Supply chains of mineral raw materials of importance to the Danish economy

Overview of current and potential supply risks

Per Kalvig & Jakob Kløve Keiding

MiMa rapport 2024/1

MiMa
CENTER FOR MINERAL RESOURCES & MATERIALS

CENTER OF MINERAL RESOURCES AND MATERIALS
GEOLOGICAL SURVEY OF DENMARK AND GREENLAND

GEUS

BLANK PAGE

Supply chains of mineral raw materials of importance to the Danish economy

Overview of current and potential supply risks

Per Kalvig & Jakob Kløve Keiding

MiMa rapport 2024/1

CENTER OF MINERAL RESOURCES AND MATERIALS
GEOLOGICAL SURVEY OF DENMARK AND GREENLAND

Supply chains of mineral raw materials of importance to the Danish economy

Overview of current and potential supply risks

MiMa rapport 2024/1

Authors: Per Kalvig and Jakob Kløve Keiding

Translation from MiMa rapport 2023/4: "Dansk industris brug af mineralske råstoffer – beskrivelse af udvalgte forsyningskæder"

Repro: GEUS

May 2024

ISBN: *978-87-7871-607-1*

Øster Voldgade 10
1350 Copenhagen K
Denmark

Table of Contents

Abbreviations

AMT	Ammonium Metatungstate
APT	Ammonium Paratungstate
BF	Blast Furnace
BIF	Banded Iron Formations
BOF	Basic Oxygen Furnace
CCS	Carbon Capture and Storage (of CO_2)
CIF	Carriage and Insurance Paid to a given harbour
CIS	Commonwealth of Independent States
CO_2e	Carbon Dioxide Equivalent; accounting for all greenhouse gases
DKK	Danish Kroner (Danish national currency)
DRI	Direct Reduction of Iron
EAF	Electric Arc Furnace
EI	Economic Importance (term applied in critical raw materials analysis)
EoL-RIR	End of Life Recycling Input Rate
EoL-RR	End of Life Recycling Rate
EV	Electrical Vehicle
fob-price	Free on Board price
GHG	Green House Gas
IOA	Iron-Oxide-Apatite
IOCG	Iron-Oxide-Copper-Gold
ISA	International Seabed Authority
HPA	High Purity Aluminium
HPAL	High Pressure Acid Leach
HSLA	High Strength Low Alloy (steel)
HRC	Hot Rolled Coil
Kton	Kiloton (1,000 ton)
Li-ion	Lithium ion
LME	London Metal Exchange
M.	Million
MiMa	Center for Mineral Resources and Materials
Mt	Million ton
n.a.	Not available
Nethl.	Netherlands
NdFeB	Neodymium-Iron-Boron (alloy used for permanent magnets)
NPI	Nickel Pig Iron
PGM	Platinum Group Metals
PM magnet	Permanent magnet
Rebar	Reinforced steel bar; non-corrosive; non-conductive; higher tensile strength
REE	Rare Earth Elements
RIR	Recycling Input Rate
RoW	Rest of the World (all countries outside China)
SHFE	Shanghai Futures Exchange
SI-EI	Substitution Index – Economic Importance
SI-SR	Substitution Index – Supply Risk
SRE	Supply Risk Exploitation
SRP	Supply Risk Processing

TFG	Textile Fibre Glass
TFT LCD	Thin-Film-Transistor Liquid Crystal Display
TMP	Tungsten Metal Powder
UAE	United Arabic Emirates
USGS	United States Geological Survey
USMCA	U.S.-Mexico-Canada Agreement
VFRB	Vanadium Redox Flow Batteries
WC	Tungsten carbide
wt. %	Weight percent

Explanation of Terms

Austenitic steel	Alloys with high percentage of nickel and chromium
Crude steel	Raw steel/new steel
Lifetime supply of minerals	Number of years for which a global proven reserve of a given mineral is sufficient

List of Figures

List of Tables

Summary

Due to increasing global population and growing economies, the demand for mineral resources is rapidly escalating, particularly with respect to a range of specialty raw materials associated with 'the green transition'. High growth rates and inadequate infrastructure for processing these raw materials, compounded by geopolitical conflicts, challenge the supply security of mineral resources and, consequently, national economies worldwide. In Denmark, where consumption is predominantly directed towards processed mineral raw materials and finished products thereof, the challenges for supply chains are less transparent but equally serious.

This report presents a qualitative analysis of eight raw material supply chains (bauxite/alumina/aluminium, boron, copper, iron/steel, nickel, tungsten, vanadium, and zinc), and highlights some of the conditions in the supply chains that may impact the supply leading up to 2030. The raw materials are selected because they are considered important for the Danish industry (Clausen *et al*. 2023).

The supply challenges for the analysed raw materials vary but are generally characterized by their complexity, with many intricate links in the supply chains, inadequate supply chain infrastructure, limited geographic diversity, and tendencies towards monopolization of entire or vital parts of the supply chains. None of the raw materials can be characterized as 'supply secure'.

The geological reserves for the eight raw materials are not an immediate limiting factor. However, supply chains will be challenged to meet the expected demand leading up to 2030 and 2040, due to long lead times from exploration to new active mines and the development and establishment of business models for the many necessary links in processing industries. Securing a stable raw material supply, including for 'the green transition', requires rapid and diversified capacity building in all links of the supply chains, from mineral exploration and mining to raw material processing and manufactures. Outside China, only inadequate developments of these key infrastructures are in progress.

Introduction

The global economic growth and increasing population are reflected in a significant rise in the consumption of mineral resources. Such resources are obtained through complex supply chains, extensive mineral exploration, mining, and processing of minerals into raw materials. The development takes place in response to supply and demand, where emerging technologies, particularly within electronics, communication, and data transmissions since the 1990s, impact demand. New technologies in these areas have generated a demand for resources not previously in focus, such as gallium, platinum group metals (PGM), selenium, silicon metal, rare earth elements (REE), tantalum, and others. Subsequently, international and national climate policy goals for 2030 and 2050 to reduce greenhouse gas emissions have led to a global transition towards renewable energy sources, with consequences for a variety of supply chains. This change involves solar cells, wind turbines, batteries/energy storage, and electrical transmission, accelerating the demand for a range of raw materials. For instance, the need for copper is expected to increase by 40 % and nickel by 100 % by 2030. Similarly, there is also an expectation of increased demand for many other key raw materials for the green transition (Hund *et al.* 2020, IEA 2021, Watari *et al.* 2020). The rapid upscaling of mineral resource production is unprecedented, given that starting new mines typically takes a minimum of 10 years or longer.

In addition to challenges in the supply chains for mineral resources, geopolitical factors, including wars and politically unstable countries, along with China's dominance in many supply chains, contribute to the complexity. China's quasi-monopoly status is due to political industrial strategies, domestic resource reserves, long-term agreements with foreign resource suppliers, and the development of complete supply chains for numerous critical resources. The EU and several countries regularly monitor this situation, and in November 2023, the EU adopted a raw materials regulation (European Critical Raw Materials Act, see EC (2023b)) to build competencies and infrastructure for mineral resource supplies.

Against this backdrop, the Center for Mineral and Materials (MiMa), commissioned by the Danish Business Authority, has mapped the consumption of mineral resources and raw material dependencies in Danish industry. The study consists of two parts: (i) mapping the criticality of mineral resources in Denmark (Clausen *et al.* 2023) and (ii) the present report, a qualitative analysis to investigate the causes and risks of potential raw material criticality in Danish industry.

This qualitative analysis provides a concise overview of eight raw material supply chains (bauxite/alumina/aluminium, boron, copper, iron and steel, nickel, tungsten, vanadium, zinc), highlighting expected supply challenges leading up to 2030. These raw materials are selected either because they are included in the results of the quantitative analysis of economically important raw materials for the Danish economy or because they carry a supply risk and potentially are expected to become restricted in supply in the coming years. The EU Commission assessed aluminium, boron, tungsten, and vanadium as critical raw materials in 2023 and considered copper and nickel as strategic raw materials (EC 2023a). Rare earth elements, cobalt, and lithium are not discussed in this report as they are addressed in separate MiMa reports (Kalvig 2022; Tan & Keiding 2023), and an analysis on PGM is in progress.

The analysis is based on publicly available information, compiled to provide summary descriptions of the raw materials and their supply chains for the most important applications. The goal is to highlight the main reasons for raw material criticality. A consistent approach and presentation of data for all eight selected raw materials have been attempted, but differences in data sources and coverage, as well as features relating to individual raw materials, have resulted in slight variations in chapter structures.

The report is prepared to provide information on supply-related conditions to allow Danish stakeholders to assess their own risks regarding the selected raw materials. Focus is placed on the overall global trends in both supply and demand in the mineral raw materials sectors. Factors relevant to the Danish economy, based on results in the first part of the analysis, are briefly summarized, as is the Danish consumption of the respective analysed raw materials. The analysis does not allow linking of raw material consumption to specific Danish companies. The global perspective is crucial since Danish companies are primarily 'component' industries, with productions based on imported components or raw materials. Hence, concerning semi-finished products and components, supply challenges for Danish companies are global and usually not transparent.

This report is the authors transcript of the original Danish version available at https://data.geus.dk/pure-pdf/MiMa-R_2023-4_web.pdf. We extend our sincere appreciation to Jørgen Bojesen-Kofoed for proofreading the report. However, any uncertainties or errors remain the sole responsibility of the authors.

References

Clausen, R.J., Kalvig, P., Keiding, J.K., Fold, N. & Vind, I. 2023: Dansk industris brug af mineralske råstoffer – økonomisk betydning og forsyningsudfordringer MiMa rapport 2023/2, pp. 181. https://doi.org/10.22008/gpub/32051

European Commission (EC) 2023a: Study on the Critical Raw Materials for the EU 2023 – Final Report. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

European Commission (EC) 2023b: Critical Raw Materials Act. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en

Hund, K., La Porta, D., Fabregas, T.P., Laing, T. & Drexhage, J. 2020: Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. International Bank for Reconstruction and Development/The World Bank. 110 p.

IEA 2021: The Role of Critical Minerals in Clean Energy Transitions. International Energy Agency (IEA) 283 pp. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

Kalvig, P. 2022: Rare Earth Elements (REE). Geology, technologies, and forecasts. https://mima.geus.dk/udgivelser/sjaeldne_jordartsmetaller_ree-3/

Tan, J. & Keiding, J.K. 2023: The cobalt and lithium global supply chains: Status, risks and recommendations. MiMa rapport 2023/3. https://data.geus.dk/pure-pdf/MiMa-R_2023_03_web.pdf

Watari, T., Nansai, K. & Nakajima, K. 2020: Review of critical metal dynamics to 2050 for 48 elements. Resources, Conservation and Recycling, 155, 104669.

1. Bauxite, Alumina, and Aluminium

1.1 Introduction

Aluminium (Al) with atomic number 13 in the Periodic Table of Elements, is a soft, lightweight (2.71 g/cm^3) metal that melts at 660 °C and boils at 2,519 °C. Its low density, strength, corrosion resistance, and good electrical conductivity combine to make aluminium industrially very versatile. Aluminium has various applications and is used, among other things, for alloys in the construction industry, manufacturing of transportation vehicles, food packaging, machine parts, and in electronics. The ore bauxite is a raw material for aluminium production (see section 1.4.4) and is mined in many countries, with Australia, China, and Guinea being the largest producers. The processing into alumina (Al_2O_3) is mainly carried out in China, Australia, and Brazil, while China, India, and Russia are the largest producers of aluminium. The production of aluminium has a significant environmental and climate footprint. The global demand for aluminium, especially for transportation vehicles, is expected to grow by 40 % by 2030. Moreover, aluminium is a crucial raw material for various technologies in 'the green transition'. Since 2020 and again in 2023, the EU Commission has classified bauxite as a critical raw material in the Commission's inventory of critical raw materials (EC 2020, 2023).

1.2 Applications and Sectors

Aluminium is a silver-grey metal with many attractive properties: it is lightweight, strong, and resistant to corrosion. It is flexible, easy to shape, non-toxic, imparts no taste, and has good thermal and electrical conductivity. These traits have made aluminium indispensable in a plethora of industrial applications (Figure 1-1). In particular, aluminium's weight-reducing properties (density is ⅓ of steel) have given it an advantage over many other materials. For instance, in cars and airplanes, where aluminium is widely used due to its low weight combined with high strength, making it suitable for both frame and engine parts. Overall, the scenarios for growth in aluminium demand are significantly influenced by the development of the electric vehicle market. There is also an increasing consumption of aluminium in both the electrical and electronic sectors, particularly associated with the expansion of power supply networks from solar and offshore wind power installations. In these applications, aluminium can substitute the traditional use of copper, whilst also constituting an important component in the manufacturing of the solar power installations themselves.

The applications of aluminium in the construction and building industry are particularly for facades, window frames, and structural materials where weight and corrosion resistance are crucial. However, no significant changes are expected in the use of aluminium for construction and building, leading up to 2030 (Figure 1-1).

In 2020, approximately 86.2 Mt of aluminium was produced globally, with applications for manufacturing of cars, airplanes, trains, and construction materials in the building and construction industry accounting for about half of the production. The remaining portion was mainly used in electronics, packaging, and aluminium foils (CRU 2022) (Figure 1-1). Towards 2030, the demand for aluminium is expected to reach around 119.5 Mt, representing an increase of almost 40 %. The significant growth is attributed particularly to the transportation sector, expected to rise from approximately 19.9 Mt in 2020 to 31.7 Mt in 2030, and the electrical sector, including solar power installations, projected to increase from 10.4 Mt in 2020 to 15.6 Mt in 2030 (CRU 2022). China is expected to remain the largest producer of aluminium.

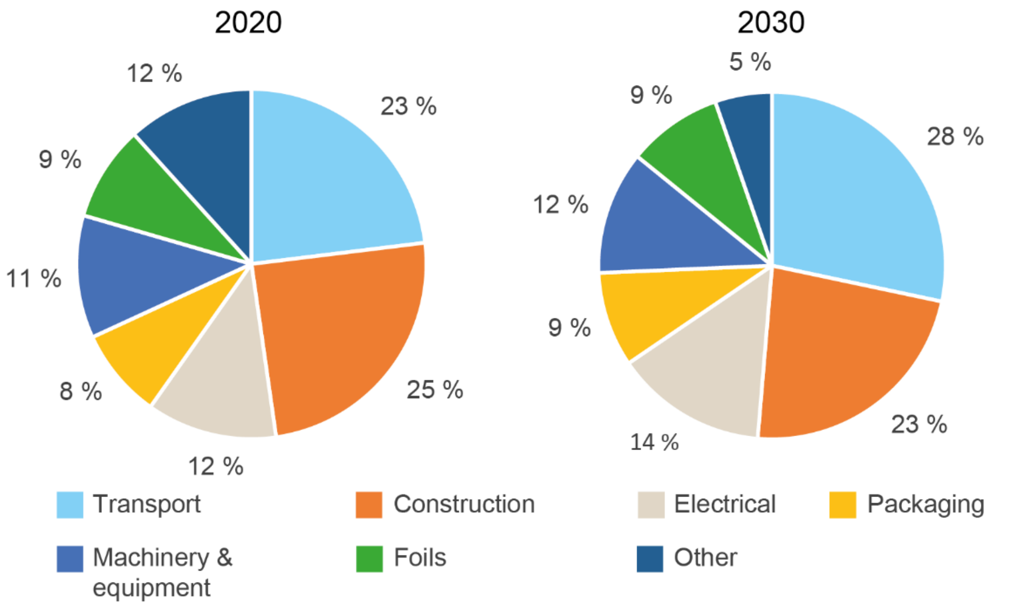


Figure 1-1 *Sector distribution of aluminium consumption in 2020 (86.2 Mt) and expected distribution of 119.5 Mt in 2030. Source: CRU (2022).*

1.3 Recycling and Substitution

There is a significant recycling of aluminium products. In the EU, the recycling rate is approximately 32 % (EoL-RR). One ton of aluminium scrap is equivalent to about eight ton of bauxite, and the energy costs for alumina production can be significantly reduced (presumably >50 % savings/kg Al) (Kolbeinsen 2020), resulting in reduced CO_2 emissions. This is an important reason to recycle aluminium, even though mixtures of alloying metals often lead to some downgrading of the scrap material.

The EU Commission (EC 2023) has estimated substitution indices of 0.86 and 0.82 for SI-SR and SI-EI, respectively. However, most substitution considerations involving aluminium tend to go in the opposite direction: replacing, for example, copper with aluminium.

1.4 Global Supply

1.4.1 Geology

Bauxite, which is the ore/raw material for aluminium production, is a brownish aluminium-rich rock dominated by a mixture of aluminium oxide minerals. Most deposits are found in tropical regions, often as 2-5 m thick near-surface layers, formed by weathering of granitic rocks. Bauxite rocks are divided into two main groups based on their mineralogical composition:

1. Lateritic bauxite: gibbsite, boehmite (Al_2O_3), kaolinite, quartz (SiO_2), goethite, hematite (Fe_2O_3), anatase, rutile (TiO_2), calcite, apatite, and crandallite (CaO).
2. Karst bauxite: boehmite, diaspore (Al_2O_3), kaolinite, quartz, chamosite, illite (SiO_2); hematite, goethite, naghemite, and magnetite (Fe_2O_3); anatase, rutile, and ilmenite (TiO_2); calcite, apatite, and crandallite (CaO).

Bauxite deposits are found in many locations (Figure 1-2), but the known attractive deposits are licensed by a small number of competing mining companies.

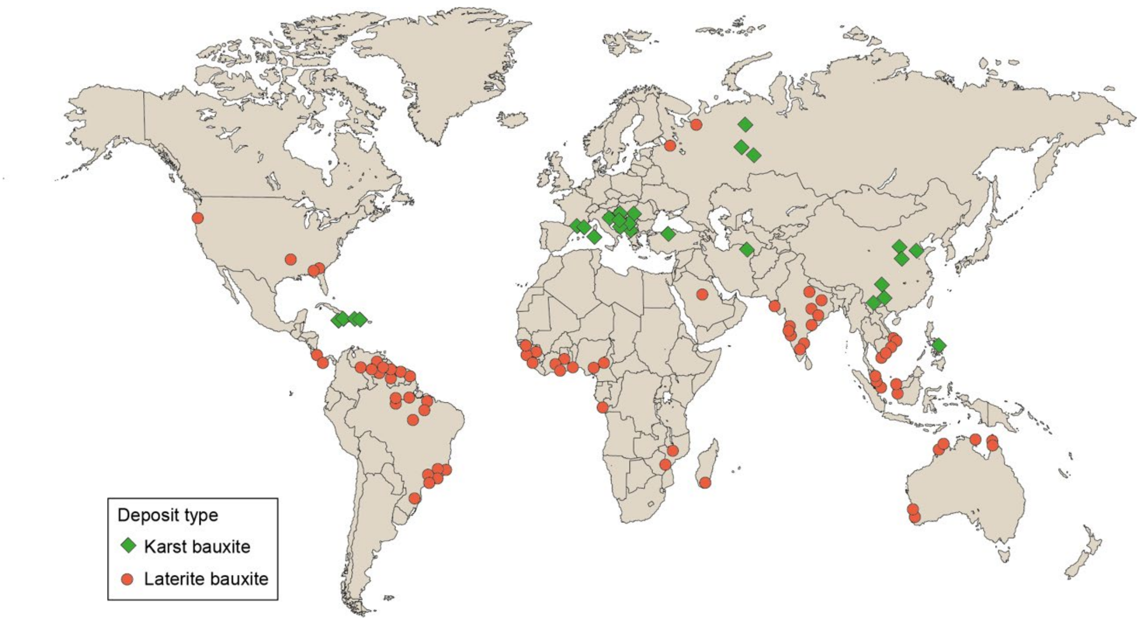


Figure 1-2 *Overview of some of the world's largest bauxite deposits, categorized as karst and lateritic bauxite. Based on Meyer (2004).*

The main minerals in bauxite are the aluminium oxides gibbsite, boehmite, and diaspore (Table 1-1). The diaspore has the same chemical composition as boehmite but is lighter and harder. Additionally, bauxite contains a significant amount of silicate minerals that need to be removed before the raw material can be used for alumina production.

Table 1-1 *Commercially important aluminium minerals.*

Mineral	Mineral formula	Al-content (Al %)
Boehmite	AlO(OH)	45
Diaspore	AlO(OH)	45
Gibbsite	$Al(OH)_3$	37

1.4.2 Global Bauxite Reserves

USGS has estimated the global bauxite reserves at approximately 31 billion ton, including both karst-type bauxite and laterite-type bauxite, with the latter being the significantly more important type. The majority of reserves are concentrated in West Africa (Figure 1-3), and more than half of the reported reserves are found in Guinea, Vietnam, and Australia (Table 1-2). The calculated lifespan of these reserves exceeds 400 years at the current consumption rate, which, compared to many other resources, is high. However, with an expected substantial increase in consumption, there will be a need for increased exploration to identify future resources. With a 7 % annual increase in consumption, the lifespan will be reduced to approximately 100 years by 2050.

The annual production of bauxite is dominated by a few countries, with Australia being by far the most significant.

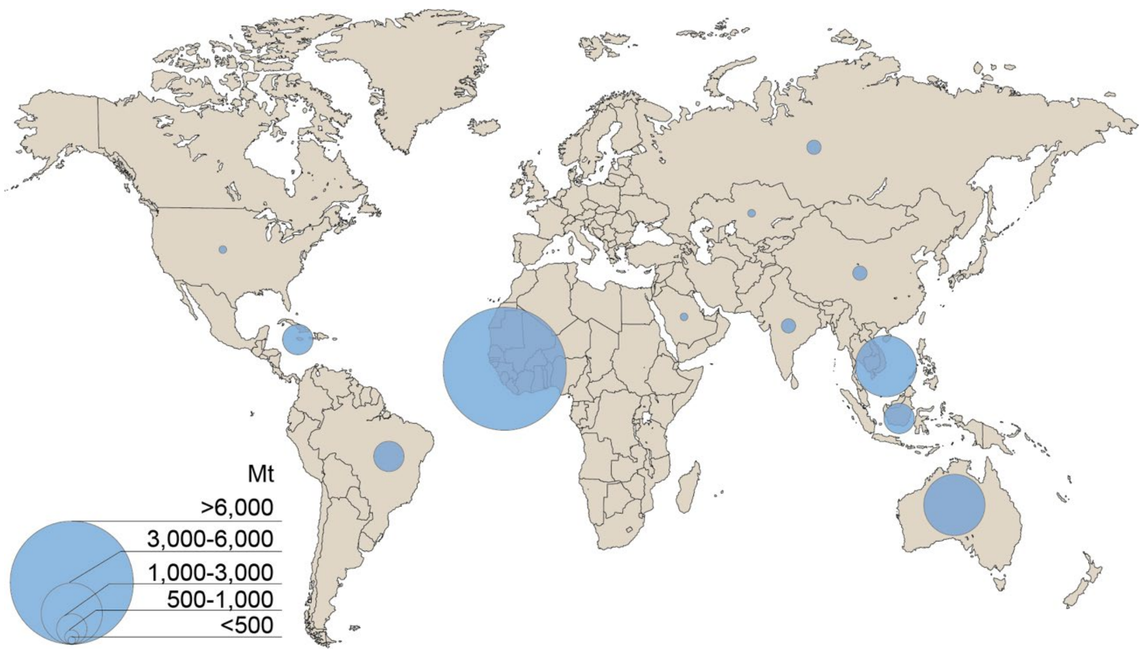


Figure 1-3 *Distribution of some of the known largest bauxite reserves. Based on Meyer (2004).*

Table 1-2 *Overview of global bauxite reserves (Mt) in 2022 categorized across 12 countries and the 'other' category. Source: USGS (2023).*

Bauxite reserves	2022 (USGS)
Guinea	7,400
Vietnam	5,800
Australia	5,100
Brazil	2,700
Jamaica	2,000
Indonesia	1,000
China	710
India	660
Russia	500
Saudi Arabia	180
Kazakhstan	160
USA	20
Others	5,199
Total	**31,330**

1.4.3 Global Aluminium Production

Aluminium production includes four stages in which semi-finished products for each stage are part of global value chains: (i) mining and pre-processing of bauxite ore (15-25 % Al); (ii) production of alumina (typically) using the Bayer process; (iii) production of primary aluminium through electrolytic smelting (Hall-Héroult process); and (iv) processing of primary aluminium and manufacturing plates, foils, tubes, wires, etc.

In 2021, 95 % of the global bauxite production of 304 Mt was carried out in 10 countries, with Australia, China, and Guinea producing 110 Mt, 86 Mt, and 85 Mt of bauxite, respectively (Table

1-3), with only negligible production in Europe (Greece). From 2000 to 2021, the annual growth in bauxite production was nearly 7 % (Figure 1-6, top), while the annual growth in aluminium production was approximately 2 % (Figure 1-6, middle). Records of the alumina-production are only available for 2015 to 2021, in which period the production increased around 14 %. (Figure 1-6, bottom). China's dominant role increases over time throughout the supply chain (Table 1-3 to Table 1-5 and Figure 1-4 to Figure 1-6). In 2021, China produced approximately 22 % of bauxite ore and was also co-owners of several major foreign mines, thus having access to 50 % of the alumina production and 56 % of the aluminium production.

Table 1-3 *Bauxite production (Mt) in 2021 distributed among the largest producing countries. Source: USGS (2022).*

Mining – bauxite	2021 (USGS)
Australia	110
China	86
Guinea	85
Brazil	32
India	22
Indonesia	18
Russia	6.2
Jamaica	5.8
Kazakhstan	5.2
Saudi Arabia	4.3
Vietnam	3.5
Others	12.0
Total	**390**

Table 1-4 *Production of alumina (Mt) in 2021 distributed among the largest producing countries. Source: USGS (2022).*

Production – alumina	2021 (USGS)
China	74
Australia	21
Brazil	11
India	6.8
Russia	3.1
UAE	2.0
Germany	1.9
Ireland	1.9
Saudi Arabia	1.8
Ukraine	1.7
Spain	1.6
Canada	1.5
Indonesia	1.5
Kazakhstan	1.5
Vietnam	1.4
Jamaica	1.2
USA	1.0
Guinea	0.4
Others	3
Total	**138.3**

Table 1-5 *Production of aluminium (Mt) distributed among the largest producing countries. Sources: USGS (2022) and WMD (2022).*

Production – aluminium	**2021 (USGS)**	**2020 (WMD)**
China	39	37
India	3.9	3.6
Russia	3.7	3.9
Canada	3.1	3.1
UAE	2.6	2.5
Australia	1.6	1.6
Bahrain	1.5	1.5
Norway	1.4	1.3
Iceland	0.9	0.7
USA	0.9	1.0
Others	9.4	8.8
Total	**68.0**	**65.0**

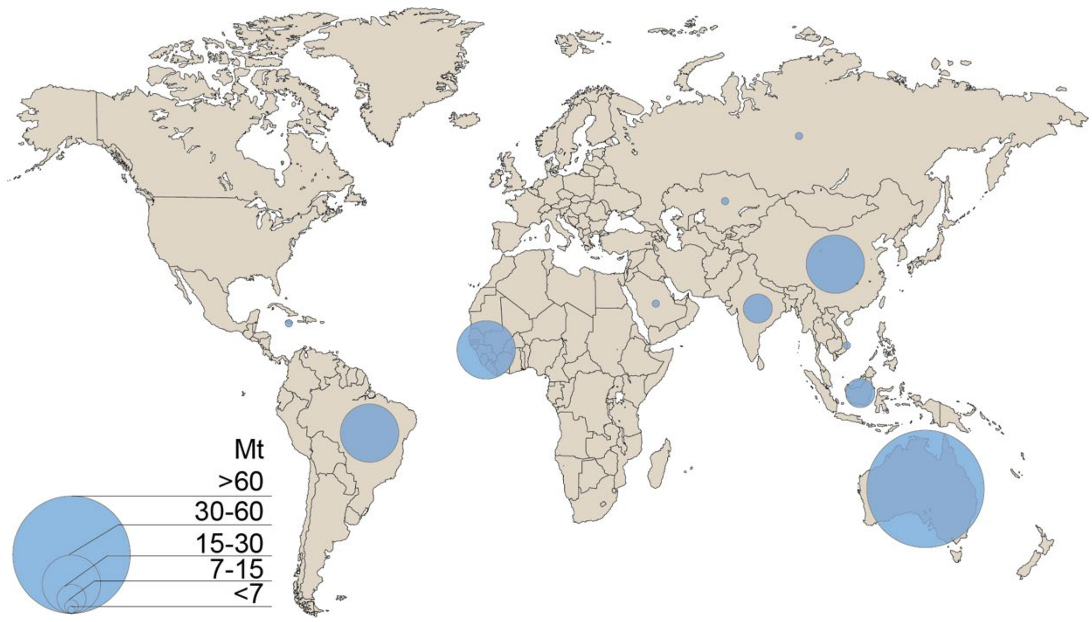


Figure 1-4 *Overview of bauxite ore production in the then largest producing countries in 2021. Source: USGS (2021); data in Table 1-3.*

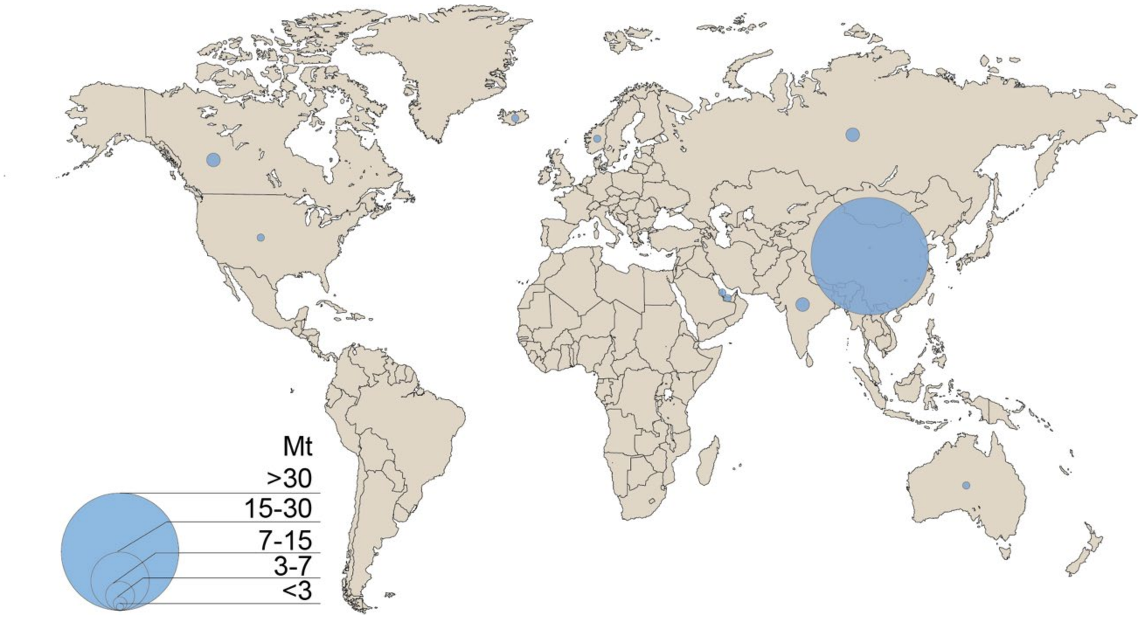


Figure 1-5 *Overview of aluminium production in the ten largest producing countries in 2021. Source: USGS (2022); data in Table 1-5.*

1.4.3.1 Companies Involved in the Supply Chains for Bauxite, Alumina, and Aluminium

The supply chains for aluminium are extensively vertically integrated, and the companies' main activities in the chains are only occasionally disclosed. Among the largest bauxite producers are Alcoa Corp, Aluminium Corporation of China (Chinalco), Rio Tinto, Vale, and Norsk Hydro (Table 1-6).

1.4.4 Production of Aluminium

Producing 1 ton of aluminium requires 4-5 ton of bauxite ore. From this, initially 2 ton of alumina, a raw material for aluminium, are produced. The manufacturing process also involves the use of various process aids such as caustic soda and synthetic cryolite.

During alumina production, about 2 ton of 'red mud' are generated (equivalent to half of the bauxite ore) (see section 1.4.5). This 'red mud' represents a potential resource for iron, titanium, as well as rare earth metals, but at the same time, it poses a significant environmental problem. Figure 1-7 depicts a generic process diagram indicating product codes for bauxite, alumina, and various major raw material products.

1.4.5 Climate and Environmental Impact

Aluminium production has extensive climate and environmental impact, which, in 2022, was responsible for approximately 3 % of the global direct industrial CO_2 emissions (IEA 2022). The emissions per ton of produced aluminium are around 16 ton of CO_2e (De Berker 2022). The distribution of CO_2 emissions typically includes less than 1 % for bauxite mining, 17 % for ore processing (refining), and 83 % for smelting, consuming 16 MWh/ton of aluminium. In China, 80 % of all aluminium was produced using coal as an energy source, constituting 5 % of China's CO_2-emissions in 2021 (Milewski 2022). The CO_2 footprint thus hinges heavily on the energy source used, and recycling of aluminium scrap reduces CO_2 emissions by almost 90 %.

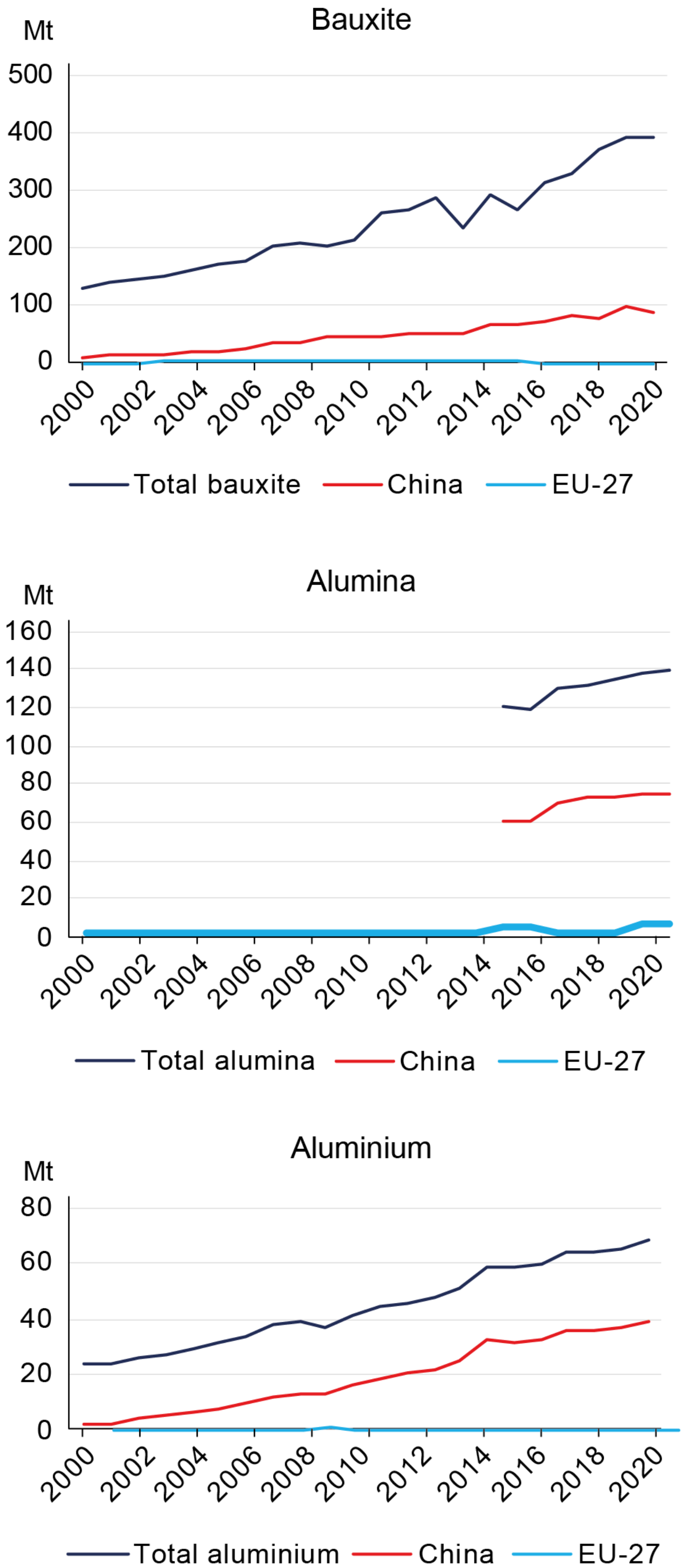


Figure 1-6 *Overview of historical production of bauxite, alumina, and aluminium in the period 2000-2023. Source: USGS (2000-2024).*

Red mud, a by-product of alumina production using the Bayer process, is often stored in large basins due to its strong alkaline nature. The chemical and physical conditions, coupled with the fact that approximately twice as much red mud is generated as aluminium produced, make this by-product a significant environmental problem. Intensive research is therefore being conducted on possible ways to utilize red mud, including its use as a filler in cement (Evens 2016).

Table 1-6 *Overview of some of the largest bauxite mines and/or alumina producers. Production figures provided for 2022. Sources: Mining Technology (2023) and various company websites.*

Company	Mine/processing plant	Production (Mt bauxite)
Alcoa Corp	Huntly Mine, Australia	25.4
Alcoa Corp/AWAC	Willowdale Mine, Australia	9.7
Aluminium Bahrain BSC	Bahrain	n.a.
Aluminium Corporation of China	Boffa Bauxite Mine, Guinea	10.7
Aluminium Corporation of China	Pingguo Mine, Guangxi	n.a.
Aluminium Corporation of China	Huaxing Mine, Shanxi	n.a.
Aluminium Corporation of China	Guizhou Mine, Guizhou	n.a.
Aluminium Corporation of China	Shanxi Other Mines, Shanxi	n.a.
Aluminium Corporation of China	Zunyi Mine, Guizhou	n.a.
Aluminium Corporation of China	Maochang, Guizhou	n.a.
Aluminium Corporation of China	Xiaoguan, Henan	n.a.
Aluminium Corporation of China	Luoyang Mine, Henan	n.a.
Aluminium Corporation of China	Yangguan, Shanxi	n.a.
Century Aluminium Company	USA	n.a.
CVG Bauxilum	n.a.	n.a.
China Hongqiao Group Co Ltd	China	n.a.
Emirates Global Aluminium	GAC Mine, Guinea	11.5
Hindalco	n.a	n.a.
Government of Guinea	Sangaredi Mine, Guinea	15.8
NALCO	Panchpatmali Mine, India	n.a.
Norsk Hydro	Paragominas Mine, Brazil	7.6
Novelis (Hindalco Industries)	USA	n.a.
Odisha Mining Company	Kodingamali Mine, India	n.a.
Rio Tinto	Gove Mine, Australia	11.8
Rio Tinto	Weipa Mine, Australia	34
Rio Tinto	14 aluminium smelters in Australia, Canada, New Zealand, Oman	n.a.
RUSAL	Timan Mine, Russia	n.a.
RUSAL	North Urals Mine, Russia	n.a.
Saudi Arabian Mining Company	Al Ba'itha Mine, Saudi Arabia	5
South 32 Ltd	Boddington Bauxite Mine, Australia	13.5
Vale	MRN, Brazil	10.5

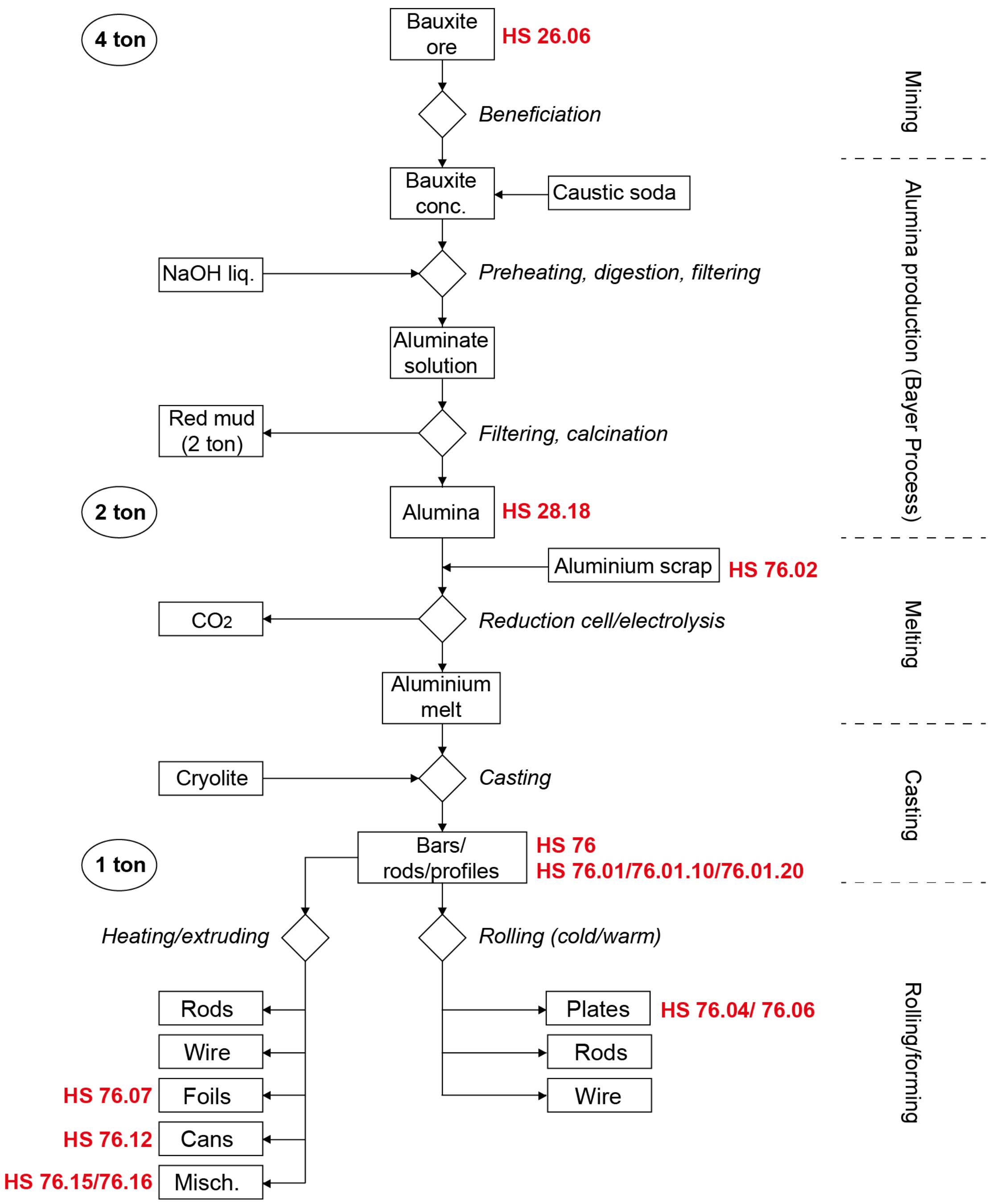


Figure 1-7 *Generic process diagram to produce alumina and aluminium, indicating selected Harmonized System (HS) codes.*

1.5 Trade

World trade in products related to the aluminium value chains amounted to approximately 178 billion USD in 2020, distributed across various trade commodity codes from bauxite ore, alumina, primary aluminium to aluminium raw materials (Table 1-7).

Aluminium and its alloys are traded on the London Metal Exchange (LME), one of the world's largest metal exchanges. A significant portion of aluminium trading also takes place through bilateral agreements based on prices from the LME. Table 1-7 provides an overview of commodity codes for some of the most common aluminium trading goods, while Table 1-8 to Table 1-10 show the main importing and exporting countries for bauxite, alumina, and primary aluminium.

Table 1-7 *Overview of commodity codes for a range of common traded goods in the supply chains for aluminium, with indication of value (billion USD) in 2020. Source: OEC World (2023).*

HS4	HS6	Description	Export value (M. USD)	Export value (M. USD)
26.06		Aluminium ore (bauxite)	5,500	
28.18		Aluminium oxide (alumina)	13,100	
76.01		Raw aluminium	49,600	
	76.01.10	Aluminium unwrought, not alloyed		25,800
	76.01.20	Aluminium unwrought, alloyed		23,800
76.02		Waste and scrap, aluminium	11,200	
76.04		Aluminium bars	15,600	
	76.04.29	Bars, rods and other profiles, aluminium alloyed		9,610
76.06		Aluminium plating	28,200	
	76.06.12	Aluminium alloy rectangular plate, sheet		23,200
76.07		Aluminium foil	12,400	
	76.07.11	Foil, aluminium, not backed, rolled but nfw		5,600
	76.04.21	Profiles, hollow, aluminium, alloyed		4,830
76.10		Aluminium structures	13,600	
	76.10.90	Aluminium structures and parts nes, for construction		9,100
76.12		Aluminium cans	5,900	
	76.12.90	Aluminium casks, drums, boxes etc		5,460
76.15		Aluminium housewares	5,800	
	76.15.10	Aluminium table/kitchen/household articles		5,550
76.16		Other Aluminium products	17,000	
	76.16.90	Articles of aluminium, nes		16,200
			177,900	129,150

Table 1-8 *The main exporting and importing countries for bauxite (HS4 26.6) in 2020. The global trade value represents the total export value. Source: OEC World (2023).*

Exporting country	Export value (M. USD)	Importing country	Export value (M. USD)
Guinea	3,007	China	2,104
		Spain	169
		UAE	151
		India	127
Australia	1,069	China	1,049
		South Korea	14
		USA	5
		Guinea	0
Indonesia	585	China	585
Brazil	174	Canada	58
		Ireland	48
		Greece	17
		Saudi Arabia	16
Subtotal	4,834		
Others	666		
Total	5,500		

Table 1-9 *The main exporting and importing countries for alumina (HS 28.18) in 2020. Source: OEC World (2023).*

Exporting country	Export value (M. USD)	Importing country	Export value (M. USD)
Australia	3,590	China UAE Russia	667 527 420
Brazil	2,433	Canada Norway USA	980 558 275
China	892	South Korea Japan USA	153 101 76
Germany	705	Italy France China	73 68 65
Subtotal Others	7,619 5,461		
Total	13,080		

Table 1-10 *The main exporting and importing countries for raw aluminium (HS 76.01) in 2020. Source: OEC World (2023).*

Exporting country	Export value (M. USD)	Importing country	Export value (M. USD)
Canada	5,482	USA The Netherlands Mexico Greece	4,504 669 196 27
Russia	4,472	Turkey The Netherlands Japan South Korea	793 618 565 318
UAE	4,402	USA Japan Malaysia Taiwan	818 489 369. 367
India	3,897	Malaysia South Korea Singapore China	1,333 903 245 242
Subtotal Others	18,253 31,339		
Total	49,592		

International trade in bauxite is dominated by China's import, which primarily comes from Guinea, Australia, and Indonesia. These countries almost exclusively export bauxite to be processed in China, where about half of the world's alumina production takes place. Australia, the world's largest bauxite producer, also produces significant amounts of alumina, which are exported to various countries; China only exports a small amount of alumina. The trade in primary aluminium, the largest aluminium product category, is significantly diversified. Canada, Russia, the United Arab Emirates, and India are the major exporters, accounting for approximately ⅓ of this export. Trade figures, illustrated in Sankey diagrams (Figure 1-8 to Figure 1-10), indicate that China's industrial demand for aluminium is secured through the processing of its own and imported bauxite resources from a few large producers.

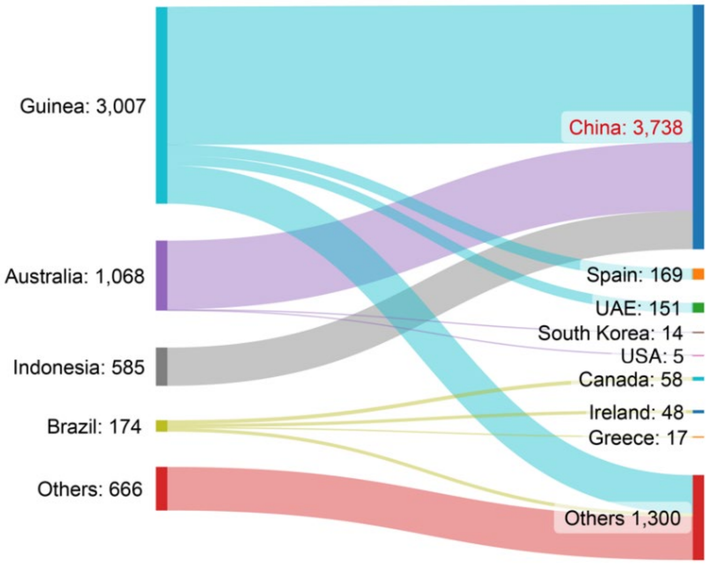


Figure 1-8 *Sankey diagram for the trade of bauxite ore (HS 26.06) in 2020. All values are in million USD, based on Table 1-8.*

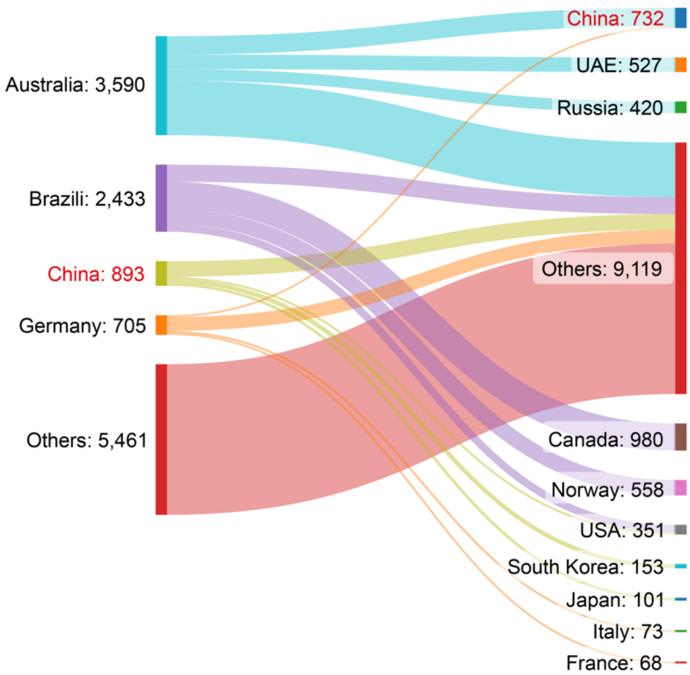


Figure 1-9 *Sankey diagram for trade of aluminium oxide/alumina (HS 28.18) in 2020. All values are in million USD, based on Table 1-9.*

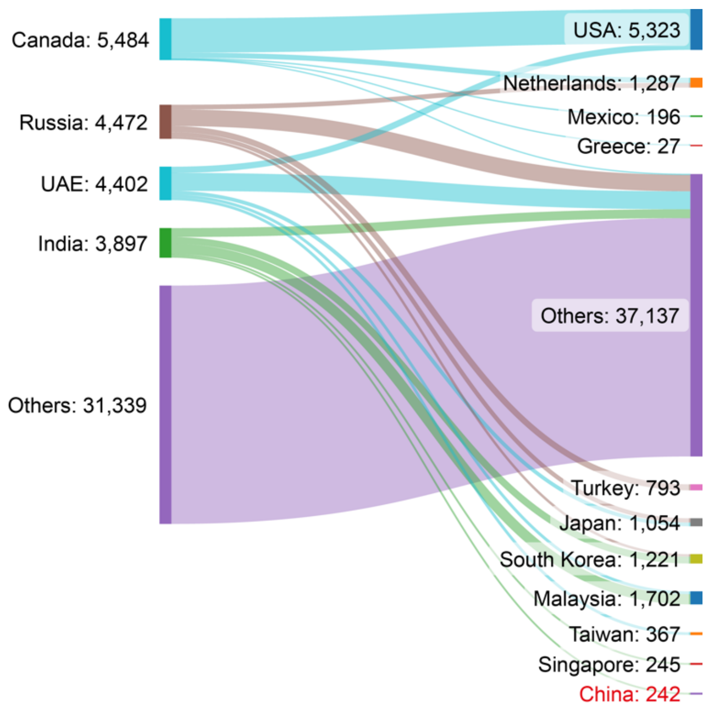


Figure 1-10 *Sankey diagram for the trade of raw aluminium (HS 76.01) in 2020. All values are in million USD, based on Table 1-10.*

1.5.1 Prices

The price of bauxite depends on its quality (reactive Al_2O_3 %; silica content, particle size, mineralogy) and varies from 41 USD/ton to 54 USD/ton, all CIF China (meaning the price includes freight and insurance to a port in China) (November 2023). The price has been relatively stable from 2014 to 2020, but with a significant increase in the price index towards mid-2022, followed by a decline. Alumina prices have generally shown a strong upward trend over the past 20 years, with minor declines during the financial crisis in 2008-09, in 2020-22. As of November 2023, the price is approximately 200 USD/ton. This stable, upward trend for alumina differs from the price fluctuations seen for aluminium. Aluminium prices have fluctuated significantly since 2000, with the lowest prices in 2008, 2015, and 2020, and the most significant peaks in 2011, 2014, 2018, and 2022. In November 2023, the price was approximately 2,260 USD/ton. Price levels for bauxite may vary among different sources, but the trends are consistent, suggesting that the prices for 2022 mark the initiation of a new period of high prices (Figure 1-11).

1.6 The Danish Consumption

Aluminium is one of the most important mineral resources for Denmark and ranks fourth in economic significance for raw materials to the Danish industry (Figure 1-12). Aluminium, and products containing the metal, had an export value for Denmark of 20 billion DKK in 2019. Danish companies had purchases of aluminium totalling 21 billion DKK, and the metal can be related to 28,000 jobs in Denmark (Clausen *et al.* 2023). About 50 % of the aluminium used in Denmark in 2019 was part of material-complex products characterized by complex supply chains, where it is difficult to trace the origin of raw materials and supply risks. The applications for aluminium in Denmark are diverse and comparable to global consumption.

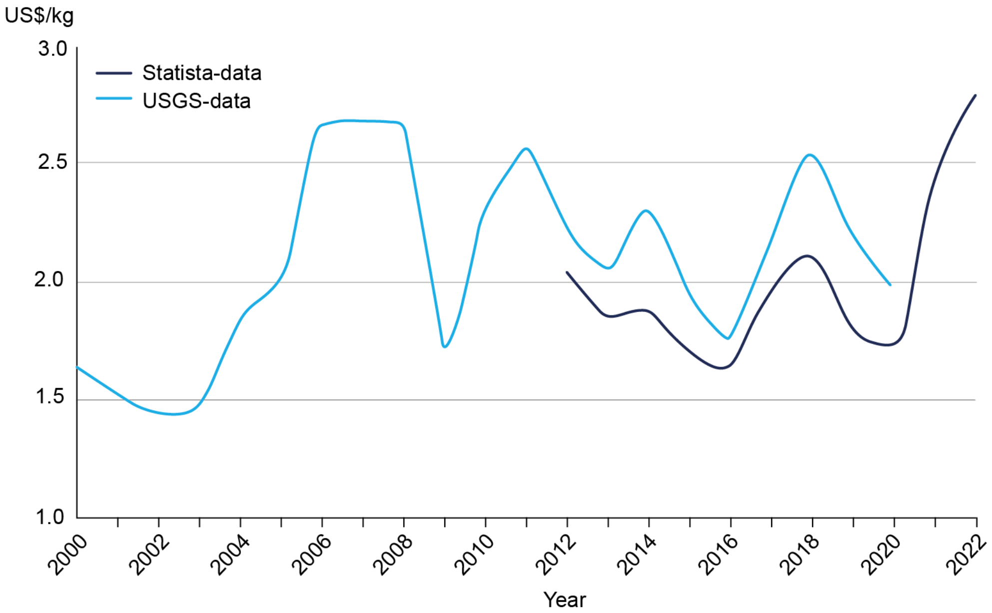


Figure 1-11 *Price development for aluminium in the period 2000-2020. Sources: Scrreen2 Aluminium factsheet (2023) and Statista (2023).*

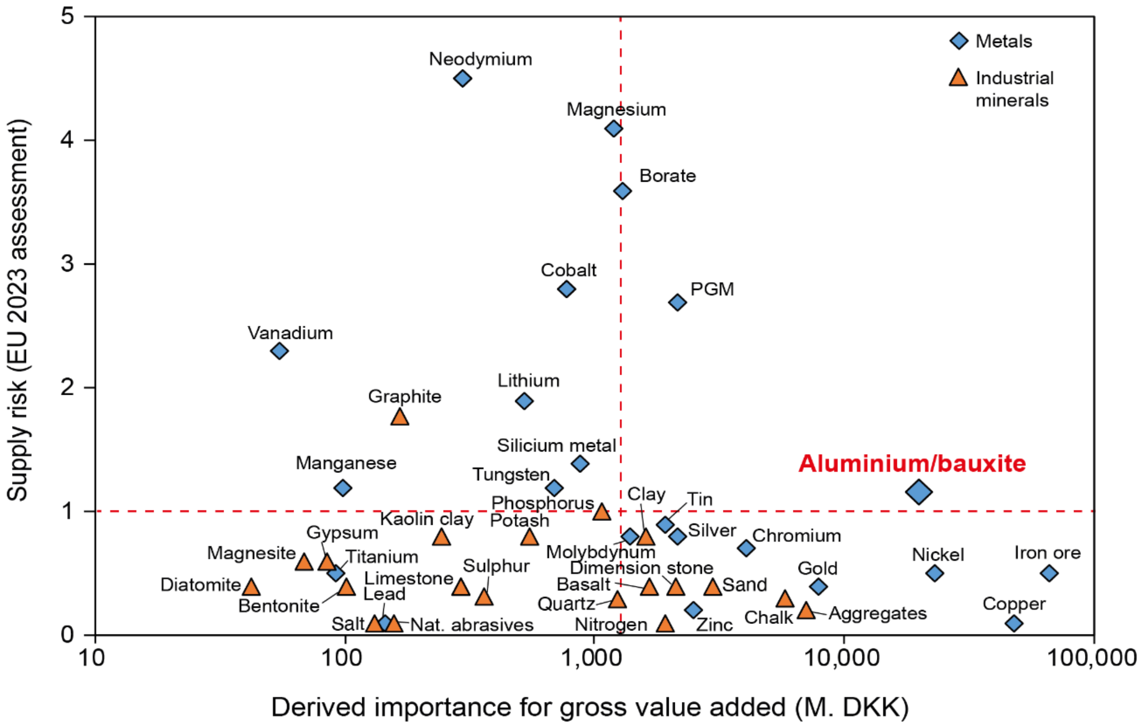


Figure 1-12 *The derived significance of aluminium and other raw materials for gross value added as a function of supply risk in Denmark. Among the analysed raw materials, aluminium, along with boron and platinum group metals (PGM), is assessed as critical for Danish industry based on the evaluation criteria used by Clausen* et al. *(2023). Figure modified after Clausen* et al. *(2023).*

1.7 Perspectives

Bauxite is mined in about 30 countries, with Australia, China, and Guinea accounting for almost three-quarters of global bauxite production. Alumina is also produced in many countries, including those without their own bauxite production. China is the world's largest alumina producer (approximately 50 %), followed by Australia and Brazil with 8 % and 5 %, respectively. Aluminium is manufactured in many countries, with most relying on imported alumina. China dominates aluminium production, accounting for 57 % of the global output, followed by Russia (6 %) and India (6 %). About 20 vertically integrated companies produce most of bauxite and alumina, with major players including Alcoa Corp, Aluminium Corporation of China (Chinalco), the Government of Guinea, South32 Ltd., and Rio Tinto. Chinalco is also one of the largest aluminium producers in China, alongside other major manufacturers such as China Hongqiao, Yunnan Aluminium, and Shandong Xinfa Aluminium Group.

