Nickel factsheet

International Resource Panel

Disclaimers

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NOTE: This factsheet was developed with public data up to April 2022.

Information and data related to lithium are available from a variety of sources, including scientific literature, reports from companies engaged in lithium exploration, mining, and the production of lithium chemicals, as well as reports from national and international institutions and consultancy firms. Due to cost constraints, the latter could not be utilized in the preparation of this factsheet.

Due to the highly dynamic nature of the lithium market and the timing of data compilation, certain sections of this report, including the scenarios, may no longer be fully up to date.

This Annex was not reviewed nor input and recommendation provided through a formal process by IRP membership.

Nickel factsheet

International Resource Panel

LIST OF ABBREVIATIONS

ASM	Artisanal small-scale mining
BEVs	Battery electric vehicles
BGS	British Geological Survey
ESG	Environmental, social, and governance
EVs	Electric vehicles
HPAL	High-Pressure Acid Leaching
IEA	International Energy Agency
INSG	International Nickel Study Group
LCO	Lithium Cobalt Oxide (LiCoO2)
LFP	Lithium iron phosphate (LiFePO4)
LME	London Metal Exchange
LMO	Lithium ion manganese oxide
MHP	Mixed-hydroxide products
MSP	Mixed suphide products
NCA	Lithium-nickel-cobalt-aluminium oxide cathodes
NMC	Lithium-nickel-manganese-cobalt-oxide cathodes
NPI	Nickel pig iron
PGE	Platinum-group elements
SDS	Sustainable development scenario
USGS	US Geological Survey

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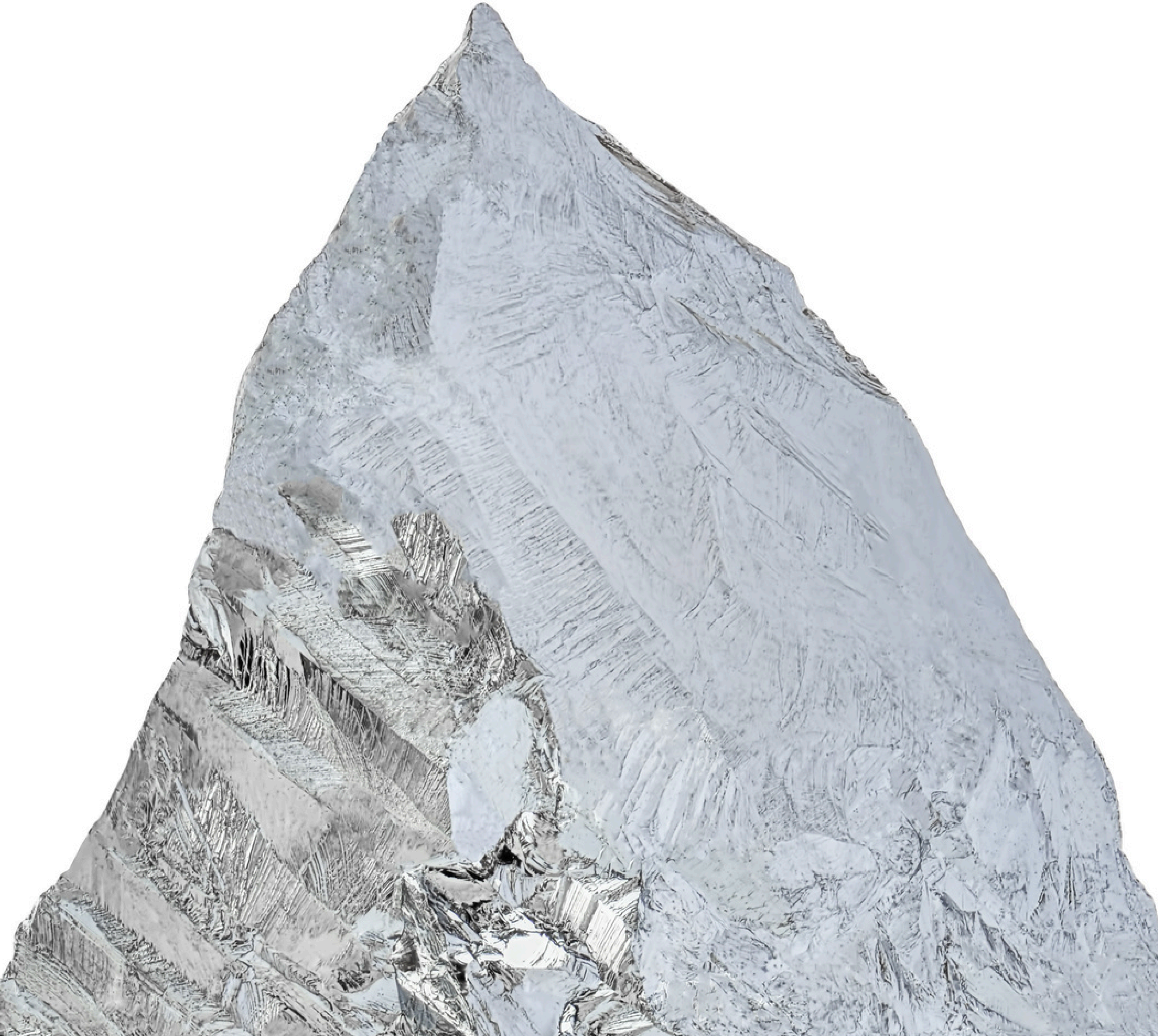


INTRODUCTION

NICKEL AS ONE CRITICAL METAL FOR ACHIEVING A LOW-CARBON FUTURE

INTRODUCTION: NICKEL AS ONE CRITICAL METAL FOR ACHIEVING A LOW-CARBON FUTURE

As the International Energy Agency (IEA) indicates in its report, nickel has high or moderate importance in six of the ten new energy technologies, including geothermal, batteries for electric vehicles (EVs) and energy storage, hydrogen, wind, concentrating solar power, and nuclear (IEA 2021). Even though nickel is only needed in small quantities in manyemissions-reducing technologies, it plays a crucial role in reducing carbon dioxide emissions.

In the rapidly expanding EVs, nickel is considered to be the most important metal by mass in the Li-ion battery cathodes used by EV manufacturers – it makes up about 80% of metal usage in Lithium-nickel-cobalt-aluminium oxide (NCA) cathodes, and at least one-third of Lithium-nickel-manganese-cobalt-oxide (NMC) cathodes (see Table 1). The production of cathode materials for Li-ion batteries requires high-purity Ni sulphate, not Ni metal. This has important consequences regarding the nickel supply chain.

Table 1: Quantities of specific metals in battery cathodes [kg/kWh].

Cathode material	Li	Co	Ni	Mn	Fe	P	Al	O
NMC 111	0.12	0.333	0.333	0.312	0	0	0	0.55
NMC 433	0.117	0.298	0.395	0.278	0	0	0	0.539
NMC 532	0.121	0.205	0.512	0.191	0	0	0	0.558
NMC 622	0.104	0.176	0.525	0.164	0	0	0	0.476
NMC 811	0.096	0.082	0.653	0.076	0	0	0	0.445
HE-NMC 2030	0.123	0	0.106	0.491	0	0	0	0.456
NCA15	0.098	0.125	0.661	0	0	0	0.019	0.451
NCA 5	0.095	0.065	0.725	0	0	0	0.011	0.439
LFP	0.084	0	0	0	0.674	0.374	0	0.772
LMO	0.08	0	0	1.266	0	0	0	0.738

Source: Marscheider-Weidemann et al. (2021).

Nickel helps deliver higher energy density and greater storage capacity of the battery at a lower cost compared with cobalt-intensive batteries. Due to limited cobalt resources, high cobalt prices, and associated environmental, social, and governance (ESG) risks, efforts to replace cobalt with more nickel are ongoing. These rechargeable batteries, when powered by electricity from renewable resources, are key components of electrical vehicles. To reduce greenhouse gas emissions and achieve the climate goals of the Paris Agreement, fuel-based vehicles are expected to be replaced by electric vehicles in the near future (Hund et al. 2020; IEA 2021). The future trend of nickel usage in EVs will be discussed in more detail in Section 1.2.

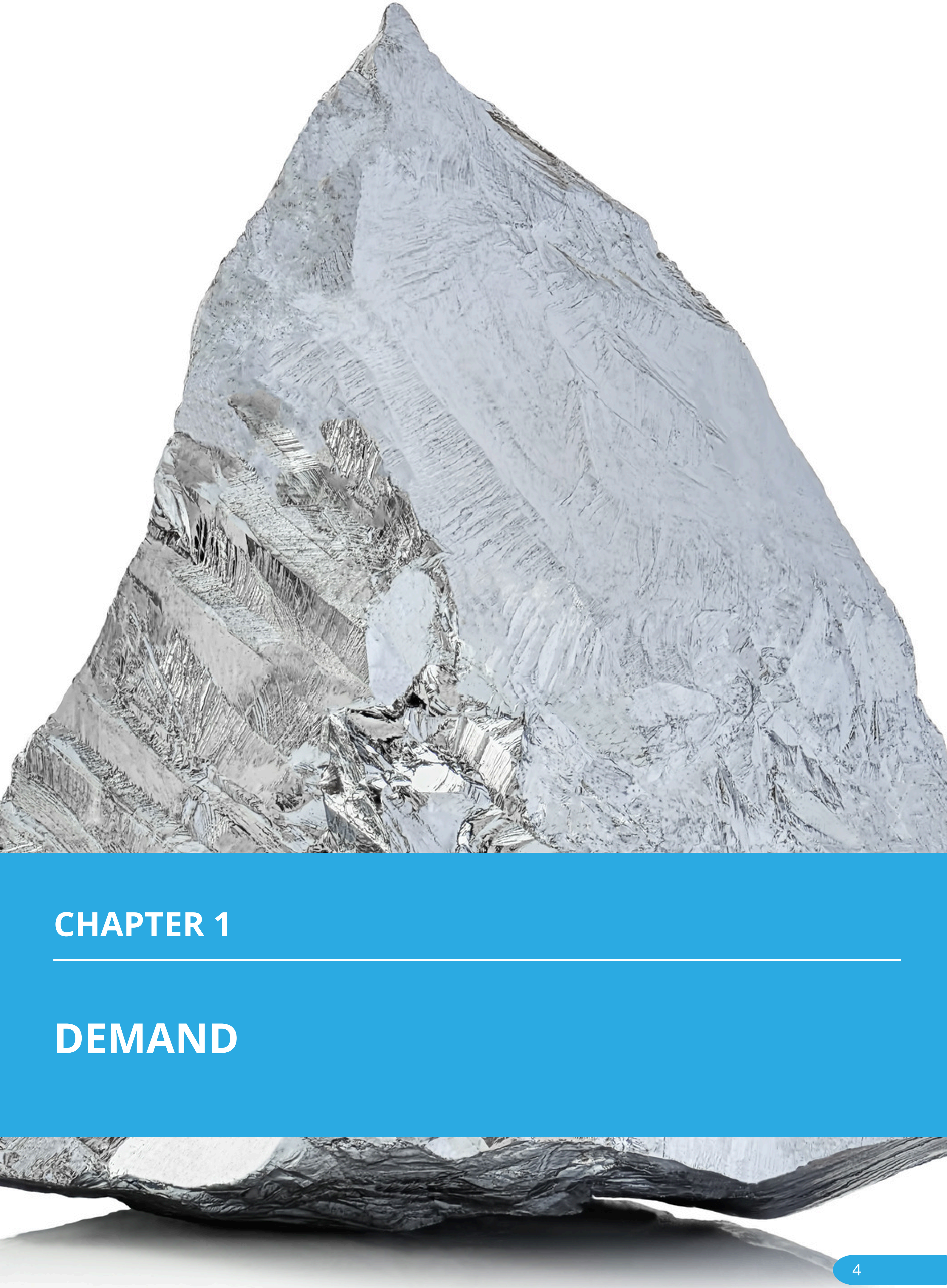
Beyond batteries for EVs, nickel is used in many clean energy technologies, such as geothermal, hydroelectric, and wind power. It serves as an important component in many, though not all, grades of stainless steel. In power generation facilities, certain alloys can contain up to a hundred tonnes of nickel (Nickel Institute 2021). These nickel-based materials are corrosion-resistant, strong, and facilitate excellent heat transfer.

Nickel has a very special market characterized by its complexities:

- of its supply chain, especially in the refining stage, where nickel ores are processes into various forms and purities to produced intermediates required by the end-use markets, including Ni sulphate for Li-ion batteries cathode production;
- of sustainability issues, including biodiversity loss and water/soil pollution from mining waste and tailings, especially in tropical regions where laterite nickel deposits are concentrated;
- of trade tensions and geopolitical risks beyond technical issues in addition to the associated ESG risks on the mining stage.

As mentioned in the note at the beginning of this publication, nickel-related information and data are available from multiple sources, including scientific literature, reports from some of the companies involved in nickel exploration, mining, refining, and trading of nickel products, and reports from national and international institutions as well as reports by consultancies. For cost reasons, the latter could not be used for the preparation of this factsheet. This factsheet is based on public data available upon July 2022.

Conclusions drawn from the scenario analysis in the factsheet are time-sensitive, thus caution should be paid for further use. Future data and knowledge may modify the assumptions and conclusions presented here. A revision of this factsheet every one to two years is highly recommended.



CHAPTER 1

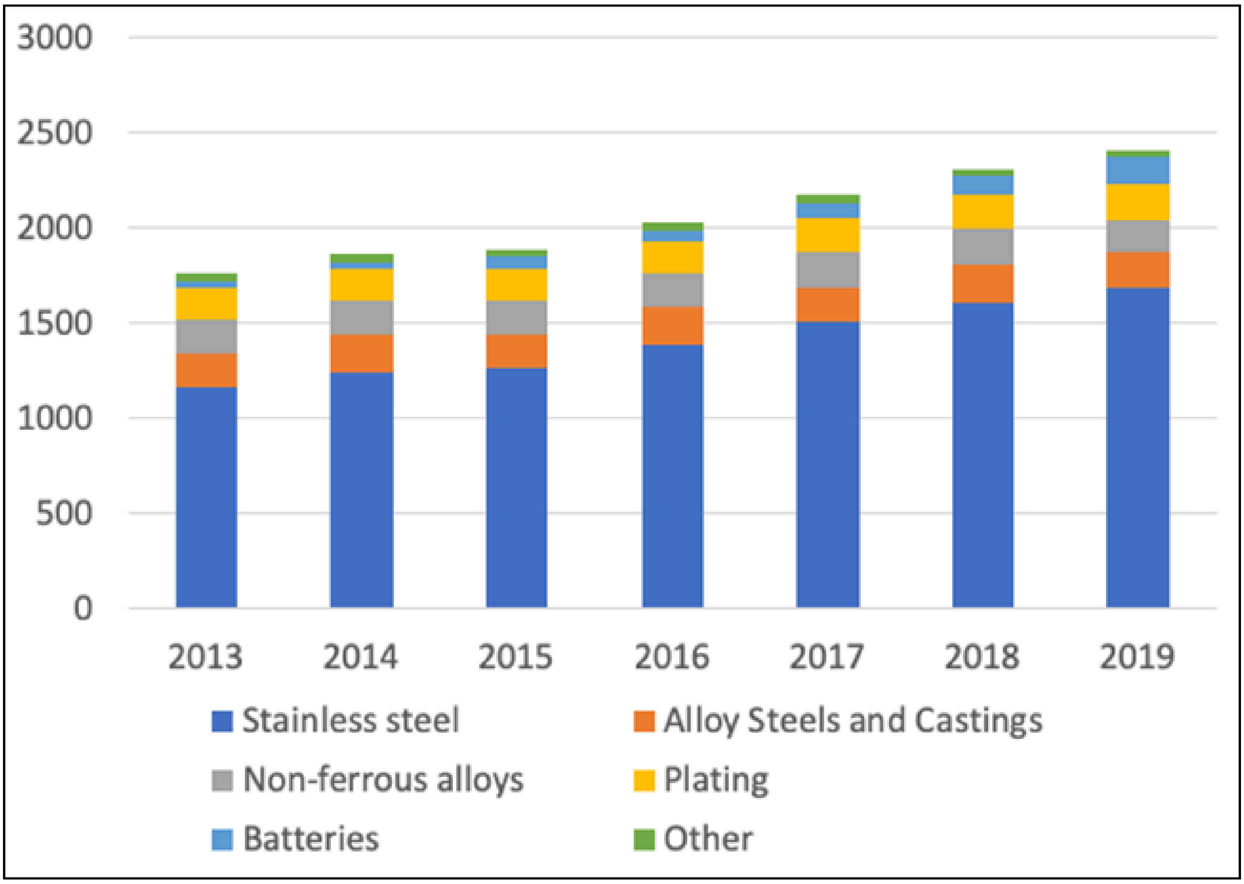
DEMAND

1.1 END-USES, AND INFORMATION FOR THE 2009-2019 PERIOD

Nickel's outstanding physical and chemical properties make it essential across a wide range of manufacturing industries. Figures 1 and 2 provide an overview of the evolution of the main uses of nickel products from 2013 to 2020.

