SCRREEN2

This project has received funding from the European

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SCRREEN

Solutions for CRitical Raw materials - a European Expert Network

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

BISMUTH

AUTHOR(S):

TABLE OF CONTENT

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BISMUTH

OVERVIEW

Bismuth (Bi) mineralization can occur in various geological settings. Main occurrences are notably in tungsten, copper, gold and lead skarn deposits, as a by-product in tin pegmatites, and in magmatic-hydrothermal mineralization related to granites (Pohl 2011). Bi is usually not recovered when it is in association with more abundant ore metals. With an increasing focus on reducing the consumption of lead globally, bismuth alloys have found roles as efficient substitutes. Its low melting point has increased its use in electronics and its low toxicity makes it ideal for use in food processing equipment and copper water pipes. The medical industry has also found it to be highly effective in X-ray shielding (Masan Resources 2019).

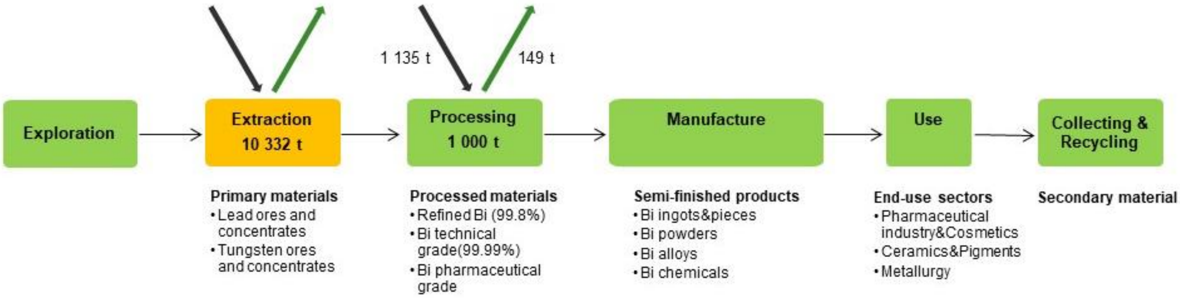

Figure 1. Simplified value chain for bismuth in the EU[1]

Table 1. Bismuth supply (WMD) and demand (EUROSTAT) in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
22,500	China 69% Laos 9% Vietnam 8% Belgium 4% South Korea 4% Japan 2% Mexico 1%	3,858	28%	China 50% Belgium 26% Thailand 9% Laos 5% South Korea 5% Vietnam 3%	71%

Prices: Between 2011 and 2021, the bismuth price has fluctuated. The price reached its peak in 2014 due to the speculative investment of Fanya Non-ferrous Metals Exchange (FYME) which claimed to hold 18,000 tonnes of bismuth (Wilburn et al., 2016). . In 2018 and 2019, the US and China trade war introduced high import tariffs on Chinese bismuth products resulting in less consumption due to expensive trade.

Primary supply: there is no primary production of bismuth. As a by-product, bismuth supply chain is firstly dependent on primary production of lead and tungsten. At the world level, the bismuth supply chain is in large

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

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part relying on Chinese supply of primary refined materials (purity of 99.8% Bi) still containing a lot of impurities. Those materials are massively exported to Europe, North America and South-East Asia for further refining.

Secondary supply: Bismuth is not recycled (MSA, 2019-2020) (SCRREEN workshops 2019). Bismuth is difficult to recycle because it is mainly used in many dissipative applications, such as pigments and pharmaceuticals (Umicore 2019).

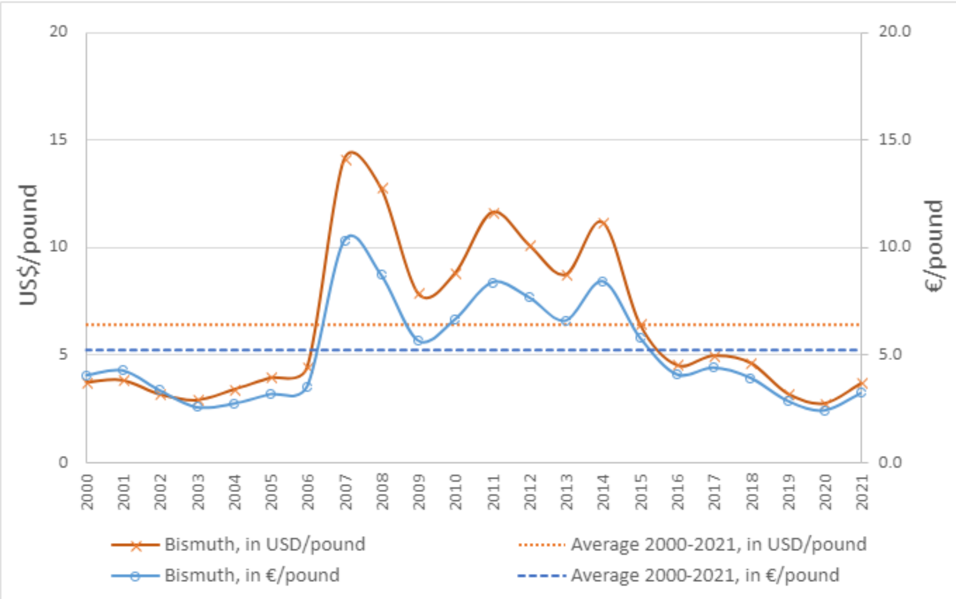

Figure 2. Annual average price of bismuth between 2000 and 2020 (USGS, 2021)[2].

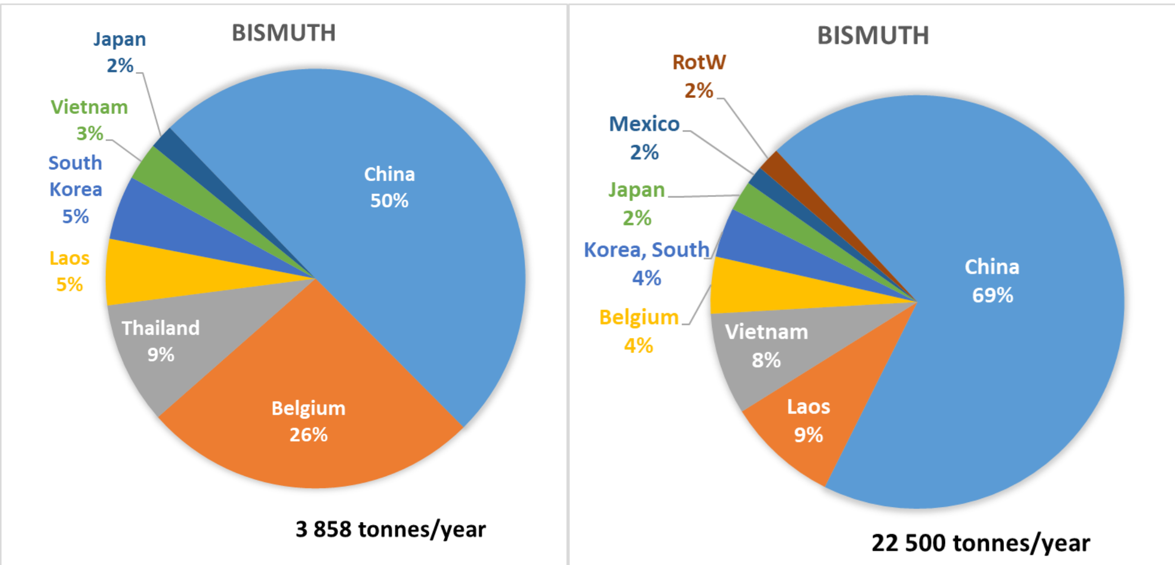

Figure 3. EU sourcing of bismuth and global mine production (2016-2020)

[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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Uses: Bismuth is considered as an "eco-friendly" material. As a result, its first sector of application is in the pharmaceutical and animal-feed industries (80% of total uses for bismuth chemicals). Fusible (low-melting) alloys represent the second most important use. Other uses include metallurgical additives and several other industrial applications such as coatings, pigments, and electronics (Ecclestone 2014).

