Horizon 2020 Programme

SCRREEN2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958211.

Start date: 2020-11-01 Duration: 36 Months

SCRREEN

Solutions for CRitical Raw materials - a European Expert Network

FACTSHEETS UPDATES **BASED ON THE EU FACTSHEETS 2020**

MOLYBDENUM

AUTHOR(S):

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MOLYBDENUM

OVERVIEW

Molybdenum (chemical symbol Mo) is a shiny silvery refractory metal with a high melting point at 2,623ºC. It has the lowest thermal expansion coefficient of all engineering materials, high corrosion resistance and a fairly high thermal conductivity. Its density (10.22 g/cm3) is lower than most other high-melting point metals.

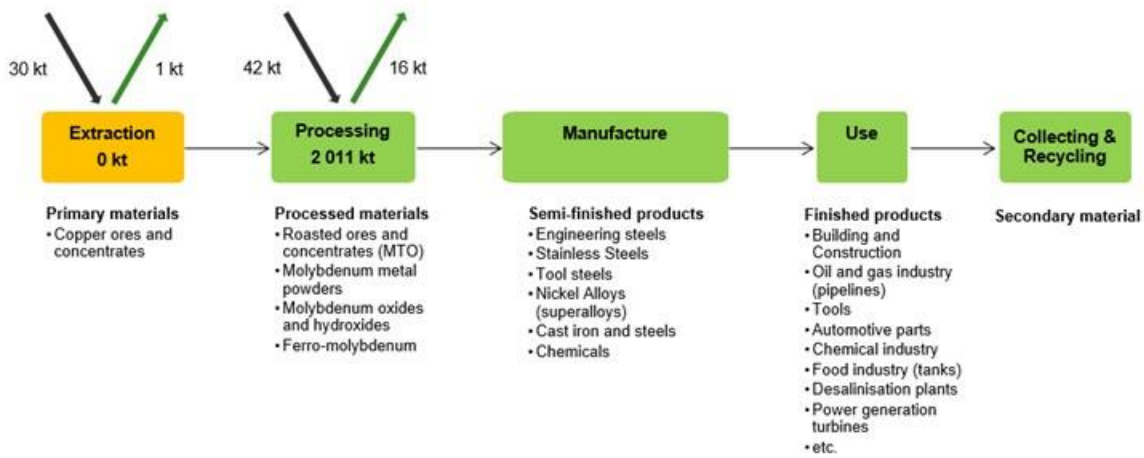

Figure 1. Simplified value chain for molybdenum in the EU[1]

Table 1. Molybdenum supply (extraction stage) and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
275,899.	China 38% Chile 21% USA 15% Peru 10% Mexico 6% Armenia 3%	9,018	10.5%	USA 64% Chile 18% Peru 9% Canada 6%	96%

Prices: Molybdenum prices are driven by oil and gas prices and stainless-steel market dynamics (EC, 2020). Oversupply drove molybdenum prices down from an annual average of USD 28/kg in 2012 to USD 14/kg in 2016. Between August 2014 and November 2015 molybdenum prices plunged below USD 10/kg with oil price contraction. Oil price began to recover in late 2016 and molybdenum prices stabilized in 2017, and molybdenum prices presented minor changes between 2018 and 2020.

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

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Primary supply: Around 60% of global molybdenum supply comes as a by-product of copper smelting form porphyry copper-molybdenum ores, with most of the remainder coming from primary sources, i.e. from the processing of ores extracted from porphyry molybdenum deposits. After extraction, molybdenum concentrate is produced by a flotation technique which separates the gangue from the molybdenum minerals. Most molybdenum concentrate contain 85-93% molybdenite. China, Chile and United States remain the leader producers of molybdenum ores. There is no molybdenum mine output in the EU and therefore all the Union needs rely on imports.

Secondary supply: According to The International Mo Association (IMOA, 2015), of the 330,000 tonnes of molybdenum used in all applications worldwide in 2013, some 86,000 tonnes, or 26%, came from recycled sources. In the same year, the share of recycled molybdenum used in stainless steel production was 39%, rising to 50% in tool and high speed steels. About two-third of the secondary molybdenum comes from revert scraps produced during the steel making process and new scrap generated by steel fabrication. Recycling scrap for the production of new materials requires less energy than the production of new metal and it causes fewer emissions. It is also often sourced locally, so transportation routes are short.

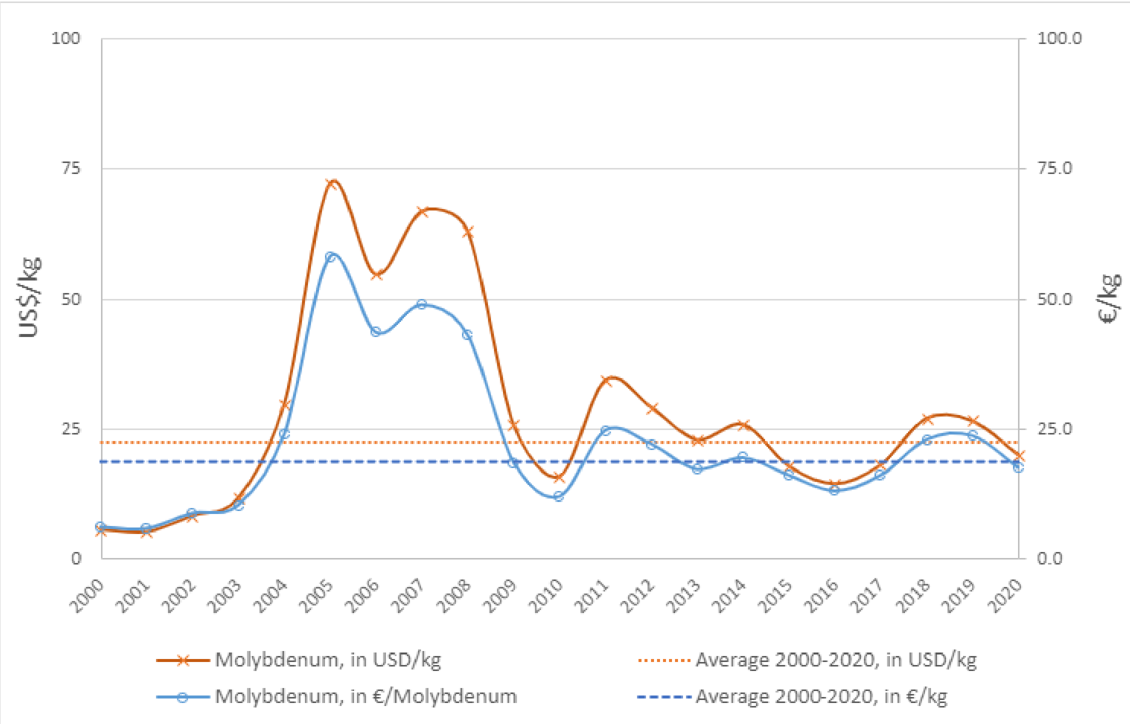

Figure 2. Annual average price of RM between 2000 and 2020 (USGS, 2021)[2].

[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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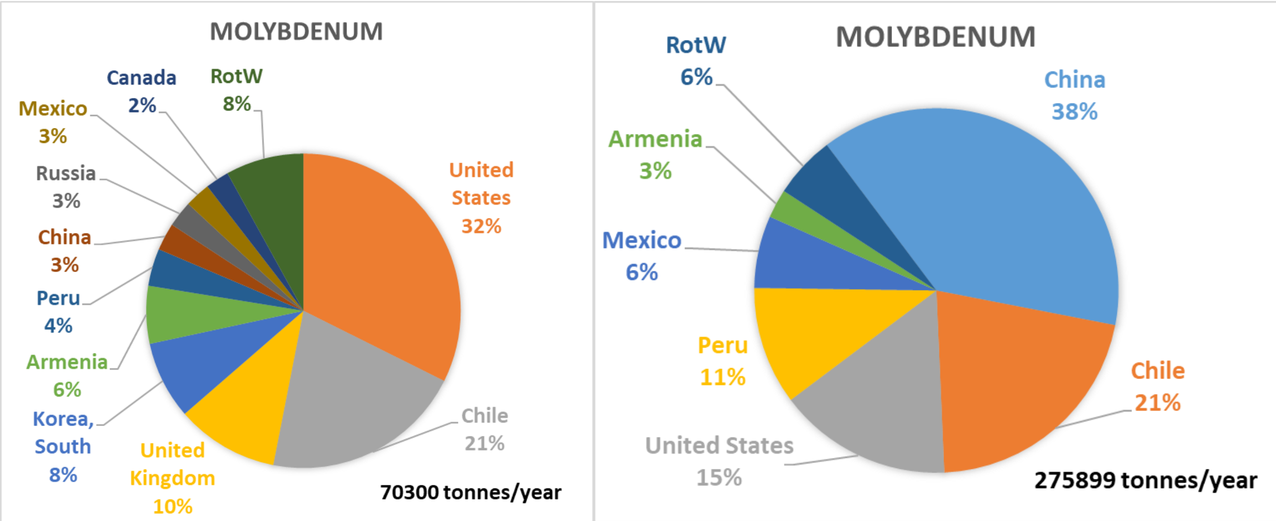

Figure 3. EU sourcing (extraction and processing) of molybdenum and global mine production

Uses: Molybdenum is mainly used in engineering steel (40%) and stainless steel (24%), then in chemicals (11%) foundries (8%) and tool steel (8%). Mo metal only represents 5% of the uses and 3% is used in nickel alloys.

