Perpetua Resources

ANTIMONY

A Critical Metalloid for Manufacturing, National Defense and the Next Generation of Energy Generation and Storage Technologies

PERPETUA RESOURCES

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ANTIMONY: A CRITICAL METALLOID FOR THE AMERICAN FUTURE

Introduction

Antimony, a listed critical mineral by the U.S. Department of Interior, is used in a wide variety of military, energy, industrial and consumer applications and yet, the country has no domestically mined source. Instead, antimony is primarily sourced directly or indirectly from China, Russia or Tajikistan which pose significant risks to the national supply chains. Other countries, including the UK, the EU, Canada, Australia, Germany, and Japan have also identified antimony as a highly strategic commodity, often ranking it equal to or higher than the rare earth elements (Surges, Leonard, 2014).

Antimony is considered critical due to its:

- Unique characteristics which make it a critical component in military, energy, and manufacturing sectors;
- Rarity of large commercially viable deposits outside of Chinese and Russian control;
- Scarcity of ore, oxide, and metal refining processing facilities outside of China;
- Low substitutability;
- Consumptive uses that result in low recycling rates;
- Much of the world's antimony comes from deposits where it is a by-product;
- Other risks of supply chain disruptions as outlined in the British Geological Survey (BGS) Critical Minerals risk list (BGS, 2015) and Critical Material list from the European Commission (EC, 2020).

In the United States, there is:

- No domestic primary antimony production;
- Very limited recycling related to lead-acid batteries only;
- Only one small scale secondary processing facility that depends on imported feedstock to produce other products;
- Resources in the U.S are located mainly in one mining district in Idaho (Stibnite-Yellow Pine), with much smaller deposits known in other places in Idaho, Alaska, Montana, and Nevada;
- Listed as a Critical Mineral by the U.S. Department of Interior (DoI, 2018) and the U.S. Geological Survey (USGS) in its most recent survey (Seal et al., 2018). This list was developed to serve as an initial focus, pursuant to Executive Order 13817, *"A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals*" (82 FR 60835).

Applications

Antimony has many industrial uses in green energy, high technology, electronics, fire retardant formulations used in nearly all consumer and industrial plastics, lead-acid batteries, a wide variety of military applications, as a catalyst in petroleum refining and the chemical industry. Emerging technology for large capacity storage batteries also points to antimony as a critical resource for the energy transition. This report will cover the applications in more details; however, highlights include:

- Flame retardant (plastics)
- Lead-acid batteries
- Military detonators
- Military smoke agents
- Solar panels
- Military primers
- Nuclear power plant shields
- Babbitt bearings for ships
- Circuit boards
- Wind turbines
- Night vision goggles
- Lasers
- Camouflage
- Large-capacity storage batteries

Upstream and Downstream Supply Chain Dominance by China, Russia, and their Allies

Much of the world's past production and known resources today occur in China, which has the bulk of the world's identified resources; other countries that have identified antimony resources include Russia, Bolivia, Canada, Mexico, South Africa, Tajikistan, and Turkey. The United States has no mined antimony sources, but the Stibnite Mining District in Stibnite, Idaho is one of the largest known economic deposits of antimony outside of China, Russia, or their satellites mines. The site is currently under environmental review for mining redevelopment by Perpetua Resources.

In terms of past, current, and potential future production, there are two broad categories: primary antimony producers and by-product antimony producers. Most the world's major deposits, in terms of contained metal, are disseminated and/or massive replacement deposits in carbonate rocks with antimony as the primary product and are concentrated in China and Russia and the deposit located in Stibnite, Idaho.

Today, some of the world's largest former antimony producers outside of China located in the Murchison Belt of South Africa were acquired by Chinese investment firms in 2015-2017 and are no longer producing antimony. Chinese interests have also obtained controlling interests in former producers in Bolivia, Australia, Tajikistan, Canada and elsewhere.

China, Russia, their satellites, and their political and economic allies dominate the world's antimony upstream supply chain (Figure 1), accounting for more than 97% of global mine production (USGS, 2021). The USGS (2021) reports U.S. net import reliance in 2020 was estimated at 81%, with most of the supplies primarily sourced directly or indirectly from China, Russia or Tajikistan (who's mines are under Chinese control).

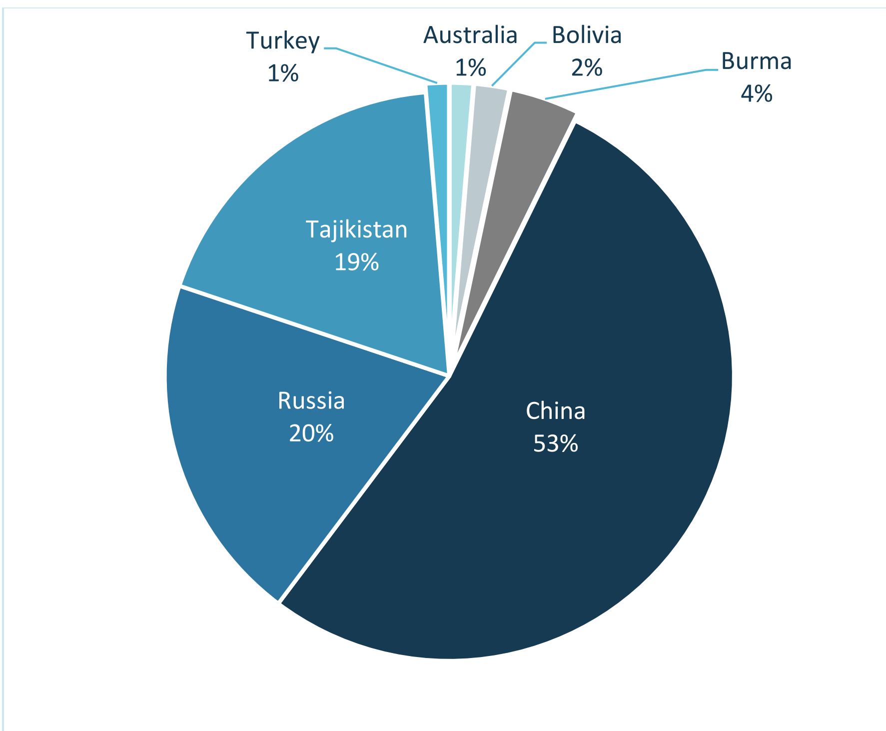


Figure 1: Distribution of Estimated Global Mine Production of Antimony (2020)

In 2013, China imposed restrictions for several years on the export of antimony-based products, reducing availability and increasing prices (Research in China, 2015). More recently, China has mentioned restricting exports of critical minerals as part of its trade negotiations (Baruzzi, 2019). As a result, the U.S. has current and potential future supply risk for antimony and antimony-based products, many of which are critical to the military, energy, and the broader economy.

Large numbers of smaller deposits occur as simple quartz-stibnite vein systems, but most of these types of deposits are small, with a few notable exceptions (Bliss and Orris, 1986). Globally a small percentage of production is sourced as a by-product of base metal mining, smelting and refining operations. Various compilations and articles describe regional antimony-enriched provinces and major individual mining districts from which antimony has been produced (Dessau, 1952; Muff, 1976; Gumiel and Arribas, 1987; Jiada, 1993; Hu and Zhou, 2012; Mascuñano et. al., 2011), but many of the districts and individual deposits in these compilations have been worked out or are not commercially viable.