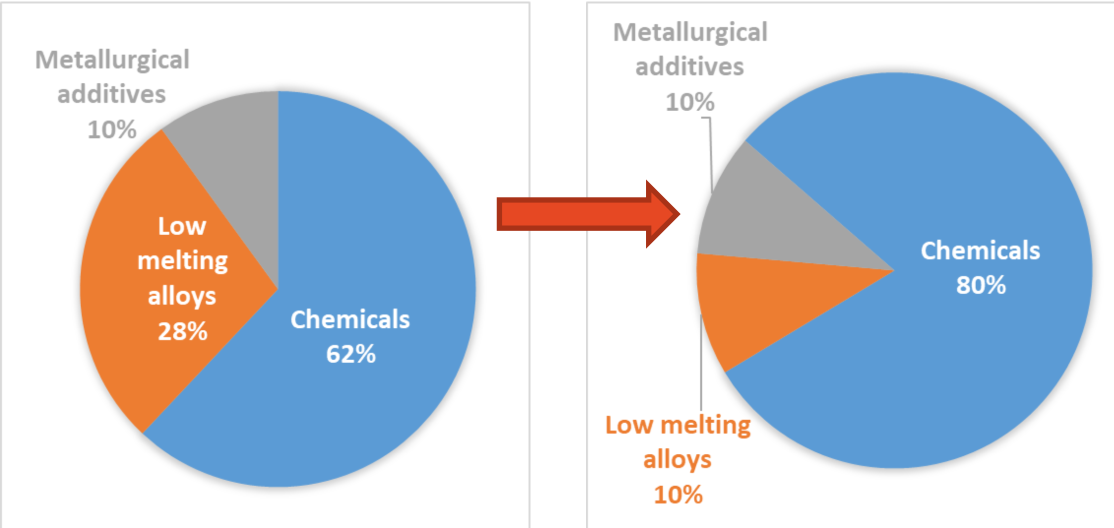

Figure 4: End uses of bismuth. Left chart, data from (Blazy 2013) (SCRREEN workshops 2019) (2012-2016 average figures). Right chart data from EC Draft data 2025-30.

Substitution: Bismuth can be substituted for most of its application. However, it is often at higher cost and reduced performance

Table 2. Uses and possible substitutes

Use	Percentage*	Substitutes	Sub share	Cost	Performance
Chemicals	84%	Alumina, magnesia, calcium carbonate (pharma)	40%	Very high costs (more than 2 times)	Similar
Chemicals	84%	Titanium dioxide-coated mica flakes (pigments)	5%	Slightly higher costs (up to 2 times)	Reduced
Chemicals	84%	Sb trioxide (in plastics as flame retardant)	5%	Very high costs (more than 2 times)	Similar
Low-melting alloys	9%	Cadmium, indium, lead, or tin (in solders)	4%	Very high costs (more than 2 times)	Similar
Low-melting alloys	9%	Lead, selenium, or tellurium (alloys)	5%	Slightly higher costs (up to 2 times)	Reduced
Low-melting alloys	9%	Glycerine-filled glass bulbs	4%	Similar or lower costs	Similar
Metallurgical additives	7%	Resins	10%	Similar or lower costs	Similar

*EU end use share of Bismuth (EU MSA 2020 Report; SCRREEN experts validation, 2022)

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Other issues: According to the Gestis substance database, Bismuth powder has a risk of explosion when in contact with ammonium nitrate, hydrazine nitrate, perchloric acid and heated nitric acid and the LD_{50} is 5000mg/kg (Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung, 2020). According to COMTRADE (2022), the values of bismuth exports remain below 0.1% in each of the exporting countries. In China, the largest tungsten-bismuth deposit has released toxic substances into the environment and therefore negatively impact the health of residents in nearby regions. Song et al (2013) investigated a close relationship between the risk of disease, mortality and proximity to the Suxian District mining industries. Approximately 82.9% of Suxian demonstrate serious soil pollution causing strong ecological risk (Chen, Y. et al., 2018).

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

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

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
22,500	China 69% Laos 9% Vietnam 8% Belgium 4% South Korea 4% Japan 2%	3,858	28%	China 50% Belgium 26% Thailand 9% Laos 5% South Korea 5% Vietnam 3%	71%

Global demand for bismuth is connected to high demand in pharmaceutical applications. Another emerging market could come from the substantial interest in developing new classes of semiconductor, thermoelectric materials, and topological insulators (EC, 2020).
Bismuth occurs naturally in the minerals bismuthinite (sulphide), bismutite (carbonate) and bismite (oxide), but is very rarely extracted as main metal (European Commission, 2020d). The main primary source of bismuth is recovery as a by- or co-product of lead and tungsten extraction and processing, and – though more rarely – from tin and copper ores processing (USGS, 2019). China was reported to hold up to 80% of production of refined bismuth worldwide in 2021 (USGS, 2022). Bismuth is not traded on any metals exchange, and there are no terminal or future markets where buyers and sellers can fix an official price (EC, 2020).

EU TRADE

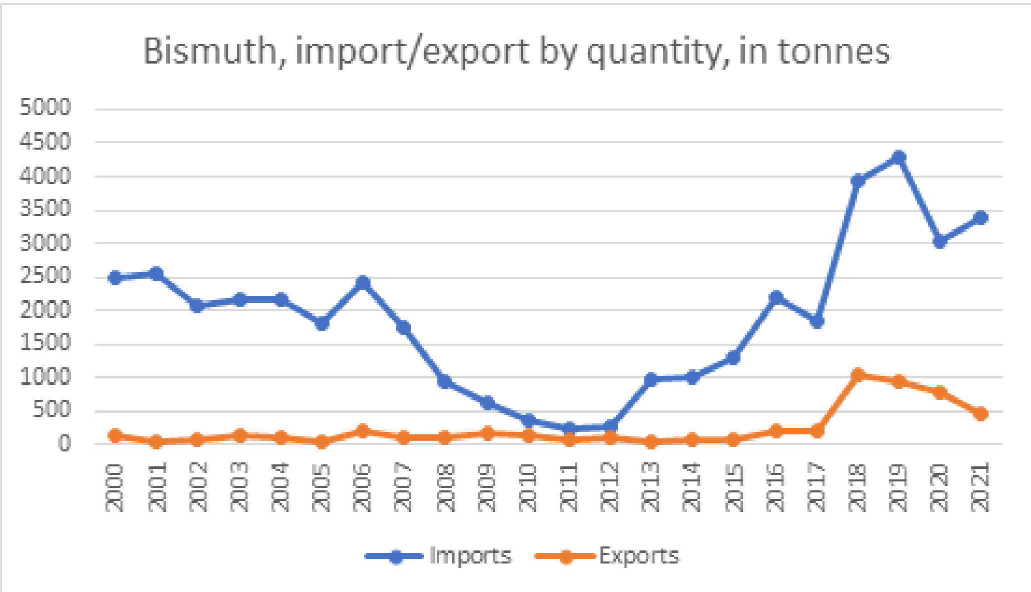

Figure 5. EU trade flows of refined Bismuth (CN 81060010) from 2000 t0 2022 (based on Eurostat, 2022)

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The EU is a net importer of refined Bismuth (99.8% Bi contained, CN8 code CN8 81060010). The average yearly net import of refined Bismuth in the period 2000-2021 was 1901 tonnes while the export was 239 tonnes. There was a continuous decline of the import from 2000 to 2011. The EU import declined from 2482 tonnes in 2000 to 248 tonnes in 2011. From 2012 onwards, the EU imports of refined Bismuth increased from 278 tonnes in 2012 to 3386 tonnes in 2021. The quantity of export increased from 2017 and reached 197 t in 2017 to 1037 t in 2021. These quantities have been calculated based on the data reported in Eurostat database.

