SCRREEN2

This project has received funding from the European

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Solutions for CRitical Raw materials - a European Expert Network

FACTSHEETS UPDATES BASED ON THE EU FACTSHEETS 2020

NIOBIUM

AUTHOR(S):

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NIOBIUM

OVERVIEW

Niobium (chemical symbol Nb) is grey in colour. It is a relatively hard, paramagnetic, refractory transition metal. It has a density of 8.57 g/cm^3 and a very high melting temperature (2,468°C). Niobium is also highly resistant to chemical attack and behaves as a superconductor at very low temperature. The upper-cristal abundance of niobium is 12 ppm (Rudnick and Gao, 2003), which is higher than some of the other refractory metals, but lower than many of the base metals. Niobium is not found as a free metal in nature, but chiefly occurs in minerals such as columbite and pyrochlore, the latter being the primary ore mineral. Some characteristics and properties are similar to other neighbouring elements on the periodic table. This is the case for tantalum, which is located just below niobium on the periodic table and often appears in the same deposits as niobium (Tercero et al. 2018)

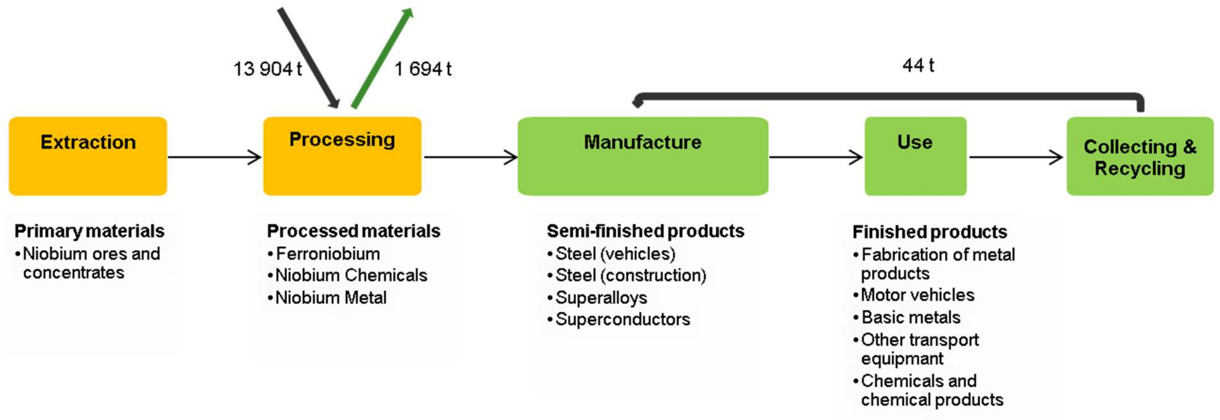

Figure 1. Simplified value chain for niobium in the EU[1]

Table 1. Niobium extraction supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
72,502	Brazil 92% Canada 7%	-	-	-	-

Table 2. Niobium processing supply and demand in metric tonnes, 2016-2020 average

[1] JRC elaboration on multiple sources (see next sections)

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Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
41,425	Brazil 89% Canada 11%	2,813	7%	Brazil 82% Canada 16%	100%

Prices: Niobium prices range from US$45 per kilogram (US$45,000 per tonne) for standard ferroniobium metal and greater than US$50 per kilogram for niobium pentoxide (Nb2O5). Higher purity and more specialised products realise higher prices. The volatility of niobium prices is low compared to other critical minerals, one key factor in customer supply-chain certainty. In the past 5 years its price has been stable around 25000 USD per tonne.

Primary supply: Brazil is the major producer, representing the 92% of the global production in 2020, while a small production is taking place in Australia, Canada, Russia and Congo. With the exception of the African countries listed above, companies extracting niobium ores are typically integrated, meaning they also produce processed niobium products, such as niobium oxide, ferroniobium and niobium metal.

Secondary supply: The niobium contained in the waste is mostly non-functionally recycled. There is very little post-consumer functional recycling of niobium globally and most is diluted into recycled steels. The annual addition to stock in landfill is estimated at around 0.2 kt (BIO by DELOITTE (2015)). According to the United Nations Environment Program (UNEP), the End-of-life Recycling Input Rate (EOL-RIR) for niobium, chiefly as a constituent of ferrous scrap, is greater than 50% (Reuter M. (2013)). However, the amount of niobium physically recovered from scrap (i.e. functional recycling) is negligible (BIO by DELOITTE (2015)), below 1%.

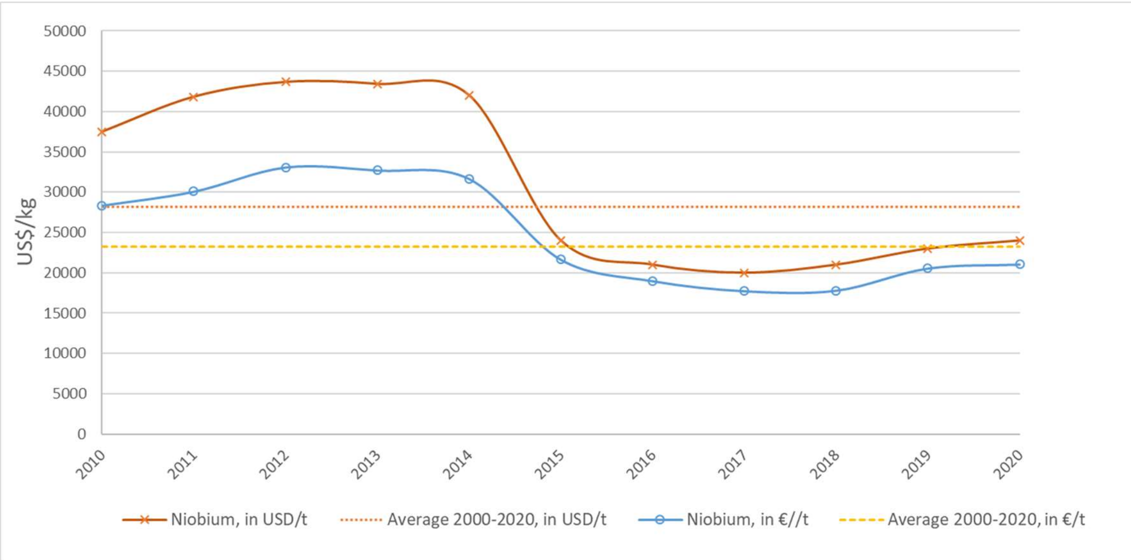

Figure 2. Annual average price of RM between 2000 and 2020 (USGS, 2021)[2].

[2] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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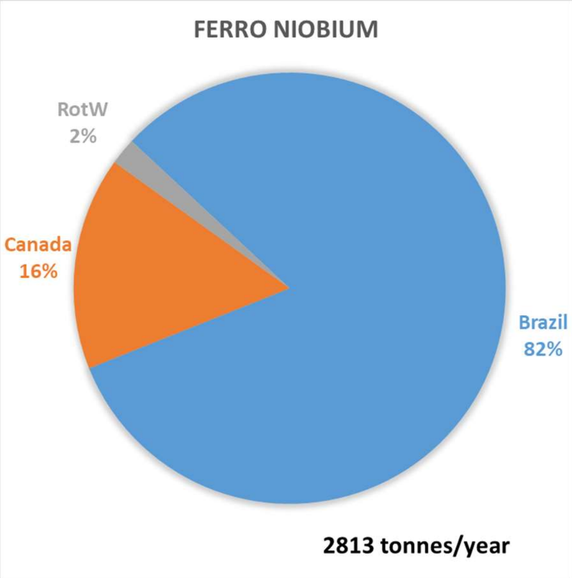

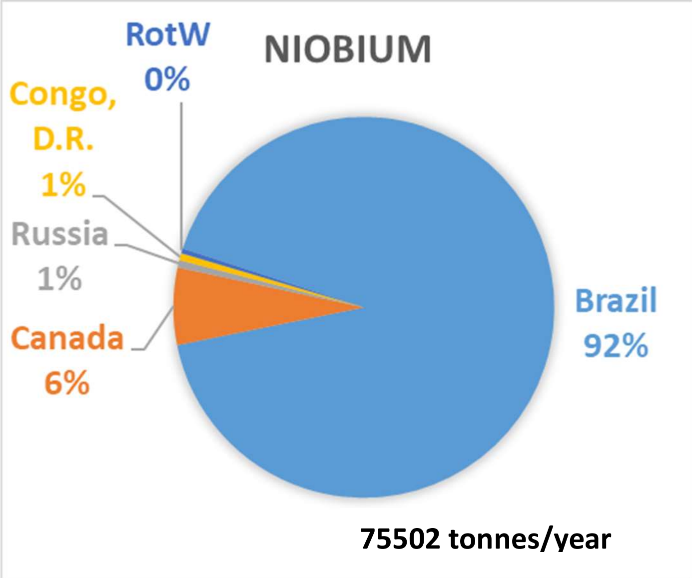

Figure 3. EU sourcing of RM and global mine production (average 2016-2020)

Uses: Niobium is mainly used in steels for automotive (22%), construction (44%), stainless steel (9%) and special steels (2). The other main application is in super alloys for oil&gas. (16%)

Substitution: Several materials can be substituted for niobium in the production of high strength, low alloy (HSLA) steel and superalloys: including other critical materials: vanadium, molybdenum, tantalum, and titanium. Other materials may include tungsten, ceramic matrix composites and gallium alloys ((USGS, 2022), (Tercero et al., 2018), (CRM_InnoNet, 2013). Most of time performances are reduced.

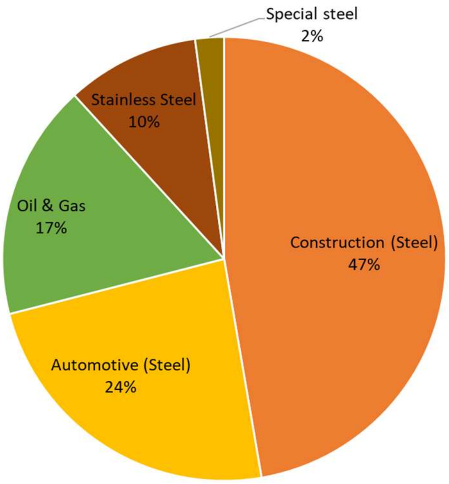

Figure 4: EU uses of RM

Table 3. Uses and possible substitutes

Application	%*	Substitute(s)	SubShare	Cost	Performance
Construction (Steel)	44%	Vanadium; Molybdenum; Titanium	33% each	Similar or lower costs	Reduced
Stainless Steel	9%	Molybdenum; Titanium	50% each	Similar or lower costs	Reduced
Oil & Gas	16%	Molybdenum; Titanium; Vanadium	33% each	Similar or lower costs	Reduced
Automotive (Steel)	22%	Vanadium; Molybdenum; Titanium	33% each	Similar or lower costs	Reduced

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Other issues: Regarding safety and health measures, the ILO specifies that "atmospheric concentrations of the aerosols of niobium alloys and compounds that contain toxic elements such as fluorine, manganese and beryllium, should be strictly controlled. During the mining and concentration of niobium ore containing uranium and thorium, the worker should be protected against radioactivity" (ILO, 2011). Niobium is indeed usually associated with high concentrations of uranium and/or thorium (German Environment Agency, 2020).

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 4. Niobium extraction supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
72,502	Brazil 92% Canada 7%	0	-	-	-

Table 5. Niobium processing supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
41,425	Brazil 89% Canada 11%	2,812	7%	Brazil 82% Canada 16%	100%

At over 90%, Brazil is by far the leading mine producer of niobium and is also an important producer of ferroniobium. Canada as the second largest mine producer accounted for 6.6% of average annual production. Russia, DR Congo, Rwanda, Nigeria, China, Ethiopia, Uganda, Mozambique and Burundi also reported minor production. The Covid-19 pandemic led to a decline in global production in 2020.