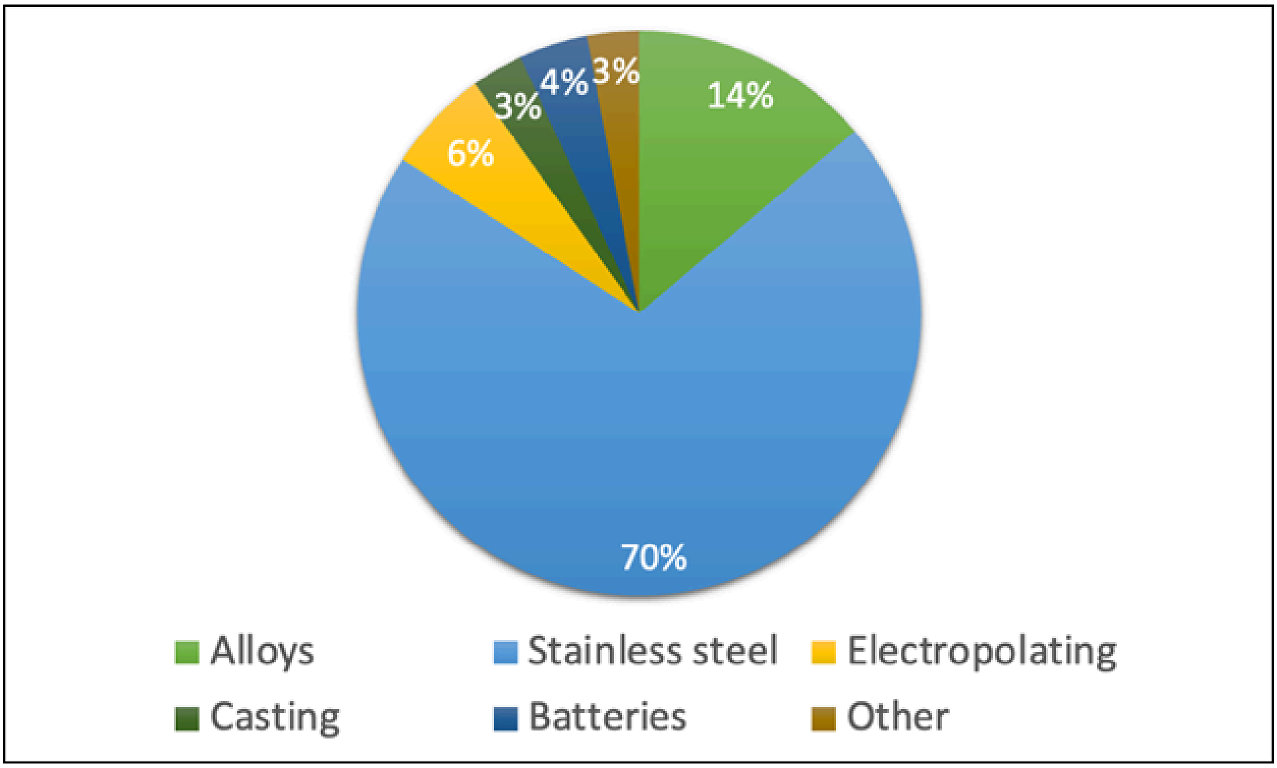
Figure 1 expresses the global nickel demand by the main usage categories in metric tonnes from 2013 to 2019 while Figure 2 shows the major industrial uses of nickel, as of 2020, in percentage of the global demand. The largest use in 2020 was for stainless steel (70%), followed by alloy production (14%), electroplating (6%), batteries (4%), metallurgical castings (3%), and other miscellaneous products (3%).

Figure 1: World demand of refined nickel by first use, 2013-2019 (kt Ni).



Data sources: Fraser et al. (2021).

Figure 2: Nickel demand for its main uses in 2020, in % of the world's production.



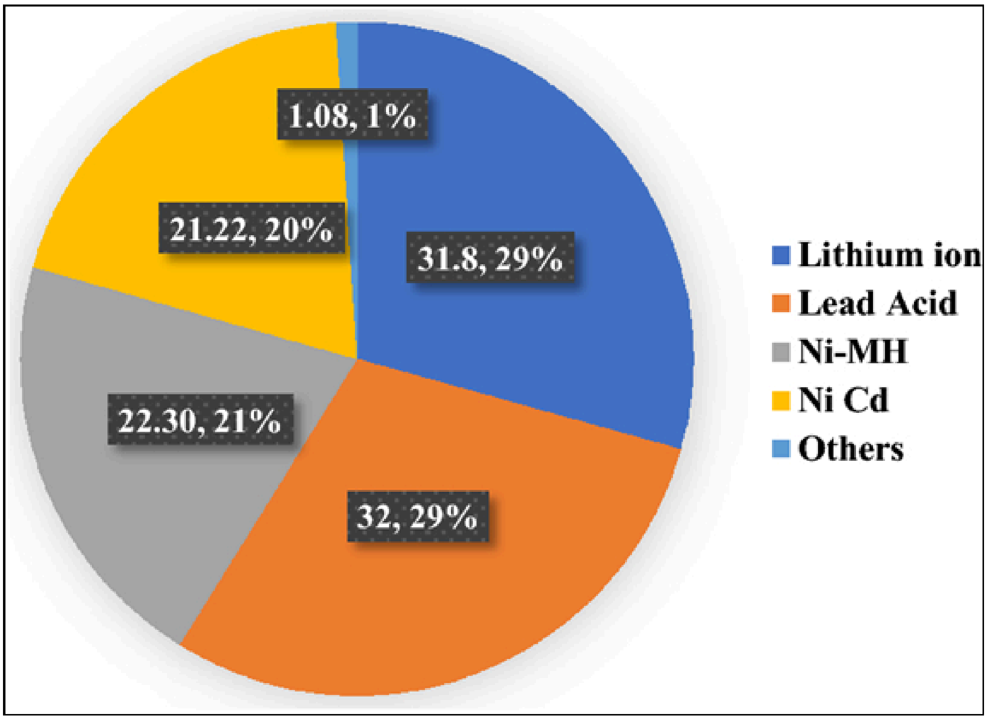
Data sources: Minerals and Metals Facts-Nickel fact, Government of Canada.

Nickel's largest application is in the production of many grades of stainless steel, where nickel is alloyed with other metals to produce steels prized for their high corrosion resistance, high-temperature strength, and high electrical resistance. In the past decades, 60-70% of nickel was used as an alloying input for stainless steel production.

Nickel-based alloys refer to a class of alloys with properties such as high strength and certain oxidation and corrosion resistance at high temperatures of 650 to 1000 °C. These alloys are mainly used as high-temperature materials in turbine engines in the aviation and aerospace industry, followed by corrosion-resistant alloys in petrochemical fields, and soft magnetic alloys and targets in the electronics industry.

Nickel has been widely used in batteries. Historically, the most common nickel-containing batteries were nickel-cadmium (Ni Cd) and rechargeable nickel-metal hydride (Ni-MH) batteries. These two types of batteries came to the fore in the 1980s and their widespread application in power tools and early digital cameras reveals the potential of portable devices which reshape human lifestyle thereafter (Assefi 2020). In the past decade, one important evolving use was in the production of some types of Li-ion batteries for electric and hybrid vehicles (see Introduction). As Figure 3 shows, Nickel-based batteries, including Ni-MH batteries and Ni-Cd batteries, plus Li-ion batteries, account for around 70% of global battery shares in 2019. With the rise of the electric vehicle industry, the proportion of battery consumption of nickel is expected to rapidly increase.

Figure 3: Estimated market share of different batteries in the year 2019 (US$ in billions, % market share).

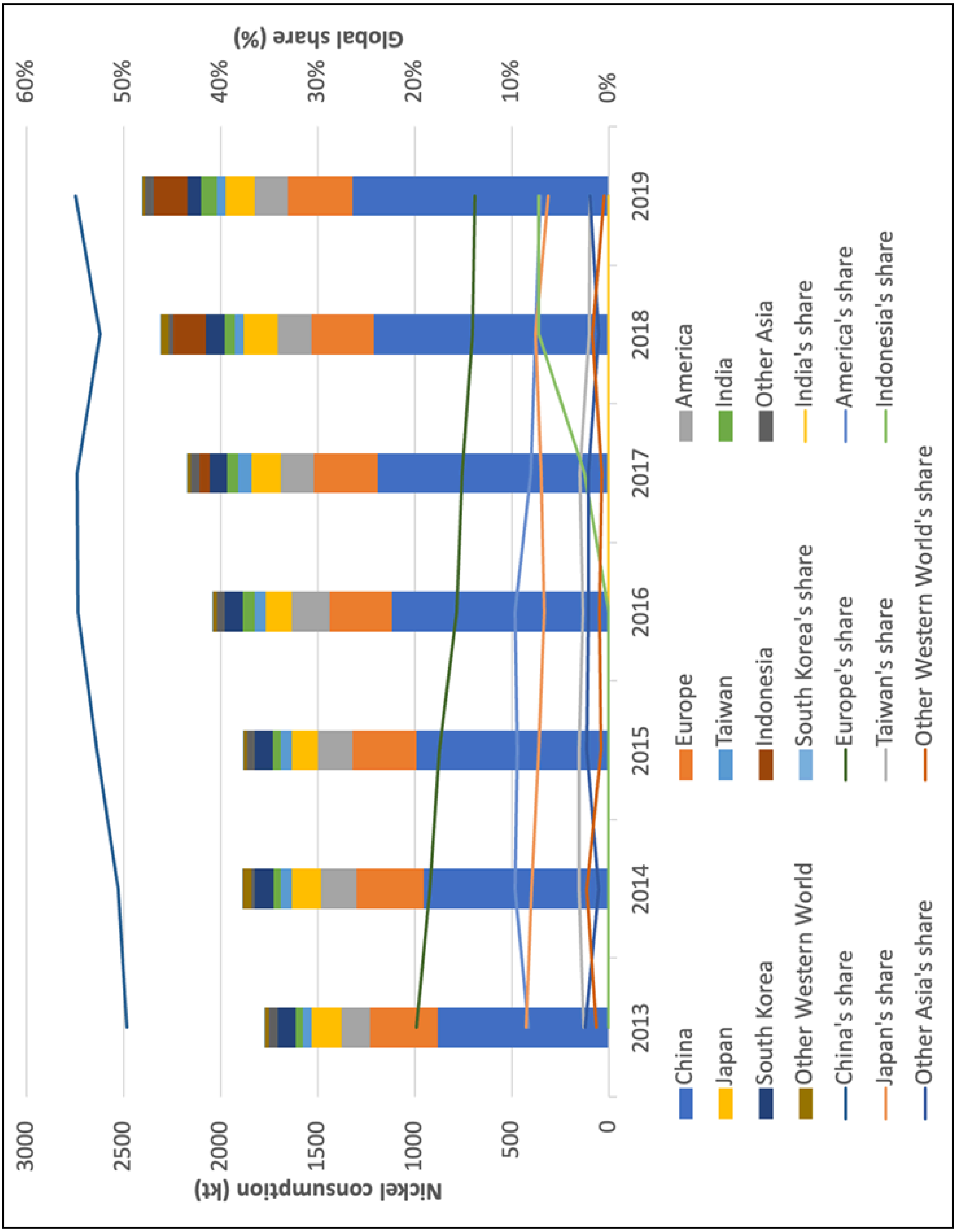


Source: Yanamandra et al. (2022).

Nickel is also used in electroplatingas a premium material for plating and coating base metal materials to improve resistance to corrosion and wear, and enhance the properties of hardness, superior strength, and ductility. Different nickel-plating processes also provide decorative effects for base metal materials with semi-bright and full-bright to matte, pearl, and satin finishes. Nickel can be plated on materials through electroplating or electroless plating independently and combined with other materials such as chromium, cadmium, tin, boron, and palladium. Based on the finished effect, nickel plating can be categorized as bright nickel plating, black nickel plating, or satin nickel plating.

Figure 4 expresses the global nickel consumption by countries or regions in metric tonnes and the percentage of the global share from 2013 to 2019. Most of the demand in 1996 came from Europe (38%) and Asia (37%) (International Nickel Study Group (INSG) 2021), but in 2019, as Figure 4 indicates, European countries accounted for only 14% of global consumption, while Asia accounted for almost three-quarters. America accounted for 9% of the global demand, and Africa barely figured on the list, accounting for just 1% of global consumption. The growth in primary nickel consumption has been mainly driven by China, which absorbed 55% of all nickel products in 2020. This surge in Chinese consumption can be explained by the significant increase in its stainless steel requirement, which is driven by China's rapid economic and social development starting from the 2000s.

Figure 4: Primary Nickel usage by country 2013-2019.



Source: Fraser et al. (2021).

1.2 2019-2040 DEMAND SCENARIOS

The future demand for nickel remains uncertain depending on numerous factors including:

- The consumption of stainless steel has a strong correlation with economic growth. The global recovery from the pandemic and the global economic growth rate in the future remains uncertain, especially the developing countries;

- The sales of battery electric vehicles (BEVs). In the IEA (2021) Sustainable Development Scenario about 72 million BEVs would be sold worldwide, as compared to 1.5 BEVs sold in 2020;

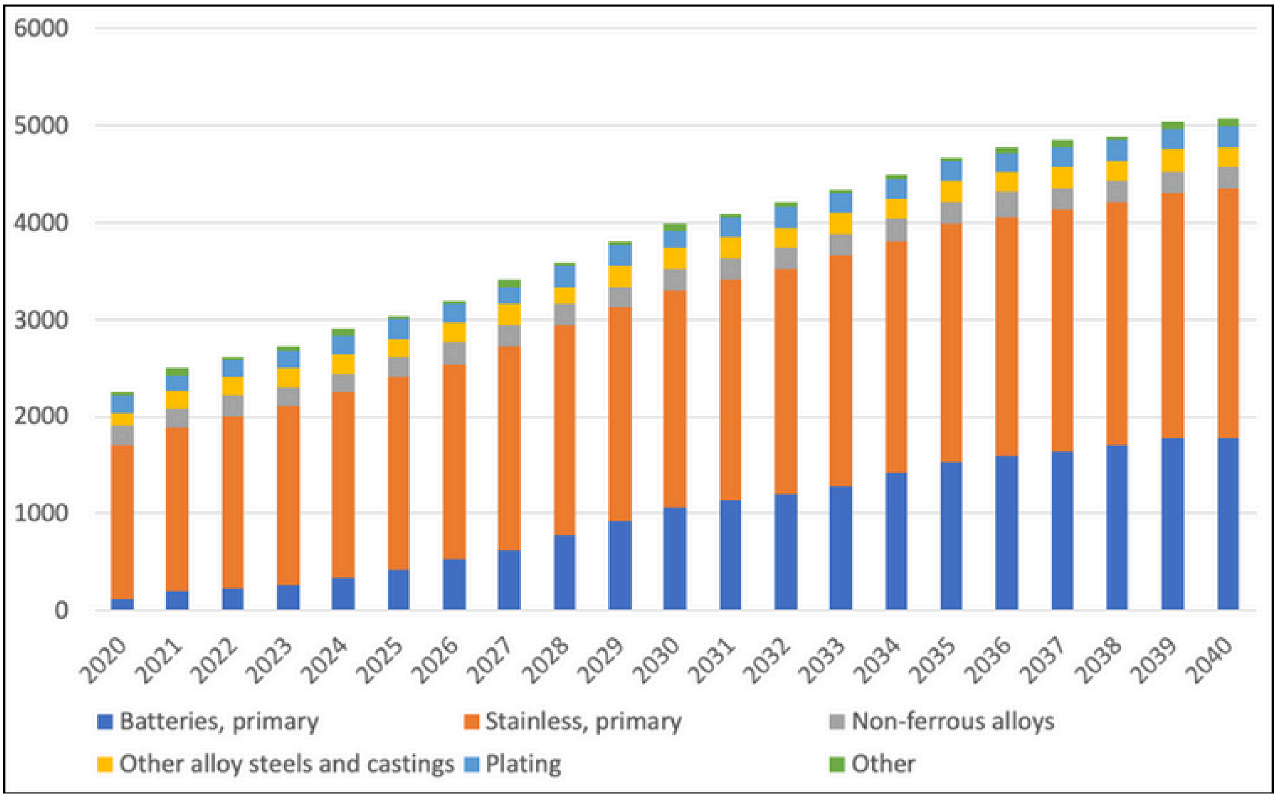
- Technological shifts may increase or decrease the nickel demand for EV batteries. At present, EV batteries are mainly divided into two technical routes: ternary lithium batteries (which adopt three metal elements of nickel, cobalt, manganese, or aluminum as components of the positive electrode, i.e. NCM and NCA batteries accordingly) and lithium iron phosphate (LFP) batteries (which use lithium iron phosphate ($LiFePO_4$) as the cathode material). With the decline of subsidies, pressure on production costs, and improvement of safety awareness, the improvement of blade battery technology may influence the future trend of these two technological routes;

- Delayed shift to nickel-rich cathodes in EV batteries. Li-ion batteries are expected to have higher nickel contents in the future since high-nickel and low-cobalt lithium batteries can further improve energy density and reduce costs. It is also likely that the development of potential competitors, such as LFP batteries and other laboratory developing batteries, will affect the timing of the shift to high-nickel Li-ion batteries;

- The pricing of BEVs, partly depending on the cost of the batteries, will be based on the cost of the battery raw materials, such as lithium, cobalt, nickel, or graphite, as one of the key cost factors for battery production (see Section 2.3 on Ni price trends).

Global nickel demand is expected to double over the 20-year forecast horizon totaling over 5,000 kt Ni by 2040, equivalent to a compound annual growth rate of 4.1% (Fraser et al. 2021). Most of the nickel was used to produce stainless steel in 2020. Stainless steel is likely to remain the largest demand segment till 2040, although batteries that currently account for a small portion of demand are estimated to become the most significant driver of nickel demand growth. As the scenario developed by Roskill (or now WoodMckenzie), a leading analyst of global minerals and metals markets, the battery sector could potentially increase its demand share from 6% in 2020 to 36% in 2040, representing a six-fold increase. Primary nickel demand for producing batteries is expected to reach over 1,800 kt Ni (see Figure 5).

Figure 5: Total primary nickel demand by first-use sector from 2020 to 2040 (kt Ni).



