SCRREEN2

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

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FACTSHEETS UPDATES BASED ON THE EU FACTSHEETS 2020

ANTIMONY

AUTHOR(S):

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ANTIMONY

OVERVIEW

Antimony (chemical symbol Sb) is a soft, lustrous, silver-grey metalloid. It is stable in air at room temperature, but reacts with oxygen when heated to form antimony trioxide (Sb_2O_3). It has a relatively low melting point of 630°C and a density of 6.697 g/cm^3. Antimony is rare in the Earth's crust having a (upper) crustal abundance of only 0.4 ppm (Rudnick and Gao, 2003). Antimony is found in over 100 different mineral species, typically in association with elements such as mercury, silver and gold. The principal ore mineral of antimony is stibnite (Sb_2S_3).

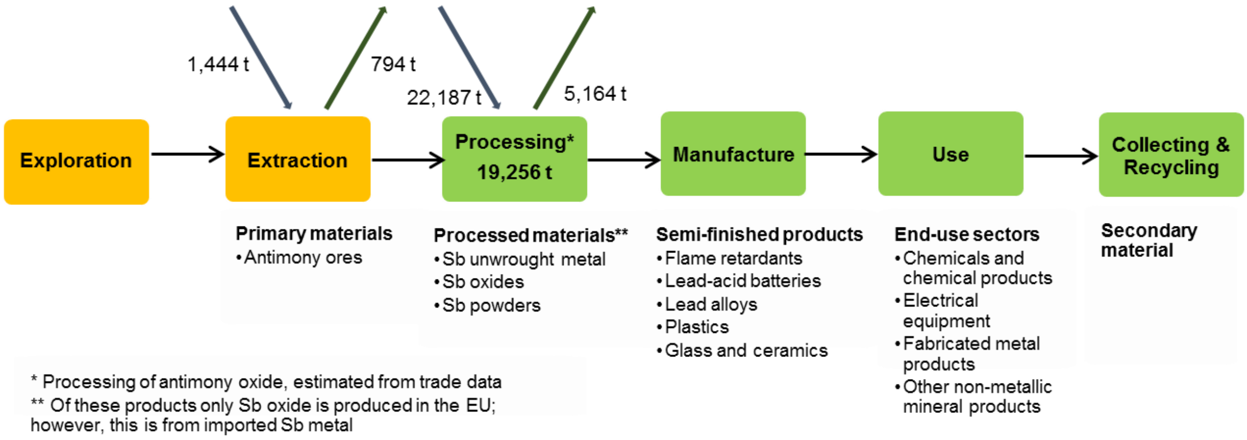

Figure 1. Simplified value chain for antimony in the EU[1]

Table 1: Antimony supply and demand at extraction stage in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
142,347	China 56% Tajikistan 20% Russia 12 % Myanmar 3% Turkey 2% Australia 2% Bolivia 2%	1,095	0,8%	Turkey 66% Bolivia 27% Guatemala 4% China 3%	100%

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

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Table 2: Antimony supply and demand at the processing stage in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
101,586	China 52% Belgium 9% France 6% Vietnam 7% Myanmar 4% Thailand 4%	40,527	40%	China 30% Belgium 21% France 15% Tajikistan 9% Vietnam 7% Spain 4% South Korea 4% Germany 2% Thailand 2%	47%

Prices: Antimony prices have declined from 2011 to 2015. Reports indicated that elevated producer stocks in China and lower–than-expected consumption in Europe contributed to the price decline (USGS, 2022b). In 2016 and 2017, in China many large-scale producers reduced production and many small-scale producers closed in response to price declines. Part of the decline in price has come from the growing volumes of stocks sold by Chinese large-scale producers of ingot and trioxide since the end of 2018 (EC, 2020). From 2017 to 2020, antimony prices remain stable.

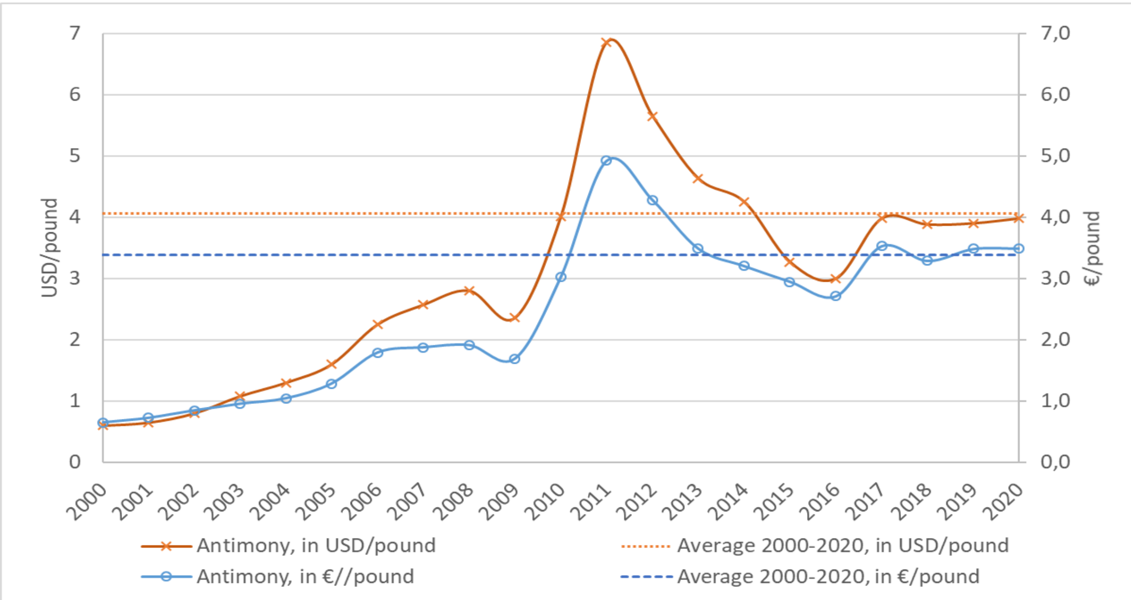

Figure 2. Annual average price of antimony between 2000 and 2020 (USGS, 2021)[2].

Primary supply: According to the WMD (2022), global mine production of antimony in period 2016-2020 showed decreasing trend and ranged between 164.000 t (2016) and 132.000 t (2020). China was the largest supplier of the antimony ores and concentrates, producing between 103.000 t (2016) and 61.000 t (2020) or approximately 63 % of world production in 2016 and 46% of world production in 2020. The only countries that

[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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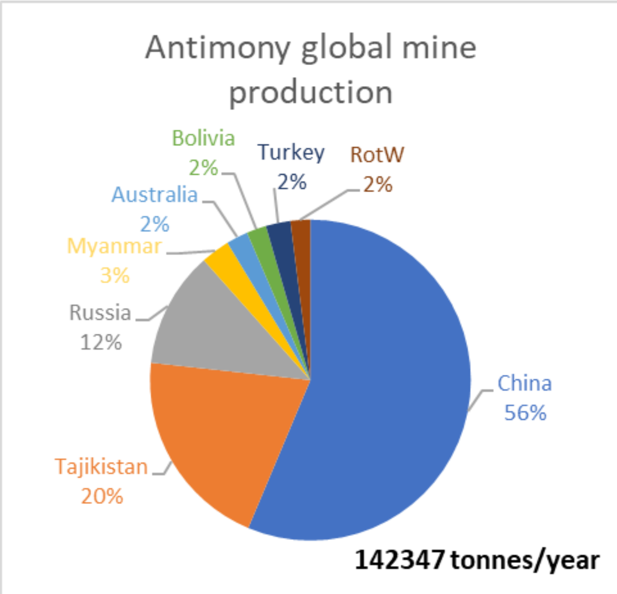
increased their production in period 2016-2020 are Tajikistan with average 5-year production of 29.000 t and Russia with average 5-year production of 17.000 t. Tajikistan and Russia are also the second and the third most important producers of antimony. There is no primary production of antimony ores or concentrates in the EU.



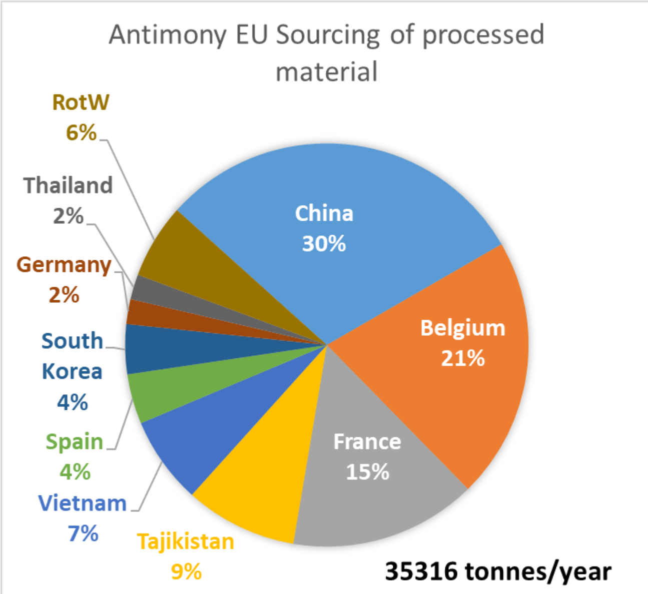


Figure 3: Global mine production of antimony and EU sourcing of processed antimony from third countries

Secondary supply: The global end-of-life (EoL) recycling rate for antimony is estimated to be between 1 and 10% (UNEP, 2013). The Raw Materials Supply Assessment (RMSA) study, undertaken by BIO by Deloitte in 2015, suggests that the EoL recycling rate in the EU for antimony is as high as 28% (BIO by Deloitte, 2015). Secondary antimony is chiefly recovered from lead-acid batteries. Therefore, the availability of secondary antimony is almost entirely dependent on the extent of lead recycling and the market conditions for lead and lead-acid battery scrap.

Uses: Around 43% of antimony (in the form of antimony trioxide, or ATO) is used in flame retardancy. Antimonial (or hard-lead alloys) are used in the manufacture of lead-acid batteries, accounting for about 32% of global antimony consumption. Around 6% of antimony, in the form of antimony trioxide (ATO), is used as a catalyst in the production of polyethylene terephthalate (PET). Antimony in the form of sodium hexahydroxyantimonate, is used in the manufacture of high-quality clear glass. This use accounts for about 5% of the global antinomy consumption.

Substitution: Major substitutes of halogenated flame retardants (and antimony trioxide) are mineral fillers, both aluminium and magnesium hydroxides. In the case of batteries, the economic impact of substituting antimony would be a serious consideration in what is a highly price sensitive application. Several metals can substitute for antimony in the production of lead alloys – including cadmium, calcium, selenium, tin and copper.