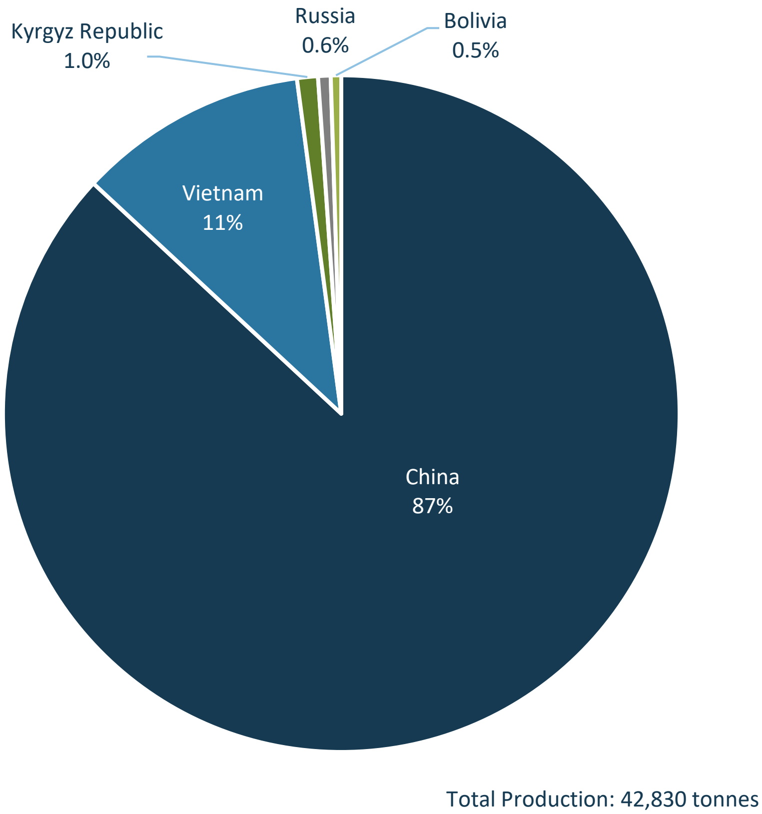


Figure 2: Recent global production distribution unwrought antimony metal 2010-14 (EC, 2017)

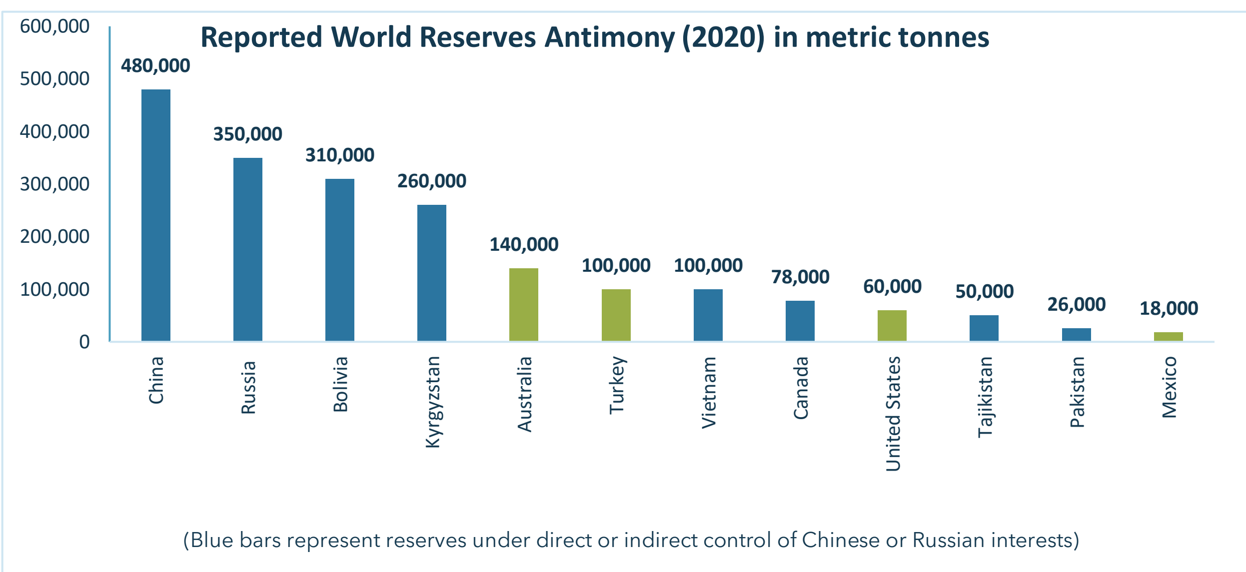


Figure 3: Reported Worldwide Reserves of Antimony in metric tonnes (from USGS 2021)

Current refined metal production is concentrated in a few countries (Figure 2: Recent global production distribution unwrought antimony metal 2010-14 (EC, 2017)Figure 2) and is reported in unwrought metal. Imports to the U.S. and other western country consumers are often routed through a complex network of traders in part to mask the dominant source of the raw materials from China and avoid trade tariffs. A similar upstream production situation exists for antimony oxides the other major form in which the metalloid is traded.

Reserve distribution is also similar to current market trading. Antimony reserves are concentrated in a few countries (Figure 3) with approximately 80% of known reserves located in countries hostile to U.S. interests (China, Russia, and their satellites and/or their political and economic allies).