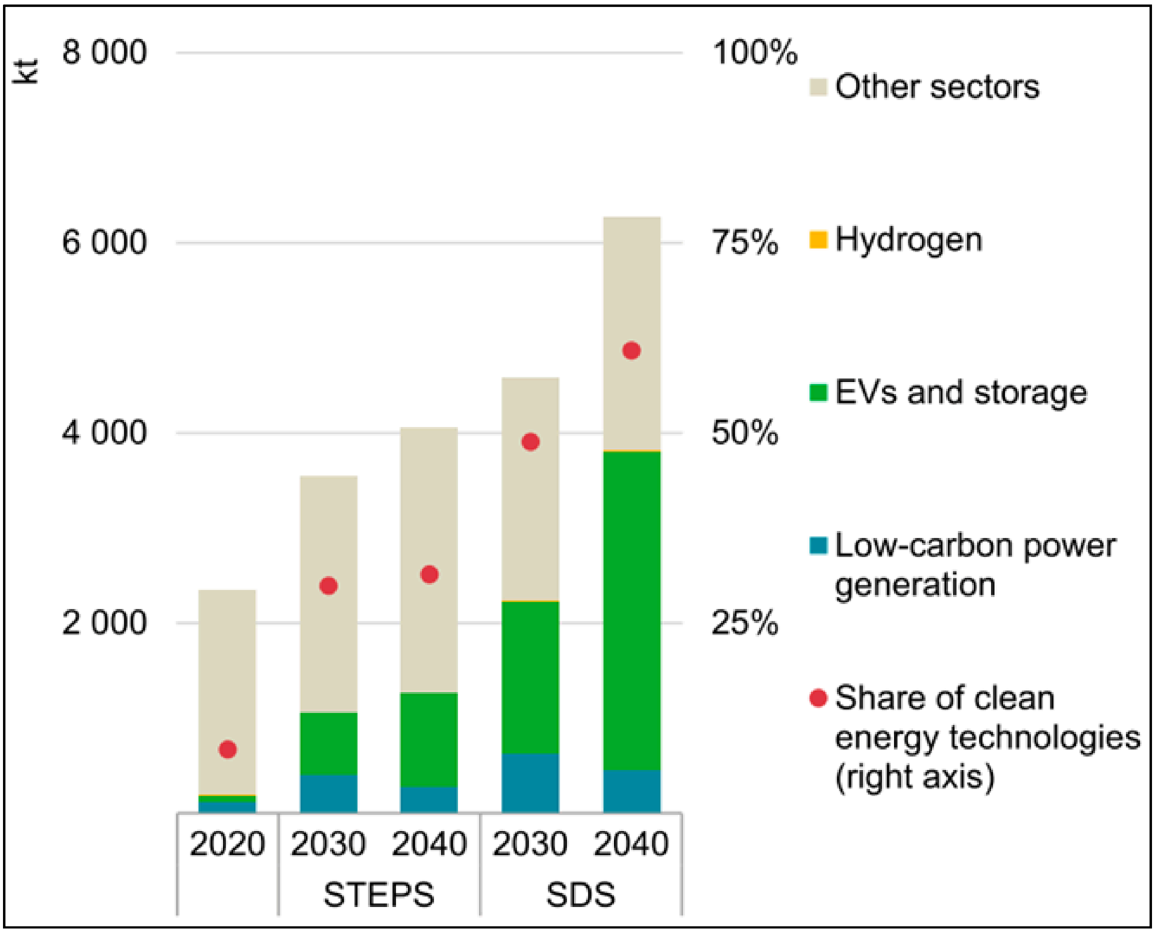
Data source: Fraser et al. (2021).

As the sustainable development scenario (SDS) provided by IEA indicates, nickel-supporting EVs and storage will reach 1592 kt (34%) in 2030 and 3352 kt (53%) in 2040. The share of clean energy technologies will rise to around 60% of total nickel demand (see Figure 6).

In terms of batteries, high-capacity, and high-energy density materials are essential for enabling long-distance travel. Among these, density is considered to be the most factor influencing EV adoption. Increasing the Ni content in lithium-ion battery cathodes enhances the amount of Li that can be cycled in and out without causing structural instability increases, and therefore improving energy density (Li et al. 2020). Furthermore, nickel-rich cathodes also eliminates the need for cobalt, a material with highly volatile prices in recent years, and significant sustainability concerns. The current nickel content in the cathode of Li-ion batteries is described in Figure 7.

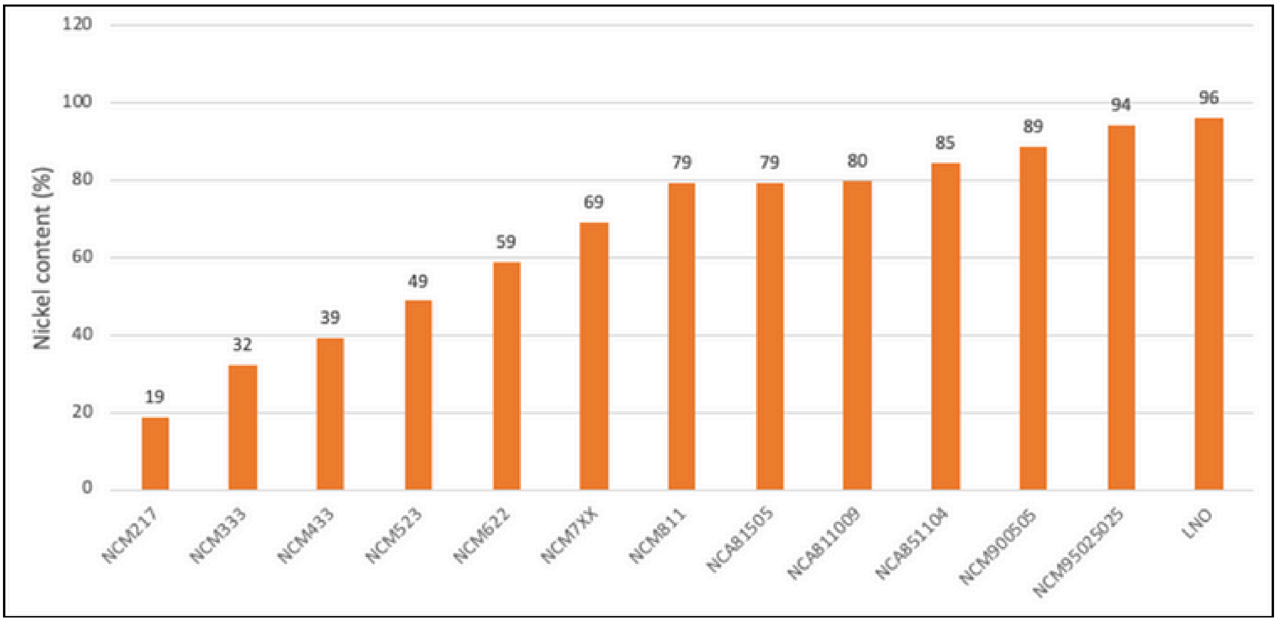
According to Fraser et al. (2021), high-nickel cathodes, such as NCM 811 and NCM 622 will take over most of the market share of NCM 523 and NCM 111 (see Figure 8). Notably, in Figure 8, Lithium Cobalt Oxide ($LiCoO_2$ or LCO), Lithium iron phosphate ($LiFePO_4$ or LFP), and Lithium ion manganese oxide (LMO) batteries do not consume Ni. In recent years, LFP batteries have gradually occupied a portion of the EV market. It is expected that in the next few years, LFP batteries will continue to increase their share in short-range vehicles, even replacing ternary lithium batteries in this field.

Figure 6: Total nickel demand by sector and scenario, 2020-2040.



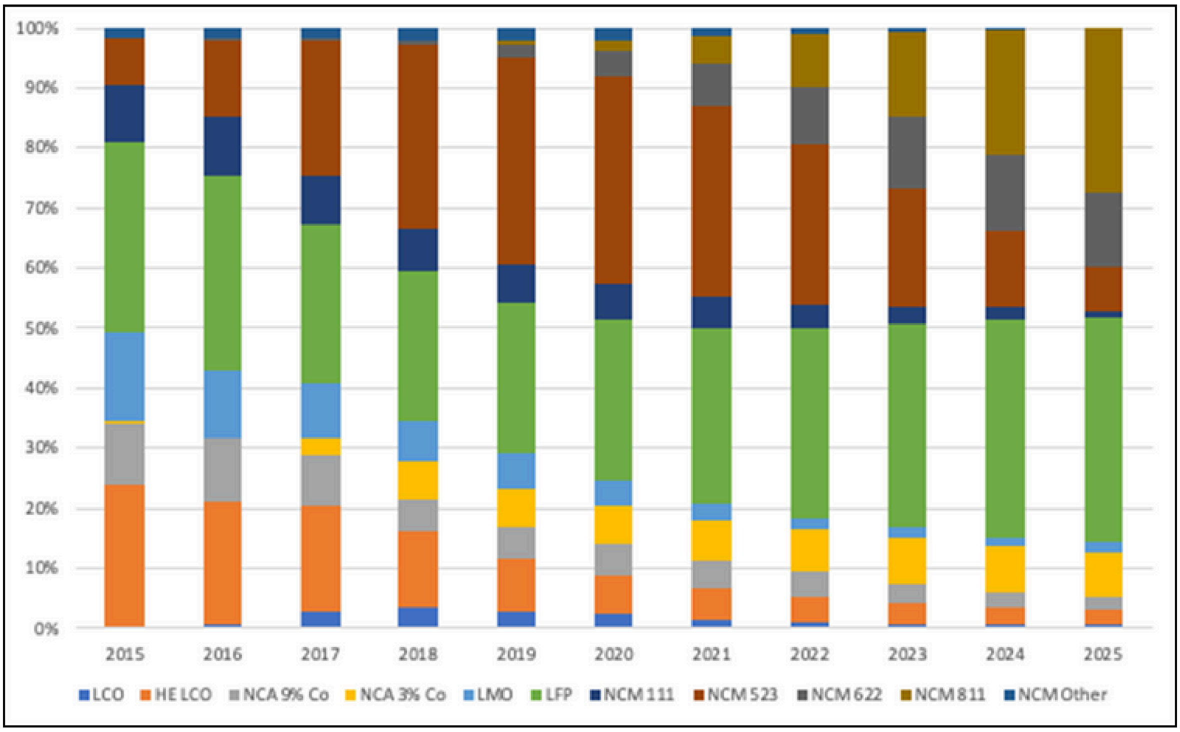
Note: STEPS- Stated Policies Scenario; SDS- sustainable development scenario
Source: IEA (2021).

Figure 7: Evolving importance of nickel in battery cathode.



Data source: INSG, 2021.

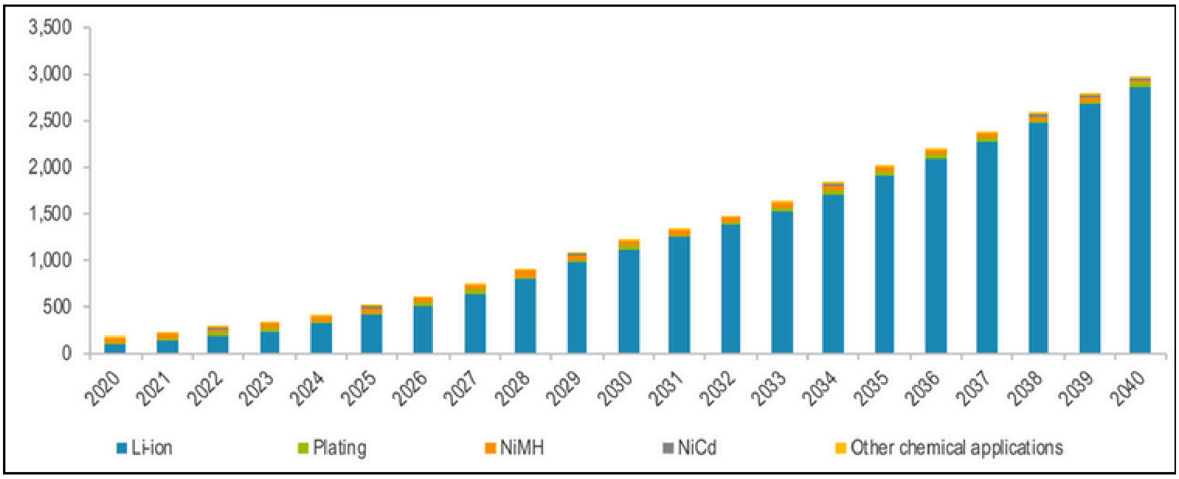
Figure 8: Battery market share from 2015-2025.



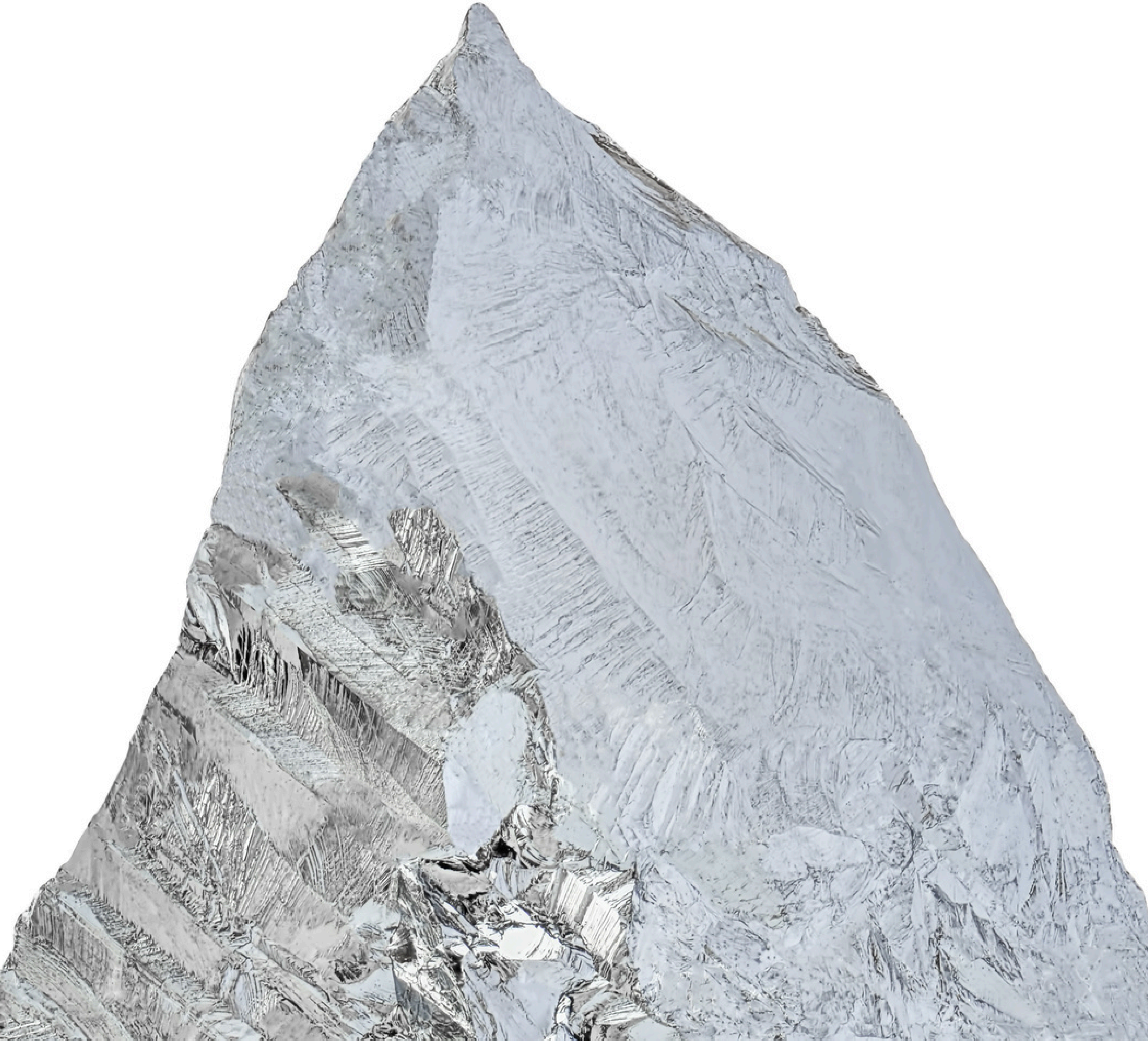
Data source: Fraser et al. (2021).

Nickel sulfate, as an important chemical intermediate, is mainly used to produce batteries, and is a hot spot in nickel industry research. Li-ion battery products and their end-uses fundamentally promote the substantial growth of nickel sulfate demand. Without Li-ion batteries, nickel sulfate will still be a relatively small niche chemical market. However, since the late 1900s, the growth of Li-ion batteries has rapidly accounted for most of the total demand for sulphate, which is assumed to reach 55% by 2020 (see Figure 9). According to the scenario provided by Roskill, it will exceed 90% of the total demand by 2030 and continue to increase thereafter. By 2020, the total global demand for nickel sulfate reached approximately 173kt Ni. From 2020 to 2030, the demand for nickel sulfate is expected to grow at a compound annual growth rate of 22%, totaling more than 1200 kt Ni. From 2020 to 2040, the compound annual growth rate is expected to be 33%, and the nickel demand will be about 3 million tonnes.

Figure 9: Nickel sulphate demand by first-use application, 2020-2040 (kt Ni).



Source: Fraser et al. (2021).



CHAPTER 2

SUPPLY-SIDE

2.1 NICKEL DEPOSITS

Nickel ranks the twenty-fourth among the elements in the order of abundance on the earth and is the fifth most abundant element by weight in the earth's crust (Ernest Mastromatteo 1986). Nickel is mainly found in three types of deposits: magmatic sulphide, laterite, and sedimentary deposits. Nickel can also be found in manganese nodules (also referred to as polymetallic nodules) and crusts (e.g. cobalt-rich crusts) on the deep-sea floor (Miller et al. 2018), but they are not yet mined.

Magmatic sulphide systems can be roughly split into sulphur-rich Ni-Cu-(PGE) (the platinum-group elements) and sulphur-poor PGE-dominated deposits that generally extract copper and nickel as by-products (Naldrett 2004; Hoatson et al. 2006). The magmatic sulphide deposits can be further subdivided into the following categories (Mudd and Jowitt 2022):

1. Archean and Proterozoic komatiites: These are magmatic sulphide deposits that are hosted by komatiites and/or komatiitic basalts or associated subvolcanic intrusions of unequivocally Archean or Proterozoic age, as exemplified by the Kambalda Ni deposits of Western Australia and the Thompson and Raglan deposits of Canada, respectively.

2. Small mafic-ultramafic intrusion-related: These deposits represent magmatic sulphide systems associated with mafic-ultramafic intrusions or conduits that are smaller than larger layered intrusions or Alaskan-type complexes and are distinct from Archean-Proterozoic komatiites. These intrusions are exemplified by the Norilsk-Talnakh deposits of Russia and deposits of the Duluth Complex of Minnesota.

3. Layered intrusive: These deposits are hosted by large layered mafic-ultramafic intrusive complexes. The structural position of this deposit is unusual compared to the other PGE-dominant deposits within this compilation (e.g., Naldrett 2004).

4. Alaskan-type deposit: These generally minor deposits are associated with Alaskan- or Urals-type ultramafic complexes that are more known for PGE production than for Ni. They are exemplified by the Turnagain deposit of British Columbia, Canada.

5. Meteorite impact melt-related: This class of deposits represents magmatic sulphide systems formed because of meteorite impact events, as exemplified by the deposits of the Sudbury area of Ontario, Canada, and the Maniitsoq meteorite impact structure of southwestern Greenland.

