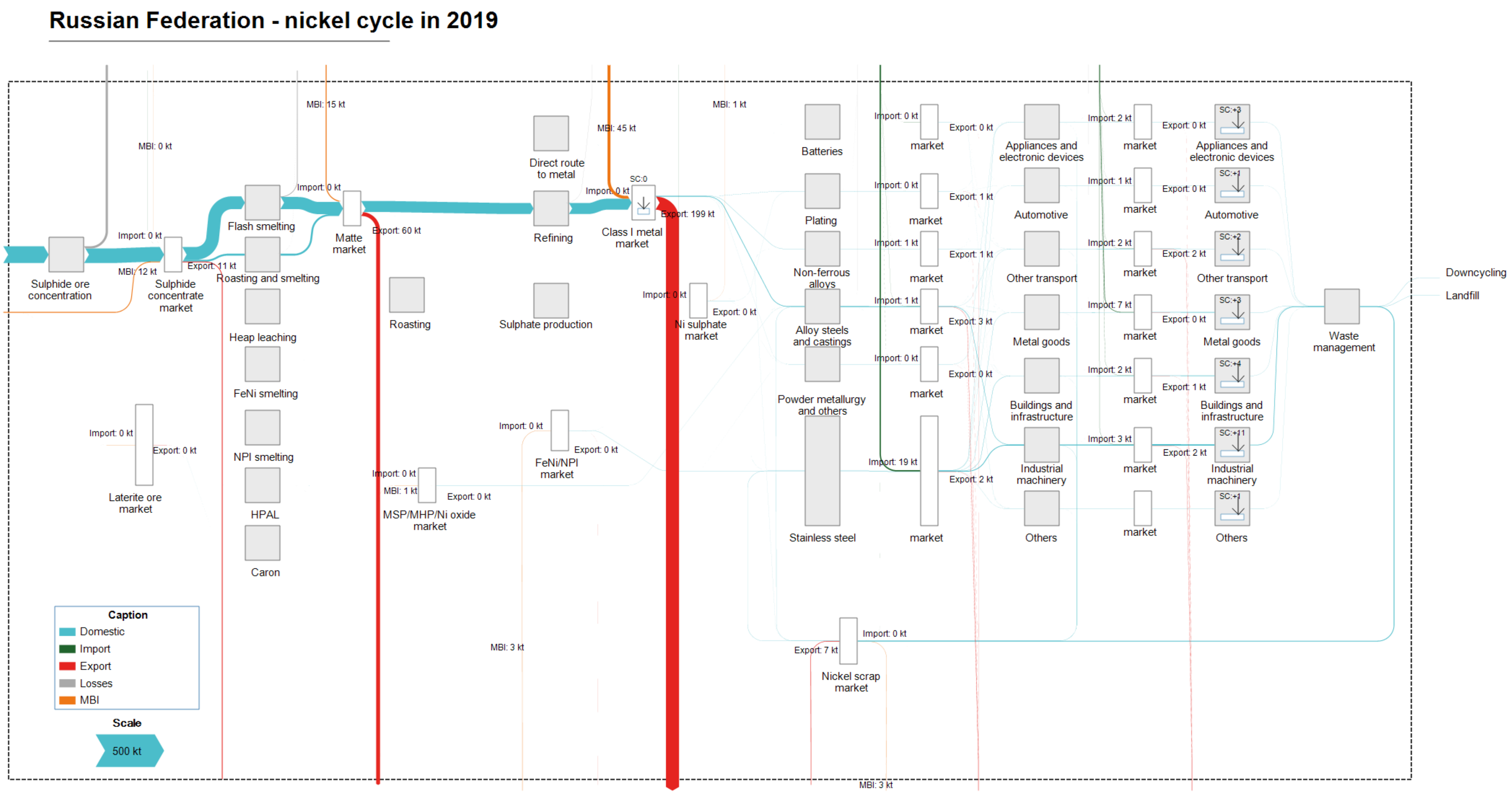


Figure 19 - Quantified nickel cycle for the Russian federation in 2019

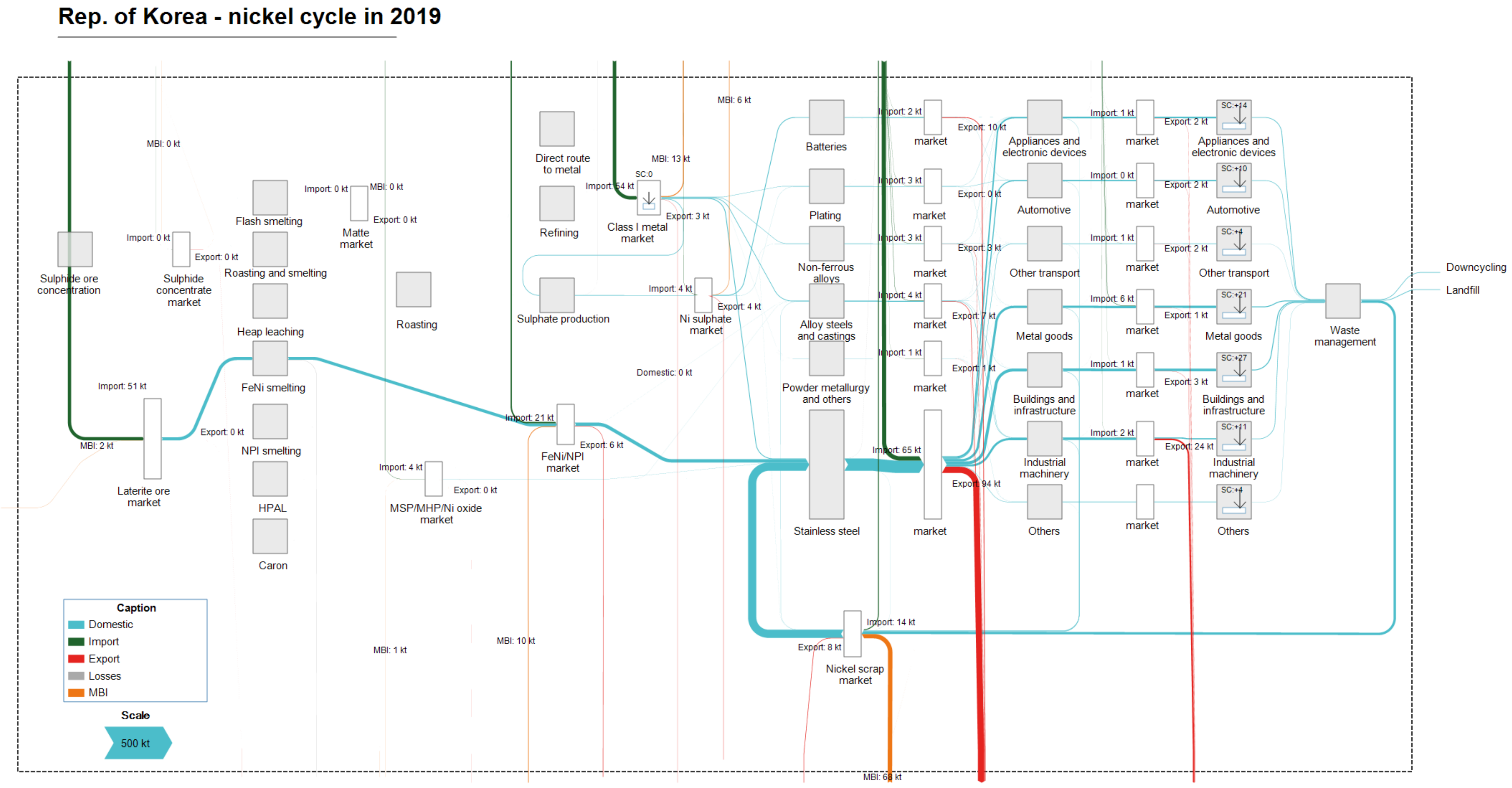