The European Commission assesses (EC 2023) that aluminium/bauxite has high economic importance for the EU (EI: 5.8) and that overall supply security is also high (SRE: 1.2; SRP: 0.5), with bauxite production being the most vulnerable. Therefore, aluminium/bauxite is classified as a critical raw material. It is also considered a critical raw material in the United States, Canada, and China (Clausen *et al.* 2023).

Towards 2030, the demand for aluminium is expected to increase due to growing consumption in electrical products, construction, and packaging, especially in the food industry. There is also an anticipated rise in demand for aluminium from the automotive and aerospace industries, where aluminium is increasingly replacing stainless steel due to its lower weight and comparable properties. Expectations include increased demand for aluminium in high-voltage cables and the aluminium market for Li-ion batteries, in the form of high-purity alumina (HPA), is also projected to be a significant growth area. The Aluminium Stewardship Initiative (2019) estimates that aluminium demand will rise from 33.3 Mt in 2020 to 119.5 Mt in 2030, with two-thirds of the demand coming from China and the rest of Asia. Milewski (2022) expects that most of this growth will be associated with the manufacturing of transportation vehicles and the electrical and electronic industries (Figure 1-13).

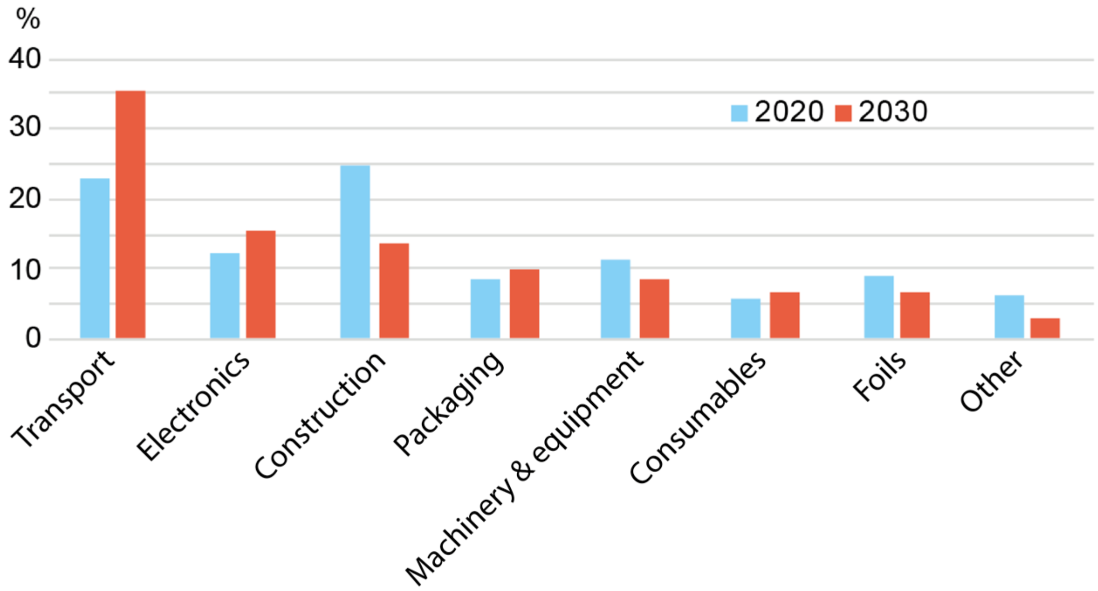


Figure 1-13 *Aluminium consumption distributed across sectors in 2020 and 2030. Based on Milewski (2022).*

The very high expected growth rates for aluminium could be checked by various factors, including China's strong dominance in all stages from alumina production to finished products and other geopolitical considerations. Additionally, the introduction of, for example, stricter environmental requirements for red mud disposal, demands for CO_2 reductions in overall aluminium production, and high energy prices may restrict growth. High energy prices have already led to closures and production reductions in Europe. In China, there have been reduced productions due to low water levels at some hydroelectric power plants supplying electricity to production, which, however, has been offset at other facilities. In addition to these factors, there are imposed trade sanctions against Russia.

1.8 References

Aluminium Stewardship Initiative 2019: The Aluminium Stewardship Initiative. Available at: https://aluminium-stewardship.org/ (Accessed: 6 August 2019)

Clausen, R. J., Kalvig, P., Keiding, J.K., Fold, N. and Vind, I. 2023: Dansk industris brug af mineralske råstoffer – økonomisk betydning og forsyningsudfordringer MiMa rapport 2023/2, pp. 181. https://doi.org/10.22008/gpub/32051

CRU 2022: Opportunities for aluminium in a post-Covid economy. CRU Reference ST2342-21

De Berker, A. 2022: Understand your aluminum emissions. Published on Carbon Chain website 27 June 2022: https://www.carbonchain.com/blog/understand-your-aluminum-emissions

European Commission (EC) 2020: Study on the EU's list of Critical Raw Materials (2020) – Final report. https://op.europa.eu/en/publication-detail/-/publication/c0d5292a-ee54-11ea-991b-01aa75ed71a1/language-en

European Commission (EC) 2023: Study on the Critical Raw Materials for the EU 2023 – Final Report. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

Evans, K. 2016: The history, challenges, and new developments in the management and use of bauxite residue. Journal of Sustainable Metallurgy, 2(4), 316-331.

IEA 2022: Aluminium https://www.iea.org/energy-system/industry/aluminium

Kolbeinsen, L. 2020: The beginning and the end of the aluminium value chain. Materiaux & Techniques 108, 506, 2020

Meyer, F.M. 2004: Availability of Bauxite Reserves, Natural Resources Research Vol 13, no 3 Sept 2004

Milewski, A. 2022: Aluminium supply shutting down as demand set to rise. The Oregon Group website besøgt 1/11-23) https://theoregongroup.com/commodities/aluminium-supply-shutting-down-as-demand-set-to-rise/

Mining Technology 2023: https://www.mining-technology.com/marketdata/ten-largest-bauxites-mines/?cf-view

Observatory of Economic Complexity World (EOC World) 2023: Database https://oec.world/

Scrreen2 Aluminium factsheet 2023: Scrreen2 Factsheets updates based on the EU Factsheets 2020 Aluminium and bauxite. https://scrreen.eu/wp-content/uploads/2023/06/SCRREEN2_factsheets_ALUMINIUM.pdf

Statista 2023: Average aluminum prices from 2012 to 2022. https://www.statista.com/statistics/276643/aluminum-prices-since-2003/

USGS 2000-2023: Mineral commodity summaries 2000-2023: U.S. Geological Survey https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries

World Mining Data (WMD) 2022: Vol 37, 28 April 2022 https://www.world-mining-data.info/wmd/downloads/PDF/WMD2022.pdf

2. Boron

2.1 Introduction

Boron (B) is element number 5 in the Periodic Table of Elements and is an important raw material with a wide range of industrial applications, including glass, fiberglass, magnets, ceramic products, fertilizers, and cleaning agents. Boron is found in nature in minerals that consist of boron, oxygen, and other elements, as well as in brines (aqueous solutions with a high content of common salts such as Na, K, B, I, Li, etc.); boron is extracted from both sources. Both boron minerals and brines are used to produce borate, borax, and boric acid, which have direct chemical applications and are also used in the production of specialty materials. Further processing into boron composite high-strength materials is carried out by specialized companies.

Turkey and the USA are by far the largest producers of boron. Production in Turkey is dominated by the state-owned Turkish company Eti Maden, and in the USA by the American-registered US Borax (owned by the Rio Tinto mining corporation), which is also a dominant producer of products in the upper and middle parts of the supply chains. In 2021, these two companies accounted for approximately 75 % of the global borate production. Both Turkey and the USA exported most of their production to China, and China carries out about 80 % of the processing and the production in the lower parts of the supply chains, such as boron carbides and other specialty products (Sun 2022).

Boron was assessed as a critical raw material by both the EU in 2020 and 2023 (EC 2020, 2023) and by Japan in 2020 and in 2023 for Denmark (Clausen *et al.* 2023). The industry estimates that there will be a supply deficit of approximately 2 Mt of boron equivalent by 2028 (Sun 2022).

2.2 Applications and Sectors

The largest consumption area for boron is in borosilicate glass, insulation materials, fiberglass, and E-glass (electrical grade glass) (Figure 2-1). The addition of boron lowers the melting point of glass melt and increases the thermal and physical strength of the glass, making it suitable for heat-resistant glass (Pyrex glass), glass fibres, and industrial and optical glass. Boron is added in the form of both mineral concentrates and refined borates such as borax pentahydrate and boric acids. Borosilicate glass contains 7-15 % B_2O_3; 5-10 % B_2O_3 is used for the glass weave in wind turbine blades.

Ceramic Products: Boron is used both as a flux to lower the melting temperature and is added to glazes and enamels to enhance utility strength.

Boron is used as perborate in laundry detergents and cleaning agents, where it bleaches, softens water, and removes dirt.

Boron is used as an additive to steel and ferroalloys, contributing to increased material strength. Boron is also part of strong magnets like NdFeB types; the boron content in these magnet types is typically around 1 %.

Boron is used in the production of boron nitride (borazon), one of the hardest known materials, and in the manufacturing of boron carbides, titanium borides, and tungsten borides, which also have very high hardness and melting points. Some of these are processed into high-tech composite materials and used in the military and aerospace industries.

In fertilizers boron is added as a micronutrient. For this purpose, calcium-carrying boron minerals are not suitable, and therefore, the fertilizer industry prefers American deposits. In addition, boron is used for various purposes such as chemicals for firefighting equipment, Teflon, plastic coatings on fibre optic cables, wood preservatives, catalysts for copper and lead smelting, medical and cosmetic products, and water treatment. Moreover, diborane (B_2H_6), pentaborane (B_5H_9), decaborane ($B_{10}H_{14}$), and alkali boron are considered potential future rocket fuels (Helvaci 2017).

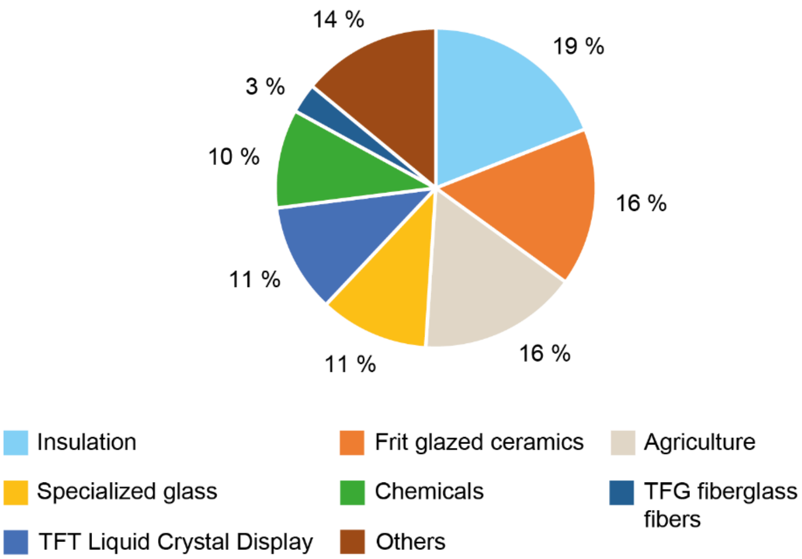


Figure 2-1 *Distribution of applications of boron in 2018. Borates are raw materials with many different areas of use. Source: Cann (2018).*

2.3 Recycling and Substitution

Most applications of boron products only occasionally allow for recycling, and the recycling rate is therefore only 1 % (EOL-RR) (EC 2023). For most applications involving boron, the raw material cannot be replaced without compromising the performance or final quality of the end-product (Scrreen2 Boron factsheet 2023). In the case of glass and ceramic products, boron can be substituted by phosphates. Where boron is used in the production of detergents, it can be replaced by chlorine and enzymes; in enamels, lithium products can replace boron. EC (2023) has estimated that for the EU, the boron substitution index SI-RR is 0.99 and SI-EI is 0.99.

2.4 Global Supply

2.4.1 Geology

The largest known borate deposits are found in China, Turkey, Tibet, Japan, the USA, and Serbia (USGS 2022). The richest deposits, including those in Turkey, contain up to 30 % borate (B_2O_3); however, in most deposits, the boron content is considerably lower. The formation process is significant in determining the types of boron minerals present in the deposits, affecting whether there may be other commercial minerals or raw materials in boron deposits, such as lithium. Differences in the formation process explain why Turkey primarily extracts colemanite, the USA focuses on kernite, and productions in Russia and China are mainly based on datolite. Consequently, the major deposits in Turkey are dominated by calcium borates, while deposits in the USA are dominated by sodium borates (Warran 2020). Table 2-1 shows the commercially important boron minerals.

Table 2-1 *Commercially important boron minerals. Source: Helvaci (2017).*

Mineral	Mineral formula	(B_2O_3 wt. %)	Main mining countries
Boracite	$Mg_3[B_7O_{13}]Cl$	62	
Colemanite	$Ca_2B_6O_{11} \cdot 5H_2O$	51	Turkey (regions: Emet, Bigadic, Kestelek) USA (minor production in Death Valley)
Datolite	$CaBSiO_4(OH)$	22	Russia; China
Kernite	$Na_2B_4O_6(OH)_2 \cdot 3H_2O$	51	USA (Kramer deposit)
Ludwigite	Mg_2FeBO_5	17	Production in China mainly based on ludwigit
Pandermite	$Ca_2B_5O_7(OH)_5 \cdot H_2O$	50	n.a.
Sassolite	H_3BO_3	56	n.a.
Tincal/borax	$Na_2[O_2B_4O_5(OH)_4] \cdot 8\ H_2O$	36	Turkey (Kirka), USA (Boron), Argentina (Tincalayu and Loma Blanca)
Ulexite	$NaCa[B_5O_6(OH)_6] \cdot 5H_2O$	43	Turkey (regions: Emet, Bigadic, Kestelek)

There are more than 250 different boron-containing minerals known. The most common are silicates such as tourmaline and axinite, but around 90 % of the global production is based on the following five minerals: colemanite, kernite, tincal/borax, datolite, and ulexite. These minerals differ mainly in their boron, sodium, calcium, and crystalline water content, leading to varying advantages and disadvantages in both raw material processing and application.

2.4.2 Global Boron Reserves

The world's total reserves of borates are commonly reported in B_2O_3 equivalents. Global borate reserves are estimated to be around 1,340 Mt, with the majority located in Turkey (Table 2-2). With the current known boron reserves, production could last for several hundred years, but global assessments are highly uncertain due to the use of different estimation methods. Additionally, some countries, such as Argentina, Bolivia, and Germany, do not report their boron resources (USGS 2023). Overall, neither the size nor the data quality is secure, and some of the reserves may not be viable for future production.

Table 2-2 *World boron reserves in 2022 compiled for six countries; in addition, there are several countries that do not provide this type of data. Source: USGS (2023).*

Boron reserves (B_2O_3 equivalents)	Mt (B_2O_3)
USA	40
Chile (ulexit)	35
China (boric oxide equivalent)	21
Peru (crude borate)	4
Russia (datolite)	40
Turkey (refined borate)	1,200
Total	**1,340**

2.4.3 Global Boron Production

USGS compiles annual reports on the global production of boron minerals (borate); however, these reports are only indicative due to inconsistent reporting methods among countries and because, for strategic reasons, the USA has chosen not to disclose its own productions. In the following, the USA's production is estimated to be approximately 60 % of Turkey's production (Elevli *et al.* 2022). In the period 2000-2012, the total borate production was 4-5 Mt/year, followed by a significant increase towards 2017, where production reached up to 14 Mt/year. Subsequently, production declined and was at its lowest level in 20 years in 2022 (Figure 2-2). No explanation has been found for either the significant increase or the recent years' declining production. China only has low-grade boron deposits, and the production of boron minerals in China has been less than 10 % of the global production, with a slight increase since 2019; thus, China relies on imports (Figure 2-2).

In 2021, the total borate production was approximately 4 Mt, with Turkey and the USA accounting for around 75 %. The remaining production came from China, Chile, and Bolivia, contributing 380,000 ton, 300,000 ton, and 210,000 ton, respectively. Additionally, there were smaller volumes from Germany, Russia, Argentina, and Kazakhstan (Table 2-3). Figure 2-3 provides an overview of some of the largest boron-producing countries, while some of the major boron mines and companies are listed in Table 2-4.

WMD (2022) reports global borate production in 2020 to approximately 3.6 Mt B_2O_3, indicating a decline compared to the previous four years, where production exceeded 4 Mt B_2O_3.

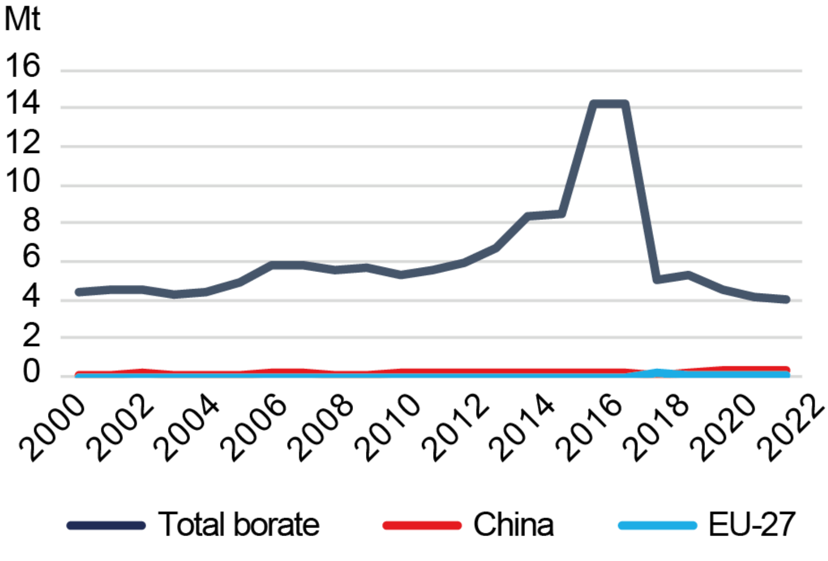


Figure 2-2 *Overview of historical borate production in the period 2000-2021. Source: USGS (2000-2022). Note: The USA has not reported its own production since 2005, and the production is therefore estimated to be 60 % of Turkey's production.*

Table 2-3 *Production of borate minerals, compiled by USGS (2023), Statista (2023), and WMD (2022). Data (in ton) show significant discrepancies between data sources.*

Mining country/mineral	2021 (USGS)	2020 (Statista)	2020 (WMD)
Argentina (untreated)	71,000	70.000	134,604
Bolivia, ulexite	210,000	200,000	258,019
Chile, ulexite	300,000	400,000	288,100
Iran, not specified	-	-	1495
Kazakhstan, not specified	-	30,000	30,000
China, boric oxide equivalent	380,000	250,000	250,000
Peru, crude borate	50,000	110,000	43,645
Russia, datolite ore	80,000	80,000	85,000
Turkey, refined borates	1,700,000	2,400,000	1.680.000
Germany, compounds	120,000	120,000	-
USA	c. 1,200,000	-	1,680,000
Total	**c. 4,000,000**	**3,660,000**	**3,601,366**

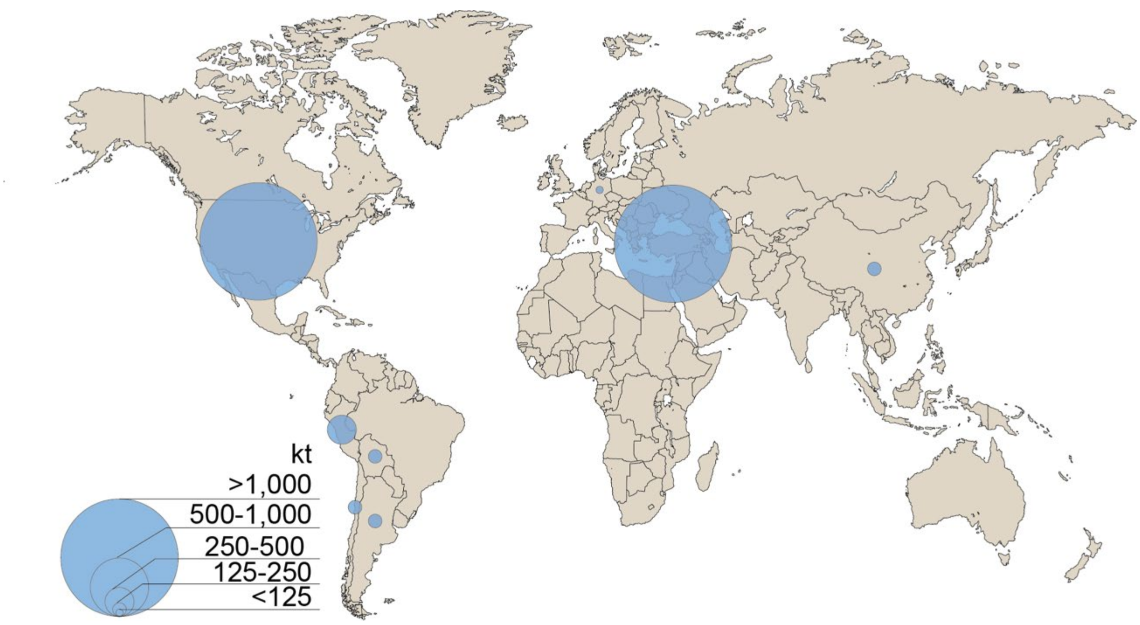


Figure 2-3 *Overview of some of the world's largest boron-producing countries. Based on data from USGS (2023).*

2.4.3.1 Companies Involved in the Production and Processing of Boron

The global production of borates is dominated by two producers:

1) The Turkish state-owned company ETI Maden, which controls the world's largest borate deposits in Turkey (mainly colemanite and smaller amounts of tincal). Production in 2019: 2 Mt. About 95 % of the products were exported (Elevli *et al.* 2022).
2) US Borax, a subsidiary of Rio Tinto. Production in 2019: 1 Mt of borates (borax pentahydrate, borax decahydrate, and boric acid based on tincal and kernite). US Borax also produces anhydrous borate products based on borax decahydrate (Elevli *et al.* 2022).

Table 2-4 *Overview of the most significant producers of primary boron products.*

Country	Company	Resource	Production	Comments/references
Argentina	Minera Santa Rita (MSR)	Saline lake deposits in the provinces Salta and Catamarca: 6 million ton	60,000 ton/y. Anticipated expansion: 75,000 ton/y	Borax Argentina S.A. overtaken by MSR from Allkem Ltd (August 2022); Li-product off-take agreement with Allkem Ltd
	Tincalayu	Tincalayu borax deposit	130.000 ton/y	Mindat (2022)
	Ulex Empresa Minera	Hydroboracit and colmanit are extracted in the mine Sol de Manana; Salta province	Unknown – small	Ulex (2022)
Bolivia		Salar de Coipase extracts evaporites	Unknown	
	Industrial Tierra	Salt lake deposit Laguna Capina and Challviri (ulexite)	15,000 ton/y (boric acid)	Borates Today (2022c)
Chile	Allkem Ltd	Salar de Atacama-deposit (open cast)		
Iran		Gharah Gol mine, Zanjan-province		University of Tehran (2023)
Kazakhstan		Inderborskiy mine	Evaporite/salt-dome (colemanit and ulexit)	USGS (2022)
China		Ludwigite-production in the provinces Liaoning and Qinghai		Borates Today (2022a)
Peru	Inkabor	Ulexite from Laguna Salinas		Production in April-November only
Russia	Unknown	Dalnegorski-mine: boronsilicates; ore grade: 6-12 % B_2O_3	C. ⅔ of the Russian boron production (about 50,000 ton in 2021)	Warren (2020)
		Tayzhonoye mine in Sakha-Yakutia-region		By-product to iron-ore mining
	MMC Bor	Unknown		Integrated boron producer, based on datolite, manufactures calciumborate, boron anhydride, boric acid and sodiumperborate and ferroboron (c. 200 ton/y).
	JSC Aviabor	Unknown		Chemical producer of borate, boric acid and borane complexes, boron hydrates, borehydrides, and organoboranes.
Turkey	Eti Maden	Kestelek-mine	Colemanite/ulexite: production of boric acid	
		Bigadic-mine	Colemanite/ulexite: production of boric acid	
		Emet-mine	Colemanite/ulexite: production of boric acid	
		Kirka-mine	Tincal: production of boric acid	
Germany	Unknown	Unknown		Borate as by-product to potassium mining, from Permian salt deposits
USA	US Borax	Boron mine, California (tincal, kernite)		

These two companies control approximately 75 % of the global borate market, with around 42 % attributed to ETI Maden and 33 % to US Borax. The remaining production is carried out by companies such as American Borate (USA), Allkem Ltd. (Chile), Inkabor (Peru, Bolivia), Searles Valley Minerals Inc. (South Africa), and Minera Santa Rita (Argentina). It should be noted that Aluminium Corporation of China Ltd (Chinalco) is the largest shareholder (14.6 %) in Rio Tinto, and thus, China has interests in US Borax's production in the USA.

There is significant vertical integration in the upper and middle parts of the boron supply chains. In addition, there are several companies that produce boron products based on purchased boron minerals, such as Boron Specialities LLC (USA) and JSC Aviabor (Russian registered).

Chinese mining companies account for 10 % of the global production and supply about ⅓ of the Chinese market. More than 80 % of China's borate production occurs in the Liaoning province, about 10 % in Tibet, and 6 % in the Qinghai province, where most of the resources are the mineral ludwigite (Borates Today 2022a). The ores from the Liaoning province contain 7-20 % B_2O_3, whereas the saline lake deposits in Qinghai contain approximately 3.3 % B_2O_3 and are produced from the minerals ulexite, pinnoite, and tincal.

China processes its own and imported raw materials into borax, boron hydroxides, perborates, boric acids, boron carbides, fluoroborates, boron trifluoride, ferroboron, boron halides, and borides. As China's own resources are low-grade, most of Chinese boron product production is based on imported boron raw materials.

2.4.4 Manufacturing of Boron Products

Supply chains for boron are typically highly vertically integrated, with the same company performing mineral extraction, ore processing, and manufacturing refined products (up to the 3rd derivative). Therefore, it is difficult to divide the supply chains for boron products into upper, middle, and lower parts of the supply chains. The following provides an overview of the typical processes from mining of boron minerals/treatment of boron-containing brines to some finished raw materials (see also Figure 2-4).

Mining/Extraction: Most of the boron extraction is carried out through open-pit mining but in addition, boron is extracted from evaporites (groundwater/surface water with particularly high salt content). The treatment of the ore/evaporite varies depending on the dominant boron mineral:

- Treatment of tincal/borax ore: The ore is crushed and dissolved in boiling water, and non-soluble components are separated. The boron-rich solution is crystallized, filtered, and dried; the products are typically borax pentahydrate and borax decahydrate. Borax pentahydrate is used to produce anhydrous borax, and borax decahydrate is especially used in the manufacture of detergents.
- Treatment of ulexite concentrate includes the following process steps: dissolution in water, filtration, calcination (625-850 °C), grinding, and sorting. The products are used either directly or as raw material in further processing.
- Treatment of colemanite ore includes the following process steps: crushing and sorting of colemanite; dissolution of colemanite in soda, resulting in sodium borate used in the production of boric acid. The boric acid is filtered, centrifuged, and sold either as crystals or powder (Elevli *et al.* 2022).
- Treatment of datolite ore (only included in Russian productions): The ore is crushed and dissolved in soda, resulting in the production of boric acids, which, when treated with sodium carbonate, are converted into decahydrate borax (Warren 2020).

Production of boric acid and borax decahydrate is carried out worldwide by companies that do not mine the ore themselves but purchase the semi-finished products. For example, Turkey exports 75 % of their production as crude borate.

Energy, water, and raw material consumption to produce boric acid, borax pentahydrate, borax decahydrate, and sodium perborate are shown in Table 2-5, indicating that water consumption, in particular, is significant.

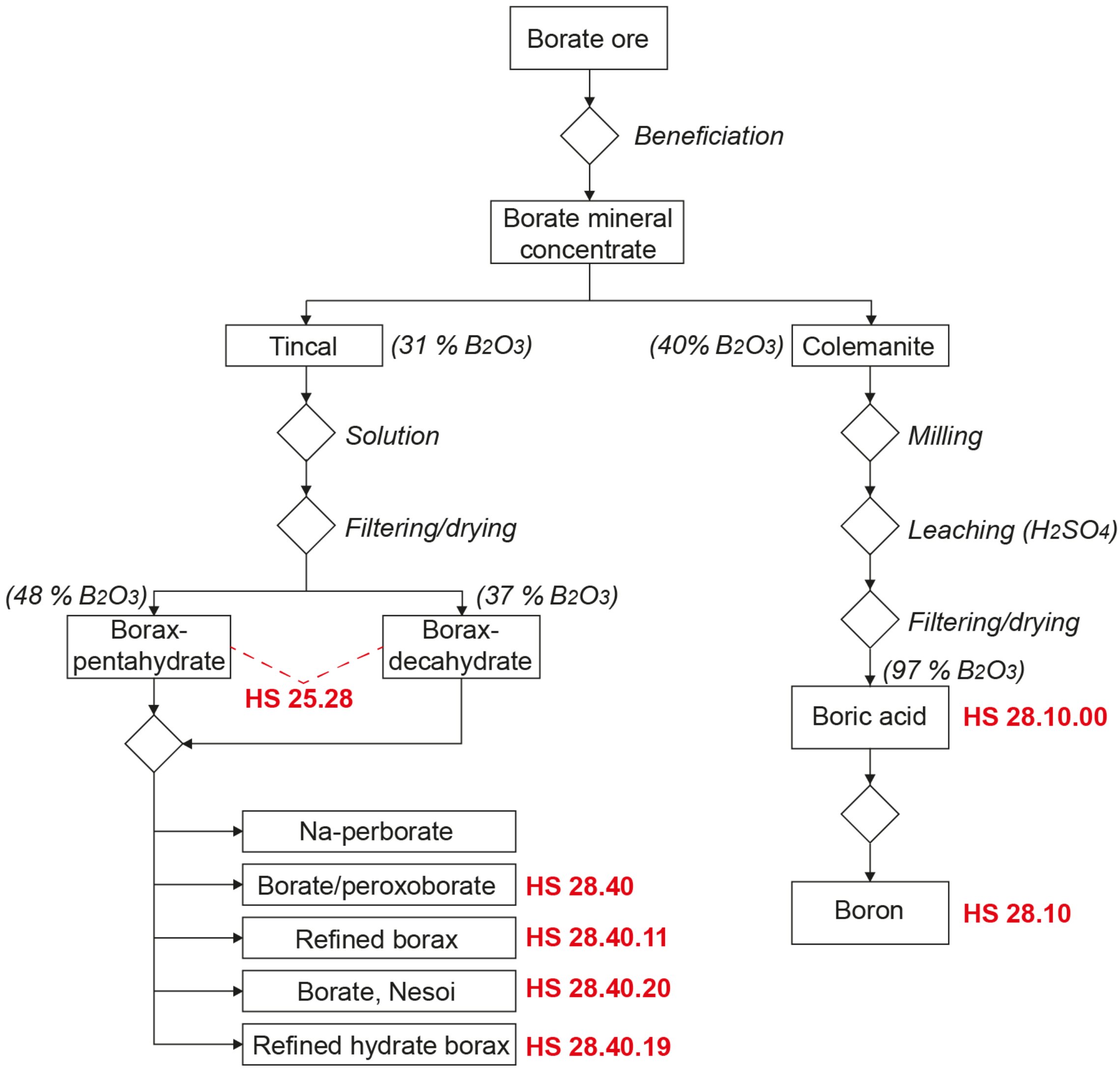


Figure 2-4 *Generic process diagram to produce boron products, indicating a range of commodity codes (HS codes).*

2.4.5 Climate and Environmental Impact

The climatic and environmental impacts of boron product manufacturing vary depending on the mineral used as raw material and the specific product being produced. Türkbay *et al.* (2022a, b) report water and energy consumption, as well as CO_2e emissions to produce various boron products (Table 2-5); depending on the process route, the values in the table may need to be added.

Table 2-5 *Overview of raw material, water, and energy consumption to produce 1 ton of refined boron product. Source: Türkbay* et al. *(2022a, b), based on 1987 data.*

Mineral	Consumption of raw material, water, and energy per ton boron product				Product
	Ton	El (kWh)	Water (m^3)	CO_2e	1 ton
Colemanite	1.5	130	25	495	Boric acid
Tincal	2.3	130	45	566	Borax pentahydrate
Tincal	1.7	125	14	1,248	Borax decahydrate
Conc. tincal	1.1	110	6	1,701	Sodium perborate

2.5 Trade

An overview of important commercial boron products is provided in Table 2-6. Trade statistics only allow for the assessment of specific commercial boron products, including mineral concentrates. International trade for borates (HS 28.40), boron (HS 28.10), and borax (HS 25.28) amounted to more than 2 billion USD in 2020 (Table 2-7).

Table 2-6 *Key commercial boron products, with indication of boron content. Source: Helvaci (2017).*

Product	Mineral formula	Typical content (B_2O_3 wt. %)
Borax decahydrate	$Na_2B_4O_710H_2O$	30
Borax pentahydrat	$Na_2B_4O_75H_2O$	47
Boric acid	H_3BO_3	56
Boron oxanhydrate	B_2O_3	100
Sodium perborate	$NaBO_34H_2O$	22
Raw-borax anhydrate	$Na_2B_2O_3$	69

Table 2-7 *International trade of selected boron products in 2020, with trade code and value. Source: OEC World (2023).*

HS-code	Code description	Value (M. USD)
25.28	Borax	404
28.40	Borates	1,100
28.40.11	Disodium tetraborate (refined borax)	73
28.40.19	Disodium tetraborate – refined	855
28.40.20	Borates of metals except refined borax	157
28.10	Boron	538

Turkey and the USA have dominated the export markets for boron products for over 20 years, and in 2020, these two countries accounted for approximately three-quarters of exports – with China being an insignificant exporter (and producer). Conversely, China is the dominant global importer, consuming about 17 % of the borax export (HS 25.28); 34 % of the boron export (HS 28.10); and 27 % of the borate export (HS 28.40)

Since Turkey and the USA dominate the markets for boron products, they also hold a complete dominance in the export of borates (HS 28.40) and boron (HS 28.10), accounting for 78 % and 58 % of global trade, respectively, measured in the trade value of global boron trade. For borax (HS 25.28), the export is dominated by Turkey and Bolivia with 54 % and 16 %, respectively. It is also evident that China is the world's leading importer for all three products and is the USA's primary importer for borates and boron, with increasing significance observed over the period from 2010 to 2020. These trade relationships are illustrated in Sankey diagrams in Figure 2-5 to Figure 2-7.

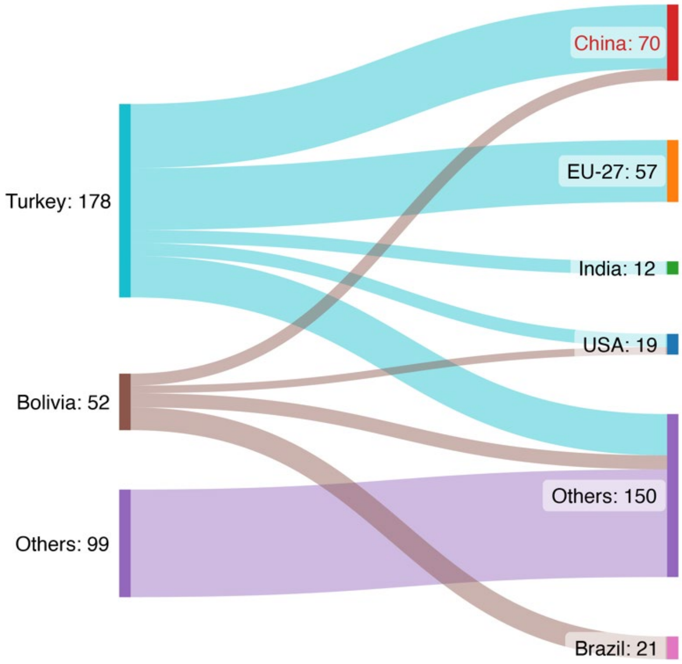


Figure 2-5 *Sankey diagram for the export-import of borax (HS 25.28) in 2020. All values in million USD. Based on OEC World (2023).*

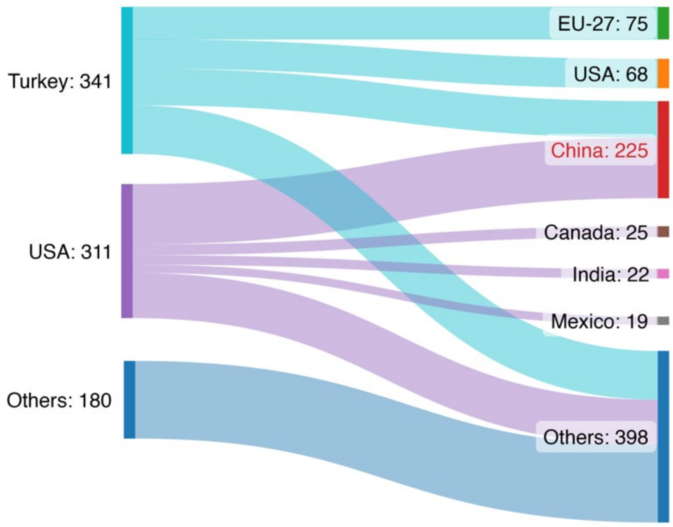


Figure 2-6 *Sankey diagram for the export-import of borates (HS6 28.40) in 2020. All values in million USD. Based on OEC World (2023).*

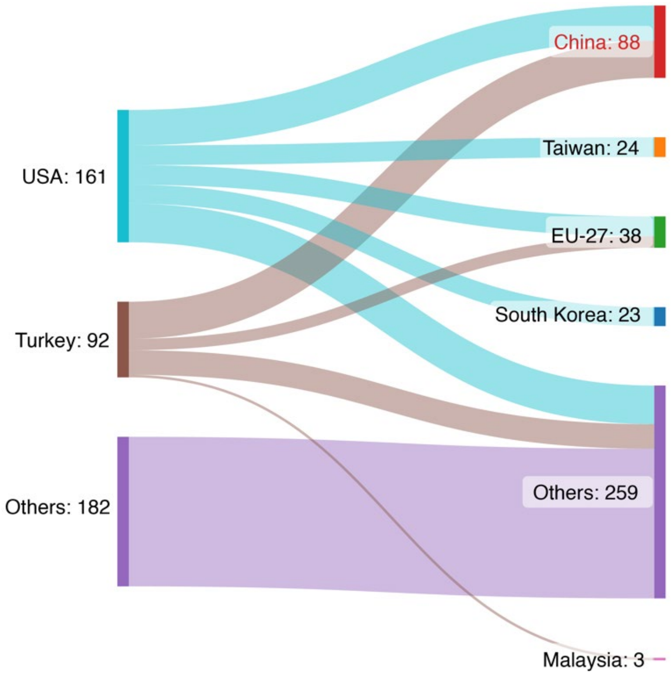


Figure 2-7 *Sankey diagram for the export-import of boron oxides and boric acid (HS 28.10) in 2020. All values in million USD. Based on data from OEC World (2023).*

2.5.1 Prices

The prices of boron mineral concentrates are determined by the boron content as well as the presence/absence of especially calcium, sodium, and potassium; for the derived products, energy consumption is also included in the price formation. The price of boron is shown in Figure 2-8, and after significant fluctuations in 2007 and the following years, the price has been relatively stable from 2013 until 2020. The price volatility for borates was around 8 % between 2016 and 2020 (Scrreen2 Boron factsheet 2023). Similarly, import prices for the most common boron products (boric acids and borax pentahydrate) to the EU have been relatively stable in the period 2010-2020.

Global Market Insights (2021) estimates that the market for boron minerals and chemicals was 3.363 billion USD in 2020, and with an annual growth rate of 4.3 %, it is expected to reach approximately 4.5 billion USD in 2027. The growth is primarily attributed to increased consumption for energy reduction (insulation materials, etc.) and for glass and ceramic materials used in the construction industry.

The market for colemanite products was approximately 175 million USD in 2020 and is expected to rise to 235 million USD in 2027. Global Market Insights (2021) anticipates that the global market for boron minerals and chemical products for glass and ceramic purposes will be around 3 billion USD in 2027.

New markets, such as applications of borates in renewable energy technologies, are expected to impact the demand for borates in the future. This may influence prices in the coming 2-3 decades (Bobba *et al.* 2020; Widmer *et al.* 2015). Despite this development, price changes are expected to remain limited due to ongoing investments in new borate factories, which are expected to secure an adequate supply for future demand (Scrreen2 Boron factsheet 2023).

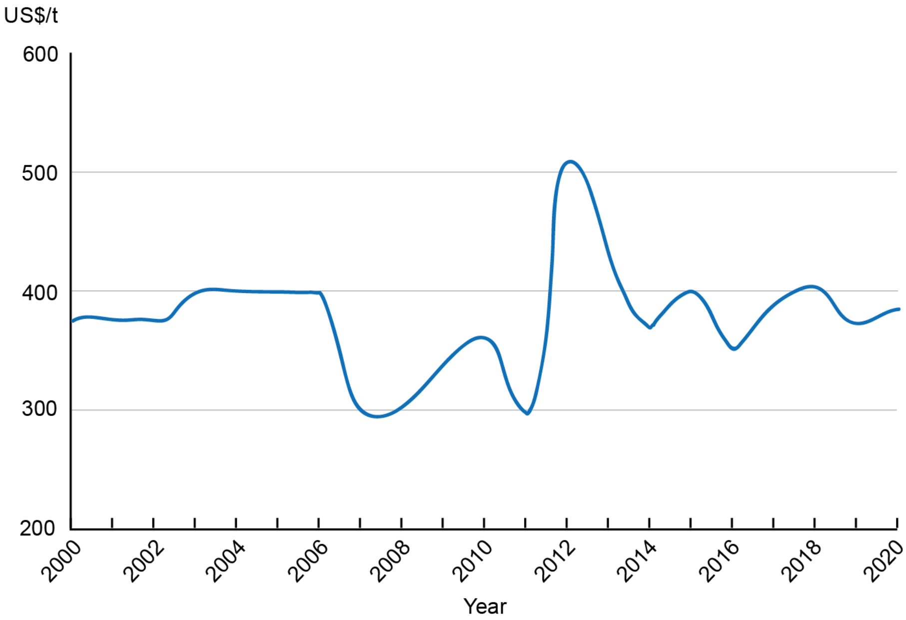


Figure 2-8 *Price development for boron in the period 2000-2020. Source: Scrreen2 Boron factsheet (2023).*

2.6 The Danish Consumption

The use of boron compounds in Denmark has not been fully mapped. However, Clausen *et al.* (2023) assessed the economic significance of boron for Danish industry and found that its primary application is in fiberglass for wind turbines (Table 2-8), where it enhances stiffness and tensile strength, and must be considered a critical raw material (Figure 2-9).

Table 2-8 *Purchases of goods made by primary and secondary sectors, for which use of boron is identified. Based on Clausen* et al. *(2023).*

Commodity	Costs (M. DKK)	Boron relative costs (%)	Costs boron (M. DKK)
Fiberglass	2,100	68	1,500
Permanent magnets for wind turbines	400	0.2	8
Chemicals	18	100	18

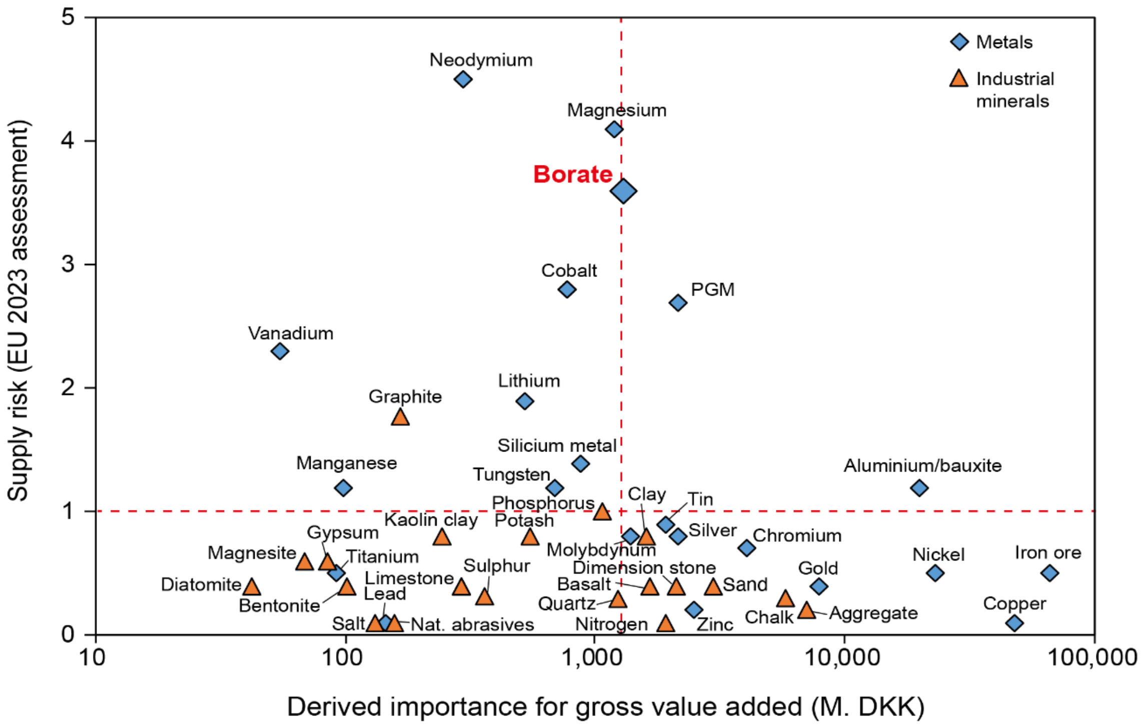


Figure 2-9 *The derived significance of boron and other raw materials for gross value added as a function of supply risk. Among the analysed raw materials, aluminium, along with boron and platinum group metals (PGM), is assessed as critical for Danish industry based on the evaluation criteria used by Clausen* et al. *(2023). Figure modified after Clausen* et al. *(2023).*

2.7 Perspectives

Extraction and production of boron are carried out in several countries, with Turkey and the USA being the dominant players, accounting for nearly three-quarters of the global production, followed by China (10 %), Chile (8 %), and Bolivia (5 %). The extraction and production of boron are controlled by two major companies: the state-owned ETI Maden in Turkey and US Borax.

The existing global supply chains for boron products are considered vulnerable due to significant portions of production being dominated by a few companies in a few countries, and China's dominant role as the world's leading importer of borax (HS 25.28), boron (HS 28.10), and borates (HS 28.40), as well as a producer of value-added boron products, such as boron carbide (>80 % from China). This is also reflected in the analyses of the EU Commission, which, since 2014 and again in 2023, has classified boron as a critical raw material with significant economic importance for the EU (EI: 3.1) and one that can only be substituted to a very limited extent. Similarly, both the extraction and processing of boron products were assessed as supply challenged (SRE: 3.6; SRP: 1.4) (EC 2020, 2023). Most other countries, except for Japan, have not classified boron as a critical raw material.

A significant increase in the demand for boron products is expected due to rising consumption in the agricultural industry, the ceramic industry, the glass industry, and applications related to green technologies, including as a raw material for NdFeB-magnets. However, Elevli *et al.* (2022) expect stable markets for boron products in the ceramic, agricultural, and chemical industries but anticipate an 8-10 % growth for the glass fibre industries, which are projected to account for approximately 68 % of the approximately 2 Mt allocated to these industries in 2023. Mining Journal (2018) expects an overall annual growth rate of 6 %, and 5E Advanced Materials (2022) predicts a consumption of approximately 9 Mt in 2030, doubling the 2020 consumption. At the same time, 5E Advanced Materials (2022) expects consumption to reach approximately 50 Mt by 2050, corresponding to an annual growth rate of around 8.5 %; these expectations may be related to the fact that 5E Advanced Materials is a potential new producer.

Borates Today (2022b, d) expects that the result of increasing consumption and the absence of alternatives will escalate supply challenges toward 2030, and a deficit of approximately 2 Mt of boric acid equivalents may emerge as early as 2028. This assessment has not been verified due to: (a) uncertain data for the existing global production; (b) no available data for the USA's production; (c) significant variations in national reports due to different accounting methods; (d) unknown potential for increasing existing productions; and (e) boron being a by-product of some upcoming lithium productions; examples of such coupling in new exploration projects include the Jadar project in Serbia and the Rhyolite Ridge and Fort Cady projects in the USA.

The principal industrial applications of boron in glass materials, chemicals, hard metals, cleaners, and fertilizers, allow negligible recycling only, and there is limited potential for substitution. Since increasing demand is anticipated without a corresponding increase in production by 2030, the supply of boron is likely to face further challenges in the near future.

2.8 References

5E Advanced Materials 2023: Boron: A critical super material. Boron 101 – 5E Advanced Materials, Inc

Bobba, S., Carrara, S., Huisman, J., Mathieux, F. & Pavel, C. 2020. Critical Raw Materials for Strategic Technologies and Sectors in the EU – a Foresight Study. In JRC. https://doi.org/10.2873/58081

Borates Today 2021: Boron: The Holy Grail of aerospace and defense. June 7, 2021.

Borates Today 2022a: Country Profile of China Borates. January 29, 2022. (Country Profile Of China | Borates Today)

Borates Today 2022b: Boron: New Suppliers ramp up for production. April 24, 2022, Science, Chemistry, Mining Boron: New Suppliers Ramp Up For Production | Borates Today

Borates Today 2022c: Country Profile of Bolivia. January 19, 2022. Country Profile Of Bolivia | Borates Today

Borates Today 2022d: New suppliers ramp up for production. April 24, 2022. Boron: New Suppliers Ramp Up For Production | Borates Today

Cann, C. 2018: Borates suddenly interesting Mining Journal 2018 (Borates suddenly interesting - Mining Journal (mining-journal.com)

Clausen, R. J., Kalvig, P., Keiding, J.K., Fold, N. and Vind, I. 2023: Dansk industris brug af mineralske råstoffer – økonomisk betydning og forsyningsudfordringer MiMa rapport 2023/2, pp. 181. https://doi.org/10.22008/gpub/32051

European Commission (EC) 2020: Study on the EU's list of Critical Raw Materials (2020) – Final report. https://op.europa.eu/en/publication-detail/-/publication/c0d5292a-ee54-11ea-991b-01aa75ed71a1/language-en

European Commission (EC) 2023: Study on the Critical Raw Materials for the EU 2023 – Final Report. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

Elevli, B., Yaman, I & Laratte, B. 2022: Estimation of the Turkish Boron Exportation to Europe. MDPI (Mining 2022, 2(2), 155-169; https://doi.org/10.3390/mining2020009)

Global Market Insights 2021: Boron Minerals and Chemicals Markets. November 2021. Boron Minerals and Chemicals Market Statistics - 2027 (gminsights.com)

Helvaci, C. 2017: Borate deposits: An overview and future forecast with regard to mineral deposits. Journal of Boron 2 (2) 59-70, 2017.

Mindat 2022: Tincalyu Mine, Antofagasta de la Sierra Department, Catamarca Province, Argentina. https://www.mindat.org/loc-51.html

Mishnaevsky, L., Branner, K., Petersen, H.N., Beauson, J., McGugan, M. & Sørensen, B.F. (2017): Materials for wind turbine blades: an overview. Materials 2017, 10, 1285, Nov. 2017.

Observatory of Economic Complexity World (EOC World) 2023: Database https://oec.world/

Scrreen2 Boron factsheet 2023: Scrreen2 Factsheets updates based on the EU Factsheets 2020 Boron. https://scrreen.eu/wp-content/uploads/2023/08/SCRREEN2_factsheets_BORON-1.pdf

Sun, K. 2022: A centre piece for decarbonisation: boron flies under the radar. Market Index. A centre piece for decarbonsation: boron flies under the radar (marketindex.com.au)

Türkbay, T., Laratte, B., Çolak, A., Çoruh, S. & Elevli, B. 2022a: Life Cycle Assessment of Boron Industry from Mining to Refined Products. Sustainability, MDPI, 2022, 14 (3), pp.1787.

Türkbay, T., Bongono, J., Alix, T. Laratte, B. & Elevli, B. 2022b: Prior knowledge of the data on the production capacity of boron facilities in Turkey. Cleaner Engineering and Technology 10 (2022) 100539.

Ulex Empresa Minera 2020: www.ulex.com

University of Tehran 2023: Abstract on the Gharah-Gol borate deposit. - (ut.ac.ir)

USGS 2000-2023: Mineral commodity summaries 2000-2023: U.S. Geological Survey https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries

USGS 2022: Producer in Kazakhstan with commodities Boron-Borates, Potassium, Gypsum-Anhydrite, Clay. Mineral Resource Data System (MRDS). Inder (MRDS #10055357) B (usgs.gov)

Warran, J. 2020: Geology and production of saline borate salts. Feb. 29, 2020; www.saltwork-consultants.com. https://saltworkconsultants.com/downloads/57 %20Borates.pdf

Widmer, J. D., Martin, R. & Kimiabeigi, M. 2015: Electric vehicle traction motors without rare earth magnets. Sustainable Materials and Technologies, 3, 7–13. https://doi.org/10.1016/j.susmat.2015.02.001

World Mining Data (WMD) 2022: Vol 37, 28 April 2022 https://www.world-mining-data.info/wmd/downloads/PDF/WMD2022.pdf

3. Copper

3.1 Introduction

Copper (Cu), with atomic number 29 in the Periodic Table of Elements, is a malleable, ductile metal with excellent thermal and electrical conductivity. When combined with high corrosion resistance, these properties make copper suitable for a wide range of purposes. Copper melts at 1,085 °C and boils at 2,562 °C. Copper has been utilized for coins and decorations since 8,000 years BCE and has been a crucial raw material since the industrial revolution. Additionally, it plays a central role in green energy technologies. As a result, there are significant growth rates in copper consumption, expected to continue towards 2050. In 2021, 26.7 million ton of copper were used, with approximately 32 % based on recycling (Copper Alliance 2023). Most of the copper is used in various alloys, including brass and bronze.