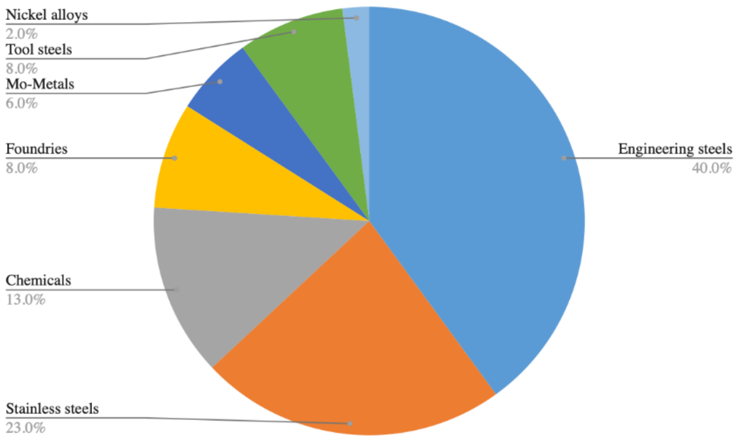

Figure 4: EU uses of RM

Table 2. Uses and possible substitutes

Use	Percentage*	Substitute	Comment on substitute
Engineering steels	39%	Chromium (Cr); Vanadium, Nickel, Boron	Slightly higher cost (up to 2x). Covers only 1% of sub-share of end-uses. Includes other critical materials.
Stainless steel	24%	Grade 445M2 (higher Cr content)	Similar or lower costs Covers only 1% of sub-share of end-uses
Chemicals	13%	No substitute	
Foundries	8%	Under 10%, not assessed	
Mo-metals	5%	Under 10%, not assessed	
Tool steels	8%	Under 10%, not assessed	
Nickel alloys	3%	Under 10%, not assessed	

* EU end use consumption share.

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Substitution: Substitution of molybdenum in the noted applications is low as most alternative applications incur performance losses, higher costs, and potential harmfulness of possible substitutes. Potential substitutes for molybdenum in some of its applications (USGS 2022) include Chromium, vanadium, niobium and boron in engineering steels, Tungsten in tool steels, Graphite, tungsten, and tantalum for refractory materials in high temperature electric furnaces, Chrome-orange, cadmium-red, and organic-orange pigments for molybdenum orange, and Chromium and cadmium for pigments (although substituting for harmful toxic substances).

Other issues: Legislation about molybdenum (Mo) addresses its most used form during processing, which is molybdenum trioxide (MoO3). IARC (2018) classifies MoO3 in 2B category (possibly carcinogenic, given its carcinogenicity in non-human animals). The EU (CLP, 2008) classifies MoO3 as carcinogenic 2, suspected of causing cancer, and it stands that such substance "causes serious eye irritation" and "may cause respiratory irritation". The Annex VIX of the REACH regulation classifies lead chromate molybdate sulphate red (C.I. Pigment red 104), due to its carcinogenicity of class 1B and reproductive toxicity of class 1A, both caused by the presence of lead and chromate (REACH, 2006). The (WHO, 2003) sets a maximum guideline value for molybdenum concentration in drinking water at 0.07 mg/L. On the other side, the (drinking water EU Directive, 2020) does not provide any threshold value for the concentration of this metal in drinking water. The effects of molybdenum on human health and the environment are low, albeit chronic exposure even to low concentrations to this substance is considered toxic for livestock, wildlife, and vegetation (US Department of Health and Human Services, 2020). A life cycle assessment (LCA) found that the solvothermal process for MoS_2 (molybdenium sulphide) nanomaterial production is highly energy intensive and with a high global warming potential (GWP) of 6.34 MJ/kg and 391.33 kg CO_{2eq}/kg, respectively. However, the ecotoxicity of this industrial process is low for terrestrial and aquatic ecosystems.

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3: Molybdenum (extraction) supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
275,899.	China 38% Chile 21% USA 15% Peru 10% Mexico 6% Armenia 3%	9,018	10.5%	USA 64% Chile 18% Peru 9% Canada 6%	96%

Molybdenum demand is driven by oil and gas drilling activity, and infrastructure spending. Demand from the oil and gas sector is the biggest source of molybdenum demand volatility. In 2021, global production of molybdenum increased compared with 2020, where China, Chile, the United States, Peru, and Mexico supplied 93% of total global production (USGS, 2022a). Chinese molybdenum imports continued to be at historically high levels as China continued to focus on infrastructure growth to support its COVID-19 recovery (USGS, 2022a). By the first quarter of 2022, molybdenum production declined by 7% compared to the first quarter of 2021. In contrast, the global demand of molybdenum increased by 9% (IMOA, 2022). China remained the largest supplier and consumer of molybdenum worldwide in 2021-2022 (IMOA, 2022).

Molybdenum roasted concentrates or technical molybdenum oxide (TMO) is traded on the London Metals Exchange, in which each contract represented 6 tonnes of molybdenum and was quoted in US dollars. (LME, 2022). Key players operating in the global molybdenum market include Freeport-McMoRan, Group Mexico, Codelco, China Molybdenum, Jinduicheng Molybdenum (EC, 2020).

EU TRADE

For this assessment, molybdenum is evaluated at both extraction and processing stage.

Table 4. Relevant Eurostat CN trade codes for molybdenum

Mining		Processing/refining	
CN trade code	**title**	**CN trade code**	**title**
26139000	Molybdenum ores and concentrates - excluding roasted	26131000	Roasted ores & concentrates
		72027000	Ferromolybdenum
		81021000	Molybdenum powders
		28257000	Molybdenum oxides and hydroxides

The EU imports and exports molybdenum in various forms. In 2021, Molybdenum is mainly mined in the United States, Chile, China, Peru, and Mexico (USGS, 2022). The conversion of molybdenum ores into unroasted molybdenite concentrates normally happens at or nearby the mine site (Lee, G., Carter, A., Gargiulo, A.,

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Miqdadi, J., 2021). Output at some molybdenum mines was interrupted due to Covid-19 pandemic. For example, Freeport-McMoRan's cut production at their Climax Molybdenum mine in the United States due to reduced demand in the developed world (Lee, G., Carter, A., Gargiulo, A., Miqdadi, J., 2021). The EU is a net importer of molybdenum ores and concentrates (See Figure 5). The EU exports have been relatively stable since 2005. The EU imports reached 45,424 tonnes in 2021 while the EU exports sat at 1,694 tonnes in 2021. The major suppliers of molybdenum ores and concentrates to the EU are the United States, Chile, Peru, and Canada (See Figure 6).

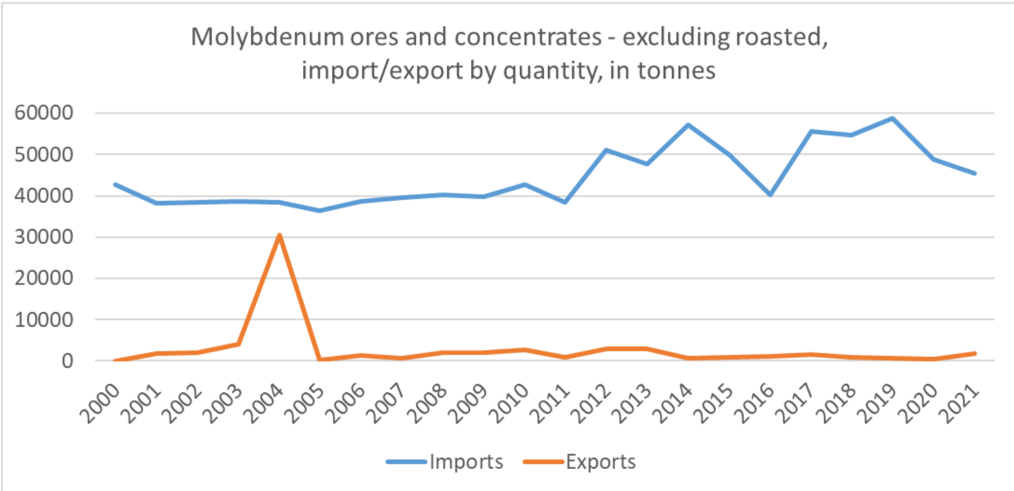

Figure 5. EU trade flows of Molybdenum ores and concentrates - excluding roasted (CN 26139000) from 2000 to 2021 (Eurostat, 2022)

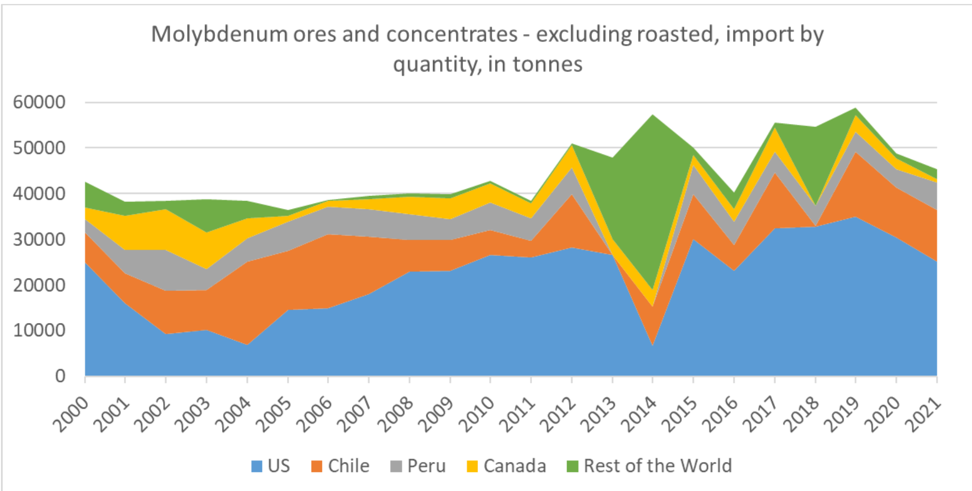

Figure 6. EU imports of Molybdenum ores and concentrates - excluding roasted (CN 26139000) by country from 2000 to 2021 (Eurostat, 2022)

More than 95% of Unroasted molybdenum ores and concentrates is converted to roasted molybdenite concentrate (Also known as technical grade molybdenum oxide) by molybdenum roasters (Lee, G., Carter, A., Gargiulo, A., Miqdadi, J., 2021). Further processing generates higher value-added molybdenum products such as ferromolybdenum, molybdenum metal, or chemical molybdenum oxides (Metals Hub, 2020).

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In terms of processed molybdenum, the EU is a net importer of molybdenum roasted ores and concentrates (Figure 7) and ferro-molybdenum (Figure 9). The main suppliers to the EU are Chile, United States, China, Mexico, and the United Kingdom for roasted molybdenum ores (Figure 8). The past 10 years from 2011 to 2021 saw fluctuations of EU ferro-molybdenum suppliers' shares from the main exporters such as the United Kingdom, Armenia, South Korea, Chile, China, and Russia (Figure 10).

The EU exports of molybdenum powders were higher than the EU imports until 2015. In 2016, the EU exports started to exceed the imports (Figure 11). This condition continued until 2021, sitting at 334,885 tonnes of exports vs 101,169 tonnes of imports. The major suppliers of molybdenum powders to the EU by quantity are the United Kingdom, The United States, Russia, The United Kingdom, and China (Figure 12).