Figure 20 - Quantified nickel cycle for the Republic of Korea in 2019

Philippines - nickel cycle in 2019

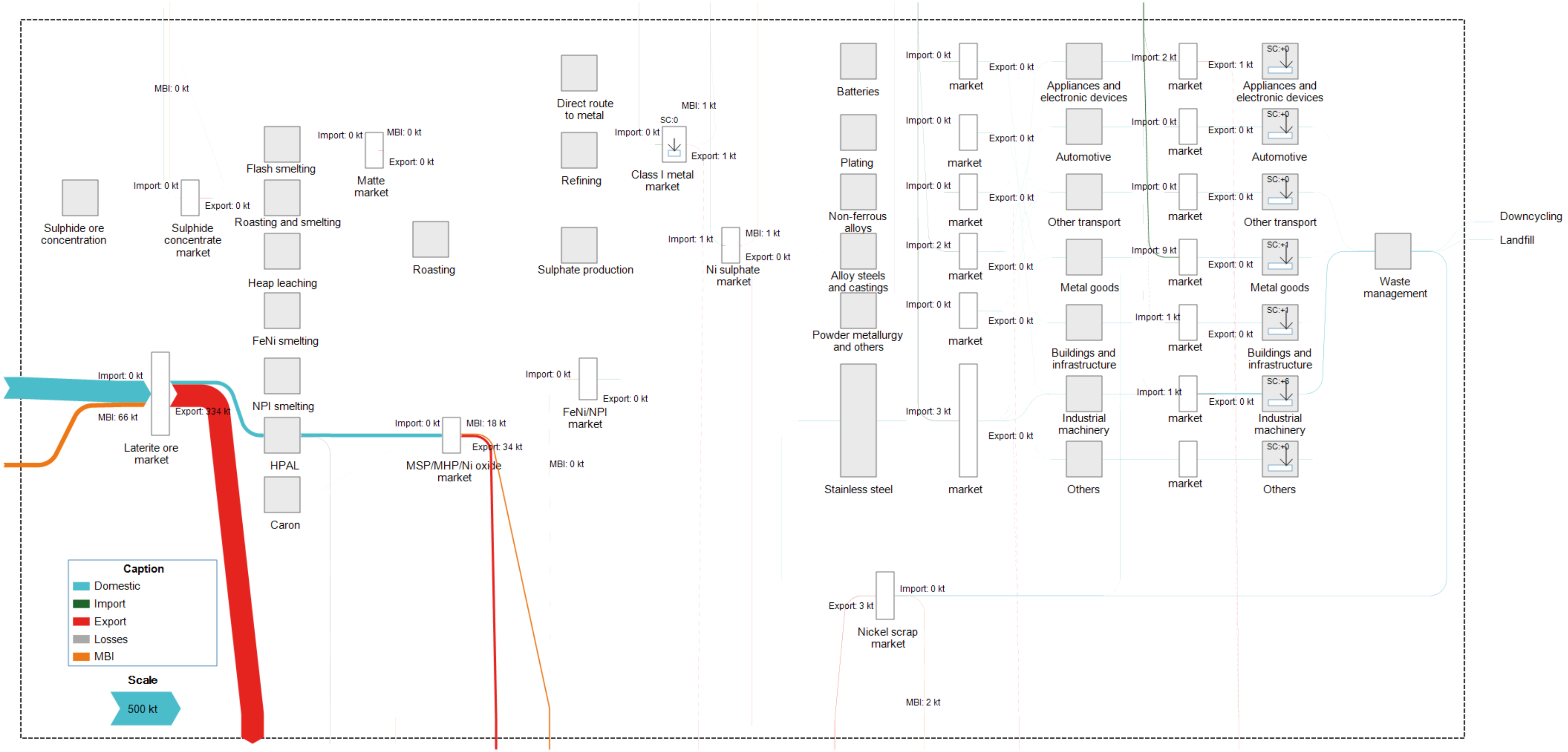