Laterite nickel ore forms through the lateralization of oceanic crust that has been over-thrusted over continental crust or volcanic arcs. This process occurs primarily in tropical or subtropical regions where large-scale and long-term weathering, leaching, alteration, and metamorphism take place under humid tropical conditions. Geologist refer to this phenomenon, in which oceanic crust is thrust over continental material and/or oceanic island arcs, as obduction (Putzolu 2020). It is a loose clay-like ore composed of iron, aluminum, silicon, manganese, and other hydrous oxides. The ore is red due to the oxidation of iron, so it is called laterite. The laterization process leads to the progressive development of a profile that includes three recoverable components, from the surface down to the fresh un-weathered oceanic crust material (see Figure 10):

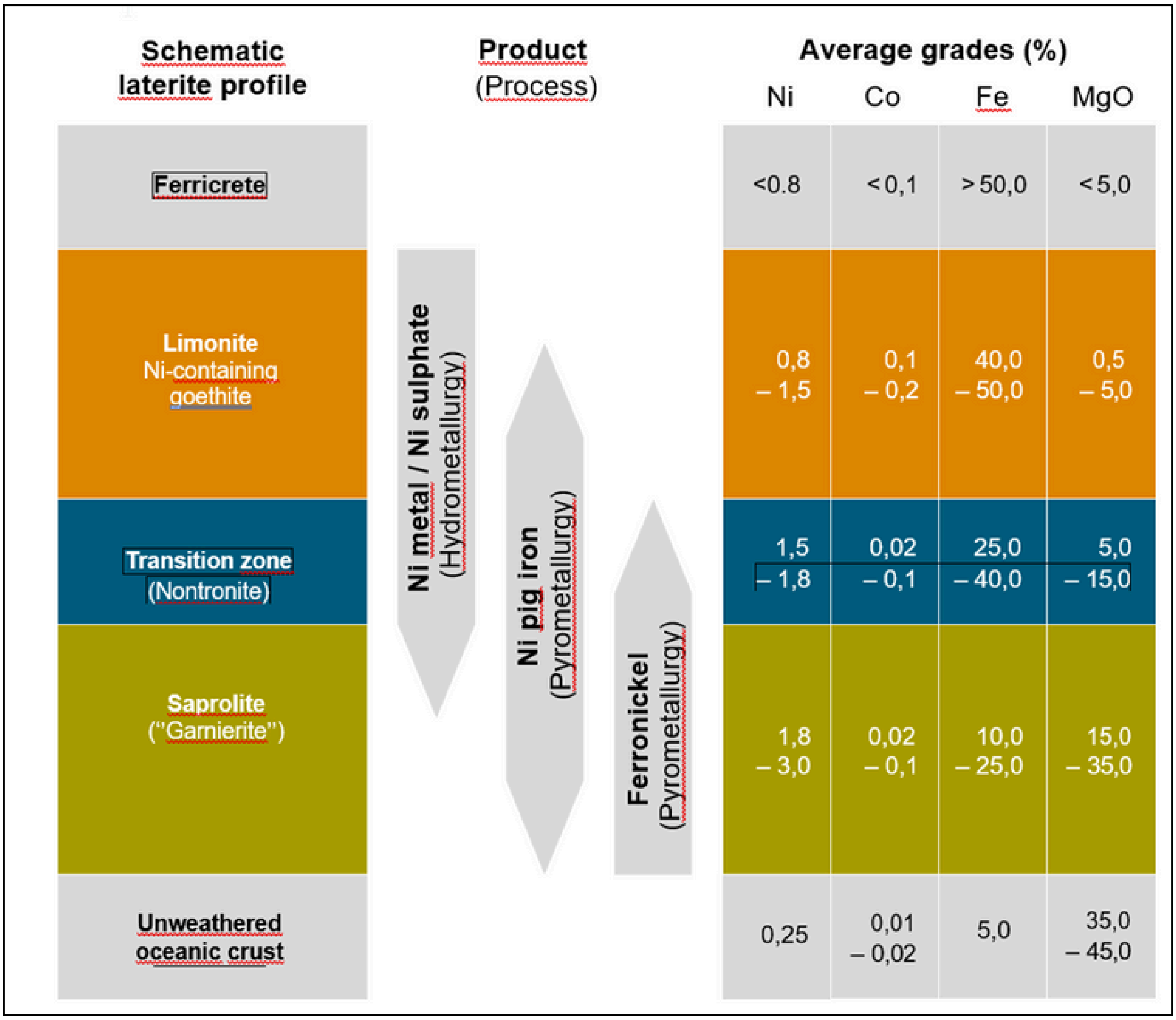
1. Limonite:
Oxide laterites containing Ni are substituted or adsorbed onto goethite.

2. Saprolite:
Hydrous Mg silicate laterites where Ni is hosted by Ni-rich hydrous manganese silicates, such as garnierite which is a mixture of different Ni-rich silicate clay-like (phyllosilicates) minerals.

3. Transition zone:
Clay silicate laterites where Ni is hosted by Ni-rich nontronite and saponite smectites.

Sedimentary deposits are pyrite-rich black shales, frequently metamorphized into pyrite-rich deposits. Ni can be recovered by bacterial bioleaching (biohydro-metallurgical process) from these low-grade deposits. While deposits are known in Canada (Alberta and Yukon), in China (in 10 Southern China provinces), and in Sweden, they are so far only mined by Terrafame[1] in Finland.

Figure 10: Ideal profile of nickel laterite and processes used for Ni recovery from its different components.



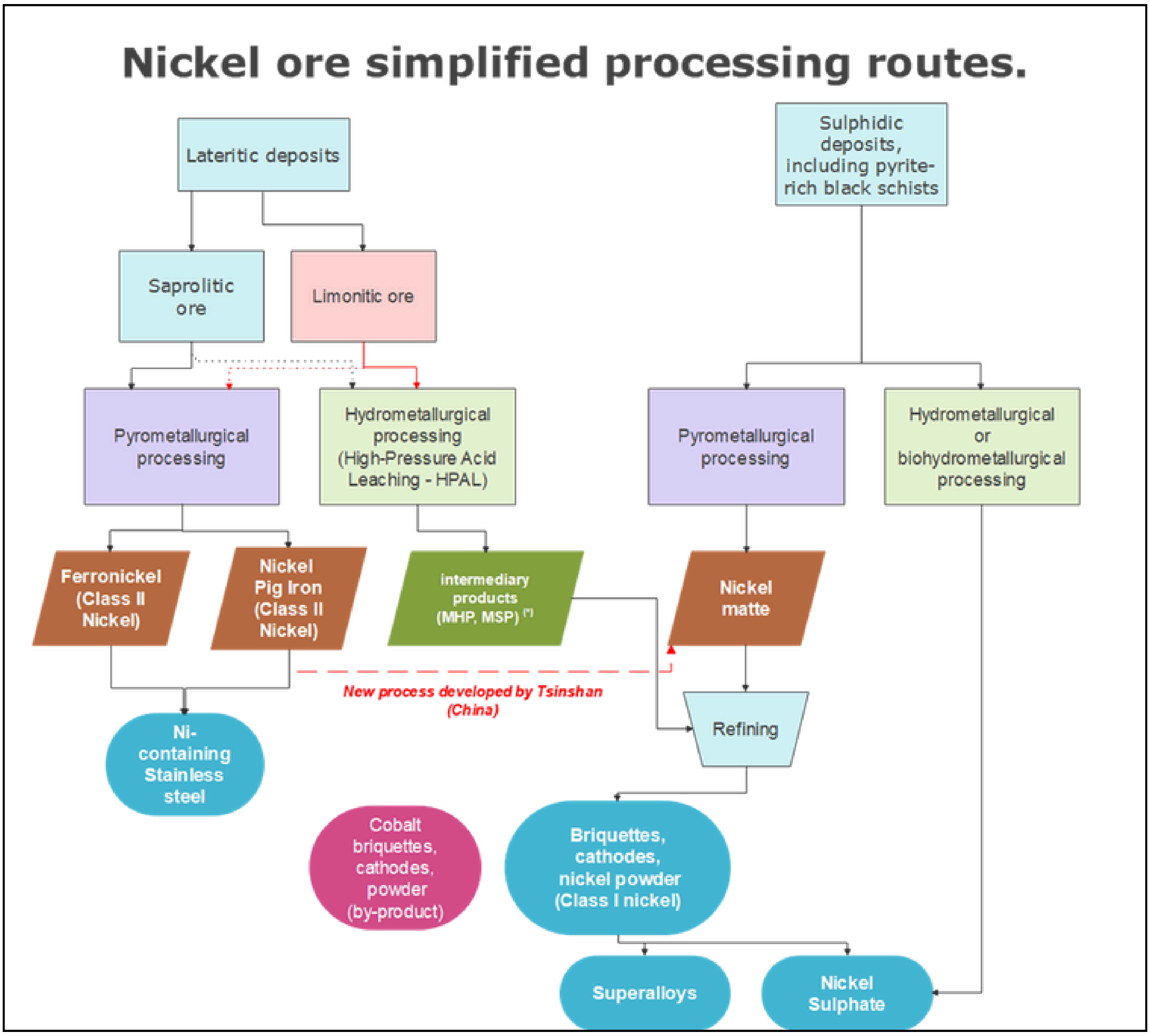
Note: The process selection is mainly dependent on the Ni, Fe, and Mg content of each laterite profile component (Translated from Szurlies et al. 2021, which itself was adapted from Wedderburn 2009).

[1] https://www.terrafame.com/front-page.html

The smelting method of nickel sulphide ore mainly adopts pyrometallurgy and the production of nickel matte smelting, i.e., various grades of nickel sulphide ores are smelted into a low-nickel matte by pyrometallurgical processes. Then the low-nickel matte is blown into a high-nickel matte (nickel sulphide and copper sulphide alloy). High-nickel mattes are finally processed in nickel refineries to produce different nickel products. The pyrometallurgical technologies of nickel sulphide are mature and have been widely used in the smelting of nickel sulphide concentrate (Zhao 2022). Bacterial biohydrometallurgical leaching of metals, including nickel, is used for the extraction of nickel from pyrite-rich black schists in Finland.

For laterite nickel ores, pyrometallurgy and hydrometallurgy are both applied to produce nickel products, and the process used depends on the nature of the ore (see Figure 11). The limonite layer is high in iron, and low in nickel and magnesium. It is suitable for adopting the hydrometallurgy route, such as the High-Pressure Acid Leaching (HPAL) process, to produce nickel intermediary nickel products. The saprolite layer has high nickel and magnesium content, and low iron, and cobalt content. Pyrometallurgy is usually applied.

Figure 11: Simplified representation of the nickel ores processing routes.



Note: MHP stands for mixed-hydroxide products and MSP stands for Mixed Sulphide Products).

2.2 TOP 10 PRODUCING COUNTRIES IN 2010 AND 2020, AND THEIR PRODUCTION

2.2.1 At the mining level

Table 2 and 3 show the top nickel producing countries in 2010 (for reference) and in 2020 respectively, together with the world production.

Table 2: Top 10 Nickel producing countries in 2010, and world production (in metric t Ni contained in the ore).

	MINE PRODUCTION 2010, in metric tonnes contained Ni			
	Top 10 producing countries	Annual mine production, in metric t contained Ni	Deposit type	Production share, in % of world total
	Russia	269,000	Magmatic sulfide	17%
	Indonesia	232,000	Laterite	15%
	Philippines	173,000	Laterite	11%
	Australia	170,000	Laterite and Magmatic sulfide	11%
	Canada	158,000	Magmatic sulfide	10%
	New Caledonia	130,000	Laterite	8%
	China	79,000	Magmatic sulfide	5%
	Colombia	72,000	Laterite	5%
	Cuba	70,000	Laterite	4%
	Brazil	59,100	Laterite and Magmatic sulfide	4%
Total of top 10 producing countries , and share of the world total >>>				89%
Wolrd Total >>>		***1,590,000***		

Data source: USGS (2012).

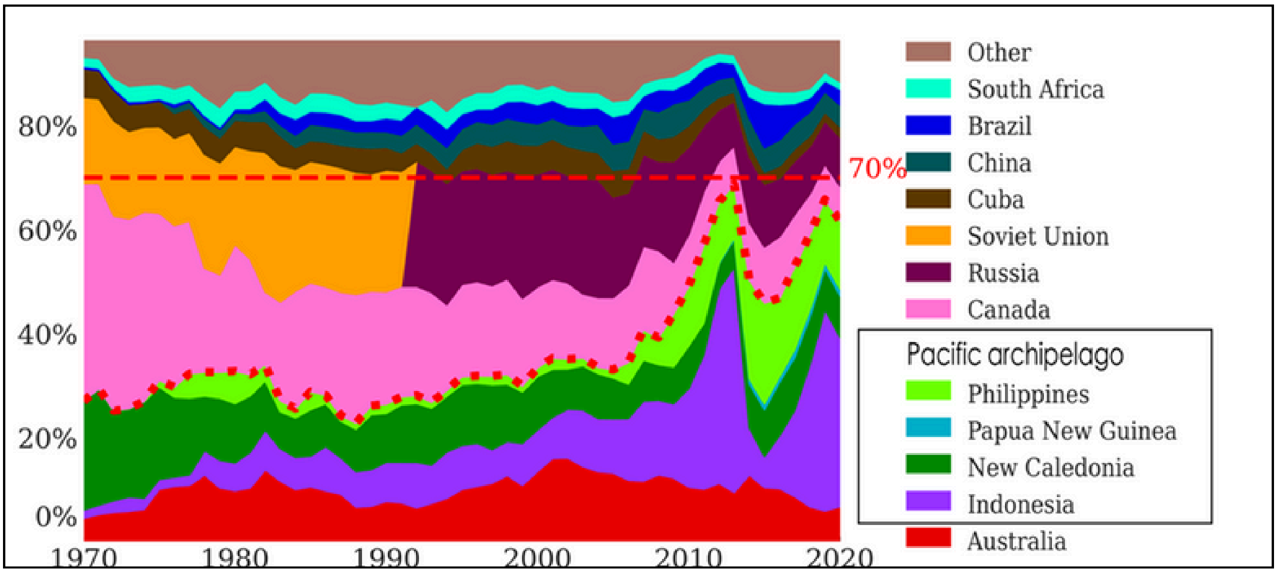
Table 3: Top 10 Nickel producing countries (at mine level) in 2020, and World production (in metric t Ni contained in the ore).

	MINE PRODUCTION 2020, in metric tonnes contained Ni				CAGR 2010
	Top 10 producing countries	Annual mine production, in metric t contained Ni	Deposit type	Production share, in % of world total	CAGR 2010-2020
	Indonesia	771,000	Laterite	31%	12.8%
	Philippines	334,000	Laterite	13%	6.8%
	Russia	283,000	Magmatic sulfide	11%	Not significant
	New Caledonia	200,000	Laterite	8%	4.4%
	Australia	169,000	Laterite and Magmatic sulfide	7%	2.7%
	Canada	167,000	Magmatic sulfide	7%	Not significant
	China	120,000	Magmatic sulfide	5%	5.2%
	Brazil	77,100	Laterite and Magmatic sulfide	3%	2.7%
	Guatemala	68,363	Laterite	3%	No production in 2010
	Cuba	50,000	Laterite	2%	-3.3%
Total of top 10 producing countries , and share of the world total >>>				89%	
Wolrd Total >>>		***2,510,000***			4.7%

Data source: USGS (2020), BGS (2020), Mudd and Jowitt (2022).

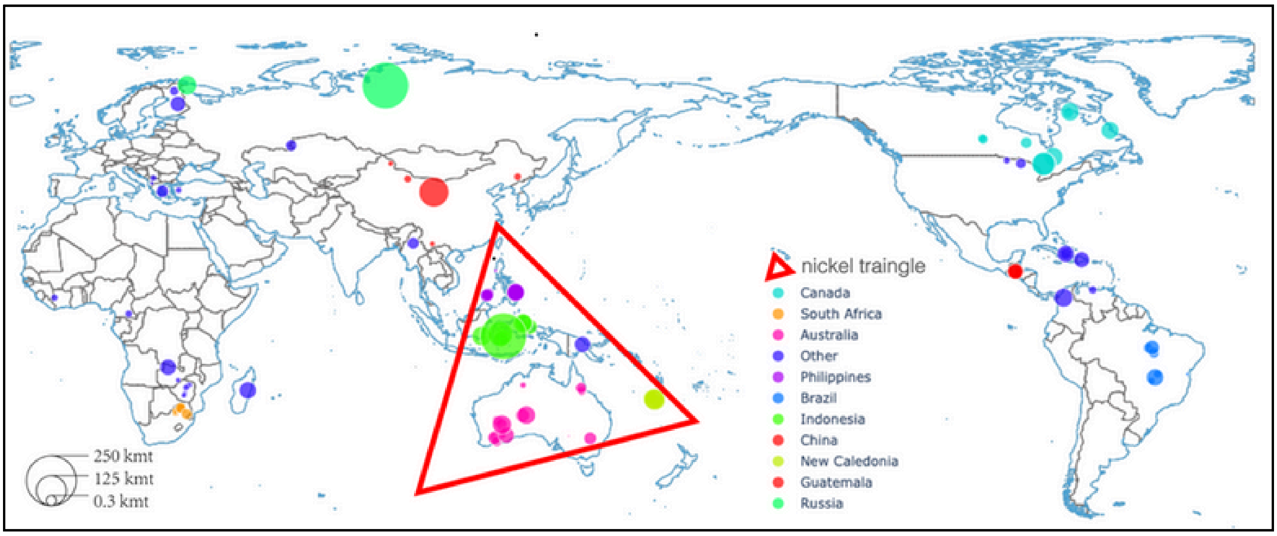
In 2020, Indonesia, the Philippines, and Russia were the dominating nickel producers. The top ten nickel-producing countries represent 89% of the 2020 world production, as shown in Table 3. From a geographical point of view, in 2020, around 70% of world nickel resources and annual nickel production were located across the Pacific archipelago (i.e., Indonesia, Philippines, Papua New Guinea, New Caledonia) and in Australia, forming a triangle region which can be called ‘nickel triangle’ (see Figure 13).

Figure 12: Historical world nickel production by country or region in percentage from 1970 to 2020.