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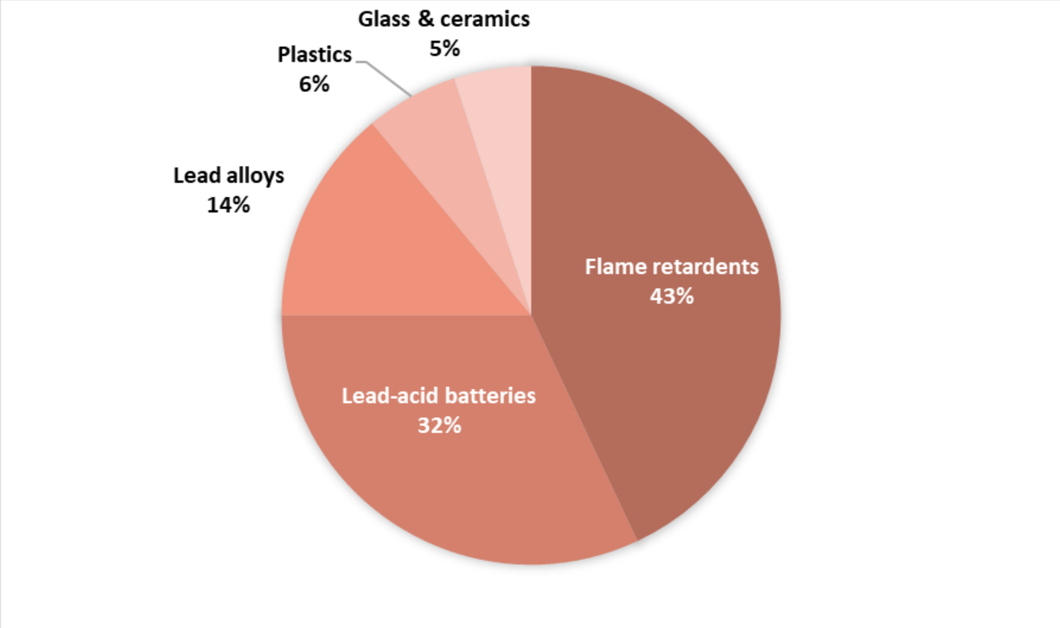

Figure 4: EU uses of antimony

Other issues: Antimony (Sb) is a potentially toxic metalloid and is released into the environment through various pathways, including mining, ore transportation, smelting, manufacturing, and use of their products, disposal of wastes, and sludges, wastewater, and so on. (Stančić 2022, Mengchang et al 2019). Studies indicate that antimony is retained in the soil through adsorption and can sorb onto clay minerals, oxides, and hydroxides in the soil and aquatic sediment (ATSDR 2019). Strong enrichment of soils in Sb can pose a considerable risk to the environment. It should be stressed, however, that real hazards will depend on Sb solubility rather than on its total concentrations (Lewińska 2018) Workplace exposure limit values are in place for one or more forms of antimony. In Europe, the most accepted limit is 0.5 mg/m³, but more severe limits exist, such as the 0.25 mg/m³ in Sweden (GESTIS 2022). However, some agencies are revising the existing limits and calculating new ones that involve respirable occupational exposure limits (OEL) instead of inhalable OELs. In 2018 the German BAuA (Federal Institute for Occupational Safety and Health) published a limit of 0.006 mg respirable Antimony/m³ for Antimony trioxide and Antimony trisulfide as part of the German TRGS 900 (Technical Rules for Hazardous Substances) (International Antimony Association 2022a).

Table 3. Uses and possible substitutes

Use	Percentage*	Substitute	Sub share	Cost	Performance
Flame retardants	43 %	Hydrated aluminium oxide	10 %	Similar or lower costs	Reduced
Flame retardants	43 %	Zinc oxide	10 %	Similar or lower costs	Reduced
Flame retardants	43 %	Boron oxide	10 %	Similar or lower costs	Reduced
Flame retardants	43 %	No substitute	70 %		
Lead-acid batteries	32 %	Calcium	10 %	Similar or lower costs	Similar

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Lead-acid batteries	32 %	Copper	10 %	Similar or lower costs	Similar
Lead-acid batteries	32 %	Selenium	10 %	Very high costs (more than 2 times)	Similar
Lead-acid batteries	32 %	Sulphur	10 %	Similar or lower costs	Similar
Lead-acid batteries	32 %	Tin	10 %	Very high costs (more than 2 times)	Similar
Lead-acid batteries	32 %	No substitute	50 %		
Lead alloys	14 %	Calcium	10 %	Similar or lower costs	Similar
Lead alloys	14 %	Copper	10 %	Similar or lower costs	Similar
Lead alloys	14 %	Selenium	10 %	Very high costs (more than 2 times)	Similar
Lead alloys	14 %	Sulphur	10 %	Similar or lower costs	Similar
Lead alloys	14 %	Tin	10 %	Very high costs (more than 2 times)	Similar
Lead alloys	14 %	No substitute	50 %		
Plastics (catalysts & stabilisers)	6 %	Not assessed, the share is under 10%			
Glass & ceramics	5 %	Not assessed, the share is under 10%			

*EU end use consumption share.

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 4: Antimony supply and demand at extraction stage in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
142,347	China 56% Tajikistan 20% Russia 12 % Myanmar 3% Turkey 2% Australia 2% Bolivia 2%	1,095	0,8%	Turkey 66% Bolivia 27% Guatemala 4% China 3%	100%

Table 5: Antimony supply and demand at the processing stage in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
101,586	China 52% Belgium 9% France 6% Vietnam 7% Myanmar 4% Thailand 4%	40,527	40%	China 30% Belgium 21% France 15% Tajikistan 9% Vietnam 7% Spain 4% South Korea 4% Germany 2% Thailand 2%	47%

Antimony is traded in several forms such as ores and concentrates, antimony trioxide (ATO), unwrought antimony metal and powders, and scrap. As halogenated antimony trioxide is still highly used as an effective flame retardant, ATO is likely to remain the principal market for antimony in the EU. The continued use of ATO in flame retardants is also likely to be driven by increasingly stringent fire regulations. The use of antimony in lead-acid batteries is estimated to decrease as various producers substituted antimony in this application on environmental grounds in many developing nations (EC, 2020; CRM Alliance, 2022).

Global consumption of antimony is expected to increase from 2016 to 2020, primarily in the use applications: flame retardants, lead-acid batteries, and plastics. Asia is projected to remain the leading region regarding consumption, accounting for about 60% of global consumption by 2021 (USGS, 2022a). However, antimony production (both extraction and processing) was reduced in 2021 due to environmental audits in China, and various temporary mine shutdowns during the global COVID-19 pandemic (USGS, 2022a).

A new antimony plant in Oman was planned to operate in 2019. The plant was set up to treat 40,000 tonnes per year of antimony-gold concentrates producing 20,000 tonnes per year of antimony metal and antimony

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trioxide, making it the largest antimony roaster outside of China. Nevertheless, according to experts, most of the conversion of antimony ores into antimony metal or ATO would occur in China (EC, 2020).

EU TRADE

The relevant commodities of Antimony and their CN code are listed in Table 6.

The EU is a net importer of Antimony ores and concentrates in the observed period (2000-2021). Like all other materials, the production cuts and lockdowns due to the Covid-19 pandemic has impacted the supply of Antimony ores to the EU, with a decrease to the level 1000 tonnes in 2020. The EU exports has been seen an increasing trend until 2012 and then drastically declining until 2020.

Table 6. Relevant Eurostat CN trade codes for Antimony.

Mining		Processing/refining	
CN trade code	**title**	**CN trade code**	**title**
26171000	Antimony Ores and Concentrates	28258000	Antimony Oxide
		8110000	Unwrought antimony; antimony powders

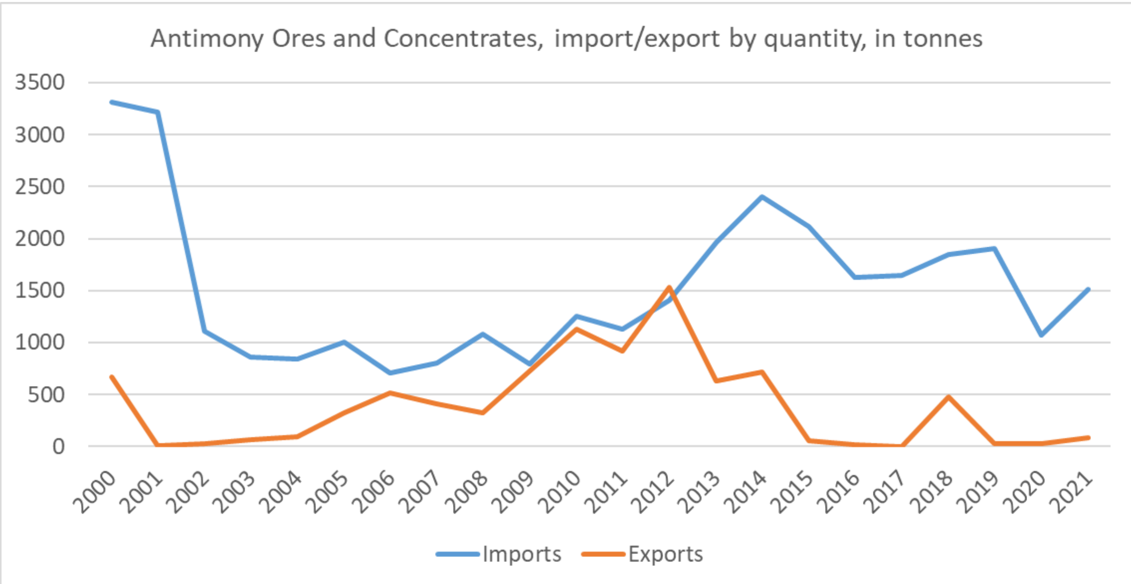

Figure 5. EU trade flows of Antimony ores and concentrates (CN 26171000) from 2000 to 2021 (Eurostat, 2022)

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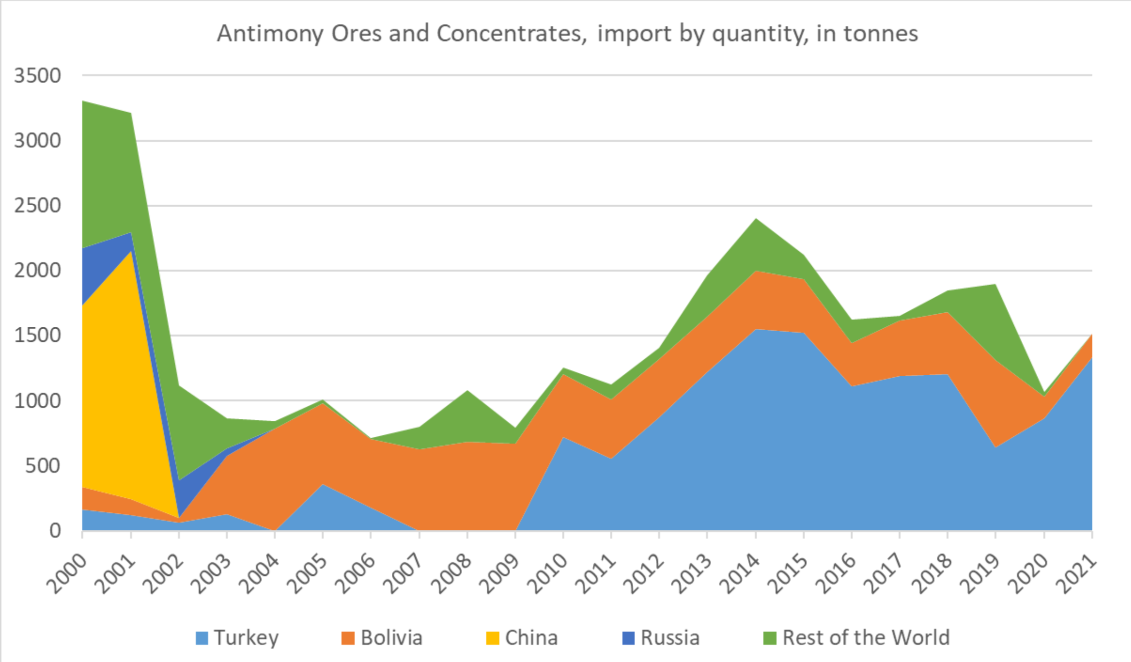

Figure 6. EU imports Antimony ores and concentrates by country from 2000 to 2021 (Eurostat, 2022)

The main import partners of EU for Antimony ores and concentrates are Turkey and Bolivia. Import from Turkey has increase from around 700 tonnes in 2010 to 1334 tonnes in 2021. The import from Bolivia has remained stable in past 20 years with an average of 350 tonnes in past 20 years. EU also import considerable quantities from China and Russia.

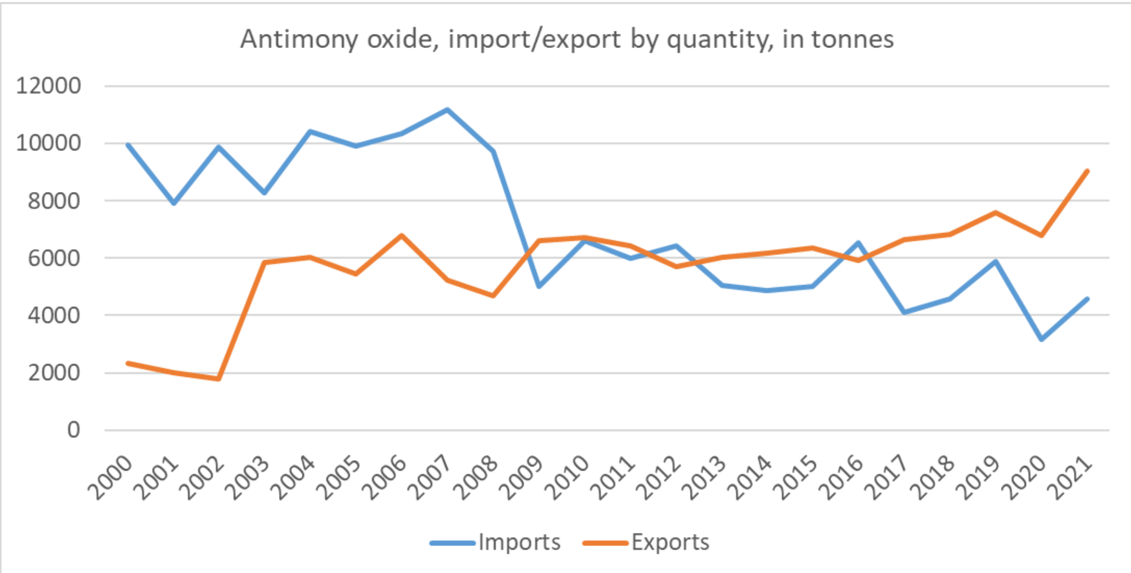

Figure 7. EU trade flows of Antimony oxides from 2000 to 2021 (Eurostat, 2022)

The EU import of Antimony oxide has declined over the years from 9956 tonnes in 2000 to 4571 tonnes in 2021. The oxide import was higher than export until 2009. However, the export of antimony oxide from EU has gradually but slightly been increasing from 2336 tonnes in 2000 to 9049 tonnes in 2021.