Estimates by the USGS (2022a) of world niobium reserves amount to over 17 million tonnes. At 16 million tonnes, Brazil holds the largest reserves.

Companhia Brasileira de Metalurgia e Mineração (CBMM) is by far the world's leading producer with from its Araxá niobium mine in Brazil. Other important producers are Niobras Mineração Ltda. a subsidiary of China Molybdenum Co., Ltd. (China) and Mineração Taboca S.A., a subsidiary of MINSURA S.A. in Brazil and Niobec, a subsidiary of Magris Resources Inc. in Canada.

Niobium minerals are typically converted at the mine site to ferroniobium and other value-added products such as niobium metal and oxide. Ferroniobium is the leading commercial niobium material and most important niobium material traded. Other globally traded niobium materials include niobium metal, ores and concentrates, and scrap (USGS, 2021). Brazil and here CBMM is by far the leading supplier of ferroniobium and niobium metal and oxides.

Niobium materials are not traded on exchanges. Purchase contracts are negotiated confidentially between buyer and seller.

Market demand for niobium closely follows the steel industry, as most of the world's niobium is added to steel as ferroniobium. Ferroniobium is typically consumed in the production of high-strength low-alloy (HSLA) steel. Other uses of niobium include the fabrication of nonferrous and niobium alloys and production of niobium

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carbides and chemicals (USGS, 2021). Ferroniobium is used as a steel alloy substitute for ferro-vanadium and ferro-manganese. In 2018, as vanadium prices rose sharply, demand for ferroniobium also increased. The growth was due to higher Chinese demand as more stringent standards were enforced for construction materials.

Niobium production will continue to be concentrated in Brazil. CBMM's Araxá deposit has the reserves and capacity to significantly expand production. Already in the past, CBMM has increased production several times to meet long-term market demand and to force new competitors out of the market.

EU TRADE

For this assessment, NIOBIUM is evaluated at the extraction stage with CN26159000 (Niobium, tantalum or vanadium ores and concentrates, from 2010) and CN26159010 (Niobium, tantalum ores and concentrates, before 2010) and at the processing stage with CN72029300 (Ferroniobium).

Estimating the amount of niobium potentially accounted under the CN codes 26159000 and 26159010 is not obvious since no data are available for a precise disaggregation of the information. The following hypothesis was made here: For CN26159000, the first hypothesis is that the ratio between Nb Ta and V ore follow the ration of the respective mine production for each material. This lead to 55% for vanadium, 44% for Nb and 1% Ta based on the average 2016-2020 production. The second hypothesis is that niobium in under Nb2O5 form in the contrite (70% of Nb). This third hypothesis is that the concentrate contains 55% of Nb2O5. With this, it is estimated that the amount of Nb in CN26159000 is about 17%. The same approach leads to 38% in CN26159010

Table 6. Relevant Eurostat CN trade codes for niobium

Mining		Processing	
CN trade code	**title**	**CN trade code**	**title**
26159000	Niobium, tantalum or vanadium ores and concentrates, Nb content of 17%	72029300	Ferroniobium, 65% of Nb content
26159010	Niobium, tantalum ores and concentrates, Nb content of 38%		

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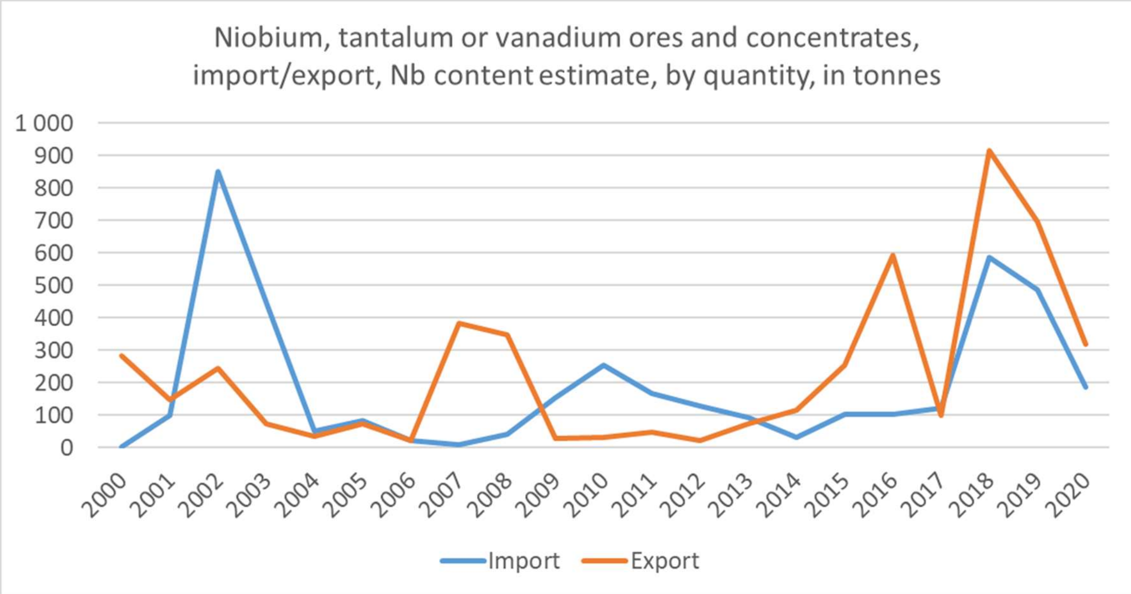

Figure 5 .EU trade flows of niobium, tantalum and vanadium ores and concentrates (CN26159000 and CN26159010), estimated in Nb content, by country from 2000 to 2021 (Eurostat, 2022)

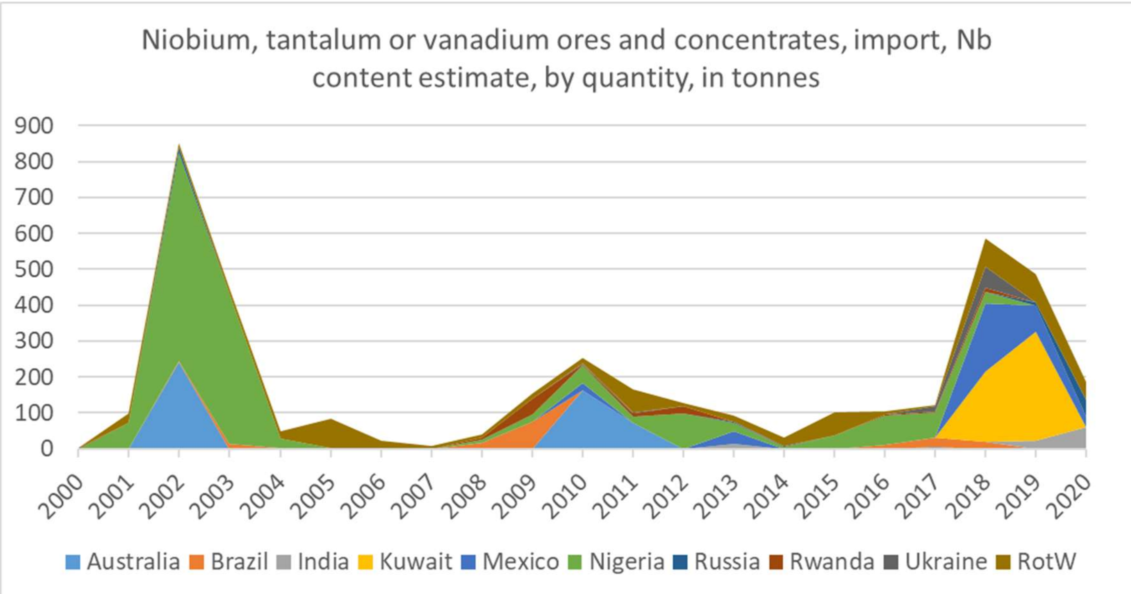

Figure 6 .EU imports of niobium, tantalum and vanadium ores and concentrates (CN26159000 and CN26159010), estimated in Nb content, by country from 2000 to 2021 (Eurostat, 2022)

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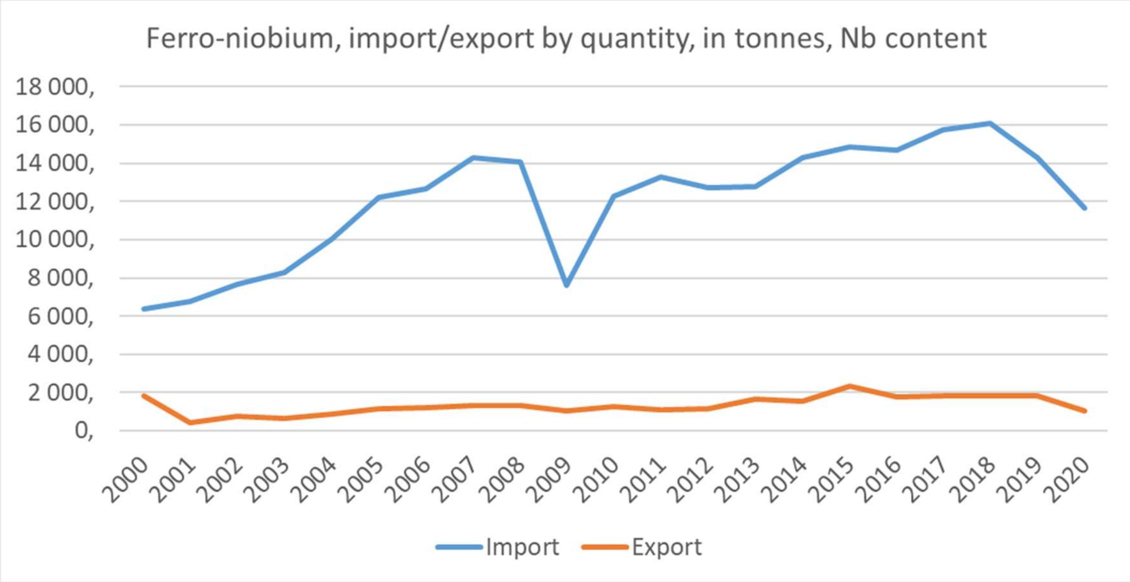

Figure 7. EU trade flows of Niobium (CN 72029300) from 2000 to 2021 (Eurostat, 2022)

The COVID-19 pandemic halted the rising demand for ferroniobium in the early part of 2020, however analysts report that demand is returning to more normal levels since mid-year with China largely recovered from the effects of the pandemic. Import in EU dipped for 2019 and 2020 year but it can be observed that as consumption rises import has also grown sharply in 2021. Exports, however, is still on a declining trend.