China remains the major supplier of Bismuth to the EU with 47% of the total EU imports. Figure 6 suggests that United Kingdom (450 t/year), Mexico (107 t/year) and Thailand (95 t/year) are major suppliers of Bismuth to the EU between 2000 and 2008. The figure for Thailand is questionable since both the USGS and World Mining Data did not report Thailand among one of the major producers of Bismuth in this period. According to the figures in Mineral Statistics of Thailand 2015 – 2019 (Statistics Group Information and Communication Technology Centre Department of Primary Industries and Mines, 2020) the production of Bismuth slime from tin in Thailand jumped from 1 tonne in 2017 (exported to Malaysia), 3 tonnes in 2018 (exported to South Korea), and 710 tonnes only in 2019 (Statistics Group Information and Communication Technology Centre Department of Primary Industries and Mines, 2019). It should also be mentioned that the import from Mexico has been stopped since 2008.

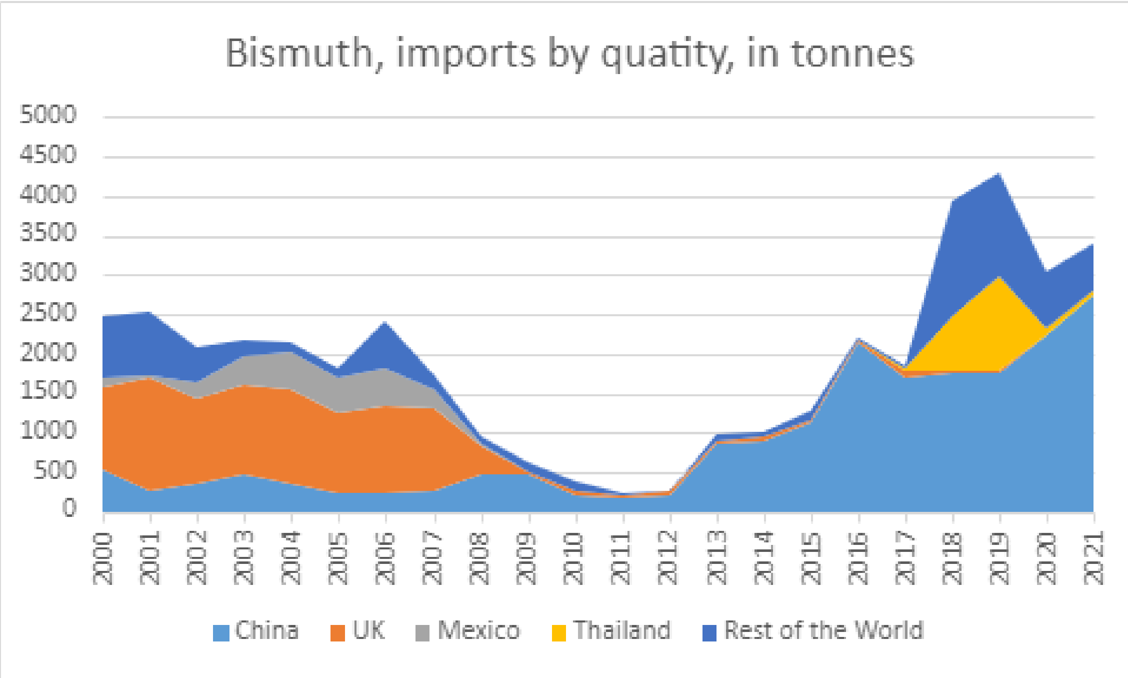

Figure 6. EU imports of Bismuth (CN 81060010) by country between 2000-2021 (based on Eurostat, 2022).

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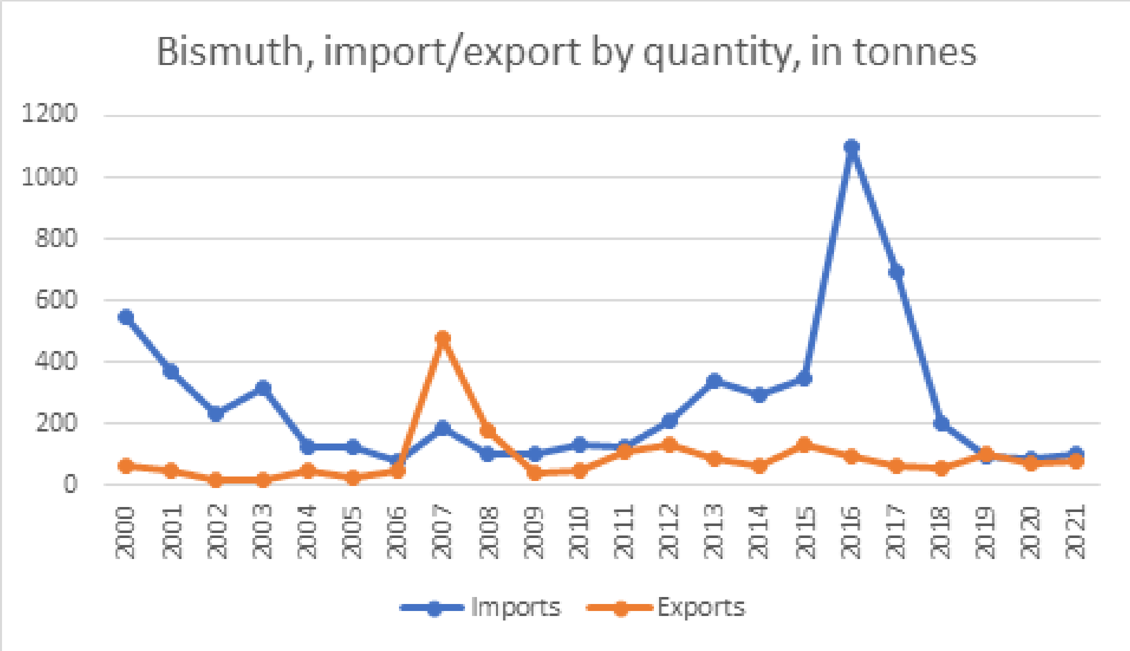

Figure 7. EU trade flows of refined Bismuth (CN 81060090) from 2000 t0 2021(based on Eurostat, 2021)

The EU is also a net importer of Bismuth articles (unspecified, CN8 code 81060090 - Articles of bismuth, n.e.s.) with average yearly import at 269 t and export at 90 t. There has been a decreasing trend of EU import of this commodity, down to the minimum in 2010 to 2012. The major suppliers of Bismuth articles to the EU are the United Kingdom (53%), China (40%) and United States (21%).

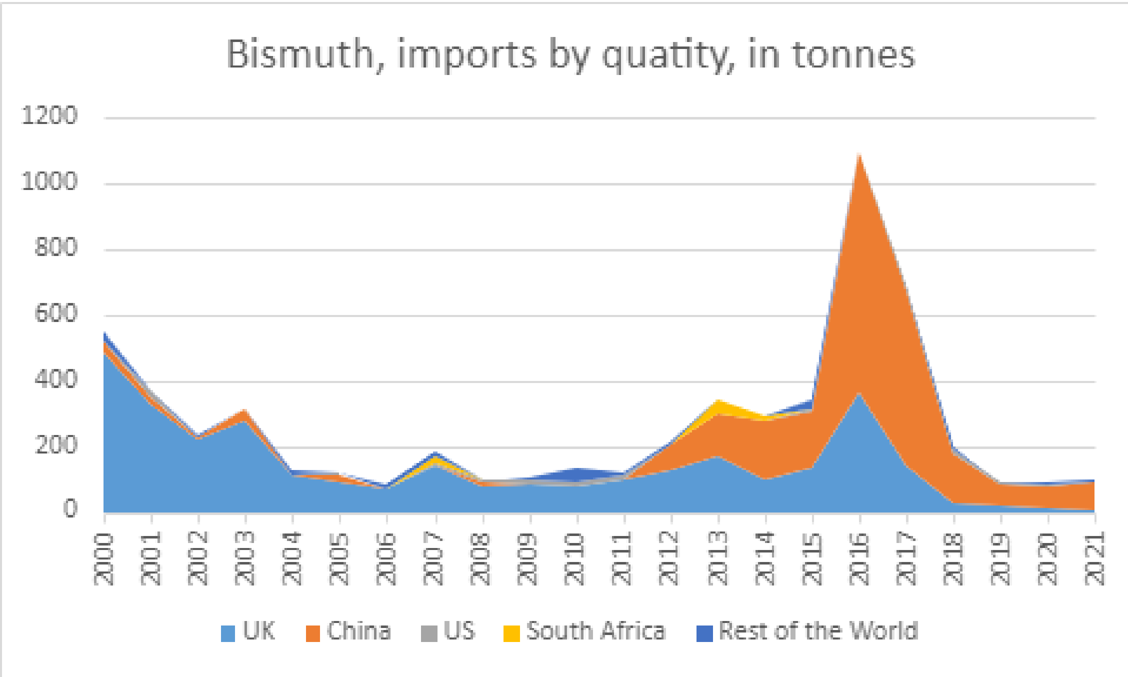

Figure 8. EU imports of Bismuth (CN 81060090) by country between 2000-2021 (based on Eurostat, 2021).