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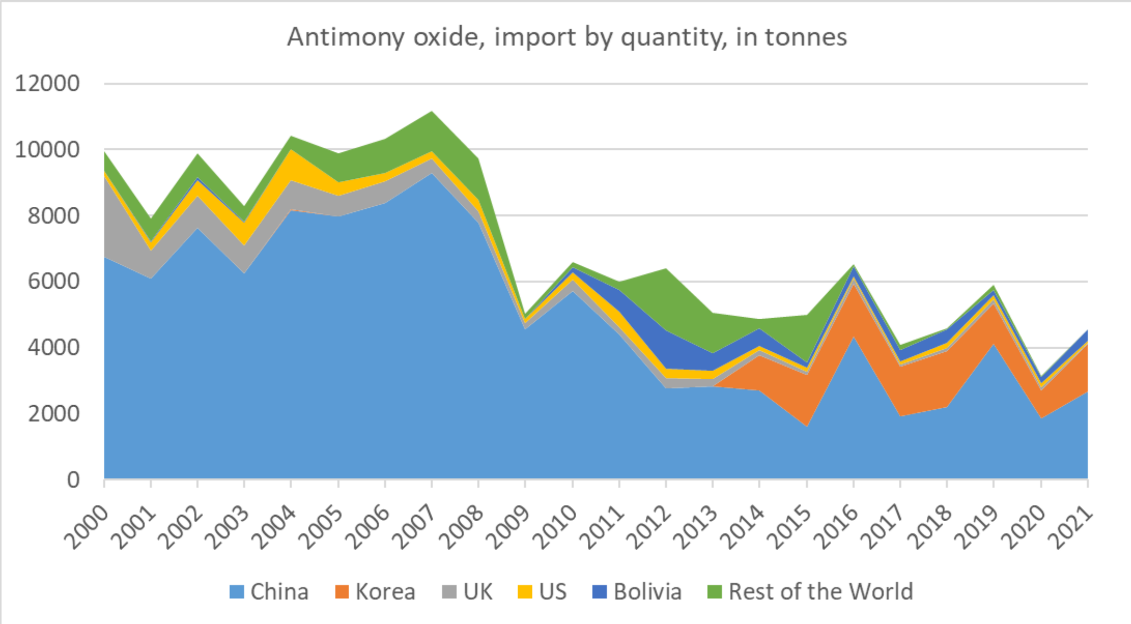

Figure 8. EU imports of Antimony oxides by country from 2000 to 2021 (Eurostat, 2022)

The supply of Antimony oxides to the EU is more concentrated than ores and concentrates. The major suppliers to the EU in 2000-2021 are China and South Korea totalling more than 95 percent. Minor quantities are supplied U.S, U.K and Bolivia and their share has declined in recent years.

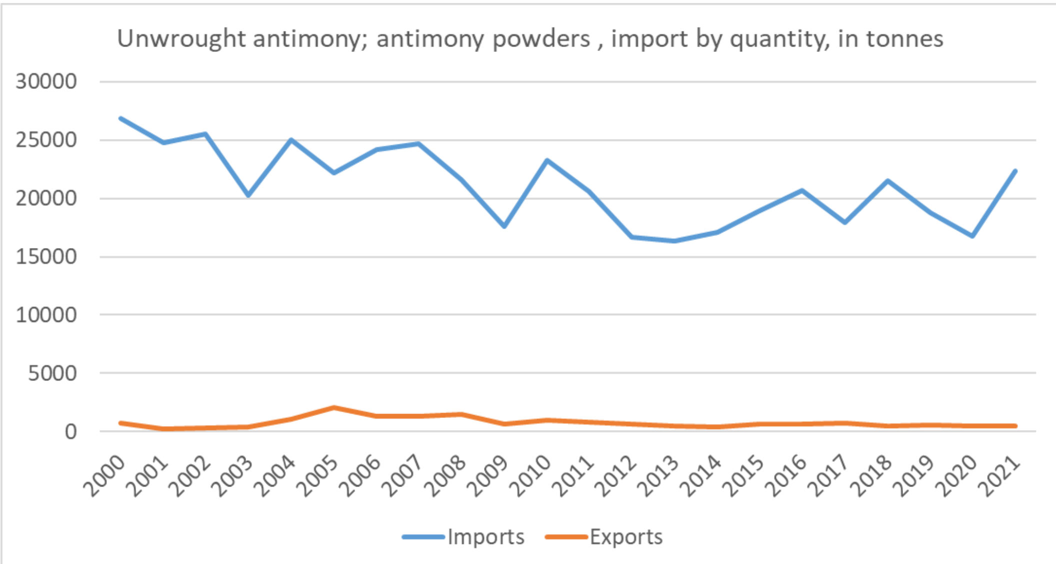

Figure 9. EU trade flows of Antimony articles from 2000 to 2021 (Eurostat, 2022)

Figure 9 shows the EU export and import of Antimony articles. The EU is a net importer of Antimony articles. The import volume is considerably higher than EU's import of Antimony ores and oxides. The import has slightly decreased in last twenty years from 26899 tonnes in 2000 to 22346 tonnes in 2021.

EU also exports minor quantities of antimony articles with an average 600 tonnes in last 20 years. The export was 464 tonnes in 2021.

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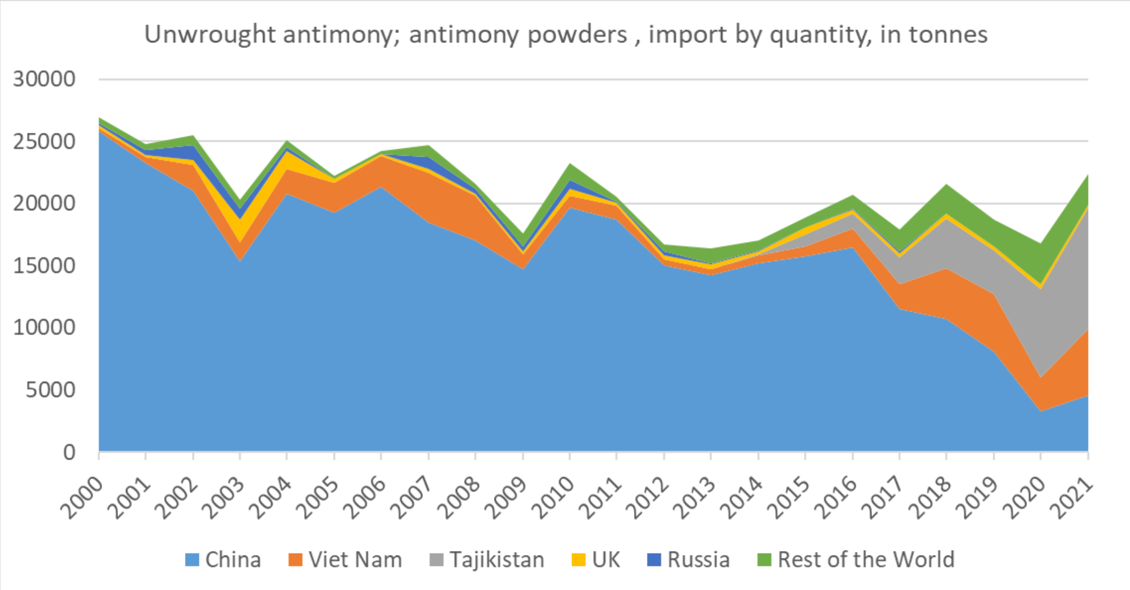

Figure 10. EU imports of unwrought antimony and antimony powders by country from 2000 to 2021 (Eurostat, 2022)

PRICE AND PRICE VOLATILITY

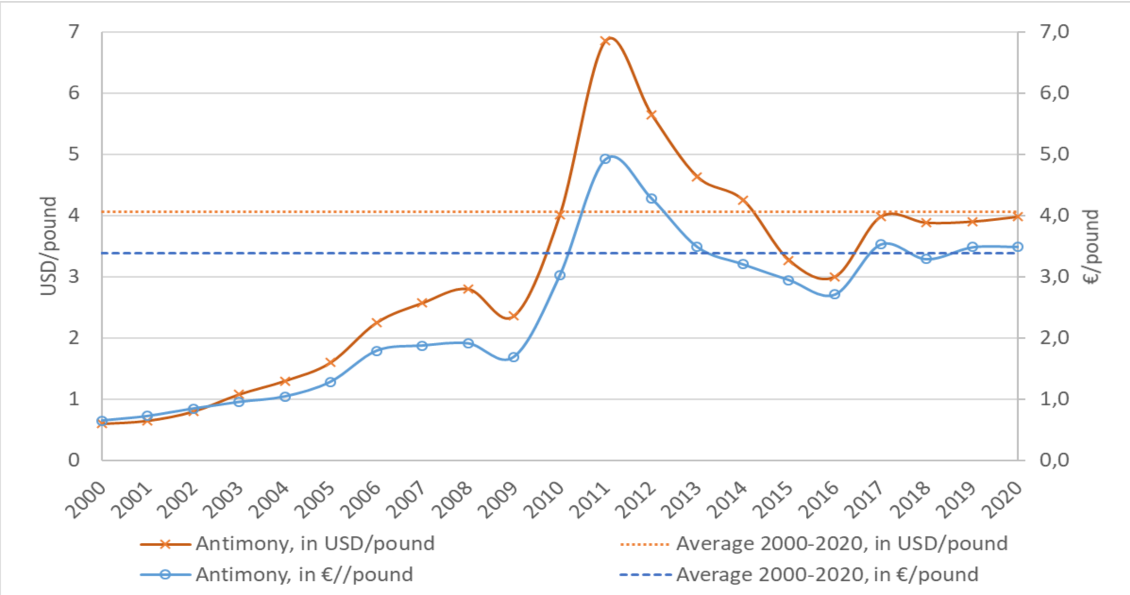

Figure 11. Annual average price of antimony between 2000 and 2020, in USD/pound and €/pound3. Dash lines indicate average price for 2000-2020 (USGS, 2022b)

[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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Antimony prices have declined from 2011 to 2015. Reports indicated that elevated producer stocks in China and lower–than-expected consumption in Europe contributed to the price decline (USGS, 2022b). In 2016 and 2017, in China many large-scale producers reduced production and many small-scale producers closed in response to price declines. Part of the decline in price has come from the growing volumes of stocks sold by Chinese large-scale producers of ingot and trioxide since the end of 2018 (EC, 2020). From 2017 to 2020, antimony prices remain stable.

DEMAND

EU DEMAND AND CONSUMPTION

Antimony extraction stage EU consumption is presented by HS code CN 26171000. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from WMD (2022).

Antimony processing stage EU consumption is presented by HS codes CN 28258000 Antimony oxides and CN 81101000 Unwrought antimony; antimony powders. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2022) using PRCCODE 20121975 Antimony oxides and PRCCODE 24453045 Antimony. Unwrought antimony; powders.