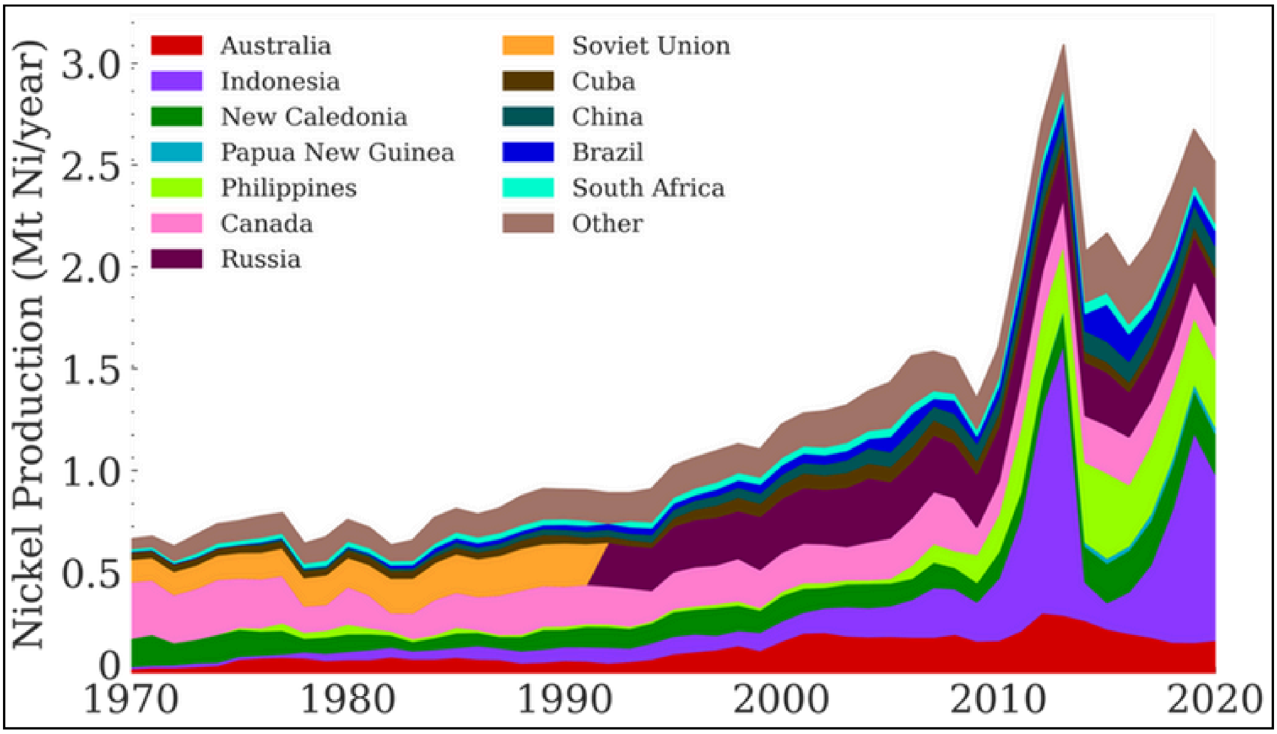
Data source: data synthesized from BGS, 1970–2020.

Figure 13: World distribution of nickel production on mine level in 2019.



Over the 2010-2020 period, the world production rose by about 160%, or by a compound annual growth rate of 4.7%. The nickel triangle region has also seen rapid growth in nickel mining in the past decade, primarily driven by the increase in production capacity in Indonesia and the Philippines (see Figure 14).

Figure 14: Historical world nickel production by country or region in metrics from 1970 to 2020.



Data source: data synthesized from BGS, 1970–2020.

As several important projects in Indonesia are scheduled to come online in the coming years, the dominance of Indonesia in primary nickel production will not be shaken for decades to come. In addition, the production capacity of the nickel industry is expected to surpass demand starting in 2022. But there is no guarantee that the status of the surplus will continue after 2025 and be sufficient to meet the demand scenarios presented in Section 1.2.

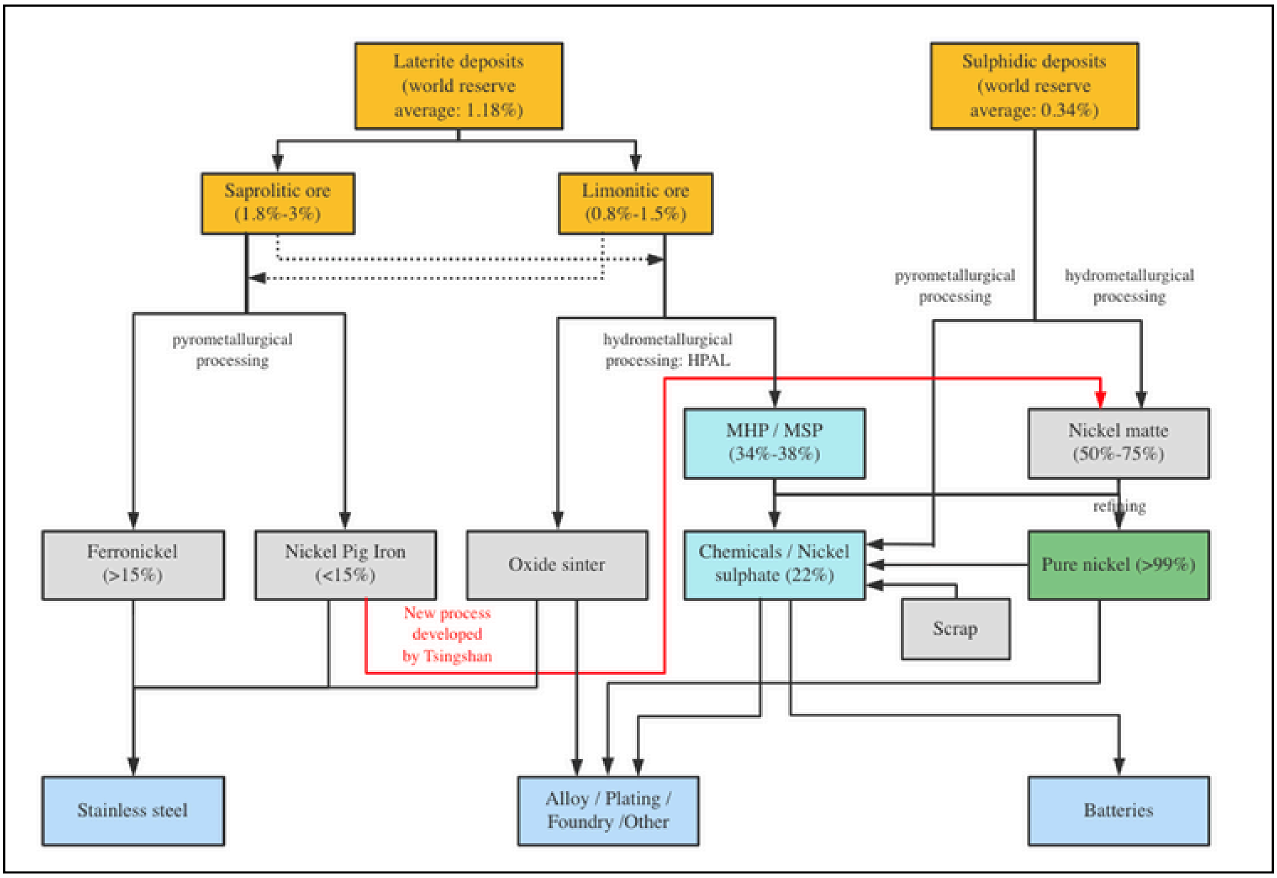
2.2.2 At the metallurgical / refining level

Nickel products can be roughly divided into three categories: (1) refined nickel (pure nickel or nickel metal), (2) ferronickel (FeNi)/nickel pig iron (NPI), and (3) nickel salts and chemicals:

- Refined nickel includes nickel plates, nickel beans, nickel powders, and nickel beads. Among them, nickel plates and nickel beans are the most common forms of pure nickel.
- FeNi and NPI are the products of laterite nickel ore primarily through the pyrometallurgical process. They have different levels of nickel content, and they are mainly used to produce stainless steel.
- Nickel sulphate is the major nickel salt for the electroplating and battery industry. Li-ion batteries utilizing nickel-rich cathodes require high-purity nickel as a building block, typically in the form of nickel sulphate (Schmidt et al. 2016).

According to the Nickel Institute, nickel products can also be classified into Class I nickel (pure metal) and Class II nickel (others) based on their degree of purity. Class I nickel has a nickel content of 99.98% or more and comes from both sulphide and laterite nickel mines. There are multiple technical routes involved in refining and processing both sulphide and laterite ores so that they can be converted into concentrates and ultimately Class I nickel. The production of cathode materials for Li-ion batteries requires high-purity nickel sulfate, which comes from Class I nickel. HPAL processing of the limonitic ore from lateritic profiles makes it possible to produce class I nickel from laterite ores. In addition, Tsingshan (China) has developed a process that allows the production of Class I nickel from saprolite ore, a potential game-changer for the nickel industry (see the red line in Figure 15). Class II nickel, such as alloys and ferronickel, mainly coming from laterite deposits, has a lower degree of purity and is primarily used in the stainless steel industry.

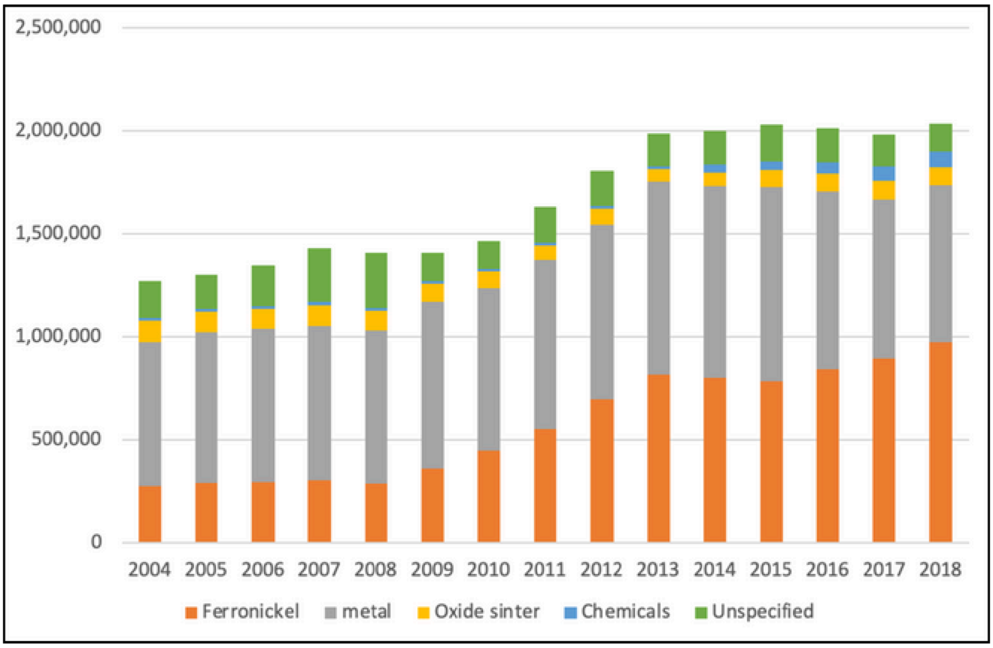
Figure 15: The nickel ores processing routes.



Notes: MHP stands for mixed-hydroxide products and MSP stands for Mixed Suphide Products).

Figure 16 depicts the world's primary nickel production by products from 2014 to 2018, showing that in the past two decades, the increase of the primary nickel supply concentrated on the production of ferronickel. Furthermore, since 2014, the supply of nickel salts, mainly nickel sulfate, has increased significantly, which will become the driving force for future nickel supply.

Figure 16: World primary nickel production by products, in metric tonnes, contained nickel.



Data source: USGS (2004-2018).

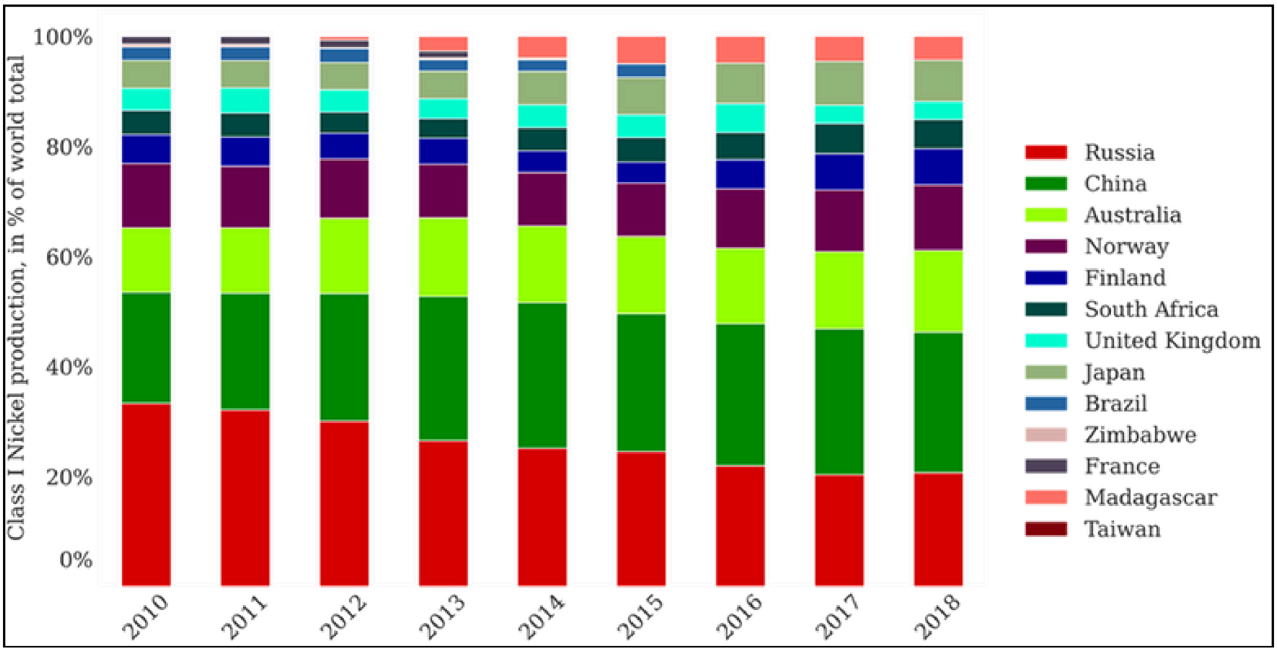
The world's largest producers of Class I nickel remained China and Russia in 2018, accounting for 26% and 21% of the world total, respectively (see Table 4). From a dynamic perspective, Russia once accounted for over 1/3 of the world Class I nickel production, but its market share keeps declining whereas China and Australia took over its reduced share. Meanwhile, China is also the largest producer of FeNi and NPI, accounting for 50% of the total production. In addition, the production of chemicals, mainly nickel sulphate, is concentrated in China and Japan, accounting for 59% and 20% respectively.

Table 4: World primary nickel production, by country or locality and product, in metric tonnes, contained nickel.

WORLD PRIMARY NICKEL PRODUCTION, by country or locality and product, in metric tonnes contained nickel						
Country or Locality	Ferronickel & NPI	Metal	Chemicals	Oxide Sinter	Unspecified	Total
China	476,040	195,000	45,200	--	--	716,000
Japan	68,200	57,517	15,624	45,438	--	187,000
Russia	--	158,005	--	--	--	158,005
Canada	--	--	--	--	133,200	133,200
Australia	--	113,500	--	--	--	113,500
New Caledonia	82,114	--	--	25,800	--	107,914
Indonesia	98,200	--	--	--	--	98,200
Norway	--	90,800	--	--	--	90,800
Brazil	65,200	--	--	--	--	65,200
Other	184,829	148,711	15,825	16,000	3,667	369,032
World total >>>	974,000	764,000	76,600	87,200	137,000	2,040,000

Data source: USGS (2018).

Figure 17: Historical world Class I nickel production by country or region in percentage.



Data source: Data reproduced from USGS Mineral Summaries, 2010–2018.

Increasingly, the nickel needed to drive EV batteries will come from Indonesia, particularly through the application of HPAL technology, meant to produce battery-grade nickel sulphates from lower-grade laterite ores. Among the eight HPAL projects in operation in 2020 around the world, half of them are in Indonesia. Nickel producers are developing six new HPAL projects that collectively can produce 220,000 metric tonnes of battery-grade refined nickel, and 70 percent of this capacity is being developed in Indonesia (Pandyaswargo et al. 2021).

2.3 LONG-TERM AND RECENT NICKEL PRICE TRENDS

Spot prices, despite not reflecting a commodity's full market, reflect the market sentiment and are widely used by traders, investors, and the industry as references they use for their own business. The London Metal Exchange (LME) is a future and forwards exchange with the world's oldest and largest market in standardized forward contracts, futures contracts, and options on base metals, including nickel. According to the specification, the deliverables of LME nickel must be refined nickel, which includes nickel plates, nickel beans, nickel powder, etc. In line with the American Society for Testing and Materials ASTM B39-79 (2018), the deliverables of LME nickel content are not less than 99.8%. Shanghai Futures Exchange (SHFE) used to allow only nickel plates to be deliverables, but starting in 2011, it began to allow the delivery of nickel beans. Some Spot market prices for Ni products are available from free-of-charge sources such as Trading Economics[1] or the Shanghai Metals Market[2], commercial sources providing further references.

[1] https://www.intratec.us/chemical-markets/nickel-price
[2] https://www.metal.com/Nickel

Other nickel-containing products are commonly priced using price coefficients. The settlement price of nickel contained in the intermediates is the average price of LME nickel (which is the arithmetic average of the LME nickel spot settlement price during the pricing period) multiplied by the corresponding price coefficient, and the final settlement price of nickel, where the price coefficient generally applies to long-term contracts and international purchases.

Value = Amount of Nickel Metal × LME Nickel Average Price × price coefficient.

Many of the nickel products traded worldwide are traded via direct agreements between nickel producers and battery manufacturers. These manufacturers establish agreements with upstream suppliers to meet their future nickel demand. Table 5 below shows examples of such engagements.

Table 5: Nickel supply engagements between battery supply chain participants and miners, 2017-2020.

Deal type	Date	Buyer	Industry of buyer	Type of material	Seller company
Offtake	2017	Beijing Easpring	Cathode	Ni sulphate	Clean TeQ
Investment	2017	Trafigura	Trading	MSP/Ni sulphate	Terrafame Group
Offtake	2018	SK Innovation	Batteries	Ni sulphate	Australian Mines
Share purch	2018	CATL Canada	Batteries	Ni sulphate	North American Nickel
Offtake	2018	Beijing Easpring	Cathode	Ni & Co sulphate	Pacific Rim Cobalt
Investment	2018	LG Chem	Batteries	Ni sulphate	Chemco
JV	2018	GEM/CATL	Precursor/Cathode	Ni sulphate	Tsingshan
JV	2018	BASF	Cathode	Ni sulphate	Nornickel
Offtake	2018	Ecopro	Cathode	Ni(OH)2 + NCA	GEM
Partnership	2018	BYD/Guoxuan	Auto/Batteries	NCM precursor	Minmetals (MCC)
JV	2019	Ecopro	Cathode	Ni sulphate	Blackstone Minerals
Offtake	2020	GEM	Precursor/Cathode	Ni MHP/sulphate	PT Halmahera HL

Source: Fraser et al. (2021).