The EU exports of molybdenum oxides and hydroxides have been lower than the imports (Figure 13). However, since 2014 the EU exports have started to rise. Recently, in 2021, the EU export sat at 4292 tonnes while the import was 3580 tonnes. The EU imported molybdenum oxides and hydroxides mainly from Chile, the United Kingdom, the United States, and China (Figure 14). In the past 21 years from 2000-2021 the supply of molybdenum oxides and hydroxides from Chile to the EU has been increasing.

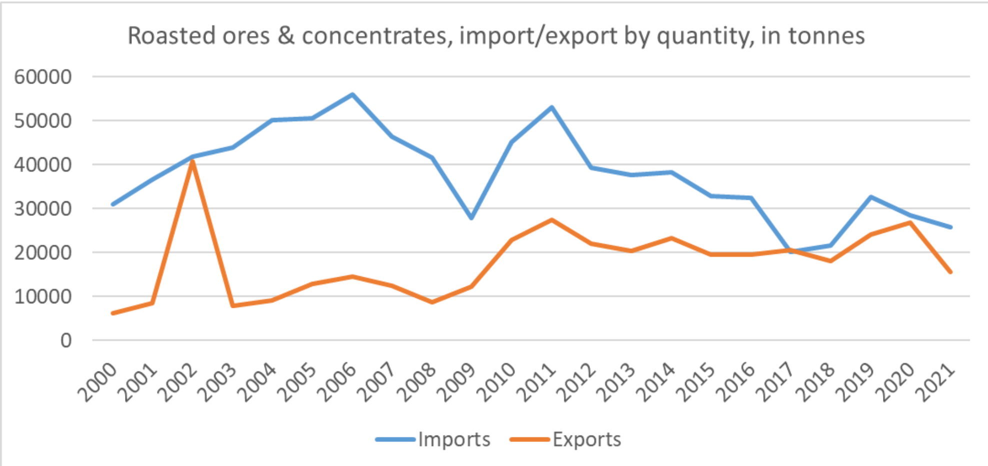

Figure 7. EU trade flows of Roasted ores & concentrates (CN 26131000) from 2000 to 2021 (Eurostat, 2022)

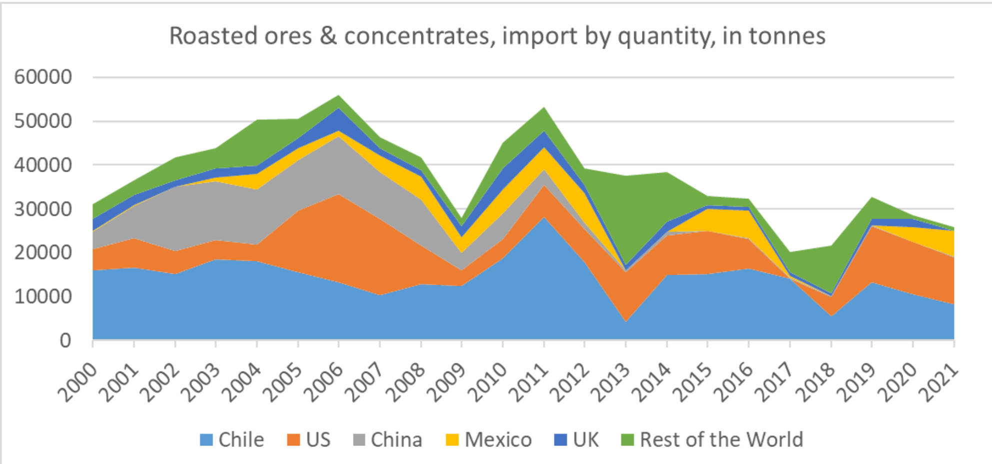

Figure 8. EU imports of Roasted ores & concentrates (CN 26131000) by country from 2000 to 2021 (Eurostat, 2022)

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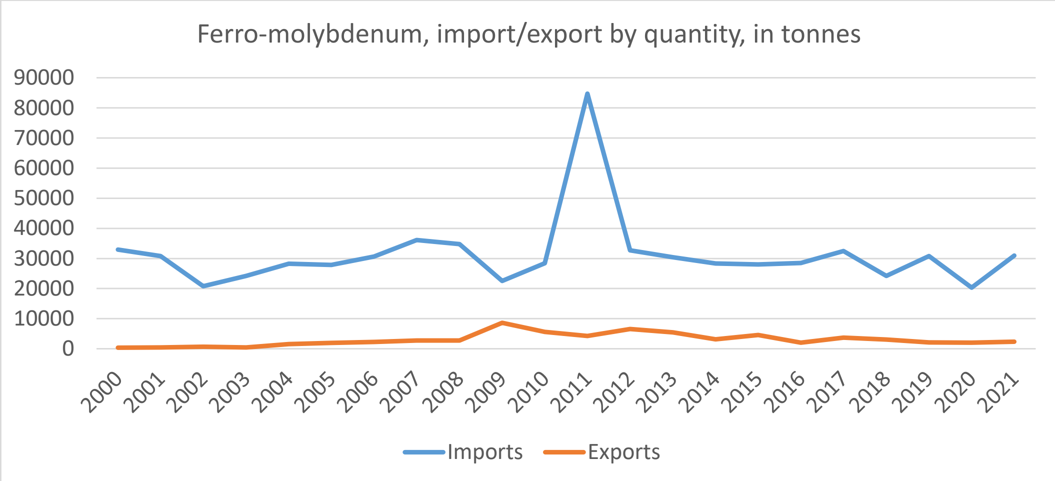

Figure 9. EU trade flows of Ferro-molybdenum (CN 72027000) from 2000 to 2021 (Eurostat, 2022)

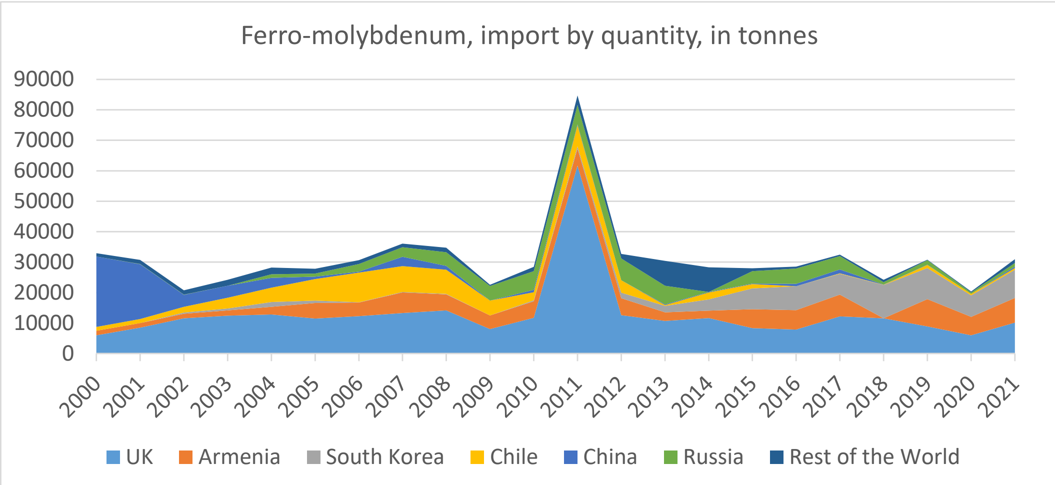

Figure 10. EU imports of Ferro-molybdenum (CN 72027000) by country from 2000 to 2021 (Eurostat, 2022)

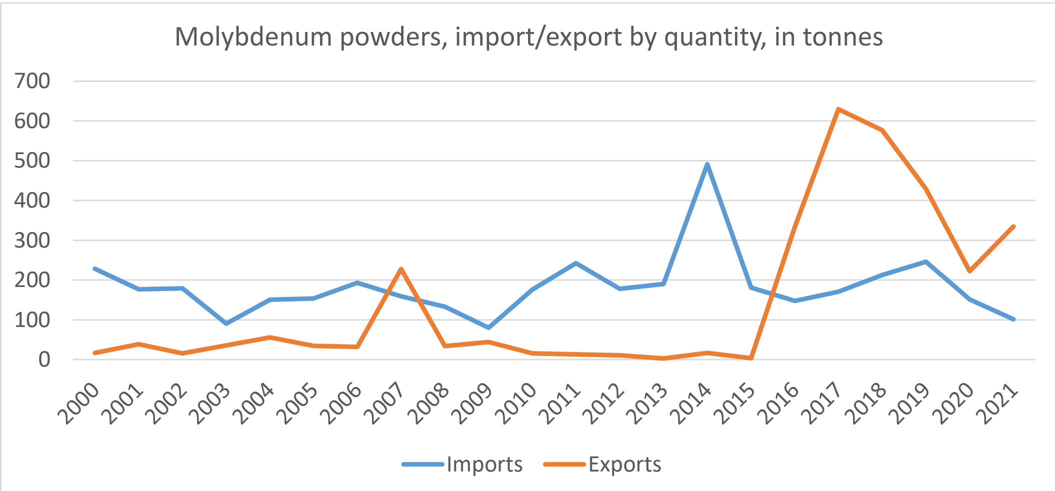

Figure 11. EU trade flows of Molybdenum powders (CN 81021000) from 2000 to 2021 (Eurostat, 2022)

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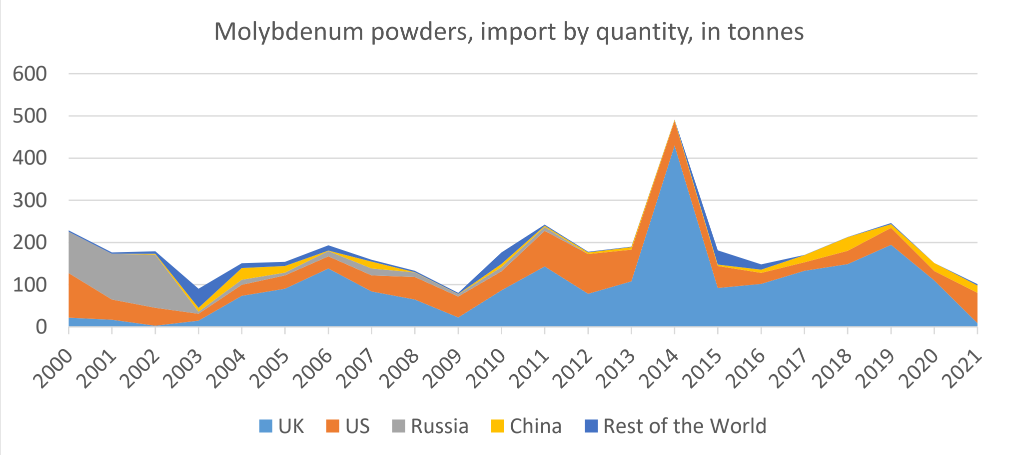