Figure 21 - Quantified nickel cycle for the Philippines in 2019

Norway - nickel cycle in 2019

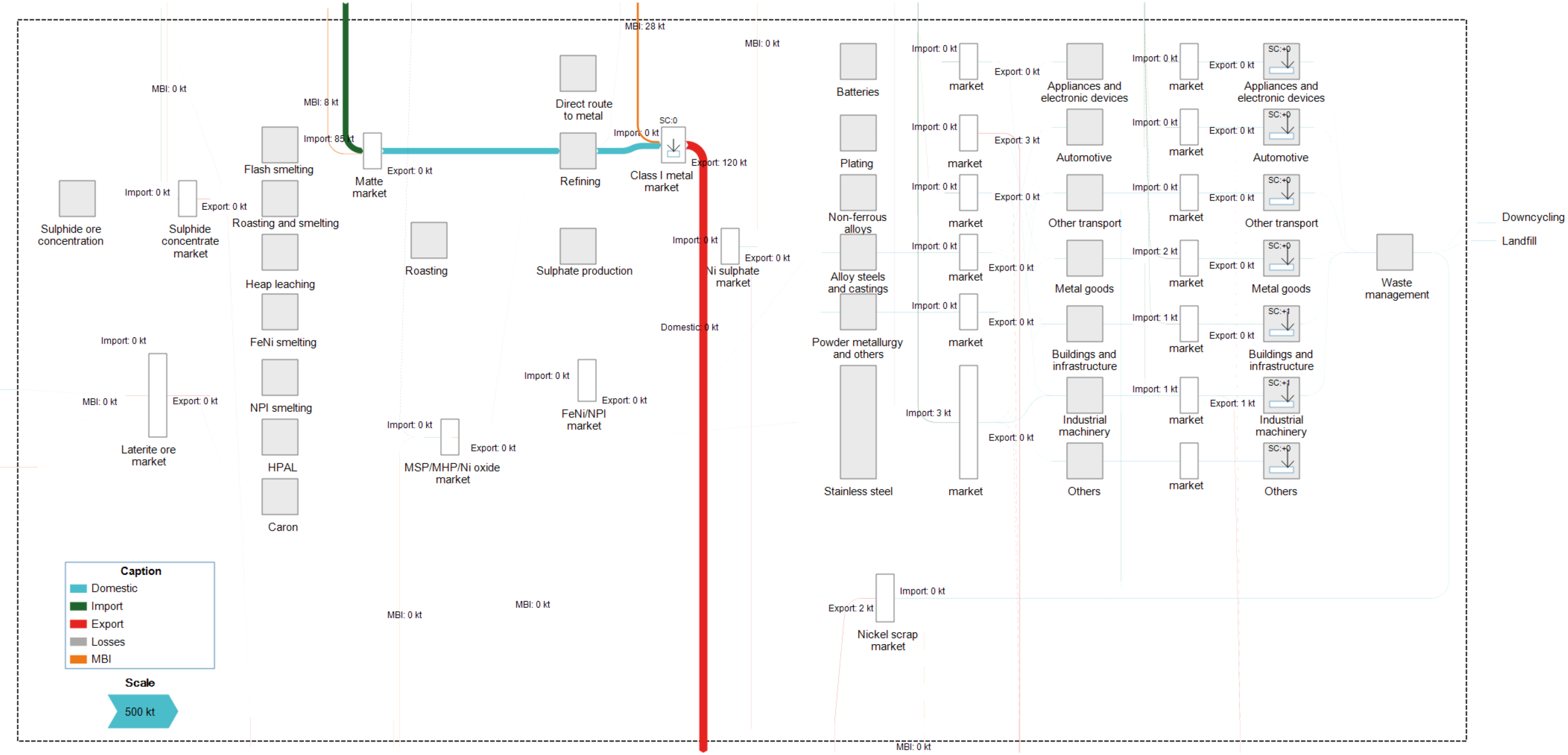