Copper is mined in many countries, but Chile, Peru, China, and the Democratic Republic of Congo (DR Congo) produced over 60 % of the world's production in 2022. China dominates the supply chains that process copper into industrially usable raw materials, and Chinese industries are also major consumers of copper. In March 2023, the European Commission defined copper as a strategic raw material due to its central role in the green transition. The analysis did not classify copper as a critical raw material, mainly because supply chains are not significantly dominated by individual countries (EC 2023).

3.2 Applications and Sectors

Copper is used primarily due to the metal's electrical conductivity, corrosion resistance, or thermal conductivity. Copper readily forms alloys with other metals such as tin (bronze), zinc (brass), and nickel (nickel silver). In these alloys, copper's physical and chemical properties are altered, providing numerous new applications, particularly in the construction industry for the manufacturing of electrical cables, outlets, water pipes, and boilers. In the industry, copper alloys are also used in silicon chips, enhancing the speed and energy efficiency of microprocessors, or in heat exchangers, taking advantage of copper's high thermal conductivity. Figure 3-1 illustrates the main applications of copper in 2021.

Power supply and electronics: Copper is used for both wiring systems and printed circuit boards, with more than ⅔ of copper consumption linked to its electrical conductivity. Wind turbines consume 3 to 8 ton of copper per MW and a medium electrical car consumes approximately 60 kg copper. The green transition will lead to the expansion of the global electrical grid system, and by 2050, is expected to be the dominant application for copper.

Construction: Copper's physical properties, combined with its excellent workability, have made it widely used in construction for water, heating, and electrical supply systems. Around 200 kg of copper is used in modern homes.

Transport sector: Copper is especially present in the electrical systems of cars, trains, and planes. A conventional car contains about 25 kg of copper, while electric cars contain roughly twice that amount. There is thus a significant growth in the market for copper. Similarly, large quantities of copper are used in the manufacture of airplanes (about 4,000 kg for large aircraft types).

Additionally, copper is consumed in medical equipment due to its antiseptic properties and in industrial equipment, heat exchangers, valves, capacitors, and containers for aggressive liquids.

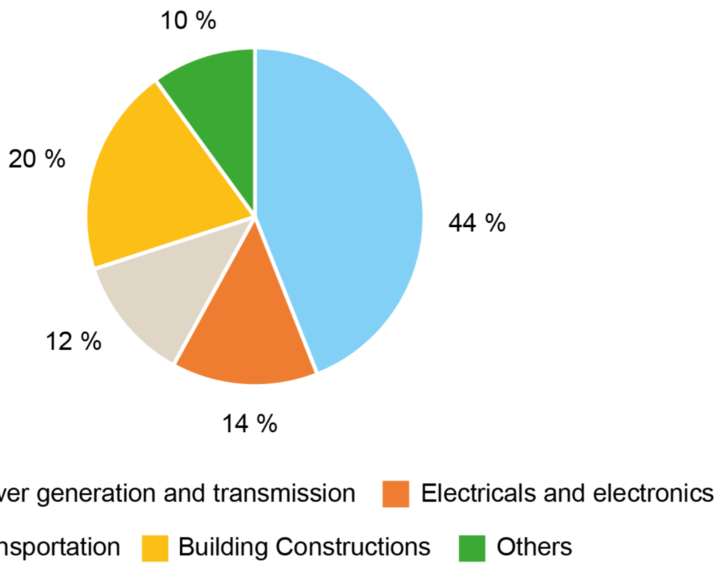


Figure 3-1 *The main application areas for copper in 2021 (Copper Alliance 2022a).*

3.3 Recycling and Substitution

It is estimated that approximately ⅔ of all copper produced to date – 690 Mt – is still in use. Copper is one of the metals with the highest recycling rate, and in 2021, the recycling rate accounted for about 32 % of the global production of 26.7 Mt (RIR) (ICA-Recycling Brief 2022). In the EU, the recycling rate (EoL-RIR) for copper is estimated to be 55 % (EC 2023), and globally it is around 30 % (ICA 2021). Most recycled copper comes from the electronics and electrical industries, followed by machinery industries and the automotive sector whereas a smaller fraction comes from buildings and infrastructure.

The bulk of the copper recycling and trading occurs in China, India, Japan, and South Korea. The copper recycling industry is dominated by several large international corporations, including Glencore, Aurubis AG, Commercial Metals Company, Schnitzer Steel Industries Inc., Umicore, Kuusakoski Group OY, and Sims Metal Management Ltd. The value of recycled copper was approximately 27 billion USD in 2022 and is expected to increase to 43 billion USD by 2031 (Recycled Copper Market 2023).

The substitution for copper is estimated to be around 1 % (Kalvman-Schueler 2022), thus having minimal significance. However, there are expectations that aluminium will substitute copper in the manufacturing of high-voltage cables; the development in this market is influenced by the copper-aluminium price difference, which has not been favourable for this transition so far.

3.4 Global Supply

3.4.1 Geology

Copper is found in various geological deposit types, of which the following are most widespread:

A. Porphyry copper deposits, typically located in areas where oceanic crust has been subducted beneath continental crust, and the resulting melt has subsequently intruded into the overlying rocks; gold can be a by-product in this type. Porphyry deposits occur in many places but are particularly common in the Andes Mountains, western North America, and the Indonesian Archipelago.
B. Copper-bearing sediments, where copper is precipitated in sandstone, shale, limestone, etc.; this type dominates in the 'Copperbelt' in Zambia and the DR Congo and is known in Eastern Europe (Kupferschiefer); they typically contain ~2 % Cu, and cobalt is extracted sporadically as a by-product.

Figure 3-2 provides an overview of the world's largest copper deposits.

Porphyry deposits dominate global copper production, with the three largest copper mines of this type being Kennecott (Utah, USA), Chuquicamata (northern Chile), and Escondida (Atacama, Chile); sedimentary types contribute about 30 % to global production (Thaarup 2017). The sedimentary type is known in Greenland from areas such as the Thule Basin and Jameson Land. Additional information regarding the copper potential in Greenland can be found in Stensgaard *et al.* (2011) and Rosa *et al.* (2023).

Both types of copper deposits can be dominated by copper sulphides and copper oxides or combinations of these groups, often with copper content <0.6 %.

The value of copper deposits is determined not only by their size and richness but also by the composition of the copper-bearing minerals (and any by-product minerals), as this affects the costs of extracting copper from the ore.

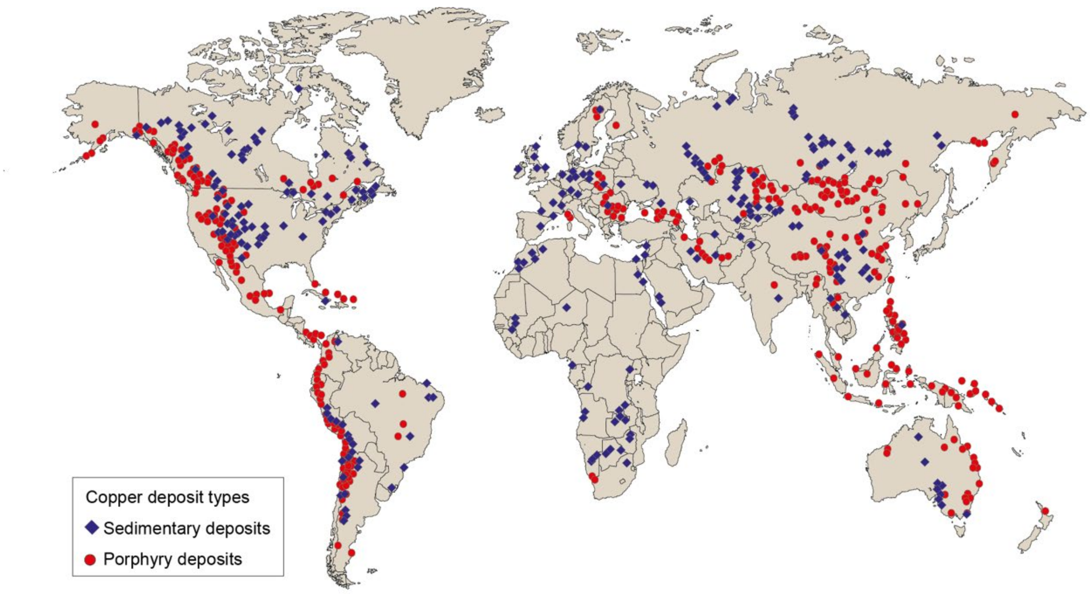


Figure 3-2 *Overview of copper deposits (porphyry deposits and sedimentary deposits). Based on USGS.*

Copper is present in many different minerals but is primarily extracted from copper oxides and sulphides; iron typically occurs in these minerals (Table 3-1). Chalcopyrite is the most utilized copper mineral, and approximately half of the world's copper production originates from this mineral (BGS 2007). However, chalcocite, cuprite, and covellite are also commercially significant.

Table 3-1 *Commercially important copper minerals.*

Mineral	**Mineral formula**	**Cu-content** (wt. %)
Native copper	Cu	>98
Bornite	Cu_5FeS_4	63
Chalcopyrite	$CuFeS_2$	35
Chalcocite	Cu_2S	80
Covellite	CuS	66
Cuprite	Cu_2O	89
Azurite	$Cu_3(CO_3)_2Cu(OH_2)$	55
Malachite	$Cu(CO_3)Cu(OH)_2$	58

3.4.1.1 By-products

Copper deposits often contain a variety of other commercially valuable minerals that vary depending on their formation: Porphyry deposits have the potential to contain molybdenum, silver, and gold; sedimentary deposits typically contain cobalt, and from massive sulphide copper deposits (not mentioned above), especially lead and zinc are extracted. Such by-products are separated from the copper minerals through processing at the mine and traded as mineral concentrates for further processing elsewhere.

Copper minerals may also contain small amounts of important metals not explicitly stated in the mineral's general chemical formula. This group is referred to as companion metals, which are very important by-products, in particular antimony (Sb), bismuth (Bi), selenium (Se), tellurium (Te), and rhenium (Re). McNulty *et al.* (2022) have estimated that potentially about 1,500 ton of antimony, 1,600 ton of bismuth, 4,200 ton of selenium, and 800 ton of tellurium could be extracted annually through copper extraction. For tellurium and selenium, this is nearly twice the current extraction from all other sources.

3.4.2 Global Copper Reserves

USGS (2023) estimates copper reserves for 13 countries and several unspecified countries at 876 Mt of copper (Table 3-2). These reserves are sufficient for 42 years of production based on the copper demand in 2021. However, with significant growth expected until 2050, the actual lifespan is considerably shorter. It should be noted that USGS data for the period from 2000 to 2021 shows that the global reserve lifespan has increased from approximately 25 years in 2002 to about 42 years in 2021. It is unclear to what extent the new reserves are related to existing mines or if they result from new projects.

In contrast to USGS data, DeCoff's data (2022) indicate that (i) the number of discoveries has generally declined in the period 2000-2021; (ii) the price per ton of discovered copper has generally increased; (iii) the annual new discoveries since 2007 have averaged only about 10 Mt, and (iv) mineral exploration activities are strongly correlated with copper prices, with increased activity at high prices. Figure 3-3 shows the 10 countries that held the largest copper reserves in 2022.

Table 3-2 *World copper reserves compiled for 13 countries; in addition, there are several countries that do not provide this type of data. Source: USGS (2023).*

Country	**Reserves 2021 (USGS) (Mt)**
Chile	200
Australia	93
Peru	77
Russia	62
Mexico	53
USA	48
DR Congo	31
Poland	31
China	26
Indonesia	24
Zambia	21
Kazakhstan	20
Canada	10
Others	180
Total	**876**

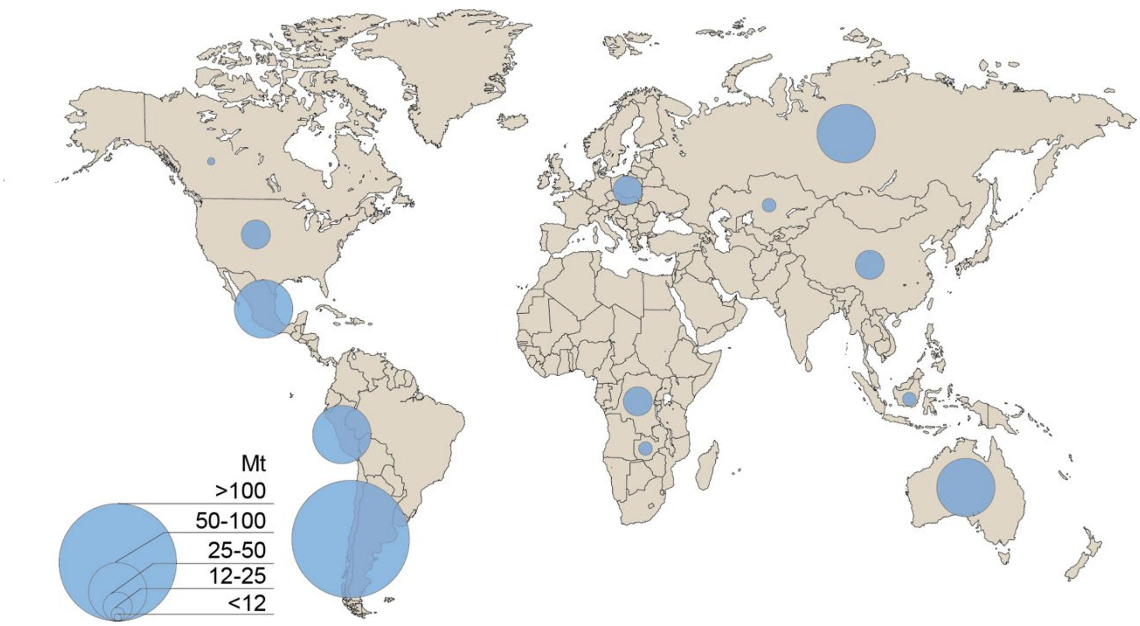


Figure 3-3 *Overview of copper reserves in the ten countries that had the largest reserves in 2021 (see also Table* 3-2*).*

Figure 3-4 depicts mineral exploration activities for copper, including budgets, resulting number of discoveries, and costs for new discoveries.

3.4.3 Global Copper Production

Copper production includes primary production from mines and secondary production from copper scrap; therefore, a distinction is often made between mine production and refined production, with the latter category also including scrap production.

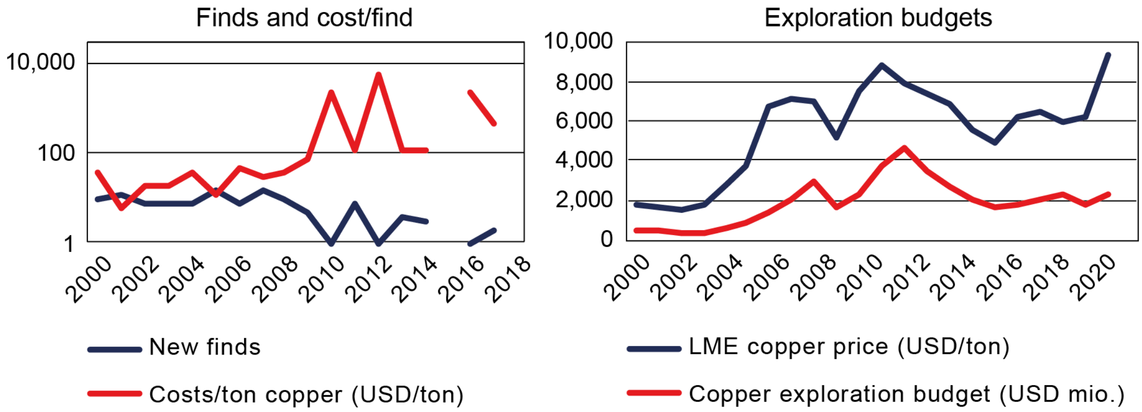


Figure 3-4 *Mineral exploration activities for copper, budgets, resulting number of discoveries, and costs for new discoveries (DeCoff 2022).*

Global copper ore production has increased by 63 % in the period from 2000 to 2021, reaching approximately 20.4 Mt (Figure 3-5). Most of this production has consistently come from Chile, Peru, Indonesia, and Russia throughout the period. Additionally, more than 20 countries, including China, are involved in copper ore production, although their contributions are relatively small. The EU-27 has only a minor copper ore production, mainly in Poland and Cyprus (Table 3-3 and Figure 3-6).

The growth in this period is attributed to both the expansion of existing mines and the initiation of new productions, with the highest growth rates observed in Peru, Chile, Mexico, and Zambia. However, Chile is experiencing a decline in production in recent years due to delayed expansion of some of its major mines.

Table 3-3 *Global production of copper ore in 2021. Source: USGS (2023).*

Country	**Production (x1.000 ton)**	**Global production rate (%)**
Chile	5.600	31
Peru	2.200	12
China	1.880	10
DR Congo	1.800	10
USA	1.200	7
Australia	900	5
Zambia	830	5
Russia	820	4
Indonesia	810	4
Mexico	720	4
Canada	590	3
Kazakhstan	520	3
Poland	390	2
Others	2.800	15
Total	**18.260**	**100**

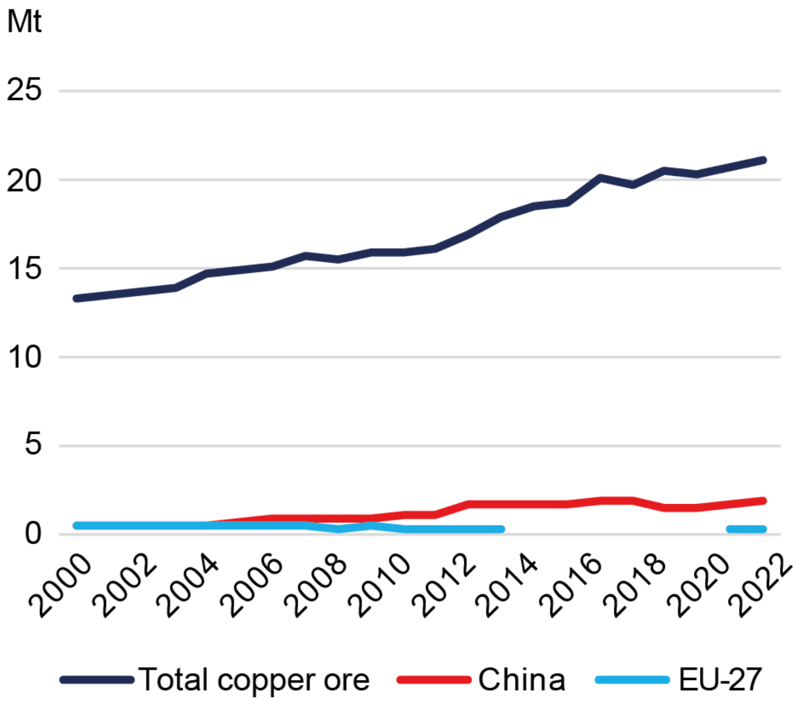


Figure 3-5 *Overview of historical copper production in the period 2000-2021. Source: USGS (2000-2022).*

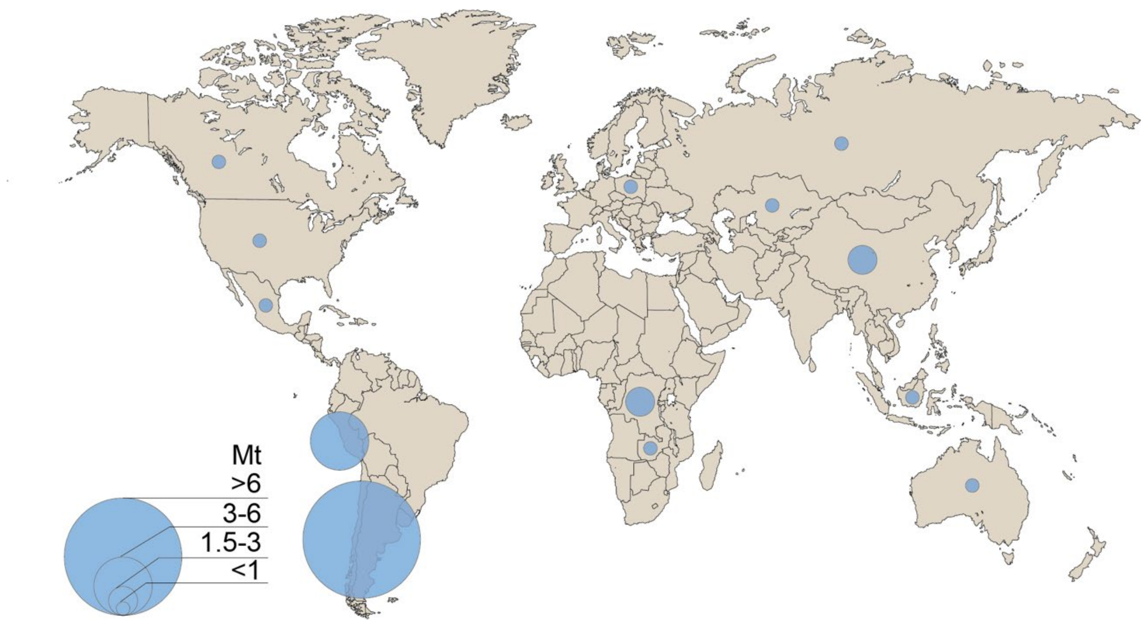


Figure 3-6 *Production of copper ore in 2021 in the ten largest producing countries (see also Table* 3-3*).*

Copper production is predominantly controlled by around 10 major companies, which contributed with approximately 50 % of the global production in 2020 (Table 3-4). Among the shareholders in nine of the ten publicly traded mining companies, one or more of 12 major capital funds are involved (Table 3-5), including BlackRock, Vanguard, and Fidelity, which are leading global capital funds. The table shows that the ownership stake of this investor group varies significantly, from less than 1 % of shares in Southern Copper to approximately 37 % in First Quantum.

China's role in the global mining industry outside China includes both Chinese-related companies' direct engagement with their own licenses and mining activities, joint venture agreements, and shareholdings in other companies (such as Rio Tinto). Direct engagement is particularly prominent in DR Congo, Zambia, Peru, and Serbia and is estimated to involve a production of 1-2 Mt of copper per year. The involvement of Chinese companies as minority shareholders in Western copper mines is not accounted for, and the off-take to Chinese smelters/refineries is also unknown.

Table 3-4 *Overview of the 20 largest producing mines, collectively accounting for approximately ⅓ of the global copper production in 2021. Data from various open sources; not comprehensive.*

Company	Mine	Country	Production (kton)	Expected closing (year)
BHP	Olympic Dam Mine	Australia	205	2061
BHP Billiton	West Musgrave (Succoth)	Australia		
CMOC (80)/Sumitomo Corp	Northparkes	Australia		
Glencore	CSA mines	Australia		
Glencore Plc	Mount Isa Copper Mine	Australia	92	2023
Glencore Plc	Ernest Henry	Australia		
Kingsgate Consolidated	Calingiri	Australia		
Newcrest Mining	Cadia Mine	Australia	106	2047
OZ Minerals	Prominent Hill Mines	Australia	63	2031
OZ Minerals	Carrapateena Mine	Australia	55	2039
Rio Tinto	Winu	Australia		
Khoemacau Mining Company	Khoemacau Mine	Botswana	60	
Centerra Gold	Mount Milligan Mine	Canada	39	2030
Copper Mountain Mining	Copper Mountain Mine	Canada	41	2051
GT Gold	Tatogga (Saddle)	Canada		
Newcrest Mining	Red Chris Mine	Canada	33	2043
Taseko Mines	Gibraltar Mine	Canada	57	2039
Teck Resources	Highland Valley Copper Mine	Canada	130	2040
Anglo American	Los Bronces	Chile	340	2057
Antofagasta (60)/(JX Nippon+Mitsubishi (40))	Los Pelambres	Chile	380	

3.4.4 Production of Copper Raw Materials

Copper production begins with the extraction of ore (often containing less than 1 % copper) and ends after a series of processing steps with sheets of 99.99 % pure copper. These sheets are commonly referred to as cathode copper, which is the raw material used in final products.

The most common types of ore, copper oxides and sulphides, are processed using two different methods: hydrometallurgy for oxides and pyrometallurgy for sulphides. Oxide deposits are often large and relatively near the surface but have lower ore grades compared to sulphides. Although more ore needs to be extracted and processed from oxide deposits, the processing method is generally less expensive compared to sulphide deposits. The latter type typically has higher ore grades, is smaller, and may be located at greater depths. The choice of mining methods – open-pit or underground – and processing is determined by factors such as mineral composition, concentration, tonnage, and the depth of the deposit. Ore deposits often contain both copper oxides and sulphides.

Table 3-5 *Examples of major investment companies' ownership stakes in copper producing companies. Data from various open sources.*

Mining company / Investor	**Antofagasta**	**BHP**	**First Quantum**	**Freeport-McMoRan Inc.**	**Glencore**	**Grupo Mexico**	**KGHM**	**Southern Copper**	**Zijin Mining Group Company**
	%	%	%	%	%	%	%	%	%
Baillie Gifford & Co.			1.5				0.9		1.8
BlackRock Fund Advisors	1.4	0.5		2.1	1.6				4.2
BlackRock Investment Management (UK) Ltd.	0.9	1.1	2.0		2.9				
BlackRock México SA de CV Asesor en Inversiones Independiente						0.8			
Capital International Ltd.			2.5						
Capital Research & Management Co. (World Investors)			13.3		1.4	2.5		0.6	
Capital Research & Management Co. (Global Investors)			10.8	5.6					
Fidelity Investments Canada ULC				2.2					
Fidelity Management & Research Co. LLC	0.9		4.8	5.0					
GIC Pte Ltd. (Investment Management)									7.9
Vanguard Investments Australia Ltd.		0.6							
The Vanguard Group, Inc.	1.1	2.5	2.1	7.8	2.7	1.3	1.9		3.2
Total shares	**4.2**	**4.7**	**36.9**	**22.7**	**8.5**	**4.6**	**2.8**	**0.6**	**17.1**

The initial stages of mining are the same for both open-pit and underground mines: blasting, hauling, and crushing. The subsequent ore processing is carried out by several specialized companies but typically follows the process illustrated in Figure 3-7.

Copper production from oxide ore involves the following treatment steps: (i) heaps of crushed ore are sprayed with sulphuric acid, which penetrates the ore heap and dissolves copper oxide minerals (heap leaching); (ii) the copper-rich liquid is collected, and the copper solution is separated (Solvent Extraction) (60-70 % Cu); and (iii) subsequent electrolysis treatment produces cathode copper (99.9 % Cu). Copper production from sulphide ore includes the following treatment steps: (i) copper-bearing sulphide minerals are separated from other minerals in the ore into a copper concentrate, a tradable commodity; the discarded minerals form a by-product deposited in tailings basins; (ii) smelting of copper sulphide minerals (at approximately 1,300 °C), resulting in copper matte (58-60 % Cu); (iii) copper matte is processed in a converter furnace where remaining iron and sulphur are removed, resulting in blister copper (98 % Cu) and anode copper (99 % Cu); 'impurities' that emerge in step (ii) may contain commercial by-products, which are subsequently treated separately; and (iv) electrolytic treatment of anode copper, yielding cathode copper (99.99 %), used in the production of plates, pipes, cables, etc.

Copper scrap and alloys are recycled through (i) melting and (ii) purification of impurities from the scrap material.

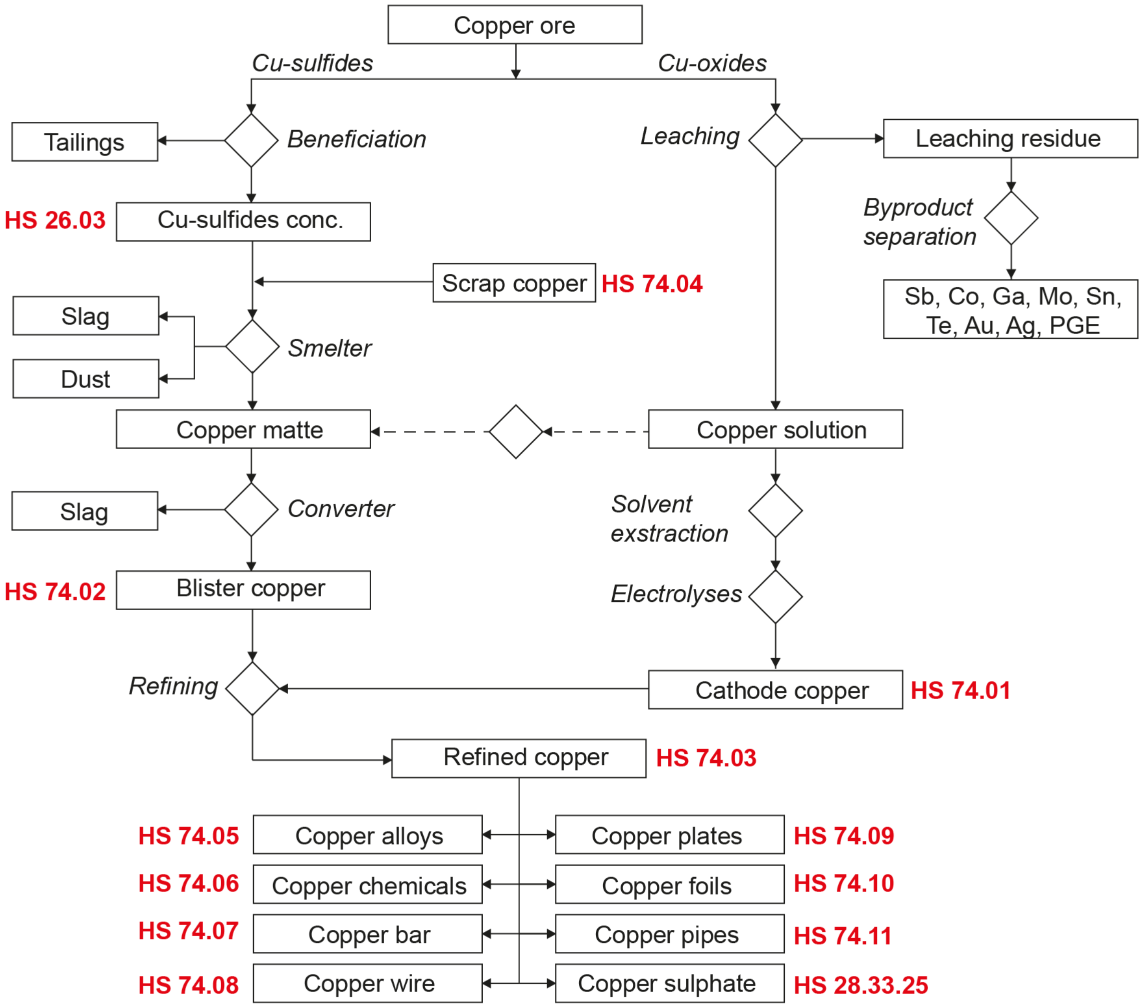


Figure 3-7 *Generic process diagram for the copper supply chains, indicating some of the common trade goods (HS codes).*

China dominates the processing of copper; 10 of the 20 largest refining facilities are located in China, including four of the top five, with a combined capacity of approximately 7 million ton, equivalent to about 33 % of global capacity. Three of the 20 largest facilities, with a total capacity of approximately 1.6 million ton, are owned by the Chilean state (Bell 2021). New copper refining facilities are expected to be established, especially in Chile, Peru, and Mexico, as well as in Asia in China, Japan, and India (Businesswire 2022).

3.4.5 Climate and Environmental Impact

The carbon footprint of copper varies depending on the ore type, the amount of copper scrap added, the production method (although the choice of method is mainly linked to the ore's mineralogy), and the energy source. Several analysts estimate that copper contributed to 0.2-0.3 % of global CO_2 emissions in 2022. The emission per ton of refined copper is calculated to be approximately 4 ton of CO_2e (Carbon Chain 2023), which is significantly higher than that for steel. The copper emission can be divided into about 1 ton of CO_2e to produce copper concentrate, while the subsequent processing steps constitute about 3 ton of CO_2e (Carbon Chain 2023). This breakdown includes 80 % processed using pyrometallurgical methods and 20 % using hydrometallurgical methods. Additionally, recycled copper accounts for about 40 % of the total copper production. Isolated from other factors, the environmental impact of using copper scrap is estimated to be in the range of 0.2-1.9 ton CO_2e per ton Cu.

Moreno-Leiva *et al.* (2019) have estimated the distribution of energy consumption in copper production, revealing that the pyrometallurgical method is 20 % more energy-intensive than the hydrometallurgical method (see Table 3-6).

Water consumption varies significantly based on mineralogy, method, and location, but accurate data on this aspect have not been found.

Table 3-6 *Overview of energy consumption for the production of copper. Based on The Warren Centre (2020).*

Pyrometallurgical route				Hydrometallurgical route			
Type of energy	**GJ/t**	**Process**	**GJ/t**	**Type of energy**	**GJ/t**	**Process**	**GJ/t**
Diesel	17	Mining	10	Diesel	11	Mining	10
Electricity	20	Melting	9	Electricity	13	Hydrometallurgy	14
		Concentrating	13				
		Refining	5				
Total	**37**	**Total**	**37**	**Total**	**24**	**Total**	**24**

3.5 Trade

Global trade in copper ore and copper articles amounted to approximately USD 377 billion in 2020, making it one of the most traded commodities. An overview of some of the key product categories is presented in Table 3-7. The trade of individual product categories has seen significant fluctuations over the past 20 years in response to varying demand, the global economy, and fluctuations in LME copper prices during the period (Figure 3-5). Data indicate, *inter alia*, a generally increasing trend in the trade of copper concentrate and raw copper over the period, whereas the trade of several categories of processed products has declined. This can probably be attributed to China's increasing acquisition of unprocessed raw materials, which are processed and consumed in China. Copper thus traded and consumed will contribute significantly to the export of product categories other than those directly related to copper. Some of the key trade relationships for selected copper products are shown in Table 3-8 to Table 3-13 and in Sankey diagrams in Figure 3-8 to Figure 3-13. The value chains for copper are characterized by a few countries and a small number of companies dominating both mining and the initial stages of ore processing. China plays a dominant role in importing these products, including copper scrap, which is subsequently processed.

There are significant differences in the trade patterns among the four largest primary copper-producing countries: Chile, Peru, China, and the DR Congo, which collectively produced about two-thirds of the global production in 2020. Peru primarily exports copper in the form of mineral concentrates (HS 26.03); Chile is the world's largest exporter of copper mineral concentrates and also has a significant export of blister copper (HS 74.01); DR Congo's exports are dominated by refined copper (HS 74.03); and China has no significant export of copper but is the world's largest importer of copper mineral concentrates (HS 26.03), blister copper (HS 74.02), refined copper (HS 74.03), and copper scrap (HS 74.04).

Among the top 10 companies involved in copper trade, four are Chinese owned (Jiangxi Copper, Golden Dragon, Ningbo Jintian Group, and Tongling Nonferrous Metal), and three are German companies (Aurubis, Wieland, and Mueller Industries).

Table 3-7 *The main copper commodity groups and their associated export values for 2020. Source: OEC World (2023).*

Commodity	HS2	Export (M. USD)	HS4	Export (M. USD)	HS6	Export (M. USD)
Copper ore (and concentrates)			26.03	61,300		
Copper articles	74	161,000				
Precipitated copper			74.01	1,230		
Copper matte					74.01.10	1,230
Cement copper (precipitated)					74.01.20	-
Raw copper (=unrefined copper), Cu-anodes, electrolyte refined Cu			74.02	14,400		
Refined copper			74.03	71,800		
Scrap copper			74.04	19,200		
Copper alloys			74.05	413		
Copper powder			74.06	1,000		
Copper bars			74.07	5,000		
Copper wire			74.08	16,800		
Copper plating			74.09	7,000		
Copper foil			74.10	6,600		
Copper pipes			74.11	6,400		
Copper housewares			74.18	700		
Other copper products			74.19	3,400		
Copper sulphate					28.33.25	600
		161,000		**215,243**		**1,830**

Table 3-8 *The four largest exporting countries and their three largest importing countries for copper ore concentrate (HS4 26.03) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Chile	21,400	China Japan South Korea	13,100 3,782 1,257
Peru	9,227	China Japan South Korea	5,864 1,041 953
Australia	3,845	China Japan South Korea	1,376 1,131 656
Canada	3,115	Japan China South Korea	805 769 568
Total	61,827		

Table 3-9 *The four largest exporting countries and their largest recipient countries for precipitated copper (HS4 74.01) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Finland	370	Russia	354
		Japan	13
		Germany	4
Chile	163	Russia	151
		South Korea	12
		Cambodia	1
Canada	144	Norway	75
		South Korea	36
		Bulgaria	20
Mexico	76	South Korea	38
		Russia	19
		Belgium	14
Total	1,222		

Table 3-10 *The four largest exporting countries and their largest importing countries for raw copper/blister copper (HS4 74.02) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Zambia	5.8	Switzerland	2.3
		China	1.2
		Namibia	1.1
Chile	1.9	China	1.1
		Canada	0.4
		South Korea	0.3
Namibia	1.4	China	0.9
		Belgium	0.2
		Germany	0.1
Bulgaria	1.0	Belgium	0.6
		Germany	0.4
		Italy	-
Total	14.4		

Table 3-11 *The four largest exporting countries and their largest importing countries for HS4 74.03 Refined Copper in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Chile	14.5	China	7.1
		USA	2.6
		South Korea	1.2
DR Congo	11.1	China	4.1
		Tanzania	1.5
		Singapore	0.7
Russia	5.0	China	1.7
		Netherlands	1.7
		Turkey	0.4
Japan	4.7	China	1.9
		India	0.8
		Taiwan	0.8
Total	71.8		

Table 3-12 *The four largest exporting countries and their largest importing countries for HS4 74.08 Copper Wire in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Germany	2.521	Italy	486
		Poland	259
		Australia	238
United Arab. Emir.	1.671	Saudi Arabia	765
		India	277
		Oman	233
Russia	1.345	Kuwait	482
		Qatar	189
		South Africa	169
Canada	976	USA	965
		Nicaragua	4
		South Africa	2
Total	16.814		

Table 3-13 *The four largest exporting countries and their largest importing countries for HS4 74.04 Copper Scrap in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
USA	2,713	China	501
		South Korea	347
		Malaysia	325
Germany	1,521	Belgium	194
		Austria	184
		Poland	164
Japan	1,219	China	795
		Malaysia	229
		South Korea	70
Netherlands	990	Germany	445
		Belgium	191
		Russia	101
Total	19,233		

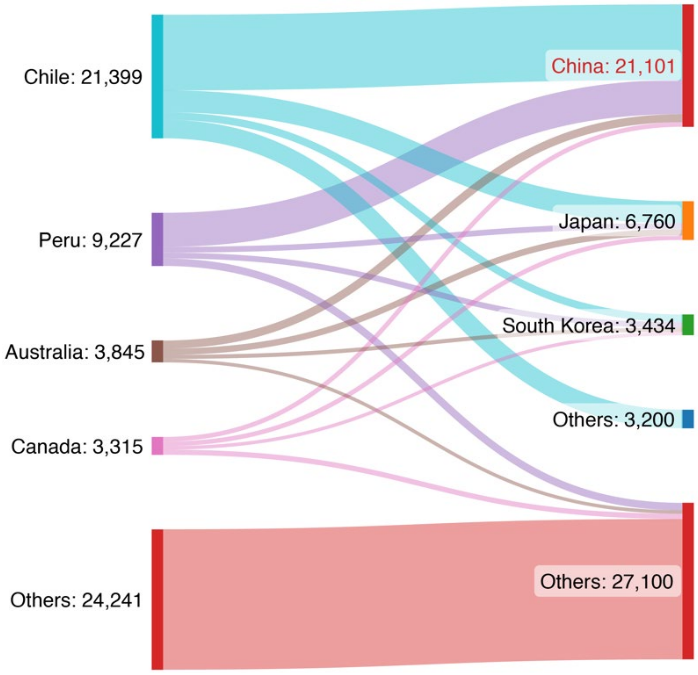


Figure 3-8 *Sankey diagram for the main exporting and importing countries in 2020 for HS4 26.03 copper ore concentrate. All values in million USD, based on data from Table 3-8.*

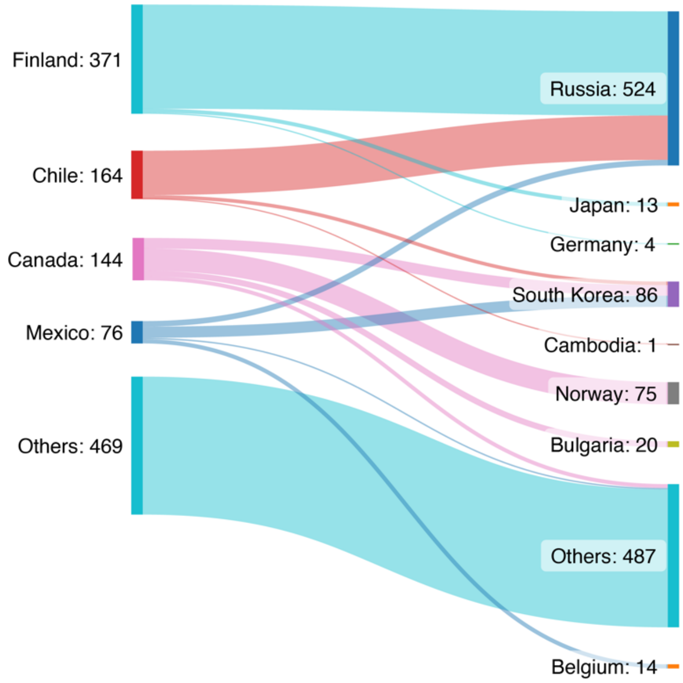


Figure 3-9 *Sankey diagram for the main exporting and importing countries in 2020 for HS4 74.01 precipitated copper. All values in million USD, based on data from Table* 3-9*.*

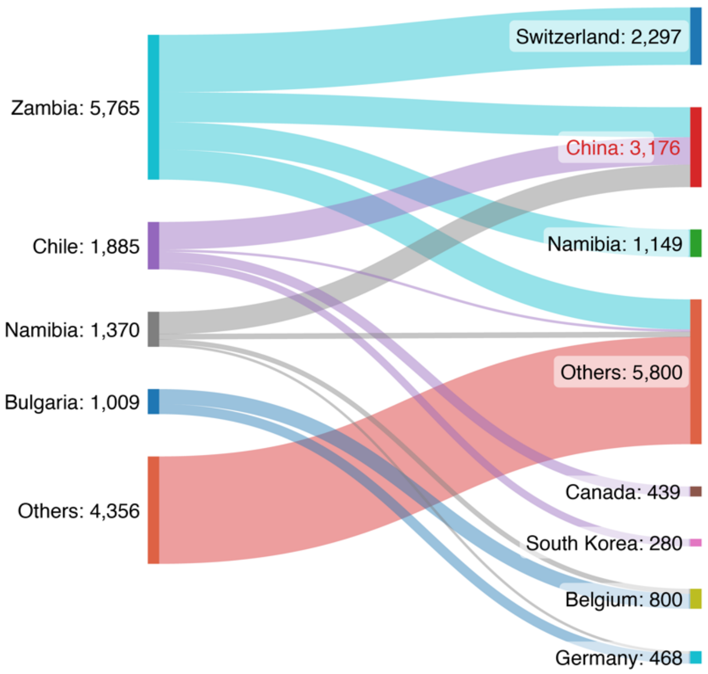


Figure 3-10 *Sankey diagram for the main exporting and importing countries in 2020 for HS4 74.02 unwrought copper (blister copper). All values in million USD, based on data from Table 3-10.*

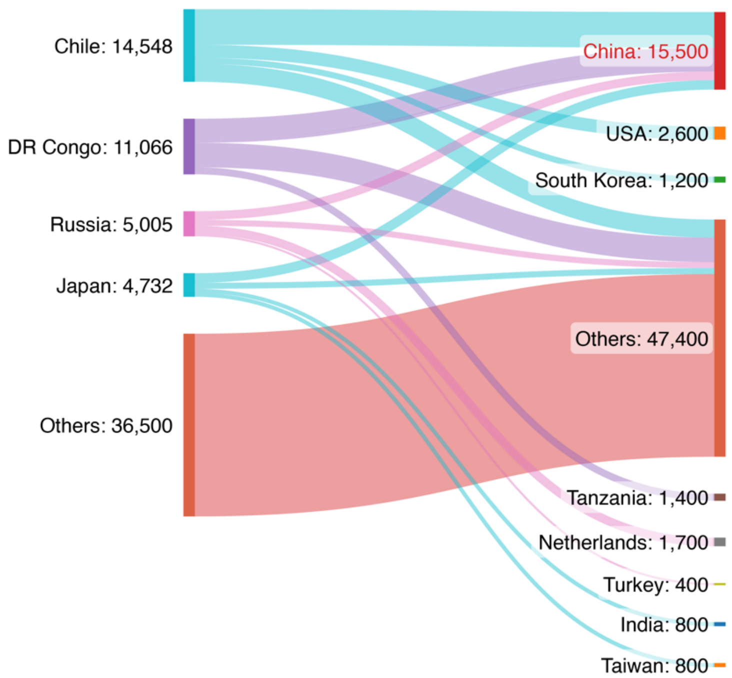


Figure 3-11 *Sankey diagram for the main exporting and importing countries in 2020 for HS4 74.03 refined copper. All values in million USD, based on data from Table 3-11.*

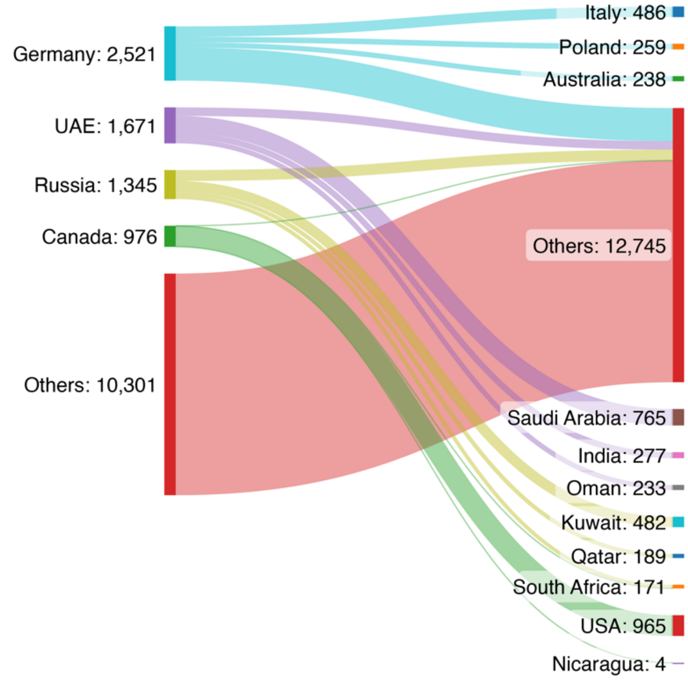


Figure 3-12 *Sankey diagram for the main exporting and importing countries in 2020 for HS4 74.08 copper wire. All values in million USD, based on data from Table 3-12.*

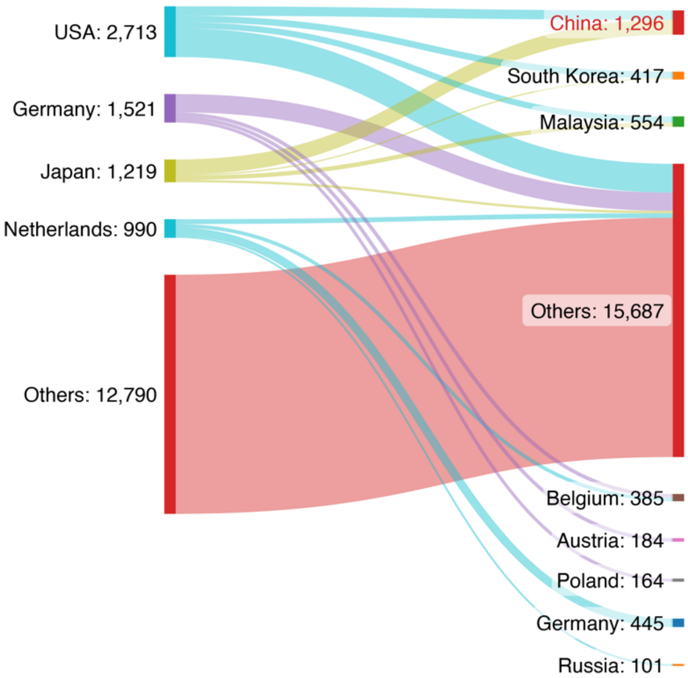


Figure 3-13 *Sankey diagram for the main exporting and importing countries in 2020 for HS4 74.04 copper scrap. All values in million USD, based on data from Table 3-13.*

3.5.1 Prices

Over the period 2000-2020, copper prices have increased by approximately 350 %, with significant declines during the recession periods of 2008-2010 and again from 2012 to 2017 (Figure 3-14). Markets anticipate rising prices in the coming years, driven by the strong growth in demand resulting from the green transition. This trend may also be enhanced by increasing costs of mineral exploration and initiation of new mines (see section 3.4.2 Global Copper Reserves).

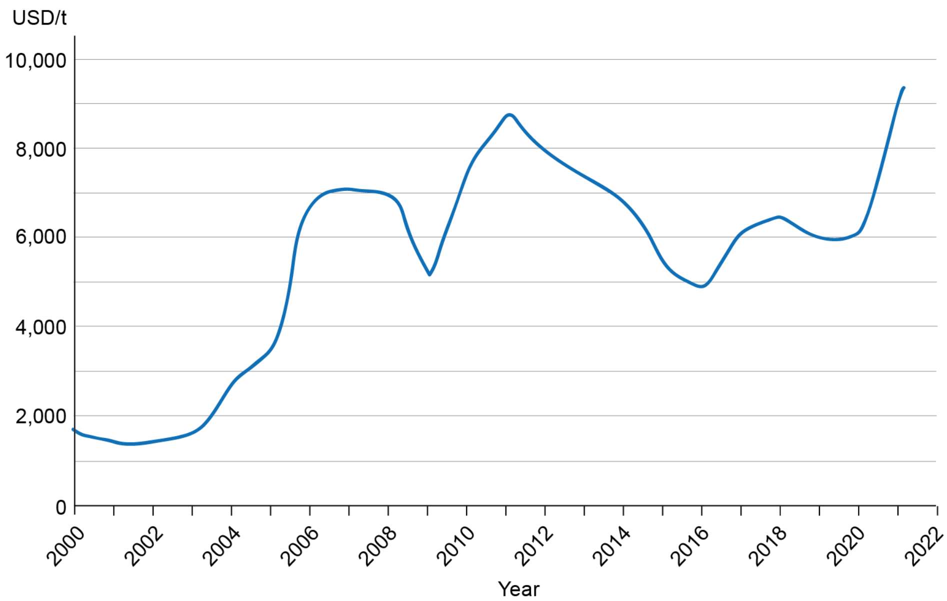


Figure 3-14 *Copper prices (USD/ton) for the period 2000-2021. Source: DeCoff (2022).*

3.6 The Danish Consumption

Copper is one of the most important mineral resources for Denmark, holding significant economic importance for the Danish industry. In 2019, both primary and secondary industrial purchases of copper amounted to 48.4 billion DKK, providing employment for approximately 30,000 persons in the Danish industry (Clausen *et al.* 2023). Copper ranks second in terms of its contribution to the derived gross value added of mineral resources used in Denmark, surpassed only by iron (Figure 3-15). In Denmark, copper is predominantly utilized within the manufacturing industry (about 67 % of purchases) and the construction sector (about 29 % of purchases). It is a key component in material-complex products, accounting for approximately 92 % of all purchases (Clausen *et al.* 2023). Typical products include machinery, pumps, vehicles, copper alloys, electronics, electric motors, and transformers. Copper is also a critical raw material for various technologies in the green energy transition, where it is used in generators, heat exchangers, and electric transmission.

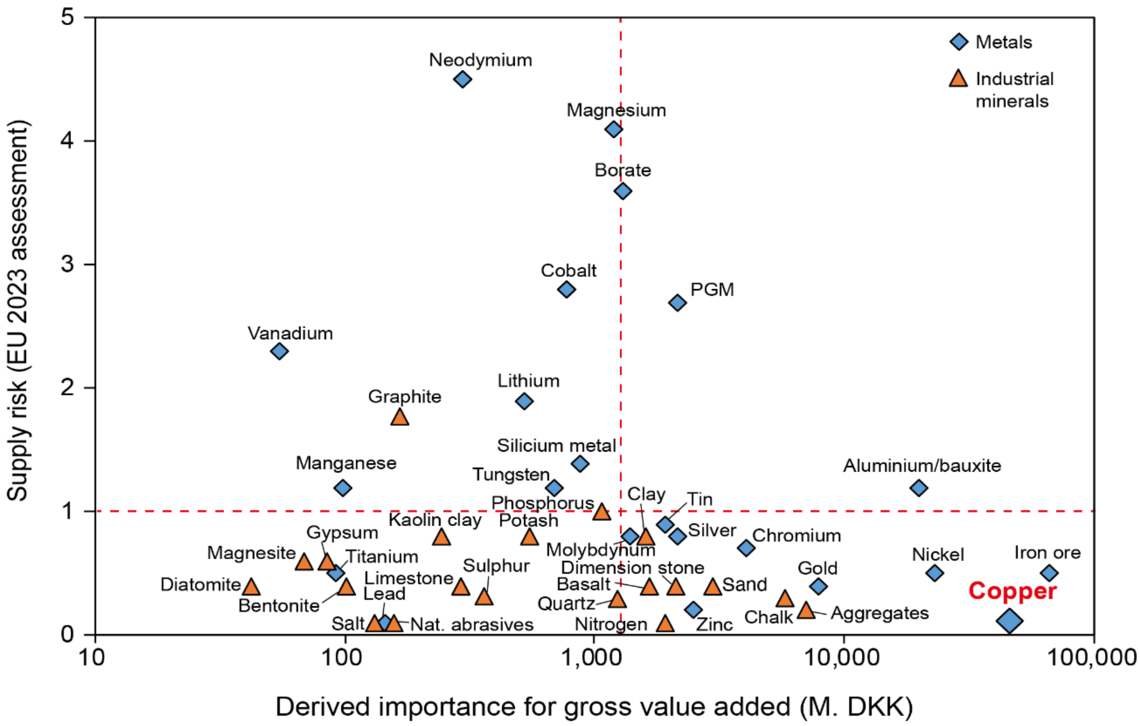


Figure 3-15 *The derived significance of copper and other raw materials for gross value added as a function of supply risk. The figure is modified after Clausen* et al. *(2023).*

3.7 Perspectives

Chile produces approximately 23 % of the world's copper ore and, along with Australia, Peru, and Russia, contributes to 50 % of global production. The remaining production is distributed among many countries, with about half of it occurring in politically unstable nations.

Out of nearly 240 active copper mines globally (McNaulty *et al.* 2022), 20 mines, owned or controlled by a handful of mining companies such as Anglo American, Antofagasta, BHP Billiton, Codelco, Glencore, MMC Norilsk Nickel, and Tech Resources, produce about 30 % of the world's copper ore. Several of these companies, along with major Chinese mining firms like CMOG Group, operate mines in multiple countries, including Peru, the DR Congo, and Zambia.

Despite the significant increase in copper production, global reserves have increased over the past 20 years. However, there have been only a few major new discoveries since 2010, and they are of relatively lower quality, leading to expectations of increased production costs in the future. It is uncertain if Chile can maintain its large production, as production reallocations and delayed initiation of new mines have adversely affected output. Further concerns are due to the lead time of 10 years or more to start new copper mines, and many significant discoveries made in the early 2010s are yet to enter production.

The European Commission (EC 2023) acknowledges the significant economic importance of copper (EI: 4.0) but considers supply risks in both copper ore production (SRE: 0.1) and processed copper (SRP: 0.1) to be low. Despite not meeting the technical criteria for this category, the European Commission has classified copper as a strategic raw material due to its substantial significance. Canada and China view copper as critical, while the USA, UK, Japan, and India do not consider copper as a critical raw material. It should be noted that criticality assessments are based on previous years' statistical data and cannot be used to assess future supply.

The production of copper commodities is spread across more than 200 smelters in various countries, with China having the largest capacity, including 10 of the world's smelters and ownership or co-ownership of smelters outside China (e.g., the Chuquicamata smelter in Chile). The global shift towards CO_2-free energy technologies, transmission networks, and electric transportation, driven in part by China's dominant supply chains, is expected to result in a demand for 37 Mt of copper in 2030 and 40 Mt in 2050, according to IEA (2023). This includes an estimated 10 % of recycled copper in 2030, increasing to 20 % in 2050. Other analysts anticipate copper demand to reach 50 Mt in 2035, potentially resulting in a production deficit of up to 10 Mt of copper ore (American Journal of Transportation 2022; Mills 2023). It is generally perceived that the global capacity for smelting and refining copper ore is not currently under significant challenge.