Figure 12. EU imports of Molybdenum powders (CN 81021000) by country from 2000 to 2021 (Eurostat, 2022)

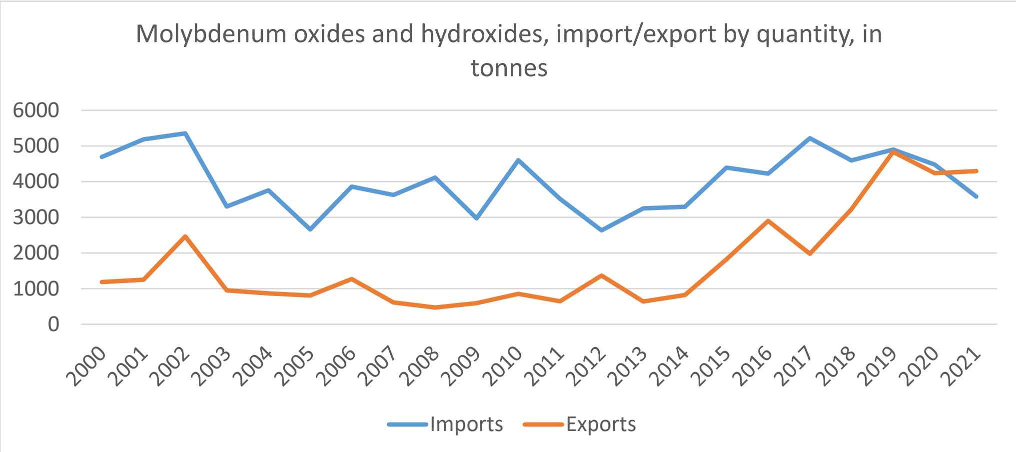

Figure 13. EU trade flows of Molybdenum oxides and hydroxides (CN 28257000) from 2000 to 2021 (Eurostat, 2022)

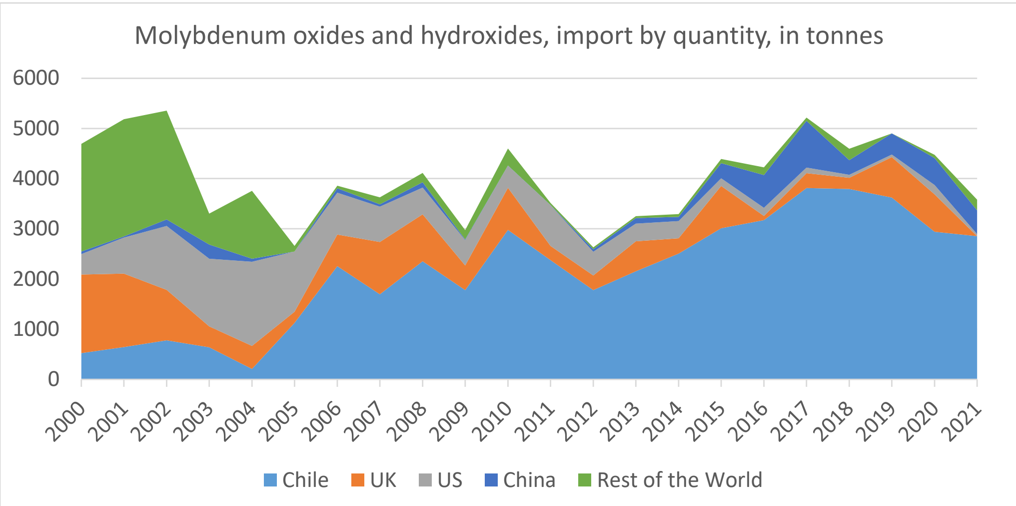

Figure 14. EU imports of Molybdenum oxides and hydroxides (CN 28257000) by country from 2000 to 2021 (Eurostat, 2022)

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PRICE AND PRICE VOLATILITY

Molybdenum prices are driven by oil and gas prices and stainless-steel market dynamics (EC, 2020). Oversupply drove molybdenum prices down from an annual average of USD 28/kg in 2012 to USD 14/kg in 2016. Between August 2014 and November 2015 molybdenum prices plunged below USD 10/kg with oil price contraction. Oil price began to recover in late 2016 and molybdenum prices stabilized in 2017, and molybdenum prices presented minor changes between 2018 and 2020.

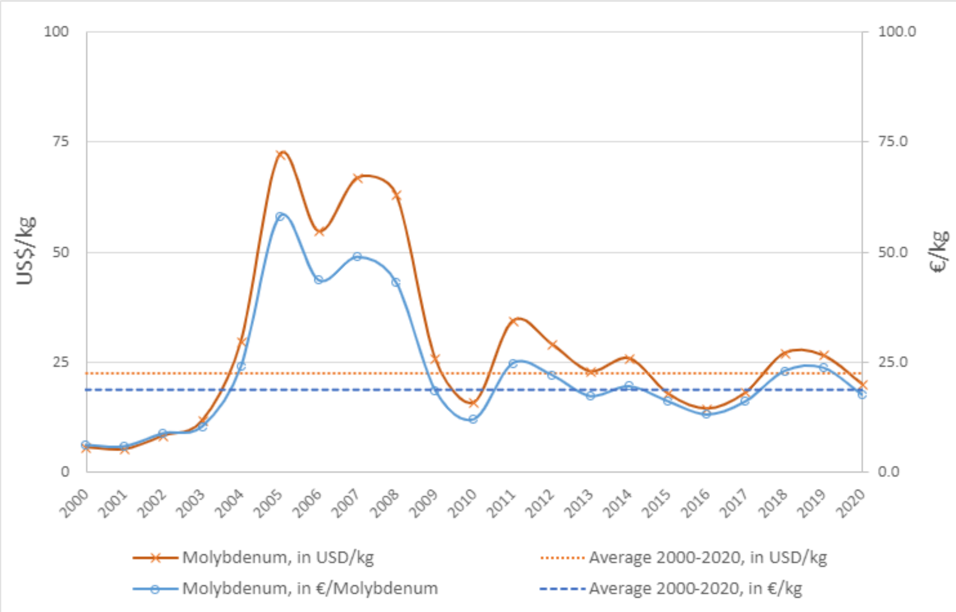

Figure 15. Annual average price of molybdenum between 2000 and 2020, in US$/kg and €/kg[3]. Dash lines indicate average price for 2000-2020 (USGS, 2022b)

DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

IMOA (2022) estimates the annual average worldwide consumption of molybdenum as about 260 ktonnes for 2017-2021 and the annual average EU consumption of molybdenum as about 60 ktonnes for 2017-2021.

Molybdenum extraction / processing stage EU consumption is presented by HS code CN 26139000 Molybdenum ores and concentrates (excl. Roasted). 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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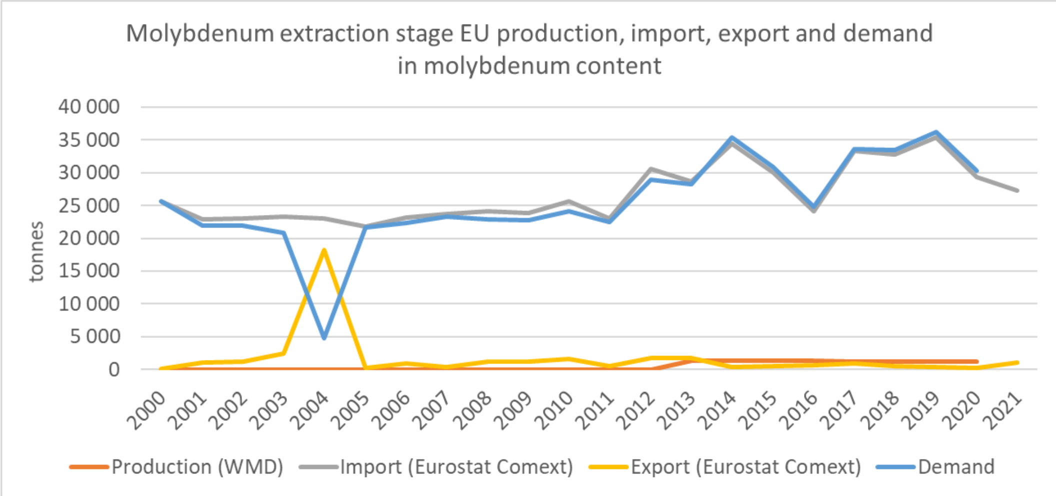

Figure 16. Molybdenum (CN 26139000) processing stage apparent EU consumption. Production data is available from WMD (2022). Consumption is calculated in molybdenum content (EU production+import-export).

Molybdenum processing stage EU consumption is presented by HS codes CN 81029400 Unwrought molybdenum, incl. bars and rods obtained simply by sintering, CN 72027000 Ferro-molybdenum, CN 81021000 Molybdenum powders, CN 26131000 Roasted molybdenum ores and concentrates and CN 28257000 Molybdenum oxides and hydroxides. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from BGS (2022).