The global nickel supply and demand have experienced four stages of changes in history, combined with the fluctuation of LME nickel prices (see Figure 18):

- The first stage (before 2007): The global demand for stainless steel drove the price of nickel to rise. The nickel required for its production mainly used electrolytic nickel as the raw material, and nickel sulphide ore was the main source of global nickel supply in this period.
- The second stage (2007-2013): Nickel prices hit a record high in 2007, and the post-financial crisis led to a decline in nickel demand. The production capacity of ferronickel from laterite nickel mines has developed rapidly. Meanwhile, the share of pure nickel in the production of stainless steel kept declining. Replaced by ferronickel, electrolytic nickel continued to be in excess. Nickel prices began to decline.
- The third stage (2014-2016): To increase the added value of metal products, Indonesia announced that the ban on nickel ores export would officially come into effect in 2014, equivalent to requiring mining enterprises to build up smelters in the country. The mining ban in Indonesia triggered a strong rebound in the falling nickel market, but the phase disturbance failed to change the downward trend.

- The fourth stage (2017-present): Indonesia relaxed the export policy of nickel ores, but then announced that the ban on the export of nickel ores scheduled to be implemented in 2022 would be brought forward to January 2020, and the export of nickel ores containing less than 1.7% nickel is no longer allowed. The supply concerns of nickel ores have once again been raised. With the rapid development of electric vehicles around the world, nickel sulphate, as an important intermediate to produce Li-ion batteries, has become a popular product in the nickel industry chain. A structural shortage of nickel sulphide supply has emerged, driving nickel prices to rebound from low levels.

Figure 18: LME nickel price from 2002 to 2022.

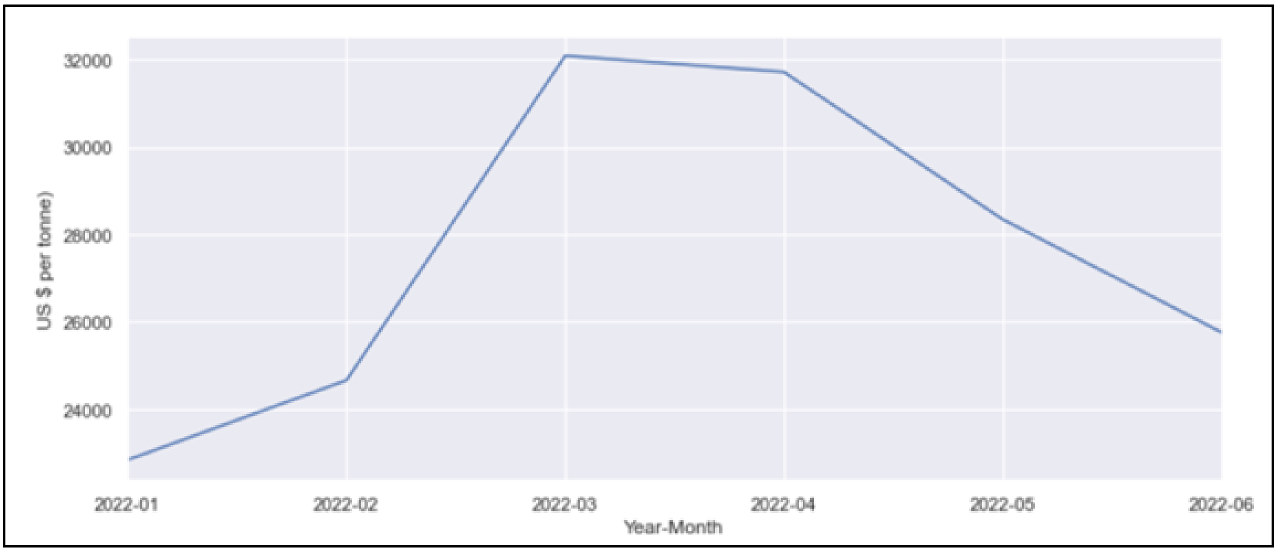
Data source: Trading Economics (Jun. 2022).

A far-reaching black-swam event in 2022 was the Russo-Ukrainian war, which contributed to the reversal of the downward price of clean technologies, such as Li-ion batteries for EVs. This was because Russia is a significant supplier of many of the metals used in battery production, including lithium (4%), cobalt (5%), and nickel (17%) (Hockenos 2022). For nickel, its price has experienced an increasing trend since 2021, which exceeds by a wide margin the largest annual increases seen in the 2010s. The supply deficit of primary nickel since 2021, month-over-month decreasing LME nickel stock starting from Jan. 2020, compounded with the concern of geopolitical tension connected to the Russia-Ukraine war, result in a dramatic increase in the nickel price (see Figure 19). Since Russia invaded Ukraine on February 24 2022, nickel metal nearly doubled its price in the following two weeks (Trading Economics 2022). Even though the nickel price has fallen back, this war will profoundly change the pattern of the nickel supply chain.

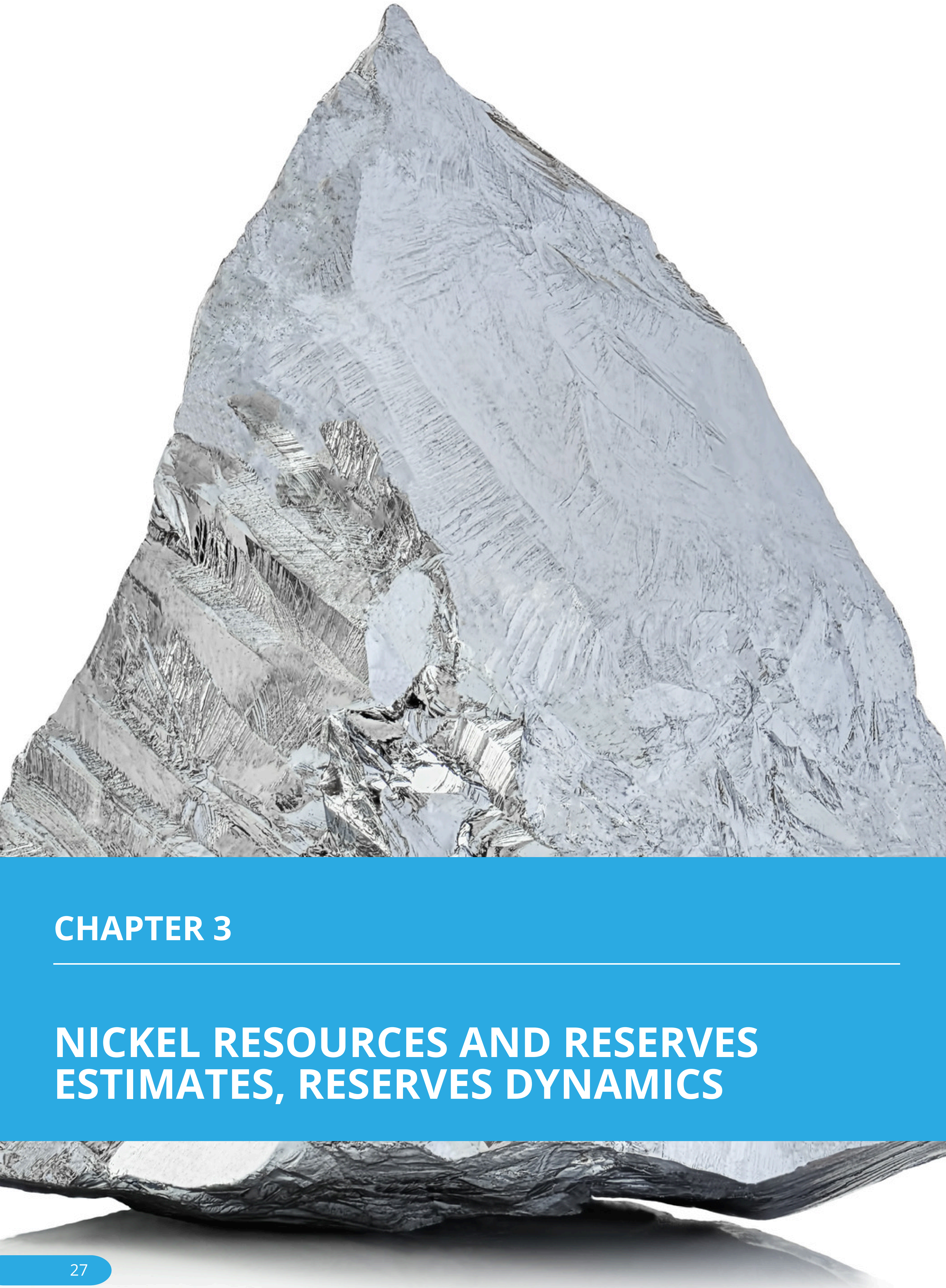
The 'demon nickel' incident of Holding Tsingshan Group is a subsequent event of the Russian-Ukraine war and a typical example of geopolitical risks on commodity markets. At the center of the event is Chinese nickel giant Tsingshan Holding Group, the world's biggest producer of metal used in stainless steel and EV batteries. When the war started, Tsingshan Group held 200,000 short shares in LME and the company did not produce or build enough inventory of LME nickel (pure nickel). The company had to secure enough metal from the market to meet the margin call although the price was climbing rapidly. Because of the drastic changes in prices in a short period, LME suspended the nickel market, the first time it had paused trading in a metal contract since 1985. The suspension of its nickel contract in March 2022 led to a sharp drop in metals trading activity. This gigantic speculative move may have dramatic consequences for the LME and some banks. The legal issues related to this case are far from being settled. The incident will prompt mining companies to consider the role geopolitical events play in nickel production.

In the short term, nickel used in stainless steel is still the mainstream, and nickel used in new energy vehicle batteries has entered a stage of rapid growth. Superimposed on the structural shortage of nickel sulphate supply, nickel prices are expected to rebound. In the medium and long term, the differentiation of supply sources of nickel sulphate for batteries will become a key factor for the subsequent trend of nickel prices. With the maturity of laterite nickel ore hydrometallurgical smelting technology, nickel intermediates will become the main contributor to nickel sulphate production. At the same time, the use of high matte nickel converted from ferronickel in nickel sulphate will continue to increase. The cost of nickel sulphate raw materials is closely related to the trend of nickel prices.

Figure 19: LME nickel price since 2022.



Data source: Trading Economics (June 2022).



CHAPTER 3

NICKEL RESOURCES AND RESERVES ESTIMATES, RESERVES DYNAMICS

3.1 RESOURCES

USGS (2022) provides a country-level estimate of nickel reserves (column a in Table 6), based on a wide range of sources (see Annex C, Part B describing the data sources compiled by USGS) on existing Ni production sites and projects still in the development phase. In parallel a database compiling reserves data (Column b) and the data of measured, indicated, and inferred resources inclusive of reserves (Column c) of projects still at various levels of development from mining companies are also reflected in Table 6. The database includes both code- and noncode-compliant Ni-containing resources.

Data in column b and c, being available from Mudd and Jowitt (2022), and limited to well-documented indicated and measured resources, can be considered with a higher level of confidence than data in column a, which can include undocumented or inferred resource data. All of this means that the data presented in columns b and c should be considered a minimum estimate of global nickel resources and reserves, representing a robust minimum estimate.

Moreover, indicated and measured resource data is no indication of the future economic, environmental, and social viability of a given project, and no indication of when new production will become available. It is only an indication of potential.

The comparison between the cumulative 2020-2040 demand scenario stated in Section 2.2 (80 million Mt Ni) and the global nickel resources (419 million Mt Ni, see Table 7) shows that the already documented indicated and measured resources are well above the anticipated demand. Even when compared with the current global nickel reserve, the figure provided by the USGS (2022, 47 Mt Ni) is still above the expected cumulative demand between 2020-2040. The global reserve figures provided by Mudd and Jowitt (47 million Mt Ni, 2022) are lower than the expected cumulative demand, but this figure represents a minimum estimate.

Consequently, there is no foreseeable geological shortage of nickel for the next few decades. Moreover, beyond 2040, technological shifts to other electricity storage systems and the gradual saturation of stainless steel demand in major economies, such as China, may reduce the further demand for nickel.

Nickel resources are geographically widely distributed and abundant, and there is considerable economic potential for the development of new deposits as the current high nickel prices and the strong demand projections attract investment in nickel exploration and development.

Table 6: World resources and reserves estimates.

	Contained Nickel in Reserves in metric tonnes (kt Ni)	Contained Nickel in Reported Ore Reserves by Deposit Types in metric tonnes (kt Ni)				Contained Nickel in Reported Resource Minerals by Deposit Types in metric tonnes (kt Ni)			
Column reference >	a	b				c			
Country or region		Magmatic sulfide	Laterite	Hydrothermal	Total	Magmatic sulfide	Laterite	Hydrothermal	Total
Russia	7,500.00	6,745.70	-	664.80	7,410.60	36,867.10	7,464.90	1,166.60	57,408.70
Indonesia	21,000.00	-	7,520.30	-	7,520.30	-	45,982.20	-	52,972.80
Australia	21,000.00	1,700.00	5,265.00	-	6,965.00	11,639.00	29,834.60	366.80	49,298.60
Canada	2,000.00	5,585.00	-	-	5,585.00	20,494.60	-	3,200.00	39,340.60
South Africa	-	4,875.60	-	-	4,875.60	30,684.20	-	-	32,332.70
Int'l waters	-	-	-	-		-	-	23,690.20	23,690.20
Philippines	4,800.00	-	4,412.20	-	4,412.20	-	18,866.20	-	22,773.30
Brazil	16,000.00	-		-		695.70	16,686.30	314.90	19,593.60
New Caledonia	-	-	1,846.40	-	1,846.40	-	11,666.90	-	18,953.00
Cuba	5,500.00	-	622.50	-	622.50	-	16,149.70	-	18,921.10
United States	340.00	367.70	-	-	367.70	9,059.50	837.20	12.00	10,393.60
China	2,800.00	-	-	-		7,588.50	-	-	9,827.80
Finland	-	194.70	-	3.20	197.90	769.20	-	4,249.20	5,474.00
Papua New Guinea	-	-	513.00	-	513.00	-	4,906.60	-	5,062.10
Guatemala	-	-	-	-		-	4,255.40	-	4,521.90
Côte d'Ivoire	-	-	-	-		97.50	4,277.80	-	4,388.00
Colombia	-	-	460.40	-	460.40	-	2,293.00	-	3,943.90
Albania	-	-	-	-	-	-	3,350.00	-	3,578.30
Tanzania	-	-	-	-	-	1,895.10	1,512.90	-	3,408.00
Burundi	-	-	-	-	-	-	3,162.90	-	3,162.90
Greece	-	-	-	-	-	-	2,210.00	-	3,049.00
Zimbabwe	-	383.10	-	-	383.10	2,287.40	-	-	2,862.10
Dominican Rep.	-	-	-	-	-	-	1,212.20	-	2,453.50
Sweden	-	-	-	-	-	559.70	-	1,821.10	2,384.10
Madagascar	-	-	1,423.20		1,423.20	-	2,138.60	-	2,364.50
Myanmar	-	-	-	-	-	-	2,059.00	-	2,189.70
Botswana	-	-	-	-	-	1,212.60	-	-	2,052.60
Grand total	>95,000	20,141.30	25,521.60	1,011.70	47,124.3	124,102.00	190,309.00	35,390.00	419,708.00

Source: Column a shows data from the USGS mineral yearbook 2022 (2022) while columns b and c show data from Mudd and Jowitt (2022) representing world reserves and resources in 2018.

3.2 RESERVES AND RESERVES DYNAMICS

In the current industry standard, a mineral resource is defined as a concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality, and quantity that there are reasonable prospects for eventual economic extraction (CRIRSCO 2014). They are subdivided, in order of increasing geologic confidence, into inferred, indicated, and measured categories.

In mineral reserves, economic, technical, social, and environmental factors (together making up "modifying factors") are taken into consideration to determine how much mineralized material can be extracted profitably. This quantity is available in the short term and could be considered a "working inventory of a mining company's supply of an economically extractable mineral commodity" (USGS 2020). Reserve estimates reflect the dynamic nature of mining operations, with modification rates being one of the key variables that change over time. The USGS estimate of world nickel reserves at the end of 2021 was 95000 kMt (column a, Table 6), a quantity comprising reserves of existing producing operations as well as information from public authorities.

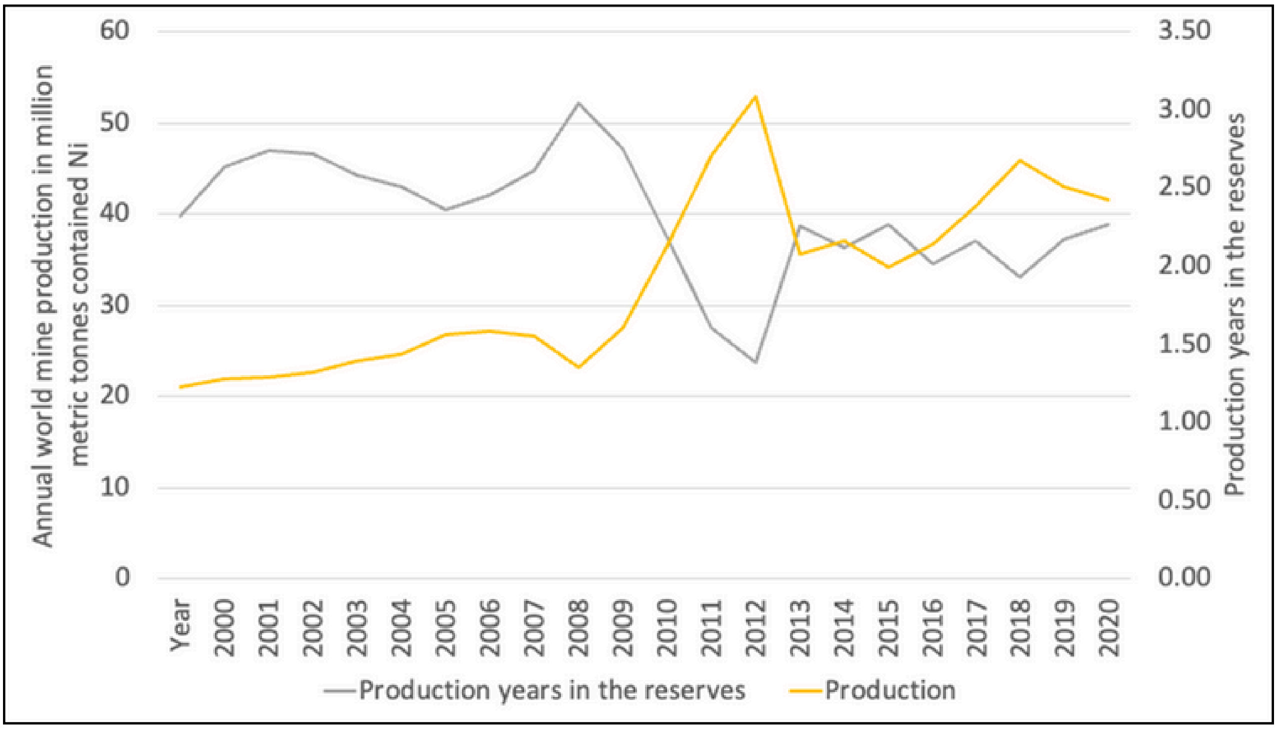
In the past decades, sulphide resources have been developed effectively and have kept pace with depletion caused by mining. In contrast, laterite resources have decreased compared to 2011, possibly because they can be more comprehensively assessed during the early stage of laterite resource and reserve estimation. While current resource levels appear sufficient to sustain present production, the anticipated rise in nickel demand may put significant pressure on future supplies. This may also be exacerbated by the increasing environmental, social, and governance (ESG) challenges facing the minerals industry globally.