3.8 References

American Journal of Transportation 2022: Copper supply deficit of 6 million ton by 2030 threatens renewables, EVs, as investment lags demand. Posted by AJOT 14. Jan. 2022. (https://ajot.com/news/copper-supply-deficit-of-6-million-ton-by-2030-threatens-renewables-evs-as-investment-lags-demand)

BGS 2007: Commodity profile copper. http://www.bgs.ac.uk/downloads/directDownload.cfm?id=1410&noexcl=true&t=Copper%20

Bell, Terence 2021: The Largest Copper Smelters. ThoughtCo, August 11, 2021, www.thoughtco.com/the-20-largest-copper-refineries-2339744

Businesswire 2022: https://www.businesswire.com/news/home/20221214005580/en/Global-Copper-Market-Analysis-Report-2022-Mined-Copper-Production-Refined-Copper-Production-Consumption-First-Use-End-Use-Region-Size-and-Trends-with-Forecast-up-to-2027---ResearchAndMarkets.com

Carbon Chain 2023: Understand your copper emissions. https://www.carbonchain.com/blog/understand-your-copper-emissions#what-causes-coppers-emissions

Clausen, R. J., Kalvig, P., Keiding, J.K., Fold, N. & Vind, I. 2023: Dansk industris brug af mineralske råstoffer – økonomisk betydning og forsyningsudfordringer MiMa rapport 2023/2, pp. 181. https://doi.org/10.22008/gpub/32051

Copper Alliance 2022: ICA RecyclingBriesf-202201-A4-R2.pdf (https://copperalliance.org/wp-content/uploads/2022/02/ICA-RecyclingBrief-202201-A4-R2.pdf)

DeCoff, S. 2022: Copper discoveries – Declining trend continues. S&P Global Market Intelligence (2022), https://www.spglobal.com/marketintelligence/en/news-insights/research/copper-discoveries-declining-trend-continues

European Commission (EC) 2023: Study on the Critical Raw Materials for the EU 2023 – Final Report. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1ICA-Recycling Brief 2022: ICA-Recycling Brief (2022202201-A4 https://copperalliance.org/wp-content/uploads/2022/02/ICA-RecyclingBrief-202201-A4-R2.pdf).

Kalvman-Schueler, K. 2022: Copper substitution Survey 2022. DMM Advisory Group 2022; https://copperalliance.org/wp-content/uploads/2022/03/Substitution.pdf

McNulty, B.A., Jowitt, S. M. & Belousov, I. 2022: The importance of geology in assessing by- and coproduct metal supply potential; a case study of antimony, bismuth, selenium, and tellurium within the copper production stream. Economic Geology (2022) 117 (6): 1367-1385.

Mills, Rick 2023: The global copper market is entering an age of extremely large deficits. Mining.com, July 25, 2023 (https://www.mining.com/the-global-copper-market-is-entering-an-age-of-extremely-large-deficits/)

Observatory of Economic Complexity World (EOC World) 2023: Database https://oec.world/

Recycled Copper Market 2023: Recycled Copper Market Outlook 2031. Company website: https://www.transparencymarketresearch.com/recycled-copper-market.html

Rosa, D. Kalvig, P. Stendal, H and Keiding, J.K. 2023: Review of the critical raw material resource potential in Greenland. MiMa rapport 2023/1, 121 pp. https://doi.org/10.22008/gpub/32049

Stensgaard, B.M., Kalvig, P. & Stendal, H. 2011: Quantitative mineral resource assessment: Sediment-hosted copper in Greenland. Danmark og Grønlands Geologiske Undersøgelse Rapport 2011/104,170 pp. https://doi.org/10.22008/gpub/28832

Thaarup, S.M. 2017: Kobber. MiMa faktaark. https://doi.org/10.22008/gpub/38041.

USGS 2000-2023: Mineral commodity summaries 2000-2023: U.S. Geological Survey https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries

Warren Centre 2020: Zero Emission Copper Mine of the Future. University of Sydney, May 2020, https://copperalliance.org/wp-content/uploads/2020/07/Emissions-Copper-Mine-of-the-Future-Report.pdf

4. Iron and Steel

4.1 Introduction

The element iron (Fe) with atomic number 26 is a widely distributed silver-grey, malleable, magnetic, and relatively heavy (7.8 g/cm³) metal. In its pure form, it melts at 1,538 °C and boils at 2,861 °C. Alloying with other metals can lower the melting and boiling points. Iron is predominantly used in the production of steel, a composite material consisting of iron, carbon, and alloying metals. Steel is a vital material in all modern societies, playing a role in the production of infrastructure, transportation, machinery, and various other industries. In 2022, more than 1,840 million ton of steel were produced, based on 2,600 million ton of iron ore, primarily from Australia and Brazil, and 600 million ton of iron scrap. China is by far the largest steel producer, and its consumption has increased by 1.7 % per year since 2000. Iron ore is not considered a critical raw material, and criticality assessments are not conducted for steel. However, the production of steel involves the use of several auxiliary materials, some of which are considered critical raw materials in the EU and other countries, posing potential challenges to steel supply chains. The World Economic Forum (2022) expects steel consumption to increase by approximately 30 % by 2050 compared to 2022, resulting in a total steel production of around 2,400 million ton. In this overview, iron and steel are treated as two separate productions.

Global steel production accounts for 7-11 % of the total annual CO_2 emissions (EU Parliamentary Research Service 2021, Hasanbeigi 2022). With the expected growth in steel consumption, numerous tests and implementations of emission-reducing methods are underway.

4.2 End-use and Consumption

In 2021, more than half of the total steel production was used for construction in buildings and infrastructure (52 %), followed by the automotive industry, trains, and ships (17 %), mechanical equipment (16 %), metal products (10 %), electrical equipment (3 %), and household appliances (2 %) (Figure 4-1). There are significant variations from country to country, with nations having large iron and steel-consuming industries and extensive infrastructure using the most. Hence, in 2020, China consumed 58 % of the steel production, while Other Asia (9 %), EU-28 (8 %), USMCA (6 %), India (5 %), CIS (3 %), Japan (3 %), Africa (3 %), Middle East (3 %), Australia and New Zealand (0.3 %), and others (2 %) consumed the remaining about 850 million ton steel that year (World Steel 2021).

Several classification types are used for steel, typically based on (a) the material's chemical compositions (carbon and alloying metals content), (b) their form and function, or (c) the physical properties of the steel. Most divisions are based on the following four main types: carbon steel, alloy steel, stainless steel, and tool steel.

The term steel originally covers iron mixed with variable proportions of carbon, 0.05-2.1 %C. Here, we use '*carbon steel'* to separate this material from other types of steel. For buildings and infrastructure, subtypes belonging to the group of low-carbon carbon steel are primarily used, making it the most produced type.

Alloy steel contains one or more of metals such as aluminium, copper, nickel, titanium, manganese, etc., typically constituting >5 %. It is used where there is a need for a corrosion-resistant material that can be processed.

Stainless steel, containing 10-20 % chromium, nickel, and molybdenum, is non-corroding and used for applications such as food equipment, medical instrumentation, and maritime products. In 2022, the production of stainless steel was 55 million ton.

Tool steel is used where a material with high wear resistance is needed; this type of steel is characterized by containing alloying metals such as cobalt, tungsten, molybdenum, and vanadium.

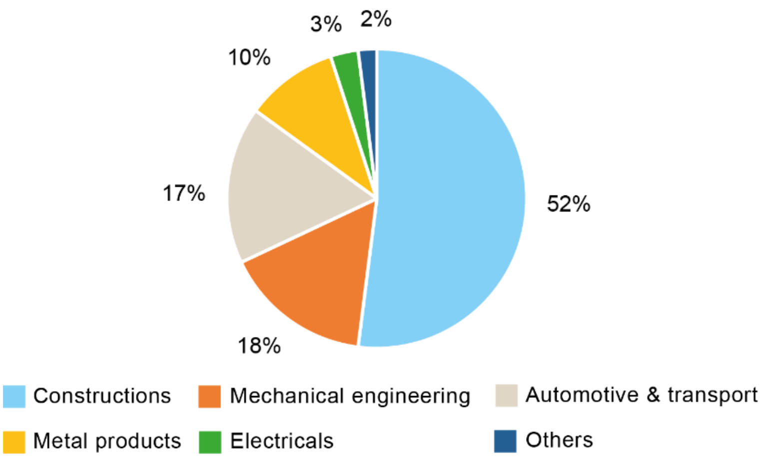


Figure 4-1 *Applications of steel by percentage in 2020. Source: Statista (2022).*

4.3 Recycling and Substitution

Iron scrap is highly sought after as a raw material to produce new iron and steel products. There are significant resource gains, using scrap for steel production. Manufacturing 1 ton of steel from iron scrap saves 1.4 ton of iron ore, 0.8 ton of coal, 0.3 ton of limestone, plus additives. In addition, CO_2 emissions are reduced by 1.7 ton, and water consumption is reduced by 40 % (Scrreen2 Iron ore factsheet 2023). According to Arcelormittal (2023), approximately 85-90 % (EoL-RR) of all steel is recycled globally. However, the recycling rate varies between different sectors and is around 50 % for electrical appliances, 85 % for construction, and up to 90 % for the automotive and machinery industries (Allwood 2016).

Although the recycling of iron and steel already covers a significant portion of global consumption and can be further optimized, the available quantities of iron scrap are insufficient to meet the raw material needs to produce new steel. This is because global steel consumption generally increases by 1-2 % per year, the lifespan of scrap is 40 years, and the collection efficiency is significantly below 100 %, and it will never be perfect.

In 2030, it is expected that there will be approximately 600 million ton of scrap available, with around 30 % from North America, the EU, and Japan, while 25 % is from China. Towards 2050, the scrap quantities in Western countries will be in the same order of magnitude as today, while especially China's scrap quantities will grow, resulting in approximately 900 million ton of iron scrap available for steel production in 2050 (Figure 4-2). Certain metals, such as copper, cannot be separated from iron scrap and therefore cannot be recycled. Additionally, an elevated copper content can deteriorate steel quality over time, affecting how the steel subsequently can be used.

In the production of steel, it is not possible to substitute iron with other metals. To reduce iron consumption and decrease the carbon footprint, development efforts are more focused on replacing steel with other materials, including wood and concrete for construction projects, as well as composite and lightweight metal materials for other sectors, including transportation and machinery industries.

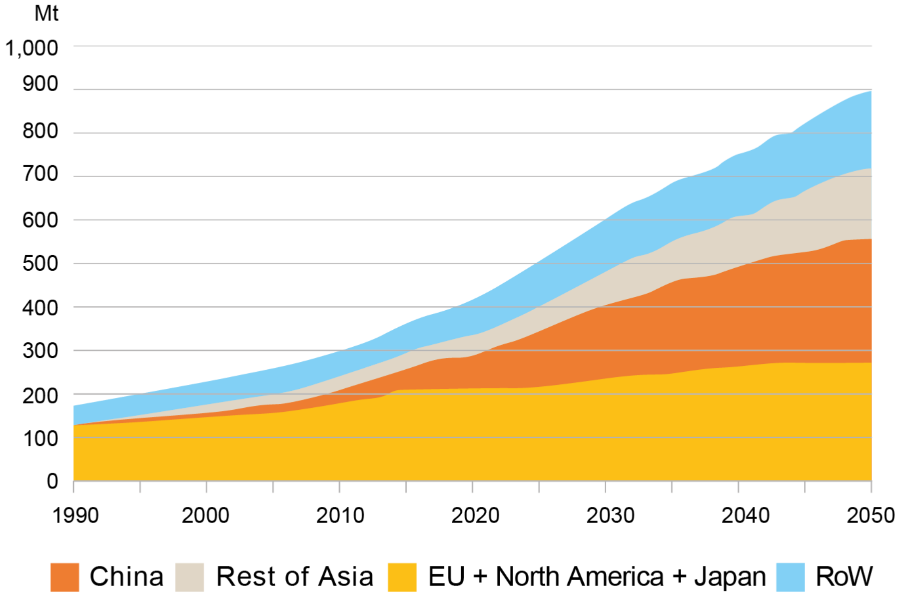


Figure 4-2 *Expectations for the demand for iron scrap until 2050. Source: World Steel Association (2022).*

4.4 Global Supply

4.4.1 Geology

Iron ore is exploited from deposits in sedimentary, igneous, and metamorphic geological environments. Deposits of sedimentary banded iron formations (BIF) are the most important type of iron ore and are mined to extract the iron-rich minerals magnetite and hematite. Some of the largest BIF deposits are known in Brazil, Australia, India, and the USA; in Greenland, the Isua iron ore deposit belongs to this group. Gold is extracted in some places as a by-product from BIF deposits.

Iron is found in a wide range of minerals, with iron oxides, especially hematite, magnetite, and titanomagnetite, being the most important as they contain the highest iron content (Table 4-1); the most commonly used processing methods are outlined in Figure 4-8 and discussed in section 4.4.4 Global Steel Production.

Magmatic iron ore deposits are divided into IOA (Iron-Oxide-Apatite) and IOCG (Iron-Oxide-Copper-Gold) deposits, where magnetite, titanomagnetite, and hematite are the dominant iron ore minerals in these types. IOA and IOCG deposits are exploited especially in South America, Asia, Africa, and Australia; in Sweden, Kiruna and Grängesberg are also of this type. Copper and gold (IOCG), rare earth elements (REE), gold, silver, and cobalt are by-products utilized in several locations.

Table 4-1 *Overview of the most used minerals to produce iron and steel.*

Mineral	Mineral formula	Iron content (wt. %)	Importance	Iron ore type
Hematite	Fe_2O_3	70	Important	Sedimentary (BIF), magmatic; and metamorphic
Magnetite (titano-magnetite)	Fe_3O_4 ($Fe(Fe,Ti)_2O_4$	60-70	Important	Sedimentary (BIF) and metamorphic
Limonite	$FeO(OH)nH_2O$	40-60	Previously used in Europe	Sedimentary
Siderite	$FeCO_3$	30-48	Marginal	
Goethite	FeO(OH)	<60	By-product; not important	Sedimentary
Chamosite	$(Fe_2, Mg)_5Al(Si_3Al)O_{10}(OH,O)_8$	low	By-product; not important	
Pyrite	FeS_2	45-53	Marginal	Sedimentary, magmatic; and metamorphic

4.4.2 Global Iron Ore Reserves

Assessments of global ore reserves are dynamic and generally not precise, as they are influenced in both upward and downward directions by contributions from new mineral exploration, iron ore prices, costs, and potential technological advancements. From 2000 to 2020, global iron ore reserves increased from approximately 140 to 183 billion ton, with the majority located in Australia, Brazil, Russia, and China (Table 4-2) (USGS 2020-2023). However, since iron ore production has increased during this period, the number of years the reserves will last in relation to demand in the reporting year has been reduced by approximately 50 %, from 140 production years in the year 2000 to 69 years in 2022.

Table 4-2 *The development in iron ore reserves from 2000 to 2021. Source: USGS (2000-2022).*

Reserves (x1.000.000 ton)	2000	2005	2010	2015	2021
USA	10,000	6,900	6,900	11,500	3,000
Australia	18,000	15,000	24,000	54,000	51,000
Brazil	7,600	23,000	29.000	23,000	34,000
Canada	1,700	1.700	6,300	6,300	6,000
China	25,000	21,000	23,000	23,000	20,000
India	2,800	6,600	7,000	8,100	5,500
Iran	n.a.	1,800	2,500	2,700	2,700
Kazakhstan	8,300	8,300	8,300	2,500	2,500
Mauretania	700	700	1,100	n.a.	n.a.
Mexico	n.a.	700	700	n.a.	n.a.
Russia	20,000	25,000	25,000	25,000	29,000
South Africa	1,000	1,000	1,000	1,000	1,000
Sweden	3,500	3,500	3,500	3,500	1,300
Ukraine	22,000	30,000	30,000	6,500	6,500
Venezuela		4,000	4,000		
Others	17,000	11,000	11,000	18,000	18,000
Total	**137,600**	**160,200**	**183,300**	**185,100**	**180,500**

Figure 4-3 shows the geographical distribution of the world's largest iron ore reserves.

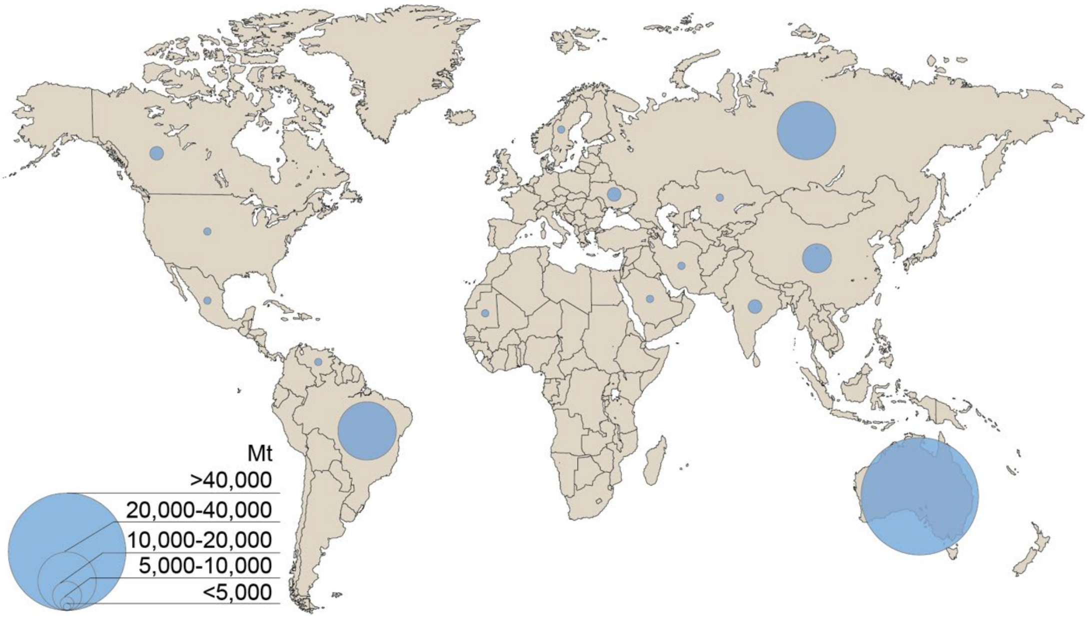


Figure 4-3 *Geographic distribution of the largest iron ore reserves in 2021. Source: USGS (2022).*

Significant new iron ore mining projects are under development/establishment in Australia (including Iron Bridge Project, Hawsons, CEIP, Eliwana, South Frank, Koodaideri), West Africa (Simandou and Nimba in Guinea, Tonkolili in Sierra Leone, Baniaka in Gabon), and Brazil (including Jiboia, Capanema, and Jambreiro). Deposits with high iron content (>65 %) are particularly attractive, since they allow iron and steel plants to replace Basic Oxygen Furnace (BOF) treatment with Direct Reduced Iron (DRI) followed by Electric Arc Furnace (EAF), which is less carbon dioxide-intensive (see section 4.4.4 Global Steel Production). However, only a few of the upcoming projects meet this requirement, which may delay the reduction of carbon emissions from steel production (S&P Global 2022).

4.4.3 Global Iron Ore Production

In 2022, approximately 2.6 billion ton of iron ore were produced; it was primarily extracted in Australia (33 %), Brazil (15 %), China (14 %), and India (11 %). Sweden was the only European producer, contributing with 1 %.

Iron ore production grew by around 200 % in the period from 2000 to 2015 and has increased by about 2 % per year, with China being the dominant producer. After 2015, China's production was significantly reduced over a few years (Figure 4-4), which was compensated for by increased production elsewhere, particularly in Australia. From 2012 to 2016, Australia experienced strong growth in production, and it has been the largest producer of iron ore since 2016. The substantial drop in China's iron ore production in 2015-2016 is attributed to a significant price decline in iron ore from 2014 to 2016, leading to the closure of some private iron mines in the Anhui and Shandong provinces (S&P Global 2016). MiMa considers it likely that the reduction in China's iron ore production is also related to changed industrial strategies, where China increasingly outsources raw material supply and expands/develops the middle and lower parts of the value chains. China's iron ore supply security is tied to financial and technical agreements with foreign mining companies.

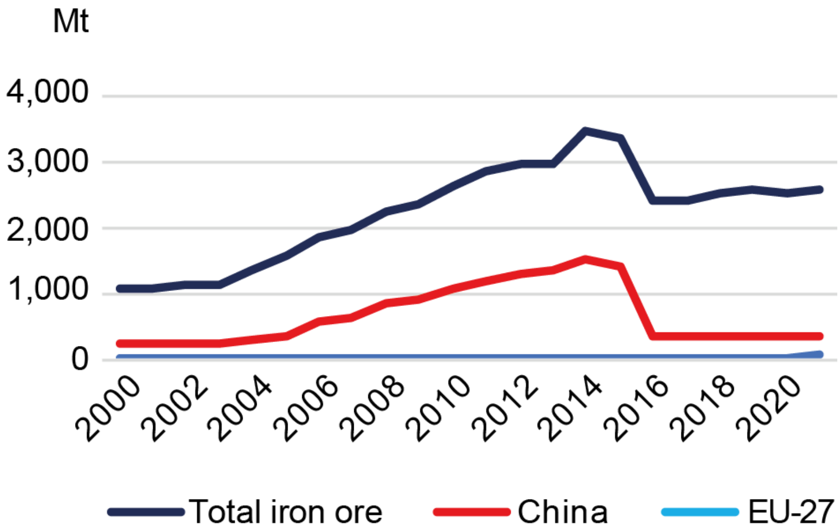


Figure 4-4 *Iron ore production in the period 2000-2021. Source: USGS (2000-2022).*

Figure 4-5 shows the geographical distribution of iron ore production in 2022, and Figure 4-6 illustrates the geographical distribution of raw steel production in 2022.

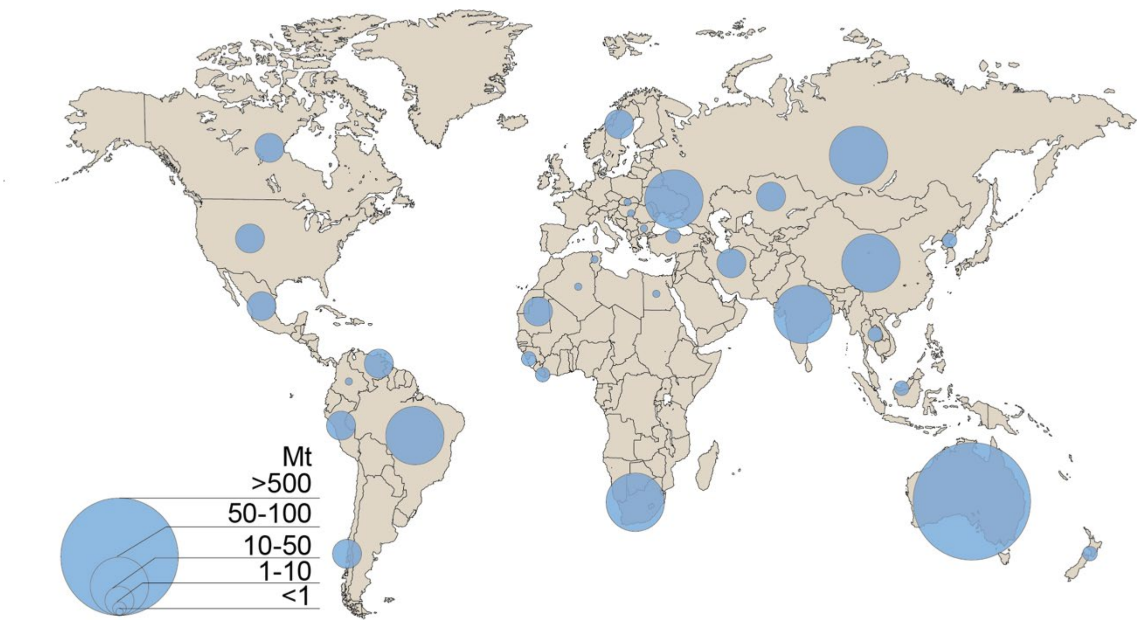


Figure 4-5 *Geographic distribution of iron ore production in 2022. Source: USGS (2023).*

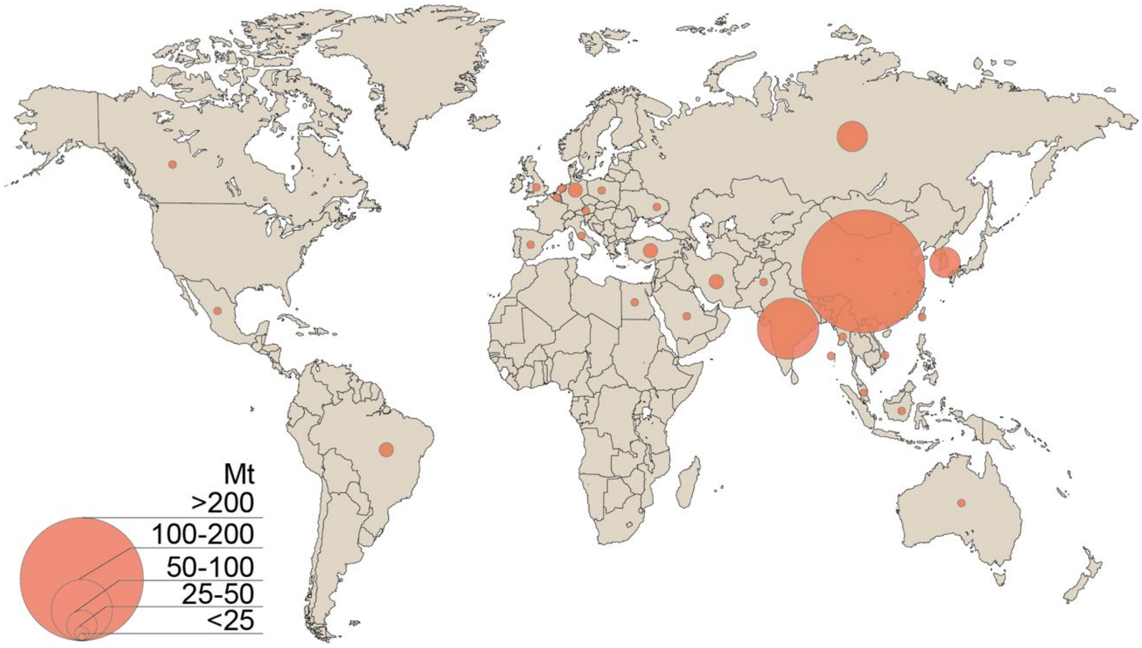


Figure 4-6 *Geographic distribution of raw steel production in 2022. Source: World Steel Association (2023).*

4.4.3.1 Iron Ore Mining Companies

The 20 largest iron mines, with a combined production of approximately 1.2 billion ton of iron ore, are controlled by 10 mining companies. The three largest companies, Rio Tinto (26 %), Vale (24 %), and BHP (22 %), accounted for almost three-quarters of iron ore production in 2021 (Table 4-3). The dominant companies are geographically concentrated, with BHP operating iron ore mines only in Australia, Vale and Anglo America operating exclusively in Brazil, while Rio Tinto deviates from this pattern by operating in both Australia and Canada. Russian iron ore production reached 61 million ton in 2021 and was produced by the companies Metalloinvest and Novolipetsk. Ownership structures for the four largest companies are dominated by investment and venture companies, several of which have significant stakes in multiple companies. Rio Tinto, as mentioned before, deviates from other major Western companies as almost 15 % is owned by Aluminium Corporation of China Ltd (Chinalco); the ownership of Fortescue Metals, Metalloinvest, and Novoliletsk is dominated by a few individuals.

All four major Western iron ore producers have established significant vertically integrated value chains for iron and steel production. There is no available breakdown of major mining companies' customer relationships, including the extent to which iron ore producers supply their own or other iron and steel mills in the country where the ore is mined. However, export records indicate significant exports of iron ore concentrate to China, primarily from Australia and Brazil (see section 4.5 Trade), where it is incorporated into Chinese value chains. China's substantial need for iron ore is met partly by domestic production and partly by large quantities of iron ore produced by a few Western companies, especially in Australia and Brazil.

Table 4-3 *Geographical and capacity overview of the 20 largest iron ore producers in the Western world. Mining Intelligence Data (2022).*

Iron ore mine	Country	Owner	2021 (Mt)	2020 (Mt)
Hamersley Mines and Channar	Australia	Rio Tinto	207	220
Northern System	Brazil	Vale	185	192
Vargem Grand	Brazil	Vale	31	25
Fortescue Operation	Australia	Fortescue Metals	183	180
Paraopeba	Brazil	Vale	24	23
Mariana	Brazil	Vale	21	18
LKAB Group	Sweden	LKAB	27	27
Itabira	Brazil	Vale	24	23
Area C and Yandi	Australia	BHP Group	148	142
Newman and Jimblebar	Australia	BHP Group	132	147
Hope Downs and West Angelas	Australia	Rio Tinto	81	83
Robe Valley	Australia	Rio Tinto	26	30
Minas Rio	Brazil	Anglo American	23	24
Mont-Wright	Canada	ArcelorMittal	23	23
Sishen	S. Africa	Kumba Iron Ore	29	25
Lebendinsky	Russia	Metalloinvest	22	22
Mikhailovsky	Russia	Metalloinvest	19	18
Stoilensky	Russia	Novolipetsk Steel	20	19
Carol Lake	Canada	Rio Tinto	16	18
Minas Centrais	Brazil	Vale	20	16
Dataigou Mine	China	Glory Harvest Group	22	
Yuanjiachun mine	China	Taiyuan Iron & Steel Group	12	
Qidashan Mine	China	Anshan Iron & Steel Group	11	
Hujiamiaozi Mine	China	Ansteel Group	8	
Total			**1,261**	**1,275**

4.4.4 Global Steel Production

The global production of crude steel in 2022 was approximately 1,900 million ton (Mt) and has grown by almost 225 % since 2000, driven by general improvements in the world economy, population growth, urbanization, a growing transportation sector, and infrastructure developments – areas all characterized by significant steel consumption. A substantial portion of the demand growth is attributed to China, and the growth in production is also linked to China, where the share of global crude steel production has increased from around 15 % in 2000 to approximately 53 % in 2022.

Figure 4-7 illustrates the crude steel production from 1970 to 2022. The global steel production capacity has been around 30 % higher than the actual production in the past 20 years, and there is a tendency for this margin to increase (OECD 2023).

The metal iron is not mechanically strong or chemically robust, and thus has limited applications in its pure form. However, iron serves as the raw material for steel production. Steel refers to materials manufactured from raw iron (pig iron/hot metal iron/direct reduced iron) through a series of processes involving melting, addition of flux agents, alloying metals, casting, and rolling into plates, bars, or rods with specific mechanical, thermal, and chemical properties. These finished products are subsequently processed into final goods.

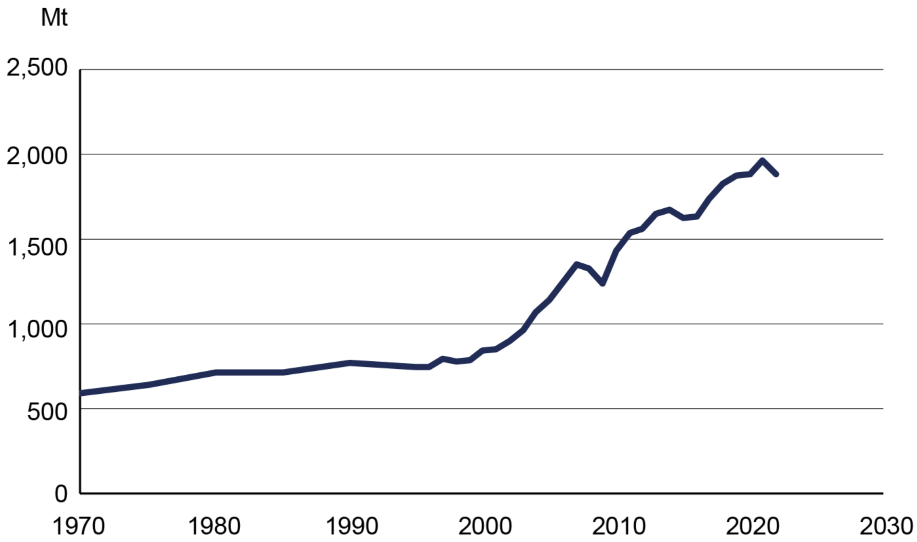


Figure 4-7 *Raw steel production in Mt in the period 1970-2022. Source: World Steel Association (1970-2023).*

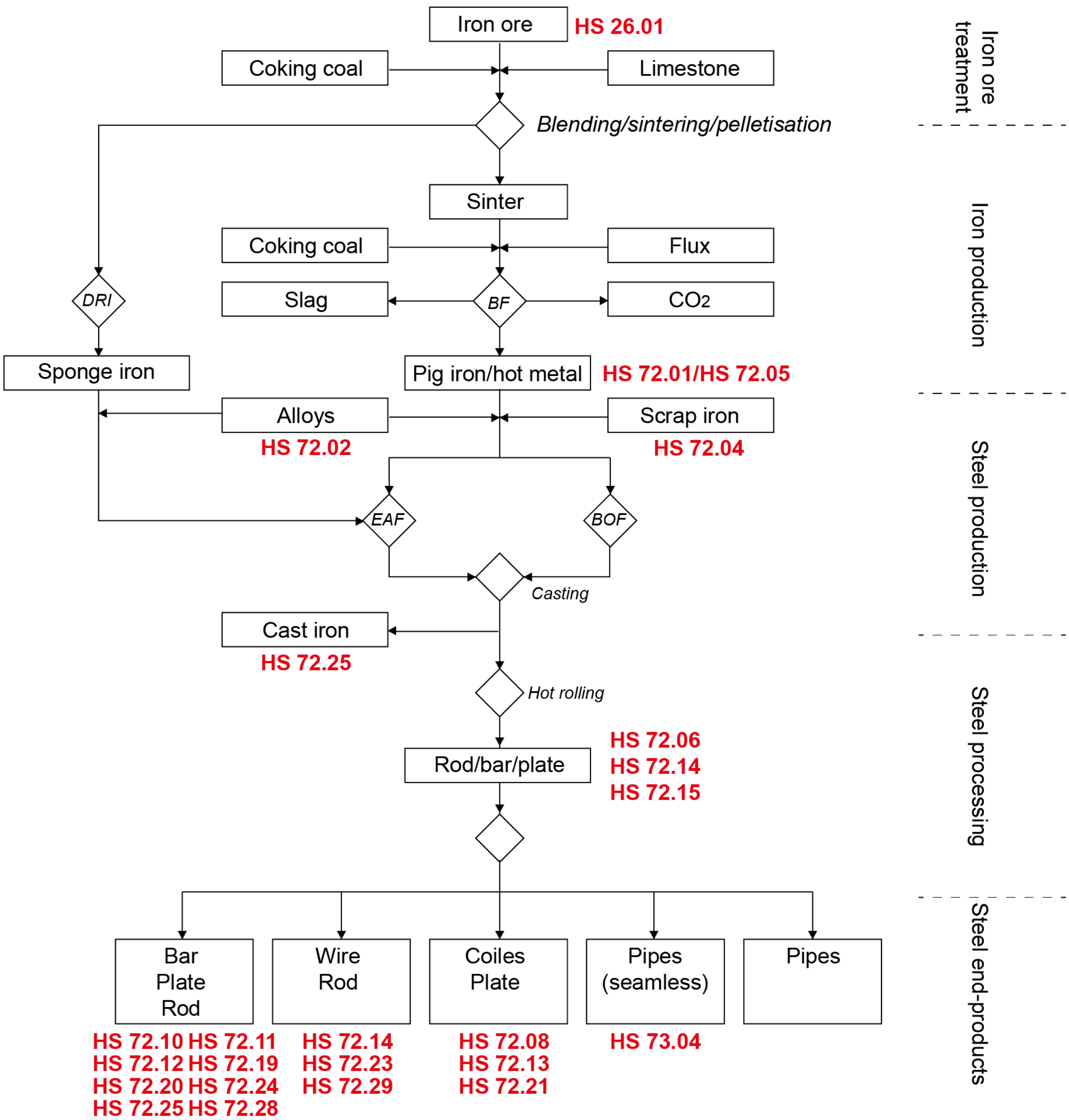
The initial treatment of iron ore involves crushing, after which the iron-bearing minerals are separated into a mineral concentrate. This treatment is commonly conducted at the mine, and only the iron ore concentrates are sent to smelters, where they are mixed with flux agents that act as aids in the reduction of iron oxide to iron and CO_2. Flux agents include carbon in the form of coking coal, graphite, or gas, as well as calcium and magnesium, often in the form of lime/dolomite, and possibly olivine, along with fluorine for adjusting the melt's pH. To produce 1 ton of pig iron, approximately 1.4 ton of sinter material, 0.5 ton of coking coal, and 0.25 ton of limestone/dolomite are used; about 0.3 ton of waste slag is generated in the process.

Subsequently, three different methods are employed in steel production (Figure 4-8):

- Integrated method: This involves using a blast furnace (BF) followed by treatment in an oxygen-blown furnace (Basic Oxygen Furnace (BOF)). To produce 1 ton of steel using this method, approximately 1.4 ton of iron ore, about 0.1 ton of iron scrap, around 0.8 ton of metallurgical coal, and about 0.3 ton of limestone are used.
- Electric Arc Furnace (EAF) method: Primarily uses iron scrap and directly reduced iron or molten iron from the BF. To produce 1 ton of steel, about 0.7 ton of iron scrap, approximately 0.6 ton of iron ore, about 0.15 ton of coal, and around 0.1 ton of limestone are used.
- Direct Reduction of Iron (DRI) method: Utilizes carbon monoxide (CO) and hydrogen (H) from natural gas or coal, where iron ore is reduced in solid form. Subsequently, EAF furnaces are typically used for the actual steel production. The DRI method is being phased in due to its lower environmental impact.

In 2021, the BOF method was used for approximately ⅔ of the global steel production, while the EAF method was used for the remaining ⅓. In China, steel production was distributed with approximately 9/10 using the BOF method and 1/10 using the EAF method. Globally, in 2021, around 1,400 Mt of steel were produced with the BOF method, using 1,300 Mt of pig iron/iron from BF and 240 Mt of iron scrap. Additionally, about 560 Mt of steel were produced with the EAF method, consuming around 60 Mt of pig iron/iron from BF, 120 Mt of directly reduced iron, and 450 Mt of iron scrap.

A generic process diagram for iron and steel processes, indicating some typical products, is shown in Figure 4-8; some of the key trade codes (HS codes) can be seen in the figure.



BF: Blast Furnace *BOF*: Basic Oxygen Furnace *DRI*: Direct Reduced Iron *EAF*: Electric Arc Furnace

Figure 4-8 *Generic process diagram for the manufacturing of iron and steel products, indicating Harmonized System (HS) codes for commonly traded commodities.*

4.4.4.1 Companies Involved in Production of Steel

Table 4-4 shows the 40 largest steel mills and their production in 2022. In 2022, the largest steel-producing countries were China (1,013 Mt), India (1,215 Mt), Japan (89 Mt), the USA (81 Mt), and Russia (72 Mt). However, unlike iron ore production, the steel industry is distributed among several hundred companies. Among these, the top 40 facilities collectively produced approximately 1,400 Mt of steel in 2022.

Table 4-4 *The 40 largest steel smelters and production in 2022. Source: World Steel Association (2023).*

Ranking	Steel and/or rolling plants	Country	Mt
1	China Baowu Steel Group	China	131.84
2	ArcelorMittal	Luxembourg	68.89
3	Ansteel Group	China	55.65
4	Nippon Steel	Japan	44.37
5	Jiangsu Shagang	China	41.45
6	Hesteel Group	China	41.00
7	POSCO	South Korea	38.64
8	Jianlong Steel	China	36.56
9	Shougang	China	33.82
10	Tata Steel	India	30.18
11	Shandong Iron and Steel Group	China	29.42
12	Delong Steel	China	27.90
13	JFE	Japan	26.20
14	Valin Steel Group	China	26.2
15	JSW Steel	India	23.4
16	Nucor Corporation	USA	25.7
17	Fangda Steel	China	20.2
18	Hyundai Steel	South Korea	19.6
19	Liuzhou Iron and Steel	China	18.8
20	Steel Authority of India Limited	India	17.9
21	Novolipetsk Steel	Russia	17.3
22	IMIDRO	Iran	16.7
23	Baotou Steel	China	16.5
24	United States Steel Corporation	USA	16.3
25	Cleveland-Cliffs	USA	16.3
26	China Steel	Taiwan	16.0
27	Jingye Steel	China	15.4
28	Techint	Argentina	14.9
29	Hebei Sinogiant Group	China	14.3
30	Gerdau	Brazil	14.2
31	CITIC Limited	China	14.0
32	Magnitogorsk Iron and Steel Works	Russia	13.6
33	Rizhao Steel	China	13.6
34	Evraz	Russia	13.6
35	Zenith Steel Group	China	12.8
36	Shaanxi Iron and Steel	China	12.4
37	Tsingshan Stainless Steel	China	12.4
38	Steel Dynamics	USA	12.2
39	Guangxi Shenglong Metallurgical	China	12.2
40	ThyssenKrupp	Germany	12.0

As a result of China's raw material and industrial strategic initiatives, China dominates all direct and derived value chains related to iron and steel production, controlling over half of the largest facilities, which together contribute to about half of the global production. China's production systems are predominantly based on processes involving BF, followed by BOF and EAF, resulting in a relatively high CO_2 emission.

4.4.4.2 Critical Raw Materials used in Steel

Alloying metals for the steel industry, ferroalloys, are added to provide steel products with properties that make them suitable for specific applications (Table 4-5). Ferroalloys are produced almost exclusively for consumption in the steel industry and are therefore part of the supply chains for iron and steel production. Several alloying raw materials include essential metals, identified as critical by the EU in 2023 (highlighted in red in Table 4-5) (EC 2023). Examples include ferromanganese, ferrosilicon, ferronickel, ferrotungsten, ferrovanadium, and ferroniobium. China imports a significant portion of the global production of ferronickel from Indonesia, New Caledonia, and Myanmar, and ferroniobium from Brazil, Singapore, and Canada. China also exports, among other things, ferrosilicon, ferromolybdenum, and ferrotungsten.

Table 4-5 *Overview of commonly used ferroalloys and their functions; red markings indicate raw materials assessed as critical for the EU in 2023. Sources: EC (2023) and Matmatch (2023).*

Element	wt.% in steel	Function	Approx. ratio applied in the steel industry (%)
Aluminium	0.95-1.30	Deoxidizer; prevent growth of austenitic grains	?
Bismuth	-	Improves processing properties	30
Boron	0.001-0.003	Improves strength	
Carbon (graphite)	0.05-2.1	Improves mechanical strength and hardness for refractory materials	50
Fluor		pH-regulator	36
Phosphor		Harmful – enhance fragility. Increases hardness but reduce processing properties	
Chromium	0.5-2.0	Forming carbides and increases hardness	
	4-18	Improves corrosion resistance; Stainless steel contains typically 12 % Cr	
Cobalt		Reducing grain growth and improves heat resistance.	50
Copper	0.1-0.4	Improves corrosion resistance but reduces processing properties. Max. 0.5 %	
Lead	-	Improves processing properties	
Manganese	0.25-0.40	Reduces ductility	
	>1	Increases hardness; improves welding properties	
Molybdenum	0.2-0.5	Forming carbides and thus improves the mechanical strength	
Nickel	2-5	Improves toughness	75
	12-20	Improves corrosion resistance	
Niobium		Improves strength and toughness	70
Nitrogen		Forming nitrides and thus improves strength and toughness; but fragility increases.	
Silicium	0.2-0.7	Improves strength and toughness	?
	2	Improves material ductility	
	>2	Improves magnetic properties	
Sulphur	0.08-0.15	Normally not wanted; small amounts improve processing properties.	
Titanium	-	Reducing martensitic hardness in chromium-steel	10
Tungsten	-	Improves hardness and wearability	80
Vanadium	0.15	Improves strength, without growth of microstructure, and reduced processing properties.	95

For steel production, a variety of process auxiliaries are also used, some of which the EU has identified as critical. For example, fluorine, of which approximately ⅓ of the production is used for pH regulation in the steel industry, and graphite, of which about ½ of the production is consumed in the steel industry as both a process auxiliary and for the manufacturing of refractory materials.

To the extent that alloying metals and auxiliaries in the steel industry cannot be substituted with non-critical raw materials, it may be relevant to consider steel as a critical resource.

4.4.5 Climate and Environmental Impact

Iron and steel production have a significant carbon footprint, with the production of 1 ton of steel emitting approximately 1.8 ton of CO_2. In April 2021, the expectation was that steel production in 2021 would account for around 7 % of global CO_2 emissions and about 4 % of EU emissions (EU Parliamentary Research Service 2021). According to Hasanbeigi (2022), iron and steel production contribute to 11 % of global CO_2 emissions and constitute 7 % of all greenhouse gas (GHG) emissions.

CO_2 emissions from the steel industry result from the extensive energy consumption of fossil fuels in mining, ore processing, and the transportation of iron ore from the mine to the smelting plant. The subsequent processes involved in transforming iron ore into steel also contribute to emissions. The major CO_2 contributions are linked to processes where coal/carbon is used as a reducing agent to eliminate the oxygen content of iron ore ($Fe_2O_3 + 3\ CO \rightarrow 2\ Fe + 3\ CO_2$) and to the calcination process, which reduces the silicon oxide, sulphur, and phosphorus content, traditionally using limestone that converts to CO_2 ($CaCO_3 \rightarrow CaO + CO_2$).

The steel industry employs various strategies to reduce CO_2 emissions, including:

- Transitioning to green energy sources.
- Substituting coal with hydrogen (H), resulting in water and/or methane (CH_4) as by-products, serving as alternative reducing agents. Methane is found in natural gas and is readily available, whereas hydrogen is produced in very limited quantities.
- Carbon Capture and Storage (CCS) technologies that can contribute to reducing CO_2 emissions. For instance, top gas from blast furnaces contains both CO_2 and reducing agents such as H_2 and CO, where CO_2 can be captured and stored, and the reducing agents can be recycled in the furnace, reducing CO_2 emissions by up to 75 % (Afanga *et al.* 2012).
- Increased use of iron scrap, as it reduces CO_2 emissions by 1.5 ton of CO_2 per ton of steel (World Steel Association 2022).
- Implementation of new furnace technologies, including the Hisarna iron ore process (Tata Steel 2020), hydrogen plasma method (EU Parliamentary Research Service 2021), hydrogen direct-reduced iron method (H2 DRI), and iron ore electrolysis method (Boston Metal 2022).
- Reduction of steel demand in steel-consuming industries.

To make the iron and steel industry carbon-neutral by 2050, it would require investments of around USD 1.4 trillion for technology transformations in processing industries and CCS systems for capturing and depositing approximately 470 Mt of CO_2 (Wood Mackenzie 2022). Achieving this goal would also assume that the iron and steel industry in 2050 has access to around 2,000 GW of ‘green’ power out of the global capacity of 27,000 GW required for the world to be carbon-neutral by 2050 (PWC 2022).

The production of ‘green steel’ is more energy-intensive than ‘conventional’ steel. For example, manufacturing H_2 to replace coking coal, coal, and natural gas as a reducing agent is energy intensive. In cases where BOF plants cannot be replaced with EAF, pre-melters will be established, increasing energy consumption. Consequently, the production of one metric ton of green steel using the H_2-based DRI and EAF route will require a minimum of 3 MWh (renewable energy), compared to a fully integrated blast furnace-basic oxygen furnace (BF-BOF), which consumes approximately 0.1 MWh (Baroyan *et al.* 2023).

4.5 Trade

International trade in iron and steel is one of the largest commodity groups, with a combined value of approximately USD 900 billion in 2020 (HS 72 + HS 73). An overview of various products and their corresponding trade values is presented in Table 4-7. For six selected commodity categories, representing value chains from mining to stainless steel to some extent, summaries of the key trade relationships between countries have been compiled. This is illustrated in a series of tables and figures, with details available in Table 4-6.

Table 4-6 *Overview of six selected product categories, HS codes, tables, and figures illustrating the key trade relations between countries.*

Trade code	HS-Code	Table	Figure
Iron ore	26.01	Table 4-8	Figure 4-9
Pig iron	72.01	Table 4-9	Figure 4-10
Iron and steel scrap	72.04	Table 4-10	Figure 4-11
Ferroalloys	72.02	Table 4-11 and Table 4-12	Figure 4-12
Hot-rolled iron	72.08	Table 4-13	Figure 4-13
Flat-Rolled stainless steel	72.19	Table 4-14	Figure 4-14

Trade in iron and steel products are recorded according to various commodity codes, and the current overview of trade is based on HS commodity codes. The main groups for the supply chains of iron and steel are indicated in a process diagram (Figure 4-8); in addition, the values for selected commodity codes for the year 2020 are listed in Table 4-7.

Global iron ore exports are distributed among many countries, with Australia, Brazil, South Africa, Ukraine, and Canada being the largest exporting countries. China is the dominant importing country for iron ore (HS 26.01), constituting approximately 60 % of the transactions in 2020. China is, therefore, the largest trading partner for the five largest iron ore-producing countries. For Australia and Brazil, trade in iron ore with China accounted for 81 % and 63 %, respectively. China also dominates the global trade in pig iron (HS 72.01), most of which comes from Brazil, with smaller amounts from Russia, Ukraine, Indonesia, Japan, and India. In 2020, Russia had significant exports to the USA, Turkey, and Italy, while Ukraine exported mainly to the USA. Significant changes are expected in the export pattern due to the adoption of international trade sanctions against Russia in 2022. Scrap iron (HS 72.04), like iron ore, is a raw material for iron and steel products. The trade in scrap is dominated on the export side by the USA, Germany, the Netherlands, UK, and Japan, but on the import side, there is no specific dominance. Approximately 50 % of the trade in ferroalloys (HS 72.02), a crucial raw material for steel production, is exported from Indonesia, South Africa, Brazil, India, and Kazakhstan, with China being the largest importing country (around 30 %).

In general, the trade patterns for products in the upper parts of the supply chains for iron and steel clearly illustrate China's need to supplement its own iron ore production with imported raw materials. However, China's import of scrap iron (HS 72.04) is negligible. The trade patterns for downstream semi-finished products, such as rolled iron (HS 72.08) and rolled stainless steel (HS 72.19), show that both exports and imports are distributed among many countries. The patterns also demonstrate that China exports value-added steel products.

Table 4-7 *Overview of global trade codes (HS system) for iron and steel goods with indication of value (2020). Trade codes are also visible in Figure 4-8. Source: OEC World (2023).*

Trade code description	HS-code	Value (M. USD)
Iron ore	26.01	220,000
Iron ore, conc, not iron pyrites	26.01.11	193,000
Iron ore, concentrate, not iron pyrites, agglomerated	26.01.12	27,100
Iron oxides and hydroxides	28.21	1,130
Iron and steel	72	550,000
Pig iron	72.01	7,160
Ferro alloys	72.02	43,300
Iron reductions	72.03	6,470
Ferrous waste and scrap	72.04	56,600
Granules and powder og pig iron	72.05	2,770
Iron and non-alloy steel in ingots	72.06	651
Iron or non-alloy steel – semifinished	72.07	42,200
Iron or non-alloy steel; flat rolled; hot rolled	72.08	73,600
Iron or non-alloy steel, flat rolled cold rolled	72.09	22,200
Coated flat-rolled iron	72.10	72,400
Large flat-rolled iron	72.11	6,000
Large coated flat-rolled iron	72.12	5,890
Hot-rolled iron bars	72.13	19,100
Raw iron bars	72.14	24,600
Other iron bars	72.15	3,390
Iron blocks	72.16	17,900
Iron wire	72.17	9,500
Stainless steel ingots primary forms	72.18	5,680
Large flat-rolled stainless steel	72.19	40,300
Flat-rolled stainless steel	72.20	6,030
Hot-rolled stainless steel bars	72.21	2,450
Other stainless steel bars	72.22	7,200
Stainless steel wire	72.23	2,870
Steel ingots	72.24	4,490
Flat-rolled steel	72.25	38,700
Flat-rolled iron	72.26	4,230
Steel bars	72.27	5,910
Other steel bars	72.28	14,900
Steel wire	72.29	3,480
Iron or steel articles	73	355,000
Iron Pipes	73.04	21,700

Table 4-8 *Overview of global trade in iron ore (HS4 26.01) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Australia	118,091	China	95,718
		Japan	9,101
		South Korea	7,921
		Taiwan	2,655
		Vietnam	1,393
Brazil	46,208	China	28,891
		Malaysia	2,827
		Japan	1,907
		Bahrain	1,794
		Oman	1,288
South Africa	7,675	China	2,116
		Netherlands	1,059
		Mozambique	908
		Germany	628
		Japan	627
Ukraine	6,829	China	2,918
		Czech Rep.	650
		Austria	535
		Poland	533
		Slovakia	441
Canada	5,760	China	2,093
		Japan	612
		Germany	491
		France	489
		South Korea	312
Subtotal	178,804		
Others	41,430		
Total	220,235		

Table 4-9 *Overview of global trade in pig iron (HS4 72.01) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Russia	1.342	USA	426
		Turkey	329
		China	230
		Italy	208
		Poland	30
Brazil	1.145	China	637
		USA	199
		Netherlands	86
		Mexico	56
		Hong Kong	36
Ukraine	1.050	USA	541
		China	201
		Saudi Arabia	119
		Turkey	55
		Italy	47
Japan	172	China	125
		Taiwan	20
		South Korea	17
Indonesia	166	China	166
India	140	China	123
		Nepal	5
Subtotal	4.015		
Others	66		
Total	4.781		

Table 4-10 *Overview of global trade in HS4 72.04 Iron and Steel Scrap in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
USA	7,805	Turkey	1,576
		Mexico	1,054
		Vietnam	625
		Bangladesh	593
		Taiwan	590
Germany	5,418	Belgium	1,114
		Italy	955
		Netherlands	867
		Luxembourg	442
		Finland	291
Netherlands	4,173	Turkey	1,343
		Germany	616
		Finland	598
		Belgium	415
		Egypt	282
UK	3,968	Turkey	947
		Egypt	636
		Pakistan	432
		Spain	301
		Bangladesh	295
Japan	3,767	South Korea	1,739
		Vietnam	993
		Taiwan	337
		China	211
		Malaysia	137
Subtotal	25,131		
Others	31,453		
Total	56,584		

Table 4-11 *Global trade in ferroalloys (HS4 72.02) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Indonesia	7,156	China	6,327
		India	495
		Taiwan	194
		South Korea	98
		Netherlands	10
South Africa	4,325	China	1,055
		UAE	611
		Indonesia	533
		USA	372
		South Korea	292
		Mozambique	244
Brazil	3,700	China	1,001
		Netherlands	542
		USA	338
		South Korea	308
		Japan	289
India	3,113	China	442
		Italy	25
		Japan	250
		South Korea	228
		Taiwan	220
Kazakhstan	2,572	China	925
		Japan	564
		USA	238
		Indonesia	165
		South Korea	164
Subtotal	20,866		
Others	22,456		
Total	43,322		

Table 4-12 *Trade in ferroalloys in 2020, indicating the largest exporting and importing countries. Source: OEC World (2023).*

HS6	Commodity	Export value (M. USD)	Export country 1	Export country 2	Export country 3	Import-country 1	Import country 2	Import-country 3
72.02.60	Ferro Ni	12,000	Indonesia*	Brazil	New Caledonia	USA	Germany	Netherl.
72.02.41	Ferro Cr >4 %C	8,949	South Africa	Kazakhstan	Turkey	China	Indonesia	Japan
72.02.30	Ferro Si-Mn	5,060	India	Ukraine	Georgia	USA	Turkey	Italy
72.02.21	Ferro Si >55 %Si	4,410	China	Russia	Norway	Japan	South K.	Germany
72.02.93	Ferro Nb	3,130	Brazil**	Canada	Netherl.	China	Holland	Japan
72.02.70	Ferro Mo	2,700	South K.	China	Chile	Netherl.	USA	Germany
72.02.11	Ferro Mn >2 %C	1,740	India	Malaysia	France	USA	Germany	Netherl.
72.02.19	Ferro Mn <2 %C	1,430	Norway	South Korea	India	USA	Netherl.	Germany
72.02.92	Ferro V	1,030	Austria	Czech Rep.	China	Netherl.	Germany	USA
72.02.99	Ferro nes	920	China	Brazil	DR Congo	China	Germany	India
72.02.49	Ferro Cr<4 %C	727	Russia	Kazakhstan	Turkey	South K.	Japan	USA
72.02.29	Ferro Si <55 %Si	609	Norway	Netherl.	China	Netherl.	Germany	South K.
72.02.91	Ferro Ti	342	Russia	UK	Germany	Netherl.	Germany	Brazil
72.02.80	Ferro W	157	China	Russia	Netherl.	Netherl.	Japan	Germany
72.02.50	Ferro Si Cr	131	Kazakhstan	Poland	China	USA	Germany	Japan

* 60 %, ** 73 %

As an example of trade in significant steel products, hot-rolled steel (HS4 72.06) and flat-rolled stainless steel (HS4 72.19) have been selected (Table 4-13 and Table 4-14). It is evident from these tables that China has significant transactions involving these value-added products, which are largely manufactured based on imported iron ore.