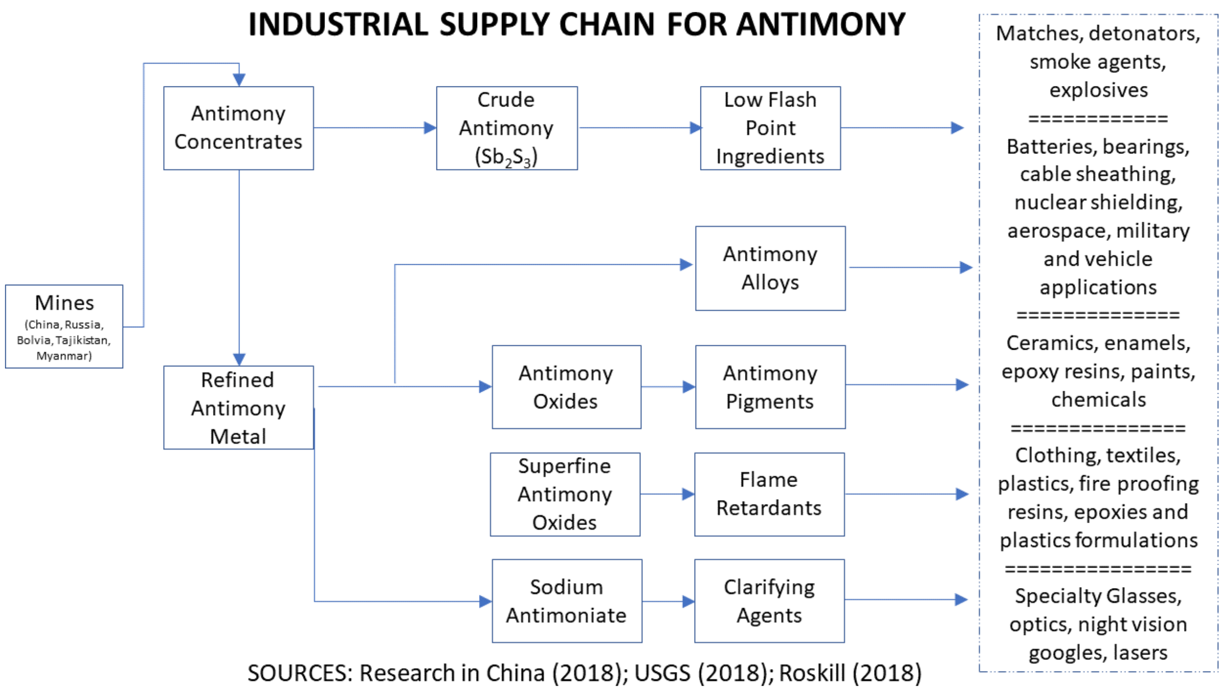


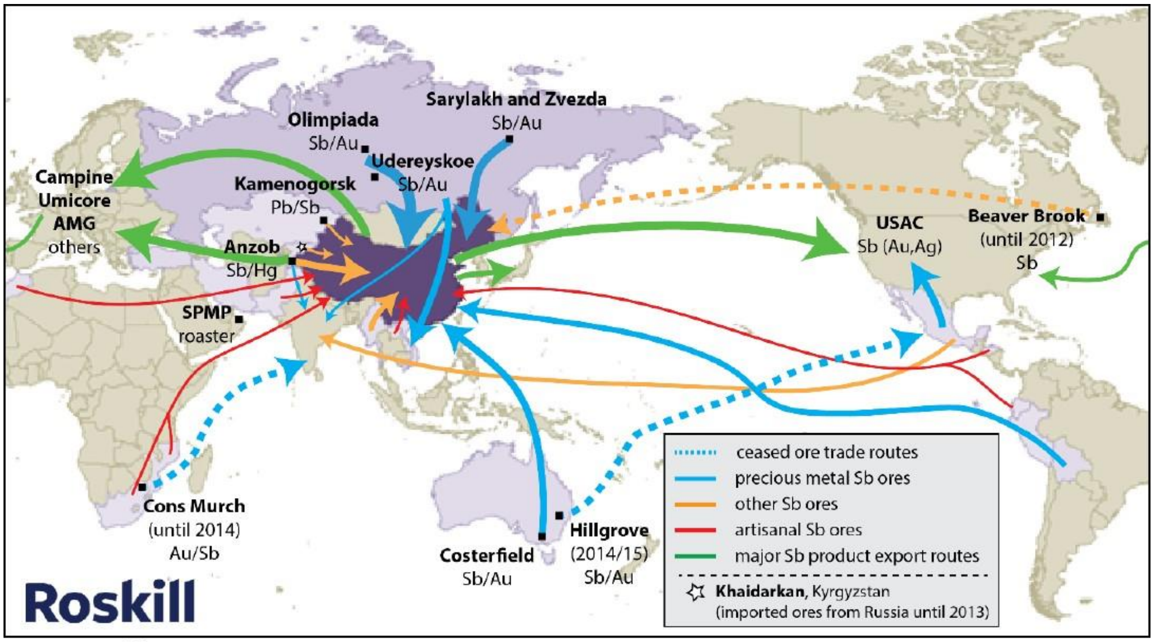
Figure 4: Antimony Supply Chain Architecture

Supply Chain

The antimony supply chain is complicated (Figure 4). It is concentrated around Chinese production, processing and fabrication facilities that extend through the downstream value-added manufacturing end of the supply chain with near total dominance throughout the entire sector, including direct and indirect control of other deposits and/or feedstock in Russia, Bolivia, Tajikistan, Canada and elsewhere.

Processing Facilities and Capacity

China dominates the world's antimony mining and beneficiation facilities – essentially controlling both the upstream and downstream ends of the commodity supply chain. Figure 5 shows a supply chain commodity flow map of antimony, highlighting the dominance China has over the antimony supply chain at both production and processing ends. The overwhelming majority of the world's antimony trioxide (used as flame retardant) processing facilities are in China with other smaller processing facilities, predominantly in Europe (Belgium), U.S. (Montana), South Korea, Japan, and India. Most of the non-Chinese facilities source their raw materials from China directly or indirectly and tracking of these largely private transaction supply chains is problematic. Construction of the Oman Antimony Roaster (OAR) was hoped to relieve some of this supply chain dominance by Chinese interests. The facility was hoped to potentially treat approximately 40ktpy of antimony-gold concentrates to produce antimony trioxide and approximately 20ktpy of antimony metal upon commercial startup. The facility must still obtain feed stocks and contracts and complete construction and may be at risk given recent military activity and unrest in the area and ownership and operations at the facility have not met expectations.



Source Roskill
Note: Purple shading represent relative scale of mine production

Figure 5: Antimony Supply Chain Dynamics Map (Roskill, 2018)

Demand Uncertainties

Antimony is typically traded in private transactions versus open markets and thus the movement of concentrates and refined products is not transparent and difficult to document. Many antimony applications involve the use of proprietary formulations and tracking the use and consumption of antimony-bearing products in the downstream supply chain is poor. Import numbers reported by the U.S. Department of Commerce and the USGS commodities groups are likely underestimating both net consumption and imports. There are essentially no significant processing facilities outside of China. Although there are small operations in several countries, none of these have enough capacity to significantly impact Chinese and Russian control over the markets.

Criticality

Antimony is the poster child of critical materials, appearing on almost every risk list published. In fact, antimony is considered a critical mineral by most western countries (EC, 2020; Australia, 2020; Nakano, 2021; NRCAN 2021, UK; BGS, 2015) including the U.S. (USGS, 2018) due to the metalloid's rarity, energy and defense applications, limited beneficiation facilities and the dominance of China and, to a lesser extent, Russia, and its satellites in the upstream and downstream supply chain.

In May 2018, the U.S. Department of the Interior, in coordination with other executive branch agencies, published a list of 35 critical minerals (DoI, 2018), that included antimony. This list was developed to serve as an initial focus, pursuant to the 2017 Executive Order 13817, *"A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals"* (82 FR 60835). In 2021, President Biden signed an Executive Order reinforcing the need to secure America's critical supply chain.

The 35 minerals and metals listed as "critical minerals" were chosen based on the significant role they play in U.S. economic and national security and because there is limited to no domestic supply. In the case of antimony, it is critical for defense applications, technology, and energy, and plays a role in every part of the secure and prosperous American life. Yet, with no domestic source, the supply chain is dominated by foreign adversaries and a small number of suppliers and processors who are generally not transparent in terms of quantities of materials mined, processed and supply chain marketing.

Antimony scores extremely high on the Herfindahl-Hirschman index (HHI), which measures the concentration of production by country (DoI, 2018). Higher scores on the index indicate a concentration of production from a single or limited source. The higher the score the more control a single or limited number of companies or countries has on a commodity, resulting in a high risk of supply chain disruptions.