Figure 22 - Quantified nickel cycle for Norway in 2019

New Caledonia - nickel cycle in 2019

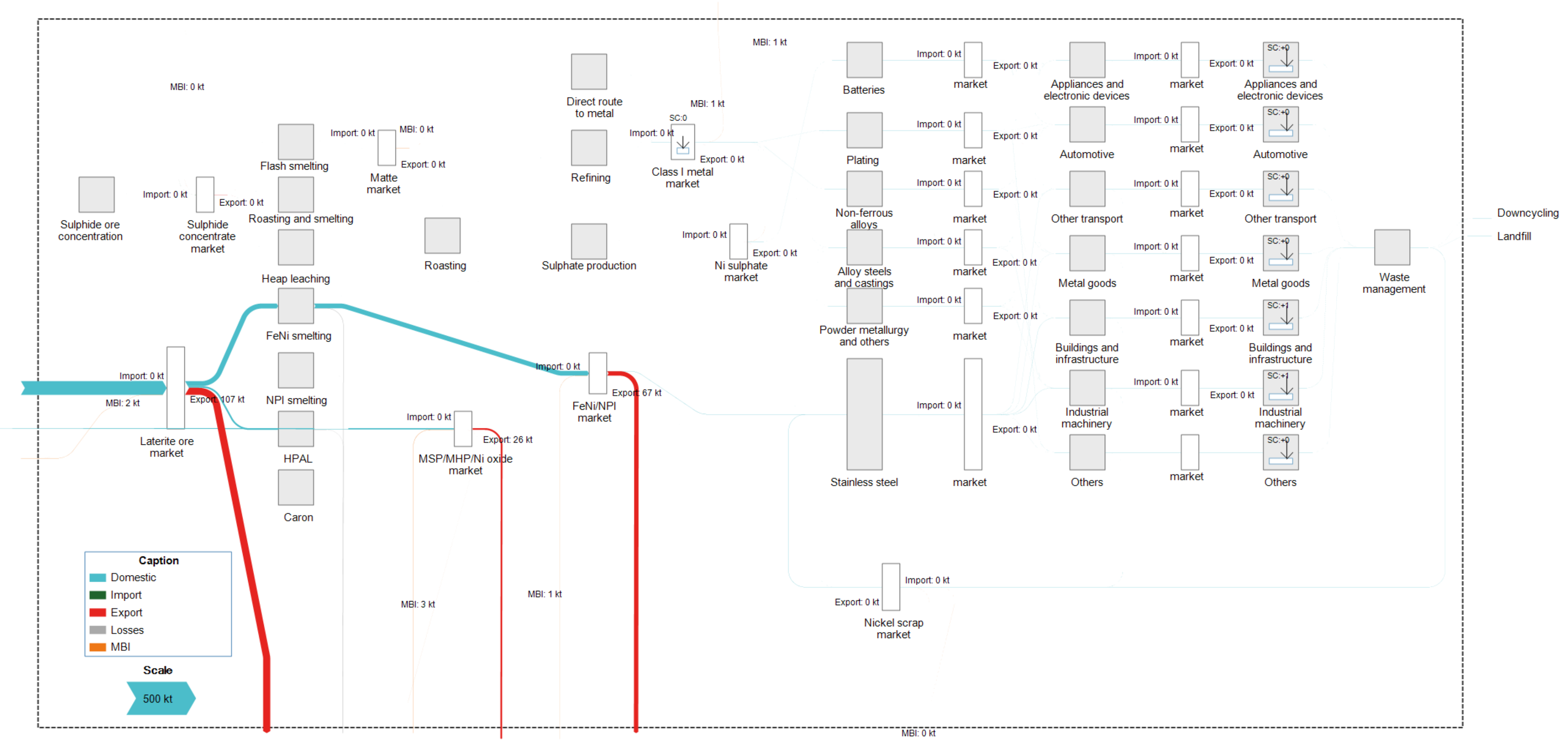