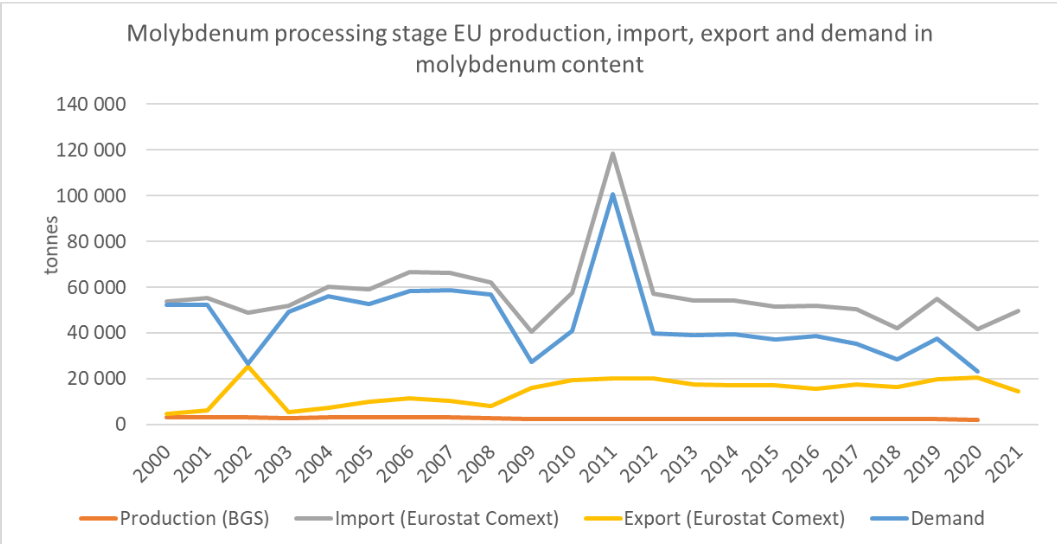

Figure 17. Molybdenum (CN 81029400, CN 72027000, CN 81021000, CN 26131000 and CN 28257000) processing stage apparent EU consumption. Production data is available from BGS (2022). Consumption is calculated in molybdenum content (EU production+import-export).

Average import reliance of molybdenum at extraction stage is 96.0 % and at processing stage 92.3 % for 2016-2020.

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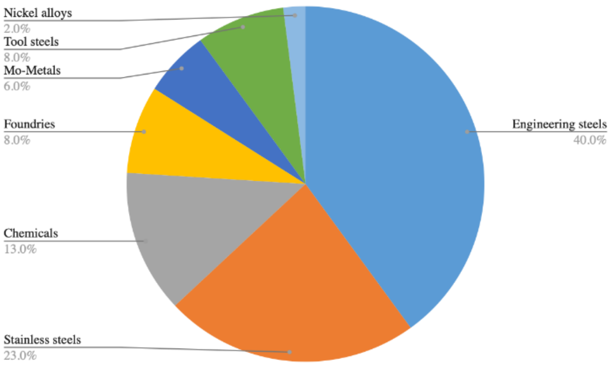
EU USES AND END-USES



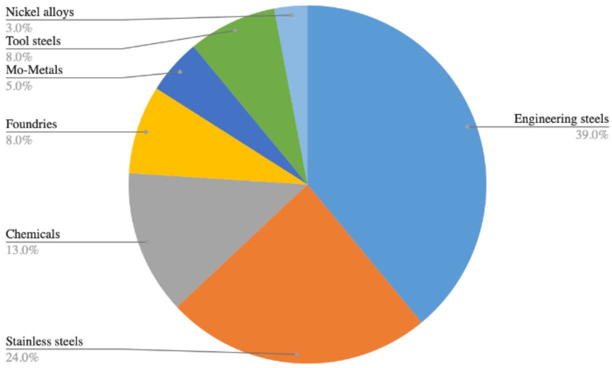


Figure 18: EU end uses for Molybdenum (2015, left, IMOA (2019)), and global end uses (2021, right, EU CRM study (2023))

EU data for 2015 and global data for 2021 show no significant deviations.

APPLICATIONS OF MOLYBDENUM

ENGINEERING STEELS

- Engineering steels (carbon steels) accounted for 39% of the global demand of primary molybdenum in 2017 (International Molybdenum Association, 2019).
- Engineering steel has small amounts of one or more alloying elements, such as manganese, silicon, or molybdenum, producing specific properties that are not found in regular carbon steel.
- Engineering steels with a high amount of molybdenum will have a greater resistance to corrosion and strength at higher temperatures.
- Typical molybdenum contents in the steels does not exceed 1%. T
- hey are used in a wide range of marine environment applications (e.g. offshore oil rigs), as well as oil and gas pipelines.

STAINLESS STEEL

- Ca. 23% of global molybdenum demand is used to make molybdenum grade stainless steel.
- The most widely used grade is an austenitic stainless steel containing 2-3% molybdenum (Type 316).
- The addition of molybdenum strengthens the stainless steels and inhibits corrosion.
- Among many other uses, molybdenum grade stainless steels are used in tanks and piping in food handling and processing, pulp and paper mills, ocean tankers, desalination plants and pharmaceuticals.

TOOL STEELS

- Molybdenum in tool steels (global demand of 8%) increases their hardness and resistance to wear.
- Regular tool steels contain up to 3% molybdenum.
- High-speed tool steels containing 5-10% molybdenum are used to make drills and cutting tools.

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FOUNDRIES

- Molybdenum increases the strength, hardness, temperature and pressure tolerance of cast iron and steels, which are used in automobile engines (more specifically to make cylinder heads, motor blocks, and exhaust manifolds). These applications account for about 8% of molybdenum demand.

MO-METALS

- High purity molybdenum metal and alloys have high strength and mechanical stability at high temperatures and are used in many applications - including high temperature heating elements, glass melting furnace electrodes etc.

NICKEL ALLOYS

- Molybdenum is also used in nickel alloys (2%) to increase their corrosion or high-temperature resistance.
- These are high-performance superalloys containing up to 28.5% molybdenum (B-3® alloy) and are used in the production of jet engines, turbochargers, power generation turbines and in thevchemical and petroleum industries.

CHEMICALS

- About 13% of molybdenum extracted is used chemicals, mostly in catalysts for petroleum refineries and plastics industries.
- Molybdenum disulfide (MoS_2 – molybdenite, the most common molybdenum mineral) is used as a dry lubricant additive in greases, friction materials etc. after purification.
- Other uses include inks for circuit boards, pigments and electrodes.

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 5 and visualised in Figure 19.

Table 5: Molybdenum applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector (Eurostat 2022).

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit CPA
Engineering steels	C25 - Manufacture of fabricated metal products, except machinery and equipment	186,073	C25 11
Stainless steels	C19 - Manufacture of coke and refined petroleum products	24,896	C19.20 Refined petroleum products
Chemicals	C20 - Manufacture of chemicals and chemical products	117,150*	C20.12 Manufacture of dyes and pigments
Foundries	C28 - Manufacture of machinery and equipment n.e.c.	200,138*	28.11 Engines and turbines, except aircraft, vehicle and cycle engines; 28.92 Machinery for mining, quarrying and construction

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Mo-Metals	C28 - Manufacture of machinery and equipment n.e.c.	200,138*	28.21 Ovens, furnaces and furnace burners
Tool steels	C28 - Manufacture of machinery and equipment n.e.c.	200,138*	C28.15 Manufacture of bearings, gears, gearing and driving elements
Super alloys	C28 - Manufacture of machinery and equipment n.e.c.	200,138*	C28.1.1 - Manufacture of engines and turbines, except aircraft, vehicle and cycle engines

* Data up to 2014 only.

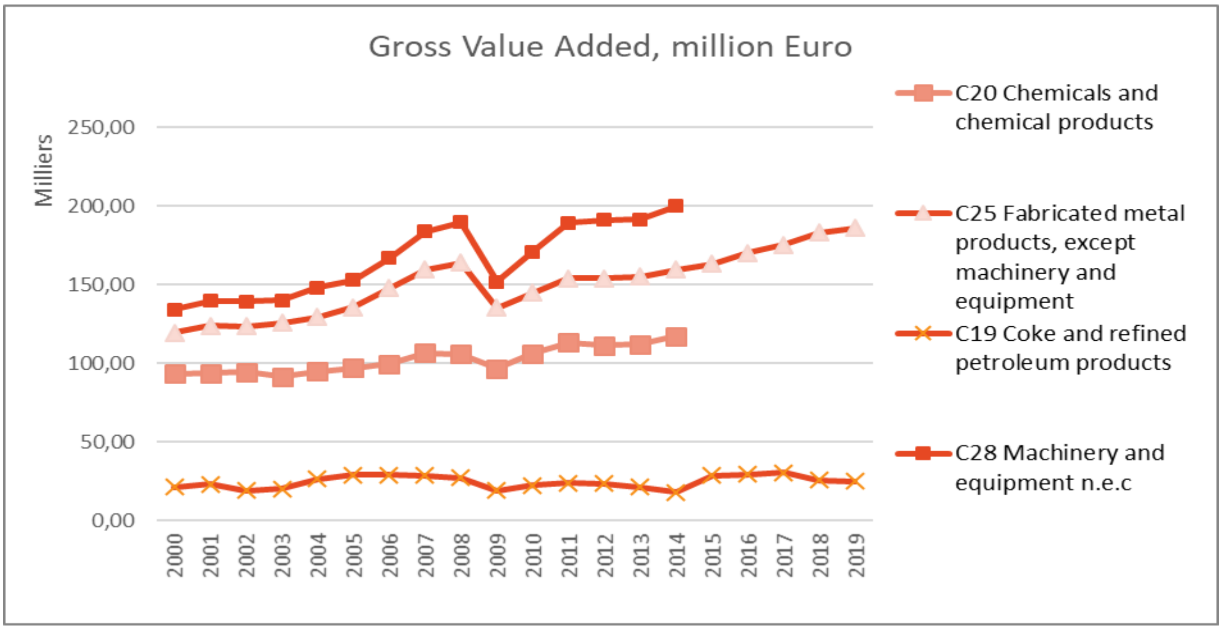

Figure 19. Value added per 2-digit NACE sector over time (Eurostat, 2022).

SUBSTITUTION

A recent EU CRM study (EU CRM, 2023) has assessed the degree to which molybdenum can be substituted in its main applications, data shown below.

Table 6: Substitution options for molybdenum by application

Use	Percentage*	Substitute	Comment on substitute
Engineering steels	39%	Chromium (Cr); Vanadium, Nickel, Boron	Slightly higher cost (up to 2x). Covers only 1% of sub-share of end-uses. Includes other critical materials.
Stainless steel	24%	Grade 445M2 (higher Cr content)	Similar or lower costs Covers only 1% of sub-share of end-uses
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* EU end use consumption share.

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Substitution of molybdenum in the noted applications is low as most alternative applications incur performance losses, higher costs, and potential harmfulness of possible substitutes.