Table 4-13 *Overview of trade in HS4 72.08 Hot-Rolled Iron in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Japan	10,850	South Korea	1,898
		Thailand	1,566
		China	1,371
		Vietnam	771
		Indonesia	498
South Korea	6,183	Japan	827
		USA	769
		India	696
		Vietnam	568
		China	552
Russia	5,384	Turkey	1,220
		Poland	521
		Vietnam	445
		Italy	312
		Uzbekistan	289
India	5,226	Vietnam	1,286
		USA	805
		Italy	701
		Turkey	491
		Nepal	278
China	3,757	South Korea	690
		Vietnam	536
		Saudi Arabia	286
		Pakistan	157
		Philippines	139
Subtotal	31,400		
Others	42,169		
Total	73,569		

Table 4-14 *Overview of trade in HS 72.19 Rolled Stainless Steel in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Indonesia	6,676	China	2,353
		Taiwan	1,794
		Vietnam	525
		Italy	433
		Malaysia	422
China	6,618	South Korea	744
		Taiwan	674
		Turkey	602
		Russia	572
		Vietnam	514
Belgium	3,447	France	1,403
		Germany	775
		Italy	391
		Poland	130
		Netherlands	108
Finland	3,145	Netherlands	1,481
		Germany	703
		Italy	308
		Sweden	67
		China	56
Taiwan	2,416	USA	428
		Italy	293
		Belgium	255
		Japan	117
		Canada	102
Subtotal	22,302		
Others	18,013		
Total	40,315		

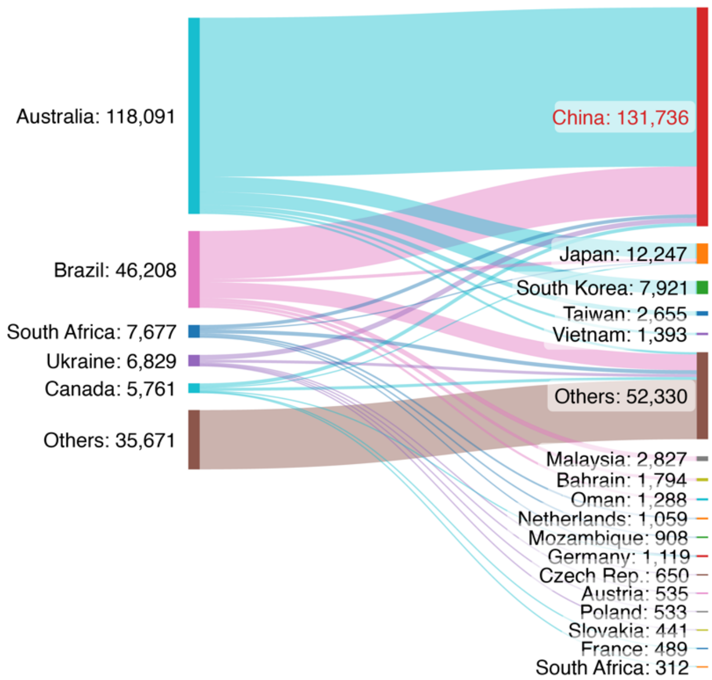


Figure 4-9 *Sankey diagram for global trade in iron ore (HS 26.01) in 2020. All values in million USD, based on Table 4-8.*

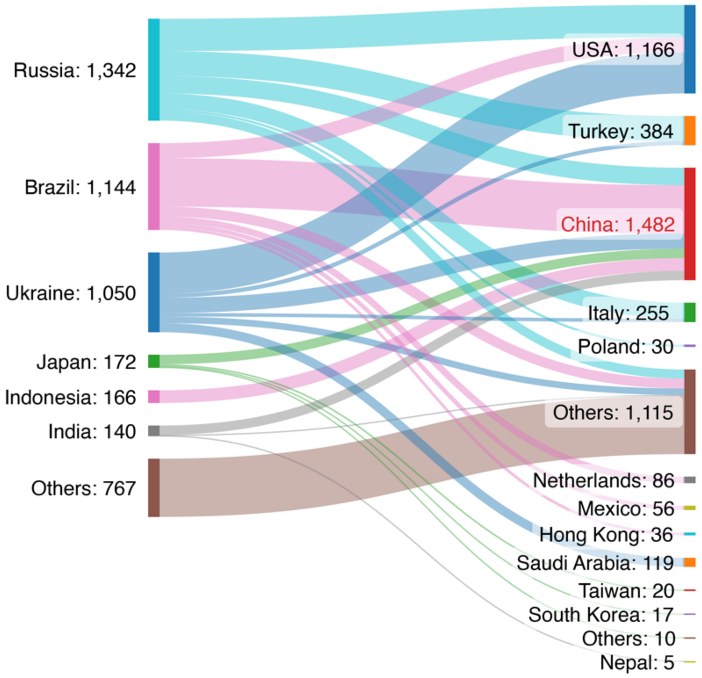


Figure 4-10 *Sankey diagram for global trade in pig iron (HS 72.01) in 2020. All values in million USD, based on Table 4-9.*

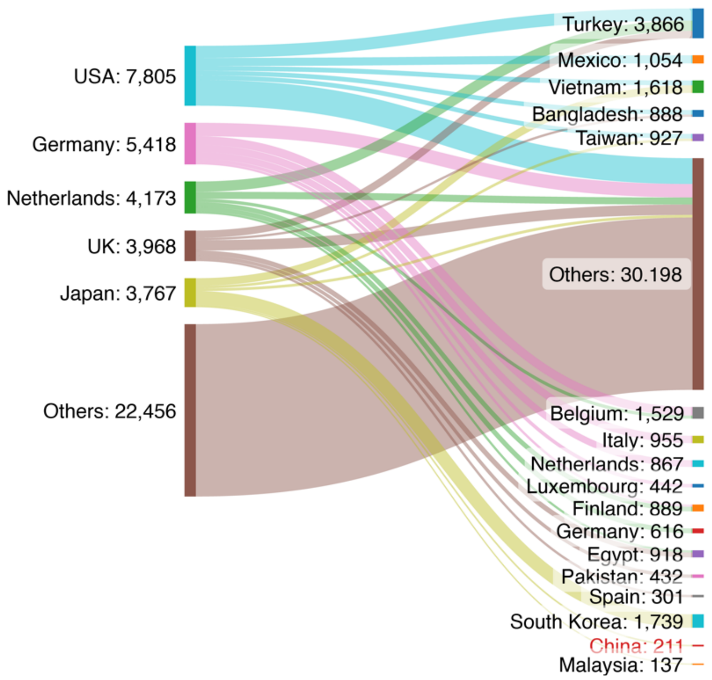


Figure 4-11 *Sankey diagram for global trade in iron and steel scrap (HS 72.04) in 2020. All values in million USD, based on Table 4-10.*

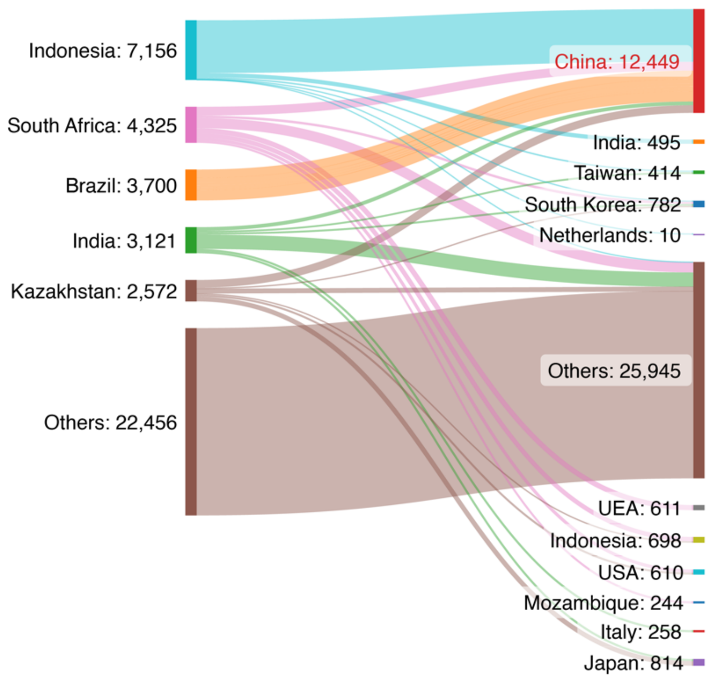


Figure 4-12 *Sankey diagram for global trade in ferroalloys (HS 72.02) in 2020. All values in million USD, based on Table 4-11 and Table 4-12.*

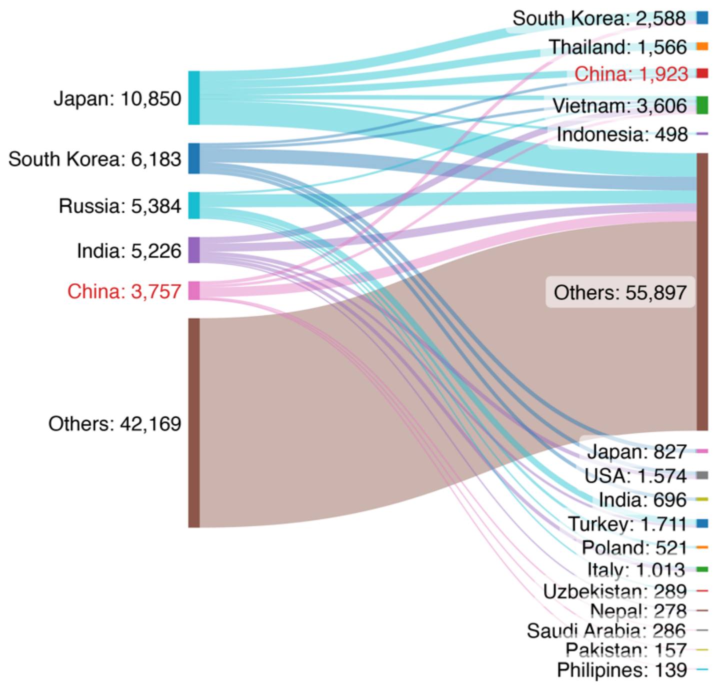


Figure 4-13 *Sankey diagram for global trade in hot-rolled iron (HS 72.08) in 2020. All values in million USD, based on Table 4-13.*

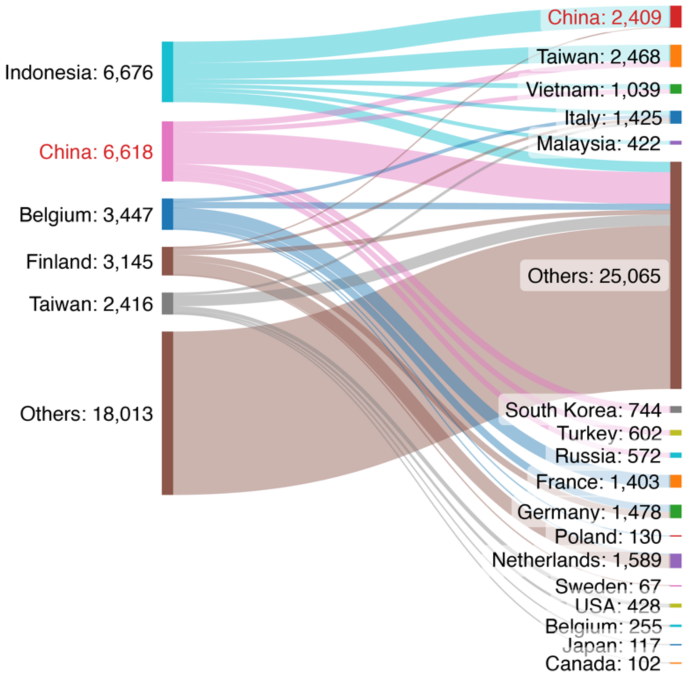


Figure 4-14 *Sankey diagram for global trade in rolled stainless steel (HS 72.19) in 2020. All values in million USD, based on Table 4-14.*

4.5.1 Prices

Iron and steel prices are cyclical and primarily reflect developments in the global economies, as well as specific events such as COVID-19, which resulted in reduced consumption and, consequently, falling prices. More recently, the war between Ukraine and Russia and the resulting trade embargo on Russian goods have adversely affected Russia's significant shares in the global trade of iron and steel products. Examples of this dynamic are illustrated in Figure 4-15, which depicts the prices for iron ore, coking coal, and scrap iron from 2008 to 2022. Industry analysts operate with 3-4 years price cycles and anticipate that low prices leading up to 2025 will be succeeded by a high-price period in 2028 (Steel on the Net 2023). The historical changes for steel products, such as hot-rolled coil (HRC) and rolled steel (rebar), are illustrated in Figure 4-16.

4.6 The Danish Consumption

Steel is a vital raw material for Danish industrial, construction, and engineering companies and cannot be significantly substituted. In 2020, Danish companies purchased iron and steel for 16.4 billion DKK and iron and steel goods for 36.9 billion DKK, constituting approximately 10 % of the industry's total commodity purchases. About half of this was used by industrial companies, and around 20 % in the construction and engineering sectors, with the remaining portion primarily used by the utility sector. The derived impact on gross value added is the highest among 36 raw materials and is estimated at approximately 95 billion DKK in 2019 (Figure 4-17) (Clausen *et al.* 2023). The European Commission assesses the supply risk as very low. However, it should be noted that the assessment does not include steel's typical alloying metals, which may be critical for the EU (EC 2023).

The Danish consumption of and trade in iron and steel scrap, along with the associated challenges, are discussed in more detail in Tan *et al.* (2020).

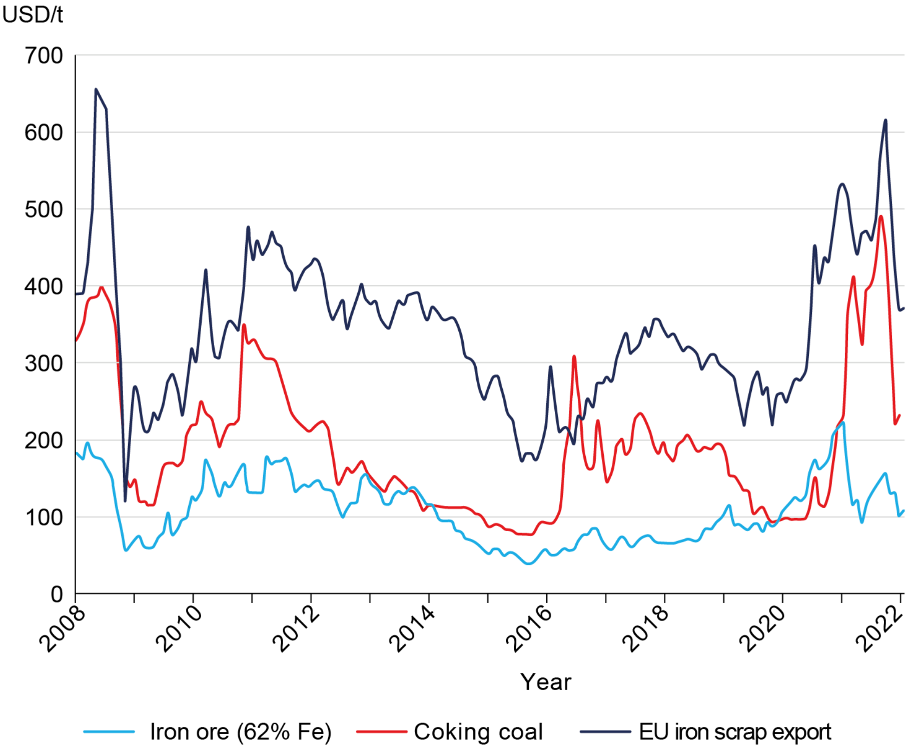


Figure 4-15 *Price variations for iron ore, coking coal, and iron scrap in the period 2008-2022. Source: OECD (2023).*

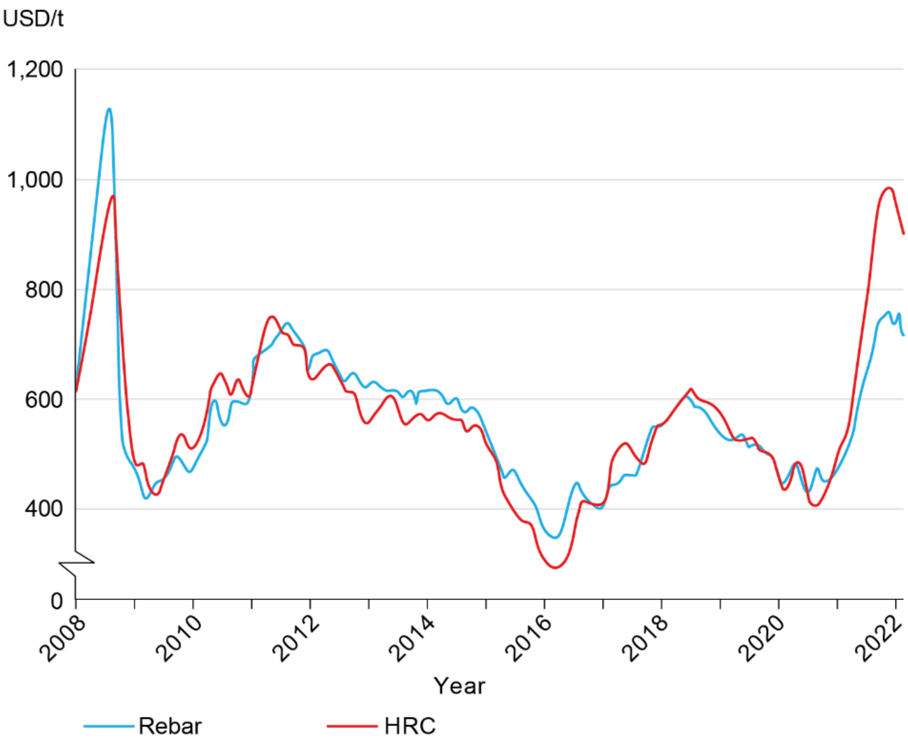


Figure 4-16 *Historical prices for the steel products hot rolled coil (HRC) and rolled steel (rebar). Prices are average export FOB prices (USD/ton). Source: Steel on the net (2023).*

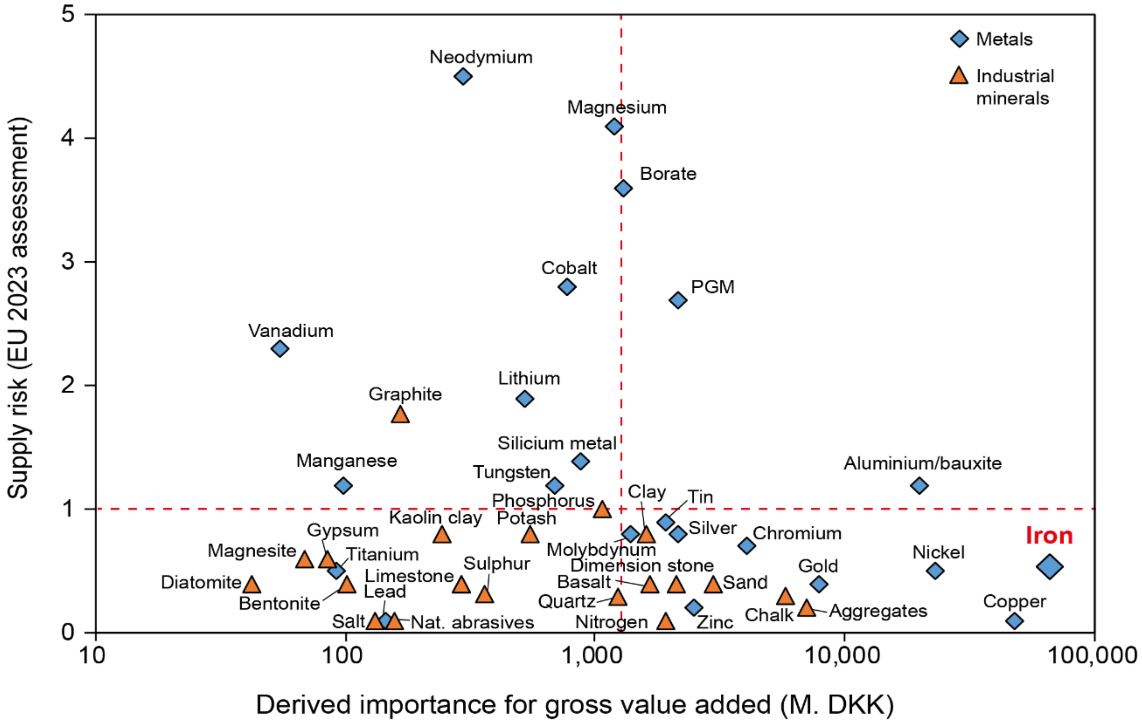


Figure 4-17 *The derived significance of iron and other raw materials for gross value added as a function of supply risk in Denmark. Among the analysed raw materials, steel is not considered a critical raw material, as the EU assesses the supply risk as low (Clausen* et al.*, 2023).*

4.7 Perspectives

Iron ore is produced in many countries and by many companies, but there is a clear trend towards increasing dominance by a few key players. In 2022, Australia, Brazil, China, and India collectively produced about ⅔ of the world's iron ore, with approximately half of that coming from Australia. The global iron ore production has been growing at a rate of around 2 % per year since 2000. This significant growth in production has not been balanced by mineral exploration to increase reserves, resulting in a reduced lifespan from 140 production years in 2000 to approximately 70 years in 2022.

Outside of China, iron ore production is dominated by mining companies such as Rio Tinto, Vale, and BHP, while in China, Glory Harvest Group, Taiyuan Iron & Steel Group, and Anshan Iron & Steel Group play significant roles. Mineral exploration projects have increased global iron ore reserves, and new major iron ore mines are expected to open in the coming years, including in West Africa and Australia. However, due to the rapid increase in total production, this has still not prevented a decline in reserve lifespan.

With the strong dominance of a few large and efficient iron ore-producing companies operating in few countries, the supply situation is considered to have good potential to meet the rising demand in the coming years. However, from a geopolitical and market-oriented perspective, the supply situation for iron ore can be viewed as challenged (illustrated for example in Figure 4-9), as more than half (55 %) of the Western world's iron ore production is exported to China.

In the European Commission's criticality assessment (EC 2023), iron ore and steel are considered together. In 2023, iron ore/steel was evaluated as a raw material with significant economic importance (EI: 7.2). However, the supply risks for both iron ore mining and iron and steel production were assessed as low (Supply Risk - Mining: 0.5 and Supply Risk - Steel Production: 0.2). For steel production, in addition to iron, various reducing agents and alloying metals are used, and some of these are considered critical raw materials in several countries (such as cobalt, titanium, tungsten, and vanadium). Assessments of the supply situation for these materials should be considered to evaluate the steel supply situation, but they are not included in this analysis, and this issue is not addressed in the present report.

Steel consumption is expected to grow to 1.7 billion ton in 2025 and 1.85 billion ton in 2030 before stagnating (Accenture Strategy 2017; Lutter 2021). If the expected available amounts of iron scrap are included, there will be approximately 2.25 billion ton of iron ore available in 2025 and 2030 for use. However, consumption is expected to decline after that.

The demand is expected to be highest for Electric Arc Furnace (EAF) steel, which has a smaller carbon footprint than Basic Oxygen Furnace (BOF) steel. However, EAF steel is projected to increase only from around 30 % in 2020 to 37 % in 2030.

4.8 References

Allwood, J. M. 2016: A bright future for UK steel: A strategy for innovation and leadership through up- cycling and integration. University of Cambridge, pp. 1–16.

Arcelormittal 2023: https://corporate.arcelormittal.com/sustainability/by-products-scrap-and-the-circular-economy

Accentury Strategy 2017: Steel demand beyond 2030. Presentation to OECD, 2017. https://www.oecd.org/industry/ind/Item_4b_Accenture_Timothy_van_Audenaerde.pdf

Afanga, K, Mirgaux, O. & Patisson, F. 2012: Assessment of Top Gas Recycling Blast Furnace: A Technology To Reduce CO_2 Emissions in the Steelmaking Industry. Carbon Management Technology Conference. OnePetro. doi:10.7122/151137-MS.

Baroyan, A. Kravshenko, O., Prates, C., & Vercammen, S. & Zeumer, B. 2023: The resilience of steel: Navigating the crossroads. The resilience of steel: Navigating the crossroads | McKinsey.

Boston Metal 2022: Molten Oxide Electrolysis for steel decarbonization. Fact Sheet. https://www.bostonmetal.com/green-steel-solution/

Clausen, R. J., Kalvig, P., Keiding, J.K., Fold, N. & Vind, I. 2023: Dansk industris brug af mineralske råstoffer – økonomisk betydning og forsyningsudfordringer MiMa rapport 2023/2, pp. 181. https://doi.org/10.22008/gpub/32051

European Commission (EC) 2023: Study on the Critical Raw Materials for the EU 2023 – Final Report. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

EU Parliamentary Research Service (EPRS) 2021: Carbon-free steel production. Cost reduction options and usage of existing gas infrastructure. Scientific Foresight Unit PE 690.008 April 2021, https://www.europarl.europa.eu/RegData/etudes/STUD/2021/690008/EPRS_STU(2021)690008_EN.pdf

Hasanbeigi, A. 2022: Steel Climate impact. An international benchmarking of energy and CO_2 intensities. Report 31 pp. Global Efficiency Intelligence website https://www.globalefficiencyintel.com/steel-climate-impact-international-benchmarking-energy-co2-intensities

Lutter, P. 2021: Green transformation needs clear orientation: Forecasting the steel demand in 2030. New Supply BC_Newssupply_012_en.pdf (bronk-company.com)

Matmatch 2023: https://matmatch.com/learn/material/alloy-steel

Mining Intelligence Data 2022: https://www.miningintelligence.com/top-20-iron-ore-producers/

Observatory of Economic Complexity World (EOC World) 2023: Database https://oec.world/

OECD 2020: Steel market developments, Q4 2020: https://www.oecd.org/industry/ind/steel-market-developments-Q4-2020.pdf.

OECD 2022: Steel market developments, Q4 2022: https://one.oecd.org/document/DSTI/SC(2022)11/FINAL/en/pdf

PWC 2022: Bridging the gaps: Setting the stage for an orderly energy-system transition. (https://www.pwc.com/gx/en/issues/esg/the-energy-transition/bridging-gaps-to-reach-energy-transition-goals.html)

Scrreen2 Iron ore factsheet 2023: Scrreen2 Factsheets updates based on the EU Factsheets 2020 iron ore. https://scrreen.eu/wp-content/uploads/2023/08/SCRREEN2-factsheets_IRON-ORE.pdf

S&P Global 2016: China's run-of-mine iron ore output falls 7.7 % on year to 1.38 bil Mt in 2015 (https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/metals/012616-chinas-run-of-mine-iron-ore-output-falls-77-on-year-to-138-bil-Mt-in-2015).

S&P Global 2022: Lack of high-quality iron ore supply threatens steel's green push. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/lack-of-high-quality-iron-ore-supply-threatens-steel-s-green-push-70947714

Statista 2022: Distribution of steel end-usage worldwide in 2022, by sector, https://www.statista.com/statistics/1107721/steel-usage-global-segment/

Steel on the net 2023: Steel market outlook & forecasts for 2024 2025 prices. https://www.steelonthenet.com/market-outlook.html.

Tan, J., Wehde, M.V., Brønd, F. & Kalvig, P. 2020: Udfordringer for bæredygtig genanvendelse af dansk jern- og metalskrot. MiMa rapport 2020/2. https://worldsteel.org/steel-topics/statistics/steel-data-viewer/

Tata Steel 2020: Hisarna – Building a sustainable steel industry. Tata Steel Fact Sheet 2020 https://www.tatasteeleurope.com/sites/default/files/tata-steel-europe-factsheet-hisarna.pdf

USGS 2000-2023: Mineral commodity summaries 2000-2023: U.S. Geological Survey https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries

Wood Mackenzie 2022: Decarbonizing global iron ore and steel industry by 2050 necessitates urgent action and USD 1.4 trillion of investment. News Release Wood Mackenzie https://www.woodmac.com/press-releases/decarbonising-global-iron-ore-and-steel-industry-by-2050-necessitates-urgent-action-and-us$1.4-trillion-of-investment/

World Economic Forum 2022: Net-Zero Industry Tracker, 2022 Edition https://www3.weforum.org/docs/WEF_NetZero_Industry_Tracker_2022_Edition.pdf

World Steel Association 1990-2023: World Steel in Figure annual reports https://worldsteel.org/steel-topics/statistics

World Steel Association 2022: Scrap use in the steel industry (Fact sheet) https://www.saisi.org/wp-content/uploads/2021/06/Scrap-Fact-Sheet.pdf

World Steel Association 2023: World Steel in figure https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2022/#world-crude-steel-production-1950-to-2021

World Steel in Figures 2021: https://worldsteel.org/wp-content/uploads/2021-World-Steel-in-Figures.pdf

5. Nickel

5.1 Introduction

Nickel (Ni) with atomic number 28 in the Periodic Table of Elements is a silver-grey metal with a high melting point (1,455 °C) and a combination of sought-after properties, including corrosion resistance, high strength, and ductility, even at very low temperatures. Nickel has electrical and magnetic properties that make it widely used in various sectors. The primary application of the metal is as an alloy in stainless steel, constituting around 70 % of global nickel production. Nickel has also become a crucial raw material for the green transition, with rapidly growing demand for various types of batteries. Overall, nickel holds significant industrial importance for a broad range of end products, including buildings and structures, metal goods, the transportation sector, electronics, and electric vehicles. Economically, it ranks as the third most important mineral resource for Danish industry (Clausen *et al.* 2023). In total, nearly 3 Mt of nickel were used worldwide in 2022 (Nickel Institute 2023a).

In nature, nickel minerals occur in intrusions, weathered lateritic soils in the tropics, and manganese nodules in the deep sea, but extraction is only feasible from the first two types. The known onshore reserves are sufficient for approximately 35 years, considering a consumption rate of around 3 Mt per year.

As of 2023, the EU Commission does not classify nickel as a critical raw material, but it is categorized as a strategic raw material due to its importance in the green transition, as well as in defence and aerospace industries (EC 2023).

5.2 Applications and Sectors

The largest market for nickel is in the production of stainless steel, where nickel (approximately 8-40 % Ni) is combined with iron (about 50-70 % Fe) and chromium (18-25 %); corrosion resistance and strength are particularly determined by the nickel content.

Nickel alloyed with various metals, especially iron, as well as copper, aluminium, cobalt, and others, exhibits magnetic properties used in electronics, car generators, long-distance telephone cables, and underwater defence technology ultrasonic transducers. Some of these alloys have trade names such as Permalloy and Alnico. Other nickel alloys are used to counteract thermal expansion; this type of alloy is often referred to as Invar.

The market for nickel in Li-ion batteries is expected to grow by 7 % annually until 2030, becoming the second most important application for nickel.

Nickel is used in chemical compounds such as nickel sulphate and nickel chlorides, both of which are used for various types of electrochemical surface treatments. Additionally, nickel sulphamate, nickel fluoroborate, nickel carbonyl, and others are employed.

In Figure 5-1, the global distribution of nickel's industrial applications in 2022 is shown.

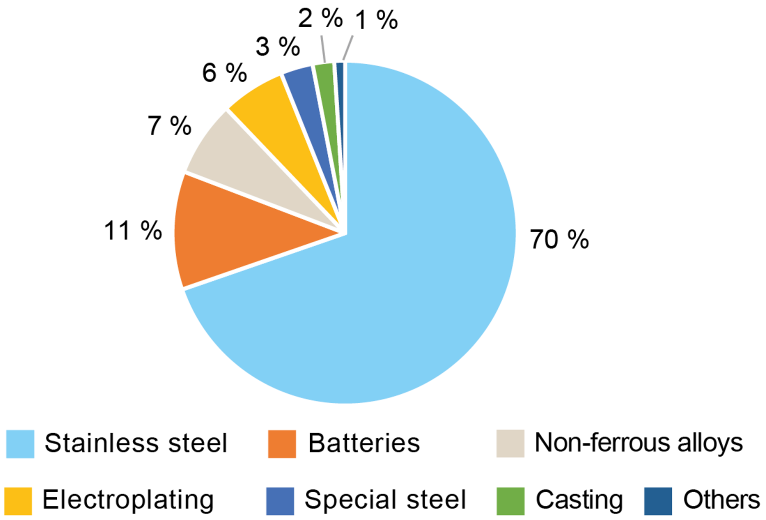


Figure 5-1 *Global distribution of nickel's industrial applications in 2022. Source: Nickel Institute (2023a).*

5.3 Recycling and Substitution

The high price of nickel (see section 5.5.1 Prices) and its sought-after properties are strong incentives for high recycling rates. In 2019, nickel recycling (EOL-RR) accounted for 60 % globally (IEA 2021), while 16 % of the EU's nickel production came from recycled nickel (EOL-RIR) in 2022 (EC 2023).

To produce high-quality steel, there are limited alternatives to replace nickel. Nickel-free specialty steels are used in some contexts as substitutes for stainless steel. Titanium alloys can also partially substitute for nickel metal or nickel-based alloys in corrosive chemical environments. Moreover, both plastic and ceramic materials have the potential to replace nickel. Experiments are in progress to use plastic alloys as a substitution for nickel but presently, the material properties are not satisfactory. Furthermore, replacing nickel in superalloys with ceramic materials is being investigated, and lithium-ion batteries can, in some cases, replace nickel-metal hydride batteries.

5.4 Global Supply

5.4.1 Geology

In nature, nickel occurs in magmatic intrusions, in weathered lateritic soils in the tropics, as well as in manganese nodules and crusts in the deep sea, although the latter are not exploited. The geographical distribution of some of the world's largest nickel mines by type is shown in Figure 5-2.

The magmatic sulphide deposits are formed in connection with mafic and ultramafic magmas and are exploited from several geological types:

a) often associated with the rock type norite. This type often also contains copper, cobalt, and platinum group metals. The nickel content in the ores extracted is typically 1-2 %, predominantly found in nickel sulphide minerals. Major nickel deposits of this type are Stillwater in the USA and Bushveld in South Africa.

b) komatiite deposits, formed as lens-shaped bodies with nickel ranging from 1-5 % and copper (0.1-0.3 %); may also contain platinum group metals. This type is known from locations such as Thompson in Canada and deposits in Zimbabwe.
c) basalt nickel deposits are associated with continental rift zones; this type is exploited in the Norilsk-Talnakh region in Siberia, Russia.

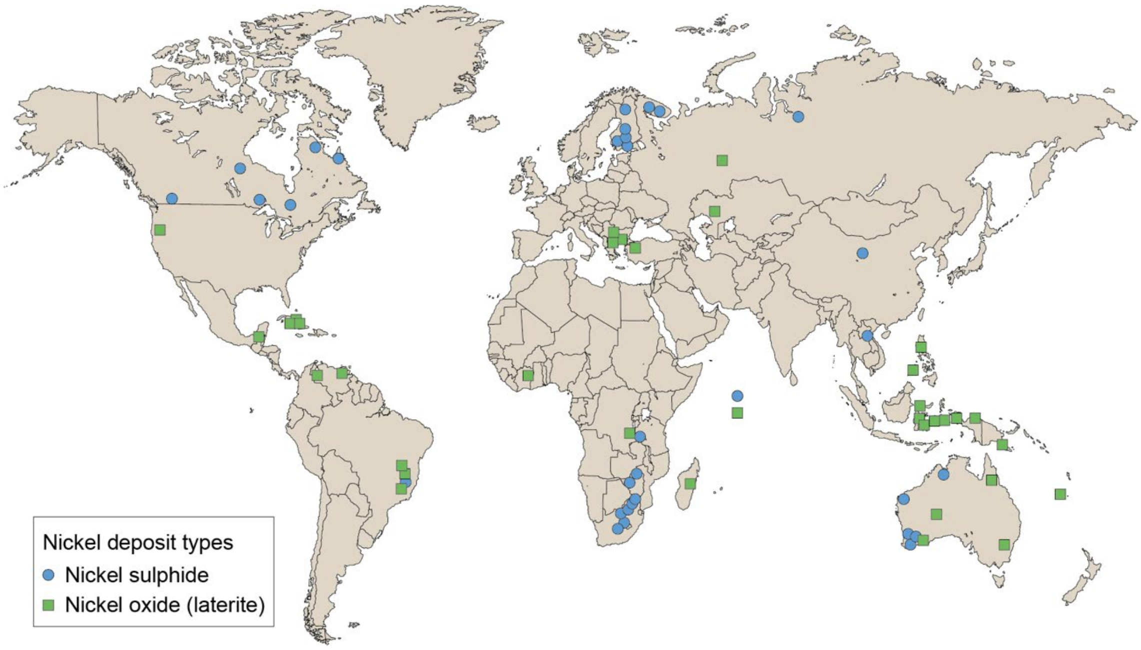


Figure 5-2 *Overview of some of the largest geological nickel deposits. Source: Nickel Institute (2023a).*

Tropical weathering soils, known as laterite, appear as 2-25 m thick near-surface layers with extensive lateral distribution. Laterite is rich in iron and aluminium hydroxides and may also contain economic quantities of nickel and cobalt. The nickel content is typically distributed with an upper, less rich zone (0.5-1 % Ni) and a lower, richer zone (1.5-3 % Ni), which may also contain cobalt. Typical minerals include nickel-rich limonite in the upper zone and garnierite in the lower zone. These two types differ in that limonite deposits are often very large (10-100 Mt bauxite ore) but relatively low-grade, whereas garnierite deposits have slightly higher grades but are often considerably smaller (<100 Mt bauxite ore). Both types are mainly found in countries within the equatorial belt, including New Caledonia, the Philippines, Indonesia, Colombia, and Cuba; in addition, fossil deposits exist in other climatic zones such as Greece.

Potentially significant deposits in the deep sea occur as polymetallic nodules and crusts. However, only a few preliminary studies on the quantities and qualities of these deposits have been conducted, and no commercial deep-sea mining is currently taking place. The International Seabed Authority (ISA) provides a preliminary assessment indicating that polymetallic nodules on the ocean floor cover areas of about 3 million km^2, with exploration licenses for 1.28 million km^2 (NORI 2022). Extraction license conditions for this type have not yet been approved by ISA. Polymetallic nodules contain 0.5-1.3 % Ni (Hein *et al.* 2020); deep-sea resources are poorly quantified but are estimated to be larger than known terrestrial resources. A recent study showed that Ni-Co-Cu deposits from deep-sea sources have a smaller climate footprint compared to traditional magmatic and laterite deposits (Benchmark Mineral Intelligence 2023), but there is widespread concern about environmental impacts from deep-sea mining (e.g., Sharma 2015; Durden *et al.* 2019; Washburn *et al.* 2019), and potential ecological and biodiversity consequences remain unknown.

In Greenland, there are several examples of nickel deposits related to magmatic intrusions. The main nickel deposit is located north of Maniitsoq in West Greenland within the so-called norite belt, which has been explored in recent years by North American Nickel Inc. Nickel mineralization in the area appears to be associated with a series of smaller intrusive norite bodies, forming an approximately 75 km long and 10 km wide belt with a high nickel content (around 4 %) and copper. Further information on the nickel potential in Greenland can be found in Rosa *et al.* (2014, 2023).

Several nickel-bearing minerals are used, with the most important ones being pentlandite, pyrrhotite, and garnierite; and to a lesser extent, millerite, niccolite, gersdorffite, and others (Table 5-1).

Table 5-1 *Commercially important nickel minerals.*

Mineral	Mineral formula	Common geological types
Chalcopyrite	$(Cu,Ni)FeS_3$	Mafic intrusions
Garnierite	$(Ni,Mg)_3Si_2O_5(OH)$	Laterites
Gersdorffite	NiAsS	Mafic intrusions
Limonite (nickel)	(Fe,Ni)I (OH)	Laterites
Millerite	NiS	Mafic intrusions
Pentlandite	$(Ni,Fe)_9S_8$	Mafic intrusions
Phyrhotite	(Fe,Ni)S	Mafic intrusions

5.4.1.1 By-products

In addition to nickel minerals, nickel deposits can also contain other minerals with commercially significant contents of metals such as copper, cobalt, and platinum group metals. These can be separated into distinct mineral products during ore processing. Such products are often defined as by-products, where the composition of the by-products is closely tied to the geological formation of the nickel deposit.

Nickel minerals also often contain small amounts of other metals, some of which may have commercial value. Some of these metals are not explicitly mentioned in the mineral's chemical formula; this group is often referred to as 'companion metals' or simply 'by-products' and includes metals such as indium (In), cobalt (Co), molybdenum (Mo), rhenium (Re), and selenium (Se). Companion metals do not form distinct minerals in the deposit and can only be extracted during the smelting and refining of the main mineral. The content of companion metals varies between different geological deposit types and is generally highest in magmatic types; furthermore, the content also varies within the same deposit types.

5.4.2 Global Nickel Reserves

The confirmed global nickel reserves amount to approximately 100 Mt (Table 5-2) and are primarily located in seven countries, with the majority of reserves found in Australia, Indonesia, and Brazil (Figure 5-3). Reserves increased from 57 Mt to about 95 Mt between 2000 and 2021. However, as consumption during the same period has grown more rapidly than mineral exploration has added to the reserves, the reserve lifespan decreased from approximately 46 years to about 33 years of consumption. Most reserves are associated with laterite types.

Futhermore, there are nickel resources of about 130 Mt with a 1 % nickel content, along with various lesser-known resources, including manganese nodules on the ocean floor. In addition to these, there are known nickel deposits that have not yet been assessed.

Table 5-2 *World nickel reserves in 2021, reported in 9 countries; in addition, there are several countries that do not provide this type of data. Sources: Statista (2022c) and USGS (2023).*

Country	USGS (Mt)	Statista (Mt)	Dominating type
Australia	21	21	C. ⅓ sulphide type and ⅔ laterite
Indonesia	21	21	Laterite
Brazil	16	16	Laterite
Russia	7.5	7.5	Sulphides
New Caledonia	n.a.	7.1	Laterite
Philippines	4.8	n.a.	Laterite
China	2.8	2.1	Sulphides
Canada	2.0	2.2	Sulphides
USA	0.3	0.4	Sulphides
Others	20	20	
Total	**95.4**	**97.3**	

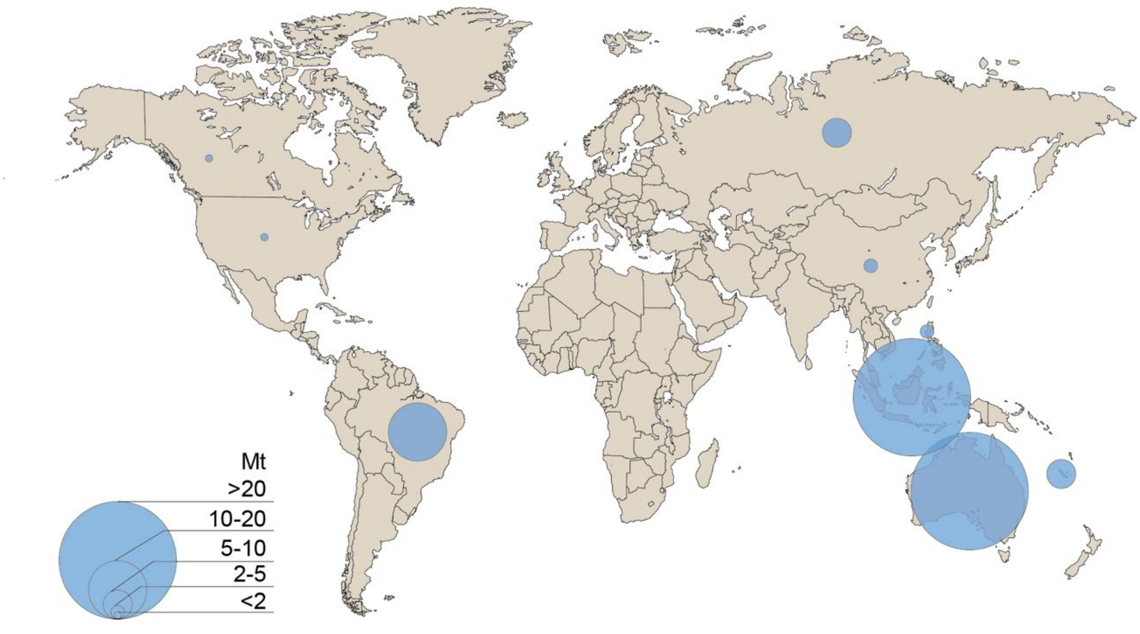


Figure 5-3 *Geographic overview of the nine countries with the largest registered nickel reserves. Source: USGS (202).*

5.4.3 Global Nickel Production

Nickel production has more than doubled since 2000, increasing from around 1.3 Mt in 2000 to 2.8 Mt in 2021, with Indonesia playing a significant role in the growth. In 2021, Indonesia accounted for about ⅓ of the world's production (Table 5-3 and Figure 5-4). China is a modest producer of nickel and, to secure its substantial needs, has established a collaboration with

Indonesia. This collaboration includes the development of mines, processing facilities, and off-take agreements.

In 2020, the total nickel production was distributed with 35 % from sulphide ore and 65 % from lateritic ore, with most coming from saprolite-laterite (McKinsey & Comp. 2020).

Table 5-3 *Global nickel production in 2021, reported by USGS (2023).*

Country	2021 (ton)
Indonesia	1,000,000
Philippines	370,000
Russia	250,000
New Caledonia	190,000
Australia	160,000
Canada	130,000
China	120,000
Brazil	100,000
USA	18,000
Others	410,000
Total	**2,748,000**

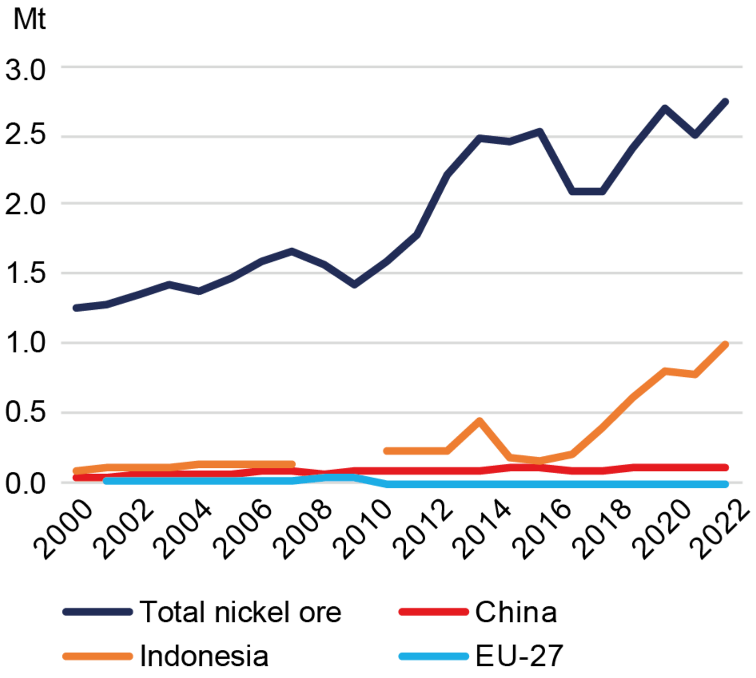


Figure 5-4 *Overview of historical production of nickel ore (reported as nickel content) in the period 2000-2021. Source: USGS (2000-2023).*

Nickel is mined in more than 25 countries, with production coming from both sulphide and laterite ores. Since the turn of the millennium, the production has shifted from being predominantly sulphide ores to being dominated by laterite ores today. Mining methods depend on the size, grade, and depth of the deposits. Laterite deposits, being near the surface, are always produced from an open mine. The 'strip mining' method is commonly used, where the topsoil is first removed and deposited, after which the ore is excavated. Upon mine closure, the area is restored using the deposited topsoil. Since laterite layers are only 5-25 m thick, and the grades are low, very large areas are involved in mining. In New Caledonia, to produce 1 Mt of nickel ore, approximately 20 hectares of land need to be stripped, equivalent to 500 Mt of topsoil, and 5 Mt of tailings are produced. An overview of the most productive nickel mining companies, their activities, and annual primary production based on publicly available information is shown in Table 5-4.

Table 5-4 *Overview of some of the largest nickel mines and companies. Source: Mudd & Jowitt 2022.*

Company	Mine	Country	Production ton 2021/22	Expected closing year
BHP	Mount Keith	Australia	39,000	2037
BHP	Leinster	Australia	21,000	2033
First Quantum Minerals	Ravensthorpe	Australia	29,000	2051
Glencore	Murrin Murrin	Australia	30,000	2042
IGO	Nova Bollinger	Australia	29,000	2027
Anglo American	Barro Alto	Brazil	35,000	2040
Glencore	Raglan	Canada	38,000	2027
Vale	Voisey's Bay	Canada	40,000	2034
Terrafame	Talvivaara mine	Finland	29,000	-
Asahan Aluminium	Gag Island	Indonesia	27,000	-
Asahan Aluminium	Pomalaa	Indonesia	26,000	-
CNGR Advanced Materials	Sulawesi	Indonesia	30,000	-
Hengjaya Mineralindo	Hengjaya Mine; Morwali	Indonesia	19,000	-
Huake Nickel Indonesia/Tsingshan	Weda Bay Industrial Park	Indonesia	40,000	2069
Indonesia Asahan Aluminium (INALUM)	Pomalaa	Indonesia	23,000	-
Nickel Asia Corp (NAC)	Taganito Mine	Indonesia	74,000	2049
Nickel Asia Corp (NAC)	Rio Tuba Mine	Indonesia	47,000	2028
QMB New Energy Materials/Tsingshan	Morowali Industrial Park	Indonesia	75,000	-
Solway	Asara Mine	Indonesia	30,000	-
Solway Investment Group	Asera Mine	Indonesia	32,000	-
Solway Investment Group	Bahoomahi	Indonesia	20,000	-
South32 Ltd	Cerro Matoso Mine	Indonesia	43,000	2049
Tsingshan	Huashan	Indonesia	45,000	-
Vale/Sumitomo/PT Indonesia Asahan Aluminium	Sorowako Mine	Indonesia	79,000	2045
Yiwan Mining	Yiwan Mine	Indonesia	43,000	-
Youshan Nickel Indonesia/Tsingshan	Weda Bay Industrial Park	Indonesia	34,000	-
Zhejiang Huayou Cobalt	Morowali Industrial Park	Indonesia	75,000	-
MMC Norilsk	Kola MMC Mine	Russia	145,000	-
MMC Norilsk	Oktyabrsky	Russia	53,000	2025
MMC Norilsk	Komsomolsky	Russia	42,000	-
MMC Norilsk	Taimyrsky	Russia	42,000	2038
MMC Norilsk	Skalisty	Russia	25,000	2043
MMC Norilsk	Kola MMC	Russia	23,000	-
First Quantum Minerals	Enterprise (expl)	Zambia	20,000	-

Figure 5-5 shows top nine nickel-producing countries in 2021, based on information from USGS 2022. The five largest nickel producers are Nornickel, Nickel Asia Corp (NAC), Glencore, Solway, and Vale, which together accounted for about 20 % of the global production in 2021. Among the major producers are also the Indonesian state-owned Ashan Aluminium and several Chinese mining companies such as Tsingshan and Zhejiang.

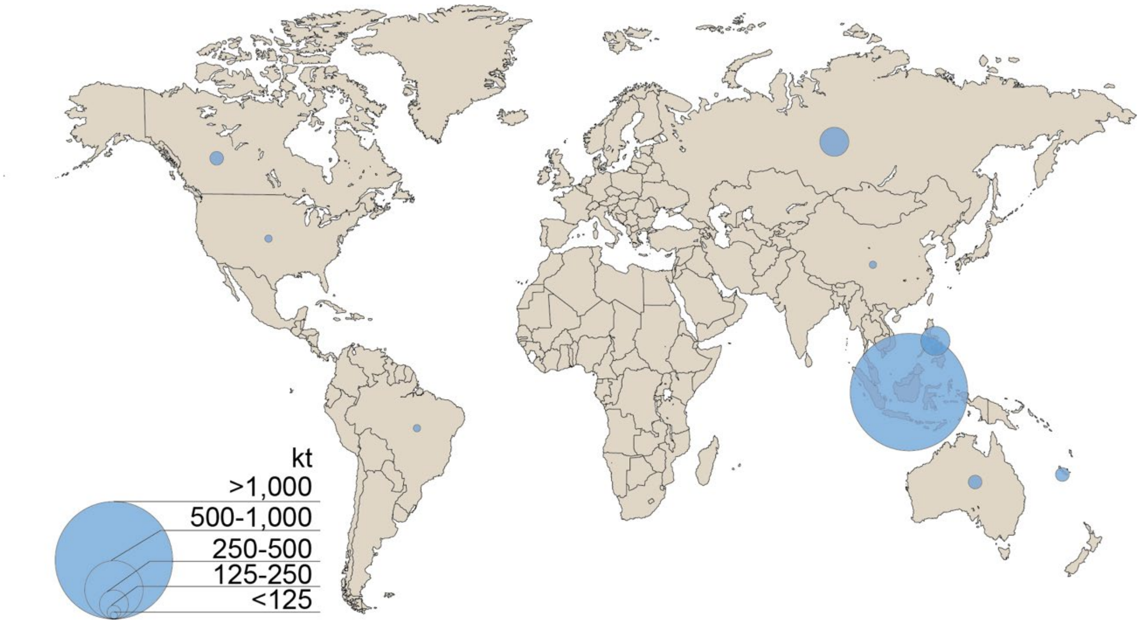


Figure 5-5 *Geographic overview of the nine countries that extracted the most nickel ore in 2021. Source: USGS (2022).*

5.4.4 Manufacturing of Nickel Products

The nickel industry's supply chains are largely dominated by vertically integrated companies, making it challenging to identify specific countries or companies' production of nickel matte, 'nickel pig iron', and subsequent nickel products.

Different methods are used for the treatment of Ni-sulphide ore and Ni-laterite (Figure 5-6):

- Sulphide ore is crushed, grinded, and a concentrate of sulphide minerals (10-20 % Ni) is produced by flotation. The sulphide mineral concentrate is treated with H_2SO_4 and smelted (at 1,350 °C), forming nickel matte (Ni-Fe sulphide) (25-45 % Ni) or copper-iron-nickel matte (70-80 % Cu-Ni). The matte is subsequently treated in a rotary converter, producing nickel matte (70-75 % Ni), which can be used to produce nickel cathode material and other 'Class 1' raw materials (> 99.9 % nickel). Copper and other by-product metals (e.g., platinum group metals, gold, silver, tellurium, and selenium) need to be separated afterwards.
- Laterite ore is crushed, and the minerals' water content (35-40 %) is removed by drying in a rotary oven. Subsequently, nickel oxide is converted to nickel metal in a smelting furnace (1,360-1,610 °C), forming unrefined ferronickel, which, after purification of carbon and sulphur content, is primarily used to produce stainless steel.
- An alternative process for treating laterite ore is the 'High Pressure Acid Leach' (HPAL) technology, especially used to produce 'Nickel Pig Iron' (NPI) based on low-grade laterite ore. NPI is used as nickel alloy material in steel production. However, the HPAL

method is also employed to produce Class 1 products from high-grade laterite ores, and this method is expected to become dominant in supplying Class 1 products to the Li-ion industry.

In 2019, most of Class 1 products came from mines in Russia (20 %), Canada (19 %), Australia (14 %), China (10 %), and Indonesia (7 %), and were processed in China (25 %), Russia (15 %), Japan (14 %), Canada (12 %), and Australia (10 %) (McKinsey & Comp. 2020).