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PRICE AND PRICE VOLATILITY

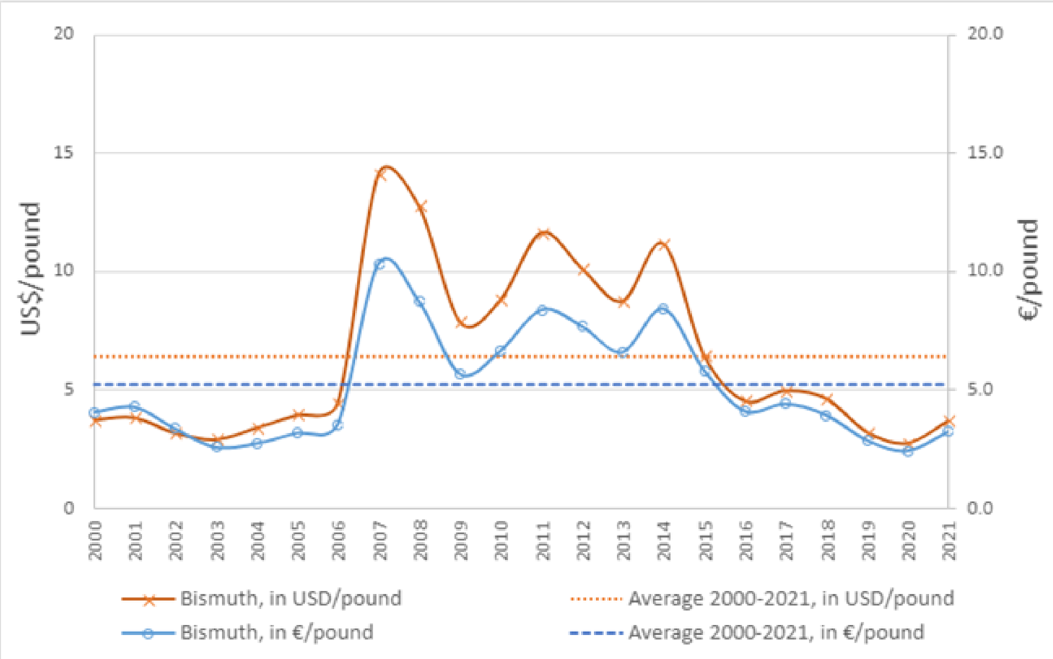

Figure 9. Annual average price of bismuth between 2000 and 2021, in US$/pound and €/pound [3]. (USGS, 2022)

Bismuth price reached its peak in 2007 due to the speculative investment of Fanya Non-ferrous Metals Exchange (FYME) which claimed to hold 18,000 tonnes of bismuth (Wilburn et al., 2016). This tightened supply and encouraged an increase in demand. In 2018 and 2019, the US and China trade war introduced high import tariffs on Chinese bismuth products resulting in less consumption due to expensive trade. To stimulate the demand in exports, suppliers lowered the prices even further and the price has not recovered since then (USGS, 2022). The impacts of the COVID-19 pandemic which slowed down the economies of both China and the US also worsened the situation (USGS, 2022). The bismuth price in Europe has fallen close to the cost of production, and main suppliers were operating at very low margins (Fastmarkets, 2019).

MARKET OUTLOOK

On the supply side, Fortune Minerals Ltd. in Canada (London, Ontario) with NICO gold-cobalt-bismuth-copper mine Project in the Northwest Territories (NWT) Canada has received environmental assessment approval and the major mine permits for the facilities. The Company has completed a Socio-Economic Agreement with the NWT Government (Fortune Minerals, 2021). Bismuth output from this project was expected to be 1,700 t/y of bismuth (EC, 2020). Fortune Minerals will conduct a review of the existing process data and metallurgical test work for the bismuth circuits (Fortune Minerals, 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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DEMAND

The European apparent consumption of bismuth in the period 2012-2016 is estimated at 1,985 tonnes per year. For 2019-2020, the apparent average EU consumption of bismuth is 4,277 tonnes per year.

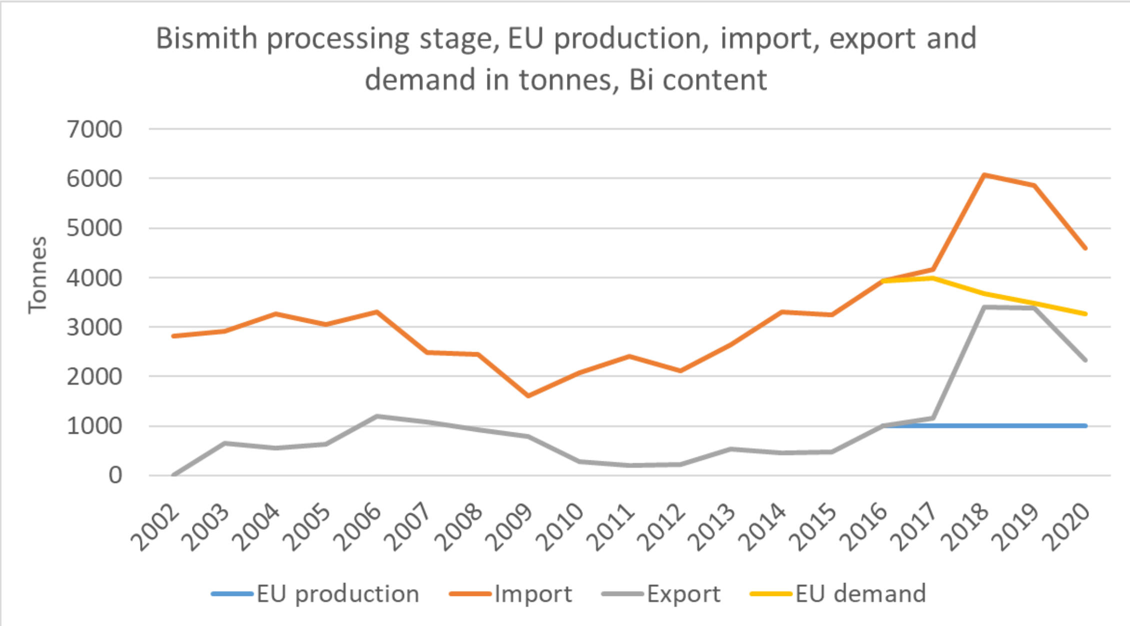

Figure 10. Bismuth (CN 81060000) processing stage apparent EU consumption. Production data from DG-Grow. Import and export data from Eurostrat. EU demand = EU production+import-export.

Bismuth processing stage EU consumption is presented by HS codes CN 810600 bismuth and CN 81011000 unwrought bismuth. Import and export data is extracted from UNComtrade (2021) for CN 810600 bismuth. Production data is extracted from Eurostat Prodcom (2021) for unwrought bismuth using PRCCODE 24453031 and WMD (2021) for bismuth.

The average import reliance of bismuth at processing stage is 71 % for 2016-2020.