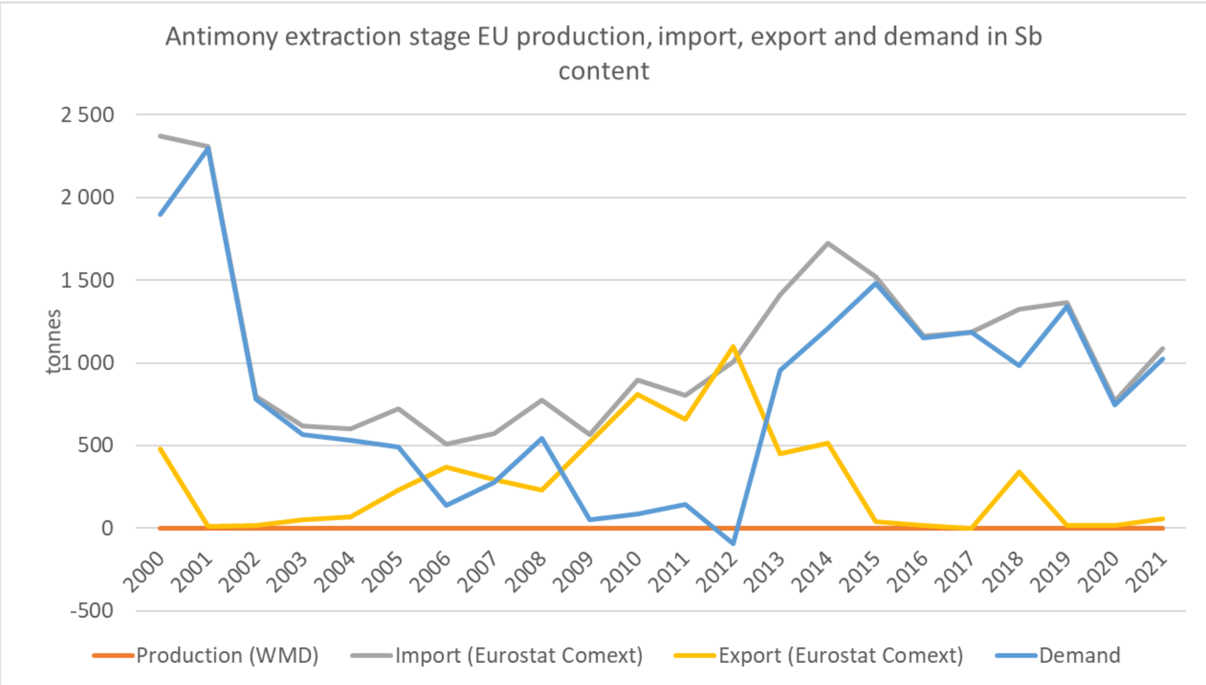

Figure 12. Antimony (CN 26171000) extraction stage apparent EU consumption. Production data is available from WMD (2022). Consumption is calculated in antimony (Sb) content (EU production+import-export).

Average import reliance of antimony at extraction is 100 % and at processing stage is 47% for 2016-2020 (imports minus exports divided by domestic material consumption).

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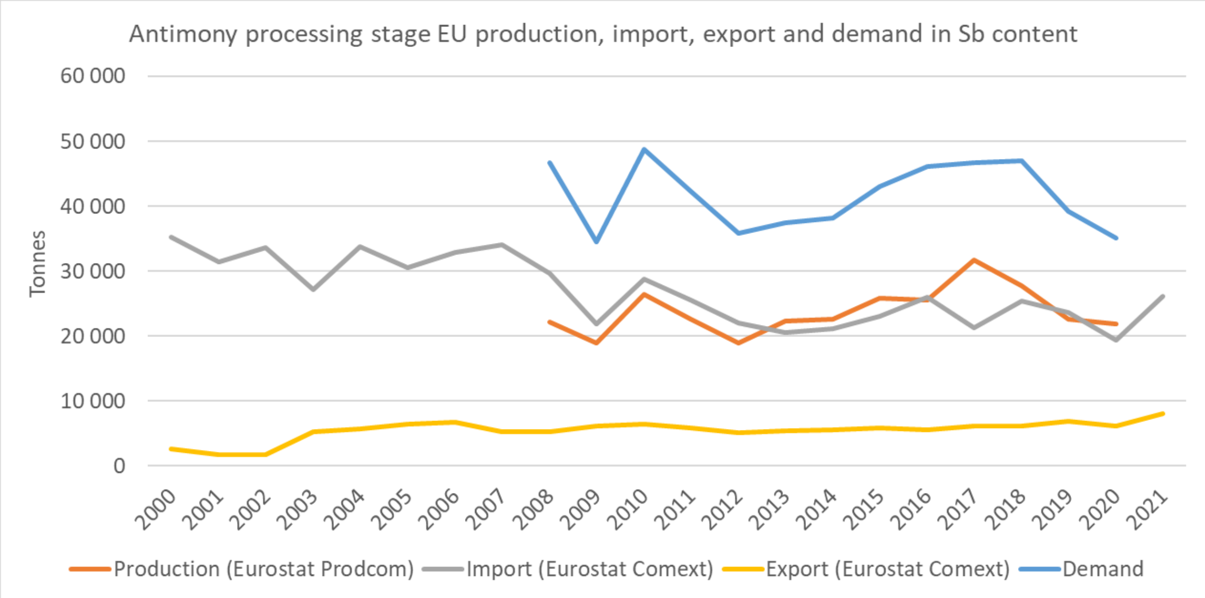

Figure 13. Antimony (CN 28258000 and CN 81101000) processing stage apparent EU consumption. Production data is available from Eurostat Prodcom (2022) for 2008-2020 (antimony oxides) and 2019-2020 (Unwrought antimony; antimony powders). Consumption is calculated in antimony (Sb) content (EU production+import-export).

EU USES AND END-USES

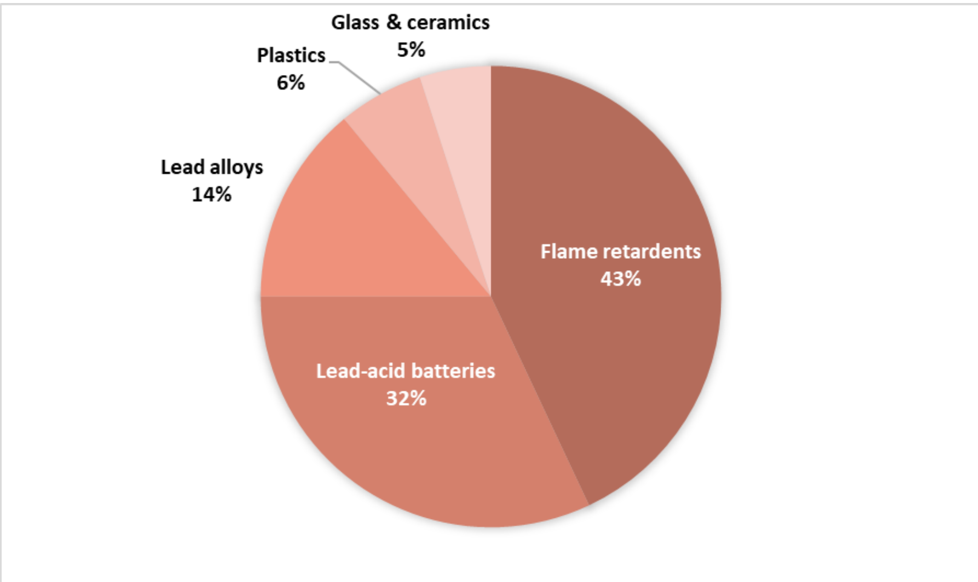

Figure 14. EU end uses of antimony. Average EU import figures of antimony ores and concentrates for 2012-2016 (SCRREEN, 2019) . No change following review by SCRREEN / EC experts 2022.

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 7 and visualised in Figure 15.

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Table 7. Antimony 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
Flame retardants	C20 - Manufacture of chemicals and chemical products	117,150*	C2059 - Manufacture of other chemical products n.e.c.
Lead-acid batteries	C27 - Manufacture of electrical equipment	97,292	C2720 - Manufacture of batteries and accumulators
Lead alloys	C25 - Manufacture of fabricated metal products, except machinery and equipment	186,073	C2599 - Manufacture of other fabricated metal products n.e.c.
Plastics (catalysts and stabilisers)	C20 - Manufacture of chemicals and chemical products	117,150*	C2016 - Manufacture of plastic in primary forms
Glass and ceramics	C23 - Manufacture of other non-metallic mineral products	72,396	C2311 - Manufacture of flat glass

**Data up to 2014 only*

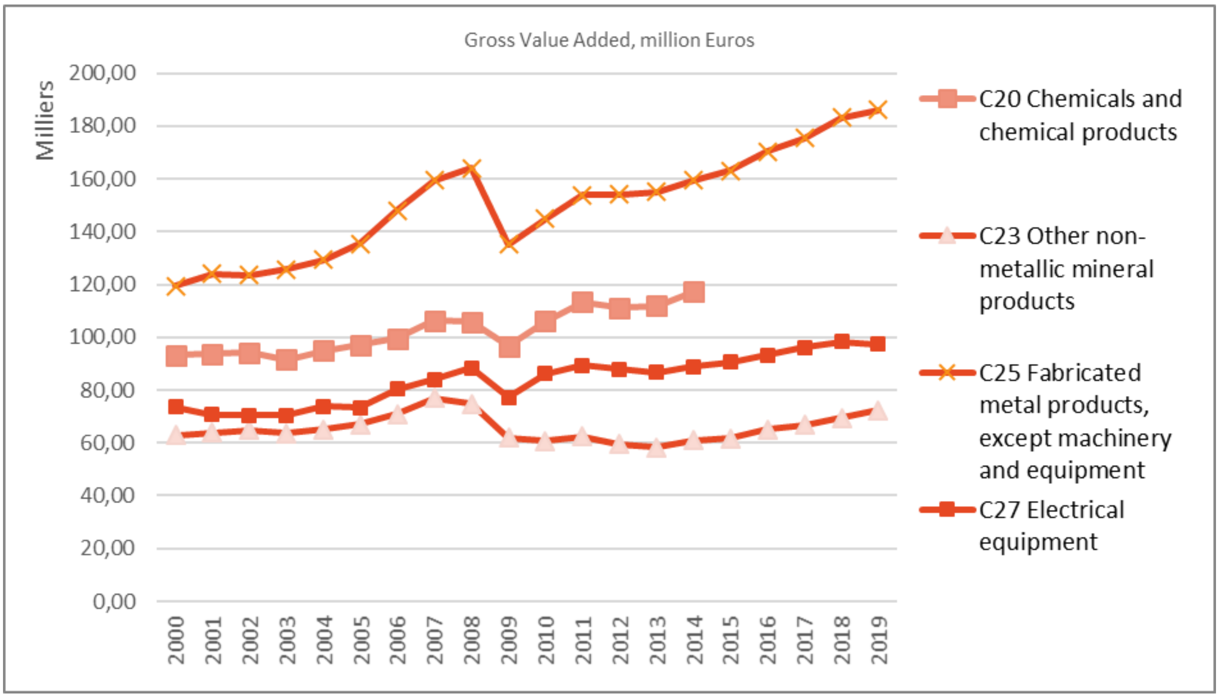

Figure 15. Value added per 2-digit NACE sector over time (Eurostat, 2022).

APPLICATIONS OF ANTIMONY

In the following, for each of these categories the specific applications are described.

FLAME RETARDENTS

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- Around 43% of antimony (in the form of antimony trioxide, or ATO) is used in flame retardancy.
- Antimony-based flame retardants are used in plastics, cable coatings, upholstered furniture, car seats, fabrics and household appliances (i2a, 2014).
- Antimony trioxide, which is not is not a flame retardant in itself, is used as a co-synergist with halogenated (i.e., brominated or chlorinated) flame retardants to enhance their effectiveness as retardant compounds, achieved by hindering the chain reaction of the flame gas phase through stepwise release of the halogenated radicals, which inhibit ignition and pyrolysis in solids, liquids and gases.
- They also promote the formation of a char-rich layer on the substrate, which reduces oxygen availability and volatile-gas formation (Schwarz-Schampera, 2014).

LEAD-ACID BATTERIES

- Antimonial (or hard-lead alloys) are used in the manufacture of lead-acid batteries, accounting for about 32% of global antimony consumption,
- The incorporation of 1-15 % antimony in these alloys improves tensile strength and thus charging characteristics. Further, it also prevents the production of unwanted hydrogen during charging.
- Antimony-lead alloys that contain 1-3% antimony are easy to cast and are used in the production of grid plates, straps and terminals in lead-acid batteries (Schwarz-Schampera, 2014; CRM_InnoNet, 2015).