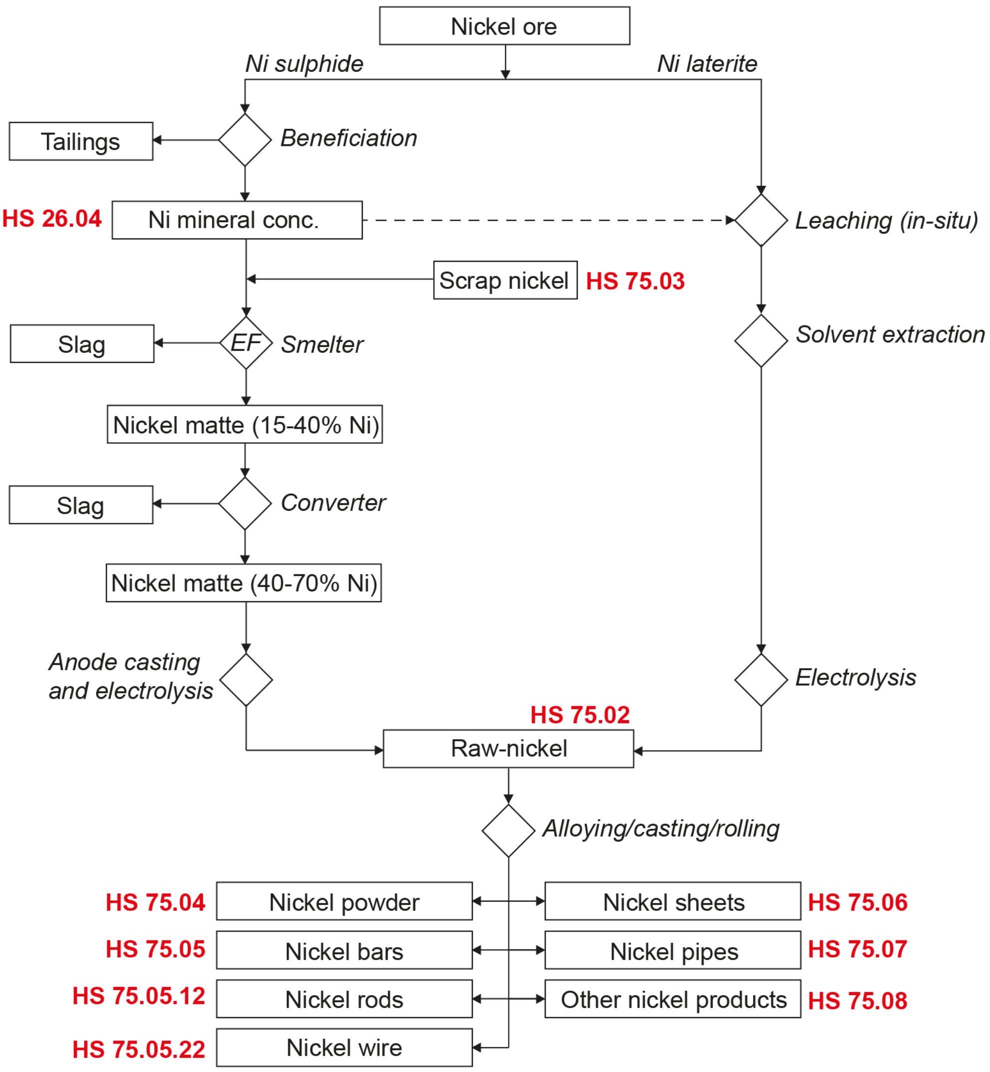


Figure 5-6 *Generic process diagram to produce nickel and nickel products through traditional pyro-metallurgical process and hydrometallurgical process, indicating selected Harmonized System (HS) codes for finished and semi-finished products.*

5.4.5 Climate and Environmental Impact

Nickel production, with a high-water consumption of 193 m^3/ton of nickel (Meissner 2021) and emissions from smelters of sulphur dioxide, nitrogen oxides, and particles, has significant environmental impacts.

The climate impact of nickel production is highly dependent on ore type and quality, as well as the specific product being estimated. Nickel production is reported to contribute to 0.27 % of global emissions (Nickel Institute 2022b). Wai *et al.* (2020) have estimated greenhouse gas (GHG) emissions and energy consumption associated with four different nickel products: nickel metal (Ni), nickel oxide (NiO), ferronickel (FeNi), and nickel pig iron (NPI). The estimates show that emissions can be up to 30 ton of CO_2e/ton of NiO, but emissions can be as high as 60 ton of CO_2e/ton of Ni if nickel is produced via an NPI route from laterite ore. The energy consumption is 370 GJ/ton, and emissions are calculated with existing mixed energy sources. Hydropower can significantly reduce emissions (Table 5-5). However, some of the most substantial reductions are achieved with the use of high-grade ore. Nevertheless, the trend is that ore grades are declining, and laterite ores are the largest in terms of volume.

Table 5-5 *Overview of energy consumption and CO_2 emissions to produce various nickel raw materials. Based on Wei* et al. *(2020).*

	Notes	**Ni**	**NiO**	**FeNi**	**NPI**
Emission (1) (CO_2e/ton)	Existing sources of energy	14	30	6	7
Emission (2) (CO_2e/ton)	Potential sources (Hydro)	7	17	5	7
Energy consumption (GJ/t)	Current	170	370	110	60
Energy consumption (GJ/t)	Ore-grade: 0.5 % Ni	200			
Energy consumption (GJ/t)	Ore-grade: 1 % Ni	120			
Energy consumption (GJ/t)	Ore-grade: 2 % Ni	50			

5.5 Trade

In Table 5-6 the main raw materials and HS codes for nickel supply chains, including trade value in 2020, is shown.

Nickel markets encompass both nickel minerals (‘nickel ore’) and semi-products manufactured at various stages of the supply chain, using the following market terms:

- Class 1 nickel (=refined nickel): Nickel product >99.8 % Ni (e.g., cathodes, briquettes, pellets).
- Class 2 nickel: Nickel product <99.8 % Ni (e.g., NPI, FeNi).
- NPI: Nickel Pig Iron – low nickel content produced from lateritic nickel ore (3-14 % Ni).
- FeNi: Ferronickel – low nickel content product (15-35 % Ni).
- Nickel matte: Typically, 30-60 % Ni.

The major product categories for selected nickel products, distributed among export and import countries, are shown in Table 5-7 to Table 5-11. It is evident from these tables that China is one of the largest importers of nickel, a trend traditionally driven by China’s globally dominant role as a steel producer.

Table 5-6 *The main raw materials and HS codes for nickel supply chains, with indication of trade value in 2020. Source: OEC World (2023).*

Ni-commodities	HS2 code	M. USD	HS4 code	M. USD	HS6 code	M. USD
Nickel Ore			2604	3700		
Ferro nickel					72.02.60	8900
Nickel articles	75	26400				
Nickel mattes			75.01	6200		
Nickel mattes					75.01.10	3700
Nickel oxide sinters					75.01.20	2500
Raw nickel			75.02	11100		
Nickel unwrought/not alloy					75.02.10	10100
Nickel unwrought/alloy					75.02.20	1000
Scrap nickel			75.03	900		
Nickel powders and flakes			75.04	1200		
Nickel bars			75.05	2900		
Bars, rods and profiles					75.05.12	1700
Wire, nickel alloy					75.05.22	1100
Nickel sheets			75.06	1003		
Nickel pipes			75.07	1000		
Other nickel products			75.08	1800		
Nickel sulphate					28.33.24	600

Table 5-7 *The four largest exporting countries and their three largest recipient countries for nickel ore (HS4 26.04) in 2020. However, China is the sole recipient of Australia's entire production. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Philippines	1,504	China Japan South Korea	1,387 107 9
New Caledonia	538	China Japan South Korea	304 280 150
Australia	308	China	308
Subtotal Others	2,602 1,088		- -
Total	3,690		-

Table 5-8 *The four largest exporting countries and their largest recipient countries for nickel matte (HS4 75.01) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Canada	1,211	Norway UK South Korea	995 193 15
Russia	1,193	Finland Switzerland China	910 169 61
Indonesia	1,172	Japan UK South Korea	776 344 33
Finland	570	China Norway France	185 138 117
Subtotal Others	4,146 2,044		
Total	6,190		

Table 5-9 *The four largest exporting countries and their largest recipient countries for raw nickel (HS4 75.02) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Russia	2,265	China Schweiz Germany	715 658 331
Canada	1,522	USA China Netherlands	761 207 177
Australia	1,508	China Singapore Japan	417 201 193
Norway	1,311	Netherlands China UK	551 161 128
Subtotal Others	6,605 4,521		
Total	11,126		

Table 5-10 *The four largest exporting countries and their largest importing countries for nickel bars (HS4 75.05) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
USA	734	China Mexico France	124 122 87
Germany	416	USA Italy UK	74 56 51
Austria	337	Germany UK USA	208 39 17
France	288	Germany Switzerland USA	86 75 42
Subtotal Others	1,775 1,092		
Total	2,867		

Table 5-11 *The four largest exporting countries and their largest importing countries for nickel scrap (HS4 75.03) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
UAE	264	Pakistan India UK	258 4 1
USA	90	Canada Japan UK	39 11 9
UK	77	USA Sweden Germany	42 8 5
Germany	47	Sweden USA UK	10 10 5
Subtotal Others	479 415		
Total	894		

International trade in nickel products shows that the major mining countries are generally the largest exporters of nickel ore concentrate (HS 26.04) and nickel matte (HS 75.01). Among the analysed product categories, the export values from just four countries account for 55-66 %, while the rest are distributed among many countries. China is the largest importer of nickel ore concentrate, primarily sourced from the Philippines, New Caledonia, and Australia. China is also the largest importing country for raw nickel (HS 75.02) and certain nickel semi-products such as nickel bars (HS 75.05). However, there are no trade data to map the value chains for Indonesia's significant primary production, which is only prominent in the export of nickel matte (HS 75.01). This ambiguity may be attributed to changes in the country's industrial policy, aiming to ensure increased value addition in all production and thus is only reported in one of the analysed product categories. Large quantities of nickel matte are imported to Norway and Finland from Canada and Russia, respectively. Data for trade in nickel scrap (HS 75.05) show import relationships, especially among several Western industrial countries. Furthermore, the data reveal that almost 30 % of the export-import is from the United Arab Emirates (UAE) to Pakistan, without specifying prior imports to the UAE. The relationships between the exporting and importing countries for the five major product categories are illustrated in Sankey diagrams (Figure 5-7 to Figure 5-11).

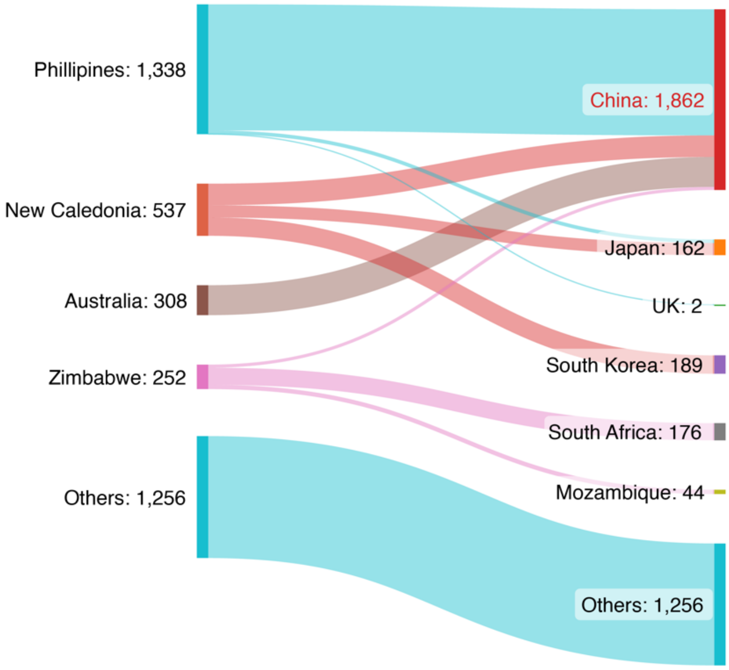


Figure 5-7 *Sankey diagram for trade in nickel ore (HS 26.04) in 2020. All values in million USD, based on Table 5-7.*

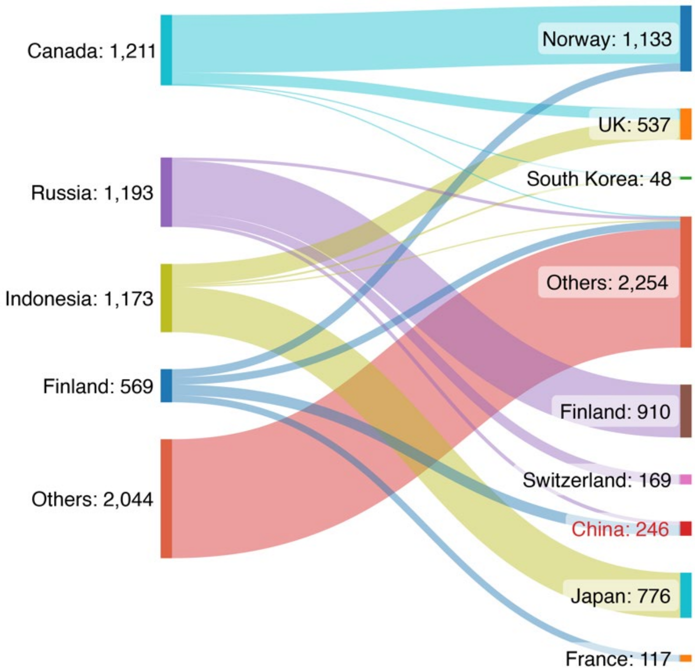


Figure 5-8 *Sankey diagram for trade in nickel matte (HS 75.01) in 2020. All values in million USD, based on Table* 5-8.

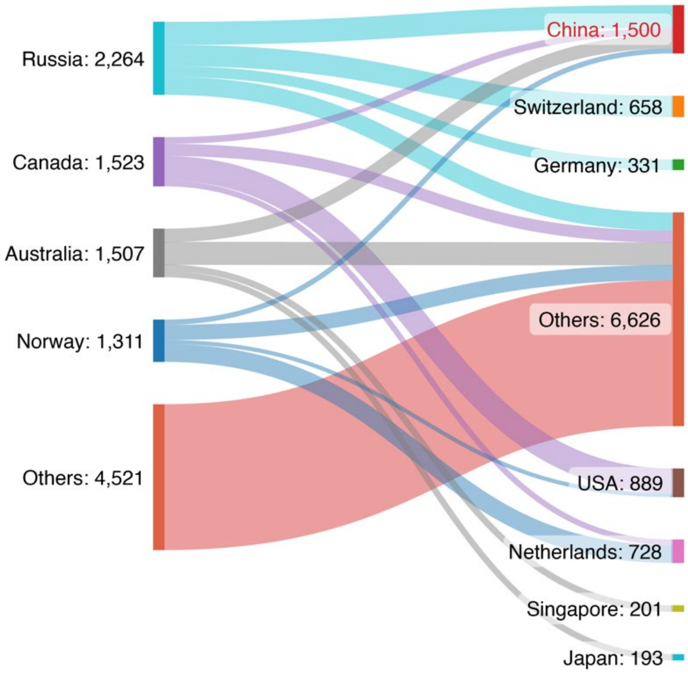


Figure 5-9 *Sankey diagram for trade in raw nickel (HS 75.02) in 2020. All values in million USD, based on Table 5-9.*

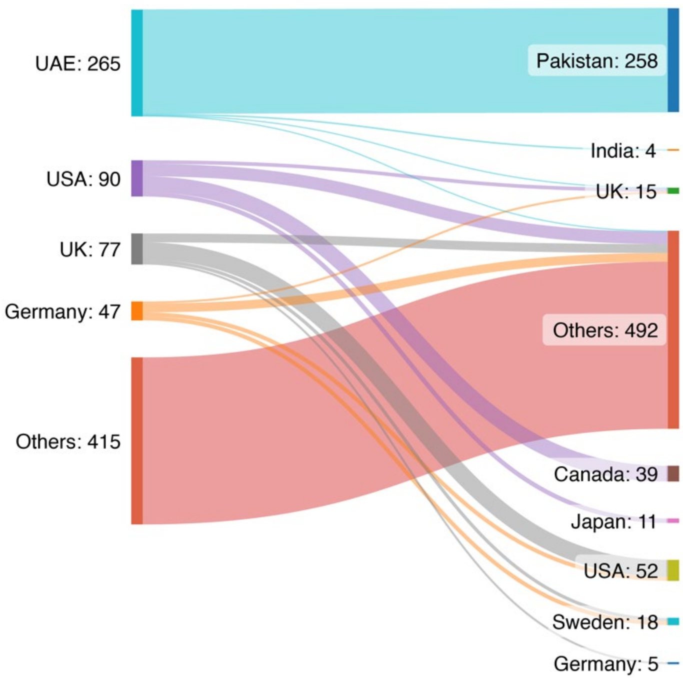


Figure 5-10 *Sankey diagram for trade in nickel bars (HS 75.05) in 2020. All values in million USD, based on Table* 5-10*.*

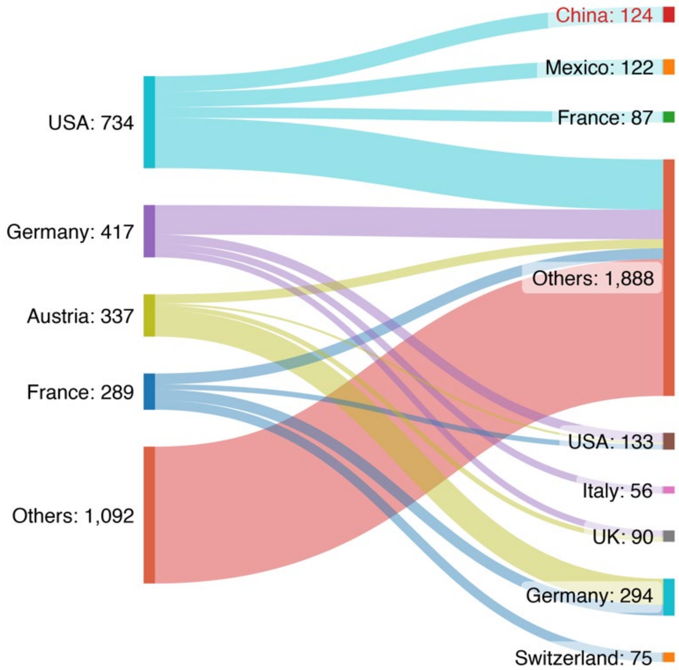


Figure 5-11 *Sankey diagram for trade in nickel scrap (HS 75.03) in 2020. All values in million USD, based on Table 5-11.*

5.5.1 Prices

The nickel market is volatile and sensitive to geopolitical events. Russia's invasion of Ukraine led to significant price increases since, before the invasion, Russia accounted for about 10 % of global nickel consumption and 15 % of Class 1 supplies.

Nickel is priced and traded on international metal exchanges, including the London Metal Exchange (LME), which has faced challenges from competing exchanges in the past year due to speculation issues against nickel following Russia's invasion of Ukraine. In March 2022, the LME had to halt nickel trading and cancel trades after prices surged by over 250 % in two days to over 100,000 USD/ton. This was attributed to a 'short period of time in which' investors who had sold nickel futures (in anticipation of price declines were forced to cover positions in a low-liquidity market). One nickel futures on LME represents 6 ton of nickel, and during the first month of 2022, total open interest in nickel futures represented roughly 1.3 million ton. The market has since stabilized.

Figure 5-12 shows average annual nickel prices from 2000 to 2022. Generally, nickel prices have been influenced by the production of steel and other iron alloys that incorporate nickel. The construction boom in China in the early 2000s and subsequent economic slowdown after the 2007 financial crisis played a crucial role in price development. Other significant events in the past decade include export bans on nickel (and their relaxations) in Indonesia, disruptions in nickel deliveries in the Philippines due to mine closures for environmental reasons, the COVID-19 pandemic, and Russia's invasion of Ukraine. All these factors have led to highly fluctuating nickel prices.

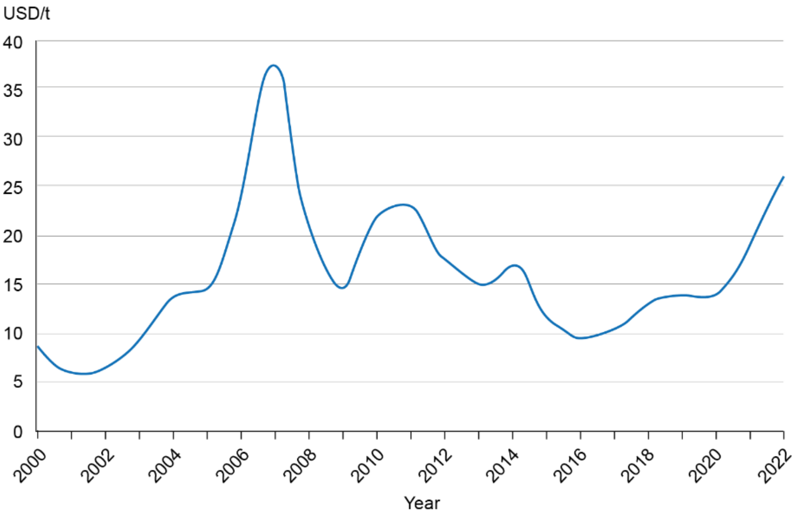


Figure 5-12 *Price development for nickel in the period 2000-2022. Source: Scrreen Nickel factsheet (2023) and Statista (2023a).*

5.6 The Danish Consumption

Nickel is one of the most significant raw materials for Danish industry, with an export value of 22 billion DKK and purchases totalling 48 billion DKK. In 2019, approximately 30,000 people were employed in relation to nickel in Denmark (Clausen *et al.* 2023). Nickel holds the third-highest derived importance for gross value-added growth, amounting to 35 billion DKK, surpassed only by iron and copper (Figure 5-13).

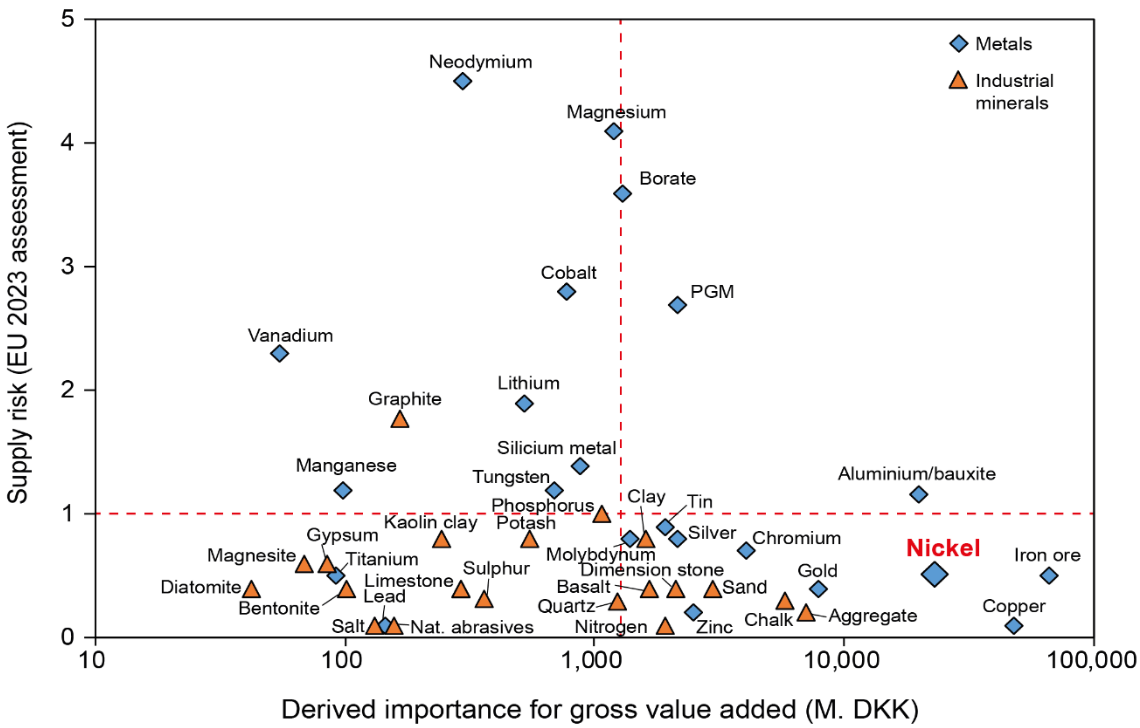


Figure 5-13 *Nickel and other raw materials' derived impact on gross value added as a function of supply risk. The Figure is modified from Clausen* et al. *(2023).*

Around 60 % of primary and secondary nickel purchases in Denmark are incorporated into material-complex products characterized by intricate supply chains, making it difficult to trace the origin of raw materials and assess supply risks. Typical end products in Denmark include construction steel, process plants, and various types of pipes (Clausen *et al.* 2023).

5.7 Perspectives

The production of nickel has increased by more than 5 % annually since 2000, reaching nearly 2.8 million ton in 2021. In recent years, exploration has been insufficient to mitigate a decline in the global reserves' lifespan. The majority of the world's nickel ore production occurs in countries facing political challenges, such as Indonesia, the Philippines, and Russia, which could impact production. A few large companies handle production, with major nickel ore producers being the Russian company Norilsk (330 kton in 2022), Nickel Asia Corp. (NAC) in Indonesia (111 kton in 2022), and Vale, which operates in both Canada and Indonesia (119 kton). China dominates other parts of the supply chains, and Indonesia is collaborating with Chinese companies to develop the country's industrial nickel infrastructure.

In 2023, the EU Commission assessed nickel as a strategic raw material due to its high economic significance (EI: 5.7). This designation signifies that nickel is a resource requiring special attention, despite the estimated low supply risks for both nickel ore (SRE: 0.4) and processed nickel (SRP: 0.5). Nickel does not technically meet the criteria for strategic raw materials. Criticality assessments are based on previous years' productions and trades and cannot be used for future scenarios. Nickel is considered a critical raw material in UK, USA, Japan, India, Canada, and China. However, the EU Commission (2023) did not classify nickel as a critical raw material, mainly because production is distributed among several countries, including traditionally stable producers like Canada and Australia, and because the recycling rate is relatively high. Due to nickel's crucial role in strategic technologies in Europe and expected increased demand, nickel is categorized as a strategic raw material in the EU (EC 2023).

Consensus is that the growth in Li-battery markets will influence nickel demand until 2030, with a total nickel requirement of 3.5-4.5 million ton in 2030 (Benchmark Mineral Intelligence 2023) and 6 million ton in 2040 (Benchmark Source (2023); Fleishmann *et al.* (2023); Statista (2023b)). China is expected to see an annual growth in nickel consumption of 11 %, followed by Canada (6 %), the EU (5 %), and Japan (4 %). Until 2035, the largest consumption area for nickel will be stainless steel, after which the demand for nickel in batteries will become dominant. These high growth rates pose a challenge to the supply side, leading several car manufacturers to invest in both mining and processing facilities, such as Ford Motor Co.'s 4.5 billion USD investment in mining and processing plants in Indonesia (Donovan 2023). Indonesia expects to produce approximately 60 % of the global nickel production in 2030.

Most analysts anticipate a minor nickel supply deficit in 2030 (e.g., Fleischmann *et al.* 2023). Indonesia is expected to become a significant future nickel producer, establishing an integrated supply chain for nickel products from mines to finished raw materials for the battery industry. This entire infrastructure is based on the country's abundant resources, numerous active mines, and a ban on nickel ore exports (minimum processing grade is NPI products). China is heavily involved, financially, trade-wise, technically, and advisory, in building Indonesia's nickel sector, especially to secure nickel supplies for cathodes in batteries for electric vehicles.

Only half of the global nickel production can be used to produce Class 1 products for Li-ion batteries, since other finished nickel products are contaminated by iron and copper (McKinsey & Company 2020). This is due to nickel ore mineralogy and/or manufacturing processes and poses a potential problem for future supplies.

5.8 References

Benchmark Source 2023: Nickel demand for batteries to overtake stainless steel in late 2030s. Nickel demand for batteries to overtake stainless steel in late 2030s | Benchmark Source (benchmarkminerals.com)

Benchmark Mineral Intelligence 2023: The Metals Company – Life Cycle Assessment for TMC's NORI-D polymetallic nodule project and comparison to key land-based routes for producing nickel, cobalt and copper. https://metals.co/wp-content/uploads/2023/03/TMC_NORI-D_LCA_Final_Report_March2023.pdf

Clausen, R. J., Kalvig, P., Keiding, J.K., Fold, N. & Vind, I. 2023: Dansk industris brug af mineralske råstoffer – økonomisk betydning og forsyningsudfordringer MiMa rapport 2023/2, pp. 181. https://doi.org/10.22008/gpub/32051

Donovan, B. 2023 Will we have enough nickel for our EVs in 2030? The Globe and Mail, April 17, 2023. www.theglobeandmail.com/investing/investment-ideas/article-will-we-have-enough-nickel-for-our-evs-in-2030/

Durden, J. M., Lallier, L. E., Murphy, K., Jaeckel, A., Gjerde, K., & Jones, D. O. 2018: Environmental Impact Assessment process for deep-sea mining in 'the Area'. Marine Policy, 87, 194-202.

European Commission (EC) 2023: Study on the Critical Raw Materials for the EU 2023 – Final Report. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

Fleischmann, J., Schaufuss, PO., Linder, M., Hanicke, M., Hortsky, E., Ibrahim, D., Jautelat, S., Torscht, L. & Rijt van der A. 2023: Battery 2030: Resilient, sustainable, and circular. January 16, 2023: Mc Kinsey & Comp Report. Lithium-ion battery demand forecast for 2030 | McKinsey

Hein, J. R., Koschinsky, A. & Kuhn, T. 2020: Deep-ocean polymetallic nodules as a resource for critical materials. Nature Reviews Earth & Environment, 1(3), 158-169.

IEA 2021: The Role of Critical Minerals in Clean Energy Transitions. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

McKinsey & Company 2020: How clean can the nickel industry become? https://www.mckinsey.com/industries/metals-and-mining/our-insights/how-clean-can-the-nickel-industry-become

Meissner, S. 2021: The impact of metal mining on global water stress and regional carrying capacities – A GIS based water impact assessment. Resources 2021, 10, 120. Doi.org/10.3390 resources 10120120

Mudd, G.M. & Jowitt, S.M. 2022: The new century for nickel resources, reserves and mining: Reassessing the Sustainability of the Devil's Metal. Economic Geology, Feb. 2022

Nickel Institute 2023a: About Nickel. https://nickelinstitute.org/en/about-nickel-and-its-applications/

Nickel Institute, 2023b: How to calculate GHG emissions from nickel production. https://nickelinstitute.org/en/blog/2022/may/how-to-calculate-ghg-emissions-from-nickel-production/

NORI 2020: Scoping document for a social impact assessment for the NORI-D Polymetallic nodule colletion project.Report 103 pp. https://metals.co/wp-content/uploads/2022/12/NORI-D-SIA-Scoping-Dec_2022.pdf

Observatory of Economic Complexity World (EOC World) 2023: Database https://oec.world/

Rosa, D. Kalvig, P. Stendal, H and Keiding, J.K. 2023: Review of the critical raw material resource potential in Greenland. MiMa rapport 2023/1, 121 pp.

Rosa D., Stensgaard, B.M. & Sørensen, L.L. 2013: Magmatic nickel potential in Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2013/57, pp. 134.

Sharma, R. 2015: Environmental issues of deep-sea mining. Procedia Earth and Planetary Science, 11, 204-211.

Scrreen2 Nickel factsheet 2023: Scrreen2 Factsheet updates based on the EU Factsheets 2020 Nickel. https://scrreen.eu/wp-content/uploads/2023/03/SCRREEN2_factsheets_NICKEL.pdf

Statista 2023a: Average prices for nickel worldwide from 2014 to 2024 https://www.statista.com/statistics/675880/average-prices-nickel-worldwide/

Statista 2023b: Renewable energy demand for nickel in worldwide in 2020, with forecast figures for 2030 and 2040, by sector and scenario. https://www.statista.com/statistics/1258903/worldwide-nickel-demand-for-renwable-energy-by-sector-and-scenario

Statista 2023c: Reserves of nickel worldwide as of 2022, by country. https://www.statista.com/statistics/273634/nickel-reserves-worldwide-by-country/

USGS 2000-2023: Mineral commodity summaries 2000-2023: U.S. Geological Survey https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries

Wei, W., Samuelsson, P.B., Tilliander, A., Gyllenram, R. & Jönsson, P.G. 2020: Energy Consumption and Greenhouse Gas Emissions of Nickel Products. Energies, vol 13, Issue 21

Washburn, T. W., Turner, P. J., Durden, J. M., Jones, D. O., Weaver, P., & Van Dover, C. L. 2019: Ecological risk assessment for deep-sea mining. Ocean & coastal management, 176, 24-39.

WMD 2022 (World Mining Data): Vol 37, 28 April 2022 https://www.world-mining-data.info/wmd/downloads/PDF/WMD2022.pdf

6. Tungsten

6.1 Introduction

Tungsten (W), which is number 74 in the Periodic Table of Elements, is a silver-grey, hard, heavy, and corrosion-resistant metal (19.3 g/cm^3) with an extremely high melting point (3,410 °C) and boiling point (5,555 °C). These properties make tungsten suitable for a variety of products, especially in industries such as transportation, mining equipment, construction, energy, and defence.

The production of tungsten products is based on the mining of tungsten-bearing minerals, which are exploited in many countries, with China being the dominant player in both mining and trade of tungsten. Globally, approximately 85 kton of tungsten mineral concentrate were produced in 2022 (USGS 2023). There are no comprehensive records of the total annual production of tungsten metal powder, the raw material for most tungsten products, and the proportion of recycled tungsten is also uncertain.

Tungsten's significant industrial importance, coupled with China's dominance in the supply chains, is why several countries consider tungsten a critical raw material, including the EU (EC 2023).

6.2 Applications and Sectors

Tungsten is particularly used in the following four industrial contexts:
Hard metal/Carbide: As tungsten carbide (WC), which is a material with hardness slightly less than diamond. Tungsten carbide, being hard, possessing high strength, and combinable with metallic binder materials such as cobalt, nickel, and iron, is especially used in the manufacturing of cutting and mining products such as drills, and mills. This sector consumes approximately two-thirds of the production.
Alloy Metal: Tungsten is used either as pure metal or mixed with other metals to produce alloys. Tungsten alloys, known for their strength, flexibility, resistance to wear and corrosion, and good electrical conductivity, are used in tungsten steel alloys to produce rocket motor nozzles, turbine blades, wear-resistant parts, and coatings. In certain steel types, tungsten content can reach up to 18 %.
Electronics: Tungsten, with its high melting point (3,410 °C) and low vapor pressure, is used in high-temperature applications such as bulbs, cathode ray tubes, and vacuum tube filaments. Due to tungsten's conductive properties and chemical inertness, it is also used in electrodes in devices like electron microscopes. Furthermore, tungsten's tolerance to intense heat makes it applicable in electronics, such as interconnect material in integrated circuits between the dielectric silicon dioxide material and transistors.
Chemicals: Tungsten chemicals are used in the form of tungsten oxides, tungstates, tungstic acid, silicotungstic acid, phosphotungstic acid, or tungsten sulphides. These chemicals find applications in oil and lubricants, mining, electronics, medical industry, etc., and serve as catalysts for desulphurization in coal-fired power plants.

The distribution between the mentioned applications is illustrated in Figure 6-1, which also shows the industries utilizing these products.

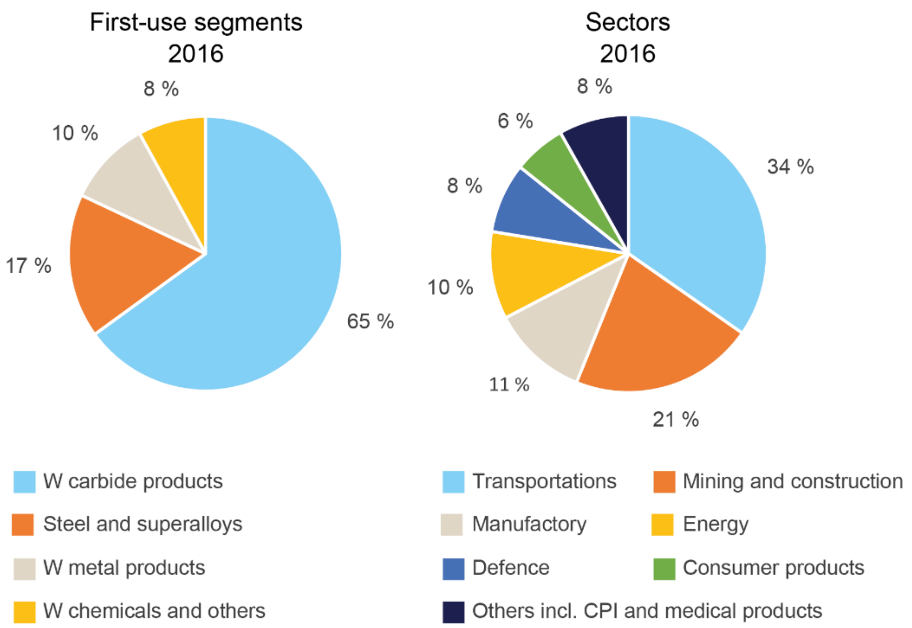


Figure 6-1 *Distribution of tungsten in relation to product types and industrial applications; data from 2016. Source: Zeiler* et al. *(2023).*

6.3 Recycling and Substitution

Recycled tungsten from both post-consumer scrap and end-use scrap constitutes a significant contribution to global tungsten consumption. End-of-Life Recycling Rate (EoL-RR) accounts for approximately 30 % (Zeiler *et al.* 2021); the quantities of tungsten scrap are expected to increase by around 8 % annually (Asian Metal 2023). Tang *et al.* (2020) estimates that the recycling rate in China is only about 10 %.

For certain purposes, tungsten can be substituted by other metals; this is the case, for example, with tungsten carbide for cutting tools, where tungsten carbide can be substituted by boron nitride, which has roughly similar properties. For certain applications, molybdenum and nickel can substitute tungsten in steel (Graedel *et al.* 2013). The European Commission (EC 2023) has estimated the EU's substitution indices, SI-SR and SI-EI, at 0.86 and 0.82, respectively.

6.4 Global Supply

6.4.1 Geology

Tungsten is found in various geological environments, where the ore commonly also contains other economically important metals. The main types of occurrences are:

- Veins: formed where metal-rich fluids have infiltrated fractures, often in granitic rocks; wolframite is the dominant tungsten mineral, and typical by-products include tin, copper, and molybdenum. Tungsten content typically varies between 0.5-5 % WO_3. Examples in Europe include Panasqueira (Portugal) and San Fix (Spain).
- Skarn Deposits: where tungsten, along with other metals, has precipitated in carbonate rocks; scheelite is the dominant tungsten mineral, and typical by-products include copper, molybdenum, zinc, and bismuth. Grades vary but are typically 0.3-1 % WO_3. An example in Europe is Los Santos (Spain).

- Porphyry Deposits: formed in connection with subduction zones, tungsten is found in both scheelite and wolframite; typical by-products include molybdenum, bismuth, and tin. Grades are typically 0.1-0.3 % WO_3. An example in Europe is Mittersill (Austria).
- Tungsten Sand Deposits/Placers: where tungsten is found in both scheelite and wolframite, typically accompanied by minerals containing tin, copper, molybdenum, bismuth, and gold.

Tungsten resources worldwide are associated with fold belts in Southern China, Thailand, Myanmar, South Korea, and Japan, as well as in Southern Siberia, Kazakhstan, Uzbekistan, Kyrgyzstan, and the Caucasus, in Eastern Australia, Western Canada, the USA, Bolivia, and Peru. In Europe, tungsten belts extend from Germany and Czechia through France, Spain, and Portugal (Figure 6-2).

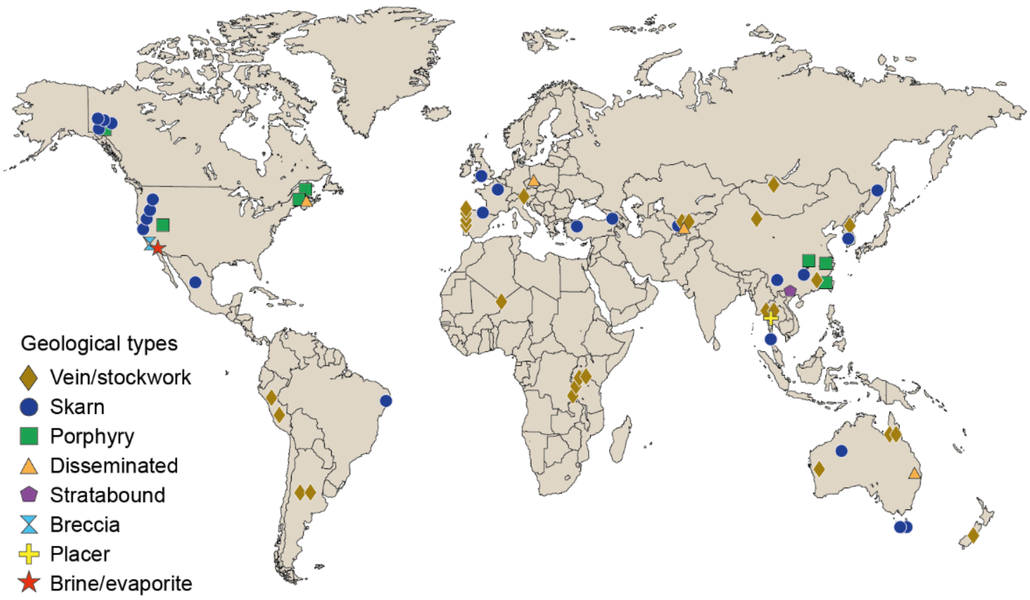


Figure 6-2 *Overview of some of the largest geological occurrences of tungsten, categorized by type. Source: Han* et al. *(2021).*

6.4.1.1 Minerals and By-products

More than 30 tungsten-bearing minerals are known, but only scheelite ($CaWO_4$) and wolframite ($(Fe,Mn)WO_4$) are considered commercial. Tungsten mineralization occurs in various geological environments, which determine the tungsten minerals present and the potential for by-products. The important geological types and mineralizations are listed in Table 6-1.

Table 6-1 *Typical tungsten minerals, grades, and potential by-products distributed for some of the most important geological types with tungsten.*

Geological types	Ore-grades (WO_3 %)	Tungsten mineral	Mineral formula	Potential by-products
Skarn/greisen	0.3-1.4	Scheelite	$CaWO_4$	Cu, Mo, Zn, Bi
Vein	variable	Wolframite	$(Fe,Mn)WO_4$	Sn, Cu, Mo, Bi, Au
Porphyry	0.1-0.4	Wolframite +/- scheelite	$(Fe,Mn)WO_4$ + $CaWO_4$	Mo, Bi, Sn
Pegmatite	0.5-0.8	Scheelite +/- wolframite	$CaWO_4$ + $(Fe,Mn)WO_4$	Li, Be, Nb, Ta, REE, Sn
Placer	<0.5	Wolframite + scheelite	$(Fe,Mn)WO_4$ + $CaWO_4$	Sn, Cu, Mo, Bi, Au

6.4.2 Global Tungsten Reserves

There are various estimates of global tungsten reserves and resources. USGS (2023) estimates global tungsten reserves to be approximately 3.4 million metric ton of WO_3, with China holding almost half (1.8 million ton), Russia around 400 kton, and Vietnam 95 kton. Within the EU, approximately 70 kton are reported (Austria, Portugal, and Spain). Additionally, 1.4 million ton are accounted for in various other countries, including Australia, North Korea, and Vietnam. Hughes (2020) estimates, based on data from 2018, that Australia's resources are around 400 kton WO_3, and Russia's are approximately 240,000 ton WO_3. Tungsten reserves were reported as 1.9 million ton for 2010 and 2.9 million ton for 2020 (USGS 2001, 2011), with most of the increases, similar to those of the past decade, attributed to China (Table 6-2). However, these estimates are highly uncertain as the industry releases very limited information. Reserve assessments do not include information about the type of occurrence, but based on Han *et al.* (2012), reserves are believed to be dominated by scheelite associated with vein and skarn types. Reliable assessment of global resources is not possible, and consequently, the lifespan of reserves cannot be estimated.

Table 6-2 *World tungsten reserves in ton of WO_3 for the years 2001, 2010, and 2022, compiled for 14 countries and the category 'other'. Sources: USGS (2001, 2011, 2023).*

Land	2001	2010	2022
USA	140,000	140,000	
Australia	1,000		
Austria	10,000	10,000	10,000
Bolivia	53,000	53,000	
Brazil	20,000		
Myanmar	15,000		
Canada	260,000	120,000	
China	820,000	1,900,000	1,800,000
Portugal	25,000	4,200	3,100
Russia	250,000	250,000	400,000
Spain			56,000
South Korea	58,000		
Thailand	30,000		
Vietnam			100,000
Andre	300,000	400,000	1,400,000
Total	**1,982,000**	**2,877,200**	**3,769,100**

6.4.3 Global Tungsten Production

The primary production of tungsten from mining over the past 22 years reflects global economic development and China's industrialization strategy. For more than two decades, China has been the dominant producer of tungsten in all parts of the value chains and primary tungsten production. In the same period, the EU has been a marginal producer (Figure 6-3 and Table 6-3). In 2014, China introduced production quotas for tungsten. The production quota for 2023 allows for a production of 110 kton of WO_3 produced in China, which is more than the total global production (Figure 6-4).

Mining of tungsten minerals occurs both from open-pit and underground mines, as well as from loose deposits (tungsten sand deposits).

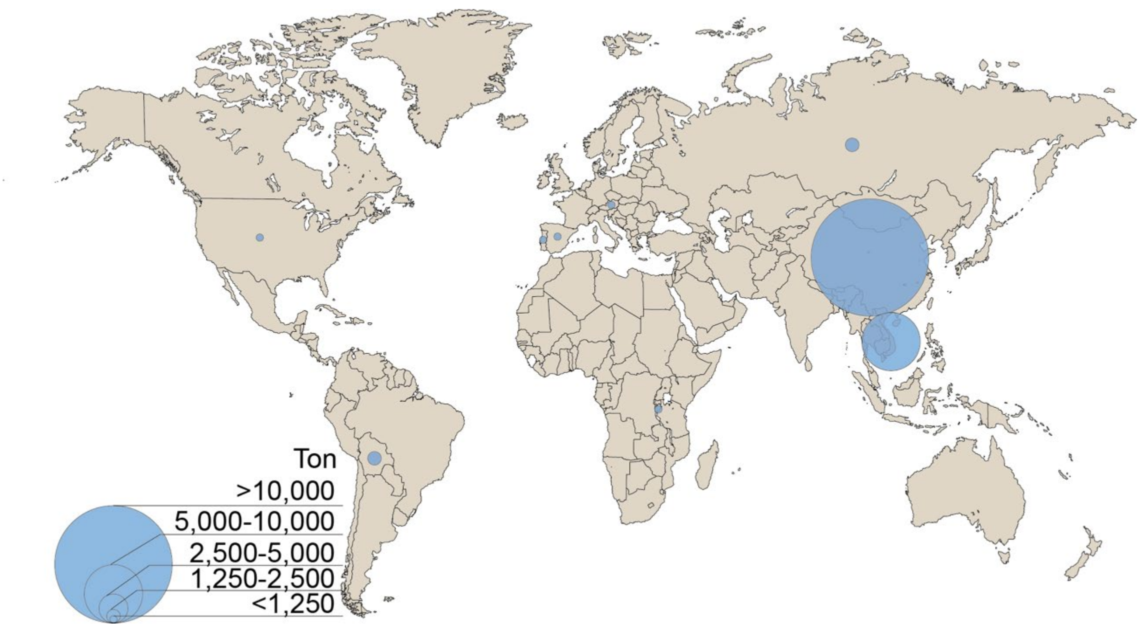


Figure 6-3 *Overview of the ten largest tungsten mining countries. Source: USGS (2023).*

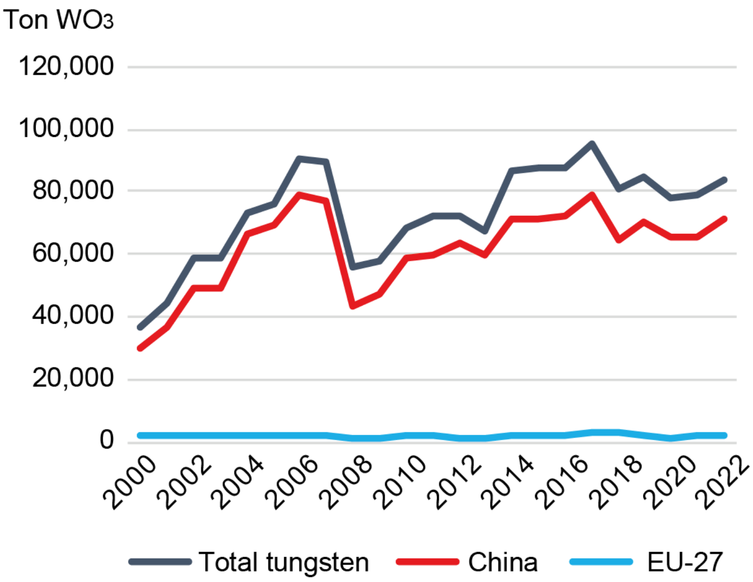


Figure 6-4 *Overview of historical tungsten (WO_3) production in the period 2000-2022. Source: USGS (2000-2023).*

6.4.3.1 Companies Involved in the Production and Processing of Tungsten

There is only limited information on the primary production of tungsten and the contributions of major producers in the supply chains. Table 6-4 provides an overview of major mines that extract tungsten as either a primary or by-product. Additionally, Table 6-5 presents a list of exploration and production projects involving tungsten; both are compiled based on publicly available information and are incomplete. Table 6-6 shows an incomplete overview of companies involved in the value chains of tungsten products.

Table 6-3 *Tungsten mining production in ton. Sources: USGS (2023) and WMD (2023).*

Production country	2022 (USGS)	2020 (WMD)
China	71,000	71,450
Vietnam	4,800	8,066
Russia	2,300	2,274
Bolivia	1,400	1,347
Rwanda	1,100	1,075
Austria	900	896
Spain	700	400
Portugal	500	553
USA	n,a,	n,a,
Others	1,400	1,446
Total	**84,100**	**87,507**

Table 6-4 *Overview of major mines extracting tungsten as either a primary or by-product. Incomplete overview.*

Mine	Country	Company
King Island	Australia	Group 6 Metals
Kara Mine	Australia	Tasmania Mines Pty
Chojillia Mine	Bolivia	Comibol
Tasna	Bolivia	Comibol
Juan Tungsten Mine	Bolivia	Comibol
Xi’an Huashan	China	ChongYiZhangYuan Tungsten Group
Lianhuashan (Guangdong)	China	
Shizhuyuan (Hunan)	China	Hu Nan Shizhuyuan Non-ferrous Metal Ldt Corp.
Yaogangxian Tungsten Mine, Yizhang County, Chenzhou, Hunan	China	China Tungsten & High-tech Material Co. Ltd
Panasqueira	Portugal	Almonty Industries
Kordonnoe	Russia	Primosky GOK
Novoorlovsky Mine	Russia	
Vostok-2	Russia	Primosky GOK
Musha Ntunga Mines	Rwanda	Trinity Metals Ltd
Rutongo Mines	Rwanda	Trinity Metals Ltd
Nakabingo	Rwanda	Trinity Metals Ltd
Los Santos mine (care & maint)	Spain	Almonty Industries
Okbang	South Korea	
Sangdong	South Korea	Jinheung Mining Company/Almonty Industries
Climax	USA	Freeport-McMoRan Copper & Gold
Nui Phao	Vietnam	Masan Resources
Mittersill	Austria	Wolfram Bergbaqou und Hütten AG

Table 6-5 *Incomplete overview of exploration and production projects. The Dolphin W and Hemerdon Mine are under development.*

Exploration project	Country	Company	Geological type	Resource	Grade (WO_3 Wt.%)
Dolphin W-project	Australia	King Island Scheelite/Almonty Industries	Skarn	-	-
Hemerdon Mine	UK	Tungsten West	Skarn	26.7 Mt	0.19
Big Hill project	Australia	Tungsten Mining	Vein	-	-
Hatches Creek	Australia	Tungsten Mining	Vein	-	-
Kilba project	Australia	Tungsten Mining	Skarn	5 Mt	0.27
Molyhil Tungsten	Australia	Thor Mining	Skarn	9 kton	-
Mount Carbine	Australia	Icon Resources	Vein	-	-
Mount Mulgine project	Australia	Tungsten Mining	Vein	145 kton	-
Watershed W project	Australia	Vital Metals/Tungsten Mining	Skarn	-	-
Dublin Gulch	Canada	Victoria Gold Corp	Skarn	-	-
Dungarvon	Canada	Geodex Minerals Ltd	Vein	-	-
Mt Pleasant	Canada	Adex Mining Inc	Porphyry	14.4 Mt	0.26
Sisson W-Mo - project	Canada	Northcliff Resources	Porphyry	-	-
Remoor	UK	Strategic Minerals Plc	Vein	-	-
Xingluokeng (Fujian)	China		Porphyry	142 kton	-
Heinze Basin	Myanmar	n.a.	Placer	-	-
North Osterdalen	Norway	Playfair Mining Ltd		-	-
Folldal	Norway	Playfair Mining Ltd	Skarn	-	-
RKV	Norway	Playfair Mining Ltd		-	-
Barruecopardo	Spain	Ormonde Mining	Vein	8.7 Mt	0.3
Valteixal	Spain	Almonty Industries	Skarn	2.5 Mt	0.34

6.4.4 Production of Tungsten

Processing tungsten ore is organized based on whether the ore is dominated by wolframite or scheelite and considering any potential by-products, typically tin, copper, molybdenum, zinc, bismuth, and gold, which may be present as separate minerals. The typical processing includes crushing, grinding, and subsequent separation (based on gravimetry), flotation, magnetic and/or electrostatic separation. The final product is typically a mineral concentrate containing 50-75 % WO_3. The mineral concentrate can be used directly in the steel industry and as raw material to produce tungsten metal powder (TMP).

Most productions involve leaching and the production of ammonium paratungstate (APT), some of which is used to produce ammonium metatungstate (AMT), while the rest is used to produce tungsten metal powder, a raw material for most of commercial tungsten products, including carbides, alloys, and cast/rolled products (Figure 6-5). Leal-Ayala *et al.* (2015) estimate that approximately 73 % of tungsten mineral concentrate is used for TMP production, with about 70 % of that used to produce tungsten carbides. The production of 1 ton of tungsten carbide consumes approximately 2 ton of tungsten mineral concentrate, with most of the loss occurring in the APT production process.

Table 6-6 *Overview of major companies involved in the manufacturing of tungsten products. Incomplete list.*

Company	Country	Company	Country
Group 6 Metals Ltd	Australia	Zhuzhou Cemented Carbide Group Corp Ltd	China
Tungsten Metals Group Ltd	Australia	Zigong Cemented Carbide Co Ltd	China
Tungsten Mining NL	Australia	OC Oerlikon Corp	Switzerland
Venture Minerals Ltd	Australia	Saloro SLU	Spain
Eurotungstene	Belgium	Sandvik Group	Sweden
Umicore N.V.	Belgium	Taegu Tec Ltd	South Korea
Fireweed Metals Ltd	Canada	Lianyou Metals Co Ltd	Taiwan
OMCD SpA	Italy	Betek GmbH & Co KG	Germany
Advanced Material Japan Corp	Japan	Cronimet Ferroleg GmbH	Germany
ALMT Corp	Japan	Grondmet GmbH & Co Kg	Germany
Hitachi Metals	Japan	HC Starck Tungsten GmbH	Germany
Japan New Metals	Japan	Stadler Metalle eK – Handel & Aufbereitung	Germany
Kohsei Co Ltd - Kitakyushu Plant	Japan	American Elements	USA
Mitsubishi Materials Corp	Japan	Buffalo Tungsten Inc	USA
Sumitomo Corp	Japan	Extramet products LLC	USA
CERATIZIT	China	Federal Karbide Comp.	USA
China Minmetals Non-Ferrous Metals Co	China	Global Tungsten & Powders	USA
China Tungsten & Hightech Materials Co Ltd	China	Greystone Alloys Inc	USA
Chongyi Zhangyuan Tungsten Co Ltd	China	Hyperion Materials & Technologies USA LLC	USA
Guangdong Xianglu Tungsten Co Ltd	China	Kennametal Inc	USA
Jiangxi Tungsten Holding Group Co Ltd	China	Mi-Tech Tungsten Metals LLC	USA
Jiangxi Yaosheng Tungsten	China	Tungco Inc	USA
Nanchang Cemented Carbide Ltd Co	China	Masan High-Tech Materials	Vietnam
Xiamen Tungsten Co	China	Wolfram Bergbau-und Hutten AG	Austria

6.4.5 Climate and Environmental Impact

Most of the total energy consumption to produce tungsten carbide from tungsten mineral concentrate is consumed in the processes from APT to WC (tungsten carbide) (via WO_3 and W). It is estimated that the overall energy consumption is 16 MWh/ton of tungsten carbide. Efforts are underway to change the process to a carbothermic reduction process of the mineral concentrate, with an expected reduction in energy consumption of approximately 50 %. The proposed direct method will also reduce CO_2 emissions by around 30 % and decrease material loss and the release of environmentally harmful waste streams (Polini *et al.* 2021). The production of 1 ton of tungsten carbide requires approximately 117 m^3 of water, primarily used in the hydrometallurgical processes of mineral concentrates for APT production. As a result of these processes, almost 1 ton of hazardous waste is generated per ton of tungsten carbide.