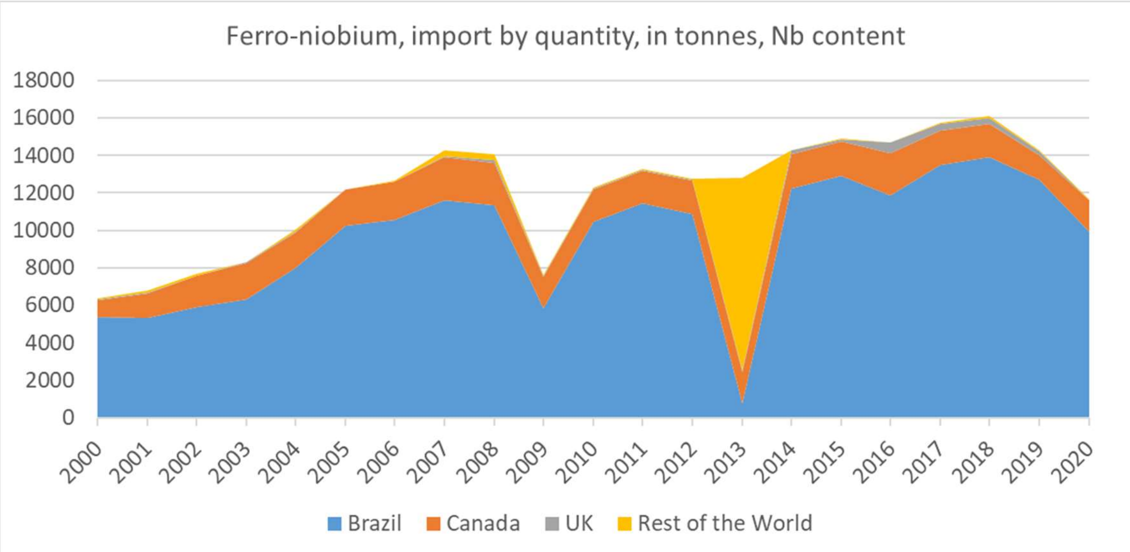

Figure 8. EU imports of NIOBIUM (CN 72029300) by country from 2000 to 2021 (Eurostat, 2022)

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PRICE AND PRICE VOLATILITY

Niobium prices range from US$45 per kilogram (US$45,000 per tonne) for standard ferroniobium metal and greater than US$50 per kilogram for niobium pentoxide (Nb_2O_5). Higher purity and more specialised products realise higher prices. The volatility of niobium prices is low compared to other critical minerals, one key factor in customer supply-chain certainty. In the past 5 years its price has been stable around 25000 USD per tonne.

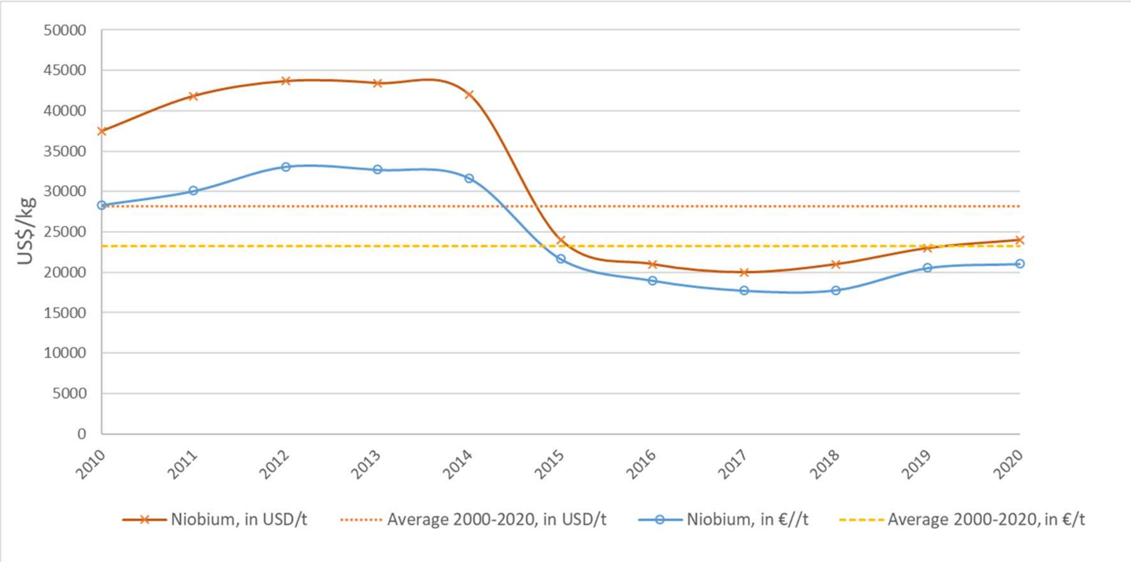

Figure 9. Annual average price of ferroniobium between 2000 and 2020, in US$/t and €/t[3]. Dash lines indicate average price for 2000-2020 (USGS, 2022b)

DEMAND

EU DEMAND AND CONSUMPTION

Bakry et al. (2022), based on Cradle resources (2021), estimates the annual average worldwide consumption of ferroniobium as about 100-110 ktonnes.

Niobium extraction stage EU consumption is presented by HS codes CN 26159000 + CN 26159010 Niobium, tantalum, vanadium and zirconium ores and concentrates (assumed 38 % niobium content). Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from WMD (2022).

[3] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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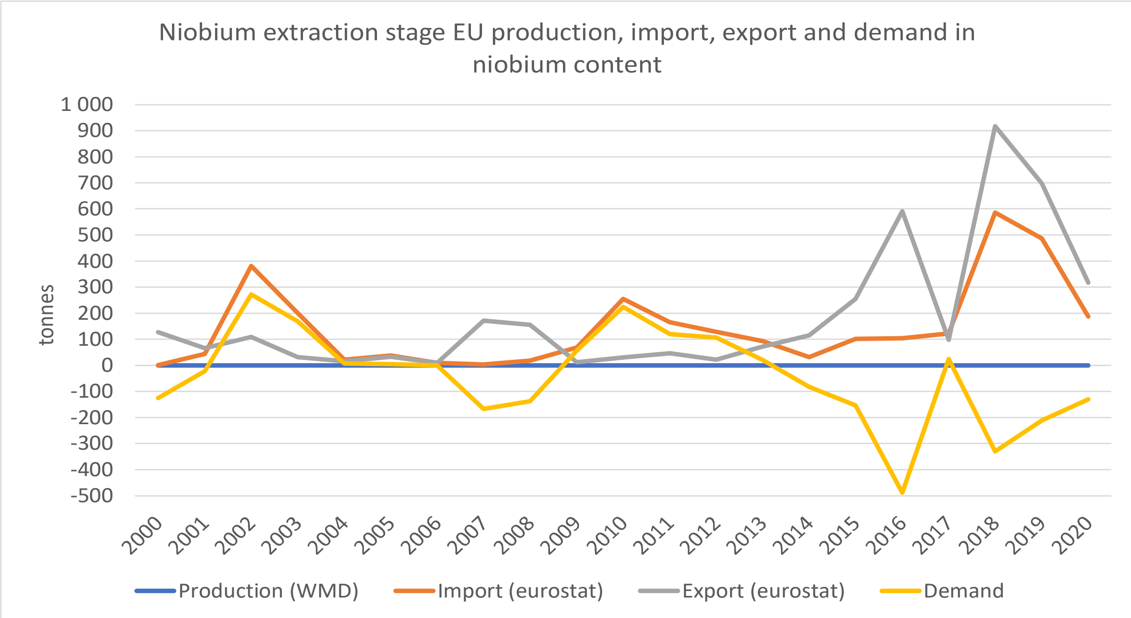

Figure 10. Niobium (CN 26159000 + CN 26159010) extraction stage apparent EU consumption. Production data is available from WMD (2022) for 2000-2020. Consumption is calculated in niobium content (EU production+import-export).

Niobium processing stage EU consumption is presented by HS code CN 72029300 ferroniobium. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2022) using PRCCODE 24101270 Ferroniobium.

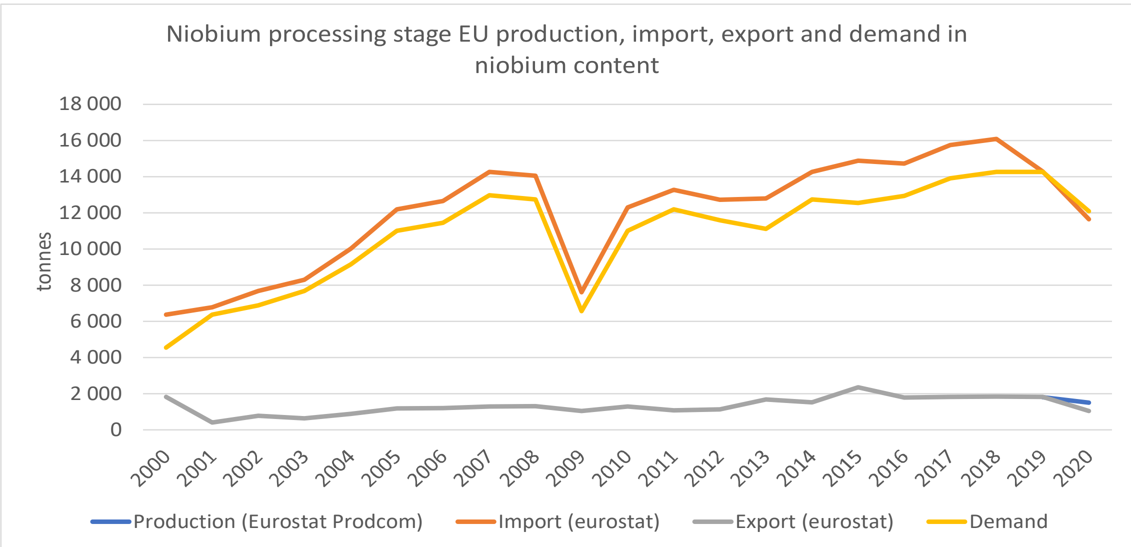

Figure 11. Niobium (CN 72029300) processing stage apparent EU consumption. Production data is available from Eurostat Prodcom (2022) for 2019-2021. Consumption is calculated in niobium content (EU production+import-export).

Based on Eurostat Comext (2022) and Eurostat Prodcom (2022) average import reliance of niobium is at extraction stage 100 % for 2016-2020 and at processing stage 95.0 % for 2019-2020 and 98% for 2016-2020.

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4.2 EU USES AND END-USES

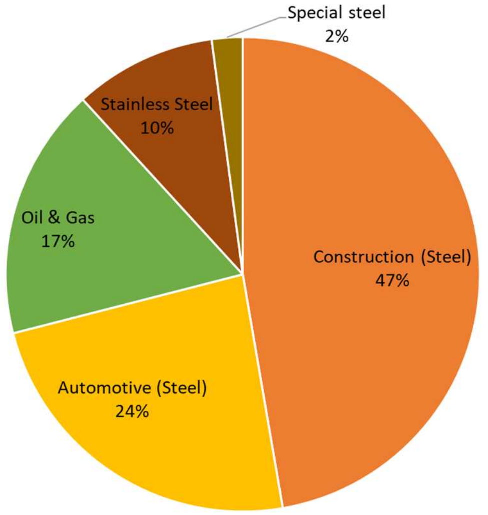

Figure 12: End uses of Niobium in the EU (CBMM, 2019), averaged over 2012-2016 (CBMM, 2019; EC Data 2023).

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors.

Table 7: Niobium applications, 2-digit NACE sectors, associated 4-digit NACE sectors, and value added per sector (Data from (Eurostat, 2022)).