LEAD ALLOYS

- The production of lead alloys accounts for about 14% of global antimony use.
- These alloys are used in the manufacture of low-load bearings applications in the automotive sector and io household and decorative items (such as teapots, vases and lamp stands.)
- Tin-lead-antimony solders are used extensively in the electronics industry (Schwarz-Schampera, 2014; CRM_InnoNet, 2015).

PLASTICS (CATALYSTS & STABILISERS

- Around 6% of antimony, in the form of antimony trioxide (ATO), is used as a catalyst in the production of polyethylene terephthalate (PET).
- PET is one of the key input materials for the manufacture of plastic bottles, also for water and food bottles.
- ATO is also used as a heat stabiliser in polyvinyl chloride (PVC) (Schwarz-Schampera, 2014).

GLASS & CERAMICS

- Antimony in the form of sodium hexahydroxyantimonate, is used in the manufacture of high-quality clear glass. This use accounts for about 5% of the global antinomy consumption. In this particular application, antimonates are primarily used as degassing agents, which act to remove trapped air bubbles from the cooling glass. They also act as a fining agent for removing impurities (e.g. iron) that may produce unwanted colouration (Schwarz-Schampera, 2014).

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SUBSTITUTION

Substitutes have been identified for the applications of Antimony.

Table 8. Substitution options for antimony by application

Use	Percentage*	Substitute	Sub share	Cost	Performance
Flame retardants	43 %	Hydrated aluminium oxide	10 %	Similar or lower costs	Reduced
Flame retardants	43 %	Zinc oxide	10 %	Similar or lower costs	Reduced
Flame retardants	43 %	Boron oxide	10 %	Similar or lower costs	Reduced
Flame retardants	43 %	No substitute	70 %		
Lead-acid batteries	32 %	Calcium	10 %	Similar or lower costs	Similar
Lead-acid batteries	32 %	Copper	10 %	Similar or lower costs	Similar
Lead-acid batteries	32 %	Selenium	10 %	Very high costs (more than 2 times)	Similar
Lead-acid batteries	32 %	Sulphur	10 %	Similar or lower costs	Similar
Lead-acid batteries	32 %	Tin	10 %	Very high costs (more than 2 times)	Similar
Lead-acid batteries	32 %	No substitute	50 %		
Lead alloys	14 %	Calcium	10 %	Similar or lower costs	Similar
Lead alloys	14 %	Copper	10 %	Similar or lower costs	Similar
Lead alloys	14 %	Selenium	10 %	Very high costs (more than 2 times)	Similar
Lead alloys	14 %	Sulphur	10 %	Similar or lower costs	Similar
Lead alloys	14 %	Tin	10 %	Very high costs (more than 2 times)	Similar
Lead alloys	14 %	No substitute	50 %		
Plastics (catalysts & stabilisers)	6 %	Not assessed, the share is under 10%			
Glass & ceramics	5 %	Not assessed, the share is under 10%			

*EU end use consumption share.

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FLAME RETARDANTS

- Major substitutes of halogenated flame retardants (and antimony trioxide) are mineral fillers, both aluminium and magnesium hydroxides.
- These fillers yield crystallization water at higher temperatures, achieving a certain flame retardancy, but at high levels of filling in the range of 150–200 parts of the hydroxide per 100 parts of, for example, unsaturated polyester resin, it is possible to achieve self-extinguishing and a low smoke density. The disadvantage of such systems is that the entire material has a high density and whilst applications such as plastics, cable sheathing and carpets can tolerate some level of mineral filler, fabrics cannot.
- As a replacement for antimony in halogenated fire-retardant systems there is the potential use of zinc hydroxystannate or zinc borate at similar levels, however they are only effective in certain systems and not as good as antimony trioxide.

LEAD ACID BATTERIES

- In the case of batteries, the economic impact of substituting antimony would be a serious consideration in what is a highly price sensitive application.

LEAD ALLOYS

- Several metals can substitute for antimony in the production of lead alloys – including cadmium, calcium, selenium, tin and copper.
- The properties of a given alloy are not controlled by a single metal, but rather by the combination of several metals, where each metal may produce a range of effects in the alloy (Schwarz-Schampera, 2014) (CRM_InnoNet, 2015). Accordingly, any substitution would be associated with a price and/or performance penalty which, in general, means that there appears to be little economic or technical incentive to substitute antimony in its principal applications.

PLASTICS (CATALYSTS & STABILISERS) & GLASS

- Various combinations of cadmium, barium, calcium, lead, tin, zinc and germanium may substitute for antimony in the production of plastics, where antimony acts as a stabiliser or catalyst, but this option is commonly more expensive.
- Compounds of chromium, tin, titanium, zinc and zirconium can substitute for antimony in the manufacture of pigments and glass.

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SUPPLY

EU SUPPLY CHAIN

The flows of antimony through the EU economy in 2012 are demonstrated in Figure 16.

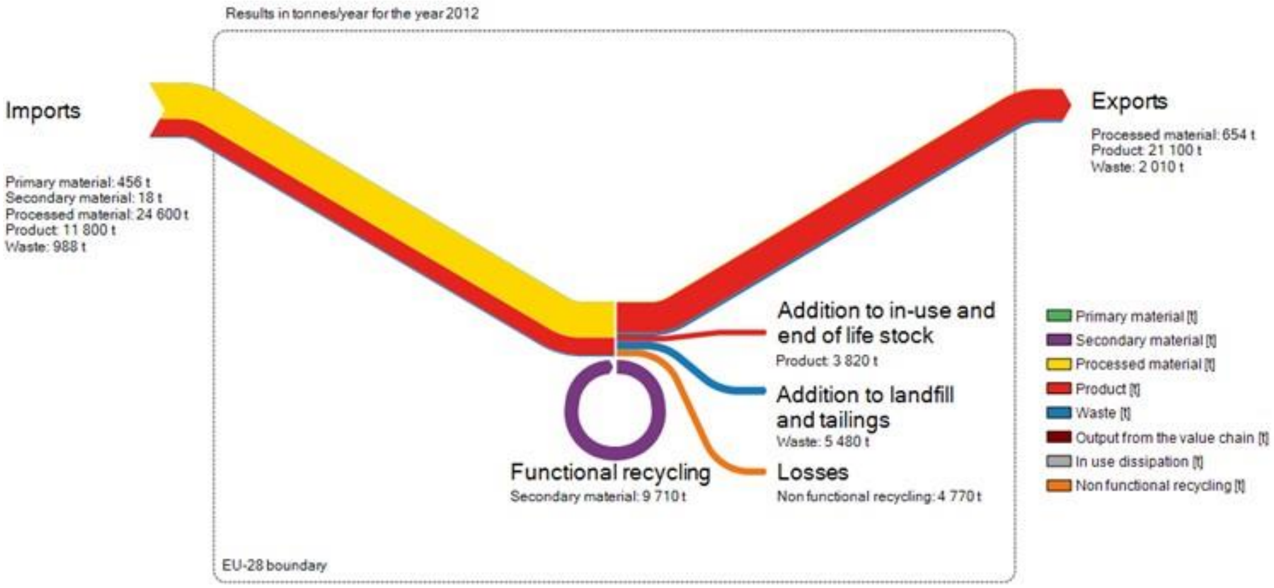

Figure 16: Material System Analysis of antimony in 2012, EU-28 (Bio Intelligence Service, 2015)

There is no primary production of antimony ores or concentrates in the EU. The EU is a net importer of antimony ores and concentrates (CN code 2671000) with an import reliance of 100 %. The average annual import of antimony ores and concentrates to the EU in period 2016-2021 was 1078 t - mainly from China, Bolivia and Turkey with minimal further exports (70 t per year on average) to China, South Korea and United Kingdom. Thus, the average annual consumption of antimony ores and concentrates in EU in period 2016-2021 is 1008 t.

However, the main trade products of antimony are processed materials such as antimony oxides, unwrought antimony and powders. Their Prodcom codes are listed in Table 9. During 2016-2021 the EU annually imported 23,125 t of processed antimony and exported 6,450 t of processed antimony. Therefore, the annual EU antimony consumption can be estimated on 16,675 t of processed antimony. Noticeably in 2020, during the Covid-19 pandemic, antimony imports decreased to only 18,800 t, while exports remained almost on the same level, which means that the EU consumed only about 12,000 t of antimony in 2020. In 2021, after the lockdown imports reached pre-pandemic level, while the exports increased by almost 2,000 t.

Most (between 70 and 80 %) of the antimony is imported as unwrought antimony and antimony powders (CN code 81101000). The main suppliers are China, Tajikistan, Vietnam, Myanmar, South Korea, Thailand, Turkey and the United Kingdom. Antimony oxides (CN code 28258000) are imported mainly from China, South Korea, Bolivia, the United Kingdom and the United States of America.

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EU Member States are one of the largest producers of antimony trioxide in the world. Antimony oxides (CN code 28258000) therefore account for 95 % of EU antimony export. Antimony oxides are exported to a wide array of countries - Brazil, Canada, China, Egypt, India, Israel, Japan, Mexico, Norway, Russia, Saudi Arabia, South Africa, South Korea, Switzerland, Turkey and Ukraine with the United Kingdom and the United States of America being the main markets.

Table 9. Relevant Eurostat PRODCOM production codes for antimony

Mining		Processing/refining	
Prodcom code	**title**	**Prodcom code**	**Title**
07.29.19.45	Antimony ores and concentrates	**20.12.19.75**	Antimony oxides
		20.13.41.11	Sulphides of calcium, of antimony or of iron
		20.13.41.20	Sulphides; polysulphides, whether or not chemically defined; dithionites and sulphoxylates (excluding of calcium, antimony and iron)
		24.43.11.50	Unwrought lead containing antimony (excluding lead powders or flakes)
		24.45.30.45	Antimony. Unwrought antimony; powders
		24.45.30.46	Antimony and articles thereof (excluding unwrought antimony; powders; waste and scrap)

SUPPLY FROM PRIMARY MATERIALS

Antimony forms a wide range of minerals from native Sb (100 wt.% Sb), most common ore mineral stibnite (72 wt.% Sb) as well as antimony oxides valentinite (83 wt. % Sb) and its polymorph senarmontite (88 wt.% Sb) to the vide array of sulfosalts such as chalcostibite (49 wt. % Sb), famatinite (27 wt. % Sb), pyrargyrite (23 wt. % Sb), tetrahedrite (30 wt. % Sb), jamesonite (35 wt. % Sb), boulangerite (26 wt. % Sb), bournonite (25 wt. % Sb) etc. (Dill, 2010 and Schwarz-Schampera, 2014).

GEOLOGY, RESOURCES AND RESERVES OF ANTIMONY

GEOLOGY

The most important types of the antimony deposits, based on their ore resources, include: (1) greenstone-hosted quartz-carbonate veins and carbonate replacement deposits; (2) gold-antimony (epithermal) deposits; and (3) reduced magmatic gold systems. In many of these deposits, stibnite (Sb_2S_3) is the principal ore mineral (Schwarz-Schampera, 2014).

Greenstone-hosted antimony deposits are of particular economically importance. They are estimated to tens of millions of tonnes in size and typically contain between 1.5 and 25% Sb_2S_3. These deposits typically comprise

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a stockwork of gold-antimony-quartz-carbonate veins hosted by metavolcanic and/or metasedimentary rocks. Carbonate replacement deposits are also found in some of these metasedimentary sequences (e.g. Xikuangshan, China), which are thought to form by hydrothermal alteration of the host material (Schwarz-Schampera, 2014).

Epithermal gold-antimony deposits are generally smaller than greenstone-hosted deposits. They are typically up to 1 million tonnes in size and have lower ore grades (up to 3.5% Sb_2S_3). The formation of these epithermal deposits is linked to the emplacement of magmatic porphyry copper systems in the shallow crust (upper 1.5 km). The mineralisation generally takes the form of veins, or disseminations of stibnite and/or tetrahedrite ($(Cu,Fe)_{12}Sb_4S_{13}$) in the host rocks (Schwarz-Schampera, 2014).