Potential substitutes for molybdenum in some of its applications (USGS 2022) include:

- Chromium, vanadium, niobium and boron in engineering steels.
- Tungsten in tool steels.
- Graphite, tungsten, and tantalum for refractory materials in high temperature electric furnaces.
- Chrome-orange, cadmium-red, and organic-orange pigments for molybdenum orange.
- Chromium and cadmium for pigments (although substituting for harmful toxic substances) (MSP-Refram Ref. Ares(2016)6763191 - 02/12/2016).

SUPPLY

EU SUPPLY CHAIN

The EU did not produce molybdenum concentrates (WMD 2018) but processed imported material into technical molybdenum oxide, ferromolybdenum, chemicals and metal. The annual average imported and exported molybdenum amount in EU in the period 2016-2020 is about 117 kt and 33.5 kt, respectively. Roasted molybdenum ores (CN 26131000), initial ores and concentrates (CN 26139000) and molybdenum trioxide (CN 282257000) are included in the imported products. The amount of the exported molybdenum products presents a significant increase during the last years (from 26.4 kt in 2016 to 52.4 kt in 2020). The recycling rate in EU is estimated at 30% (Eurostat, 2021).

GEOLOGY, RESOURCES AND RESERVES OF MOLYBDENUM

GEOLOGICAL OCCURRENCE:

Molybdenum concentration in the Earth continental upper crust is estimated to be 1.1 ppm (Rudnick & Gao, 2014). Molybdenite (MoS_2) is the main molybdenum mineral.

Porphyry deposits are the world's most important source of molybdenum and account for more than 95% of the world production. Molybdenum is mainly produced from two types of porphyry deposits, porphyry-copper deposits which are associated with continental volcanic arcs and porphyry molybdenum deposits. Porphyry Cu-Mo deposits defined as containing <0.05 wt% molybdenum and molybdenum/copper-ratios <1 are now supplying about 60% of the molybdenum world production as a by-product (Chile, Peru). Porphyry molybdenum deposits represent large-scale mineralization which contain molybdenum grades >0.05 wt% and Mo/Cu-ratios >1 (Carten et al., 1993) and produce molybdenum as the primary product. This type of deposits includes the giant Climax-type porphyry molybdenum deposits exemplified by the Climax and Henderson deposits in Colorado and Chinese deposits (Taylor et al., 2012) for porphyre molybdenum Global resources and reserves.

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GLOBAL RESOURCES AND RESERVES

Global reserves of molybdenum at the end of 2018 were estimated at around 17,000,000 tonnes (USGS, 2019), with China accounting for almost half of the total (48%), followed by the United States (16%) and Peru (14%) (Table 1). Identified world molybdenum resources are approximately 25,000,000 tonnes (USGS, 2019).

Table 7: Global reserves of molybdenum in year 2021 (USGS, 2022)

Country	Molybdenum Reserves (ktonnes)
China	8,300
United States	2,700
Peru	2,300
Chile	1,400
Russia	430
Turkey	360
Mongolia	NA
Armenia	150
Mexico	130
Argentina	100
Canada	96
Uzbekistan	60
Iran	43
World total (rounded)	16,0

EU RESOURCES AND RESERVES:

Resource data for some countries in Europe are available at Minerals4EU (2019) but cannot be summed as they are partial and they do not use the same reporting code.

Table 8: Reserve data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2019)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
Greenland	NI 43-101	52.9	Mt	0.23%	Measured
Ireland	None	0.24	Mt	0.13%	Historic Resource, Estimate
France	None	42	kt	0.02-0.03%	Historic Resource, Estimate
Poland	Nat. rep. Code	0.29	Mt	0.05%	C2+D
Greece	USGS	12	kt	0.25%	Measured
Turkey	NI 43-101 JORC	168	Mt	0.006%	Indicated
		51	Mt	0.0125%	Inferred
Norway	None	200	Mt	0.14%	Historic Resource, Estimate
Sweden	FRB- standard	509.1	Mt	19 g/t	Measured
Finland	None	9.6	Mt	0.1%	Historic Resource, Estimate

The EU potential includes include porphyry molybdenum deposits in the Tertiary igneous Province of East Greenland (Malmbjerg) and the Myszków Molybdenum and tungsten porphyry deposit in Poland.

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Malmbjerg is a porphyry molybdenum sulphide deposit hosted within a north-northeast trending belt of sedimentary and intrusive rocks of Carboniferous to Lower Tertiary age. Molybdenum mineralisation at the deposit is associated with hydrothermal alteration and occurs in the form of molybdenite, which is found disseminated in fractures and stockworks The Malmbjerg project was estimated to hold 245 million tonnes (Mt) of mineral reserves grading 0.176% molybdenum disulphide (MoS_2) and containing 571Mlbs of molybdenum metal as of February 2022. The ore will be enriched through a conventional multi-stage flotation circuit. The Malmbjerg concentrator plant will have a capacity to process 35,000t of molybdenum-rich ore a day (nsenergybusiness.com, 2022). The Terms of Reference for the Environmental Impact Assessment (EIA) and Social Impact Assessment documents of Greenland Resources, the company that is going to exploit the deposit, were recently (September 2022) approved by the Government of Greenland (businesswire, 2022).

WORLD AND EU MINE PRODUCTION

Around 60% of global molybdenum supply comes as a by-product of copper smelting form porphyry copper-molybdenum ores, with most of the remainder coming from primary sources, i.e. from the processing of ores extracted from porphyry molybdenum deposits. After extraction, molybdenum concentrate is produced by a flotation technique which separates the gangue from the molybdenum minerals. Most molybdenum concentrate contain 85-93% molybdenite.

Figure 20 and Figure 21 present the global mining production of molybdenum ores since 1984 and since 2000 according to WMD and USGS, respectively (WMD, since 1984, USGS, since 2000). China, Chile and United States remain the leader producers of molybdenum ores. There is no molybdenum mine output in the EU and therefore all the Union needs rely on imports.

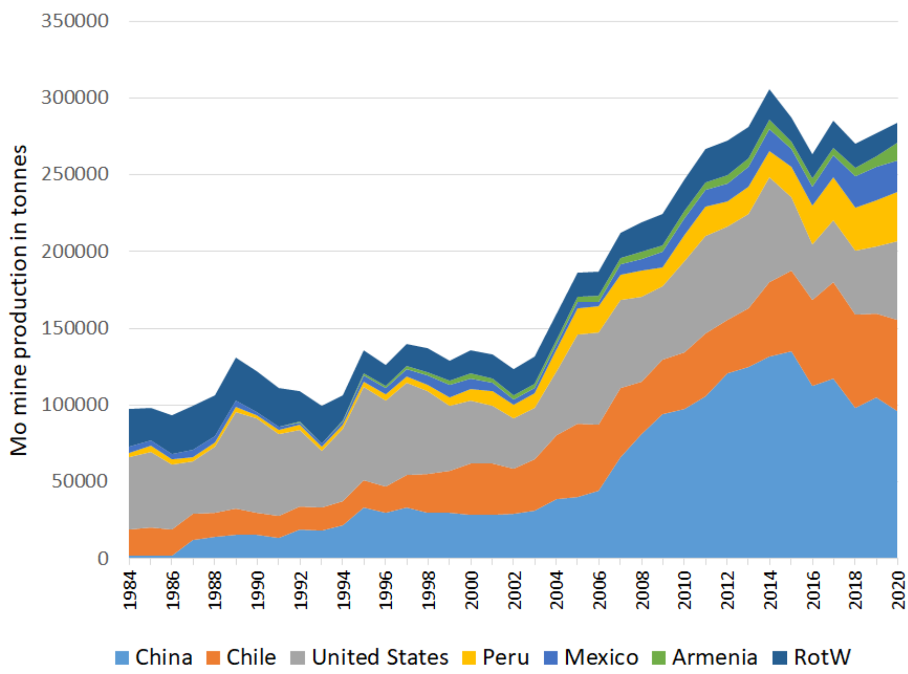

Figure 20: Global primary molybdenum production since 1984 according to WMD data (WMS, since 1984).

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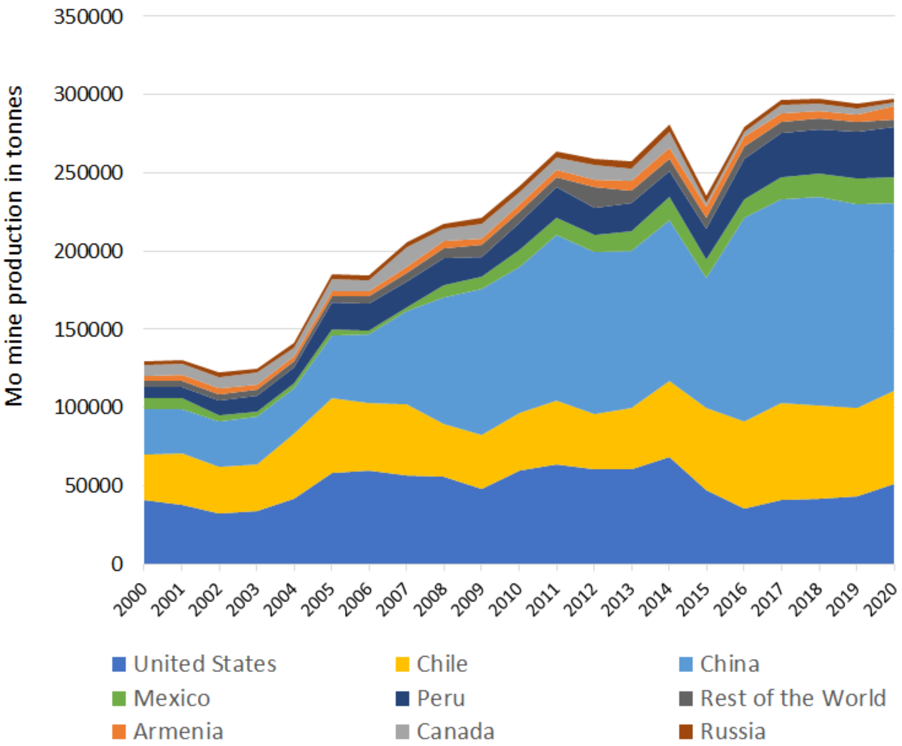

Figure 21: Global primary molybdenum production since 2000 according to USGS data (USGS, since 2000).

OUTLOOK FOR SUPPLY

The global molybdenum market is expected to grow in the forecast period of 2022-2027 at a rate of 4% due to the increased demand in moly steel alloys that are used in various engines constructions related to the green energy (expertmarketresearch.com, 2022). However, there are no published studies describing how this gap between the increased demand and the supply will be balanced.