Applications	2-digit NACE sector	Value added of sector (millions €)	4-digit NACE sector
Automotive (Steel)	C29 - Manufacture of motor vehicles, trailers and semi-trailers	234, 398	C2910 Manufacture of motor vehicles
Construction (Steel)	C25 - Manufacture of fabricated metal products, except machinery and equipment	186,073	C2511 Manufacture of metal structures and parts of structures
Oil & Gas	C24 - Manufacture of basic metals	63,700	C2420 Manufacture of tubes, pipes, hollow profiles and related fittings, of steel.
Stainless steel	C24 - Manufacture of basic metals	63,700	C2420 Manufacture of tubes, pipes, hollow profiles and related fittings, of steel.
Special steel	C30 - Manufacture of other transport equipment	49,129*	C3030 Manufacture of air and spacecraft and related machinery

*data up to 2014 only

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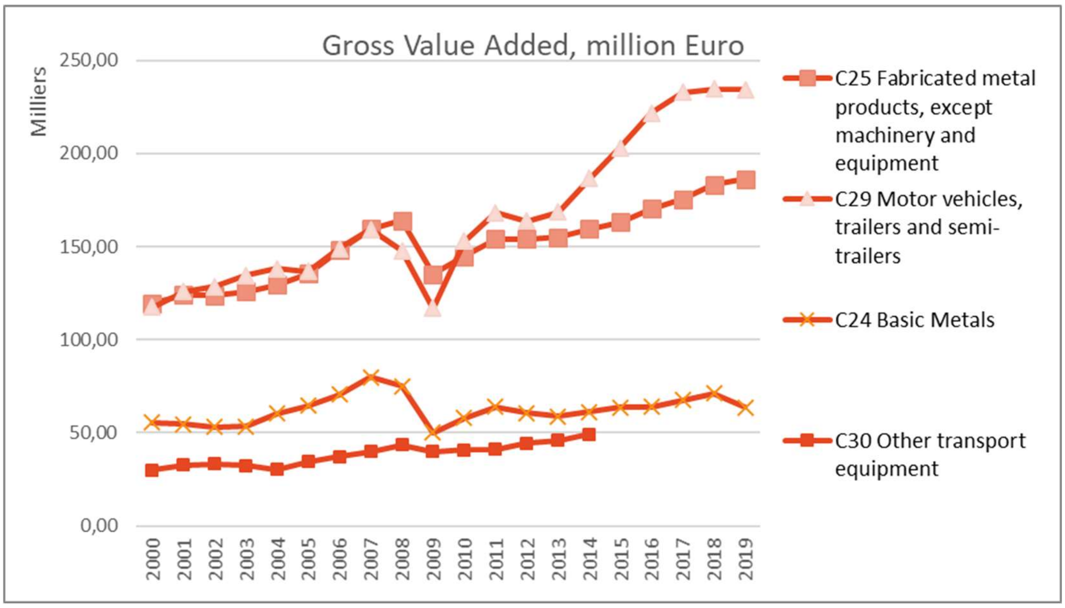

Figure 13: Value added per 2-digit NACE sector over time (Eurostat, 2022).

APPLICATIONS OF NIOBIUM

STEEL (CONSTRUCTION, STAINLESS, AUTOMOTIVE, SPECIAL)

Globally, about 90% of niobium (in the form of ferroniobium, in 2017) is used in the production of High-strength low-alloy (HSLA) steels. It is used as an additive in steel as it increases strength by refining the grain microstructure; and these strength increases allow weight savings in the final product.

In the EU, about 44% of niobium is used in construction, 22% in the production of automotive vehicles, 9% for stainless steel, and 2% for other special steels (CBMM, 2019).

OIL & GAS

Niobium is used in superalloys for oil and gas piping and turbines, accounting for 16% of the total EU use (CBMM, 2019). The advantages of using Nb in ferrous alloys are improved safety, optimum mechanical properties, cost reduction, lower environmental impact and GWP potential (Niobium, 2023).

OTHER

Other uses of Nb in industrial applications include:

- <u>Niobium-bearing alloys</u>
  Steels which contain significant quantities of niobium are typically used in high-performance industries, or specialised applications where traits such as corrosion resistance and high strength at high operating temperatures are sought. This type of alloys is also used in the nuclear (e.g. reactor parts) and space industry. Other alloys of niobium include niobium-titanium and niobium-tin alloys, which are used to

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manufacture the superconducting magnets fund in MRI (Magnetic Resonance Imaging) scanners (BGS, 2011).

- Niobium-based chemicals
  Niobium-based chemicals have unique optical, piezoelectric (i.e., the ability to generate an electric charge in response to mechanical stress) and pyroelectric (i.e., the ability to generate an electric charge in response to heating or cooling) properties that are sought after in several high-technology applications. For example, high-purity niobium oxide is used in the production of high-refractive index glass used in the manufacture of camera lenses.
  Compounds such as lithium niobate are used in the production of capacitors and surface acoustic wave filters, which are used in the manufacture of mobile phones and other touch screen devices.
  Niobium nitride is also used in the production of superconducting magnets found inside MRI scanners (T.I.C., 2019).
- Production of niobium carbide.
  Niobium carbides_are extremely hard ceramic substances which are produced by sintering niobium powder with carbon at high temperature. They are resistant to wear and high-temperature and are used to produce hard cutting tools (e.g. industrial high-speed cutting tools) and refractory coatings that are used in nuclear reactors and industrial furnaces (BGS, 2011).

SUBSTITUTION

An EU CRM study (EU CRM, 2023) validated the degree to which niobium can be substituted in its main applications. The corresponding data is shown in Table 8:

Table 8: Substitution options for niobium by application (USGS 2022, SCRREEN Experts ; EC Data 2022).

Application	%*	Substitute(s)	SubShare	Cost	Performance
Construction (Steel)	44%	Vanadium; Molybdenum; Titanium	33% each	Similar or lower costs	Reduced
Stainless Steel	9%	Molybdenum; Titanium	50% each	Similar or lower costs	Reduced
Oil & Gas	16%	Molybdenum; Titanium; Vanadium	33% each	Similar or lower costs	Reduced
Automotive (Steel)	22%	Vanadium; Molybdenum; Titanium	33% each	Similar or lower costs	Reduced

* EU end use consumption share.

STEEL

- Several materials can be substituted for niobium in the production of high strength, low alloy (HSLA) steel and superalloys: including other critical materials: vanadium, molybdenum, tantalum, and titanium. Other materials may include tungsten, ceramic matrix composites and gallium alloys ((USGS, 2022), (Tercero et al., 2018), (CRM_InnoNet, 2013).

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- Assuming 1:1 substitution in alloys is overly simplistic. Alloy properties are not controlled by a single metal, but by several metals, and each metal may produce a range of effects in the alloy.
- For example, in the production of HSLA steel, niobium is used in combination with small amounts of other metals, including (but not limited to) chromium, nickel, copper, vanadium, molybdenum, titanium, calcium, rare earth elements and zirconium. The interaction between these additions is complex, but they can be used to modify properties such as strength, toughness, corrosion resistance and formability (Beta Technology, 2016). Therefore, it cannot be reasonably assumed that the increased addition of one of these metals in the absence of niobium would produce a steel with the same properties.
- Any substitution would be associated reduced performance and could involve the use of other raw materials assessed as critical.
- In general, there appears to be little economic or technical incentive to substitute niobium in its principal applications.

SUPPLY

EU SUPPLY CHAIN

Niobium ores and concentrates are not mined in the EU, nor are they traded within the EU. Ferroniobium is also not produced in the EU, meaning the EU is entirely reliant on ferroniobium imports to meet demand. However, specialist niobium-based alloys (e.g. superalloys) and chemicals (e.g. lithium niobate) are manufactured in Europe, although it is difficult to quantify how much ((BIO Intelligence Service, 2015), (Beta Technology, 2016)). NPM Silmet (Estonia) is a European refiner of niobium producing highly pure niobium. Figure 1 depicts the flows of niobium within the EU economy.

Ferroniobium is primarily used in the production of HSLA steels, with the majority (about 11,000 t) of EU imports going to only eight countries: Austria, Belgium, Germany, France, Finland, Italy, Spain and Sweden. Germany is the largest steel producer in Europe (World Steel Association, 2018) and therefore accounts for the greatest share of ferroniobium imports. Ferroniobium imported amount by EU in 2019 presents an increase (21.6 kt) (Worldbank, 2019) in comparison to the imported amounts of the period 2012-2016.

There are currently no export quotas placed on ferroniobium exported to the EU from other countries. However, ferroniobium exports from China entering the EU are subject to an export tax of between 25 and 75% (OECD, 2019).

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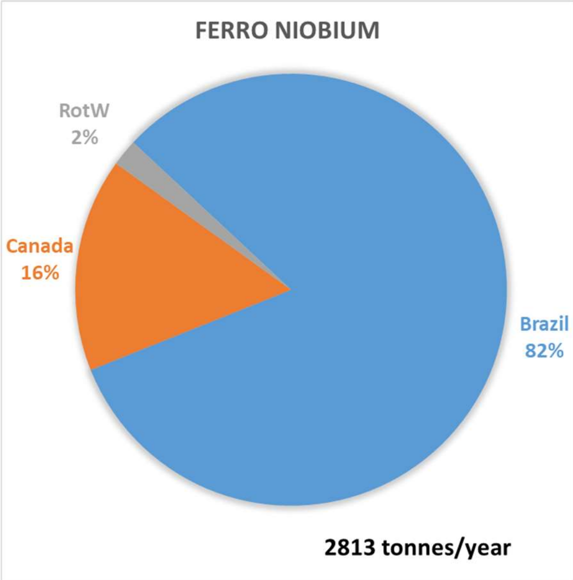

Figure 14. EU sourcing (domestic production + imports) of ferroniobium, average 2012-2016 (Eurostat, 2019b), (WMD 2018)

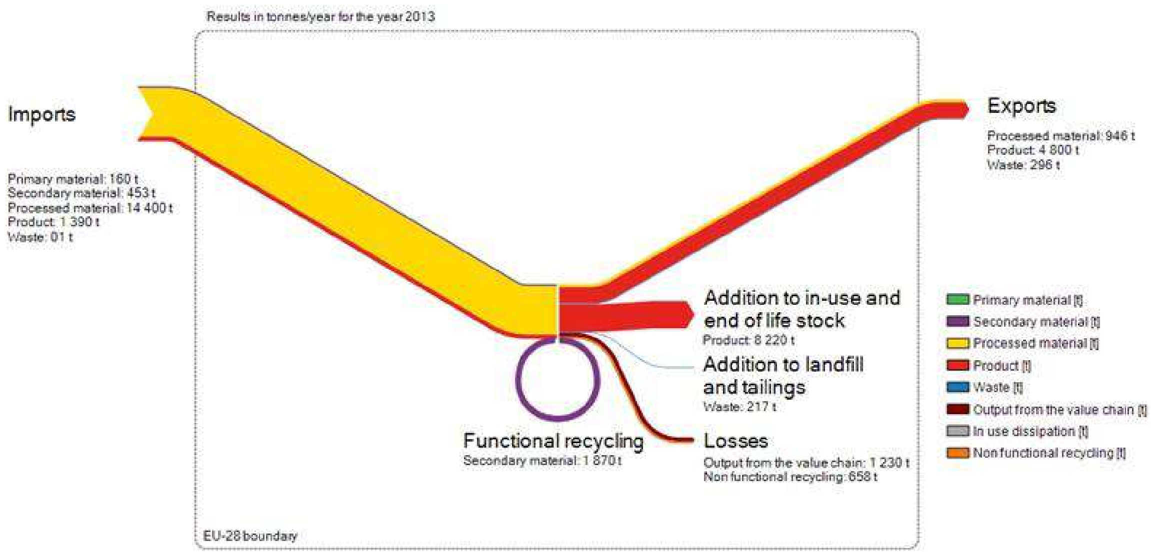

Figure 15. Sankey diagram showing the material flows of niobium in the EU economy in 2013 ((BIO Intelligence Service, 2015))

GEOLOGY, RESOURCES AND RESERVES OF MOLYBDENUM

GEOLOGICAL OCCURRENCE/EXPLORATION

In terms of metallurgical extraction, the most important minerals from an economic point of view are those of the columbite-tantalite group followed by the pyrochlore group. Nb content in columbite is 78.2%. Minerals of the pyrochlore group are the second most important source of Nb (Crockett and Sutphin 1993).

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Niobium deposits are most commonly associated with peralkaline granites or syenites, and/or carbonatites (i.e. an igneous rock that consists of more than 50% primary carbonate minerals). Secondary deposits of niobium, such as laterites, and residual placers, typically form by the weathering of igneous deposits (Dill, 2010). An overview of these deposits is given in Table 9.

Niobium deposits associated with peralkaline granites and syenites are typically less than 100 Mt in size (BGS, 2011) and have ore grades of between 0.1 and 1 wt. % Nb_2O5, contained in ore minerals such as columbite, eudialyte and loparite. Alkaline magmas responsible for the formation of these deposits are derived by melting of enriched sub-continental lithospheric mantle and are typically enriched in the High Field Strength Elements (HFSE) (i.e. niobium, zirconium and rare earth elements). These incompatible (i.e. elements that become concentrated in molten magma rather than early crystallising solid minerals) HFSE are further upgraded by magmatic (e.g. fractional crystallisation) and/or hydrothermal processes (BGS, 2011).