EU USES AND END-USES

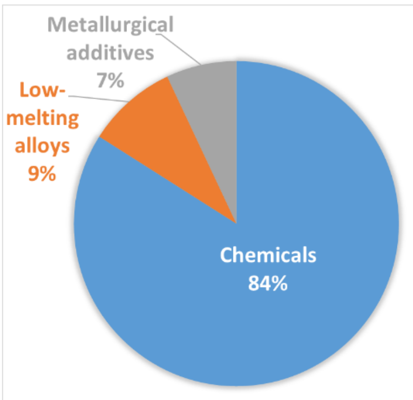

Figure 11. End uses of bismuth - 2016-2020 averages (EU MSA 2020 Report) SCRREEN validation WS, 2022)

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Relevant industry sectors are described using the NACE sector codes (Eurostat 2022).

Table 4. Bismuth applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat 2022).

Applications	2-digit NACE sectors	Value added of NACE 2 sectors (M€) 2019	4-digit NACE sectors
Chemicals	C20 - Manufacture of chemicals and chemical products	117,150*	C2029 - Manufacture of other chemical products n.e.c.
Low melting alloys	C32 – Other manufacturing	65,757 (inc. C31)	C3290 - Other manufacturing n.e.c.
Metallurgical alloys	C24 - Manufacture of basic metals	63,700	C2431 – Casting of iron

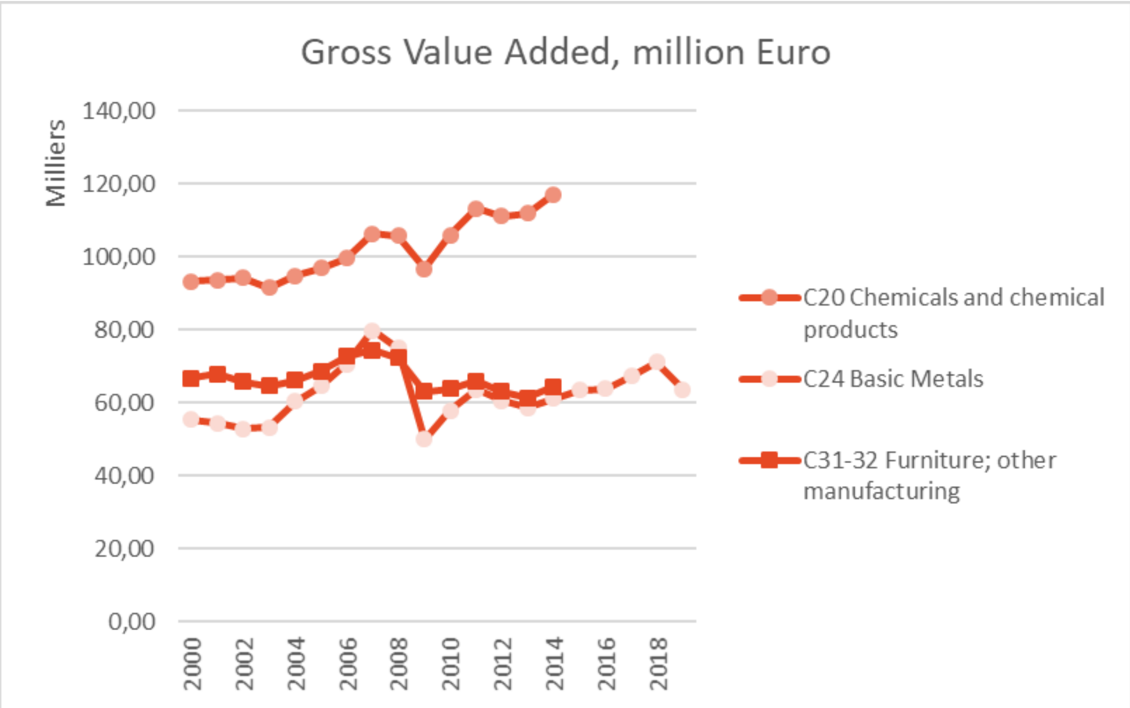

Figure 12. Value added per 2-digit NACE sector over time (Eurostat, 2022)

APPLICATIONS OF BISMUTH IN THE EU:

CHEMICALS

Bismuth is considered as an "eco-friendly" material.

As a result, its first sector of application is in the pharmaceutical and animal-feed industries (80% of total uses for bismuth chemicals). In modern medicine, compounds of bismuth are mainly applied clinically for gastrointestinal disorders as anti-ulcer agents. Examples are De-Nol and Pepto-Bismol used to treat and prevent gastric and duodenal ulcers. The use of bismuth (III) is also seen in nuclear medicine, anticancer, antitumor and antimicrobial studies (Yang 2007).

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LOW-MELTING ALLOYS

Fusible (low-melting) alloys represent the second most important use.

Bismuth is used as a replacement for more harmful metals (on top of which is lead) in solders.

METALLURGICAL ADDITIVES

Other uses include metallurgical additives and several other industrial applications such as coatings, pigments, and electronics (Ecclestone 2014).

With an increasing focus on reducing the consumption of lead globally, bismuth alloys have found roles as efficient substitutes. Its low melting point has increased its use in electronics and its low toxicity makes it ideal for use in food processing equipment and copper water pipes. The medical industry has also found it to be a highly effective in X-ray shielding (Masan Resources 2019).

SUBSTITUTION

Table 5. Potential substitution options for bismuthin main uses

Use	Percentage*	Substitutes	Sub share	Cost	Performance
Chemicals	84%	Alumina, magnesia, calcium carbonate (pharma)	40%	Very high costs (more than 2 times)	Similar
Chemicals	84%	Titanium dioxide-coated mica flakes (pigments)	5%	Slightly higher costs (up to 2 times)	Reduced
Chemicals	84%	Sb trioxide (in plastics as flame retardant)	5%	Very high costs (more than 2 times)	Similar
Low-melting alloys	9%	Cadmium, indium, lead, or tin (in solders)	4%	Very high costs (more than 2 times)	Similar
Low-melting alloys	9%	Lead, selenium, or tellurium (alloys)	5%	Slightly higher costs (up to 2 times)	Reduced
Low-melting alloys	9%	Glycerine-filled glass bulbs	4%	Similar or lower costs	Similar
Metallurgical additives	7%	Resins	10%	Similar or lower costs	Similar

*EU end use share of Bismuth (EU MSA 2020 Report; SCRREEN experts validation, 2022)

Substitutes exist for bismuth in many applications, primarily for its non-toxicity as a replacement for already existing materials (metals).

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CHEMICALS

In pharmaceutical applications, bismuth can be replaced by alumina, calcium carbonate, and magnesia.

In pigment uses, it can be replaced by titanium dioxide-coated mica flakes or fish-scale extracts, and in devices such as fire sprinklers, by glycerine-filled glass bulbs.

LOW-MELTING ALLOYS

Free-machining alloys can contain lead, selenium, or tellurium as a replacement for bismuth (USGS 2019).

METALLURGIC ADDITIVES

Resins can replace bismuth alloys for holding metal shapes during machining.

SUPPLY

EU SUPPLY CHAIN

As a by-product, bismuth supply chain is firstly dependent on primary production of lead and tungsten. At the world level, the bismuth supply chain is in large part relying on Chinese supply of primary refined materials (purity of 99.8% Bi) still containing a lot of impurities. Those materials are massively exported to Europe, North America and South-East Asia for further refining.

Chinese control of the first steps of the bismuth market is an important aspect of this metal’s criticality. China became one of the only producers of bismuth by reducing costs of production and increasing capacities in the early 2000s. In 2007, China announced the consolidation of the sector by the merging of six Hunan bismuth producers accounting for 30% of China's refined bismuth metal production in a single consortium (Hunan Bismuth Industry Co). This was done in response to the merging of the two largest players in Europe (MCP Aramayo Ltd in the UK and Sidech SA in Belgium to create MCP group, then acquired in 2011 by Canada's 5N Plus). Also, China announced the reduction of production due to environmental and mine safety issues, together with export restrictions. It succeeded in its objective to tighten supply to the rest of the world and become by far the leading producer in the following years.