Future supply will very much depend on any project overcoming two important hurdles:

- The timely completion of all the permitting procedures is needed before the final investment decision;
- The timely commitment of the investments needed to expand, where feasible, production of existing mines and commission of new ones. This, in turn, depends on numerous factors such as environmental issues and the social acceptance of the expansion of existing projects or the development of new operations.

Figure 20 illustrates the evolution of nickel production and reserves evolution from 2000 to 2020. The reserves for each year are indicated in terms of the number of years of nickel production that would be possible according to the reserves available, at that year's production level. A sharp decline in the production capacity from known reserves is observed between 2008 and 2012 due to rapidly increasing demand from Asia. At the end of 2020, the reserves would entail over 40 years of production at the 2020 production rate, with a huge potential for further nickel deposit development in areas so far underexplored as increasing nickel price will make nickel mining more profitable than any time before. Notably, production years using 2010 data are half of that using 2020 data, indicating an optimistic reserve dynamic in the past two decades and possibly in the future, if the development of new reserves is timely.

Figure 20: Annual nickel production (in metric tonnes Ni metal equivalent) and reserves (expressed in years of potential production from the stated annual reserves estimate).



Data sources: For production data: BGS (2000-2020); for reserves data: USGS Mineral Commodity Summaries, annual editions from 1997 to 2020.

3.3 IS THERE ENOUGH NICKEL TO MEET THE DEMAND SCENARIOS?

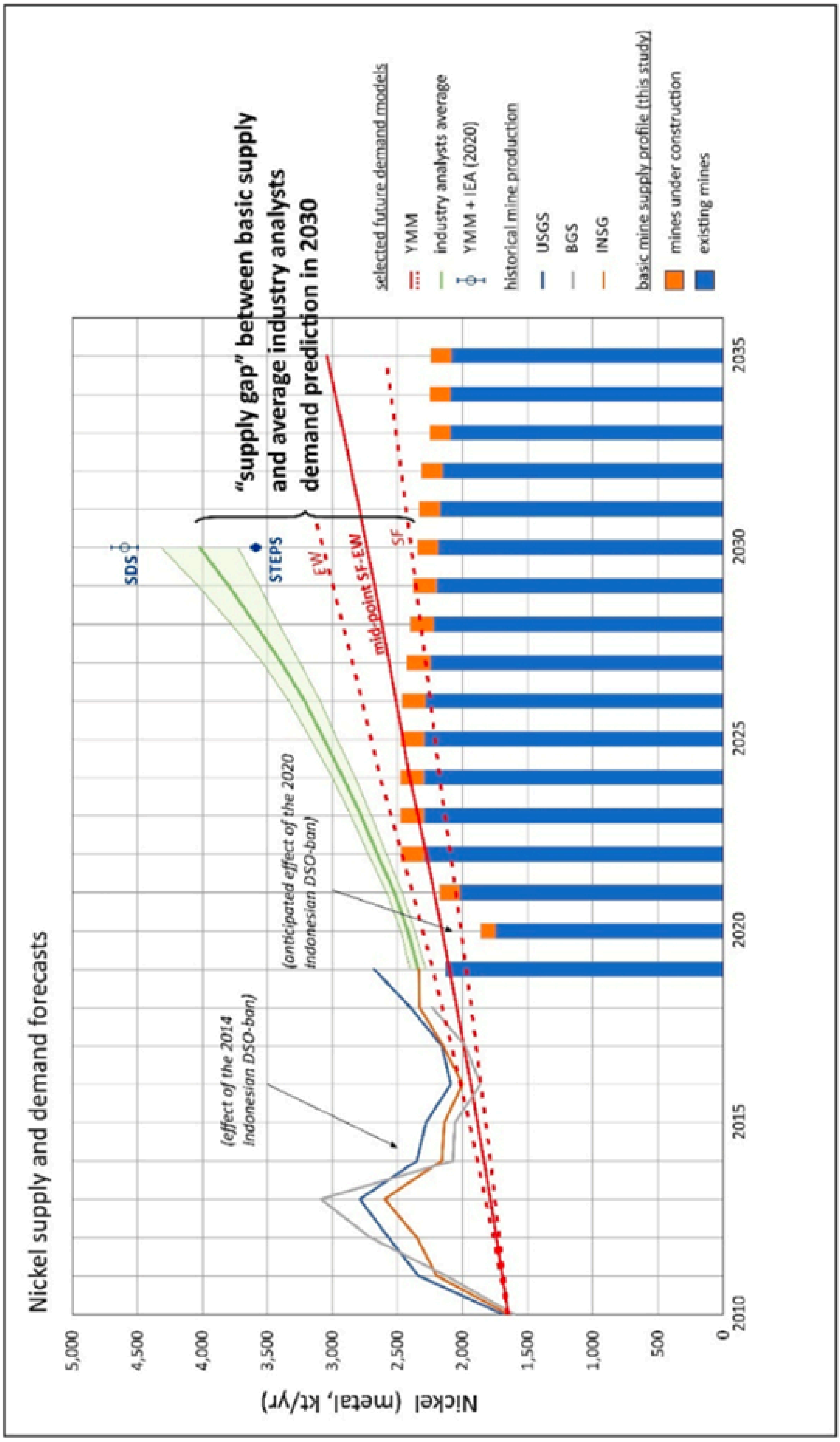
The future nickel supply depends on a range of factors:

- The capacity of already producing operations to expand their production;
- The timely launch of production from new projects still in the development stage;
- The development of exploration activities, much needed to meet the long-term demand;
- The development of secondary nickel supply from stainless steel and battery recycling.

The Critical Minerals Working Group in the Wilson Center proposed that there is no silver bullet to respond to the foreseeable supply shortage for critical minerals, but rather the need for a “Mosaic Approach,” involving action by both the private sector and the government at the national and international levels (Wilson Center 2021).

Figure 21 shows the limits and potentials of new mines for nickel (Heijlen et al. 2021), regarding both the size of the total anticipated production capacity and the pace of mine development. From a commercial perspective, although current resources are sufficient to enable current production to be sustained, the expected increase in demand for nickelput pressure on short-term supplies. Even including the production capacity of mines under construction, the supply gap between basic supply and most demand predictions provided by industry analysts or academic institutions will emerge, at late as 2025. This gap may further be exacerbated by the increasing environmental, social, and governance challenges facing the minerals industry globally.

Figure 21: Evolution of basic primary nickel supply from land-based mines over the 2019–2035 period compared with historical production estimates from different sources (2010–2019) and with several forecasts for total nickel metal demand.

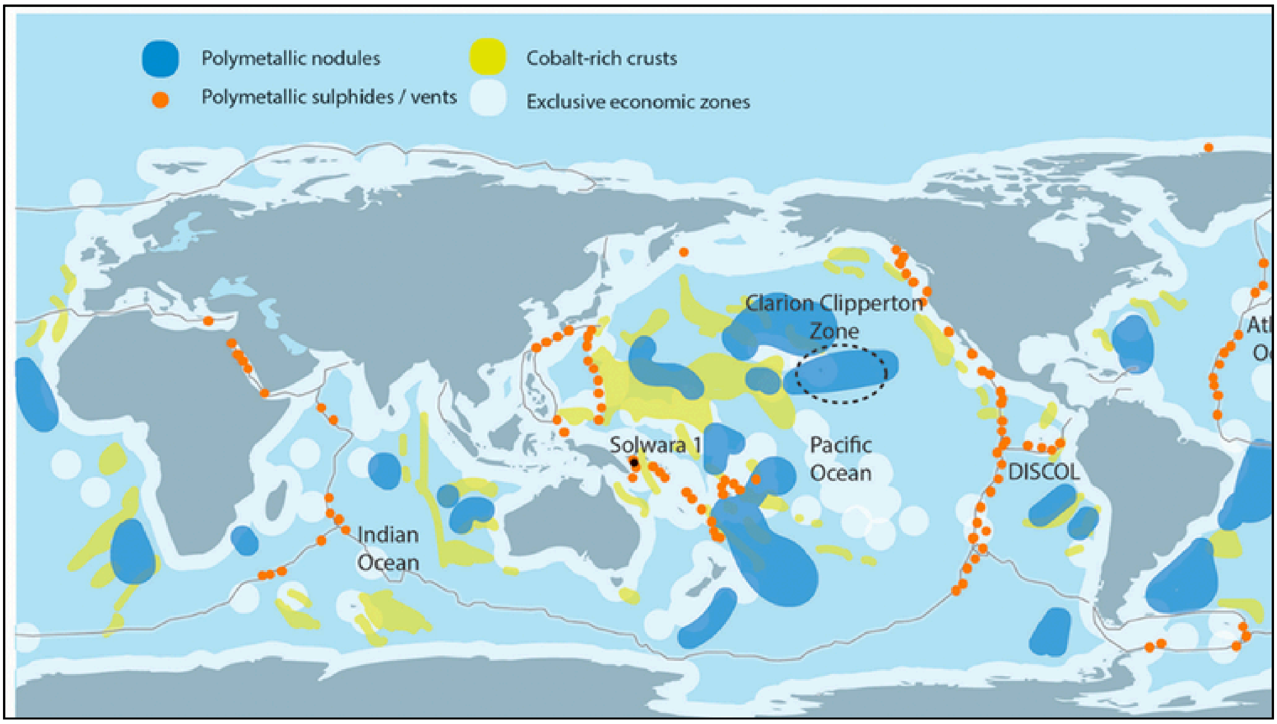


Note: These different demand models concern primary refined nickel and do not concern nickel recovered from steel scrap (i.e. recycled nickel). The light green field represents the standard error on the average demand growth prediction from six major industry analysts (Bloomberg, Bernstein, Benchmark Mineral Intelligence, Wood Mackenzie, Roskill, and DBS Group Research). Red hatched lines represent demand predictions from the minimum ("SF") and maximum ("EW") scenarios from the Yale Major Metals model (YMM; Elshkaki et al. 2018). The thick red line is the mid-point growth curve for these two extremes. Blue points and associated error bars represent predicted demand growth for the EV sector according to the STEPS- and SDS scenario of the IEA (2020) in combination with the mid-point growth curve from the YMM scenarios for non-EV demand. Error bars represent possible variability due to battery chemistry.

To fill the possible supply deficit of critical metals, including nickel, some commercial organizations turn to the mining of deep-sea resources. Such resources containing rich nickel include cobalt-rich crusts and polymetallic nodules. Cobalt-rich crusts form on the slopes and summits of seamounts and contain manganese, iron, and a wide array of trace metals, including nickel, cobalt, copper, and platinum. Polymetallic nodules form on vast deep-water abyssal plains and comprise primarily manganese and other critical metals, such as nickel (1.3%), copper (1.1%), cobalt (0.2%), molybdenum 0.059%), and rare earth metals (0.081%) (Hein et al. 2013).

Although the price and the demand for nickel continue to rise, deep-sea mining is still an emerging industry, and the lack of practical experience and related supporting policies makes it commercially unachievable in the short term. Many environmental groups and academic institutions around the world have called for a moratorium on deep-sea mining because little is known about the possible hazards that deep-sea mining may bring to marine ecosystems (Le Meur 2018).

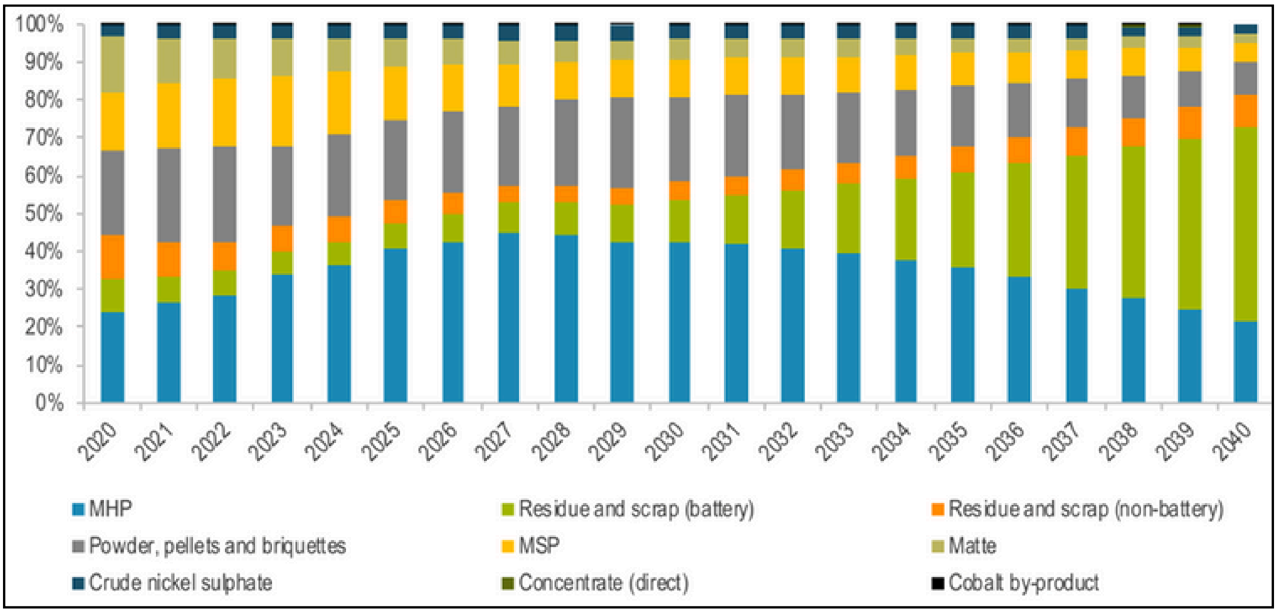
Figure 22: A world map showing the location of the three main marine mineral deposits: polymetallic nodules (blue); polymetallic or seafloor massive sulphides (orange); and cobalt-rich ferromanganese crusts (yellow).



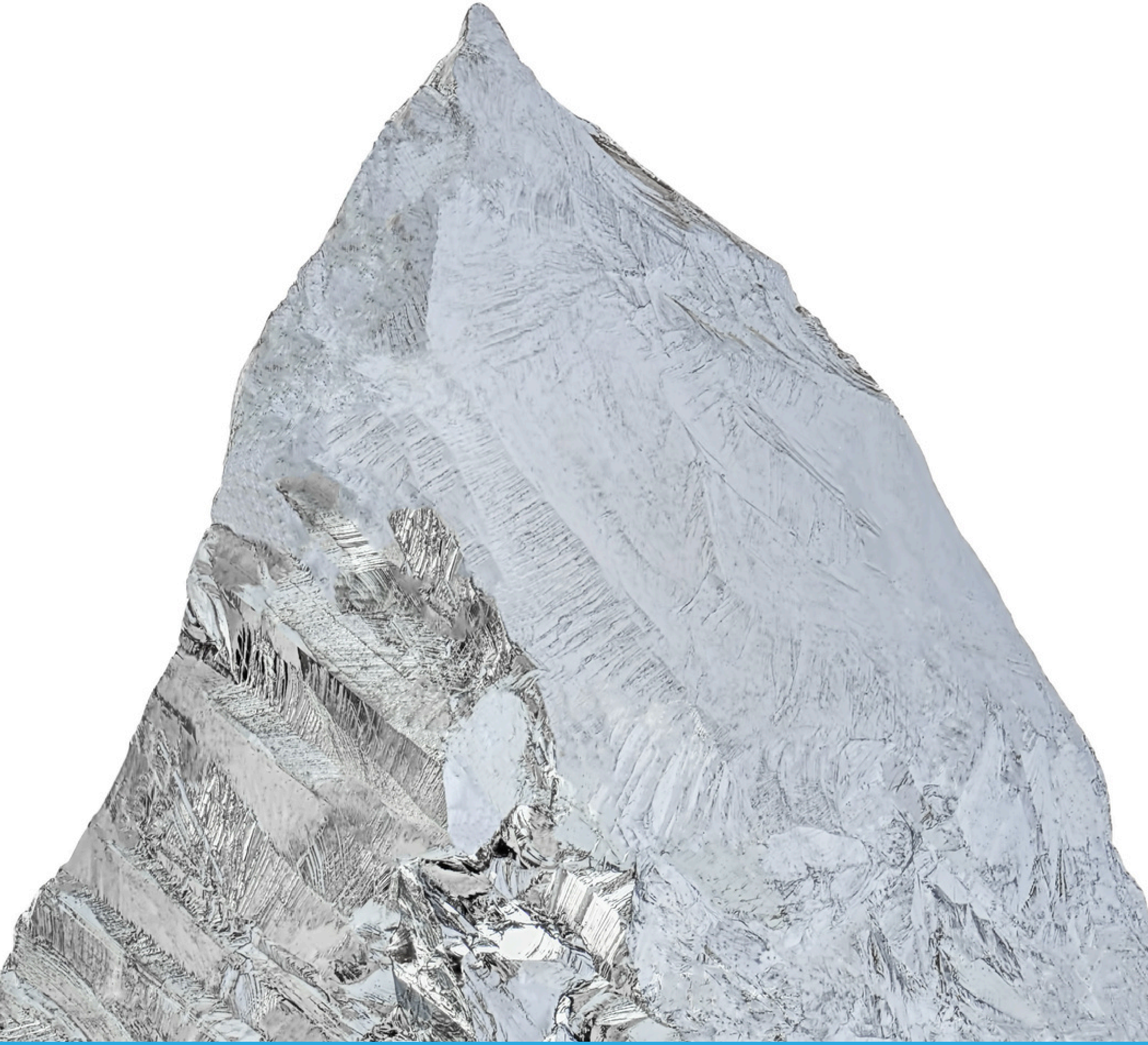
Source: Redrawn from several sources including Hein et al. (2013).