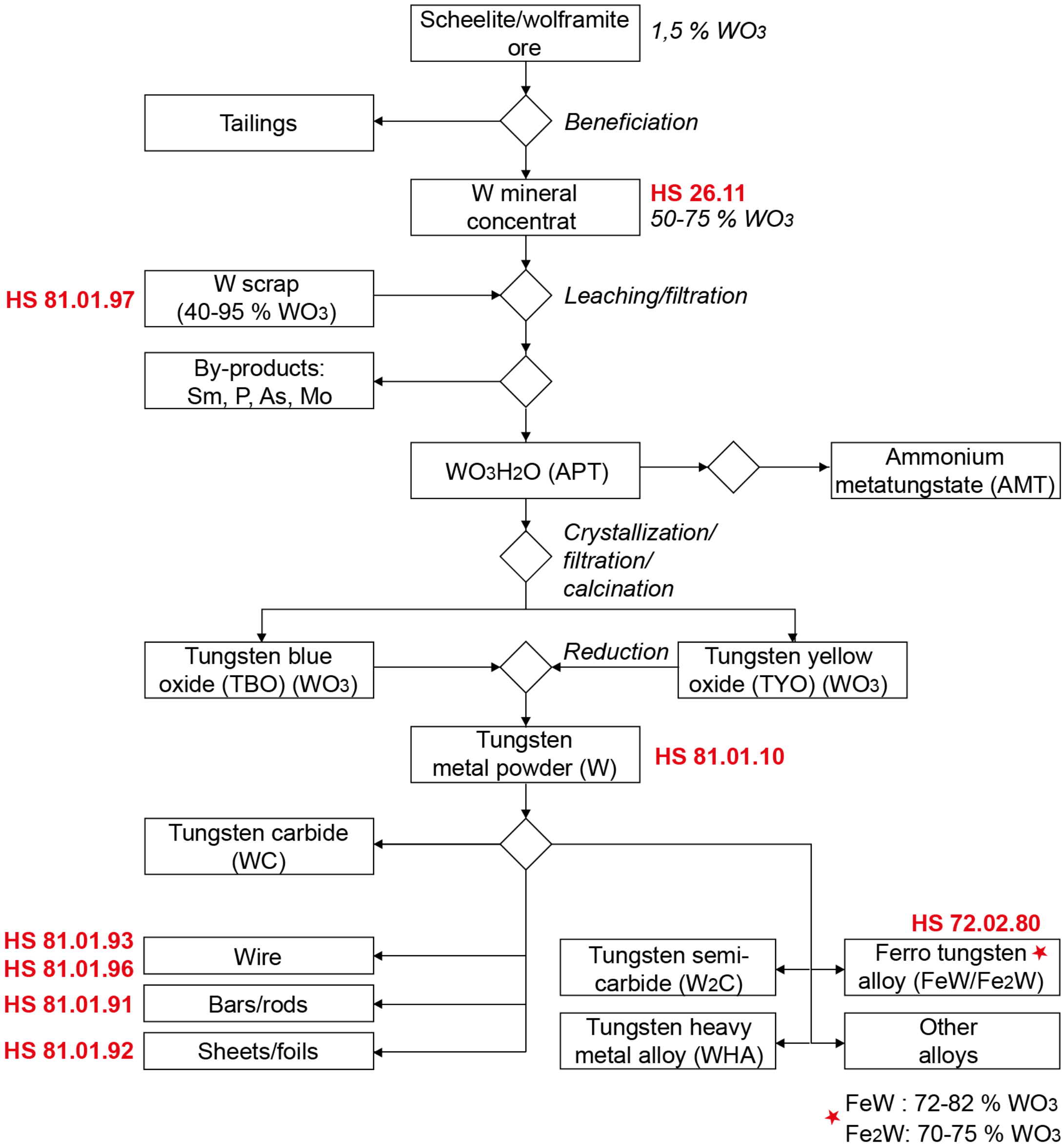


Figure 6-5 *Generic process diagram to produce tungsten, indicating selected Harmonized System (HS) codes for finished and semi-finished products. Based on, among others, Leal-Ayala* et al. *(2010).*

6.5 Trade

Tungsten is traded in a wide range of forms, including the aforementioned products/semi-finished goods such as APT, AMT, tungsten metal powder (W), tungsten carbide (WC), tungsten trioxide (WO_3), Tungsten Blue Oxide (TBO), ferrotungsten (FeW and Fe_2W). The diverse products are reflected in complex trading patterns, occurring either through bilateral agreements directly between primary producers, secondary processing companies, and tertiary producers or through intermediaries (Keiding 2014).

Tungsten trade primarily involves the main groups of tungsten ore (HS 26.01) and Tungsten and articles thereof (HS 81.01), which accounted for USD 217 million and USD 1.24 billion in 2020, respectively (Table 6-7). Neither of these product categories specifically includes the semi-finished products APT and AMT, which are commercial products and form the basis for pricing.

Rwanda, Russia, Bolivia, Myanmar, and Portugal are the largest exporters of tungsten ore (HS 26.11), with China being the largest importer (Table 6-8 and Figure 6-6). In Europe, particularly Austria and the Netherlands import tungsten ore, some of which is sourced from Russia. Vietnam's reportedly significant production of tungsten ore does not result in the export of the most common tungsten products. None of the three largest tungsten ore-exporting countries appears to export processed tungsten raw materials. However, there is a significant overlap in countries that import tungsten ore and export tungsten powder (HS 81.02.10). This includes China, which also has a large domestic production of tungsten ore, as well as the USA and Austria. The origin of raw materials for the Czech Republic's export of tungsten powder is not clear (see Table 6-9 and Figure 6-7).

There is a considerable international trade in tungsten scrap (HS 81.01.97), with Germany being the dominant exporting country, supplemented by Japan, the USA, and China. The trading pattern for this trade shows that several countries both import and export scrap, such as the USA, Germany, and China (Table 6-12 and Figure 6-8).

Table 6-7 *Overview of traded tungsten products with indication of trade value and product code. Source: OEC World (2023).*

HS4	Commodity	Export (M. USD)	HS6	Commodity	Export (M. USD)
26.11	Tungsten ore	217	26.11.00	Tungsten ores and concentrates	217
81.01	Tungsten	1,240	81.01.10	Powders, tungsten	237
			81.01.91	Tungsten unwrought	477
			81.02.92	Tungsten profiles, sheet or foil	-
			81.01.93	Tungsten wire	111
			81.01.94	Tungsten bars and rods	109
			81.01.95	Bars and rods	-
			81.01.96	Wire	114
			81.01.97	Waste and scrap	392
			81.01.99	Tungsten and articles thereof	416
			85.39.21	Filament lamps, tungsten halogen	1,510

Table 6-8 *The main export and import countries for tungsten ore and concentrates (HS6 26.11.00) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Rwanda	52	Singapore	14
		UAE	12
		Hong Kong	11
		Luxembourg	7
		China	6
Russia	34	Austria	12
		Netherlands	11
		China	4
		USA	4
		South Korea	1
Bolivia	32	USA	14
		China	11
		Netherlands	3
		Austria	2
		Canada	1
Myanmar	18	China	16
		Vietnam	2
Portugal	14	USA	10
		Austria	4
Subtotal	149		
Others	67		
Total	217		

Table 6-9 *The main export and import countries for tungsten powder (HS6 81.01.10) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
China	72	South Korea	35
		USA	13
		Japan	11
		Canada	3
		Nigeria	2
Czech Rep.	30	Austria	12
		France	6
		Poland	5
		Germany	3
		Finland	2
USA	28	Canada	18
		Germany	2
		Mexico	1
		South Africa	1
		Netherlands	1
Austria	26	Germany	15
		USA	6
		France	2
		Italy	1
		Czech Rep.	0
Canada	15	USA	11
		Germany	2
		Australia	1
		China	1
Subtotal	171		
Others	66		
Total	237		

Table 6-10 *The main export and import countries for tungsten and its articles (HS4 81.01) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
China	333	USA	207
Germany	194	Germany	149
USA	111	Japan	109
Japan	110	Austria	103
Austria	68	South Korea	78
Subtotal Others	816 425		
Total	1,241		

Table 6-11 *The main export and import countries for tungsten filaments (HS6 85.39.21) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
China	455	USA	299
Germany	357	Germany	128
Poland	80	Poland	80
Japan	80	France	72
USA	67	China	50
Subtotal Others	1,039 469		
Total	1,508		

Table 6-12 *The main export and import countries for tungsten scrap (HS6 81.01.97) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Germany	127	Austria USA Finland France Singapore	47 35 18 4 4
Japan	29	Taiwan Germany Singapore South Korea Austria	6 5 5 3 3
USA	27	Finland Germany UK Canada Pakistan	14 5 3 1 1
China	24	Japan UK USA Germany Netherlands	12 5 5 1 1
Subtotal Others	207 185		
Total	392		

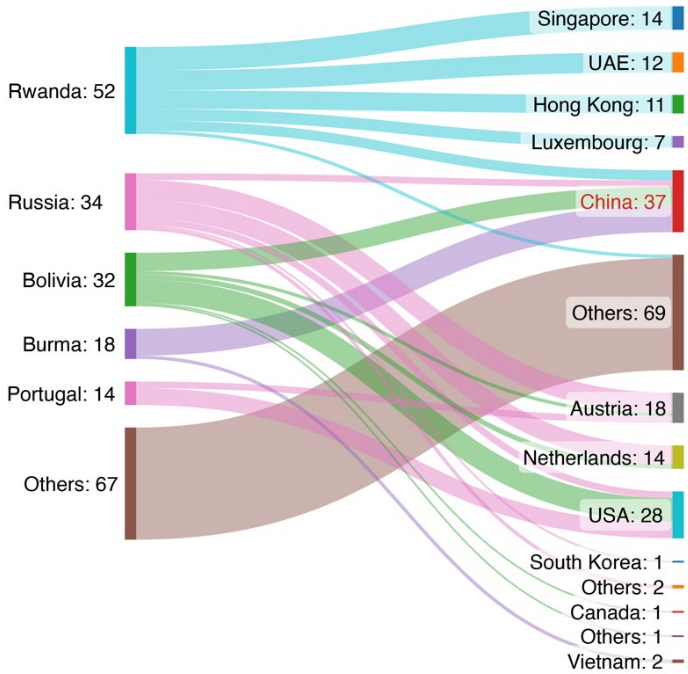


Figure 6-6 *Sankey diagram for global trade in tungsten ore and concentrates (HS4 26.11) in 2020. All values in million USD, based on data from 6-8.*

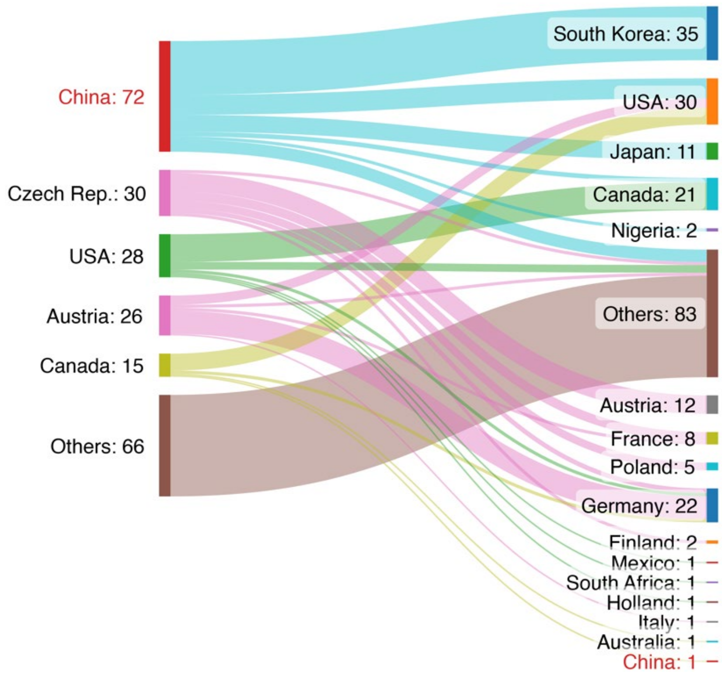


Figure 6-7 *Sankey diagram for global trade in tungsten powder (HS6 81.01.10) in 2020. All values in million USD, based on data from table 6-9.*

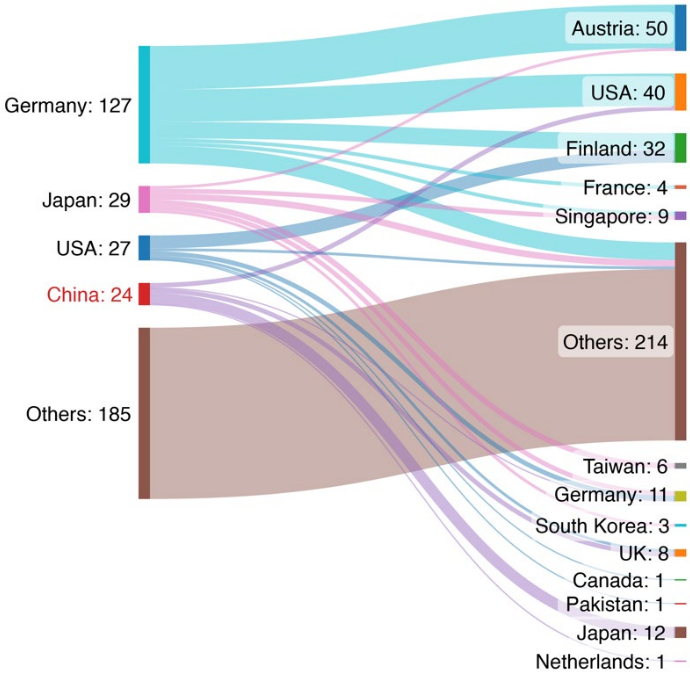


Figure 6-8 *Sankey diagram for global trade in tungsten scrap (HS6 81.01.97) in 2020. All values in million USD, based on data from Table 6-12.*

6.5.1 Prices

Tungsten, in the form of mineral concentrate (scheelite and/or wolframite) (65 % WO_3), APT, and tungsten carbide, is traded on Chinese exchanges, and price changes are reflected in all three product types. The price development for all three products has shown an increasing trend since 2000, with a significant decline in 2016-2017. Since 2020, prices have been on the rise due to growing demand, China's quota schemes for tungsten production and export, as well as increased environmental measures and the impact of COVID-19. Analysts expect continued price increases in 2024. It should be noted that the price development of tungsten products is also influenced by the negotiation of long-term contracts between relatively few large companies, such as Zhang-yuan Tungsten Industries and Jiang Tungsten Group. Figure 6-9 illustrates the prices in China for wolframite, APT, and tungsten powder.

6.6 The Danish Consumption

In Denmark, tungsten is primarily used for hard metals (including carbides) and as an alloying metal in steel, mainly in the machine industry for products like tools and wear-resistant steels. Purchases of tungsten amounted to 829 million DKK in 2019, whereas the metal was related to exports of around 1 billion DKK and providing employment for approximately 1,000 people in the same year (Clausen *et al.* 2023). Tungsten and vanadium have the least economic significance in Denmark among the eight raw materials analysed in this report (Figure 6-10). However, it should be noted that the data coverage for tungsten (and vanadium) is low in the study, and thus is subject to considerable uncertainty.

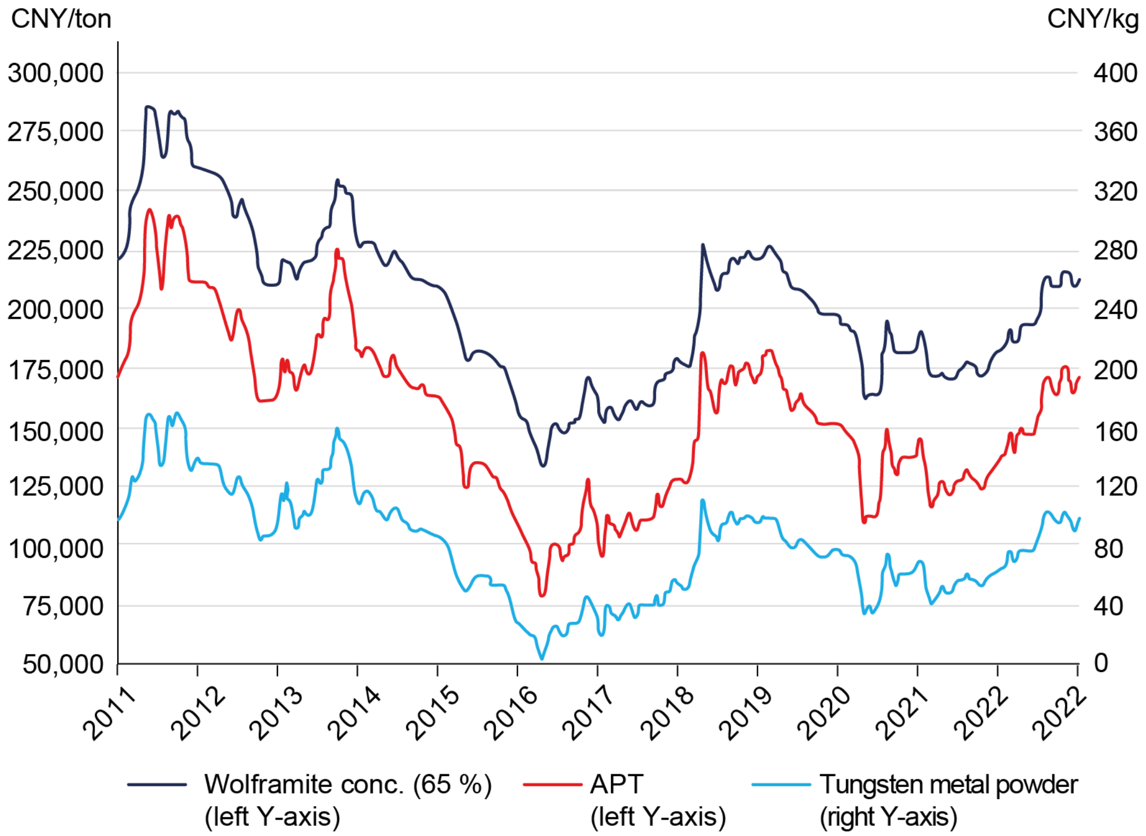


Figure 6-9 *Price development in China from 2011 to 2022 for tungsten mineral concentrate (65 % WO_3), ammonium paratungstate (APT), and tungsten carbide. Source: China Tungsten (2022).*

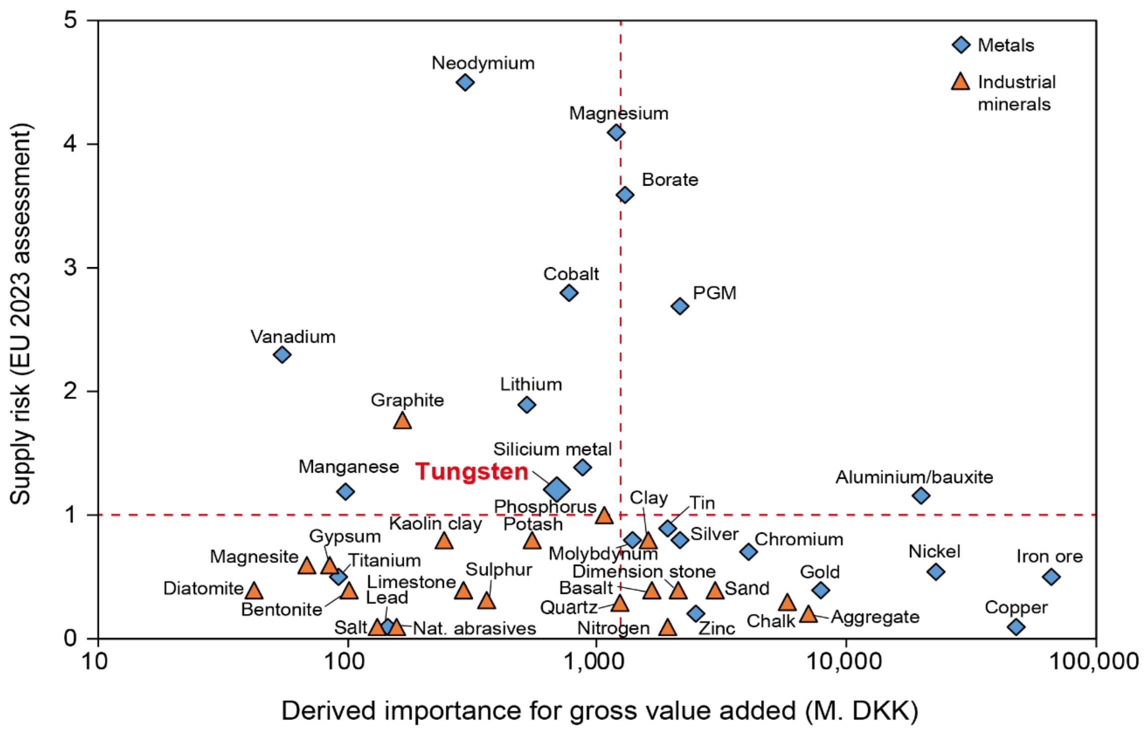


Figure 6-10 *Tungsten and other raw materials' derived impact on gross value added as a function of supply risk. Modified from Clausen* et al. *(2023).*

6.7 Perspectives

The EU Commission considers tungsten a critical raw material due to its significant economic importance for the EU (Economic Importance: 8.7). Tungsten is assessed to have a relatively high supply risk, especially linked to processing (Supply Risk Processing: 1.2), whereas the supply risk for extraction is considered low (Supply Risk Extraction: 0.5). Tungsten is also classified as critical by the UK, the USA, Japan, Canada, and China, despite China being the dominant tungsten producer.

Global tungsten ore production is dominated by China (84 %), followed by Vietnam, Russia, Bolivia, and Rwanda, which together produce about 11 %. These countries are generally considered economically/politically unstable. The supply chains for tungsten from mine to raw materials are dominated by a few vertically integrated companies, including China Tungsten & High-tech Material Co in China, Primosky GOK in Russia, Comibol in Bolivia, and Trinity Metals Ltd in Rwanda.

The most needed products in the future are expected to be hard metal/carbides, superalloys, and wear parts, particularly required by the automotive, aviation, and electrical/electronic industries. The global tungsten industry is projected to grow from approximately 120 kton in 2022 to 170 kton in 2030, representing about 6 % growth (MMR 2023). For countries outside of China, these growth scenarios may pose a challenge due to China's production quotas for tungsten, set at 110 kton of mineral concentrate (65 % WO_3) for 2023 (Reuters 2023), and not expected to change in 2024; China's production capacity is estimated to be approximately 170 kton. Tang *et al.* (2020) expects that China's dominance in tungsten production will decrease over time due to its relatively low-grade ore deposits. The high growth rate may be accommodated if more new projects in Australia, Canada, Norway, and Spain are put to production, and supply chain infrastructure is developed in countries other than China.

6.8 References

Asian Metal 2023: http://metalpedia.asianmetal.com/metal/tungsten/recycling.shtml (visited nov. 21, 2023)

China Tungsten 2022: (http://news.chinatungsten.com/en/tungsten-product-news/146140-tpn-11061.html)

Clausen, R. J., Kalvig, P., Keiding, J.K., Fold, N. & Vind, I. 2023: Dansk industris brug af mineralske råstoffer – økonomisk betydning og forsyningsudfordringer MiMa rapport 2023/2, pp. 181. https://doi.org/10.22008/gpub/32051

European Commission (EC) 2023: Study on the Critical Raw Materials for the EU 2023 – Final Report. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

Graedel, T.E., Harper, E.M, Nassar, N. & Reck, B.K. 2013: On the materials basis of modern society. Proceedings of the National Academy of Science. Online ISSN: 1091-6490

Han, Z., Golev, A. & Edraki, M. 2012: A review of tungsten resources and potential extraction from mine waste. Minerals 2021, 11(7), 701; https://doi.org/10.3390/min11070701

Hughes, A. 2020: Australian Resource Reviews. Tungsten 2019. https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/tungsten

Keiding, J.K. 2014D: Wolfram (tungsten). Fakta om råstoffer 3, 4 pp. https://doi.org/10.22008/gpub/38032

Leal-Ayala, D.R. Allwood, J.M., Petavratzi, E., Brown, T.J. & Gunn, G. (2015): Mapping the global flow of tungsten to identify key material efficiency and supply security opportunities. https://core.ac.uk/download/pdf/33453755.pdf)

MMR 2023: Tungsten market – Global industry analysis and forecast (2023-2029). Tungsten Market - Global Industry Analysis and Forecast (2023-2029) (maximizemarket-research.com)

Observatory of Economic Complexity World (EOC World) 2023: Database https://oec.world/

Polini, R., Marcucci, A., D'Ottavi, C., Nunzinate, P. & De Filippis, P. 2021: Towards Green

Tang, L., Wang, P., Graedel, T.E., Pauliuk, S., Xiang, K. Ren, Y. & Chen, W-Q. 2020: Refining the understanding of China's tungsten dominance with dynamic material cycle analysis. Resources, Conservation and Recycling, Vol. 158, Jul 2020, 104829.

Reuters 2023: China sets 2023 mining quota for tungsten concentrate at 110 kton. https://www.nasdaq.com/articles/china-sets-2023-mining-quota-for-tungsten-concentrate-at-111000-metric-ton

USGS 2023: Mineral commodity summaries 2020-2023: U.S. Geological Survey https://pubs.er.usgs.gov/publication/mcs2023

Zeiler, B., Bartl, A. & Schuberts W-D. 2021: Recycling of tungsten: current share, economic limitations, technologies and future potential. Int. Journal of Refractory Metals and Hard Materials. Vol 98, https://www.sciencedirect.com/science/article/pii/S0263436821000780

WMD 2022 (World Mining Data): Vol 37, 28 April 2022 https://www.world-mining-data.info/wmd/downloads/PDF/WMD2022.pdf

7. Vanadium

7.1 Introduction

Vanadium (V), with atomic number 23, is a silver-grey metal that, in its pure form, is soft and malleable, with a high melting point (1,910 °C) and boiling point (3,407 °C). Vanadium is chemically highly reactive and readily forms compounds with other metals. Therefore, vanadium is widely used as an alloying metal in materials where extra strength and corrosion resistance are required; almost 90 % of vanadium production is used in steel for construction (reinforcement bars, 'rebar') and automotive industries. The known geological reserves of vanadium are significant, but the metal is mainly extracted as a by-product from the production of other metals, which governs the quantity of vanadium in the market. Vanadium consumption is expected to increase significantly with the production of Vanadium Redox Flow Batteries (VFRB) in the future. Due to China's dominant role in vanadium supply chains, vanadium is classified as a critical raw material in the EU (EC 2023).

7.2 Applications and Sectors

Vanadium is primarily used in the manufacturing of high-strength steel alloys, including stainless steel, special steel, etc. The metal also finds some applications in chemicals (as a catalyst in sulphuric acid production), batteries (flow batteries and V-Li-ion batteries), and titanium alloys (Figure 7-1). The demand for vanadium in steel has grown, partly due to changing requirements for vanadium content in rebar steel. However, a growing area for vanadium is its use in the production of Vanadium Redox Flow Batteries (VRFB) (Mining Review Africa 2023).

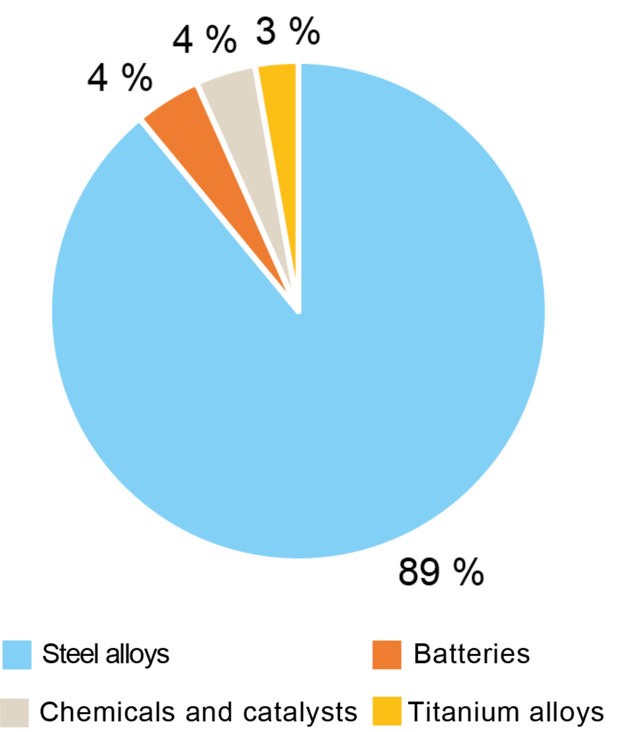


Figure 7-1 *Global utilization of vanadium reported in 2023. Source: Mining Review Africa (2023).*

7.3 Recycling and Substitution

The recycling rate for vanadium is variable and poorly estimated (Petranikova *et al.* 2020), but it is generally considered to be low (EoL-RIR 1-6 %) (EC 2023). The focus of vanadium recycling is especially on vanadium-containing slags, which are waste products from steelworks and are found in large volumes. Some steelworks utilize these vanadium resources, and several vanadium producers are planning modifications to their processing facilities to exploit these slags. The methods for processing slags typically involve pyrometallurgical methods (roasting) followed by hydrometallurgical methods (leaching with sodium bicarbonate or similar) (Sadeghi & Alamdari 2021).

The company 'Critical Metals Corp' works to establish a recycling plant in the Nordic region, where the input is based on both scrap and residual materials from current and former mining and smelting activities, including SSAB's steelworks in Luleå and Oxelösund in Sweden and Raahe and Pori in Finland. It is estimated that the slags contain 63,000 ton of V_2O_5, and an annual production of 6,000 ton of V_2O_5 is expected (Critical Metals 2020).

For most applications, vanadium can be substituted with other metals, albeit with a loss in quality and/or increased costs. Vanadium cannot be substituted where it is used for vanadium-titanium high-quality alloys for the aerospace industry. For alloys, the most commonly used substitution metals for vanadium are manganese, molybdenum, niobium, titanium, and tungsten (Scrreen2 Vanadium factsheet 2023). For chemical vanadium products used as catalysts, vanadium can be substituted by nickel and/or platinum. For vanadium pigment products, titanium can, to some extent, substitute for vanadium.

7.4 Global Supply

7.4.1 Geology

Vanadium occurrences are found as magmatic and sedimentary deposits. Magmatic deposits, especially vanadium-bearing magnetite, titanomagnetite, ilmenite, and chromite, are commonly utilized. Sedimentary deposits include heavy-mineral sand deposits (placers), which may also consist of magnetite and titanomagnetite, and occasionally the uranium-vanadium mineral carnotite. Secondary weathering deposits can contain minerals such as vanadinite and roscoelite, with the former associated with lead-zinc mineralizations and the latter found in oil shale deposits.

Vanadium is typically a by-product of the production of other metals, requiring additional processing steps to extract vanadium from the mineral.

Figure 7-2 illustrates some of the largest vanadium deposits categorized by geological types.

In addition to primary by-product vanadium production, vanadium is, *inter alia*, also extracted from metallurgical slags and by-products of oil refining.

Vanadium forms only a few minerals with high vanadium content, such as vanadinite and roscoelite; most commercial vanadium minerals contain <5 %. Typical vanadium content in primary minerals is 1-2 % V_2O_5, and >5 % V_2O_5 in secondary materials. About 85 % of vanadium is extracted from magnetite and titanomagnetite, while the remainder is obtained from ilmenite, slags from the steel industry, and by-products from aluminium and magnesium smelters, the phosphate industry, and fly ash from coal-fired power plants. The vanadium content in minerals is shown in Table 7-1, whereas the content in secondary raw materials is listed Table 7-2. Among the secondary resources are scrap from end-of-life products, new scrap, and slags from the steel industry.

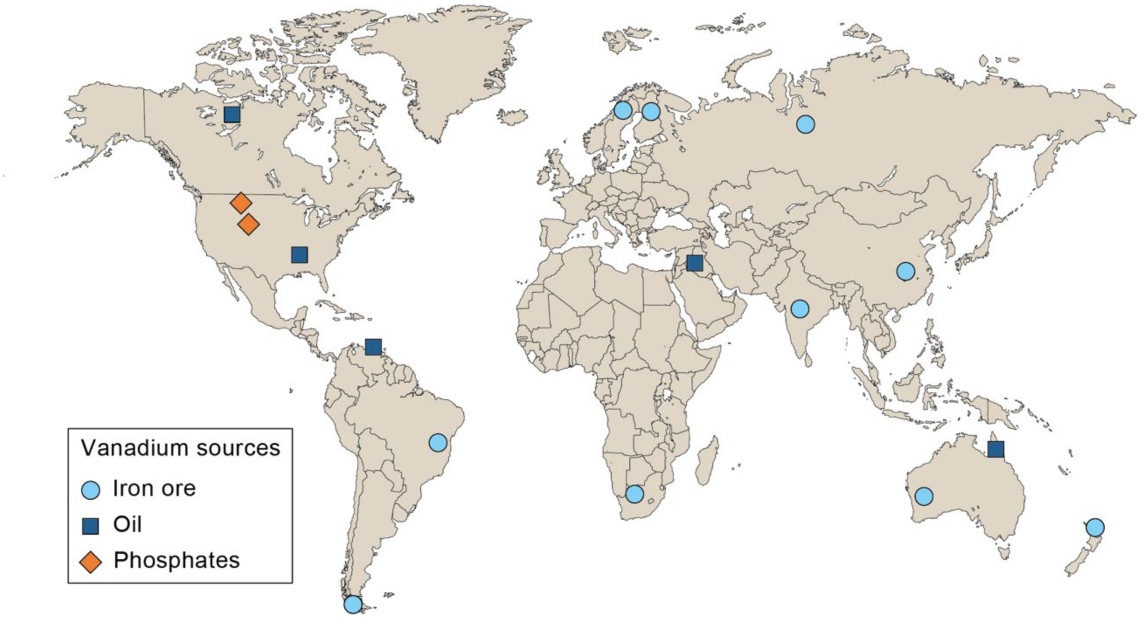


Figure 7-2 *Overview of some of the largest vanadium deposits distributed by geological types. Modified after Imtiaz* et al. *(2015).*

Table 7-1 *Commercially important vanadium minerals.*

Vanadium mineral	Mineral formula	V content (Wt.% V_2O_5)	Typical geological types
Carnotite	$K_2(UO_2)_2(VO_4)_2$	21.4	Sedimentary
Coulsonite	FeV_2O_4	< 5	Secondary
Ilmenite	$FeTiO_3$	0.3-0.6	Magmatic
Chromite	$FeCr_2O_4$	0.2	Magmatic
Magnetite	Fe_3O_4	0.1-0.6	Magmatic
Mottramite	$Pb(Cu,Zn)(OH)(VO_4)$	22.3	Secondary
Patronite	VS_4	15-60	Hydrothermal
Roscoelite	$K(V^{3+,} Al, Mg)_2AlSi_3O_{10}(OH)_2$	n.a.	Secondary
Titanomagnetite	$Fe(Fe,Ti)_2O_4$	0.4-3	Magmatic
Vanadinite	$Pb5(VO_4)_3Cl$	19.6	Secondary

Table 7-2 *Most used materials for extracting vanadium from secondary resources.*

V-raw material	V content (Wt.% V_2O_5)
Steel slag	1
Coal ashes	<0.1
Bauxite slag	0.03-0.2
Phosphate slag	0.2

7.4.2 Global Vanadium Reserves

The global vanadium reserves are estimated to 26 million metric ton of V_2O_5 (USGS 2023), with China, Russia, and South Africa holding 37 %, 19 %, and 13 %, respectively. It is unclear to what extent deposits with low vanadium content are included in global assessments.

Assessed in relation to the current global consumption of approximately 100,000 ton per year, the known reserves are sufficient for over 250 years of production. As mentioned in section 7.5 Trade, there are analyses predicting 20 % annual increases in consumption, which would reduce the lifespan of the current reserves to around 25 years.

7.4.3 Global Vanadium Production

The resources for global vanadium production in 2019 included approximately 19 % from ore with vanadium as the primary product, 69 % from by-product vanadium in iron and titanium production, 12 % from recycled vanadium, and vanadium extracted from sources such as coal fly ash, aluminium, and magnesium production (Perles 2020). From 2000 to 2022 the primary production of vanadium increased from approximately 40,000 ton to approximately 100,000 ton of pure vanadium (Figure 7-3) excluding production from recycling and secondary. Ore production increased by around 250 % during this period, mainly due to growth in China. In 2022, China produced about 68 % of the global mineral production, followed by Russia, South Africa, and Brazil with 17 %, 9 %, and 6 %, respectively (Table 7-3).

The same countries that dominate the mining of vanadium-bearing ore also lead in the production of vanadium pentoxide (V_2O_5), with smaller productions from the USA, Canada, Europe, South Korea, and Japan.

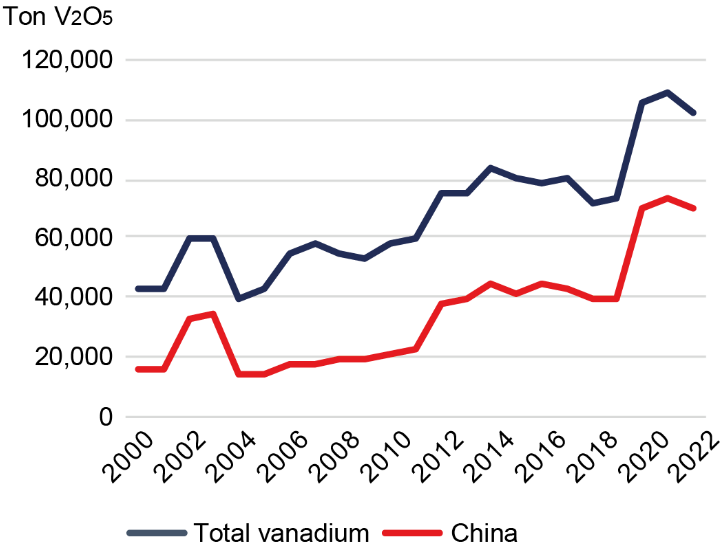


Figure 7-3 *Overview of historical production of primary vanadium in the period 2000-2022. Source: USGS (2000-2023).*

7.4.3.1 Companies Involved in Vanadium Mining

Since vanadium is primarily produced as a by-product from minerals mined for their iron, titanium, and/or chromium content, only sporadic information exists on exploration projects, mines, and smelters specifically focused on vanadium. Table 7-4 provides an incomplete overview of mines/smelters, countries, and companies extracting vanadium as a main or by-product. Table 7-5 similarly presents an incomplete list of exploration projects, countries, and companies.

Table 7-3 *Production of primary vanadium in ton distributed among the largest producer countries. Sources: USGS (2023) and WMD (2023).*

Production	2022 (USGS)	2021 WMD
China	70,000	63,800
Russia	17,000	20,052
South Africa	9,100	8,799
Brazil	6,200	7,212
Total	102,300	99,969

Table 7-4 *Overview of mines/smelters that mine vanadium as either a main or by-product. The overview is incomplete due to limited publicly available information.*

Mine/smelting plant	Country	Company
Windimurra	Australia	Atlantic
Maracas Menchen	Brazil	Largo Resources
Bulcari	Brazil	Largo Resources
Kuranakh (K&S Mine)	Russia	IRC Ltd
Baicao	China	China Vanadium – Titano-Magnetite Mining Comp
Panzhihua	China	Pangang Group Vanadium Titanium & Resources
Panzhihua	China	Panzhihua New Steel & Vanadium Co (største V-producent)
Sichuan	China	Desheng Group
Hebei	China	Hebei Iron & Steel Group (HBIS) Chengsteel (second largest V-producer
Tangshan, Hebei	China	Beijing Jianlong Heavy Industry Group
Melbourne	New Zealand	Blue Scope
Sobstvenno-Kachkanarskoye	Russia	Evraz KGOK (mine) - Evraz NTMK (steelworks)
Witbank	South Africa	Evraz Highveld Steel and Vanadium steelworks
Mapochs	South Africa	Bushveld Vanchem
Vametco Vanadium	South Africa	Busheld Minerals
Rhovan	South Africa	Glencore
Brits	South Africa	Bushveld Minerals
Makopane	South Africa	Bushveld Minerals
Colorado	USA	Energy Fuels Inc
Arkansas	USA	US Vanadium LCC

7.4.4 Production of Vanadium

Processing methods for vanadium-containing raw materials are illustrated in Figure 7-4 and include either pyrometallurgical or hydrometallurgical refining. The hydrometallurgical method typically involves reduction, roasting (which converts the raw materials into water-soluble salts), and subsequent leaching of the precipitated products (red cake); residues of vanadium in the leachate are typically extracted using solvent extraction and/or ion exchange methods. Red cake is processed through several intermediate steps to produce vanadium oxide (V_2O_5). In the pyrometallurgical method, the vanadium-rich concentrate (e.g., V-Ti magnetite) is melted, resulting in vanadium-rich slag and molten pig iron (semi-steel); the vanadium slag is oxidized/roasted and leached, and hydrometallurgical methods are then used to produce vanadium oxide (V_2O_5).

Table 7-5 *Overview of exploration projects extracting vanadium as either a primary or by-product. The overview is incomplete due to limited publicly available information.*

Exploration projects	Country	Company
Jervois	Australia	Arafura Resources
Saint Elmo	Australia	Multicom Resource
La Blache	Canada	Argex Mining Inc
Buttercup	Canada	Prophecy Development Corp
Garinskoye	Russia	IRC Ltd
Häggån	Sweden	Aura Energy
Routivare	Sweden	Beowulf
Airijoki	Sweden	Kendrick Resources
Hörby	Sweden	Province Resources Ltd
Gibellini Project	USA	Nevada Vanadium Mining

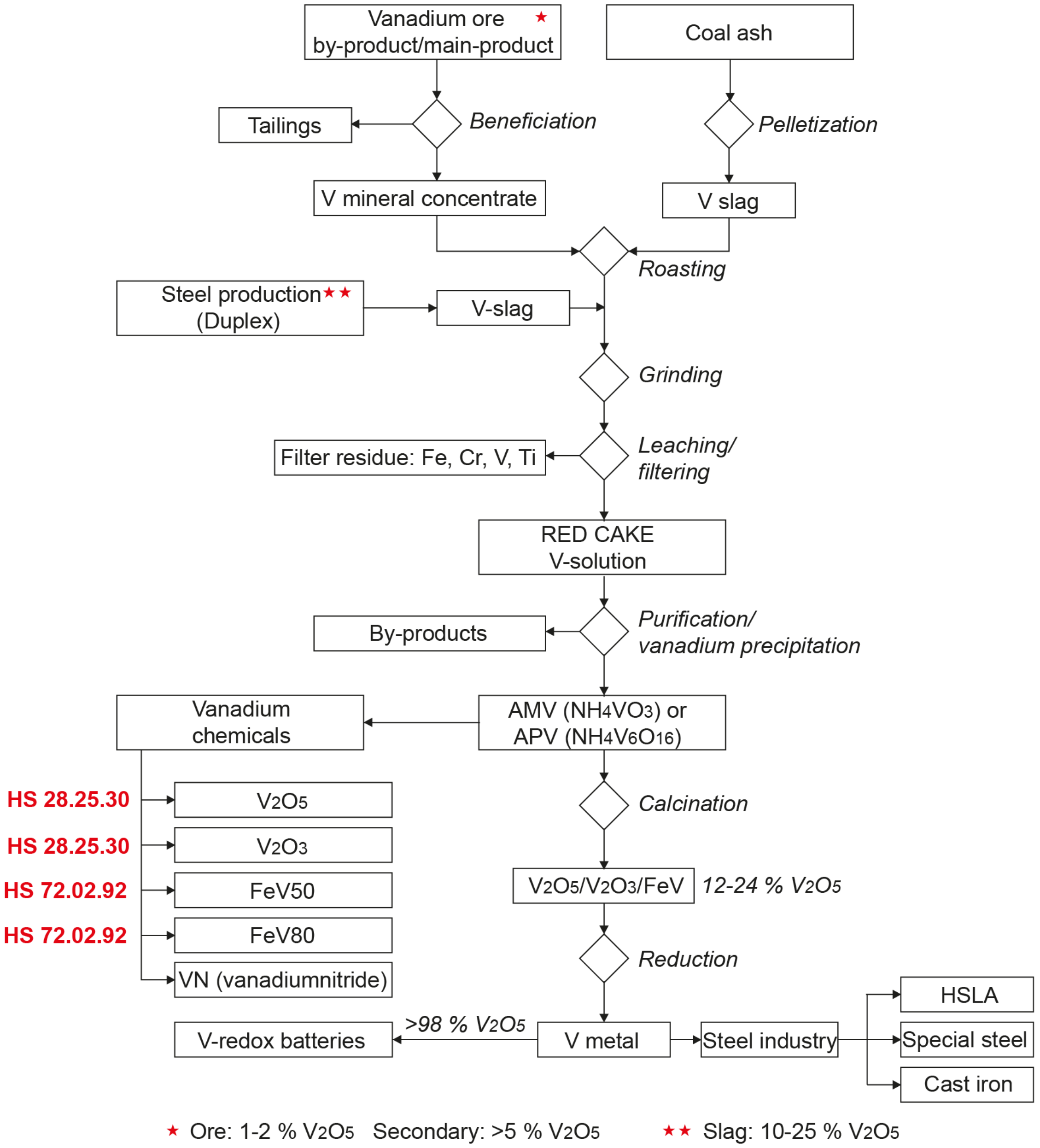


Figure 7-4 *Generic process diagram for vanadium. Based on Nasimifer & Mehrabani (2022) and Lee* et al. *(2021).*

7.4.5 Climate and Environmental Impact

Vanadium production has increasing toxic effects on plants and animals, leading to growing concerns. A direct correlation between vanadium smelters and contaminated agricultural soil has been particularly reported in China (Imtiaz *et al.* 2015; Li *et al.* 2020). Ongoing discussions revolve around whether vanadium should be considered a toxic metal.

The CO_2 contribution from vanadium production is estimated to be approximately 16.2 ton of CO_2 per ton of V_2O_5 product. This high level is expected to be reduced with the introduction of new electrochemical technologies (VanadiumCorp 2017).

7.5 Trade

A significant portion of the trade in products within the vanadium supply chain is not specifically reported for vanadium but is combined with other raw materials. This is the case, for example, with the trade of vanadium mineral concentrates, which is reported together with niobium, tantalum, and zinc (HS 26.15.90) (Table 7-6). An overview of international trade in the two vanadium-specific items (HS6 28.25.30 Vanadium oxides and hydroxides and HS6 72.02.92 Ferrovanadium) is provided in Table 7-7 and Table 7-8.

Vanadium oxides (vanadates, V_2O_5) serve as raw materials for various industries. In 2020, Brazil, Russia, South Africa, and China were the largest exporting countries, accounting for three-quarters of global trade. A significant portion of this export is imported by the Czech Republic, the Netherlands, South Korea, and the USA. Reportedly, more than 90 % of Russia's export to the Czech Republic is possibly used to produce ferrovanadium.

The export of ferrovanadium in 2020 was dominated by Austria, South Africa, the Czech Republic, China, and South Korea, collectively representing approximately 75 % of the export. These products were imported by various countries, with the largest importers being the Netherlands, Germany, Taiwan, South Korea, and Japan (Table 7-8).

Table 7-6 *Overview of traded vanadium products in 2020, including trade value and product code. Source: OEC World (2023).*

HS4	Commodity	Export (M. USD)	HS6	Description	Export (M. USD)
26.15	Nb, Ta, V & Zr ore	1,830			
			26.15.90	Nb, Ta, V & Zr ore & concentrate	527
			26.20.50	Ash Residues containing V	-
			28.25.30	Vanadium oxides & hydroxides	564
			72.02.92	Ferro vanadium	1,030
			81.12.40	Vanadium, articles thereof, waste or scrap/powder	-
			81.12.92	Ga, Ge, Hf, In, Nb, Rh & V articles thereof, unwrought including waste and scrap/powder	577

Table 7-7 *The main export and import countries for vanadium oxides and hydroxides (HS6 228.25.30) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Brazil	138	Netherlands	60
		South Korea	35
		Canada	18
		USA	11
Russia	134	Czech Rep.	123
		China	6
		USA	3
		India	1
South Africa	101	Netherlands	27
		USA	22
		Japan	17
		Russia	14
China	60	South Korea	32
		Japan	9
		Netherlands	7
		Canada	6
Subtotal	443		
Others	121		
Total	564		

Table 7-8 *The main export and import countries for ferrovanadium (HS6 72.02.92). Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Austria	190	Germany	44
		Taiwan	32
		USA	17
		Italy	13
South Africa	152	Netherlands	57
		Germany	17
		South Korea	13
		Sweden	12
Czech Rep.	151	Japan	25
		USA	24
		Taiwan	17
		Turkey	15
China	140	South Korea	50
		Japan	30
		Netherlands	20
		Taiwan	11
South Korea	116	Netherlands	64
		Germany	9
		Poland	7
		India	7
Subtotal	749		
Others	278		
Total	1,027		

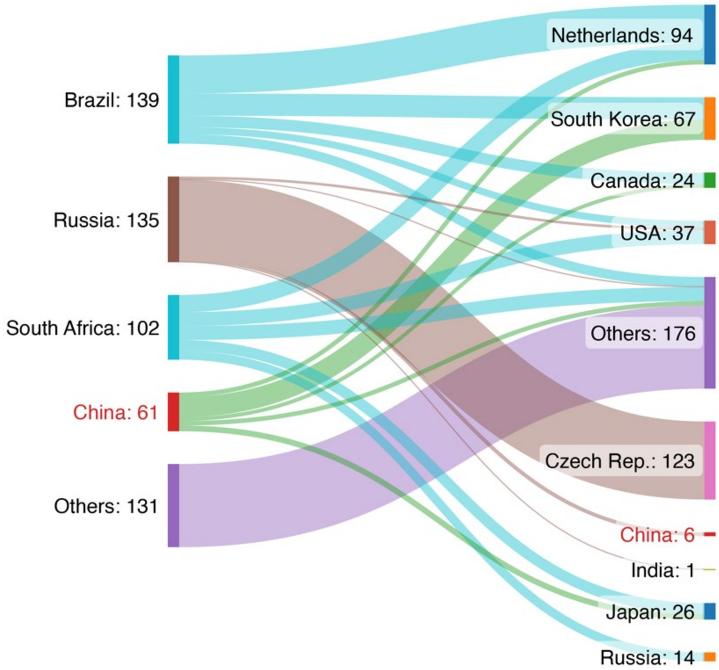


Figure 7-5 *Sankey diagram for trade in vanadium oxides and hydroxides (HS 28.25.30) in 2020. All values in million USD, based on table 7-7.*

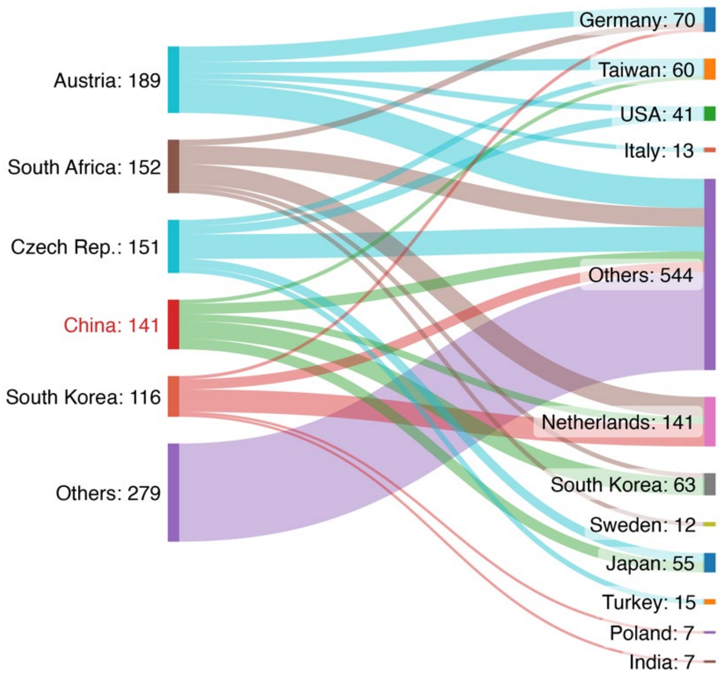


Figure 7-6 *Sankey diagram for trade in ferrovanadium (HS 72.02.92) in 2020. All values in million USD, based on table 7-8.*

7.5.1 Prices

Vanadium is not traded on exchanges. Prices are determined by the parties involved and are relatively volatile. Looking at the period from 2000 to 2023, the overall trend shows a fairly stable price level for both vanadium pentoxide (12-14 USD/kg) and ferrovanadium-80 (28-40 USD/kg), with significant price fluctuations in 2004-2005, 2008, and 2018 (Figure 7-7). The subsequent decline may be related to reduced demand following the COVID-19 pandemic. Since the production of primary vanadium is carried out by a small group of producers, changes in a single or a few companies can influence price development. For example, the significant price increases in 2018 are believed to be triggered by the Highveld Steel & Vanadium, South Africa, going bankrupt, combined with reduced production quotas in China. Reasons for other price fluctuations are unknown.

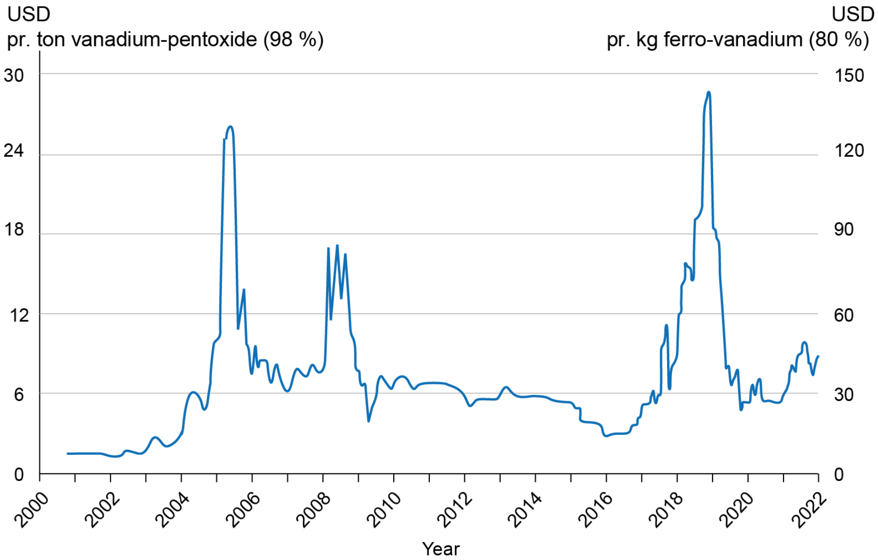


Figure 7-7 *Price development for vanadium pentoxide (V_2O_5) and ferrovanadium (FeV-80) in the period 2000-2022. Source: Vanadiumprice.com (2023).*

7.6 The Danish Consumption

The Danish consumption of vanadium is poorly mapped but based on Tan *et al.* (2020) and Clausen *et al.* (2023), it is estimated that the consumption in Denmark is mainly for stainless steel and special steel types, which is also the case globally. Vanadium is used in both stainless and alloyed steel as well as in carbides in tool steel. For steel, manganese is the most common alloying metal, but significant amounts of vanadium and other metals are also used.

Clausen *et al.* (2023) assessed that vanadium has relatively little significance for the Danish economy (Figure 7-8), but it should be emphasized that vanadium is a raw material with poor data coverage in the study, leading to considerable uncertainty regarding vanadium's derived importance for gross value added and other economic parameters calculated in Clausen *et al.* (2023).

7.7 Perspectives

Since 2017, the European Commission has considered vanadium a critical raw material for the EU. In the 2023 assessments, the economic importance was rated at 3.9, and the supply risks for extraction (SRE) and processing (SRP) were rated at 2.3 and 1.7, respectively (EC 2023). The classification of vanadium as a critical raw material is shared with UK, the USA, Japan, India, and Canada. China, being the world's largest producer, does not consider vanadium as a critical raw material.