Figure 23 - Quantified nickel cycle for New Caledonia in 2019

Japan - nickel cycle in 2019

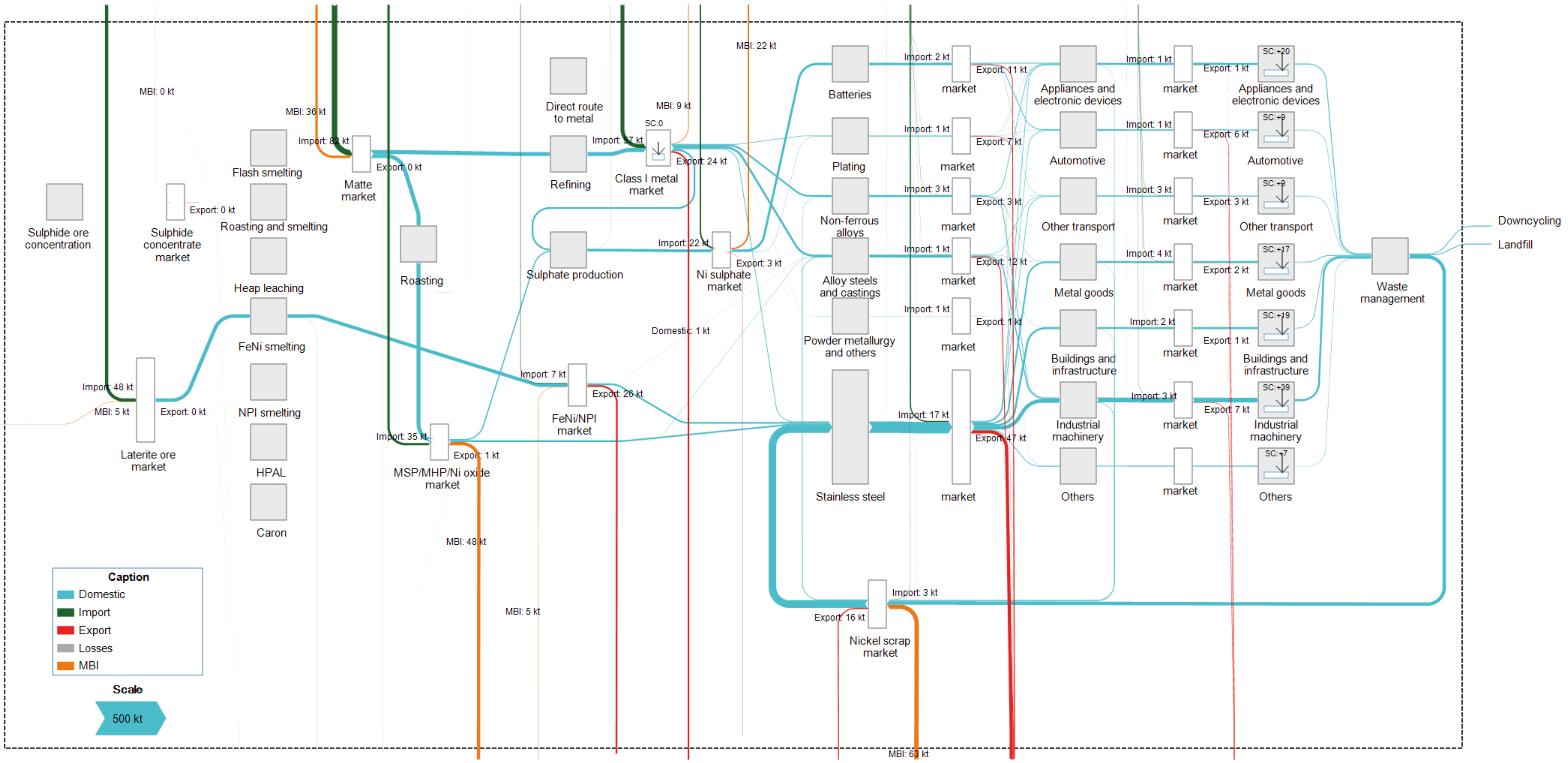