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

NEW AND OLD SCRAP RECYCLING

According to The International Mo Association (IMOA, 2015), of the 330,000 tonnes of molybdenum used in all applications worldwide in 2013, some 86,000 tonnes, or 26%, came from recycled sources. In the same year, the share of recycled molybdenum used in stainless steel production was 39%, rising to 50% in tool and high speed steels.

About two-third of the secondary molybdenum comes from revert scraps produced during the steel making process and new scrap generated by steel fabrication. Recycling scrap for the production of new materials requires less energy than the production of new metal and it causes fewer emissions. It is also often sourced locally, so transportation routes are short. Therefore, molybdenum recycling cannot only bring cost benefits but also environment benefits. Engineering steels which contain less than 0.5% molybdenum are not recycled

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for their molybdenum content but are put back in general steel production of lower quality. The amount of molybdenum recycled as part of new and old steel and other scrap may be as much as 30% of the apparent supply of molybdenum (USGS, 2020).

In 1998, old scrap molybdenum recycling efficiency (molybdenum recycled from old scrap divided by total molybdenum in old scrap produced) in the USA was 30% (Blossom, J.W., 2002). This figure for old scrap molybdenum recycling efficiency is also used by UNEP (UNEP, 2011). Based on a comparison between global end-of-life recycling rates with end-of-life recycling rates in the USA we estimate that the global end-of-life recycling rate of molybdenum is 20% (Henckens M.L.C.M., 2018). The main reason the amount of secondary molybdenum is so low is that old scrap containing molybdenum is normally purchased and recycled not for the sake of molybdenum, but for other metals, mostly iron. Old scrap is largely molybdenum-bearing alloys recycled after serving their useful life and spent catalysts used in chemical and petrochemical industries. The recycling efficiency of molybdenum is not expected to increase significantly as long as cheaper alternatives are available in the form of relatively cheap primary molybdenum.

4.3.2 RECYCLING METHODS

At present, there are many methods for recycling molybdenum waste, but they are mainly based on pyrometallurgical supplemented by hydrometallurgical methods. The common methods are as follows (ARM, 2019):

- Sublimation: Molybdenum metal is oxidised at a certain temperature to molybdenum trioxide then sublimation and trapping recovery method occur (recovery rate is up to 98%). The method is mainly used for the recovery and utilization of waste molybdenum powder, molybdenum strip, molybdenum piece, molybdenum wire, molybdenum rhenium alloy and high-speed steel grinding waste material.
- Molten zinc: It mainly uses heating, distillation, roasting method to recycle hard alloy and super alloy scrap.
- Oxidation roasting acid leaching method: This method is mainly used for the recovery of the molybdenum-containing catalysts. The recoveries of cobalt and molybdenum are 97% and 95% respectively.
- Sodium carbonate roasting leaching method: This method is mainly used for the recovery of molybdenum-containing waste catalyst, but the main recovery of cobalt and nickel, their leaching rate is above 90%.
- Alkaline leaching method: Mainly used for the recovery of molybdenum and nickel waste catalyst. The leaching rate of molybdenum, aluminium, and nickel is 96.9%, 86.7%, and 90.1% respectively.

4.4 PROCESSING OF MOLYBDENUM

A small fraction of molybdenite concentrate is purified and used in MoS_2 lubricants. The concentrate is mostly processed into technical molybdenum oxide MoO_3 (TMO) by roasting in air at temperatures between 500 and 650°C. The roasted concentrate MoO_3 contains a minimum of 57% molybdenum.

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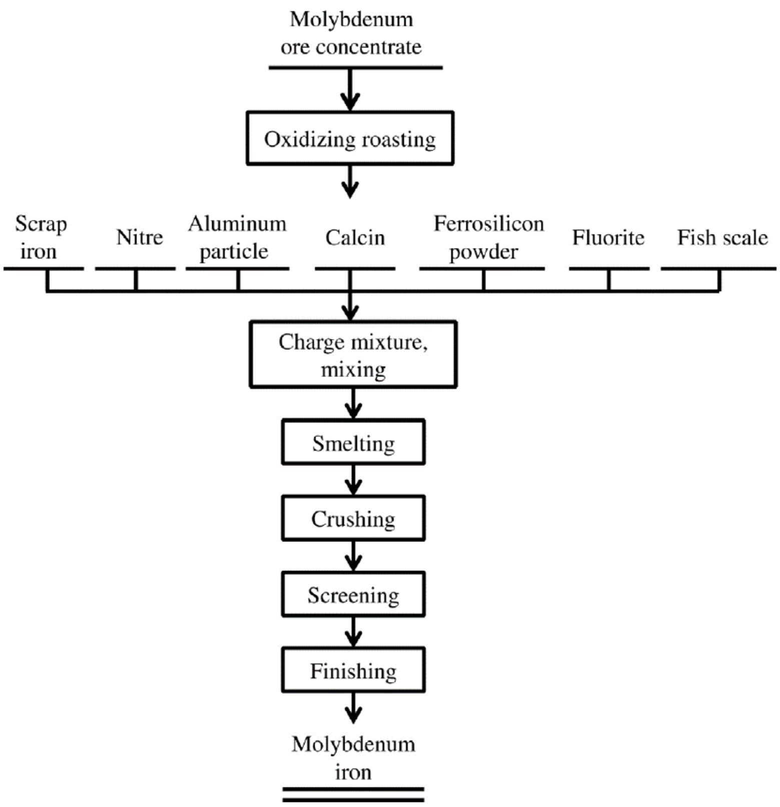

Figure 22: Simplified flowsheet of the production of ferromolybdenum (FeMo) (Xiao, 2017).

Between 30 and 40% of the production of technical molybdenum oxide (MTO) is processed into ferromolybdenum (FeMo) which contains between 60 and 75% Mo. Another 25% is processed into a number of chemical products such as pure grade molybdenum trioxide, ammonium and sodium molybdates, and metal. Molybdenum metal is produced by hydrogen reduction of pure grade molybdenum trioxide or ammonium molybdate (IMOA, 2019).

Ferromolybdenum is produced by either "block method" using carbon as a reducing agent in electric furnace smelting, or via metallothermic reduction in reductive furnaces using silicon (Si) and aluminum (Al) as reducing agents. The second approach characterized by energy efficiency is more widely applied (Figure 22). Concerning molybdenum chemicals, ammonium molybdate compounds (i.e. ammonium molybdate and ammonium para-molybdate) consists significant intermediate products in Mo smelting process. They are mainly used as basic raw materials for synthesizing high purity Mo products, such as MoO3, and other chemicals that applied in catalysts and pigments sectors. Ammonium molybdates production methodology by molybdenite is relatively complex including pyro- (roasting) and hydro- (ammonia leaching) metallurgical steps (Figure 23).

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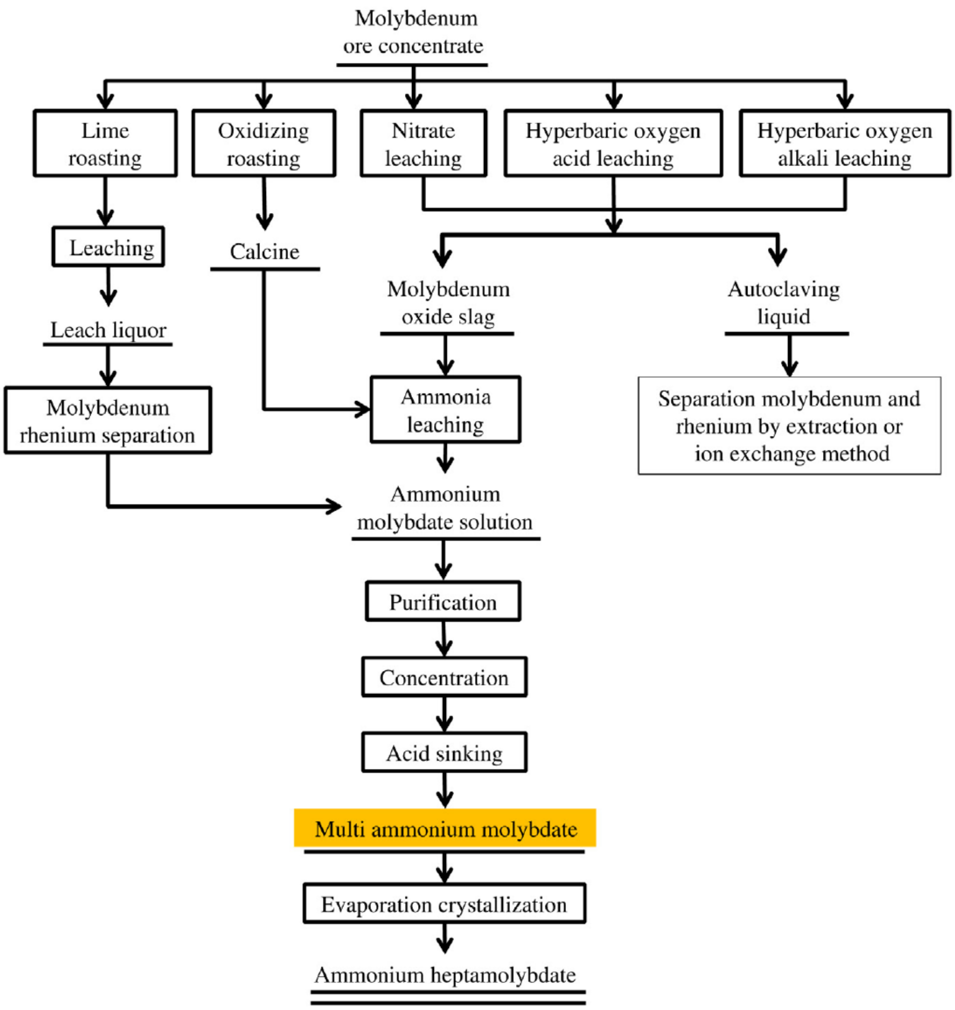

Figure 23: Simplified flowsheet of the production of ammonium molybdate ($(NH_4)_2[Mo_7O_4]$) and ammonium para-molybdate ($(NH_4)_6[Mo_7O_{24}]$) (Xiao, 2017).