Carbonatite-hosted niobium deposits can be divided into primary and secondary deposit types. Primary deposits are generally in the tens of millions of tonnes size range and typically have ore grades of less than 1 wt. % Nb_2O_5. Carbonatites are found in areas of crustal extension or rifting and are thought to be derived from direct melting of the mantle. They are enriched in HFSE (e.g. niobium, zirconium and rare earth elements), but also barium, strontium, thorium and uranium. Important ore minerals in these rocks include perovskite and pyrochlore, and niobium-rich silicates such as titanite (BGS, 2011). Secondary niobium deposits are associated with deep, tropical weathering of carbonatites and are typically very large (up to 1 000 Mt) and have very high ore grades (up to 3 wt. % Nb_2O_5 in lateritic deposits, but as high as 12 wt. % Nb_2O_5 in some residual placers). Pyrochlore is the most common ore mineral in these secondary ore deposits (BGS, 2011).

Table 9: Summary of important niobium deposit types (BGS, 2011)

Deposit type	Brief description	Typical grades and tonnage	Major examples
Carbonatite-hosted primary deposits	Niobium deposits found within carbonatitic igneous rocks in alkaline igneous provinces	Niobec, proven & probable reserves: 23.5 Mt at 0.59% Nb2O5	Niobec, Canada; Oka, Canada
Carbonatite-sourced secondary deposits	Zones of intense weathering or sedimentary successions above carbonatite intrusions in which niobium ore minerals are concentrated	< 1 000 Mt at up to 3% Nb2O5 in lateritic deposits. Up to 12% Nb2O5 in placer deposit at Tomtor, tonnage not known	Araxá and Catalão, Brazil; Tomtor, Russia; Lueshe, DRC
Alkaline granite and syenite	Niobium and lesser tantalum deposits associated with silicic alkaline igneous rocks. Ore minerals may be concentrated by magmatic or hydrothermal processes	Generally < 100 Mt, at grades of 0.1 to 1% Nb2O5 and < 0.1% Ta2O5	Motzfeldt and Ilímaussaq, Greenland; Lovozero, Russia; Thor Lake and Strange Lake, Canada; Pitinga, Brazil; Ghurayyah, Saudi Arabia; Kanyika, Malawi

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GLOBAL RESOURCES AND RESERVES

Global resources of niobium are about 84 Mtonnes, but occur almost exclusively in Brazil, which currently accounts for about 96% of all global resources (Linnen et al., 2014). Most of the world's identified resources of niobium occur as pyrochlore in carbonatite (igneous rocks that contain more than 50%-by-volume carbonate minerals) deposits. World resources of niobium are more than adequate to supply global projected needs (Padilla et al., 2019).

Known global reserves of niobium (as Nb) are estimated to be more than 17000 ktonnes (Table 10). There is no data about niobium reserves in Europe in the Minerals4EU (2019) website. Niobium is concentrated within certain igneous and sedimentary deposits in U.S. These resources occur in nine states, while resources are estimated at 1400 kt. Only 210 ktonnes of U.S. resources were estimated to be economically mineable. The amount of Nb resources in Burundi, China, Ethiopia, Nigeria, Russia, Rwanda, and Uganda is not exactly defined (Navarro et al. 2020).

Table 10: Global reserves in 2021 according to USGS (USGS, since 2000)

Country	Niobium (Nb content) Reserves (k tonnes)
United States	170
Brazil	16.000
Canada	1.600
World total	17.000

EU RESOURCES AND RESERVES:

Table 11: Resource data for the EU compiled in the European project SCRREEN D3.1 ((Lauri, 2018))

Country	Quantity (Mt of P2O5)	Location
Austria	No information	Occurrences associated with granitic pegmatites, which contain niobium
Czech Republic	No information	Occurrences mainly related to granitic pegmatites that contain Nb and Ta minerals
Finland	250 Mt of ore at 0.21 % Nb	Sokli P-Fe-Nb deposit
	8.15 Mt of ore with Nb oxide contents ranging from 0.12 % to 0.76 % and a calculated total amount of 13 000 t Nb_2O_5	Jokikangas, Katajakangas and Kontioaho
France	1 860 t of Nb_2O_5	Tréguennec deposit
	No information	There are other Nb and Ta-bearing mineral occurrences in France, which are mostly in granitic pegmatites
Germany	No information	Deposits and occurrences hosted by granitic and alkaline rocks
Italia	No information	There are over ten Nb-Ta occurrences in Italy that are hosted by granitic pegmatites.
Malta	No information	One sedimentary phosphorite occurrence
Netherlands	No information	Two sedimentary phosphorite occurrence
Portugal	350 t Nb_2O_5	Almendra deposit
Slovakia	No information	Four deposits with both niobium and tantalum as the main commodities, which are hosted by granitic pegmatites

Data concerning the most significant niobium resources in EU and Greenland are presented in Table 11.

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WORLD MINE AND REFINING PRODUCTION

Figure 16 and Figure 17 present the global production of niobium concentrates in terms of Nb_2O_5 content since 1984 and since 2000 according to WMD and USGS, respectively (WMD, since 1984, USGS, since 2000). Brazil consist the major producer, representing the 92% of the global production in 2020, while a small production is taking place in Australia, Canada, Russia and Congo. With the exception of the African countries listed above, companies extracting niobium ores are typically integrated, meaning they also produce processed niobium products, such as niobium oxide, ferroniobium and niobium metal.

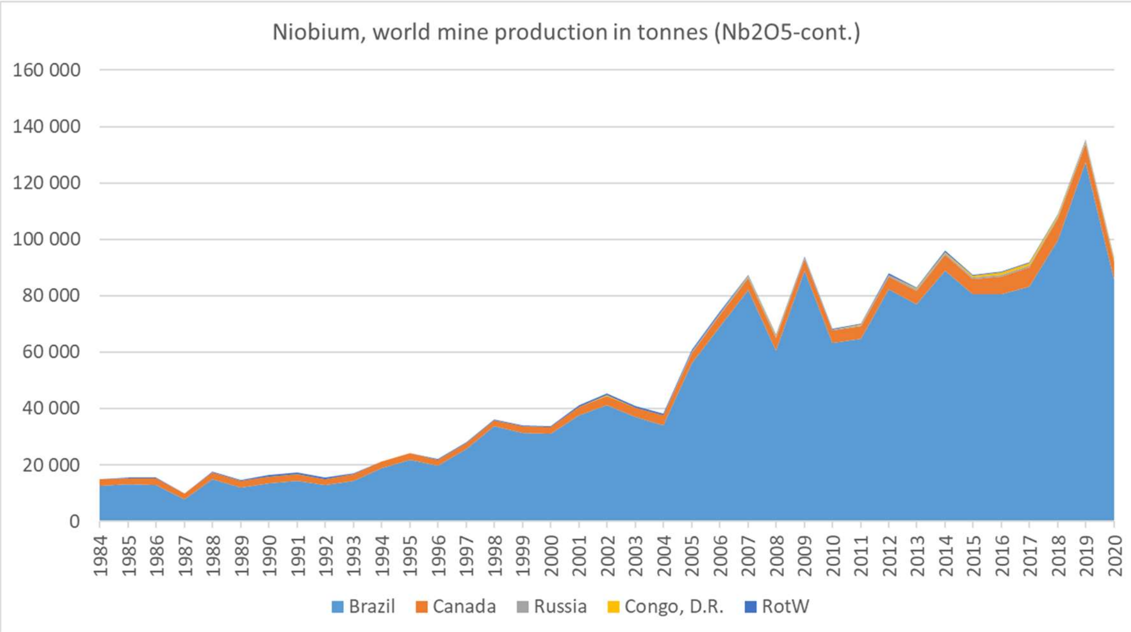

Figure 16: Global niobium production (as Ni_2O_5) since 1984 according to WMD (WMD, since 1984).

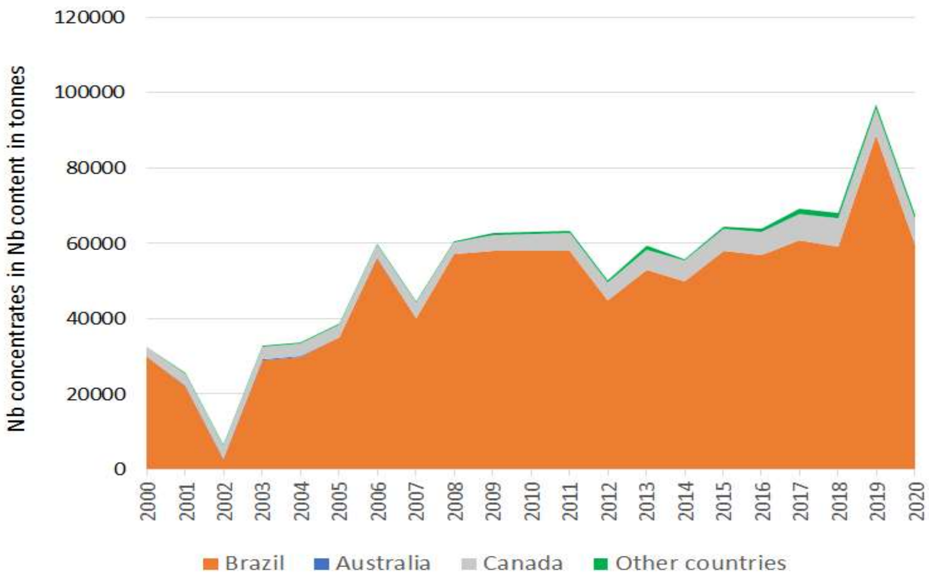

Figure 17: Global niobium production (as Nb_2O_5) since 2000 according to USGS (USGS, since 2000).

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The main companies producing Niobium are reported inTable 12. It is important to highlight that the largest deposit in the world is located in Araxa (Brazil) and is owned by Companhia Brasileira de Metalurgia e Mineracao (CBMM).

Table 12: The tree largest world producers of niobium (TIC, 2019).

Company	Mine site (location)
Companhia Brasileira de Metalurgia e Mineração (CBMM)	Araxa, Brazil
China Molybdenum previously owned by Anglo American Niobio Brasil	Catalao, Goias state, Brazil
IAMGOLD Corp	Niobec Mine in Quebec, Canada

According to the United Nations Environment Programme (UNEP) the End of Life (EoL) recycling input rate for niobium, chiefly as a constituent of ferrous (e.g. steel) scrap, is greater than 50% (Reuter, 2013). However, the amount of niobium physically recovered from scrap (i.e. functional recycling) is negligible, with estimates by BIO Intelligence Service (2015) by Deloitte given at less than 1%, i.e. 0.3% (Validation workshop 2019). In 2018, Strategic Minerals Spain (SMS) started the processing of tailings from waste-rock heaps and ponds of the old Penouta mine leading to the obtaining of tantalum and niobium minerals through a gravimetric separation process, without any chemical products orwaste that is harmful to the environment. It is estimated that the mineral resources in the remaining original deposit amount to 95.5 Mt of Measured and Indicated Mineral Resources with average grades of 77 ppm Ta and 443 ppm Sn, and in the old tailing waste-rock heaps where the company has started operations 12 Mt of resources with average grades of 35 ppm Ta and 428 ppm Sn.