Figure 24 - Quantified nickel cycle for Japan in 2019

India - nickel cycle in 2019

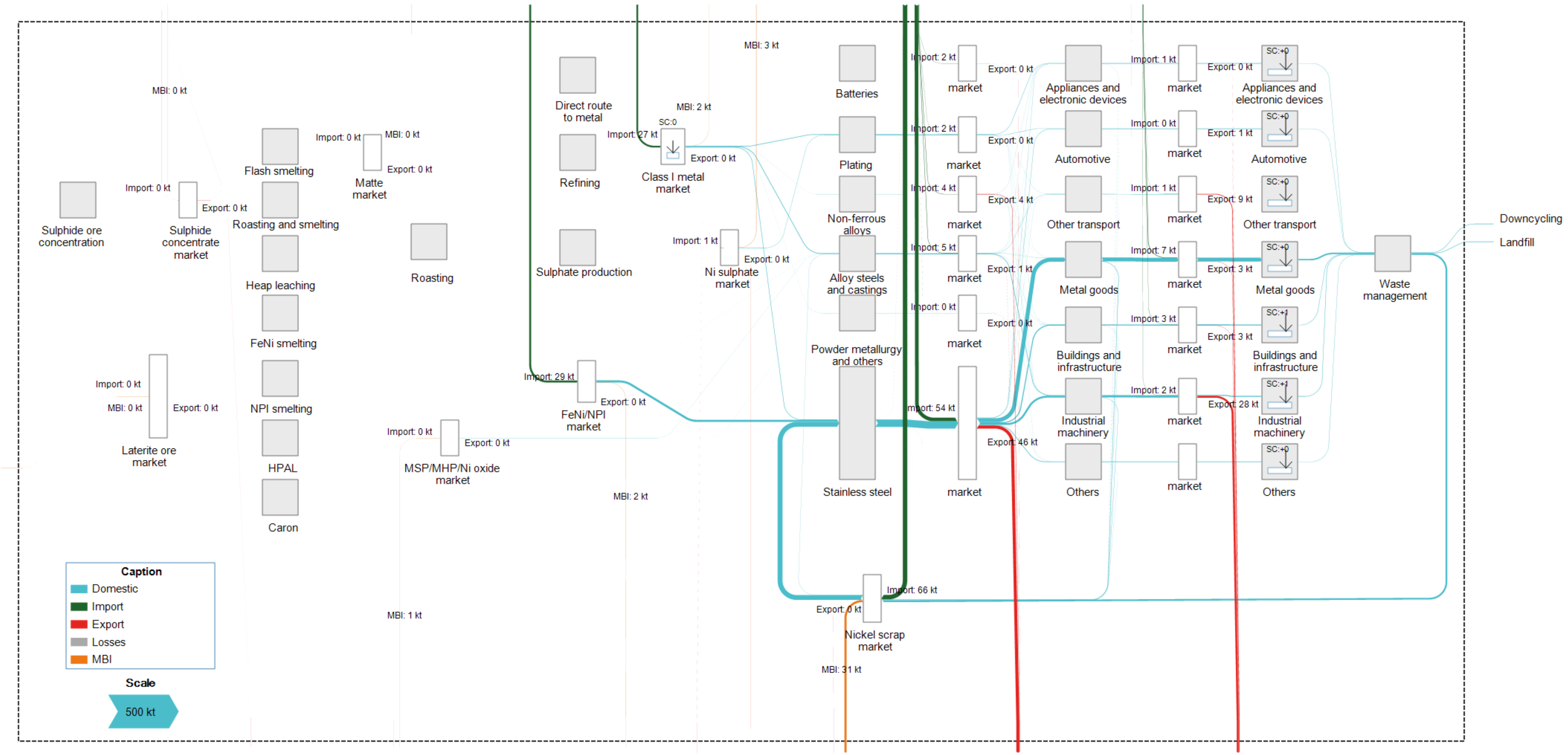


Figure 25 - Quantified nickel cycle for India in 2019