As described in Section 1.2, from 2020 to 2030, the demand for nickel sulfate is expected to grow from 173kt Ni to 1200 kt Ni (see Figure 5), equivalent to a 7-folds increase, significantly larger than any other sector's demand. The pressure of nickel supply in the next few decades will mainly focus on providing sufficient nickel sulphate for producing EV batteries, considering the complexity of the nickel supply chain. Sources of nickel sulphate include nickel intermediates (MHP/MSP), high-purity metal (powder, pellets, and briquettes) matte, scraps from batteries or non-batteries (see Figure 15 and Figure 18). As Figure 18 indicates, nickel sulphate from battery recycling is expected to increase rapidly after 2030 and become the main source of sulphate assuming others hold constant. However, it is necessary to first consider closing the potential supply gap of nickel sulphate before 2025. Application of a new processing route might be the solution, such as the processing route developed by Tsingshan which produces $NiSO_4$ from matte produced from FeNi and the one developed by Terrafame, which recovers Ni (in solution) from bacterial heap leaching (HL) of low-grade pyrite-rich black shales. However, when taking GHG emissions and energy into consideration, views may vary.

Figure 23: Outlook for nickel sulphate production by feedstock, 2020-2040 (%).



Source: Fraser et al. (2021).



CHAPTER 4

SUSTAINABILITY CONSIDERATIONS

4.1 POTENTIAL NICKEL SCARCITY / DEPLETION

Concerns have been raised regarding the mining industry's capability to supply enough primary nickel, ready for use by downstream industries. From the view of physical resources, which estimate the total amount of resources that can be recovered and produced assuming all resources can be mined, most research studies indicated that known nickel resources are sufficient to continue current levels of production for several decades to come (Mudd and Jowitt 2022), even in this century (Olafsdottir and Sverdrup 2021; Henckens et al. 2020). However, from the perspective of business development and production, the nickel shortage is likely to happen during the transition to new energy. By evaluating the size of anticipated nickel production and the lead time for nickel mine development, Heijlen et al. (2021) claimed that most climate scenarios for nickel demand over the next 10–15 years cannot be met by current and developing land-based nickel mining property alone. This will require the industry's long-term ability to supply new metal to customers, considering that it costs a median of 12 years to develop a nickel mine in the past 20 years.

Also, potential nickel scarcity might result from challenges including increased demand for EV batteries. In addition, it has been well-discussed that metal supply challenges can be exacerbated by environmental, social, and governmental (ESG) risks (Lèbre et al. 2019) and other disruption risks (Owen et al. 2021) in the mining stage. Some source supply risks of nickel have been raised and analyzed (see Section 4.2-4.3)

4.2 POTENTIAL ENVIRONMENTAL IMPACTS RELATED TO THE EXTRACTION OF Ni RESOURCES AND THE REFINEMENT OF NICKEL PRODUCTS

Many researchers have illustrated the hazards of nickel mining activities, especially the by-products, to the surrounding environment and the health of nearby residents. Nickel is considered a potentially toxic heavy metal that affects multiple organs of living systems (Das et al. 2019). Because the main source of nickel discarded in the atmosphere is through nickel mining activities, nickel mines can be a threat to neighboring residents.

4.2.1 Energy and GHG emissions related issues

The required primary energy and the associated GHG emissions for producing nickel products are summarized in Table 7.

Table 7: The required primary energy and associated GHG emissions for producing nickel products.

The required primary energy and associated GHG emissions for producing nickel				
nickel product	Primary energy (GJ/t)		GHG emissions (t CO2-eq/t)	
	alloy	contained Ni	alloy	contained Ni
nickel metal	174	174	14	14
nickel oxide	369	485	30	40
ferronickel	110	309	6	18
nickel pig iron	60	598	7	69

Data source: Wei et al. (2020).

The energy consumption and GHG emissions of nickel production are affected by several factors, such as the electricity sources, ore type, and ore grades. Since nickel occurs in two ore types essentially; magmatic sulphides and laterites, with different production routes, the associated energy consumption, and GHG emissions vary. It has been indicated that major laterite operations require 2.5 to 6 times more energy per tonne of nickel produced when compared to sulphides (Mudd. 2009).

Currently, most main Class I nickel comes from sulphide ores, and it releases 10 t CO_2-eq/t on average to produce a unit of Class I nickel (IEA 2021). In the future, as the grade of sulphide deposits declines and demand for Class I nickel increases (to produce nickel sulphate), more Class I nickel will be extracted from laterite and processed through the HPAL route or matte via the NPI route (see Figure 15), the associated GHG emissions will be 18.7 t CO_2-eq and 59 t CO_2-eq per nickel contained, respectively (IEA 2021). For the processing route of HPAL, roughly one-third of the carbon emissions can be attributed to imported electricity, one-third to acid neutralization using limestone, and one-third to logistics and other reagents.

As of now, there do not appear to be any viable alternatives that can significantly reduce nickel laterite projects' environmental costs. As mentioned in Section 3.2, 7-folds of nickel sulphate, primarily coming from Class I nickel, are required to meet the future demand for EV batteries. As a result, the nickel sector continues to face significant sustainability issues such as energy and greenhouse emissions and a question has been raised: do we need to produce a huge amount of Class I nickel (nickel sulphate) to make nickel-containing Li-ion batteries available?

4.2.2 Water-related issues

The issues related to water are not simply a matter of water stress exposure. It is more appropriate to account for varieties of water risk exposure, including physical, regulatory, and reputational aspects.

The amount of water required for nickel production averages 79 and 376.6 m^3/ton for sulphide and laterite ore respectively (Rankin 2011). When adding indirect water consumption, the total amount of water required for processing nickel limonite ore (one type of laterite ore) is significantly high (see Table 8). However, the nickel industry is likely to meet its future water requirements more easily than many other base metals, and face lower water scarcity risk. This is because nickel mines are predominantly located in water-rich equatorial rather than in arid zones (Northey et al. 2017).

Table 8: Estimated embodied water of different nickel production processes (m^3/t refined metal).

Ore type	Ore grade	Process	Direct (m3/t)	Indirect (m3/t)	Total (m3/t)
Nickel sulphite	1.3% Ni	Pyrometallurgy	68	35	102
Nickel limonite	1.3% Ni	Hydrometallurgy (HPAL)	303	1409	1712

Data source: Northey and Haque (2013).

In terms of other dimensions of water risk, nickel shows relatively low regulatory water risk, water quality status risk, and ecosystem service degradation risk, but has higher reputational water risk and flooding risk due to its geographical distribution (Morgan 2020).

Nickel is easily accumulated in the biota, particularly in the phytoplankton or other aquatic plants, which are sensitive bioindicators of water pollution. In rivers, nickel is transported mainly as a precipitated coating on particles and in association with organic matter (Cempel 2006). Even though data suggests that tropical ecosystems are not uniquely sensitive to Ni exposure (Garman 2021). Opencast nickel mine's drainage of fine particles is a source of particulate metals for freshwaters. Laterite mining may exacerbate local water and soil releases of soluble hexavalent chromium (Cr6+), a compound that may be classified as a carcinogen in the European Union (Reach regulation) and possibly in some other jurisdictions.

Additionally, the deep-sea tailings disposal practices in some laterite mining operations, such as the Ramu HPAL operation in Papua New Guinea, have faced opposition for years. The mining activities in offshore areas, such as mines in New Caledonia and Papua New Guinea, may have an impact on the flows and biogeochemical cycles of heavy metal elements at the land-sea interface (Ambrosi 2019).

With the heightened focus on ESG, there is no evidence that the next generation of laterite mining operations will be more apt to address these challenges.

4.3.3 Biodiversity issues

Biodiversity located in mineral-rich areas would be under increasing pressure from mining the metals required for a clean energy transition (Sonter 2020). A report by Verisk Maplecroft, a leading global risk and strategic consulting firm, indicated that among these metals, nickel has the highest proportion of production in extreme and high-risk areas for biodiversity (2021). In addition, the mining of nickel laterite ores is one of the highest biodiversity-impacting mining activities, since it requires clearcutting all vegetation and any biodiversity it hosts, sometimes over several tens of km^2, and about half of all ore is extracted at 5 km away or less from protected areas.

The largest laterite nickel operations are in biodiverse areas such as Indonesia, New Caledonia, and the Philippines, with large areas of tropical rainforest. It is estimated that fifty percent of all life on the planet's land masses is found in rainforests, even though rainforests cover less than two percent of the Earth's surface. However, mining activities in these areas have been increasing during the past two decades. A substantial majority (55%) of nickel ore extraction in 2019 took place in the world's richest tropical biome, with 66% attributable to two mining sites in the Indonesian Sulawesi lowland rain forests, namely Sorowako and Pomalaa. Nickel mining has been identified as one of several significant drivers of deforestation on Sulawesi Island over the past few decades (Supriatna et al. 2020).

Compensation plans such as reforesting other areas to compensate for clearcutting related to laterite mining are merely cosmetical actions, with no capacity to regenerate the same level of biodiversity as the one existing in primary tropical rainforests. Regeneration of tropical rainforest biodiversity on Maya temple sites, built 1200 years ago, is extremely low as documented by Terborgh (1992).

Similar to the discussion in Section 4.2.1, since biodiversity issues related to nickel mining primarily occur around laterite deposits, sulphate, primarily coming from Class I nickel, is required to meet the future demand for EV batteries. A similar question has been raised: do we need to produce huge amounts of Class I nickel (nickel sulphate) to make nickel-containing Li-ion batteries available at the cost of deforestation and biodiversity destruction in tropical areas?

4.3 SOCIAL ISSUES THAT MAY IMPACT THE FUTURE SUPPLY

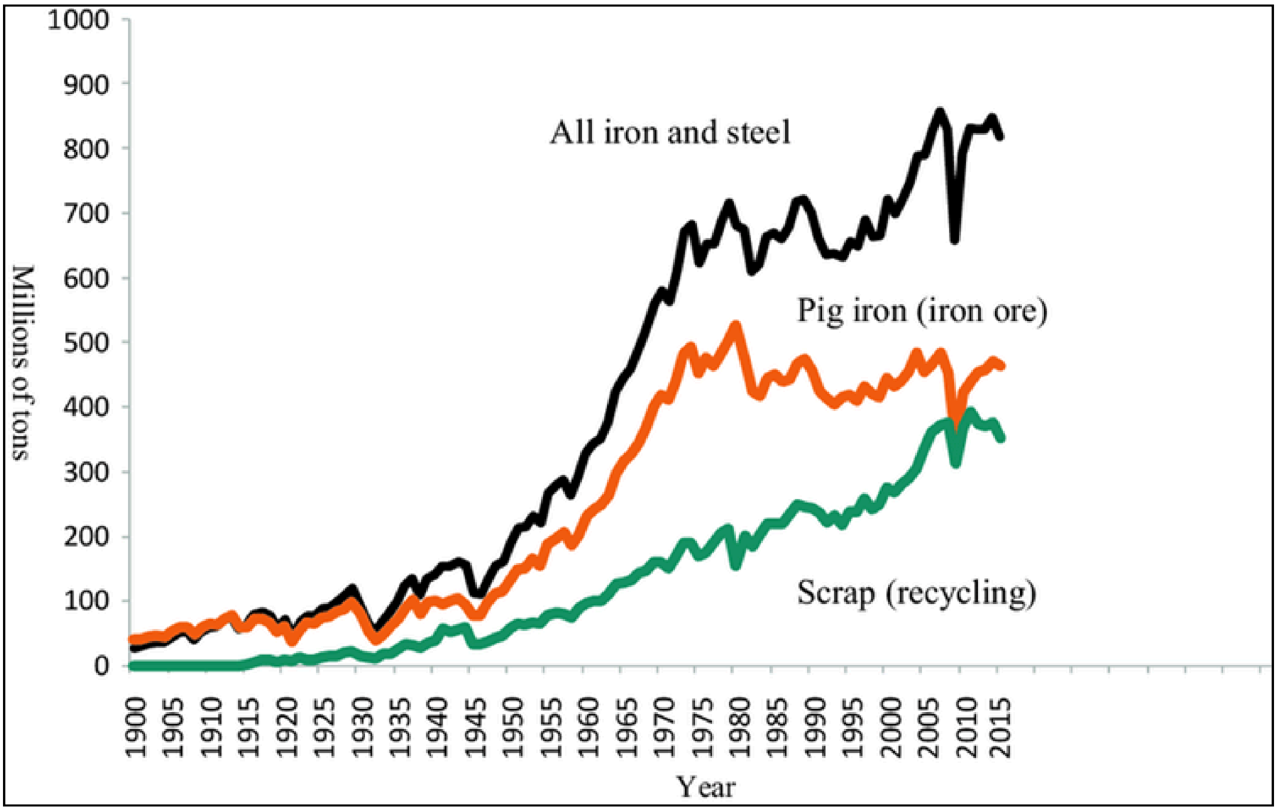
There are many immediate social concerns, intertwined with environmental issues, which are posed by the nickel mining footprints and the use of sulphuric acid. Goro mine in New Caledonia, for instance, faced years of opposition, sabotage, and legal wrangling by members of the indigenous Kanak population before the final agreement was reached in 2008. Furthermore, a sulphuric acid spill at the operation in 2010 and sewage spills followed in 2012 and 2014 attracted the ire of environmental NGOs. Likewise, the large amount of tailings inherent in laterite mining is another hotly contested point. These environmental problems are fermenting into social problems.

Another social concern is artisanal small-scale mining (ASM) in the Philippines and Indonesia. A vast network of financiers, laborers, and local elite partners is hidden behind ASM (Camba 2020). ASM facilitates greater income redistribution in the locality by bypassing the state's formal and institutionalized processes. In addition, there are implications for development strategy, as well as monitoring the social and environmental effects of ASM mining. It is important to note that governments allow mineral exploration and extraction, even in the form of ASM, not only to raise taxes and collect revenues but also to enhance long-term economic development for a specific population and the entire nation.

4.4 RECYCLING FROM END-OF-LIFE PRODUCTS

The amount of nickel-containing waste, mainly stainless steel, collected and recycled each year is estimated at 4.4-4.6 million tonnes. It contains nearly 350,000 tonnes of nickel (or about a quarter of the total nickel demand) and is primarily used to produce stainless steel. The nickel scrap processing industry consists of a few companies that operate internationally and collect scrap containing nickel from all corners globally (INSG 2019). These nickel-containing products are mainly recycled by blending steel scrap with different nickel concentrations, to obtain a mix with a nickel content that can be used for the production of stainless steel. As Figure 25 indicates, the production of stainless steel will increasingly rely on recycling. The recycled material to secondary nickel-containing stainless steel (often with a loss in quality, as there are many different Ni-containing stainless steel grades (such as the 200, 300, 400 series and many more) that get all too frequently recycled together due to the lack of proper tagging of stainless steel materials), leads to downgrading. Meanwhile, if nickel is a minor constituent, it is not economically attractive to include these products in the nickel cycle, which is the case for about 20% of total nickel scrap (Reck et al. 2008). Most importantly, stainless steel is not a suitable source for the production of the high-purity Ni sulphate needed for Li-batteries cathode production.

Figure 25: Transition of stainless steel from mining resources for production raw materials to recycling.



Source: Komiyama et al. (2018).

As the popularity of electric vehicles has exploded, the recycling of Li-ion batteries has drawn more attention. Battery recycling may become an important supplementary channel for the supply of metal resources and a method for promoting environmental protection. The key economic driver for Li-ion battery recycling is the recovery of the valuable metals and their compounds found in the cathodes and anodes. The most economically recoverable Li-ion battery materials are cobalt, nickel, and copper (Zeng 2014).

As illustrated in Section 3.3, nickel will present supply problems ahead of lithium and cobalt (if Li-ion batteries shift to a cobalt-free technological route). It is also reasonable to believe that, by then, alternative, cleaner, and more efficient recycling technology will have been developed. A very ambitious recovery target for nickel, a 95% minimum recovery rate in 2030, has been proposed by the European Parliament's Environment Committee (ENVI) in their battery regulation proposal.

4.5 SUBSTITUTION POTENTIAL

Substitution of nickel for producing stainless steel and other alloys by other materials is possible (USGS 2018), but the importance of nickel in its various applications makes large-scale substitution infeasible without loss of quality (European Commission 2014; British Geological Survey 2008).

Many battery technologies do not consume nickel, whether inside or outside of the Li-ion battery system. These technologies include $LiFePO_4$ (LFP) battery and Li-ion manganese oxide (LMO) battery in the Li-ion battery system, and Na-ion, zinc-air, aluminum-air, and Li-air batteries which are being developed in laboratories (Park et al. 2016).

The chemistry of batteries varies according to their uses, which determines the expected life span, maximum current, and capacity. As described in Section 1.2, the most realistic alternative to high-nickel batteries is the LFP battery, which is considered to be an ideal choice for urban transportation, due to the following reasons:

- Material availability and cost. Sourcing concerns to NCM and NCA batteries are initially centered around cobalt, which is mined in areas known for conflict and human rights violations. The recent market shortage of nickel and aluminum related to the Russo-Ukraine war also raise public concerns. On the other hand, phosphate is much easier to source at a relatively lower price;
- Longer cycle life. Several studies (Han et al. 2014; Liu et al. 2021) have shown that LFP batteries have a longer cycle life than NMC batteries ('Cycle lifetime' refers to how many times a battery can be charged and discharged before its capacity falls below 80% of its original value);
- LFP batteries are more stable. They can be charged to 100% for daily driving without considering the degradation of an LFP battery;
- LFP batteries face lower risks of battery fire. This is due to their higher threshold for heat.

However, the following downsides of LFP batteries might restrict their use as full replacements for high-nickel Li-ion batteries:

- The impact of temperature on LFP batteries is particularly pronounced. This causes difficulties for charging in cold weather and range loss.
- LFP batteries are heavier. Along with their lower energy density, LFP batteries are often bigger and heavier than their NCA or NMC cousins, resulting in less efficiency in an EV.
- LFP batteries have lower operating voltage. For heavy transport requiring a higher workload, LFP batteries may not be as useful as other lithium batteries, such as NCM and NCA.

Overall, LFP technology does not offer a one-size-fits-all solution, especially for long-distance travel. Over the long term, policy choices will be crucial, as far as arranging future long-distance mobility with electric vehicles while avoiding the sourcing risks associated with nickel (and cobalt).

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