In the EU, several companies are active in high added-value bismuth applications, for instance:

- 5N Plus, which controls around 50% of the bismuth market and specialty products (refined bismuth, bismuth chemicals, and low melting point alloys) and which subsidiary in Belgium is among the largest world importers of Bi (5N Plus, 2015).
- BASF, which is one of Europe's largest producers of bismuth vanadate ($BiVO_4$), a key pigment for use in coatings and paints.

The average amount of bismuth imports in EU between 2016 and 2020 were about 3360 tonnes, while an average production of bismuth, by non-primary resources, around 1350 tonnes in the years 2019 and 2020 is recorded (Eurostat, 2020). A minor primary Bi production, in the range of few tonnes, was taking place until 2011 in Bulgaria (WMD, since 1984).

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GEOLOGY, MINING AND PROCESSING OF BISMUTH

GEOLOGICAL OCCURRENCE

Bismuth mineralization can occur in various geological settings. Main occurrences are notably in tungsten, copper, gold and lead skarn deposits, as a by-product in tin pegmatites, and in magmatic-hydrothermal mineralization related to granites (Pohl 2011). Bi is usually not recovered when it is in association with more abundant ore metals. The main deposit types where significant Bi mineralization occurs are:

- Skarn
- Granite-related vein and greisen
- Reduced intrusion-related Au-Bi
- Porphyry-related
- Iron oxide copper gold (IOCG)
- Pegmatite
- Five-element vein (Co-Ni-Bi-Ag-As ± U)
- Orogenic gold
- Volcanogenic Massive Sulphide (VMS): modern and ancient
- Sediment-hosted copper

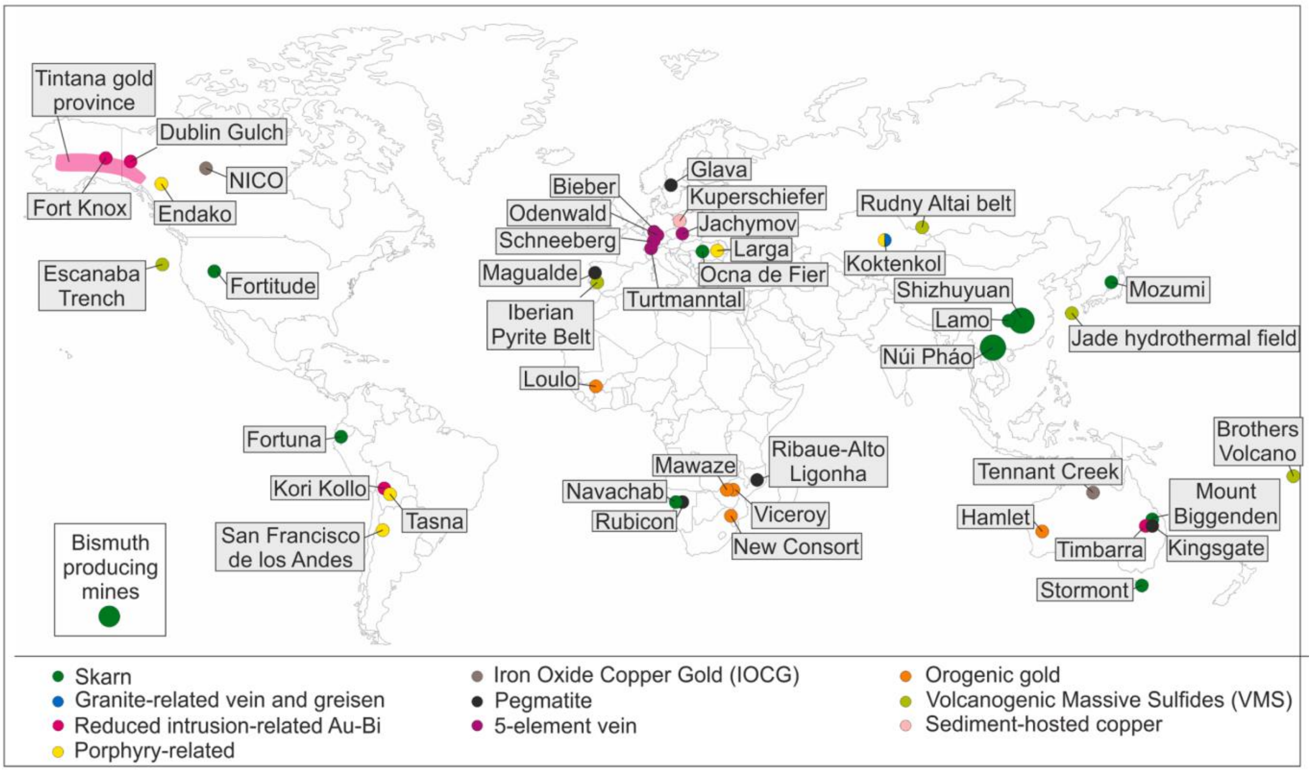

Figure 13. The distribution of Bi deposits and occurrences worldwide in respect to their geologic environment (Deady et al. 2022).

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The most elevated concentrations of bismuth (up to 10 wt.%) are observed in skarn, epithermal and porphyry-related deposits. The distribution of Bi deposits and occurrences worldwide in respect to their geologic environment is presented in Figure 13 (Deady et al. 2022).

As a by-product, extraction methods depend on the type and mineralogy of the ore. Bismuth has been mined as a main product only in the Cerro Tasna mine (Bolivia) and also in China (Shizhuyuan). In China, artisanal mining for bismuth also exists, with manual separation of bismuth-rich mineralization contributing significantly to global production of concentrates (Blazy 2013). The two main sources for the recovery of bismuth metal are known to be lead and tungsten extraction and processing, with 50 to 60% coming from lead processing according to industry experts. Minor recovery of bismuth can also come from metallurgy of tin and copper, for instance in Japan, although in most cases it is seen as a penalizing impurity in those treatments (Blazy, 2013; Krenev, 2015; SCRREEN workshops 2019).

GLOBAL RESOURCES AND RESERVES

Table 6. Global reserves of bismuth (Data from USGS, 2017)

Country	Reserves (tonnes of contained Bi)
China	240 000
Vietnam	53 000
Mexico	10 000
Bolivia	10 000
Canada	5 000
Other countries	50 000
Total	*368 000*

For reserves, the only reference at the global level is from USGS (USGS 2017) (Table 6). However, these estimations have been unchanged for many years (except for Vietnam) and are likely to be incomplete since they are based on bismuth content of lead ores only, forgetting bismuth content in copper and tungsten ores. There are no updated data concerning Bi reserves worldwide according to USGS.

EU RESOURCES AND RESERVES*:*

During the Minerals4EU (2019) project, resources of bismuth were reported only in Bulgaria in the category "No statistical data available but resources known or believed to exist". Exploration projects were mentioned in Portugal and Slovakia with no further information.

WORLD AND EU MINE PRODUCTION

Regarding mine production, China is the main producer in the world, although figures vary according to different sources (BGS, 2018; USGS, 2016; WMD 2019), partly due to the difficulty of assessing the part of artisanal production. Another important producer is Vietnam, where commercial production of bismuth concentrates started in September 2014 at the Nui Phao mine. Objectives of the company are to produce 2,000 t per year and to become the second most important producer in the world (Masan Resources 2019). Once can notice that neither WMD nor USGS report the Belgian production, estimated at 1000 tonnes/year.