Reduced magmatic gold systems are associated with the intrusion of metaluminous granite plutons, the mineralisation taking the form of quartz-carbonate sheeted veins, replacement bodies and/or skarns. The mineralisation may be enriched in several metals, including gold, tellurium, tungsten, arsenic and antimony. These deposits are similar in size to the greenstone-hosted antimony deposits, but have typically much lower grades (0.1 to 1.5% Sb_2S_3) (Schwarz-Schampera, 2014).

A more detailed classification scheme for antimony deposits based on lithology and tectonic structures is illustrated on Table 10.

Table 10. Classification scheme of antimony deposits (Dill, 2010)

1) Magmatic antimony deposits
1.1.) Granite-related vein-type (and replacement) deposits
1.1.1.) Sb-W
1.1.2.) Sb–Pb–Cu–Zn–As
1.1.3.) Sb–Hg–W–Ba
1.2.) Skarn-type Sb–(Au–Hg–As) deposit (Sarawak-type)
1.3.) Carbonate-hosted disseminated Sb–Au–Ag (Carlin-type)
1.4.) Shallow high- and low-sulfidation Sb deposits
1.5.) Near-surface low-sulfidation-type Sb–(Hg) deposits
1.6.) Sb deposits related to (ultra)mafic rocks and greenstone belts
2.) Structure-related antimony deposits
2.1.) Shearzone-hosted, mesothermal (Au-)Sb veins
2.1.1.) Monotonous Sb deposits
2.1.2.) Polymetallic Sb–(Au–W–Sn–As–Zn–Pb) deposits
3.) Sedimentary antimony deposits
3.1.) Stratabound deposit (with remobilization)
3.1.1.) Monotonous sedimentary-diagenetic Sb deposit
3.1.2.) Hg–Sb–(W) deposits in carbargillites and graphite schists
3.1.3.) Polymetallic Sb mineralization in black shales (alum shales)
3.2.) Sb-enriched coal seams

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GLOBAL RESOURCES AND RESERVES:

The world reserves of antimony exceed 2,000,000 t of contained antimony – Table 11 (USGS, 2022). Identified principal world resources of antimony are located in Australia, Bolivia, China, Mexico, Kyrgyzstan, Russia and Turkey. Apart from the countries listed in Table 11, reserves are known to exist in Guatemala, Iran, Kazakhstan, and Vietnam but there was no data on the quantity.

Table 11. Antimony reserves by country (USGS, 2022).

Country	Reserves (thousand tonnes)
China	480,000
Russia	350,000
Bolivia	310,000
Kyrgyzstan	260,000
Australia	100,000
Turkey	100,000
Canada	78,000
United States	60,000
Tajikistan	50,000
Pakistan	26,000
Mexico	18,000
Total	> 2,000,000

EU RESOURCES AND RESERVES[4]

According to the data collected in the frame of the E-mineral yearbook in Mintell4EU project published on EGDI portal, only two countries reported antimony resources in 2019 – France and Sweden (EGDI, 2022). In the previous data reporting in 2013, five countries - France, Sweden, Finland, Slovakia and Greece reported antimony resources.

Most resource figures in Europe are based on historic estimates and thus not reported in accordance with the UNFC system of reporting. These resources are currently considered to be of little economic interest. Germany also holds antimony resources, but data are not reported because data collection in that country is under the responsibility of authorities at federal state level (Minerals4EU, 2019). Resource data for some countries in Europe are available on the EGDI portal (see EGDI, 2022) but cannot be summed as they are partial, and they do not use the same reporting code.

Other than the resource estimation reported on Minerals4EU website, antimony resources are reported in Rockliden, Sweden with 0,8 Mt of indicated mineral resources with 0.18% Sb (also contains 4.04% Zn, 2.1%

[4] For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for antimony. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for antimony, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g., historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for antimony the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU 2019). Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However, a very solid estimation can be done by experts.

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Cu, 0.9 % Pb, 0.9% As, 102 ppm Ag, 0.08 ppm Au) and 9.2Mt of inferred mineral resources with 0.067% Sb (also contains 3.9% Zn, 1.7% Cu, 0.4% Pb, 0.6% As, 47 ppm Ag, 0.05 ppm Au) (Agmalm, 2021). However, Sb contents in this project are currently considered as deleterious.

In addition, antimony occurrences were also reported from Austria, Bulgaria, Czech Republic, Hungary, Italy, Luxembourg, Portugal, Romania, Slovenia, and Spain (Lauri et al., 2018).

Austria was reported to have several deposits or occurrences and past production of antimony as either main commodity or by-product. The ProMine database estimated about 20,000 tonnes of Sb reserves and resources for Italy, of which 400 tonnes of antimony was at Su Suergiu deposit in Sardinia (Lauri et al., 2018). No information on resources were available concerning occurrences of antimony in Czech Republic, Hungary, Romania, and Slovenia. However, Romania produced antimony in the past as by-product of polymetallic ore processing, but the activities ceased soon after 1991 (Constantinescu and Anastasiu, 2017).

In Portugal, antimony was mined until 1967, when the Barroca da Mina/Barroca da Santa mine was closed. Portuguese deposits were estimated to have 17,700 tonnes of remaining resources of antimony (Lauri et al., 2018).

In Bulgaria, an exploration activity for gold-antimony deposits took place in 2017. According to the reported exploration license, the estimated total endowment of antimony from these deposits was 124,000 tonnes.

A potential source for production of antimony in EU are also the lead concentres produced domestically since they can contain increased antimony levels. Concentrates with elevated Sb levels are mined in Chalkidiki mines in Greece, but produced concentrates are processed elsewhere.

Table 12: Antimony resources in EU according to the EGDI portal – data collected in the frame of Minerals4EU and Mintell4EU projects.

Country	Year	Reporting code	Quantity	Grade	Code Resource Type
France	2019	none	69,880 t	No data	Historic resource estimate
Sweden	2019	PERC	1,950 t 7,830 t 10,200 t	No data No data No data	Measured mineral resource Indicated mineral resource Inferred mineral resource
Finland	2013	none	300,000 t	0.41 % Sb	Historic resource estimate
Greece	2013	none	90,000 t	2.5 % Sb	indicated mineral resource
Slovakia	2013	none	90,000 t 3,210,000 t	2.85 % Sb 1.71 % Sb	Economic mineral resource Subeconomic mineral resource

GLOBAL AND EU MINE PRODUCTION

According to the WMD (2022), global mine production of antimony in period 2016-2020 showed decreasing trend and ranged between 164.000 t (2016) and 132.000 t (2020) (Figure 17). China was the largest supplier of the antimony ores and concentrates, producing between 103.000 t (2016) and 61.000 t (2020) or approximately 63 % of world production in 2016 and 46% of world production in 2020. The only countries that

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increased their production in period 2016-2020 are Tajikistan with average 5-year production of 29.000 t and Russia with average 5-year production of 17.000 t. Tajikistan and Russia are also the second and the third most important producers of antimony.

USGS data (Figure 18) show similar trends as the WMD, with additional production decrease in 2021. The cumulative annual quantities of world antimony production collected by USGS are for approximately 20.000 t lower as for WMD.

The majority of worlds antimony comes as a co-product or by-product - mainly from gold mines and is produced during gold-antimony concentrates refining (examples: Olimpiada mine in Russia, Talco's mine in Tajikistan) (Perpetua Resources, 2021, Brink et al., 2022, Fastmarkets, 2022).

In 2018 56% of antimony was produced as a by-product of gold, 32 % was produced as a host metal and 12 % was produced as co-product or by-product of lead, tin, silver and mercury (Brink et al., 2022). Antimony contained in polymetallic base metal ores (mainly lead-zinc ores) and can be recovered from antimony bearing residues from lead smelting and is therefore considered as secondary antimony production (Perpetua Resources, 2021).

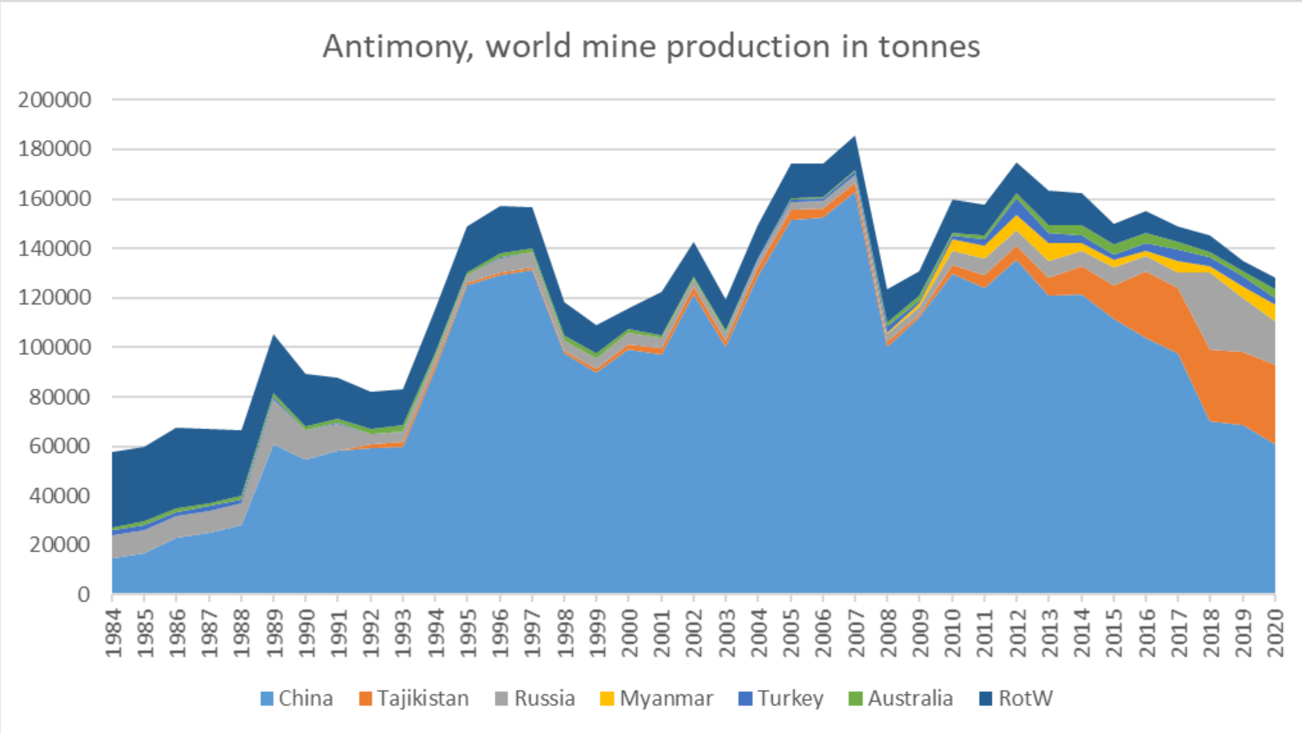

Figure 17: Global mine production of antimony in tonnes (WMD 1984-2022)

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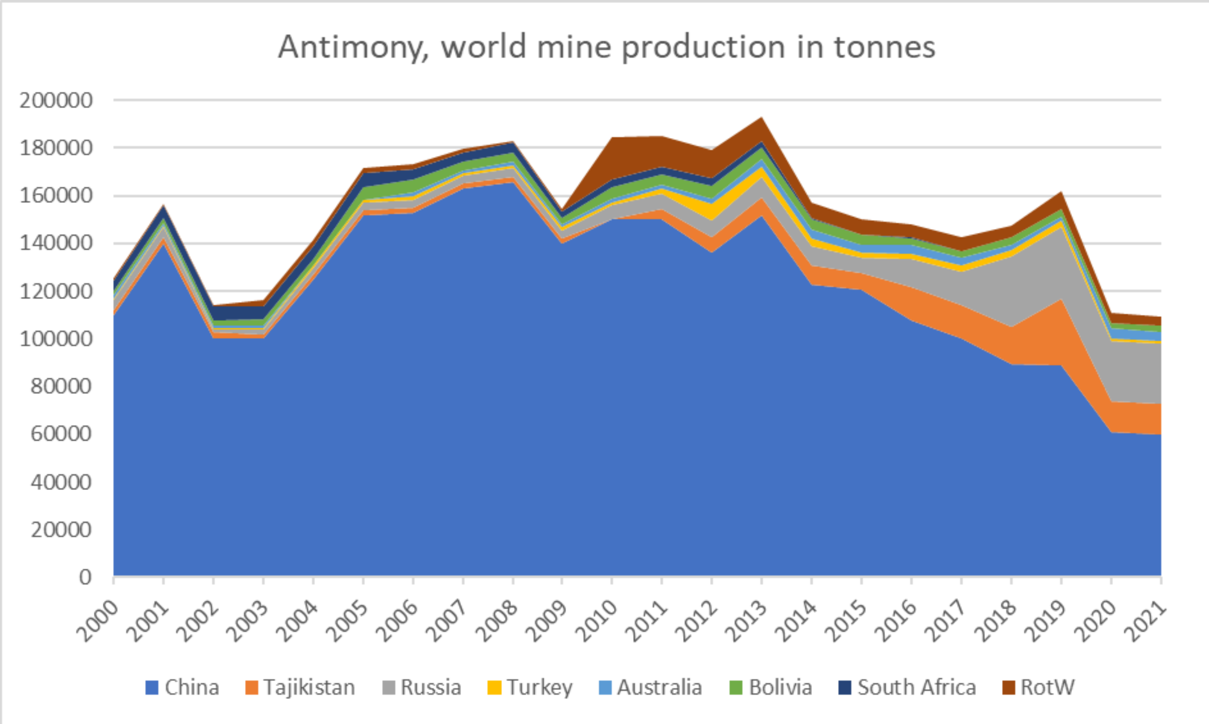