In fact, despite the publicity associated with the supply chain for Rare Earth Elements (REEs), antimony typically is ranked as high or higher on various criticality measures than REEs by the British Geological Survey, European Union, Japan, and other western industrialized countries (Figure 6) in part due to the scarcity of large deposits amenable to mining and beneficiation via modern mining.

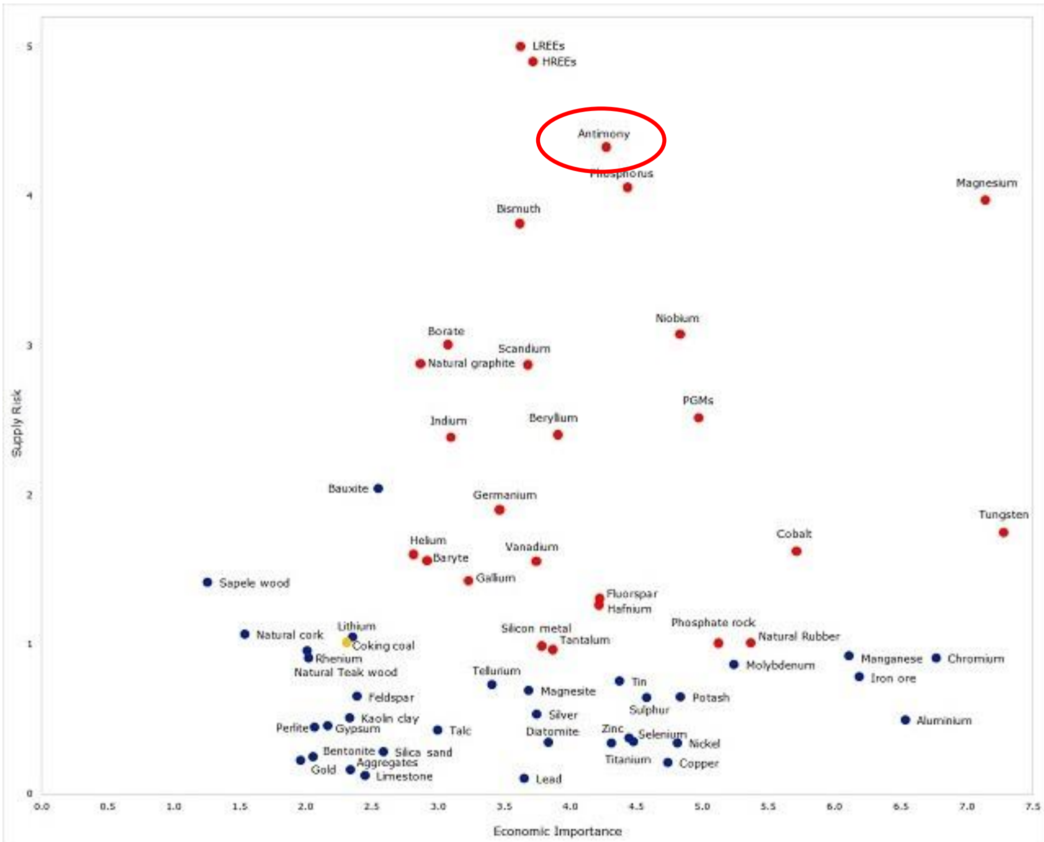


Figure 6: Antimony Supply Chain Risk and Economic Importance Chart (EC, 2018)

The 2012 the British Geological Survey identified antimony as the second most critical material on a list of 41 commodities considered to be of high risk of supply chain disruptions (BGS, 2012). Due to China's dominance of world production and reserves, compounded by the relatively low level of recycling and low substitutability it has remained high on various risk assessments (Figure 6). In 2013, 2017, and 2020 updates, antimony was still ranked high next to REEs as an element of extreme criticality. The European Commission also identified antimony as a key critical material in a report on critical raw materials for the European Union (EC, 2010), and again, in an updated study in 2014 and subsequent updates in later years (EC, 2014; EC, 2020). The European Commission noted that, out of the 19 raw materials considered critical, antimony is the only metal ranked as being in deficit in all three of the time horizons evaluated (2012, 2014 and 2020).

Here in the United States, Department of Defense (DOD) noted the importance of antimony for defense applications in 2013, when it ranked antimony #2 in the list of strategic and non-fuel defense material shortfalls (U.S. DOD, 2013) and predicted a shortfall of 20,500 tons in a four-year period and recommended strategic stockpiling of ~11,000 tons of antimony and other mitigation options to address this shortfall. The agency has been acquiring antimony at a recommended rate of approximately 1,100 metric tonnes per year (USGS, 2021) since it was re-added to the National Defense Stockpile in 2018. For the decade prior to this, between 2010-2018, the U.S. government had acquired 100% of its antimony for its munitions plants directly from China. In 2019, the DOD issued a solicitation and grant program to help locate and develop sources of high purity stibnite for ammunition primers for the Defense Logistics Agency National Strategic Stockpile (DOD, 2019).

Domestic Opportunities

There is only a single major antimony deposit in North America, located in the Stibnite-Yellow Pine Mining District of central Idaho. The only reported U.S. reserves are from this site and the operator, Perpetua Resources, has completed a positive feasibility study and is in the process of permitting mining operations at the site.

The Stibnite-Yellow Pine District provided 90% of the U.S. antimony supplies during WWII (Wooten, 1947) and the Korean War and, when Japan's invasion of China cut off supplies to the U.S., which was a well-recognized risk at the time. Henderson (1934) noted:

> "*Nearly total national dependence on antimony from China in time of peace increases the risk of a nearly total cutoff of our supply in the early months of a war. Such dependence would be carrying all our antimony eggs in the largest, but weakest basket. Continuous competition with Chinese antimony by a well-founded domestic smelting industry using ore from near sources will not only decrease the possibilities of an extreme shortage of this strategic metal in the event of war but will tend towards a reasonable average price level without violent fluctuations under peace conditions*."

During WWII, Henderson's statement rang true following the disruptions of numerous commodity supply chains, including antimony, by both the Germans and Japanese. The following statements emphasize how a minor, but critical mineral, can influence a whole war (note that the tungsten produced at Stibnite was a by-product of ongoing antimony production):

> *"…In the opinion of the Munitions Board, the discovery of that tungsten mine at Stibnite, Idaho, in 1942 [1941] shortened World War II by at least one year and saved the lives of a million American soldiers…" (Congressional Record 1956)*

> *"…A single mine [Stibnite], setting aside gold ore for a month, extracted enough tungsten to toughen 75 million pounds of steel. Because tungsten from mines in China (the previous source) had to fly the deadly Himalaya hump to reach Allied mills, the value of Idaho's tungsten was measured not in gold but in blood…" (Arrington, 1994)*

Deposits in the Stibnite District of Idaho comprise some of the largest known economic deposits of antimony in the world, outside of China, Russia or their satellite mines and is currently in the permitting stage for redevelopment. The brownfields nature of the site, largely as a result of wartime mining, provides an opportunity for site restoration and Perpetua Resources has fully integrated reclamation and restoration of the legacy mine impacts into the proposed Plan of Restoration and Operations for the Stibnite Gold Project.