World production data of technical molybdenum oxide, ferro molybdenum and Mo chemicals are not available or incomplete and data for the EU are very scarce. The major manufacturers of MTO are Molymet, Freeport-McMoRan, Codelco, Jinduicheng Molybdenum Group and China Molybdenum.

Molydenum oxide, ferromolybdenum and chemicals are all produced in the EU. MTO is produced in Belgium by Sadaci NV, a Molymet subsidiary, and in the Netherlands by Climax Molybdenum B.V, a Freeport-McMoRan subsidiary, which also produces ammonium dimolybdate and pure molybdic oxide on the Rotterdam site (FreeportMcMoRan, 2014). Treibacher Industrie AG in Austria is the only Ferro Molybdenum producer in the Union with an annual average production of 4,000 kt during the period 2012-2016 (BGS, 2017). According to the REACH Molybdenum Consortium there is one company in the Netherlands and potentially one in Germany (if production from the latter has not been relocated to the USA), which manufacture pure grade molybdenum trioxide (Carey, 2014). The chemicals and downstream production/supply chains in Europe will have sufficient capacity for most products once the Belgian-based company (Sadaci) will start the production of hyper-pure Moly oxide according to Euroalliages.

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OTHER CONSIDERATIONS

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

Legislation about molybdenum (Mo) addresses its most used form during processing, which is molybdenum trioxide (MoO3). IARC (2018) classifies MoO3 in 2B category (possibly carcinogenic, given its carcinogenicity in non-human animals). The EU (CLP, 2008) classifies MoO3 as carcinogenic 2, suspected of causing cancer, and it stands that such substance "causes serious eye irritation" and "may cause respiratory irritation". The Annex VIX of the REACH regulation classifies lead chromate molybdate sulphate red (C.I. Pigment red 104), due to its carcinogenicity of class 1B and reproductive toxicity of class 1A, both caused by the presence of lead and chromate (REACH, 2006). The (WHO, 2003) sets a maximum guideline value for molybdenum concentration in drinking water at 0.07 mg/L. On the other side, the (drinking water EU Directive, 2020) does not provide any threshold value for the concentration of this metal in drinking water.

The (US Department of Health and Human Services, 2020) alleges that exposure to inhalation of molybdenum leads to respiratory issues, while oral exposure can cause various health effects, especially weight loss and kidney damage.

ENVIRONMENTAL ISSUES

The effects of molybdenum on human health and the environment are low, albeit chronic exposure even to low concentrations to this substance is considered toxic for livestock, wildlife, and vegetation (US Department of Health and Human Services, 2020). A life cycle assessment (LCA) found that the solvothermal process for MoS_2 (molybdenium sulphide) nanomaterial production is highly energy intensive and with a high global warming potential (GWP) of 6.34 MJ/kg and 391.33 kg CO_{2eq}/kg, respectively. However, the ecotoxicity of this industrial process is low for terrestrial and aquatic ecosystems. The authors have assessed an option to curb the GWP of this production process by substituting lithium hydroxide, a high energy demand pH regulator, with a greener equivalent, sodium hydroxide. The results show that the demand for energy is decreased by 50 %, which in turn reduces significantly the overall environmental impact of MoS_2 nanomaterial production (Hachhach et al., 2022).

NORMATIVE REQUIREMENTS RELATED TO MINING OR MOLYBDENUM PRODUCTION, USE AND PROCESSING OF THE MATERIAL

The EU CLP contains the listing and details of the EU harmonized hazards classification for molybdenum trioxide (IMOA 2022). In particular, the following hazards are listed: Carcinogenic; Eye Irritation and the so called STOT SE 3, which includes Respiratory tract irritation (H335).

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SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF MOLYBDENUM FOR EXPORTING COUNTRIES

No data was found for molybdenum.

SOCIAL AND ETHICAL ASPECTS

In the early 2010's the Chinese government issued the permit for the implementation of a new smelter of Copper and Molybdenum in Shifang (Sichuan province), with a total annual output of 40,000 tonnes of molybdenum and 400,000 tonnes of copper (EJAtlas, 2016). The local population was reluctant to the project given the potential environmental and health impacts that the plant may cause. Another cause of worry was the origin of the raw materials, that were supplied by mines located in Tibet-Xizang Autonomous region and other Western provinces of China. These regions are known by their political instability and its conflicts with the central government. After several protests and conversations with the government the local population succeeded in stopping the project.

A molybdenum mining project in Oak Flat, an Apache area in Arizona, USA, was ceased by the native population to protect their sacred land and springs from mineral extraction activities. Also, another cause of worry and reluctancy of the local population was that the mining project would have used a massive volume of water from the Colorado river (EJAtlas, 2022).

At Cerro Verde, one of the biggest mines in Peru located 20 km south of the city of Arequipa, a porphyry copper deposit is exploited to extract copper and molybdenum. According to EJAtlas (2021), the site is affecting the environmental quality of the area, especially the groundwater, and for this reason it was fined by the Ministry of the Environment. Water and air pollution concerns pushed local population to fight against the expansion project presented in 2012 by Freeport, the company owning 53 % of the mine. The expansion project included three times increase of material extracted and processed per day (EJAtlas, 2021). Despite the opposition of local communities, the project took off and was finalized in 2016 (Sanchez, J. 2017). During the exploitation period the company provided the city with two water treatment plants: the first one, named "Tomilla II potabilization treatment plant" was finished in 2012, while "La Enlozada wastewater treatment plant" started operations in 2014 to treat the mining and processing wastewater before its discharge in the Chili River, a water body that is pivotal for the city's economic activities such as agriculture (Torre, C., 2018).

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Copper-zinc-tin-sulfide (CZTS) solar cells with MoS_2 buffer

Copper-zinc-tin-sulfide (CZTS) is a semiconductor that performs as a cell absorber given its high absorption coefficient, low electrical resistivity, and a band gap of 1.54 eV at room temperature (Sampad et al. 2022). Among various types of third-generation solar cells, CZTS solar cells have gained much interest due to their high raw material availability. However, a low light-to-electric power efficiency (13 %) limits their

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implementation in the market, where the performance standard is about 20 % (Krishan et al., 2019, Nugroho et al., 2020). Recently, Sampad et al. (2022) have shown through numerical modelling that the use of MoS_2 (molybdenium sulphide) as a buffer layer within CZTS layers could increase cell efficiency to up to 17.6 % while guaranteeing low cost, non-toxicity and high stability. The insertion of a buffer layer in solar panels minimizes CZTS defects and ensures that the absorber and the external layer have the correct band alignment.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- DEMOFERTILIZER: Development of novel formulations for improved molybdenum fertilization (2020-2023, EU)[4]

Molybdenum (Mo) is an important micronutrient for plant growth, and deficiency can have detrimental consequences for agriculture; therefore, mineral fertilisers enriched in water-soluble forms of Mo are commonly used. However, the fast release of Mo from soluble forms makes it difficult for plants to get what they need, as their access to Mo rapidly becomes limited due to losses by leaching of these soluble forms to the groundwater. The EU-funded DEMOFERTILIZER project is developing slow-release fertiliser Mo compounds to better match Mo availability to plant need. Various formulations will be tested and compared to water-soluble Mo to find a way to make sure plants get the Mo they need.

- MSP-REFRAM: Multi-Stakeholder Platform for a Secure Supply of Refractory Metals in Europe (2015-2017, UE)[5]

Refractory metals (tungsten, tantalum, rhenium, molybdenum and niobium) are highly strategic metals today mainly imported from a few countries. The European primary production remains below a few percentages. However, resources exist in Europe, as primary resources, but mainly as secondary resources (industrial waste, urban mines). Valorising these resources requires coordination and networking between researchers, entrepreneurs and public authorities to harmonise technologies, processes and services, develop standards, create new potential for export of eco-innovative solutions and for seizing new markets. MSP-REFRAM will addressed these challenges by creating of a common multi-stakeholder platform that will draw the current refractory metals value chains and identify its innovation potential to support the implementation of the European Innovation Partnership (EIP) on Raw Materials. Coming from industry, research, public sectors, and civil society, both Consortium Members and External Experts have joined forces with expertise covering the whole value chain including mining, processing, recycling, application. The outputs of MSP-REFRAM will help Europe improve the supply value chain of refractory metals in the coming years, optimising the use of external resources as energy and water and at the same time reducing the amount and the toxicity of waste.

- Alumina/molybdenum nanocomposites obtained by colloidal synthesis and spark plasma sintering (2022)[6]

Alumina/molybdenum nanocomposites were prepared by colloidal synthesis from alumina powder and molybdenum (V) chloride using ethanol as dispersion medium. Modified alumina was calcined at 450 °C in

[4] https://cordis.europa.eu/project/id/890943
[5] https://cordis.europa.eu/project/id/688993
[6] https://www.sciencedirect.com/science/article/pii/S027288422204130X

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air atmosphere to remove chlorides, and then treated in a tubular furnace at 850 °C under Ar/H2 to reduce the MoO3 formed in the previous stage and obtain Al2O3 with molybdenum nanoparticles on the surface. Three different molybdenum contents were proposed (1, 5 and 10 wt % Mo), and pure alumina was used as reference, that were sintered by spark plasma sintering (SPS) under vacuum atmosphere at 1400 °C for 3 min with an applied pressure of 80 MPa. Composites were characterized by microstructure, hardness, toughness, and three-point bending test. The presence of molybdenum nanoparticles resulted in a fine-grained structure promoted by the presence of molybdenum at grain boundaries and triple points, as well as by the utilization of the SPS equipment. Hardness is at least a 20% greater and fracture toughness 30% larger in the composites than in the monolithic alumina.

- A novel method for preparing tungsten and molybdenum peroxy complex solution and its application to tungsten - molybdenum separation (2022)[7]

Aiming at the shortcomings of existing separation technology of tungsten (W) and molybdenum (Mo) by hydrogen peroxide (H2O2) complexation, the chemical behaviors of W(VI) and Mo(VI) in aqueous solutions were studied and a new method for preparing W(VI)-Mo(VI)-H2O2 solution was proposed.

In this work, based on the distribution behaviors of tungsten and molybdenum in the W(VI)-Mo(VI)-H2O system and the complexation properties of tungsten and molybdenum species with hydrogen peroxide, a new method for preparing a W(VI)-Mo(VI)-H2O2 solution was proposed to achieve successful separation of tungsten and molybdenum.

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