Figure 18: Global mine production of antimony in tonnes (USGS, 2000-2022)

OUTLOOK FOR SUPPLY

China is main supplier of the antimony and will retain this position in next decade due to the availability of antimony refining and processing infrastructure. However, China antimony producers nowadays heavily rely on imported antimony concentrates (with Russia and Tajikistan as the main sources) since some of the main Chinese antimony mines have been depleted (Fastmarkets, 2022, Perpetua Resources, 2021). This also urged the Chinese authorities to strategically reduce output at local antimony mines to avoid additional depletion of domestic supplies (Fastmarkets, 2022). Chinese investment companies also secured controlling interests in antimony projects in South Africa (Murchison Belt), Bolivia, Australia, Tajikistan and Canada (Perpetua Resources, 2021).

However, Chinese antimony production from 2010 to 2020 decreased for more than 50 % - from 130,000 t in 2010 to 61.000 t in 2020 (WMD, 2022). Main reason for that is, alongside depletion of domestic antimony mines, also the China Green Shield Strategy and ecological inspections in the mines and refineries, which restricts antimony processing and mine supply if the ecological standards are not met (Vella, 2018; Brink et al., 2022).

A major antimony roasting plant outside of China is the SPMP (Strategic & Precious Metals Processing) project in Oman. It has the annual capacity of 20,000 t of antimony products (metal and trioxide) (SPMP, 2022). Project went to production in 2019 and according to the Eurostat International Trade data (2022) produces antimony. However, the facility must still obtain feed stocks and stable contracts and complete construction (Vella, 2018, Perpetua Resources, 2021).

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The Covid-19 pandemic considerably disrupted the antimony supply chain – with lack of supply of antimony concentrates, general lock downs and shipping issues, antimony production continue to fall even in 2022, which is reflected in high antimony prices (Argus, 2022). It is unclear if China can secure enough supply of antimony concentrates for their processing capacities (Fastmarkets, 2022). Russian invasion on Ukraine will have additional impact on antimony market – on the supply side (how the Russian antimony concentrates will be traded?) as well as on the demand side – stockpiling of antimony as national strategic reserves and increased consumption in military sector (Fastmarkets, 2022, Kadam, 2022).

If current trends with decreasing antimony production will continue, there will soon be a considerable shortage of the antimony, especially if it will be used for anodes in lithium-ion batteries and liquid metal batteries (Perpetua Resources, 2021, Brink et al., 2022). According to the Mordor Intelligence (2021) the antimony market will grow by more than 5% annually to the 2027, while Perpetua Resources (2021) estimates that 18,000 t of annual primary antimony mine production will need to be brought online through 2030 to meet anticipated demand.

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

The global end-of-life (EoL) recycling rate for antimony is estimated to be between 1 and 10% (UNEP, 2013). The Raw Materials Supply Assessment (RMSA) study, undertaken by BIO by Deloitte in 2015, suggests that the EoL recycling rate in the EU for antimony is as high as 28% (BIO by Deloitte, 2015). Secondary antimony is chiefly recovered from lead-acid batteries. Therefore, the availability of secondary antimony is almost entirely dependent on the extent of lead recycling and the market conditions for lead and lead-acid battery scrap. Since the supply of primary antimony is heavily concentrated in a few countries, the recovery of secondary antimony is an important part of the supply chain in countries like, for example, the United States, Japan, Canada and the EU. On a global scale, it was estimated, that in 2010 the secondary production of antimony accounted for about 20% of total antimony supply (Sundqvist Oeqvist, Pr. Lena et al., 2018). In the EU, there are companies dealing with secondary antimony. Umicore is a company headquartered in Belgium, which recovers antimony from end-of-life batteries, mostly from electric cars. At Umicore antimony is recovered from complex lead-bearing concentrates as well as various complex residues from the lead/copper/zinc industry. The antimony is extracted during the lead refining process in the form of sodium antimonite (Umicore, 2022). Solvay in France recycles halophosphate from spent fluorescent batteries (Sundqvist Oeqvist, Pr. Lena et al., 2018). Antimony used in the manufacture of plastics and flame retardants is generally not recovered because antimony is dispersed in these products (Schwarz-Schampera, 2014). However, antimony could potentially be recovered from the bottom ash resulting from the incineration of some of these products at their end-of-ife stage, but this currently does not appear to be economically viable (Braibant C., 2017). Asia Pacific is projected to dominate the global recycled antimony market during the forecast period. This can be ascribed to the increase in demand for Sb-containing packing alloys in several industries such as food & beverages. Strong economic growth, rise in standard of living, and increase in demand for packaging food are key factors propelling the demand for packaging materials in food & beverages industries. Furthermore, increase in usage of antimony flame retardants, lead-acid batteries, and plastics is estimated to drive the antimony market in Asia Pacific in the near future. (transparencymarketresearch, 2022).

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MSA FLOW	Value (t)
B.1.1 Production of primary material as main product in EU sent to processing in EU	87312
B.1.2 Production of primary material as by product in EU sent to processing in EU	0
C.1.3 Imports to EU of primary material	236303
C.1.4 Imports to EU of secondary material	0
D.1.3 Imports to EU of processed material	81142
E.1.6 Products at end of life in EU collected for treatment	130813
F.1.1 Exports from EU of manufactured products at end-of-life	193
F.1.2 Imports to EU of manufactured products at end-of-life	2847
G.1.1 Production of secondary material from post-consumer functional recycling in EU sent to processing in EU	0
G.1.2 Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU	486

PROCESSING

Antimony ore is initially beneficiated-enriched via various methodologies. Hand selection, gravity separation and flotation are the most commonly applied techniques. Gravity separation is one of the most economical and effective antimony beneficiation methods. It can also be used as a pre-enrichment operation for flotation, reducing the burden on grinding equipment and improving the efficiency of the process flow. The embedded particle size of antimony ore is generally coarse, and the specific gravity of antimony crystal is much larger than that of the associated gangue. Flotation is also an efficient technique since stibnite is an easily floated mineral. Butyl xanthate or a mixture of shale oil and ethyl thiazide, and the foaming agent is pine oil or No. 2 oil are used as flotation reagents (mineraldressing.com, 2022).

The second step comprises the oxidative roasting of the stibnite concentrates for the conversion of Sb sulphide (Sb_2S_3) to Sb oxide (Sb_2O_3) in rotary kilns at 1100-1200°C. Alternatively, the removal of sulphur can be performed via flash volatilization oxidative roasting of via volatilization smelting in blast furnace. In last case stibnite is smelted. In order to produce metallic Sb, the oxidized concentrate is submitted to reductive smelting in blast furnace. A more complex methodology is followed in case of Au-rich stibnite ores for the extraction of both Sb and Au. The antimony-gold ore, lime, and coke were smelted in the blast furnace where more than 90% of antimony was volatilized to crude antimony oxide and about 10% antimony metal stayed in the BF, as a gold carrier. Subsequently, the crude antimony was oxidized to produce enriched gold-antimony alloy which was further treated via chlorination leaching. The resulted antimony oxide is also processed by reduction smelting and oxidation blowing to produce antimony oxide and gold-antimony alloy containing high concentrations of lead. The antimony oxide was processed in the reverberatory furnace to produce antimony metal (Figure 19) (Moosavi-Khoonsari et al. 2022).

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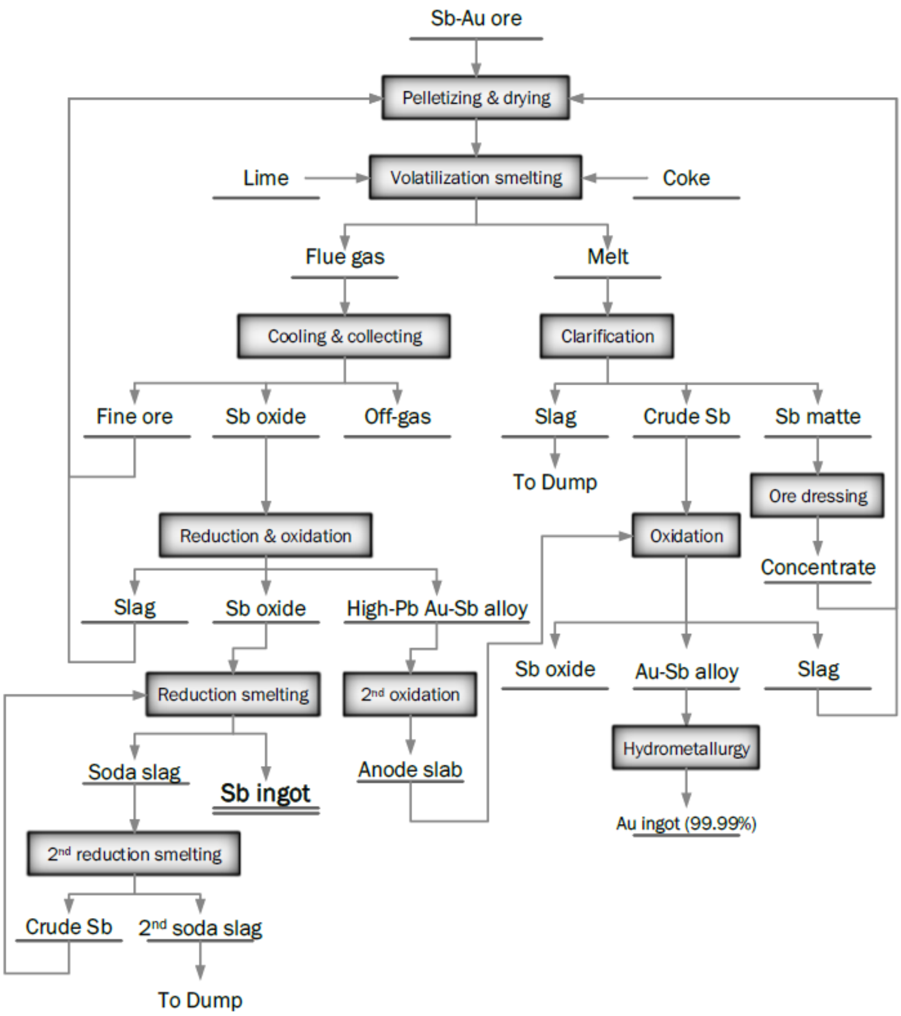

Figure 19. Flowsheet for the processing of Au-rich stibnite for the extraction of metallic antimony and gold (Moosavi-Khoonsari et al. 2022).

OTHER CONSIDERATIONS

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

Workplace exposure limit values are in place for one or more forms of antimony. In Europe, the most accepted limit is 0.5 mg/m³, but more severe limits exist, such as the 0.25 mg/m³ in Sweden (GESTIS 2022). However, some agencies are revising the existing limits and calculating new ones that involve respirable occupational exposure limits (OEL) instead of inhalable OELs. In 2018 the German BAuA (Federal Institute for Occupational Safety and Health) published a limit of 0.006 mg respirable Antimony/m³ for Antimony trioxide and Antimony trisulfide as part of the German TRGS 900 (Technical Rules for Hazardous Substances) (International Antimony Association 2022a).