If permitted, the project would provide significant gold and antimony production along with the funds to restore the site, at no cost to U.S. taxpayers. This operation if permitted as proposed could produce on average 35% of U.S. demand over the first six years of operations (M3, 2021).

By-product production from lead and silver mines in the Silver Valley, Idaho, and lead-zinc mines in the Viburnum trend in Montana has and still does provide some antimony in the form of antimony-bearing lead concentrates, but the antimony metal content is quite small and overall production is insignificant.

U.S. SUPPLY CHAIN

Historically, the U.S. met a significant amount of its demand from domestic mine production, but imports began to climb rapidly in the early 1980s from ~12,000 tonnes in 1982 to ~24,000 tonnes five years later, and passing 35,000 tonnes in 1995, before reaching a peak of 41,600 tonnes in 2000. Imports have fallen to ~22,700 tonnes in 2019 as the result of the effects of rising prices, the global financial crisis andsubstitution. According to the USGS (2019), there was no domestic mine production of antimony in 2018 or 2019, and there is one processing facility in Montana producing minor amounts of antimony metal and oxide from recycled materials and imported feedstock.

The USGS (2019) estimates U.S. net imports to continue to be dominated by China for metal, ores and concentrate and processed antimony oxides. Mexican imports are the source of the feedstock for the plant in Montana, part of which came from concentrates imported from a now closed mine in Australia for roasting in Mexico before final processing in Montana, but which meets only a minor component of U.S. demand; Belgian imports come from a processing facility there that imports feedstock from elsewhere, dominantly from China, hence imports from Belgium do not reduce U.S. reliance on China since it is the dominant feed source for those facilities – a situation common throughout the downstream processing end of the supply chain.

Current reported worldwide reserves by country (Figure 7), tells a rather stark picture as to where future antimony supplies may be, with most known reserves from countries potentially hostile to U.S. interests.

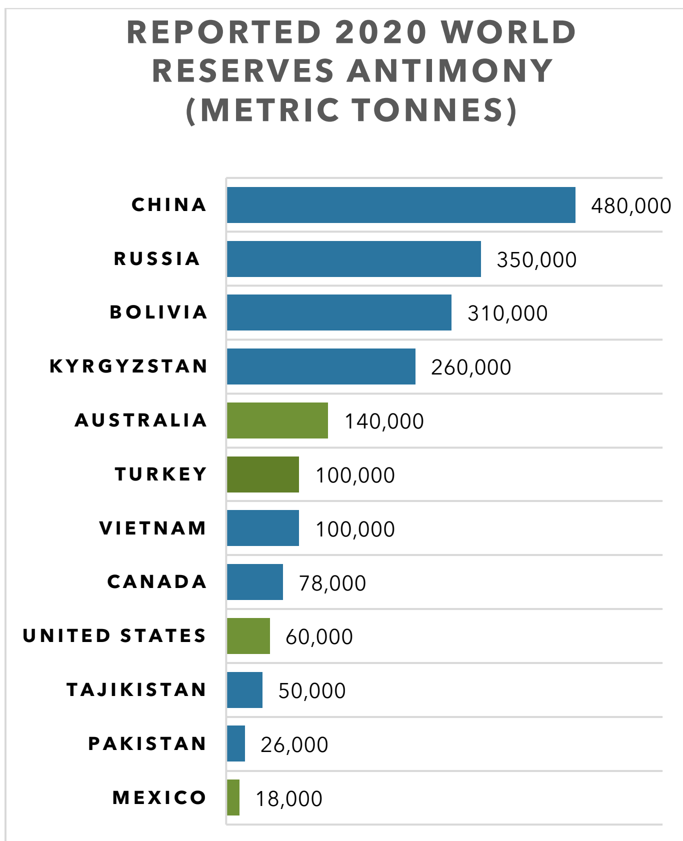


*Figure 7: Worldwide Antimony Reserves (metric tonnes) by Country**
Source: USGS 2021 Commodity Summary for Antimony, published company and country reports. Values in blue denote production under direct or indirect control of Chinese and/or Russian interests.

Smelting and Refining Components of Upstream Supply Chain

Outside of China, integration of mining and smelting (or downstream processing) has become rarer as previously integrated operations have found it difficult to compete with Chinese production. For that matter, there is little smelter production of any scale outside of China. Tri-Star Resources and U.S. Antimony Corp. (Montana) are attempting to integrate mining supply with processing facilities but are inrelatively early stages of development and neither has so far been successful, running into financial and operational hurdles. Tri-Star began construction of its smelter in Oman in 2016 and was in commissioning in 2019. If successful, this facility will become the first major non-Chinese smelter to be placed into operation since the 1990s, however, it is entirely dependent on imported feedstock from other locations. As the facility approached commercial production Chinese interests purchased the foreign mines that Tri-Star had arranged streaming agreements with and then shut them down – shuttering the ability of the Oman facility to obtain feedstock.

There are several facilities in Belgium, France, Bolivia, and India producing primary trioxide in relatively small quantities compared to Chinese output and recycling antimony from lead acid batteries; outside of Bolivia, none produce antimony from feed sourced in their respective country's mines and are therefore entirely dependent on imported feedstock.

China has been increasingly importing antimony concentrates since 2007, with imports of concentrates (not contained metal) increasing from 17,000 tonnes in 2007 to more than 68,000 tonnes in 2012 (Minmetals, 2013) and ~64,500 tonnes in 2013 (Confidential Report, 2014). Looking at contained metals, Chinese imports of antimony in concentrates are estimated at ~25,500 tonnes in 2013, led by Russia (~8,300 tonnes of contained antimony in 2013), Australia (~5,300 tonnes), Tajikistan (~4,400 tonnes) and Myanmar (~2,800 tonnes), although smuggled imports are likely much higher from Myanmar (Confidential Report, 2014). These imports illustrate the declining mine production in China discussed above.

China's State Reserve Bureau (SRB) has been active in recent years buying antimony metal in China, purchasing approximately 10,000 tonnes in 2013. The extent of China's antimony stockpiles is unknown, although they are thought to be considerable. Roskill (2015) reports the SRB does not buy under its own name but through state-owned enterprises. Given the influence of China Minmetals, Hunan Nonferrous Metals and China Tin Group (all state-owned) on the antimony market – it is near impossible to precisely quantify the extent of Chinese material stocks. Apart from the material held by the SRB, Minmetals (as of2014) was understood to have maintained a stockpile of ~20,000 tonnes of metal and oxide in Guangxi warehouses. Moving forward, it is unknown if the SRB or Minmetals will continue to purchase production for stockpiles (Confidential Report, 2014).

A private exchange, the Fanya Minor Metals Exchange, that functioned as a quasi-ETF began warehousing minor metals in 2014, reportedly held 2,600 tonnes of antimony as of June 30, 2014 (Confidential Report, 2014). As of May 2015, Fanya's figures indicated that it held 20,237 tonnes of antimony in its warehouse (Roskill, 2015). However recent news reports the rare earths arm of state-owned China Minmetals Corp. bought metal and rare earth inventories formerly held by the defunct Fanya Metal Exchange as the sole bidder in online auctions, paying US$110 million (Reuters, 2019). Global antimony production in 2018 was 140kt, according to the USGS, with China accounting for more than 70% of supply (USGS, 2019). The Fanya volume auctioned is equivalent to more than 13% of 2018's annual global output.