Canada - nickel cycle in 2019

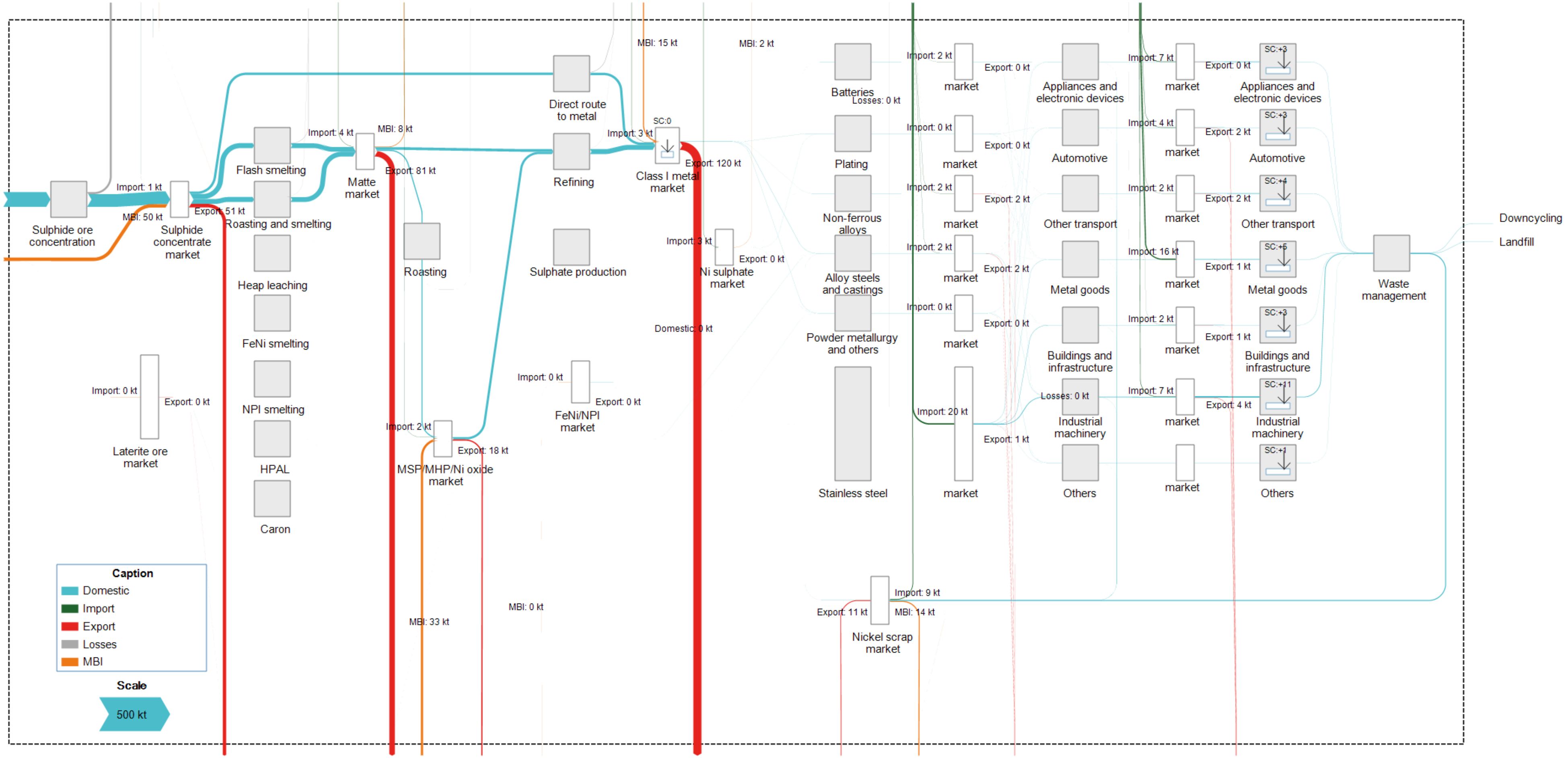


Figure 26 - Quantified nickel cycle for Canada in 2019