Directive 2009/48 relating to the safety of toys establishes three migration limits for Antimony in toys:

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- 45 mg/kg in dry, brittle, powder-like or pliable toy material
- 3 mg/kg in liquid or sticky toy material
- 560 mg/kg in scraped-off toy material

Because of its toxicity for reproduction antimony is listed as a Substance of Very High Concern under REACH in annex XIV (ECHA 2022).

ENVIRONMENTAL ISSUES

Antimony (Sb) is a potentially toxic metalloid and is released into the environment through various pathways, including mining, ore transportation, smelting, manufacturing, and use of their products, disposal of wastes, and sludges, wastewater, and so on. (Stančić 2022, Mengchang et al 2019)

Studies indicate that antimony is retained in the soil through adsorption and can sorb onto clay minerals, oxides, and hydroxides in the soil and aquatic sediment (ATSDR 2019). Strong enrichment of soils in Sb can pose a considerable risk to the environment. It should be stressed, however, that real hazards will depend on Sb solubility rather than on its total concentrations (Lewińska 2018)

The following waste and environmental restrictions are established in the EU (International Antimony Association 2022b)

- The decision 2000/532/EC of 3 May 2000 stipulates that Antimony Trioxide shall be classified as "heavy metal" in the classification of hazardous waste.
- The decision 2003/33/EC establishing criteria and procedures for the acceptance of waste at landfills, gives leaching limit values for antimony from waste acceptable at landfills for inert waste.
- The Directive 2000/76/EC on the incineration of waste, and the EU Directive 2010/75 on Industrial Emissions and its best available techniques associated emissions limit values (BAT-AELs), include maximum air emission limit values for Antimony as well as for other possible emissions.

NORMATIVE REQUIREMENTS RELATED TO MINING/ANTIMONY MATERIAL PRODUCTION, USE AND PROCESSING OF THE MATERIAL

In 2015, the government of the Popular Republic of China issued the Emission standards of pollutants for stannum, antimony and mercury industries. The standard was formulated in a bid to implement laws and regulations including the Environmental Protection Law, the Law on the Prevention and Control of Water Pollution, the Law on the Control of Atmospheric Pollution and Marine Environment Protection as well as the Air Pollution Prevention and Control Action Plan.

The standard stipulates the ceiling value for the discharge of water and air pollutants and requirements on monitoring of this set of materials, including antimony.

In the US, companies are required to provide warning to California citizens about significant exposures to Antimony trioxide released in the environment, following the California proposition 65 or Safe Drinking Water and Toxic Enforcement Act of 1986. (International Antimony Association 2022b)

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SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF ANTIMONY FOR EXPORTING COUNTRIES

Table 13 lists the countries for which the economic value of exports of Antimony represents more than 0.1 % in the total value of their exports.

Table 13: Countries with highest economic shares of Antimony exports in their total exports

Country	Export value (USD)	Share in total exports (%)
Tajikistan	14 866 582	2.07%
Bolivia (Plurinational State of)	12 869 388	0.18%

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

For all other exporting countries, this share is below 0.1 %.

SOCIAL AND ETHICAL ASPECTS

No specific issues related to social or ethical aspects were identified.

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Novel uses of antimony in catalysis

The high electrocatalytic activities of SnO_2 doped with antimony (Sb), for two-electron oxygen reduction reaction (2e–-ORR) and one-electron water oxidation reaction (1e–-WOR) with extremely low affinity for H_2O_2 are promoted for use in H_2O_2 synthesis, low- temperature oxidative organic transformations, and water purification through the decomposition of organic pollutants (H. Tada et al., 2022). Sb is also used in selective catalytic reduction of NO with NH_3 over V-Sb/Ti catalysts. The V-Sb/Ti catalyst showed excellent activity in the range 200–300 °C (compared with V/Ti), with an optimum achieved for 2 wt.% Sb. (Kwon et al., 2018).

- Thin-film Sb Chalcogenide solar cells

Antimony is an ideal dopant due to its ionic radius similar to tin, so ATO, the antimony-doped tin(IV) oxide films, exhibit the lowest resistivity value of 1.23 x 10^{-2} Ωcm and the highest transmittance of 73 % (Bright C.I., 2007, Flores-Hernández R.B. et al. 2022, Ponja Sapna D., 2018).
ATOs can be applied in smart windows, lubricant oil, catalysts, sensors (humidity, gas), LIB & SIB battery additives, EMI shielding coatings, IR attenuation films & coatings.
TRL is in “Demonstration” for: lubricant oil, catalysts, sensors (humidity, gas), LIB & SIB battery additives, EMI shielding coatings, conductive coatings, conductive composites, IR attenuation films & coatings.

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- Application of $Bi_{0.5}Sb_{1.5}Te_3$ (BST) alloys in thermoelectric membranes

Thin-film thermoelectrics structured as layers of $Bi_{0.5}Sb_{1.5}Te_3$ (BST) alloys, have shown many attractive advantages, such as the micro cooling ability for solving heat dissipation issues in electronics and light mobile devices for harvesting human body heat. The high-quality $Bi_{0.5}Sb_{1.5}Te_3$ (BST) epitaxial thin film on a sapphire substrate grown by spontaneous van der Waals epitaxy (vdWE) is exfoliated and transferred onto versatile materials, creating high-performance thermoelectric membranes. Unprecedented millimeter-size vdWE BST membranes are produced by etching a pseudomorphic Te monolayer on the surface of a sapphire substrate in a dilute HF solution. The intact exfoliation and direct transfer for vdWE BST membranes maintain the high-quality crystallinity, resulting in a remarkable zT value (~0.9 at 300 K). These results represent the realisation of long-pursued but undemonstrated high-performance thin-film thermoelectric, paving the way for the design and fabrication of arbitrarily shaped thermoelectric devices. (Liangwei et al., 2021).

- A preparative approach to geometric effects in innovative solar cell types based on a nano cylindrical structure – SOLACYLIN (EU, 2015-2020)[5];

The SOLACYN Project has developed an "extremely thin absorber" (ETA) solar cell materials system based on antimony sulphide as the light absorber. The deposition of individual layers by “Atomic layer deposition” ALD has enabled them to find by a systematic approach that the optimal thickness of antimony sulphide is 60 nm in a planar configuration. In addition, they have identified ZnSas as an interfacial layer which provides proper adhesion and anti-recombination barrier properties with an optimised thickness of 0.6 nm. They have transferred this interface engineering to coaxial nano cylindrical geometry and varied the length of the cylinders as well as the thickness of each layer. We have explored several materials as alternatives to classical semiconductors, MoS_2, HfS_2, SnO_2, and V_2O_5.

- Era Chair Of Emerging Next-Generation Photovoltaics 5gsolar – 5G SOLAR (EU, 2020-2026)[6] ;

Different innovative photovoltaic solutions and products are needed to address the EU's significant environmental challenges in achieving and sustaining a green electricity market. The EU-funded 5GSOLAR project aims to further Europe’s sustainable development and clean energy goals and contribute to the European Research Area (ERA). To this end, it will converge research, development, and innovation as well as stakeholders, policymakers and society in the photovoltaics field. It will also create an European Research Area Chair team capable of implementing strategies and building a stakeholder network to help establish a renewable energy demo/briefing centre in Estonia and an EU joint graduate school in photovoltaics. The project will play a role in furthering Europe’s potential as a climate neutrality pioneer.

- Centre of Advanced Materials Research and Technology Transfer - CAMART^2 (EU, 2017-2025)[7]

The vision of CAMART^2 is to establish ISSP as the most important centre of excellence for education, science, innovation, and technology transfer in the Baltic States. ISSP will also become the hub for a collaboration and technology transfer platform (called "RIX-STO"") for materials physics-based high technologies, including

[5] https://cordis.europa.eu/project/id/647281
[6] https://cordis.europa.eu/project/id/952509
[7] https://cordis.europa.eu/project/id/739508

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scientists, entrepreneurs, investors, and policymakers on both sides of the Baltic Sea. The commitment from the Swedish partners assures successful modernization of ISSP, including an overall refinement of the educational programs, strengthening of the research and development activities towards higher technology readiness levels, the establishment of an innovation system and Open Access Laboratory, as well as ISO 9001 certification. The partners will be active in an ambitious program for networking and outreach to make academia and high-tech industries in the region around Riga and Stockholm flourish concerning scientific results, economic growth, and increased competitiveness. The region will benefit from an injection of highly educated young people, closer collaboration between academia and industry, and offering state-of-the-art open access research infrastructure boosting innovation and economy.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- ATMEN project (2017 -2022)[8]

A recent discovery is that the scattering of the energetic imaging electrons can cause a silicon impurity to move through the graphene lattice has revealed a potential for atomically precise manipulation using the Ångström-sized electron probe. To develop this into a practical technique, improvements in the description of beam-induced displacements, advances in heteroatom implantation, and a concerted effort towards the automation of manipulations are required. This project tackles these in a multidisciplinary effort combining innovative computational techniques with pioneering experiments in an instrument where a low-energy ion implantation chamber is directly connected to an advanced electron microscope. To demonstrate the power of the method, an atomic memory will be prototyped with an unprecedented memory density and will create heteroatom quantum corrals optimized for their plasmonic properties. The capability for atom-scale engineering of covalent materials opens a new vista for nanotechnology, pushing back the boundaries of the possible and allowing a plethora of materials science questions to be studied at the ultimate level of control.

- Solution-processed antimony chalcogenides based thin film solar cells: A brief overview of recent developments (2022)[9]

The search for an ideal absorber layer in thin-film solar cells seems to be a never-ending task. Apart from the solar absorber characteristics, antimony chalcogenide materials are gaining research interest predominantly due to their ribbon orientation and bandgap tunability in the entire solar spectrum. However, the challenges with open-circuit voltage deficit and low fill factor of solar cell devices remain unresolved. The reported highest power conversion efficiency with antimony chalcogenide absorber stays at 10.7%, where the absorber is made using a solution based hydrothermal synthesis method. In this mini-review, the latest developments related to solution-derived antimony chalcogenide absorber-based solar cells and the different strategies employed for improvements are presented in detail. With emphasis on the recent developments in the hydrothermal deposition of antimony chalcogenide absorber layer, the opportunities available to further enhance its properties through bandgap engineering and controlling the crystal orientation are discussed.

[8] https://cordis.europa.eu/project/id/756277
[9] https://www.sciencedirect.com/science/article/abs/pii/S0038092X22004686

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- The role of lone-pair electrons on electrocatalytic activity of copper antimony sulphide nanostructures (2022)[10]

Crystal engineering is an elegant approach to the synthesis and design of active electrocatalysts for the large-scale production of hydrogen. Better realization of the crystal structure of the electrocatalyst assists the development of active catalysts. Different properties such as thermal properties, optical properties etc., appear to be largely affected by the presence of nonbonding lone-pair in the crystal structure. In this work, we have studied the influence of nonbonding electron pairs residing in the crystal structure on the electrocatalytic activity of the electrocatalysts. Herein, we report the synthesis of the three distinct crystal phases of copper antimony sulfide nanostructures named chalcostibite (CuSbS2), skinnerite (Cu3SbS3), and famatinite (Cu3SbS4), and studied their electrocatalytic activity in neutral medium. Chalcostibite and skinnerite phase show much better activity towards electrocatalytic hydrogen evolution reaction than the famatinite phase. This is explained due to the presence of antimony (Sb) lone pair electron in the former two cases compared to the latter.

- The separation behaviour of impurity in antimony during vacuum distillation (2022)[11]

The models for depicting the variation tendencies of contents of Cu, Fe, Ni, Pb and Bi impurities in melt and distillate were established. The results proved that the mass transfer process was determined by the hybrid steps of mass transfer processes in the liquid boundary layer and at the liquid-gas interface for Pb and Bi impurities, whereas the rate-determining step was the mass transfer process at the liquid-gas interface for Cu, Fe and Ni impurities. The experimental results of Cu, Fe, Ni and Pb impurities in melt were coincident with the calculated results, while the experimental result was lower than the calculated result for the Bi impurity; the experimental result of Bi impurity in distillate was consistent with the calculated result, whereas there existed discrepancy for the Pb impurity; the marked increase of keff of Pb and Bi impurities during distillation were responsible for the difference between the experimental and calculated results in distillate. Additionally, the removal efficiencies of Cu, Fe and Ni impurities were higher than those of Pb and Bi impurities, the reason arose from that the vapor pressures of the latter were much closer to that of antimony than those of the former.

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