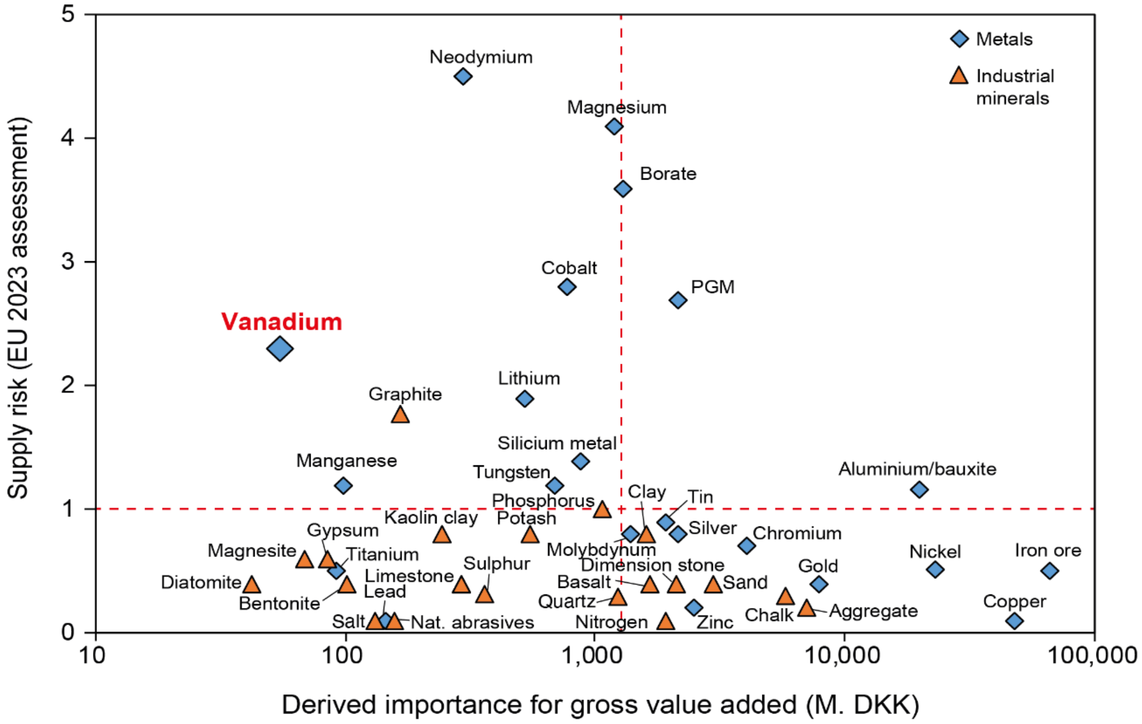


Figure 7-8 *Vanadium and other raw materials' derived impact on gross value added as a function of supply risk. The Figure is modified from Clausen* et al. *(2023).*

Vanadium extraction, both as a primary and by-product, and subsequent processing and manufacturing of vanadium raw materials, are concentrated in China, Russia, South Africa, and Brazil. Only very small quantities are produced in other countries, with recycled vanadium contributing 6-12 %. Similarly, production is concentrated among a few companies involved in vanadium production in multiple countries, with Pazhihua New Steel & Vanadium Co, Evraz, Bushveld Minerals, and Largo Resources among the largest producers. Vanadium supply chains are vertically integrated and located in countries that in the EU-perspective are geopolitically problematic, which affects criticality assessments.

There are general expectations of growing demand for vanadium for Vanadium-Redox-Flow-Batteries (VRFB). Such batteries are anticipated to be installed as 100-800 MW stationary grid-connected systems, especially in China, for storing and supplying surplus energy from solar and wind farms. Towards 2030, these are planned to be expanded with 1,000 GW of new installations. In addition, the demand for vanadium to produce steel and vanadium-containing chemicals is growing, consuming about 92 % of vanadium production. About 10 ton of V_2O_5/MWh are consumed for VRFB (McGahan 2023). If China's VRFB plans are realized by 2030, they will require approximately 10 million ton of V_2O_5, equivalent to an average annual consumption of 1.4 million ton of V_2O_5, which is considered unrealistic. Others estimate that supplies in 2030 will be around 140 kton, while the actual demand is about 180 kton (Largo 2023).

The expected growth in vanadium demand and the facts that (i) vanadium production is based on bi-/co-production, making it sensitive to price changes in accompanying metals, and (ii) vanadium production is dominated by relatively few vertically integrated producers, with Chinese industrial groups being the most significant consumers, lead to the conclusion that the vanadium market is challenged in terms of supply until 2030.

7.8 References

Clausen, R. J., Kalvig, P., Keiding, J.K., Fold, N. & Vind, I. 2023: Dansk industris brug af mineralske råstoffer – økonomisk betydning og forsyningsudfordringer MiMa rapport 2023/2, pp. 181. https://doi.org/10.22008/gpub/32051

Critical Metal 2020: Vanadium Recovery and LiB Recycling. Annual General Meeting, Sept. 2020. Company ppt-presentation. https://www.criticalmetals.eu/reports/110-201007-CMS-AGM-Presentation-Vanadium-Recoveery-and-LiB-Recycling.pdf

European Commission (EC) 2023: Study on the Critical Raw Materials for the EU 2023 – Final Report. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1Imtiaz, M., Rizwan, M.S., Xiong, S., Tu, M.S. 2015: Vanadium, recent advancements and research prospects: A review. Environment International 80 (44): 79-88.

Largo 2023: Capital 10x Deep dive report (https://capital10x.com/wp-content/uploads/2022/12/Capital-10X-Deep-Dive-Largo-Inc.pdf - visited 20 Nov. 2023)

Lee, J-C., Kurniawan, Kim, E-Y., Chung, K-.W., Kim, R. & Jeon, H-S. 2021: A review on the metallurgical recycling of vanadium from slags: towards a sustainable vanadium production. Journal of Materials Research and Technology. Vol 12, May-Ju 2021, pp 343-364.

Li, Y., Zhang, B., Liu, Z., Wang, S., Yao, J. & Bortwick, A.G.L. 2020: Vanadium contamination and associated health risk of farmland soil near smelters throughout China. Environmental Pollution, Vol 263, Part A, Aug. 2020, 114540.

McGahan, S. 2023: Vanadium electrolyte: the 'fuel' for long-duration energy storage. Energy Storage News website https://www.energy-storage.news/vanadium-electrolyte-the-fuel-for-long-duration-energy-storage/

Mining Review Africa 2023: Energy storage now the second largest consumer of vanadium. Mining Review Africa June 2, 2023. https://www.miningreview.com/battery-metals/energy-storage-now-the-second-largest-consumer-of-vanadium/

Nasimifar, A. & Mehrabani, J.V. 2022: A review on the extraction of vanadium pentoxide from primary, secondary, and co-product sources. International Journal of Mining and Geo-Engineering. IJMGE 56-4 (2022) 366661-382.

Observatory of Economic Complexity World (EOC World) 2023: Database https://oec.world/

Perles, T. 2021: Vanadium Market Analysis. Ppt-presentation TTP Squared Inc. https://www.ferro-alloy.com/en/vanadium/TTP%20Squared%20market%20summary %203 %20April %202020.pdf

Petranikowa, M., Tkaczyk, A.H., Bartl, A., Lapkovskis, V. & Tunsu, C. 2020: Vanadium sustainability in the context of innovative recycling and sourcing development. Waste Management, Vol 113, July 2020, pp 521-544. https://www.sciencedirect.com/science/article/pii/S0956053X20301707

Sadeghi, N. & Alamdari, E.K. 2020: An innovative method for recycling vanadium and valuable materials from high-lime steelmaking slag disposal. International Journal of Environmental Science and Technology, Vol 18, 2597-2606.

Scrreen2 Vanadium factsheet 2023: Scrreen2 factsheets updates based on the EU Factsheets 2020 vanadium. https://scrreen.eu/wp-content/uploads/2023/03/SCRREEN2_factsheets_VANADIUM.pdf

Tan, J., Wehde, M.V. Frederik Brønd, F. & Kalvig, P. 2020: Udfordringer for bæredygtig genanvendelse af dansk jern- og metalskrot. MiMa rapport 2020/2. 194 pp. https://doi.org/10.22008/gpub/32048

USGS 2000-2023: Mineral commodity summaries 2000-2023: U.S. Geological Survey https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries

VanadiumCorp 2017: Process Technology. https://www.vanadiumcorp.com/investors/what-is-vanadium/. Company website visited Sept. 2023.

Vanadiumprice 2023: https://www.Vanadiumprice.com

Veram Project 2023: Nine New Critical Raw Materials. Website: http://veram2050.eu/nine-new-critical-materials/. Visited Sept. 2023.

World Mining Data (WMD) 2022: Vol 37, 28 April 2022 https://www.world-mining-data.info/wmd/downloads/PDF/WMD2022.pdf

8. Zinc

8.1 Introduction

Zinc (Zn), element 30 in the Periodic Table of Elements, melts at 420 °C, boils at 907 °C, and has a density of 7.1 g/cm^3. More than half of the zinc is used to produce galvanized products in construction and the automotive industry, and it is also used in alloys such as brass and bronze. Zinc deposits are found in many countries and are mined in various places, including China, Australia, Peru, and Mexico. China dominates both zinc ore extraction, refining, and consumption. In 2022, approximately 13 million ton were extracted, with an expected annual demand growth of about 2 % until 2050. The price of zinc is expected to remain stagnant until 2025.

8.2 Applications and Sectors

Zinc has broad industrial applications (Figure 8-1):
Galvanization: Galvanization is a surface treatment for steel and iron that prevents/reduces rust formation, making it particularly useful in the automotive industry, infrastructure such as bridges, etc. About three-quarters of the production is used for this purpose.
Casting Material: Zinc is used in alloys for metal castings (die-casting) and for producing components for the electronic industry.
Alloys: Zinc is often incorporated into alloys with other metals to achieve desired properties such as strength, dimensional stability, thermal conductivity, corrosion resistance, etc. Brass refers to copper-zinc alloys and can contain up to 50 % zinc, representing the largest consumption area for alloys.
Chemical Products: Zinc oxide and zinc sulphide are used in white and fluorescent paints, rubber, cosmetics (for adding red colours), pharmaceutical products, printing inks, batteries, textiles, animal feed supplements, etc.
Other Uses: Dental and medical products, fungicides, lubricants.

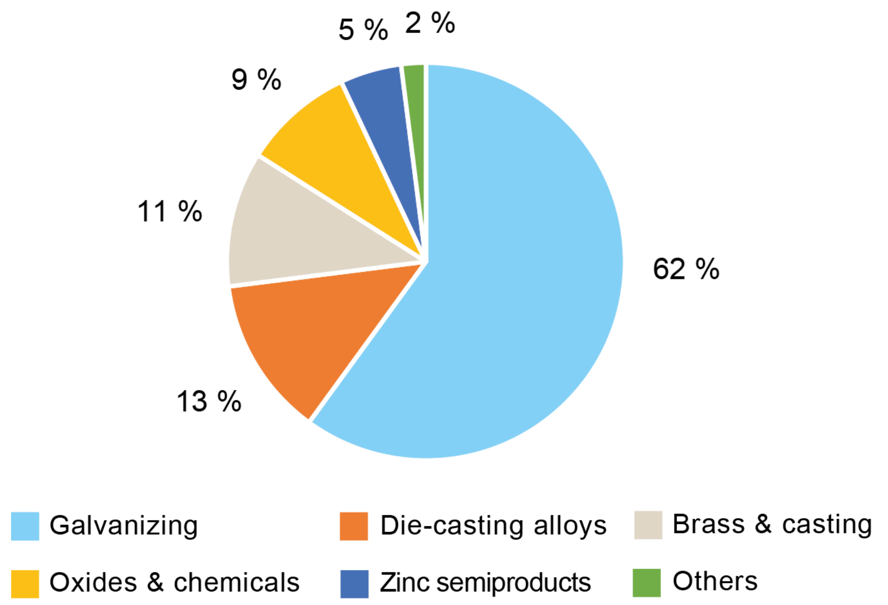


Figure 8-1 *Distribution of zinc in relation to industrial sectors in 2020. Source: Statista (2023).*

As a product, 40 % of zinc is used in the construction and infrastructure sector, 22 % is used in the transportation sector, 12 % is applied by the industrial sector, 12 % is incorporated into consumer products, and 3 % of the demand is allocated to the health and nutrition sector (Scrreen2 Zinc factsheet 2023).

8.3 Recycling and Substitution

Most of the zinc is used for the galvanization of steel, which typically involves products with a long lifespan. Zinc recycling is divided into new scrap, which consists of by-products from the production of zinc goods, and old scrap, including EoL products and tailings. However, only a portion of zinc is effectively recycled, mainly due to incomplete collection and process losses. The European Commission (EC) estimated the End-of-Life Recycling Input Rate (EoL-RIR) to be 34 % (EC 2023). Rostek *et al.* (2023) estimate that the total zinc recycling amounted to 6.2 million ton in 2019 and could increase to 9-14 million ton by 2050.

Zinc is difficult to substitute, especially when used for corrosion protection. However, alternative synthetic composite products can substitute for galvanized iron in certain applications. The European Commission (EC) estimated a Substitution Index (SI-EI) of 0.77 and a SI-SR of 0.8.

8.4 Global Supply

8.4.1 Geology

Zinc ores, often occurring together with lead ores, are formed in various geological environments: carbonate rocks (Mississippi Valley Type, MVT), volcanic massive sulphide ores (VMS), hydrothermal and skarn mineralization. In sedimentary rocks, zinc ores are found in shale, clay, or sandstone (sedimentary exhalative rocks, SEDEX).

8.4.1.1 Zinc Minerals, By-products, and Companion Metals

The main zinc mineral is sphalerite (zinc blende, ZnS). All types of zinc deposits can contain by-products of lead and copper and may also contain one or more of the following companion metals: bismuth, boron, germanium, indium, cadmium, mercury, silver, tin, and tungsten, which do not form their own minerals in zinc deposits and are therefore extracted as part of the metallurgical processes.

8.4.2 Global Zinc Reserves

Approximately 45 % of the world's zinc reserves are associated with SEDEX-type deposits; the most well-known are Century and Mount Isa (Australia), Red Dog (USA), and Changba (China), each with reserves of over 100 Mt of ore with a typical grade of 10-15 % Zn and 2-5 % Pb. Zinc deposits are found worldwide, primarily in China and Australia, but also in Peru and Mexico, where the largest measured reserves are located (Table 8-1 and Figure 8-2). In Greenland, there are several significant zinc deposits, including The Black Angel, which was an active zinc-lead mine, where the remaining reserves are estimated to be 4.4 Mt of ore with a zinc content of 8.6 % (Thaarup 2020), and the Citronen Fjord deposit mentioned below as the most important. For further information on the zinc potential in Greenland, see Sørensen *et al.* (2014, 2018).

Global zinc reserves amounted to 251 Mt in 2022, a level that has been stable since 2000. Reserves have grown in Australia and Russia since 2000 but diminished in Canada, Kazakhstan and elsewhere. In the EU, the largest reserves are in Portugal (16.5 Mt with a content of 5.9 % zinc), Ireland (14 Mt with a content of 7.4 %), and Sweden (29 Mt with a content of 5.5 %) (EU 2020a). The lifespan of zinc reserves has been relatively constant since 2000, with growth up to 2010 and a reduction since 2015, standing at approximately 16 years in 2022 (USGS 2023). The reports do not specify which reserves are related to existing zinc mines and which are related to new projects, making it impossible to determine when reserves might potentially come into production. Fitch Solution (2022) presents 20 zinc exploration projects that could contribute to future zinc supplies, most of which are in Canada, Mexico, Peru, and the USA. The Greenlandic Citronen Fjord deposit is included in the list of potential future mines (Table 8-4), and may potentially increase zinc reserves by 420 Mt. However, expectations are typically much higher than the reserves that will eventually be included in actual mining plans.

Table 8-1 *World zinc reserves calculated for the 10 countries with the largest reserves and the category 'other'. Source: USGS (2023).*

Reserves	M. ton zinc
Bolivia	n.a.
Australia	66,000
China	31,000
Russia	22,000
Peru	17,000
Mexico	12,000
India	9,000
Kazakhstan	7,400
USA	7,300
Sweden	400
Others	**30,000**

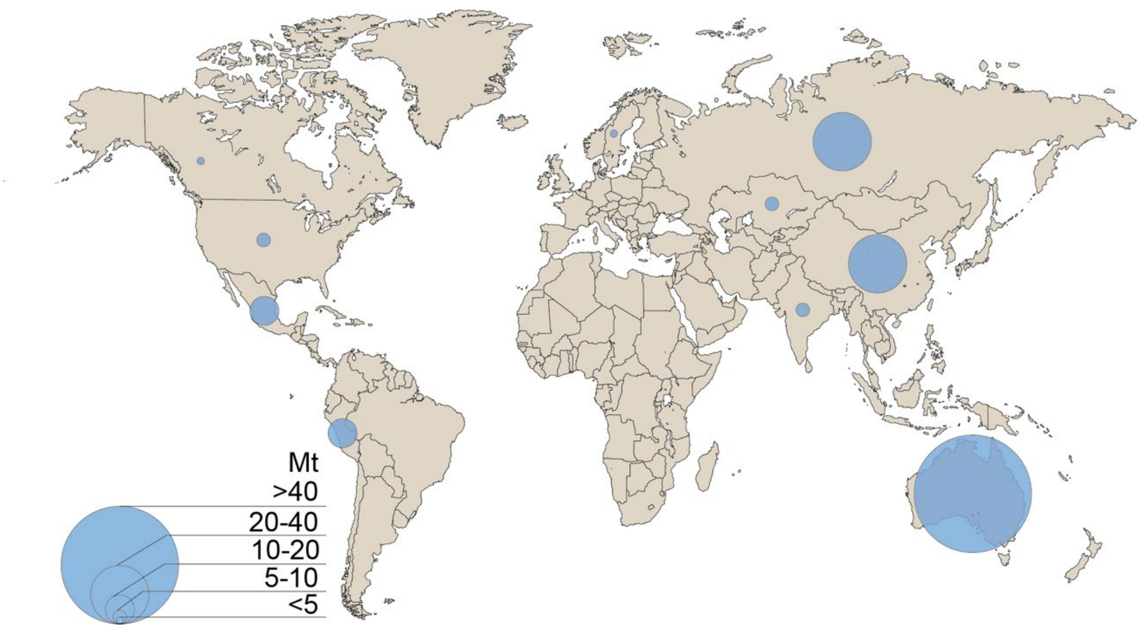


Figure 8-2 *Overview of the countries with the largest reserves of zinc ore. Source: USGS (2023). Also refer to Table 8-1.*

8.4.3 Global Zinc Production

The production of zinc from approximately 30 countries grew from around 8 Mt per year to 13 Mt per year in the period from 2000 to 2022, primarily due to production growth in China. Subsequently, the production has stabilized around 12-13 Mt per year (Figure 8-3). About 33 % of this production was in China, followed by Peru and Australia, each contributing with approximately 10 %, and India, the USA, and Mexico, each contributing with around 6 % (Figure 8-3 and Table 8-2). The production of the EU-27 countries in 2020 is not reported, but it amounted to 0.726 Mt in 2018 (EC 2020a, b), with Sweden (Garpenberg, Zinkgruvan, and Boliden-area) and Ireland (Lisheen, Tara) being the main contributors; small productions also came from Finland, Poland, Portugal, and Spain; the productions in Ireland have subsequently ceased. Overall, this is almost a doubling of the EU's production since 2004 (0.45 Mt) (European Minerals Yearbook for Zinc 2018). Figure 8-4 provides a historical overview of zinc production since 2000.

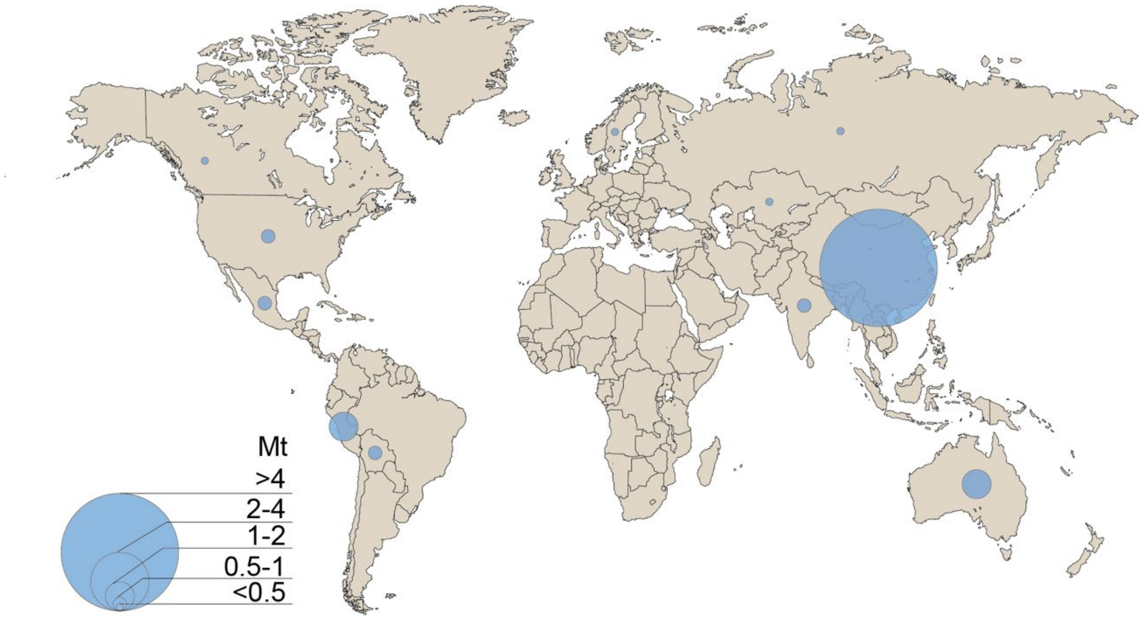


Figure 8-3 *Overview of some of the world's largest zinc-producing countries. Based on data from USGS (2023).*

Table 8-2 *Zinc production (ton) distributed among the largest producer countries. Source: USGS (2023) and WMD (2022).*

Mining country	2022 (USGS)	WMD (2020)
China	4,200,000	4,100,000
Peru	1,400,000	1,300,000
Australia	1,300,000	1,300,000
India	830,000	750,000
USA	770,000	700,000
Mexico	740,000	1,000,000
Bolivia	520,000	360,000
Russia	280,000	260,000
Canada	250,000	210,000
Sweden	240,000	235,000
Kazakhstan	200,000	310,000
Iran		215,000
Portugal		180,000
Brazil		175,000
South Africa		160,000
Turkey		135,000
Ireland		130,000
Eritrea		120,000
Spain		90,000
Burkina Faso		80,000
Others	2,000,000	
Total	**13,000,000**	**12,600,000**

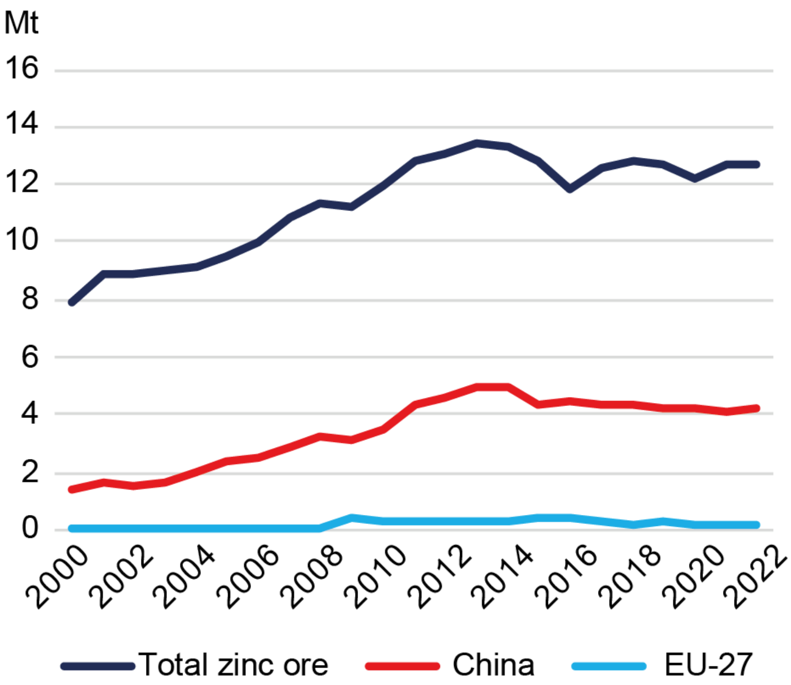


Figure 8-4 *Overview of historical zinc production from mines in the period 2000-2022. Source: USGS (2000-2023).*

8.4.3.1 Companies Involved in the Production and Processing of Zinc

The zinc production outside China is dominated by a few large mining companies, with the largest being Vedanta, Glencore, and Tech Resources. In 2022, they produced from seven mines 860,000 ton, 650,000 ton, and 550,000 ton, respectively. The largest zinc producers in China in 2021 were Shenzhen Zhongijn Lingnan Nonfemet Co. Ltd, Zijin Mining Group Co. Ltd, Western Mining Group Co. Ltd., and Griffin Mining Group Ltd, collectively producing approximately 450,000 ton. An overview of the significant zinc mines (2020) is shown in Table 8-3.

Table 8-3 *Overview of some of the largest zinc mines (2020). Based on, among others, Mining Technology (2020).*

Mine	Country	Company	Production 2021 (ton)	Expected closing year
Ghazaouet	Algeria	ENM&TMF	875,000	
Red Dog	USA	Teck Resources	500,000	2032
Antamina	Peru	Glencore Plc	430,000	2028
Rampura Agucha;	India	Hindustan Zinc Limited (including Vedanta Resources)	395,000	
Rampura Aguca	India	Vedanta Resources	370,000	2027
Mt. Isa/Hilton	Australia	Glencore Plc	330,000	2029
McArthur River	Australia	Glencore Plc	280,000	2038
Bashkirskaya Med	Russia	Ural Mining & Metallurgical	250,000	
Pentasquito	Mexico	Newmont Corp	214,000	
San Cristobal	Bolivia	Minera San Cristobal	195,000	
Golden Grove	Australia	EMR Capital Group	192,000	2031
Fankou	China	Shenzhen Zhongjin Lingnan Nonfemet Co. Ltd	190,000	2033
San Cristobal	Bolivia	Sumitomo	185,000	2024
Fankou Mine, Guangong	China	Shenzhen Zhongjin Lingnan Nonfemet Co. Ltd	183,000	2033
Wulagen Pb-Zn Minw, FuNFSONF	China	Zijin Mining Grou Co. Ltdp	100,000	2044
Sanguikou Zn-Pb Mine, Inner Mongolia	China	Zijin Mining Group Co. Ltd	75,000	242
Xitieshan Pb-Zn Mine, Qinghai	China	Western Mining Group Co. Ltd	60,000	2030
Caijiaying, Hebei	China	Griffin Mining Group Ltd.	40,000	2062

The most significant exploration and production projects outside China, potentially becoming new zinc producers, can contribute as follows: USA (370 kton/year), Canada (350 kton/year), Peru (270 kton/year), and DR Congo (240 kton/year) (Table 8-4). The Greenlandic zinc project, Citronen Fjord, expects an annual production of 200 kton/year and, if realized, will become a significant producer.

8.4.4 Manufacturing of Zinc Products

Supply chains for primary zinc typically include the following steps: (i) mining of the ore; (ii) concentration of ore minerals; (iii) smelting and refining processes; (iv) production of alloys, chemicals (oxides, sulphates, etc.), plates, bars, rods, etc. The typical traded goods in the supply chains are indicated in Figure 8-5.

Table 8-4 *Overview of investigation and production projects. Source: Fitch Solutions (2022).*

Country	Exploration project	Company	Cap. cost estimate (M. USD)	Resource (Mt)	Resource category	Expected production (ton/y)
Algeria	Tala Hamza	Terramin Australia	486	7	Indicated	
Brazil	Aripuana	Nexa Resources	591	10	Proven	70,000
Canada	Pine Point	Osisko Metals	746	13	Inferred	143,000
Canada	Macmillan Pass	Fireweed Zinc	824	11	Inferred	85,000
Canada	Akie	ZincX Resources Corp	466	23	Inferred	81,000
Canada	McIlvenna Bay	Foran Mining Corporation	437	11	Proven	41,000
Canada	Kutcho	Kutcho Copper Corp	473	7	Proven	
DR Congo	Kipushi	Ivanhoe Mines	540	3	Proven	240,000
Eritrea	Asmara	Sichuan Road & Bridge Mining Investment Development Corp	666	5	Proven	
Greenland	Citronen	Ironbark Zinc	514	8	Proven	200,000
Mexico	Pitarrilla	SSR Mining	1,221	12	Indicated	46,000
Mexico	Cordero	Discovery Silver Corp	704	151	Indicated	
Peru	Ayawilca	Tinka Resources	466	19	Indicated	155,000
Peru	Hilarion	Nexa Resources	750	25	Indicated	115,000
Peru	Corani	Bear Creek Mining	579	20	Proven	
Peru	Accha	Zincore Metals	346	11	Proven	
USA	Hermosa	South32	1,244	29	Indicated	221,000
USA	Arctic	Trilogy Metals	1,225	43	Inferred	87,000
USA	Palmer	Constantine Metal Resources	418	5	Inferred	39,000
USA	Back Forty	Aquila Resources Inc	540	8	Indicated	30,000

Below, the four process steps are described in more detail:

i. Mining: Zinc is often mined alongside copper and/or lead from the zinc mineral sphalerite (ZnS). The zinc content in the ore varies (typically 3-10 %) in ore where zinc is the main product.

ii. Ore Processing: Zinc minerals are crushed, grinded, and separated (often flotation processes are used), and a mineral concentrate is produced, which is a commercial raw material (HS 26.08.00).

iii. Smelting and Refining Process: Two methods are used: A) Electrometallurgical smelting: The zinc concentrate is roasted, leached, and purified; the resulting zinc sulphate solution is treated by electrolysis, forming cathode zinc, which may be melted to obtain high-purity zinc products; B) Pyrometallurgical smelting: Zinc ore is sintered, and the resulting sintered slags are leached, and zinc is subsequently refined (Gendersen *et al.* 2016).

iv. Alloy Production: Zinc is used in more than 20 widely applied alloys, such as brass (copper+zinc), galfan (iron+zinc), zamak (aluminium, magnesium, copper, zinc), silicontomba (copper+zinc+silicon), white bronze (copper+tin+zinc), as well as to produce chemicals and rolled products such as bars, plates, etc.

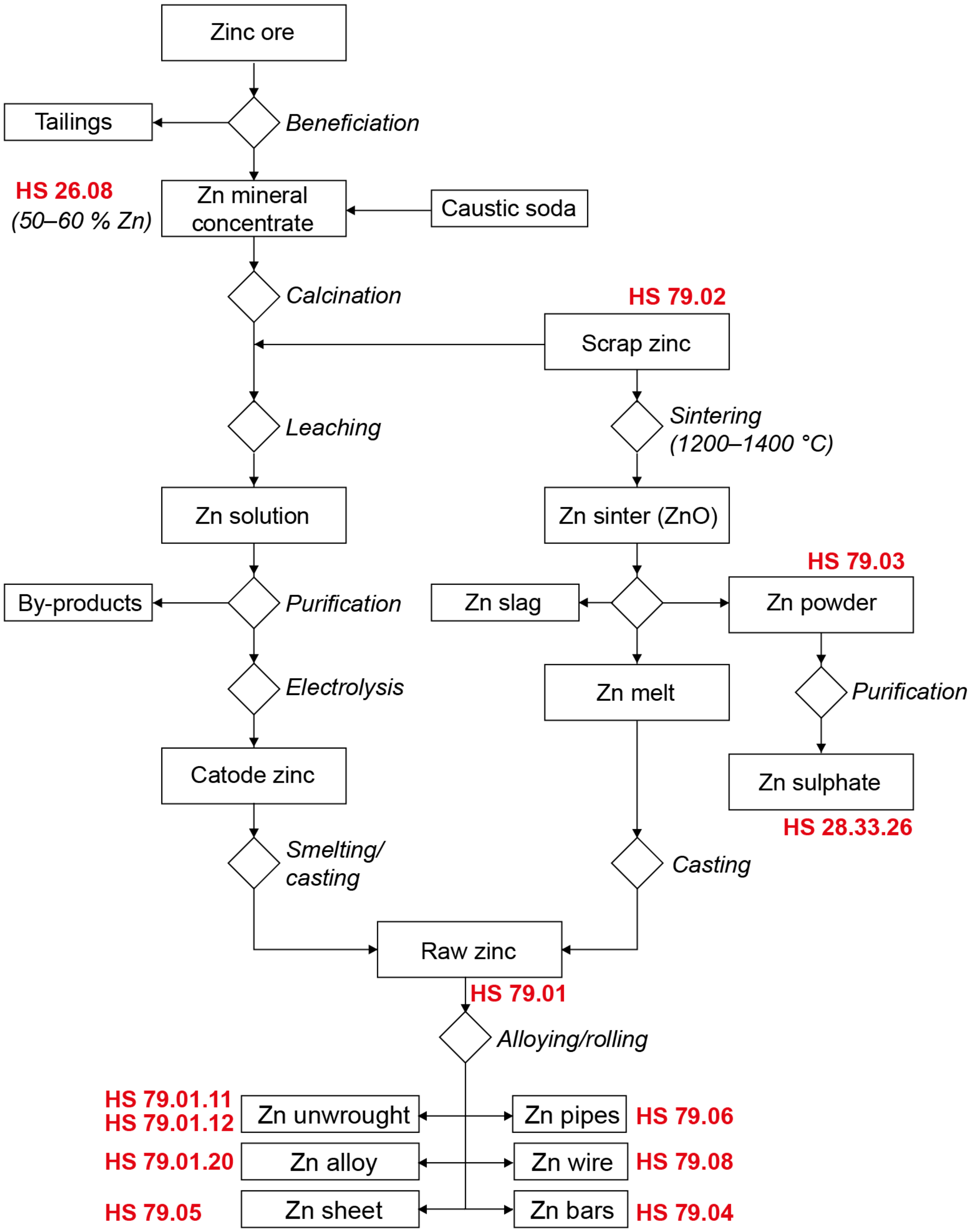


Figure 8-5 *Generic process diagram to produce zinc products, with indication of some important commodity codes (HS codes).*

8.4.5 Climate and Environmental Impact

Van Gendersen *et al.* (2016) report that the CO_2 emissions associated with zinc production in 2012 were approximately 2.6 ton of CO_2e/ton zinc, and the energy consumption amounted to 37,500 MJ/ton (Table 8-5). About 30 % of the energy consumption is used for ore/mineral processing; the smelting processes utilize >50 %, while transportation accounts for around 5 %.

Table 8-5 *Input and CO_2 emissions during the production of 1 ton of refined zinc product (Special High Grade). Source: Calvo et al. (2016) and Gendersen et al. (2016).*

Input	Unit	Consumption	Product (1 ton)
Sphalerite	ton	1,6	Zink (Special High Grade)
Electricity	GJ/ton	24-48	
Water	M^3	8,000	
CO_2 emission	CO_2e/ton	2.6 ton	

8.5 Trade

The automotive industry is the most important sector for zinc, especially in its use for galvanization, manufacturing cathodes for batteries, and producing alloys like brass, bronze, and zinc-copper, among others.

The trade in zinc ore and selected zinc products in 2020 is shown in Table 8-6; declining zinc prices in 2020 have led to a significant decrease in global trade for these products compared to the three previous years.

Table 8-6 *Overview of product codes for a range of major traded goods in the zinc supply chains, indicating their values (billion USD) in 2020. Source: OEC World (2023).*

HS4 code	Commodity	Trade value (M. USD)	HS6 code	Commodity	Trade value (M. USD)
26.08	Zinc ore	8,253			
79.01	Raw zinc	15,762			
			79.01.11	Zinc, not alloyed, unwrought >99 %	8,490
			79.01.12	Zinc, not alloyed, unwrought; <99 %	2,560
			79.01.20	Zinc alloys unwrought	1,610
79.02	Scrap	695			
79.03	Powder	589			
			79.03.90	Powder and flakes	225
79.04	Barer	217			
79.05	Sheet	575			
79.07	Other	1,300	79.07.90	Articles of zinc	1,300

As seen in Table 8-2, China has the largest production of zinc. The trade overviews (Table 8-7 to Table 8-9 and Figure 8-6 to Figure 8-8) show that China does not export its significant production of zinc ore (HS 26.08.00) but is, in fact, a significant importer of zinc raw materials for processing in China. Most zinc ore exports come from Australia, Peru, the USA, Mexico, and Bolivia, primarily exported to China (27 %), South Korea (14 %), Belgium, and Spain (together approximately 14 %).

International trade in zinc ore is substantial, amounting to around 8.25 billion USD in 2020. Based on approximate average prices for zinc ore and concentrates from Trading Economics (2023), it is estimated that the traded volumes in the period 2010-2020 were relatively stable at about 5.5 million ton, except for 2011 when the estimated quantity was about 4.5 million ton. The estimates for traded volumes are significantly lower than the total production in the West; in 2020 the reported trade was approximately 3 million ton less than the reported production. The discrepancy may be attributed to large quantities being traded in periods of low prices or some Western productions not being recorded due to domestic consumption. Zinc ore exports are dominated by major zinc-producing countries such as Australia, Peru, the USA, and Bolivia. However, China, being the largest producer of zinc ore, consumes its entire production domestically and imports additional zinc ore from Australia (almost 90 % of Australia's zinc ore trade), Peru, and Bolivia. Importing countries in Europe include Spain, Germany, and Belgium (Table 8-7 and Figure 8-6).Trade in raw zinc (HS 79.01.00) includes refined zinc products with a total trade value of USD 15.8 billion in 2020, with South Korea, Canada, Spain, and Australia as the major exporting countries. Import is predominantly characterized by smaller transactions with many countries, except for the USA, which accounts for nearly 10 % of the total trade (Table 8-8 and Figure 8-7).

International trade in zinc scrap (HS 79.02) amounted to 695 million USD in 2020, with France, Germany, and the Netherlands accounting for about 40 %. Zinc scrap was imported by many countries, with Italy, India, Belgium, and the Netherlands being the largest. This product category is characterized by multiple countries posing as both exporters and importers; this circumstance, along with the highly branched market structure evident in the Sankey diagrams (Figure 8-6 to Figure 8-8), reflects that markets for zinc raw materials are not dominated by individual countries, partly due to China's significant domestic production.

Table 8-7 *The main export and import countries for zinc ore (HS 26.08) in 2020. The global trade value represents the total export value. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
Australia	1,381	China	820
		South Korea	293
		Japan	85
		Spain	71
		Germany	55
Peru	1,013	China	302
		South Korea	196
		Spain	162
		Brazil	118
		Canada	71
USA	861	Canada	416
		South Korea	107
		Australia	98
		Japan	82
		Spain	48
Bolivia	818	Japan	386
		Australia	100
		China	93
		Belgium	85
		South Korea	54
Subtotal	4,073		
Others	4,180		
Total	8,253		

Table 8-8 *The main export and import countries for raw zinc (HS 279.01) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
South Korea	1,662	Vietnam	344
		India	306
		China	235
		Taiwan	175
		Indonesia	102
Canada	1,609	USA	1,411
		Taiwan	73
		Thailand	28
		South Korea	19
		Malaysia	18
Spain	1,464	Turkey	529
		Germany	177
		Netherlands	167
		Italy	147
		France	68
Australia	1,194	China	335
		Taiwan	202
		Vietnam	200
		Indonesia	97
		Thailand	74
Subtotal	5,929		
Others	9,833		
Total	15,762		

Table 8-9 *The main export and import countries for zinc scrap (HS 79.02) in 2020. Source: OEC World (2023).*

Export country	Trade value (M. USD)	Import country	Trade value (M. USD)
France	116	Italy	50
		Belgium	29
		Netherlands	13
		Spain	6
		India	5
Germany	105	Italy	43
		India	17
		Netherlands	10
		Malaysia	8
		Belgium	5
USA	64	India	24
		Taiwan	11
		Malaysia	8
		Japan	4
		Vietnam	3
Netherlands	61	India	16
		Belgium	13
		Italy	10
		Thailand	8
		Germany	5
Malaysia	39	India	20
		China	10
		Vietnam	3
		Japan	2
		Bangladesh	1
Subtotal	384		
Others	369		
Total	753		

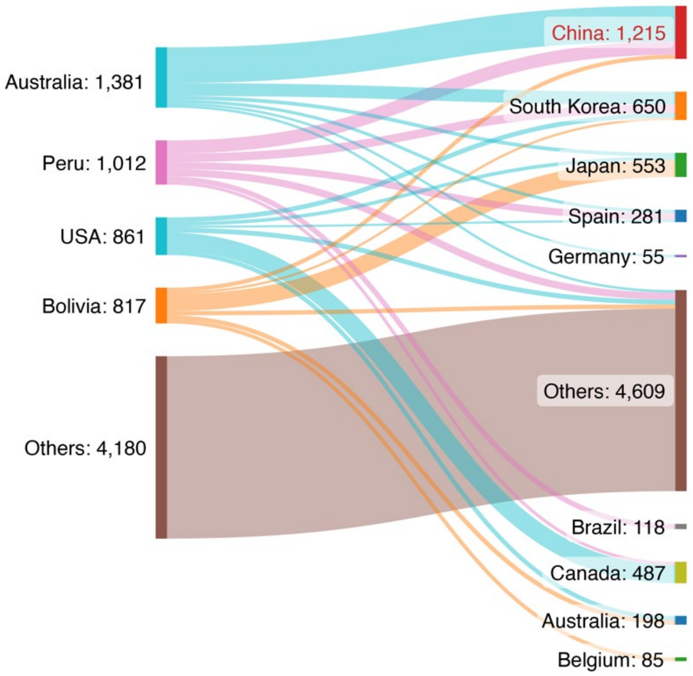


Figure 8-6 *Sankey diagram for trade in zinc ore (HS 26.08) in 2020. All values in million USD, based on Table 8-7.*

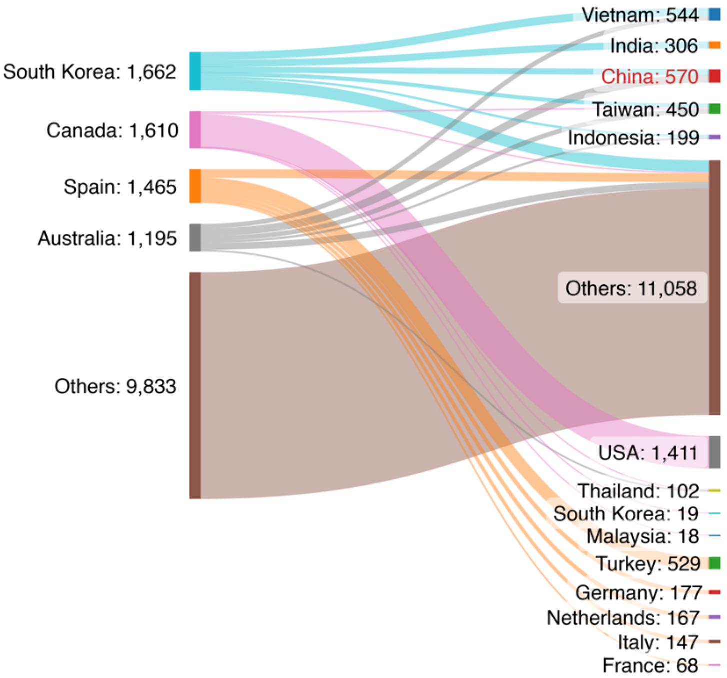


Figure 8-7 *Sankey diagram for trade in raw zinc (HS 79.01) in 2020. All values in million USD, based on Table 8-8.*

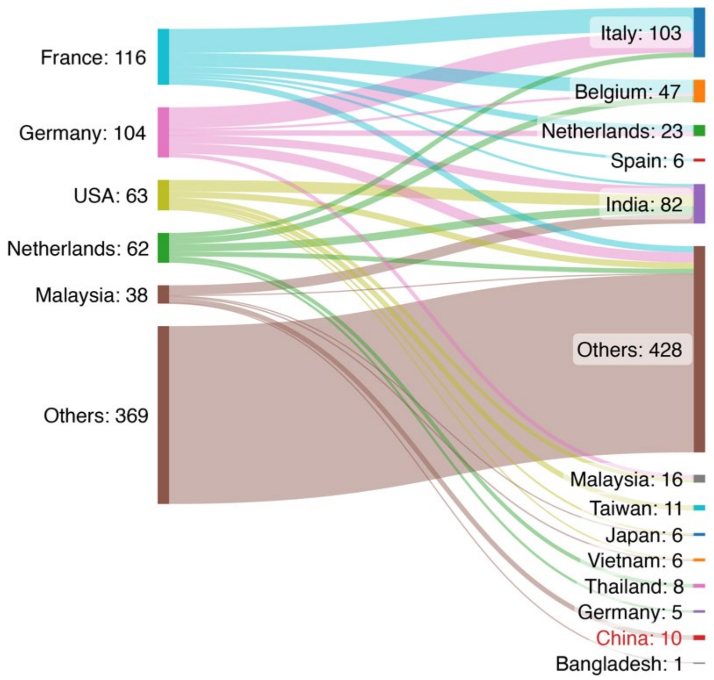


Figure 8-8 *Sankey diagram for trade in zinc scrap (HS 79.02) in 2020. All values in million USD, based on Table 8-9.*

8.5.1 Prices

A significant portion of the global zinc trade occurs through metal exchanges, especially the London Metals Exchange (LME), which conducts ongoing monitoring of zinc production and stocks for price determinations. Additionally, zinc is traded as futures on exchanges such as the Shanghai Futures Exchange (SHFE). The development of zinc prices reflects primarily the Chinese demand, which in turn is influenced by China's domestic supply. This domestic supply is under pressure due to environmental regulations, which are prone to close several Chinese mines. These factors, combined with the steel industry's generally growing need for galvanized products, are expected to cause rising prices.

Figure 8-9 illustrates the price development of zinc over the past 22 years. The figure shows a generally upward trend, with three significant price increases peaking in 2006, 2018, and, most recently, in 2022, interrupting the overall trend.

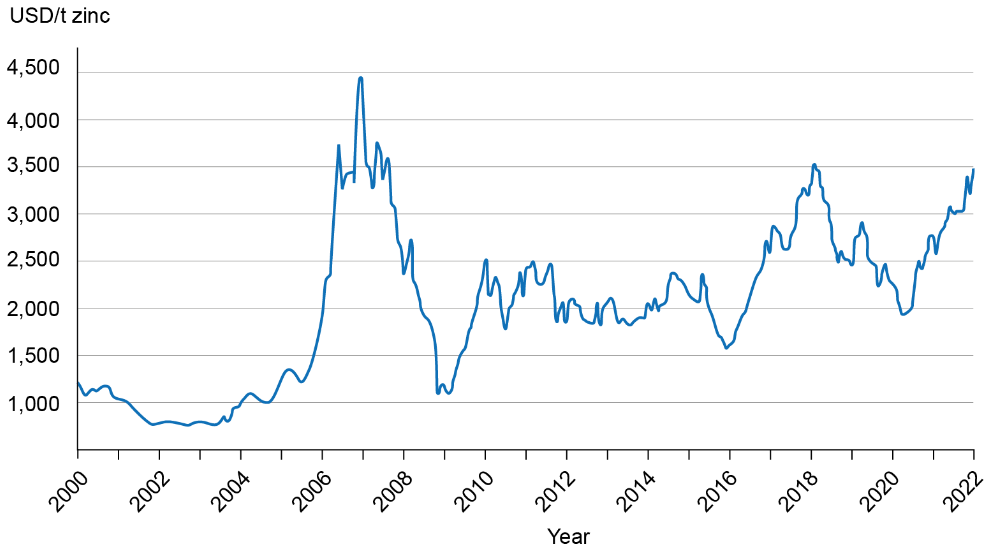


Figure 8-9 *Price development for zinc in the period 2000-2020. Source: Trading Economics (2023).*

8.6 The Danish Consumption

Zinc is an important raw material in the Danish context (Figure 8-10) and ranks as the 10th most economically significant mineral resource for the Danish industry (Clausen *et al.* 2023). In 2019, zinc purchases amounted to 2.6 billion DKK, and zinc was associated with exports from Denmark valued at 2 billion DKK (Clausen *et al.* 2023). Zinc consumption in Denmark is primarily linked to the galvanization of steel and its use in brass, predominantly applied in the industrial sector (68 %) and the construction industry (25 %).

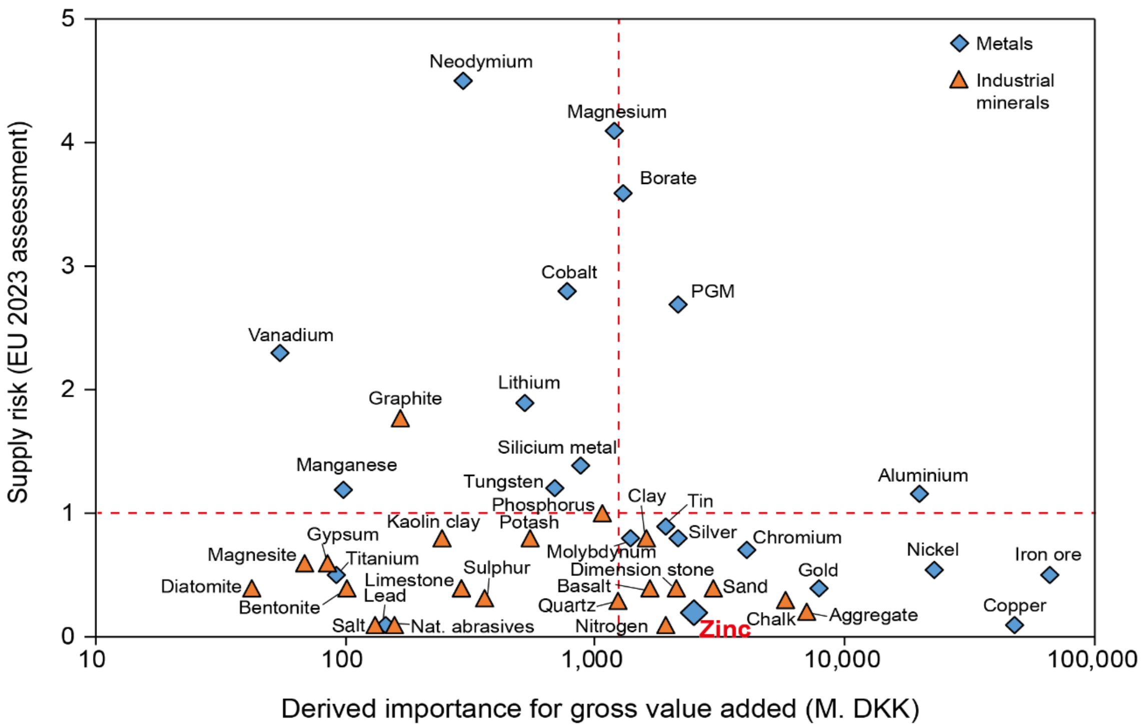


Figure 8-10 *The derived significance of zinc and other raw materials for gross value added as a function of supply risk in Denmark. Figure modified according to Clausen et al. (2023).*

8.7 Perspectives

The EU Commission assesses zinc as a raw material with significant economic importance (EI: 4.8) but considers the security of supply to be good (SRE: 0.2 and SRP: 0.1) for both extraction and processing (EC 2023). This is consistent with the assessments of most other countries; however, both Canada and the USA consider zinc a critical raw material.

China is by far the largest producer of zinc ore, accounting for approximately one-third of the global production, followed by Peru and Australia. A few relatively large mining companies dominate global production, including Glencore, ENM & TMF, Tech Resources, and Hindustan Zinc Ltd., which together contributed to more than 20 % in 2022. Mineral exploration for new zinc deposits has been insufficient, leading to a decline in the lifespan of existing mines. Several major zinc mines are expected to be depleted within the next 10 years, and the extent to which new mines can be initiated remains uncertain (Table 8-4).

Zinc ore is processed in many countries, with China, however, dominating supply chains from mining to finished raw materials.

In the context of the green transition, zinc is particularly in demand for galvanization, including for electric cars and solar panels. Additionally, the consumption of zinc for zinc batteries is expected to grow significantly. Overall, these markets are not expected to have a significant impact on zinc demand, partly because the increasing production of electric vehicles is accompanied by a decrease in the production of conventional cars. Gregoir *et al.* (2020) expect an annual growth in zinc consumption of 1.2 %, equivalent to approximately 20 Mt in 2030 and 25-27 Mt in 2050. This aligns with assessments from EC (2020b), Svemin (2021), and Rostek *et al.* (2023); the latter anticipates that recycled zinc in 2050 will account for up to 14 Mt (compared to 9 Mt in 2019).

8.8 References

Calvo, G., Mudd, G., Valero, A. & Valero, A. 2016: Decreasing ore grades in global metallic mining: A theoretical issue or a global reality. Resources 5 (4) (36), Nov. 2016

Clausen, R. J., Kalvig, P., Keiding, J.K., Fold, N. & Vind, I. (2023): Dansk industris brug af mineralske råstoffer – økonomisk betydning og forsyningsudfordringer MiMa rapport 2023/2, pp. 181. https://doi.org/10.22008/gpub/32051

European Commission (EC) 2020a: Study on the EU's list of Critical Raw Materials (2020), Factsheets on Non-critical Raw Materials https://www.researchgate.net/publication/344124852_Study_on_the_EU's_list_of_Critical_Raw_Materials_2020_Final_Report

European Commission (EC) 2020b: Critical materials for strategic technologies and sectors in the EU - a foresight study. https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf

European Commission (EC) 2023: Study on the Critical Raw Materials for the EU 2023 – Final Report. https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

European Minerals Yearbook data for Zinc 2018: http://minerals4eu.brgm-rec.fr/m4eu-yearbook/pages/bycommodity.jsp?commodity=Zinc

Fitch Solution 2022: Global Zinc Mining Outlook; 19. September 2022. Global Zinc Mining Outlook (fitchsolutions.com)

Gendersen, E. van, Wildnauer, M., Santero, N. & Sidi, N. 2016: A global life cycle assessment for primary zinc production. The international Journal of Life Cycle Assessment 21, 1580-1593

Gregoir, L., Acker, K. van, Beretta, S. & Heron, C. 2022: KU Leuven and Eurometaux Report, 117 pp. https://eurometaux.eu/media/jmxf2qm0/metals-for-clean-energy.pdf

Mining Technology 2020: https://www.mining-technology.com/marketdata/ten-largest-zincs-mines-2020/

Observatory of Economic Complexity World (EOC World) 2023: Database https://oec.world/

Rostek, L., Pirard, E. & Loibl, A. 2023: The future availability of zinc: Potential contributions from recycling and necessary ones from mining. Resources, Conservation & Recycling Advances., Vol 19, 200166

Scrreen2 Zinc factsheet 2023: Scrreen2 Factsheet updates based on the EU Factsheets 2020 Zinc https://scrreen.eu/wp-content/uploads/2023/06/SCRREEN2-factsheets_ZINC.pdf

Statista 2023: Distribution of zinc consumption worldwide in 2021, bey end use. https://www.statista.com/statistics/240626/share-of-zinc-consumption-by-category/

Svemin 2020: Climate ambitions and metal needs – opportunities for Sweden and the Swedish mining industry. Report 28 pp.

Sørensen, L.L., Kalvig, P., Thrane, K. & Rosa, D. 2018: The zinc potential in Greenland. Geology and Ore 30 12 pp.

Sørensen, L.L., Stensgaard, B.M., Thrane, K., Rosa, D. & Kalvig, P. 2014: Sediment-hosted zinc potential in Greenland – Reporting the mineral resource assessment workshop 29 November – 1 December 2011. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2013/56, 184 pp.

Thaarup S.M. 2021: Zink. Fakta om råstoffer 14. 4 pp. https://doi.org/10.22008/gpub/38043

Trading Economic 2023: https://tradingeconomics.com/comodity/zinc

USGS 2000-2023: Mineral commodity summaries 2000-2023: U.S. Geological Survey https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries

World Mining Data (WMD) 2022: Vol 37, 28 April 2022 https://www.world-mining-data.info/wmd/downloads/PDF/WMD2022.pdf

ISBN: 978-87-7871-607-1

GEOCENTER DENMARK

Geocenter Denmark is a formalised cooperation between Geological Survey of Denmark and Greenland (GEUS), Department of Geoscience at Aarhus University and the Geological Museum and Department of Geosciences and Natural Resource Management at the University of Copenhagen.

Center of Mineral Resources and Materials (MiMa) is an advisory center under The Geological Survey of Denmark and Greenland (GEUS). MiMa imparts knowledge on mineral resources, mineral occurrences, their circuit and influence on society.

De Nationale Geologiske Undersøgelser
for Danmark og Grønland (GEUS)
The Geological Survey of Denmark and Greenland

Øster Voldgade 10
DK-1350 Copenhagen K
Denmark

GEUS is research and advisory institution in the Danish Ministry of Climate, Energy and Utilities