Recycling Opportunities

The USGS (USGS, 2021) reported that approximately 18% of total antimony consumption use in the U.S. was recycled material, primarily in the lead-acid battery recycling sector. Material separations technologies are advancing, but opportunities to recover antimony through recycling are limited in part due to the consumptive use of antimony in many materials, making recovery difficult. There are numerous requirements for tracking antimony and other metallic materials in use in the U.S. due to the requirements for raw materials producers, processors, manufacturers, and end users to comply with the Resource Conservation and Recovery Act (RCRA). Because of this requirement, recycling is typically already conducted where practical and possible and additional policies or regulatory requirements would likely not change the amounts or availability of recyclable materials.

Although there is some promise, many uses of antimony are simply consumptive and recovery is difficult in part due to the compounds and alloys in which antimony is used. No recovery of antimony from flame retardants typically takes place as it is a consumptive use. Antimony is present in low concentrations in high volumes of plastics, and some unintentional reclamation takes place through normal plastic recycling routes. Traditionally, most secondary antimony has been recovered by recycling used in lead acid batteries and the material is re-used locally by the same industry.

Umicore (Belgium) has developed a processing technology to separate 17 different elements from circuit board scrap and from electronic waste, PGMs, indium and antimony are refined for re-use (Umicore, 2007). Other elements contained within the circuit board, including gallium, are generally disposed of as slag. Dupont et al.

(2016) discuss the opportunities for recycling and note that there has been limited work outside of laboratory testing to evaluate recycling of antimony from less conventional sources such as plastics.

MARKET PROJECTIONS

Roskill (2012, 2015, 2018, 2020) has noted that new capacity could enter the market to meet growing antimony demand but also notes that increased production elsewhere outside of China is likely to offset any declines in Chinese production in the short term.

Roskill (2020) has identified several significant additional potential sources of antimony concentrates in Europe, North America, Africa, and Oceania that could add over 14,000 tonnes per year antimony to world mine capacity within the next four years (but this is less than 10% of current mine supply). However, non-China antimony deposits thus far identified are insufficient to keep up with demand increases (Confidential Report, 2014). Based on the forecast for demand growth and China's falling production, it is estimated that an additional 18,000 tonnes of annual primary mine production will need to be brought online through 2030 to meet demand (Confidential Report, 2014).

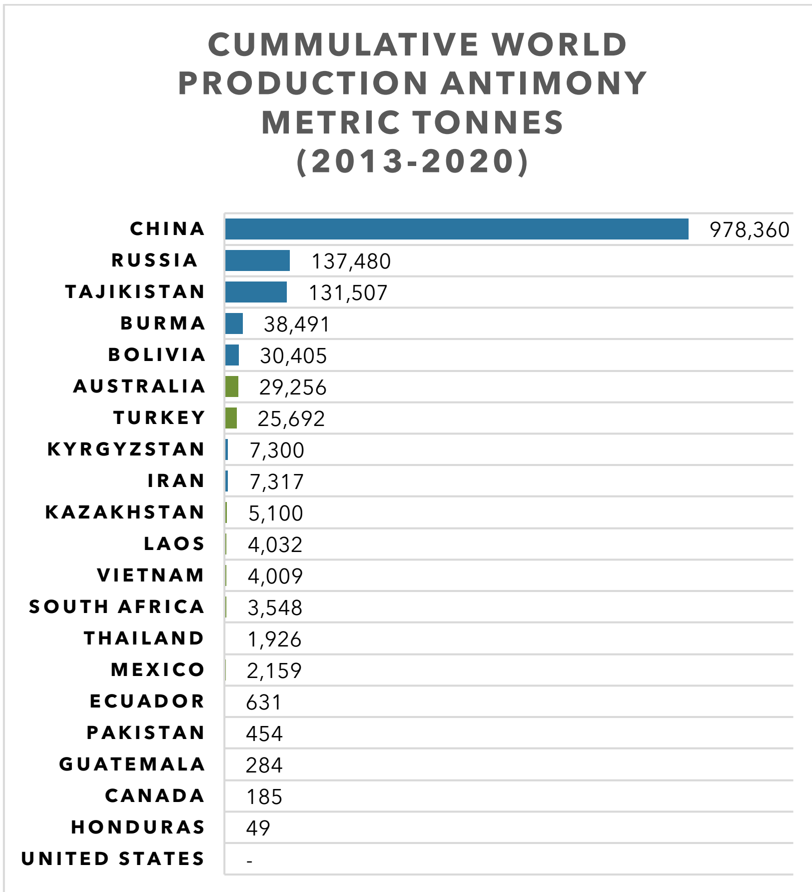


Figure 8: Total Cumulative Percent Global Mine Production Antimony by Country 2013-2020 in metric tonnes. Sources: USGS Annual Commodity Reports 2013-2021, British Geological Survey, 2017. Values in red denote production under direct or indirect control of Chinese and/or Russian interests.

Chinese supply chain problems arose in the first quarter of 2016, including the closure of the Vietnam border, a primary trade route for antimony to European and other Asian markets, leading to a ~$50/tonne increase in spot prices (Metals Bulletin, March 24, 2016). The Chinese government announced on January 4, 2016, export quotas for the first half of 2016 at 38,686 tonnes of antimony trioxide and 3,224 tonnes of antimony metal (Metals Bulletin, January 4, 2016), which equates to approximately just 20% of world demand, with significant potential supply-chain impacts given China's near monopoly of antimony supply.

The markets continue to be dominated by Chinese monopoly, as they have been through the past century (Figure 8). The steady increase in production from the 1990s forward corresponds to increasing use in flame retardants as more toxic and environmentally unfriendly flame-retardant materials have been phased out by EU and U.S. regulations. The abrupt increase in price in 2010 (Figure 9) reflects the Chinese government's shut down of exports of antimony to non-Chinese affiliated countries (simultaneously with the well-publicized worldwide embargo on REE exports).