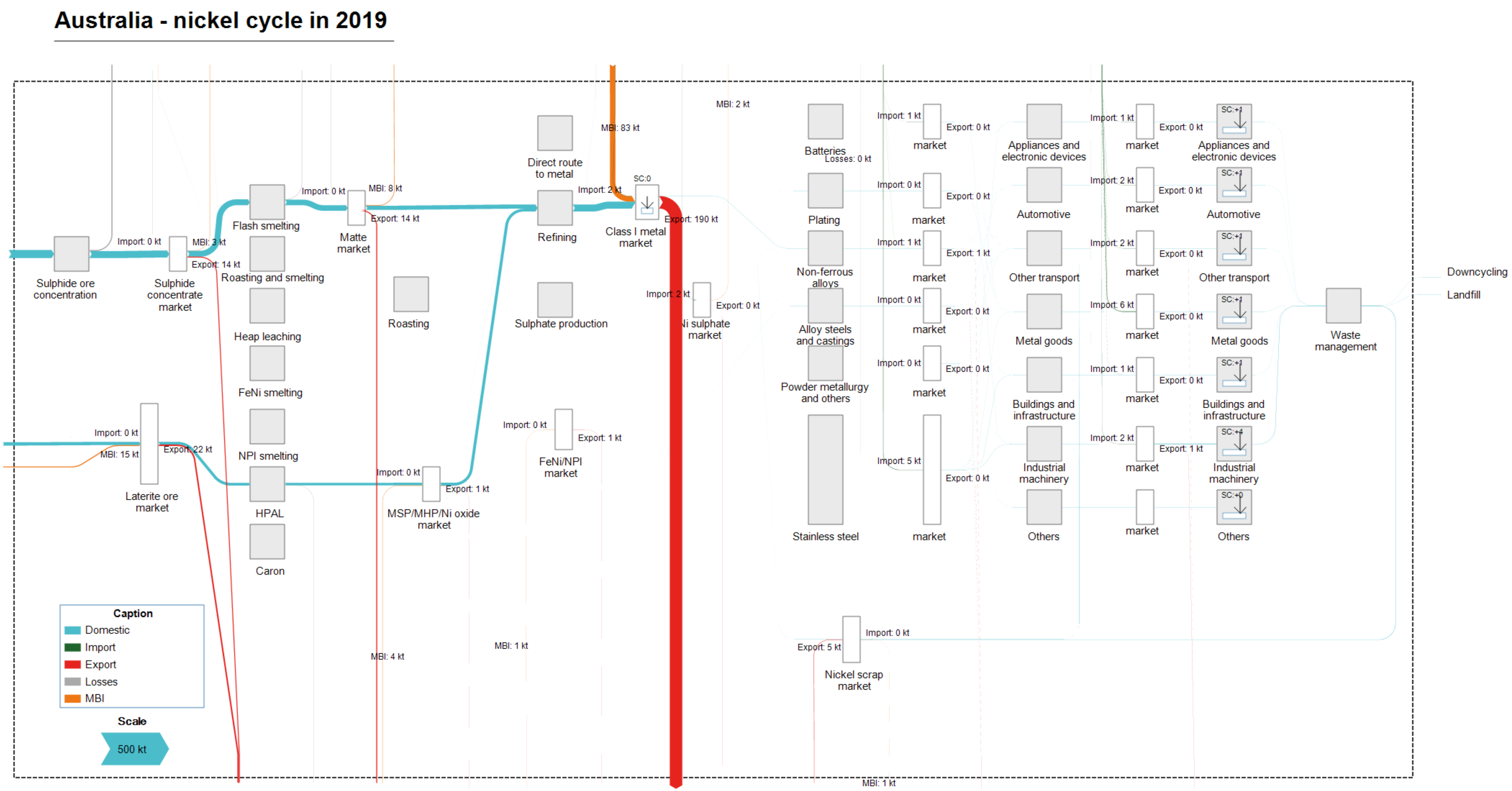


Figure 27 - Quantified nickel cycle for Australia in 2019

NTNU

Norwegian University of
Science and Technology