OUTLOOK FOR PRODUCTION

World reserves of Nb are estimated at 4.3 Mt globally, therefore, at current usage levels, they can be considered virtually inexhaustible. However, Nb is classified as critical due to the high concentration of production and occurrence in Brazil with a 95% share (4.1 Mt). Due to China's huge Nb consumption which comes from the continuous development of green energy sector, in which the metal is involved, Nb demand is expected to steadily increase until 2020 by a rate of 4.0% to 6.0%. On the other hand, Nb and FeNb production is forecasted increase till the year 2030 by a factor of 2.5% to 3.0% if the utilization of Nb kept growing constantly (Figure 18). The demand excess is expected to covered through the enhancement of the recycling of Nb-containing steel scrap (Bakry et al. 2022).

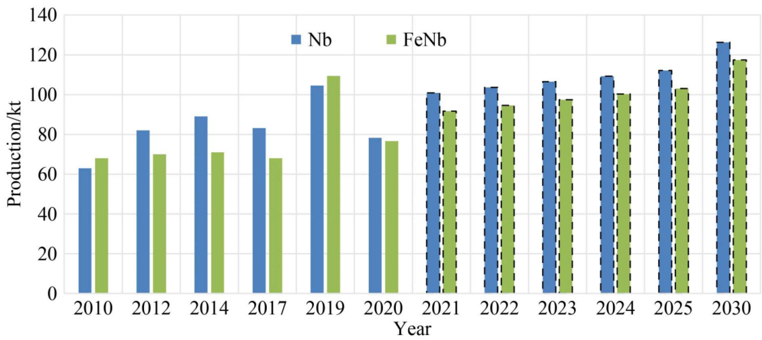

Figure 18: Forecast of Nb and FeNb production until 2030 (Bakry et al. 2022).

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Table 13: Material flows relevant to the EOL-RIR of Niobium, data from 2012 (BIO Intelligence Service, 2015)

MSA Flow	Value (t)
B.1.1 Production of primary material as main product in EU sent to processing in EU	0.00
B.1.2 Production of primary material as by product in EU sent to processing in EU	0.00
C.1.3 Imports to EU of primary material	159974.00
C.1.4 Imports to EU of secondary material	452702.00
D.1.3 Imports to EU of processed material	14368682.00
E.1.6 Products at end of life in EU collected for treatment	757471.00
F.1.1 Exports from EU of manufactured products at end-of-life	1284.00
F.1.2 Imports to EU of manufactured products at end-of-life	543.00
G.1.1 Production of secondary material from post-consumer functional recycling in EU sent to processing in EU	43896.00
G.1.2 Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU	0.00

SUPPLY FOR SECONDARY MATERIALS/RECYCLING

RESOURCES

The estimated fluxes of niobium in the world were modeled by Bakry M. (2018) (Figure 19):

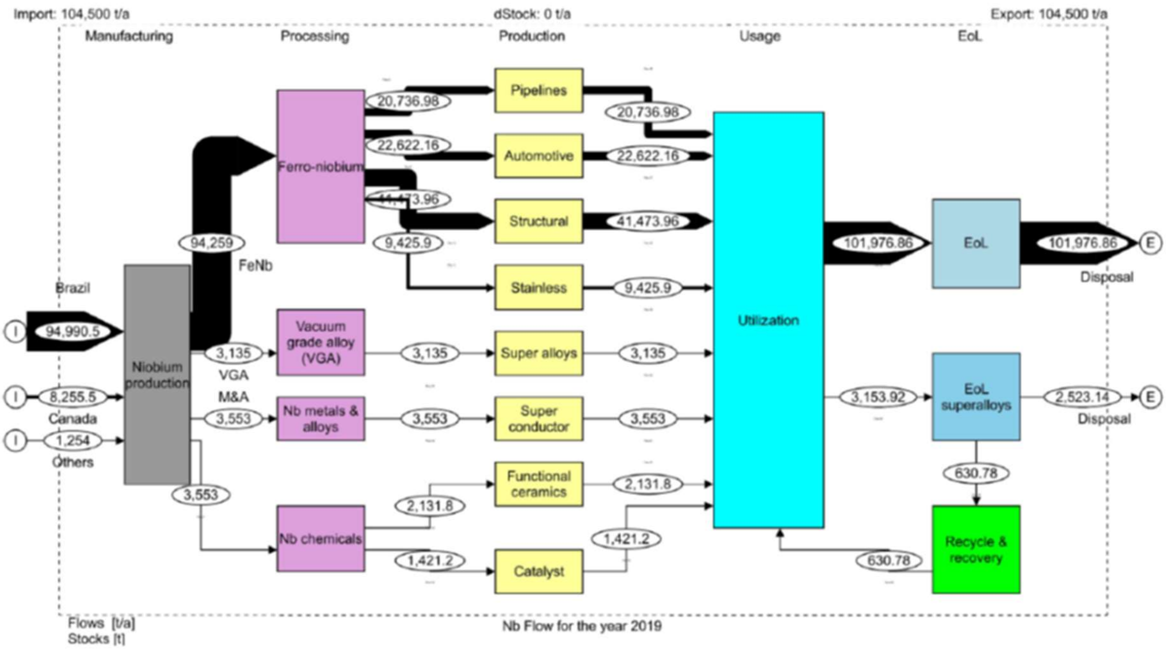

Figure 19. Global substance flow analysis for Nb in 2019 (Bakry M. (2022))

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Imports in the EU of processed materials represent around 12.7 kt in niobium content (EUROSTAT (2019)). The European industry uses these materials to manufacture various finished products which are either sold in the European market (about 8 kt in niobium content) or exported (about 4.4 kt). During the manufacturing step, some steel scrap containing niobium is produced which is non-functionally recycled with other types of steel in the EU (reprocessed) or exported. Superalloy scrap is also recycled but some of this is functionally recycled (BIO by DELOITTE (2015)).

Imports of finished products in the EU amount to 1.4 kt of niobium content, which is much less than the niobium content in the domestic production sold in the EU (BIO by DELOITTE (2015)).

The niobium contained in the waste is mostly non-functionally recycled. There is very little post-consumer functional recycling of niobium globally and most is diluted into recycled steels. The annual addition to stock in landfill is estimated at around 0.2 kt (BIO by DELOITTE (2015)).

Some articles propose a conceptual model of the global niobium material, which allowed to conduct a quantitative assessment of global disposed niobium material flow in the future (Figure 20) (BIO by DELOITTE (2015)).

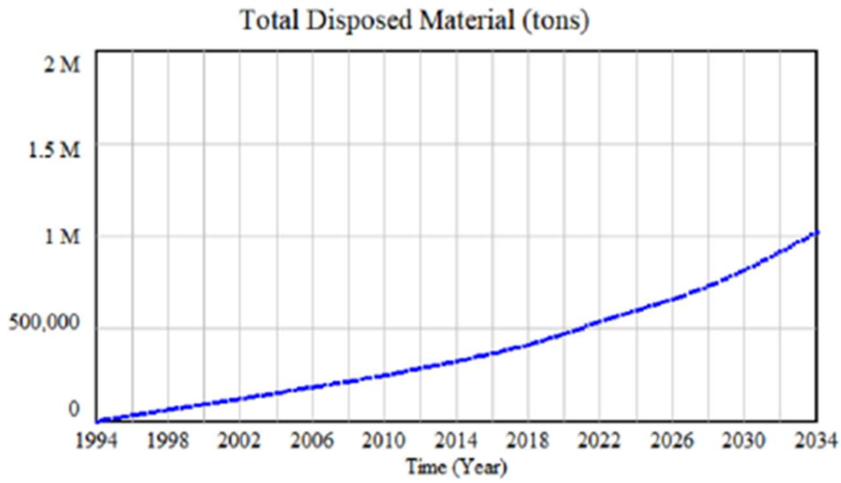

Figure 20. Simulation results of total disposed material (Krekhovetckii N. (2018))

END OF LIFE RECOVERY AND RECYCLING

Recycling of iron and steel scrap containing niobium starts with scrap collection and its primary processing. Scrap dealers purchase scrap and process it mechanically and chemically until it can be consumed in furnaces of steel mills. Usually, this process includes shredding, which allows to achieve fist-sized fragments, followed by baling to compact the scrap into bundles. Besides, there is sorting which allows classifying scrap according to different metal composition. On the next stage, steel mills carefully purchase scrap of specific composition to melt it in basic oxygen or electric arc furnaces (Krekhovetckii N. (2018)).

Recycling of end-of-life products containing niobium is strongly influenced by the least efficient stage of a recycling chain, which is typically the collection stage and related activities (Krekhovetckii N. (2018)).

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According to the United Nations Environment Program (UNEP), the End-of-life Recycling Input Rate (EOL-RIR) for niobium, chiefly as a constituent of ferrous scrap, is greater than 50% (Reuter M. (2013)). However, the amount of niobium physically recovered from scrap (i.e. functional recycling) is negligible (BIO by DELOITTE (2015)). From the definition of the indicators EOL-RIR and End-of-Life Recycling Rate (EOL-RR), the global model depicted Figure 20 enables to calculate similar values of 0.6% for the two indicators.

In the EU as in the world, the recovery of scraps specifically for niobium content remains negligible and the amount of recycled niobium is not available, but it may be as much as 20% of apparent consumption (Luidold S. (2019)). In particular, superalloys with high niobium content (e.g. EN steel number 2.4868 with up to 5.5% Nb), recycling rates of up to 70% have been reported. However, only a small fraction (approximately 4%) of niobium is used for superalloys and lower recycling rates are reported for the total niobium market; 50% in the year 1998 and 56% more recently. For instance, the Scholz company, a large scrap dealer processing 1.4 Mt steel scrap annually, has indicated that only alloying elements higher than 1% are evaluated for recycling; this implies that niobium is not considered at all (Tkaczyk A.H. (2018)).

Though at current usage levels, worldwide niobium reserves can be considered virtually inexhaustible (Tkaczyk A.H. (2018)), those figures and the existing models suggest that there will be soft scarcity in niobium after 2020–2030 with the present regime of recycling, which is far too low [BIO by DELOITTE (2015), European Commission (2020)].

Promising approaches to mitigate EU dependency and to reduce supply risk disruptions may include (Lewicka E. (2021)):

- securing CRMs supply from non-EU European countries,

- using diversified CRM supplies. Tin slags indeed represent a relatively well geographically scattered secondary source of tantalum and niobium (Allain E. (2019)). Certain other countries like China, Argentina, Congo D. R., Spain, Saudi Arabia, US, Malaysia, Rwanda, Gabon, Uganda, Ethiopia, Namibia, Thailand, Venezuela, Zimbabwe, Mozambique and South Africa have lesser deposits (Lewicka E. (2021)). For instance, NioCorp Developments Ltd. and GX Acquisition Corp II have announced the signing of a proposed business combination between the two companies, to acquire funds for high-grade niobium mining in Nebraska (U.S. Geological Survey (2020)). Prospective reserves of niobium (Nb_2O_5) in Bayan Obo (China) are 6.6 million tons, ranking second in the world (Zhang B. (2022)).

- assessing the waste sources for the recovery of CRMs,

- prioritizing the rational and effective use of raw materials (in line with circular economy approach),

- promoting the use of secondary raw materials and improving recycling rates of electronic waste (e.g., to obtain REEs and some other CRMs), coupled with restrictions on exports of electronic scrap to Asia (especially China) or Africa,

- developing the recovery of accompanying elements contained in the raw materials imported to the EU, e.g., REEs from imported phosphate rock, gallium, germanium, or indium from imported concentrates of polymetallic ores.

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To carry those two last points further, it was demonstrated for the case of the end-of-life vehicles - in 2010, the total number of ELVs was around 40 million, mainly in Germany, Italy, France, UK, Spain, USA, Canada, Brazil, Japan, China, Korea and Australia – there was a possibility to reduce annual emissions due to niobium exploitation by 18% in years 2010–2050, thanks to the reuse of niobium in secondary production rather than primary one. Globally, the recycling of niobium could save around 133–161 m GJ energy between 2010 and 2050 and reduce emissions by 44–53 mt CO_2-eq in the same period, with the highest impact in the USA, EU, China and Japan (Golroudbary S.R. (2019)).