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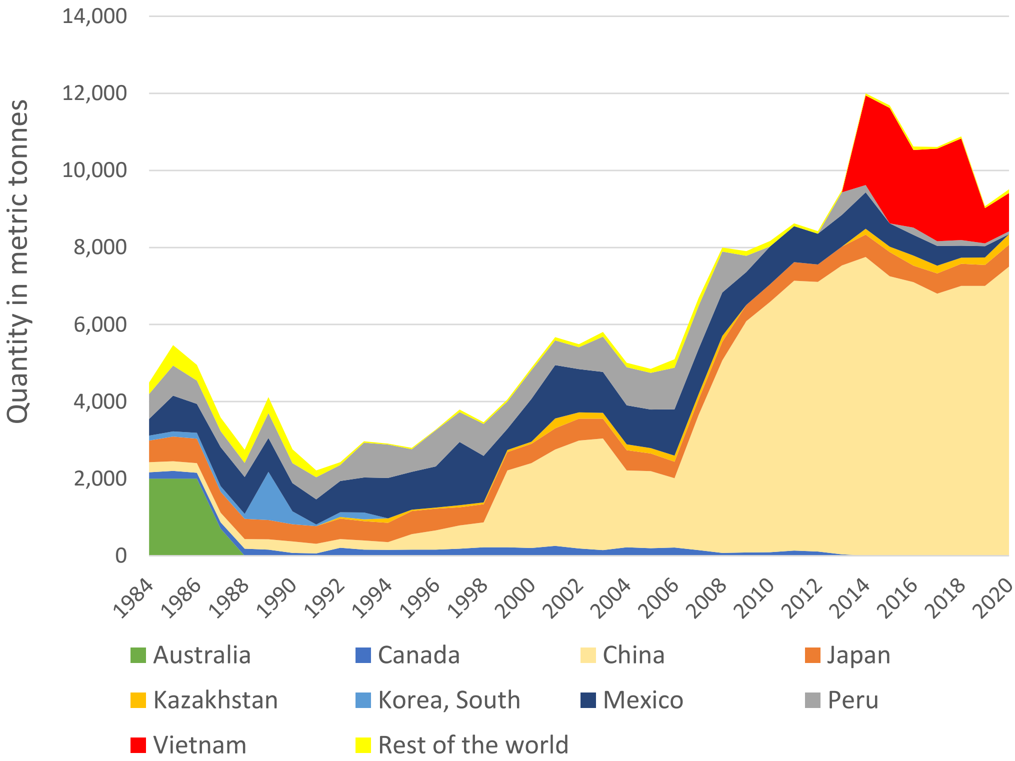

Figure 14. Global elemental bismuth production since 1984 (WMD, since 1984).

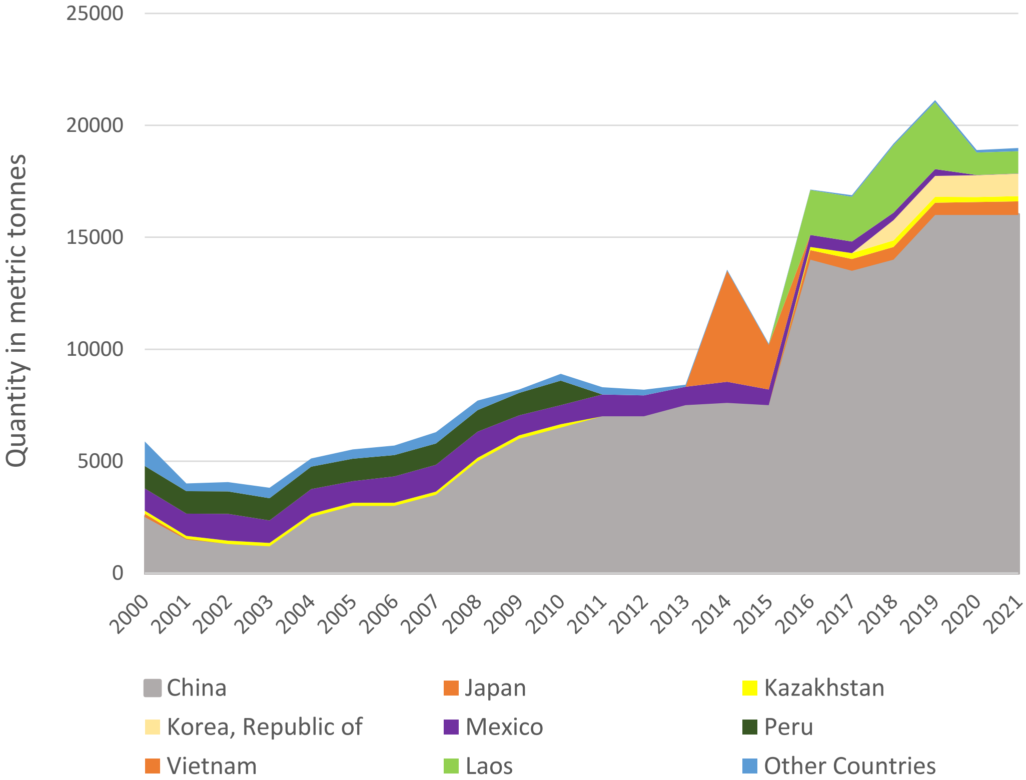

Figure 15. Global elemental bismuth production since 2000 (USGS, since 2000).

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The distortion of the bismuth market due to speculative investment in the Fanya Minor Metal Exchange in China impacted the bismuth production. Fanya began trading bismuth in March 2013 and accumulated huge stocks of the metal in a 2-year period. In November 2014, bismuth stocks were reported to reach 16,900 t for about 2 years of world production equivalent (Wilburn et al., 2016). The consequences were a dramatic fall of prices and a stronger constraint on current producers.

In Europe, BGS Mineral Statistics mention mine production in Bulgaria of 3 t in 2013. Bismuth is produced in Bulgaria as a Lead-Bismuth alloy (7% Bi content) by the Bulgarian smelter KCM 2000 Group (KCM 200 Group 2019). EU Production of a Lead-Bismuth alloy (6-12% Bi content) is also sited in Germany and produced by Aurubis (Aurubis 2019) (CRM experts 2019). The world annual production of mined bismuth in average between 2012 and 2016 is around 10,332 t of bismuth content, mainly in China (WMD 2019). The elemental bismuth production by primary resources according to WMD since 1984 is presented in Figure 14 (WMD, since 1984). As it can be easily observed, bismuth production is taking place in a limited number of countries including: China, Vietnam, Japan, Kazakhstan and Peru. Bismuth production in China represents the 79% of the global production.

OUTLOOK FOR SUPPLY

Bi demand has been decreased since 2000 as buyers were reportedly stockpiling bismuth while prices were relatively low compared with previous higher prices (USGS, since 2000). China and Vietnam are the major producers. In China Bi production is performed as a by-product from refining lead ores, while in Vietnam Bi occurs in wide range of geological deposits, global production is currently concentrated at the Núi Pháo mine in Vietnam, where it is a primary commodity. This status is not expected to change in short term. However, it has been identified that the geological availability of bismuth, which in fact is far greater than previously understood. Therefore, bismuth production could be increased in medium term through the exploitation of deposits so far not exploited worldwide and through the adaptation of metallurgical processes in Bi extraction among other co-existing metallic values the respective ores (Deady et al. 2022).

REFINING OF BISMUTH

“Refined bismuth” refers to the bismuth metal of a purity of at least 99.8%, in opposition to “Bi mine production” referring to bismuth sulphide concentrates quantities. However, confusions are often made between these two categories when considering global bismuth production (BGS, 2018; WMD 2019; USGS, 2016). Furthermore, as for many other minor metals, obtaining production figures for bismuth is quite difficult because of the opaque nature of the market and its size.

The criticality assessment was performed at the refining stage because of the import reliance of the EU on refined bismuth products. There are only a few producers in the world at this stage. The main one is in China, responsible for 80% of total world production (19,183 t), the main company being Hunan Jinwang Bismuth Industrial Co Ltd (www.en.jin-wang.com.cn) with capacities of 8,000 t.

In the EU, the company 5N Plus is a huge player on the bismuth market and specialty products (refined bismuth, bismuth chemicals, and low melting point alloys) and has a subsidiary in Belgium. DERA (2015)

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reports 1,000 t of bismuth metal produced in Belgium over 2012-2014. Belgium bismuth metal production is supplied from various EU producers manily, i.e. Umicore in Belgium, Aurubis Cu plant in Germany, Boliden in Sweden and for some years from the Nui Phao mine in Vietnam (BGR 2019).