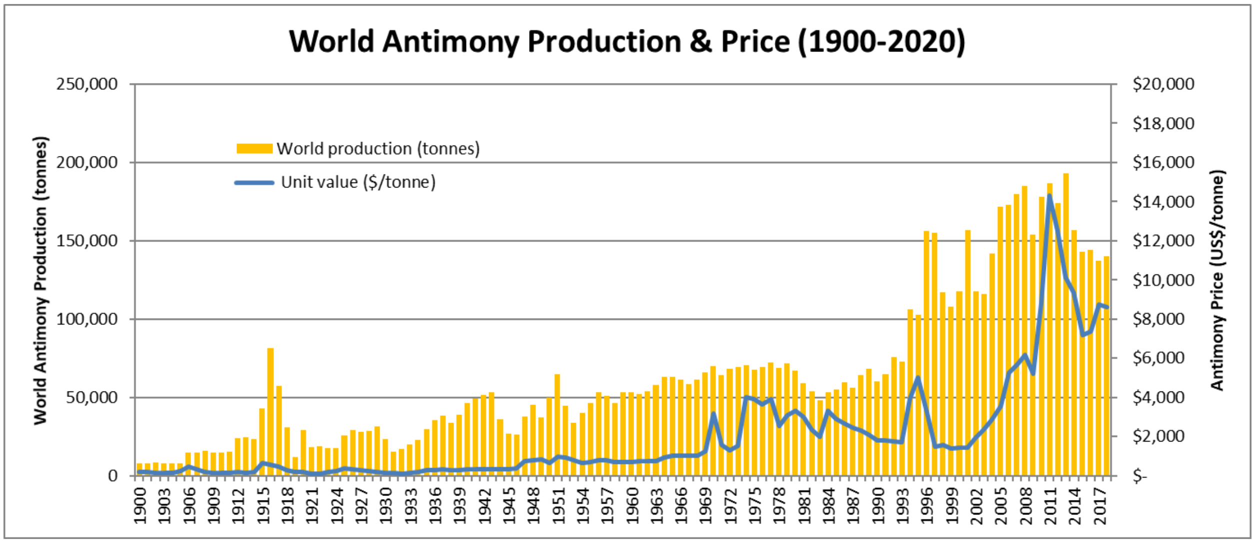


Figure 9: World Antimony Production (metric tonnes) and Price (per metric tonne) 1900-2020 Source: USGS Commodity Summaries and Mineral Yearbooks

PRIMARY PRODUCTION AND MATERIAL PROCESSING OUTLOOK

The global pandemic of 2020 and subsequent shipping disruptions created a unique awareness among Americans of our reliance on foreign nations for the goods we want and need to keep our economy running and our country safe. As policy makers look to secure our supply chains, rebuild infrastructure, and prepare for a large-scale energy transition, mined minerals and metals should take center stage.

Besides possible factors affecting the downstream development of appropriate manufacturing capabilities for materials used in new energy technology, there are significant bottlenecks in the upstream end for many commodities used to make the materials used in the manufacturing process.

Resource nationalism can, and does, affect the availability of upstream supply chains as evidenced in numerous examples in the last two decades. International and internal conflicts and wars in producing countries and regions have in the past (and are expected to in the future) presented problems as well. Loss of access to potential regions with appropriate geological characteristics for discovery of new deposits is a long-term problem, particularly in the U.S., as urbanization and land management decisions made over time have restricted access to large areas of public land potentially favorable to discovery of deposits that would maintain security of supply. In addition, there are particularly long lead times for permitting of mineral development projects, which have been put in place to protect the environment but could delay development of domestic resources vital to the energy sector during unexpected disruptions in the upstream supply chain.

Recent drops in production of antimony from China, the world's largest producer, and closure of production from other sources in South Africa, Australia and New Brunswick have been partially offset by increases from other sources, notably Russia, Mexico, Bolivia, Turkey and primarily Tajikistan. Although smaller operations may start up and temporarily provide supplies, the long-term outlook is a deficit for antimony (Roskill, 2012, 2015, 2018). Based on the forecast for demand growth and China's falling production, it is estimated that an additional 18,000 tonnes of annual primary mine production will need to be brought online through 2030 to meet anticipated demand (Confidential Report, 2014).

In the U.S., long timelines for permitting operations on both public and private lands pose additional challenges to development of domestic antimony resources. Recycling accounts for some supply, primarily from lead-acid batteries, but much of the antimony used in the U.S. cannot be recycled and is, as a result, imported.

Worldwide Upstream Supply Chain

Of the ~200,000 tonnes of contained antimony presently produced annually on a worldwide basis, approximately one-quarter is from secondary production via recycling of antimony bearing metal alloys (primarily lead-acid batteries). Of the balance, three-quarters of that is produced as primary antimony, while approximately 10% is produced from antimony bearing residues from lead smelting. As such, approximately 135,000 tonnes per annum of antimony is produced from antimony concentrates and ores (Confidential Report, 2014). As can be seen from the charts (Figure 8), China remains by far the world's largest producer of primary antimony.

CHINA

Six companies, including Hunan Hsikwangshan, Guangxi China Tin and Hunan Chenzhou Mining account for 90% of China's supply (Roskill, 2012), accounting for around 70% of official world mine production in 2011, down from around 80% in earlier years.

According to Chinese government statistics, over 75% of all of China's reported primary antimony production in 2013 was from Hunan province, followed far behind by Guangxi and Yunnan, however, government statistics under report and are adjusted regularly without explanation, making analysis challenging (Roskill, 2015). However, Hsikwangshan Twinkling Star Company Limited (Twinkling Star) is acknowledged as the world's largest integrated antimony producer. Located in Lengshuijiang, it most recently produced ~30% of antimony products in China and ~25% globally. Capacity is ~32,000 tonnes per annum of contained antimony metal plus trioxide. Twinkling Star is a state-owned company; its parent corporation is the Hunan Nonferrous Group, which itself is majority owned by China Minmetals Corporation (Minmetals). In 2012, coincident with the imposition of exports quotas by China, it was reported by the local Government in Lengshuijiang, Hunan Province, which accounts for about 60% of the world antimony supply, shuttered almost all its mines and smelters. Also, officials in

Lengshuijiang announced that after more than 110 years of continuous mining, the area now had only five years of mining life left (USGS Mineral Commodities Summary, 2012).

Further, on February 22, 2016 (Metals Bulletin, 2016), Hsikwangshan Twinkling Star, the largest antimony producer in the world, announced it had curtailed all production activities at its concentrator and cut 250 jobs to save costs amid a low-price environment. Twinkling Star cut production to 22,000 tonnes in 2015 from 28,600 tonnes of antimony metal in 2014, according to company reports.

Chenzhou Mining Company Limited (Chenzhou) is an integrated antimony and gold producer, producing approximately 19,000 tonnes of antimony products per annum and 6 tonnes of gold. As their own mine contains significant amounts of gold, Chenzhou operates a recovery circuit to capture gold from antimony smelting and separate it using an electrowinning refining process. Chenzhou Mining is majority owned by the Hunan Gold Group (aka Hunan Jinxin Gold Group) and is therefore considered a state-owned company. Other large operations in China include Multi Antimony Corp. (4,000 tonnes), China Tin Group(~4,000 tonnes), Guangxi Youngsun Metals (~10,000 tonnes) plus, following a government-imposed consolidation, there are nine smelters (apart from Twinkling Star's operation) in Lengshuijiang, each witha minimum capacity of 5,000 tonnes per annum (Confidential Report, 2014).