IMPROVEMENT OF NIOBIUM RECYCLING TECHNOLOGIES

Improving the recycling process first requires to better characterize the composition of the end-of life eligible products.

The appropriate disposal of EOL waste requires specific, in-depth knowledge, and some articles describe a methodology that could be used for the development of environmentally friendly management approaches to dispose of this class of waste (Kohl C.A. (2018)), and for any kind of EOL product.

For instance, recycling of waste electrical and electronic equipment, i.e. desktop computer waste without screen involves 16 chemical elements of which availability has dropped to critical levels. In central processing unit waste, a total number of 47 chemical elements was detected, of which 35 are classified as metals. The presence of niobium was detected in the central processing unit waste, but at trace levels under 0.0003%, in the motherboard (I/O shield), the cases and lids. The CPUs analyzed have 96.66% potential recyclability. The parts of the components with rare earth elements should be removed and appropriately stored for the time necessary and then recycled so as to recover these metals in the most efficient method possible, when industrial scale recycling processes may be used (Kohl C.A. (2018)).

Concerning HSLA steels and stainless steel, a separate collection of Nb-containing alloys would be a viable option to increase the recycling rate of niobium. In addition to alloys of higher niobium concentration, the importance of recycling alloys with niobium content below 1% (e.g. EN steel numbers beginning with 1.45 and 1.56) should be stressed, as these lower-concentration alloys account for 88% of the Nb market (Tkaczyk A.H. (2018)). The principal constraint is that recycling companies have not currently found a viable business case for recycling low-concentration niobium alloys, and the logistics cost for the separate collection of Nb-containing scrap currently overshadows the additional revenue that could be gained from the recovered niobium (Tkaczyk A.H. (2018)).

Except this reflection in progress about collecting and sorting secondary materials, advances in recycling processes are scarce and mainly concern tailing and metallurgy slag valorization. Indeed, certain challenges and shortcomings still exist in the extraction and recovery of niobium from their minerals (Nzeh N.S. (2022)).

In the Bayan Obo mines in China, the Baosteel Company annually intends to mine 69 Mt iron ore (with 35% Fe content), to produce 24 Mt iron per year. As the iron ore of the Bayan Obo mines exhibits a niobium content of 0.13%, the described annual ore mining corresponds to 89 000 t niobium mined inadvertently, which exceeds the 64 300 t annual global production of niobium, which is mined intentionally (Tkaczyk A.H. (2018)).

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Bayan Obo tailings from Baotou Steel were discharged into tailings pond. Extraction of valuable elements, such as niobium, could be achieved by roasting Bayan Obo tailings in NaCl-$Ca(OH)_2$-coal, with an innovative and more eco-friendly process (Figure 8). Calcium hydroxide was selected as clean activator. Sodium chloride was added together to accelerate the mass transfer of reactant by providing liquid phase at low temperature. Addition of pulverized coal will promote iron transfer to recyclable magnetite. Moreover, hydrochloric acid and sulfuric acid were considered to be used in fractional leaching process. For Bayan Obo tailings, under the optimal conditions, the total Nb_2O_5 leaching rate could reach up to 92.08% (Zhang B. (2022)).

Figure 21. Flowchart of the process (Zhang B. (2022))

In 2018, Strategic Minerals Spain (SMS) started the processing of tailings from waste-rock heaps and ponds of the old Penouta mine leading to the obtaining of tantalum and niobium minerals through a gravimetric separation process, without any chemical products or waste that is harmful to the environment. It is estimated that the mineral resources in the remaining original deposit amount to 95.5 Mt of Measured and Indicated Mineral Resources with average grades of 77 ppm Ta and 443 ppm Sn, and in the old tailing waste-rock heaps where the company has started operations 12 Mt of resources with average grades of 35 ppm Ta and 428 ppm Sn (Blengini G.A. (2019)).

Another illustrative example is the extraction of tin through smelting of cassiterite (SnO_2), which generates considerable amounts of slag in the main production areas of South-East Asia, Africa, and South America. Niobium naturally occurs in cassiterite deposits and is concentrated in the slag during the smelting process. Tin slags have often been disposed as industrial waste despite contents of niobium ranging from 2 to 25%. Conventional methods used for the extraction of these elements from slags are energy consuming and very polluting: they consist in their full dissolution by highly concentrated hydrofluoric acid, mixture of hydrofluoric and sulfuric acids, or smelting in electric furnaces. An efficient and less polluting process was developed: favorable leaching conditions with an acid-basic-acid sequence can lead to a 75% mass loss and to the production of a 63.3 wt% of $(Ta+Nb)_2O_5$ concentrate, which is comparable to the grade of commercial concentrates obtained from their primary mineral sources. The yield is about 86% weight of the total $(Ta+Nb)_2O_5$ contained in the raw slag (Allain E. (2019)).

PROCESSING OF NIOBIUM

Niobium is mainly mined as the primary ore. Near-surface niobium deposits are typically exploited by open-pit mining methods, which commonly involve removing overburden, digging or blasting the ore, followed by removal of the ore by truck or conveyor belt for stockpiling prior to processing. In Araxá open pit mine in Minas Gerais, Brazil – CMBB (Company: Brasileira de Metalurgia e Mineração) is extracted about the 85% of globally produced niobium.

Deeply buried niobium deposits are mined underground using conventional mining methods, such as room and pillar, where mining progresses in a horizontal direction by developing numerous stopes, or rooms, leaving pillars of material for roof support. Ore is blasted and then transported by rail, conveyor or dump truck to the processing plant.

Regardless of the mining method employed niobium ores are first crushed in jaw, cone or impact crushers and milled in rod or ball mills operating in closed circuits with vibrating screens and screw classifiers to liberate niobium mineral particles. The slurry containing niobium and waste rock is further concentrated to around 54% niobium oxide using a number of methods in multiple stages: gravity separation, froth flotation, magnetic and electrostatic separation, and acid leaching may be used, depending on the physical and chemical characteristics of the ore (BGS, 2011).

Typically, niobium ores from carbonatite-associated deposits are screened, classified, and deslimed (i.e. removal of very fine particles). Carbonate material is removed by froth flotation, followed by an additional desliming stage. Magnetite is removed by low-intensity magnetic separation, and sent to waste. The sought-after pyrochlore is collected by froth flotation. A final stage of froth flotation is used to remove sulphides, such as pyrite. Residual impurities may be leached by hydrochloric acid, leaving a final concentrate that contains about 54% niobium pentoxide ((IAMGOLD, 2019); (BGS, 2011)). Niobium concentrates are further refined by hydrometallurgical processes to produce niobium fluorides, oxides or chlorides. Usually the acid digestion of ores is applied using a mixture of hydrofluoric acid with other mineral acids, generally sulphuric acid. The key-step of the metallurgical process of niobium concerns its separation from tantalum through fractional crystallization. Separation is conducted at an acid concentration of about 1 to 7% HF, where the solubility of Niobium complex is nearly 10 to 12 times that of Tantalum. The separation of Niobium and Tantalum by fractional crystallization is feasible via the formation of double fluoride complexes with potassium. As the solubility of potassium fluotantalate (K_2TaF_7) is low, it crystallizes out. The crystalline solid is redissolved and recrystallized. The process is conducted in several stages. The process works quite satisfactorily and relatively easily as far as the preparation of pure tantalum complex K_2TaF_7 is concerned (Figure 9) (Proometia, 2021). After its isolation, Nb intermediate compounds are further treated by electrometallurgical (e.g. electrolysis) or pyrometallurgical (e.g. aluminothermic reaction) processes. Ferroniobium, containing 65–66% niobium, is also produced by aluminothermic reaction, but with the addition of iron oxide powder. Niobium carbide is produced by high temperature sintering of niobium oxide powder with carbon (Albrecht, 1989;BGS, 2011).

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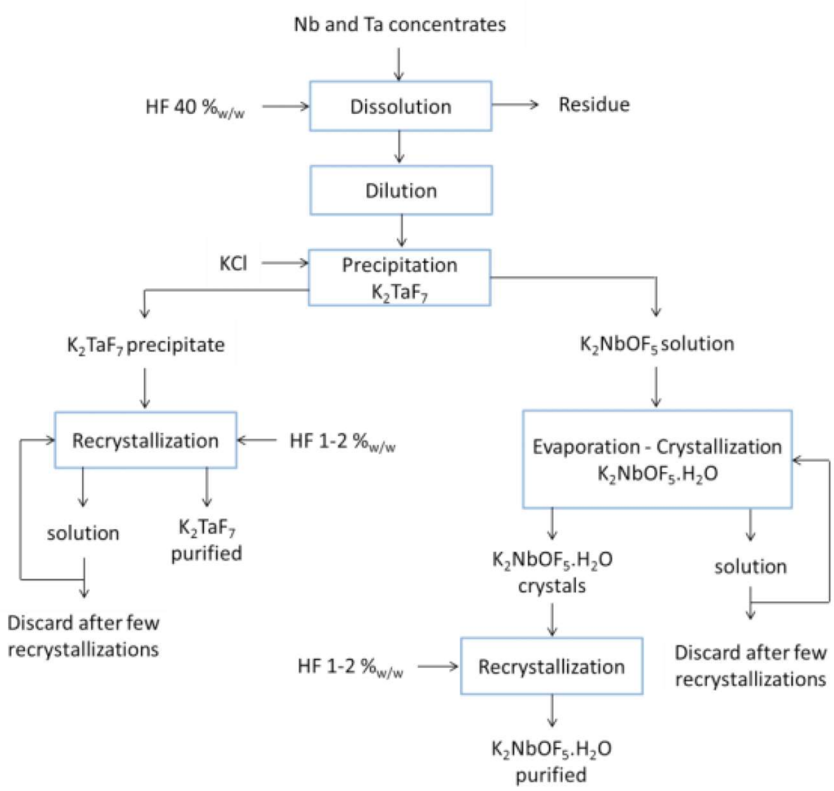

Figure 22: Simplified flowsheet diagram of the Nb extractive metallurgy including the leaching of the initial Nb-containing concentrates and the separation of Nb by Ta (Proometia, 2021).

OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES RELATED TO THE NIOBIUM OR SPECIFIC/RELEVANT COMPOUNDS AT ANY STAGE OF THE LIFE CYCLE

In the ILO Encyclopaedia of Occupational Health and Safety (International Labour Organization): "much of the information about the behaviour of niobium in the body is based on studies of the radioisotope pair ^{95}Zr-^{95}Nb, a common nuclear fission product. One study investigated cancer incidence among niobium mine workers exposed to radon and thoron daughters and found an association between lung cancer and cumulative alpha-radiation. […] After intraperitoneal injections of stable niobium in the form of potassium niobate, the LD50 for rats was 86 to 92 mg/kg and for mice 13 mg/kg. Metallic niobium is not absorbed from the stomach or intestines" (ILO, 2011). Moreover, according to the classification provided by companies to ECHA in REACH registrations niobium is a flammable solid (ECHA, 2022).

Moreover, regarding safety and health measures, the ILO specifies that "atmospheric concentrations of the aerosols of niobium alloys and compounds that contain toxic elements such as fluorine, manganese and beryllium, should be strictly controlled. During the mining and concentration of niobium ore containing uranium and thorium, the worker should be protected against radioactivity" (ILO, 2011). Niobium is indeed usually associated with high concentrations of uranium and/or thorium (German Environment Agency, 2020).

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ENVIRONMENTAL ISSUES

Alves and Coutinho (2019) estimate that Nb mining can generate approximately 40 tonnes of solid waste per tonne of ferroniobium (FeNb). The acid formation potential associated with niobium extraction is low, in a context of extraction from sulphide-free deposits (German Environment Agency, 2020).