Refining is needed to obtain bismuth metal of a purity of at least 99.8%. Most of the time, the thermal route is preferred. During this process, caustic soda and potassium nitrate are added to the molten bismuth to remove impurities (As, Sb, Se, Te, Sn). An addition of zinc metal can be necessary when impurities include copper, silver and gold (Blazy 2013). Final treatment with soda ash can bring purity to 99.99% Bi (technical grade). Others processes exist depending on the nature of the impurities and the required quality of final products. Electrolytic refining is preferred to obtain higher purity, up to 99.999% (pharmaceutical grade). Bismuth can be commercialised in the form of high purity ingots, pieces, pellets, or even as powdered oxide. The produced amount of refined bismuth worldwide according to USGS data since 2000 is displayed in Figure 15 (USGS, since 2000). As it can be observed, this amount is elevated in comparison to WMD data referred to the raw primary production (Figure 15).

RECOVERY AS A BY-PRODUCT OF LEAD EXTRACTION

During the production of high purity lead from primary sources, two cases can be distinguished (Blazy 2013):

- If the bismuth content of lead bullion is higher than 4%, the electrolytic route is preferred (Betts process). Bismuth is recovered from the impure mixture of metals left in the residual anode slimes. The slime is heated, and bismuth is finally recovered after a reduction step using carbon. Concentration reaches 70-75% bismuth;
- If the bismuth content is 0.05-3.5%, the thermal route is preferred (Kroll-Betterton process). It is based on the precipitation of bismuth using calcium and magnesium which are added to molten lead. Concentration reaches 15-40% bismuth.

RECOVERY AS A BY-PRODUCT OF TUNGSTEN EXTRACTION

Not much is known concerning Chinese operations to recover bismuth from tungsten. An important part comes from artisanal mining and uses standard gravity concentration equipment including jigs and shaking tables. At the industrial scale, one example is the Xihuashan plant, where the ore is composed of scheelite, wolframite, cassiterite, bismuthinite, molybdenite, copper sulphides and REE-bearing minerals. A commercial concentrate of bismuthinite is obtained through various flotation processes and sold for further transformation (Blazy 2013). In Vietnam, first commercial production of bismuth concentrates occurred in September 2014 at the Nui Phao mine. These concentrates are also obtained through bismuth flotation, followed by leaching and cementation (Masan Resources, 2015).

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

Bismuth is not recycled (MSA, 2019-2020) (SCRREEN workshops 2019). Bismuth is difficult to recycle because it is mainly used in many dissipative applications, such as pigments and pharmaceuticals (Umicore 2019).

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Table 7 Material flows relevant to the EOL-RIR of Bismuth

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	800.00
C.1.3 Imports to EU of primary material	3000.00
C.1.4 Imports to EU of secondary material	0.00
D.1.3 Imports to EU of processed material	1134526.00
E.1.6 Products at end of life in EU collected for treatment	0.00
F.1.1 Exports from EU of manufactured products at end-of-life	0.00
F.1.2 Imports to EU of manufactured products at end-of-life	0.00
G.1.1 Production of secondary material from post consumer functional recycling in EU sent to processing in EU	0.00
G.1.2 Production of secondary material from post consumer functional recycling in EU sent to manufacture in EU	0.00

OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES

Some Bismuth compounds (e.g. Pyrochlore, bismuth cadmium ruthenium, Bismuth, compound with nickel (1:1), Dibismuth tris (methyl arsenate) can be found restricted under REACH Regulation (EC) No 1907/2006 Annex XVII (Registration, Evaluation, Authorisation and Restriction of Chemicals). According to the Gestis substance database, Bismuth powder has a risk of explosion when in contact with ammonium nitrate, hydrazine nitrate, perchloric acid and heated nitric acid and the LD_{50} is 5000mg/kg (Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung, 2020).

The European GHS Classification and Labeling, states that in the case of fire while using Bismuth powder dry powder or dry sand should be used to extinguish it (Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung, 2020). In addition, Bismuth compounds such as Bismuth (III) chloride may cause skin and eye irritation and therefore warning symbols should be clearly labelled when being used (Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung, 2020). The mass per unit volume of 0.15 g/m3 in the exhaust gas is not allowed to be exceeded also on observance or lower deviation of a mass flow of 0.20 kg/h (Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung, 2020). The emissions of dust in the exhaust gas are not allowed to exceed a mass flow of 0.20kg/hr or mass concentration of 20 mg/m^3. Bismuth compounds are not subjected to any transportation regulation (Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung, 2020).

The Occupational Safety and Health Administration of the United States Department of Labour determines that the permissible exposure limit for Bismuth telluride (Bi2Te3, SE doped) is 5 TWA (time-weighted averages

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value of exposure over the course of an 8-hour shift) with a gravimetric factor of 1.916 (Occupational Safety and Health Administration of the United States Department of Labor 2002).

ENVIRONMENTAL ISSUES

No LCA or other studies could be found related to environmental issues at any life cycle stage or specific use of the material.

STANDARDS AND NORMATIVE REQUIREMENTS

The following Technical rules for hazardous substances apply to Bismuth compounds:
1. TRGS 500 - Protective measures; September 2019 edition.
2. TRGS 510 - Storage of hazardous substances in portable containers; Issue January December 2020
3. TRGS 720 - Dangerous explosive mixtures - General; Edition July 2020, last corrected March 2021
4. TRGS 723 - Hazardous explosive mixtures - avoidance of ignition of hazardous explosive mixtures; Edition July 2019, last changed October 2020
5. TRGS 724 - Hazardous, explosive mixtures - Measures of constructive explosion protection, which limit the effects of an explosion to a harmless level, July 2019 edition.

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF BISMUTH FOR EXPORTING COUNTRIES

According to COMTRADE (2022), the values of bismuth exports remain below 0.1 % in each of the exporting countries.

SOCIAL AND ETHICAL ASPECTS

In China, the largest tungsten-bismuth deposit have released toxic substances into the environment and therefore negatively impact the health of residents in nearby regions. Song et al (2013) investigated a close relationship between the risk of disease mortality and proximity to the Suxian District mining industries (Song et al, 2013). Approximately 82.9% of Suxian demonstrate serious soil pollution causing strong ecological risk (Chen, Y. et al., 2018).

RESEARCH AND DEVELOPMENT TRENDS

LOW-CARBON AND GREEN TECHNOLOGIES (LCGT)

EU-projects BiREDOX[4] (2019 – 2021), Let-it-Bi[5] (2020 - 2025), Bismuth Goes Radical[6] (2021 – 2026)

[4] See https://cordis.europa.eu/project/id/833361
[5] See https://cordis.europa.eu/project/id/850496
[6] See https://cordis.europa.eu/project/id/946184

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Bismuth represents an attractive element for the development of catalytic alternatives that secure sustainable and environmentally friendly approaches for organic synthesis. Despite the wide range of bismuth salts capable of performing organic transformations, their ability to participate in catalytic redox processes is largely unknown. The project aims at the rational design of novel bismuth complexes to be engaged in catalytic Bi(III)/Bi(V) redox processes for organic synthesis with a greener alternative to the scarce and expensive metals typically used in catalysis.

OTHER R&D TRENDS

- Atom manipulation in silicon[7], ATMEN[8] project (2017 – 2022, EU)

In the race for quantum supremacy, scientists have been exploring, among others, the solid-state qubit, which is the basic unit of quantum information processing. To make a qubit, the industry's technological achievements in silicon manufacturing to date, as well advantages based on the properties of silicon itself, have focused attention on the nuclear spins of positively charged donor atoms inside crystalline silicon. A major obstacle in the construction of a qubit is the precise positioning of donor impurities, called dopants, that are added in tiny amounts to alter silicon's properties. An international research team studied the behaviour of phosphorus, arsenic, antimony and bismuth in silicon under electron irradiation and discovered a non-destructive way to move dopant atoms in a silicon lattice with atomic precision. With the first proof-of-principle manipulation of bismuth dopants in silicon, the findings are possibly a key to the manufacture of solid-state qubits.

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[7] See https://cordis.europa.eu/article/id/435185-atom-manipulation-in-silicon-dances-to-the-tune-of-an-atomic-waltz

[8] See https://cordis.europa.eu/project/id/756277

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