Da Silva Lima et al. (2022) quantified the environmental impacts of FeNb and niobium oxides (Nb_2O_5) production through a cradle-to-gate life cycle assessment (LCA), based on data provided by the niobium producer responsible for roughly 75 % of the global market. For 2019, the authors calculate a global warming impact of 5.09 kg CO_2 eq./kg FeNb and 4.70 kg CO_2 eq./kg Nb_2O_5. Regarding FeNb production, the supply of aluminium is overall the main source of environmental impacts affecting all the considered impact categories. Regarding High Purity Nb_2O_5 production, processing chemicals show the main contribution, affecting all the considered impact categories. The authors finally calculate that production process improvements in 2019 resulted in significant impact reductions compared to the 2017 levels, thanks to process optimizations "such as less petroleum coke, LPG, niobium oxide processing chemicals and (bio)diesel, but especially due to the use of fully renewable electricity" (da Silva Lima, 2022).

NORMATIVE REQUIREMENTS RELATED TO NIOBIUM PRODUCTION, USE AND PROCESSING OF THE MATERIAL

In the IAEA Regulations for the transport of radioactive material (IAEA 2018), Niobium is included in the activity limits and classification, with the following values:

TABLE 2. BASIC RADIONUCLIDE VALUES (cont.)

Radionuclide (atomic number)	A_1 (TBq)	A_2 (TBq)	Activity concentration limit for exempt material (Bq/g)	Activity limit for an exempt *consignment* (Bq)
Niobium (41)				
Nb-93m	4×10^1	3×10^1	1×10^4	1×10^7
Nb-94	7×10^{-1}	7×10^{-1}	1×10^1	1×10^6
Nb-95	1×10^0	1×10^0	1×10^1	1×10^6
Nb-97	9×10^{-1}	6×10^{-1}	1×10^1	1×10^6

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SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF NIOBIUM FOR EXPORTING COUNTRIES

Table 14 lists the countries for which the economic value of exports of niobium represents more than 0.1 % in the total value of their exports.

Table 14: Countries with highest economic shares of niobium exports in their total exports

Country	Export value (USD)	Share in total exports (%)
Brazil	1,497,420,025	0.72 %
Canada	212,084,587	0.05 %

Source: COMTRADE (2022), based on data for 2020

Brazil has the largest share of exports (0.72 %) of niobium out of its total exports. For the rest of exporting countries exporting countries this share is below 0.1 % so the economic importance of these exports is limited.

SOCIAL AND ETHICAL ASPECTS

Large-scale niobium mining proposals, if carried out in the remote northwest portion of the Brazilian Amazon, would likely cause significant forest loss, and threaten biodiversity and fragile ecosystems (Vasconcelos, 2019). The government pushes for an expansion of industrial mining on indigenous lands and administration turns a blind eye to expanding illegal mining that is threatening indigenous communities in the northern Amazon. Amid an explosion of COVID-19 cases and deaths at the end April, government changed regulations that opened up nearly 10 million hectares (38,600 square miles) of Indigenous land — on reserves still not fully demarcated —to non-indigenous land people and land speculators. The measure has been challenged in court, and faces a bid for annulment by the state attorney general of Mato Grosso. (Macháček, J., et al, 2022)

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Niobium applications in Li-ion batteries

Niobium (Nb) has been playing a key role in the development of advanced Li-ion batteries made with engineered niobium components with several benefits for the performance of the batteries [CBMM, 2022]. In detail, Nb can play a role in new anode materials for batteries: niobium titanium [Griffith et al. 2018] and niobium tungsten [Yuan et al. 2020] oxides are emerging materials for anodes to reach fast charging, safer and higher energy capacity batteries. Niobium can play a role also in new cathodes materials: it is being used as a dopant to develop cobalt-reduced or -free, lithium-rich, and manganese-based Li_3NbO_4-based new materials for cathodes with higher energy density and longer-term stability [Levartovsky et al. 2021]. Moreover, Nb-

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based coatings can be used as a protective film over the surface of the cathodes, to reduce the degradation of the cathode materials and to enhance its electrochemical performance [Xin et al. 2022]. Finally, Niobium is becoming an essential element for the development of all solid-state batteries, the ultimate solution on battery technology [Wang et al. 2018, Liang et al. 2020].

- Nb-based materials for Hydrogen production and conversion

Niobium is being increasingly used in hydrogen production and Fuel Cell technologies [CBMM 2022]. In the field of green hydrogen production technologies, Niobium has a role in the synthesis of catalytic materials for solar water splitting [Kazuhiko et al. 2011] and in PEM-based water electrolysis [Yang et al. 2019]. The Niobium-based photocatalytic materials for water splitting are niobates, layered compounds and oxynitrides perovskites and nitrides. In the field of hydrogen conversion in other forms of energy, the development of niobium-containing materials is of increasing interest for applications as electroactive catalytic and support materials in PEM fuel cells [Ghoshal et al. 2017, Hsieh et al. 2017]. In all these applications, the use of niobium allows several advantages: the use of electrodes free from PGM (Platinum Group Metals) and carbon, higher resistance to corrosion in acidic media, PGM higher dispersion and better use of active sites, PGM sintering resistance, PEM Fuel Cells and PEM-water electrolysis at low overpotentials [CBMM 2022].

- Novel modular stack design for high pressure PEM water electrolyzer technology with wide operation range and reduced cost - PRETZEL project (EU, 2018– 2021)[4]

Green hydrogen produced by electrolysis might become a key energy carrier for the implementation of renewable energy as a cross-sectional connection between the energy sector, industry and mobility. Proton exchange membrane (PEM) electrolysis is the preferred technology for this purpose, yet large facilities can hardly achieve FCH-JU key performance indicators (KPI) in terms of cost, efficiency, lifetime and operability. Consequently, a game changer in the technology is necessary. The PRETZEL consortium aimed to develop a 25 kW PEM electrolyzer system based on a patented innovative cell concept that is potentially capable of reaching 100 bar differential pressure. The electrolyzer will dynamically operate between 4 and 6 A cm^(-2) and 90 °C achieving an unprecedented efficiency of 70%. This performance will be maintained for more than 2000 h of operation. Moreover, the capital cost of stack components will be largely reduced by the use of non-precious metal coatings and advanced ceramic aerogel catalyst supports. Likewise, the system balance of plant (BoP) will be optimized for cost reduction and reliability.

OTHER RESEARCH AND DEVELOPMENT TRENDS[5]

- Highly Stable Passively Q-Switched Erbium-Doped All-Fiber Laser Based on Niobium Diselenide Saturable Absorber (Hu et al. 2021)

A saturable absorber (SA) based on niobium diselenide ($NbSe_2$), which is a layered transition metal dichalcogenide (TMD) in the VB group, is fabricated by the optically driven deposition method, and the related

[4] https://cordis.europa.eu/project/id/779478

[5] The below research projects and papers are a selection representing some of the research areas related to niobium. More can be found on Sciencegate (https://www.sciencegate.app/keyword/637142)

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nonlinear optical properties are characterized. The modulation depth, saturable intensity, and nonsaturable loss of the as-prepared NbSe2 nanosheet-based SA are measured to be 16.2 %, 0.76 MW/cm^2, and 14 %, respectively. By using the as-fabricated $NbSe_2$ SA, a highly stable, passively Q-switched, erbium-doped, all-fibre laser is realized. The obtained shortest pulse width is 1.49 µs, with a pulse energy of 48.33 nJ at a centre wavelength of 1560.38 nm. As far as the authors know, this is the shortest pulse duration ever obtained by an $NbSe_2$ SA in a Q-switched fibre laser.

- Ultrasensitive molecular sensing of few-layer niobium diselenide (Qian et al. 2019)

Developing non-noble-metal-based materials with an excellent surface-enhanced Raman scattering (SERS) effect is indispensable for cost-effective, fast and non-destructive detection of trace amounts of molecules. Two-dimensional metallic transition metal dichalcogenides (TMDCs) are emerging in SERS fields by virtue of their ultra-flat atomic surface, high surface activity and abundant density of states (DOS) near the Fermi level. However, how to further decrease the limits of detection of TMDCs substrates is crucial but very challenging. In this contribution, large-area $NbSe_2$ flakes from monolayer to few-layer are controllably synthesized *via* an ambient pressure chemical vapour deposition route. The ultrasensitive SERS effect of $NbSe_2$ is demonstrated by optimizing the layer-dependent structure–effect correlation both experimentally and theoretically. As a proof of concept, Rhodamine 6G (R6G) molecules with an ultralow concentration of 5×10^{-16} M can be detected on 6L-$NbSe_2$, which is five orders of magnitude lower than that on 1L-$NbSe_2$. The ultrasensitive SERS effect of few-layer $NbSe_2$ is attributed to the strong adsorption energy and efficient charge transfer between R6G and $NbSe_2$ with specific layers induced by the highest DOS at the Fermi level. Our study provides new insight into the molecular sensing research of 2D TMDCs and paves the way for designing ultrasensitive SERS substrates.

- Safe-by-Design Exfoliation of Niobium Diselenide Atomic Crystals as a Theory-Oriented 2D Nanoagent from Anti-Inflammation to Antitumor (Miao et al. 2020)

The accompanying relationship between tumour and inflammation raises the concept of concurrent antitumor and anti-inflammation treatment in the clinic. Despite the wide application of 2D atomic crystals for cancer theranostics, their anti-inflammation function has been rarely explored. Herein, it is reported that niobium diselenide nanosheets ($NbSe_2$ NSs), a “star” 2D superconducting atomic crystal, can serve as a theory-oriented 2D nanoagent from anti-inflammation to antitumor. A safe-by-design exfoliation strategy, integration of cryo-pre-treatment and DNA-assisted exfoliation, is proposed for high-efficiency exfoliation of atomically thin $NbSe_2$ NSs. Especially, computational simulation reveals that $NbSe_2$ NSs effectively eliminate reactive oxygen and nitrogen species (RONS) via hydrogen atom transfer and redox reaction. Upon the injection of $NbSe_2$ NSs into BALB/c mice, not only U87 subcutaneous tumours are rapidly ablated after photoacoustic imaging-guided precise localization of tumour contour, but also lipopolysaccharide-induced rear thigh inflammation or photothermal therapy-mediated inflammation is efficiently inhibited through RONS scavenging. In addition, $NbSe_2$ NSs are highly biocompatible both in vitro and in vivo due to high-security element constituent and DNA modification. The work extends the biomedical application of 2D atomic crystals for anti-inflammatory treatment.

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- Two-Dimensional Metallic Niobium Diselenide for Sub-micrometre-Thin Antennas in Wireless Communication Systems (Gund et al. 2019)

The state-of-the-art of the Internet of things (IoT) and smart electronics demands advances in thin and flexible radio frequency (RF) antennas for wireless communication systems. So far, nanostructured materials such as metals, carbon nanotubes, graphene, MXene, and conducting polymers have been investigated due to their noteworthy electrical conductivity. However, most antennas based on metallic materials are thick, which limits their application in miniaturized and portable electronic devices. Herein, we report two-dimensional (2D) metallic niobium diselenide ($NbSe_2$) for a monopole patch RF antenna, which functions effectively despite its sub-micrometre thickness, which is less than the skin depths of other metals. The as-fabricated antenna has an 855 nm thickness and a 1.2 Ω sq^{-1} sheet resistance and achieves a reflection coefficient of −46.5 dB, a radiation efficiency of 70.6 %, and omnidirectional RF propagation. Additionally, the resonance frequency of this antenna at the same thickness is reconfigured from 2.01 to 2.80 GHz, while decreasing its length and preserving its reflection coefficient of less than −10 dB. This approach offers a facile process to synthesize 2D metallic transition metal dichalcogenides for the rational design of flexible, miniaturized, frequency-tenable, and omnidirectional monopole patch RF antennas for body-centric wearable communication systems.

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