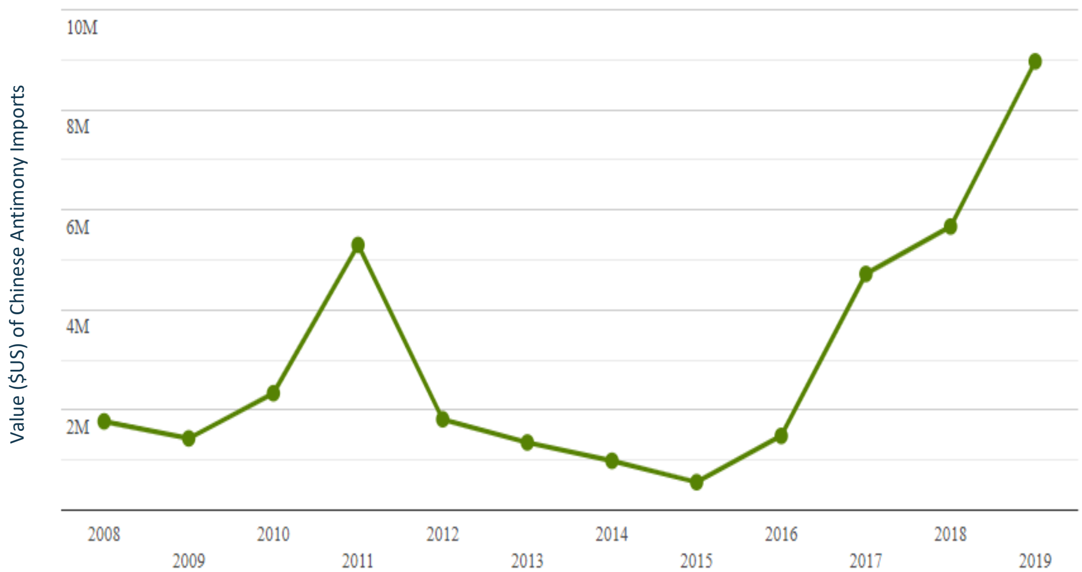


Figure 10: Total Estimate Value ($US) of Chinese Antimony imports 2008-2019
(Source: Trend Economy, 2021)

China appears unwilling (and potentially unable) to maintain its level of mine production given resource depletion, rising costs, environmental crackdowns, and resource conservation (Confidential Report, 2014). As a result, production in China is unlikely to increase over the next few years and could even fall in the face of government determination to limit environmental damage from smaller operations (Roskill, 2012).

The Xikuangshan deposit in Hunan Province, China, is and has been the world's leading source of antimony for the past century (Panov and No, 1989; Jiada, 1993; Fan and others, 2004). Operations in the District have been active nearly continuously since the 16th century (Eyi, 2012). The deposit covers an area of approximately 16 square kilometers (km2), has an average grade of 4% antimony, and contains more than 2 million metric tons of antimony (Yang et al, 2006). In addition to simple quartz-stibnite deposits, China also has important antimony-gold-tungsten deposits such as Woxi (Jiada, 1993). Chinese production is expected to continue to decline, but Chinese imports are expected to continue to rise as demand increases, thus making Chinese overtures to current and future producers become more aggressive and competitive. Figure 10 outlines the estimated amount of imports in U.S. dollars of antimony by China between 2008-2019.

RUSSIA

GEOPROMINING

Other sources of antimony outside China include several operations in Yakutia in the Russian Far East operated by GeoProMining. GeoProMining operates two underground Gold-Antimony mines at Sarylakh and Sentachan approximately 700km from each other. Gold-antimony concentrates are produced at both operations and processed at a facility near Sentachan. Although these underground mines have small throughput, they contain some of the largest known antimony resources and reserves in terms of grade and contained metal in the world outside of China. GeoProMining is not particularly transparent in their public filings regarding antimony processing and output, but some of the concentrate is shipped to China for processing. In their last public release of resources and reserves in 2017, GeoProMining outlined resources at Sarylakh-Surma operations containing 65,000 tonnes metal and reserves of 42,000 tonnes of contained antimony metal (GeoProMining, 2017). At Zvezda operations the company reported resources totaling 82,000 tonnes and reserves totaling 76,000 tonnes of contained metal. In 2017, the reported output capacity was 5,000-6,000 tonnes of contained antimony in gold-antimony concentrates which were at that time shipped to China for processing. In Q4/2019, a new processing plant near the ore deposit with an annual capacity of 30 kt of antimony-bearing concentrates was commissioned and was undergoing start-up. The company is private and is producing roughly 6,000-7,000 tpa of contained antimony in concentrate. Antimony production has steadily increased after an infusion of capital from a syndicate of Russian, CIS and European banks in 2013. Since then, GeoProMining has expanded their gold operations considerably and reported nearly doubled their gold output, but no longer reports the antimony content or production from their mines or plants in a usable format.

POLYUS

The largest known antimony deposit in the world outside China is also in the Russian Far East located at Olympiada and operated by Polyus. As with the Yakutia operations, antimony is recovered as a by-product of gold mining operations and Olympiada is Russia's largest operating gold mine. Between 2017-2018, Polyus constructed and commissioned an antimony plant which reportedly reached commercial production in 2018. Concentrates were reportedly shipped to China and South Korea for final processing. Polyus reported in 2017 and 2018 news releases and filings that it intended to produce an estimated 11 million tonnes (mt) of high antimony-gold ore between 2017 and 2026 and that it was targeting to obtain up to 15% share of global output. Reportedly approximately 11,000 tonnes of antimony in concentrate were produced in Q1/2019 (Polyus, 2019), but the antimony plant was reportedly shut down shortly after. In subsequent news reports between 2020-2021, Polyus has reported no direct sales of antimony nor quantities contained in concentrates and only a by-product credit, so output is uncertain. Presumably, the concentrates are being shipped to China as has been prior to the plant's commissioning. Total Australasian Joint Ore Reserves Committee (JORC) complaint resources at Olympiada are reported to be over 217,000 tonnes and reserves of 120,000 tonnes of contained antimony.

The high antimony ores are metallurgically complex and whether the contained antimony becomes commercially available is dependent on the success of ongoing research and development of processing techniques (Mining Technology, 2018). As of Q1/2019, Polyus reports in its annual quarterly reports that it has curtailed introduction of high antimony ores into its plants and antimony output has decreased significantly (-68%) from the previous quarter possibly reflecting the difficulties of recovery of the antimony in the plant. In 2020, Polyus reported zero production of antimony concentrates from these operations and recent industry reports indicate their plant has been plagued by recovery and operational issues, so it is questionable whether the company's forecasts are reliable (Metals Bulletin, June 5, 2020).

FORMER SOVIET SATELLITES

TALCO (TAJIKISTAN)

On June 24, 2018, (Indian Express, 2018) Tajikistan, the impoverished former Soviet satellite announced construction of a new $US200 million gold and antimony mining venture as Beijing expands its hold over the Central Asian country's mineral resources. The venture between Tajikistan's state-owned aluminum smelter Talco and Chinese company Tibet Huayu Mining Co. Ltd is expected to produce 1.5 tons of gold annually and 16,000 tons per annum of antimony in concentrates with production originally planned to start in 2020. The project has seen numerous delays, cost overruns and problems to date including conflicts between Chinese workers and Tajik citizens. The joint venture delayed its start-up because of the coronavirus pandemic and the Tajik Ministry of Mines reported plans to begin commercial production by Q4/2020 in Q2/2020 with an increase in output to as much as 21,000 tonnes of antimony per annum (Reuters, 2021). A subsequent news release by Huaya noted the project delays, announced the need for additional financing to complete the construction of the project, and a scaled back production scenario that would likely begin in 2021 at an unspecified date (Asian Metal, 2020). The venture covers the Konchoch, Chulobi and Skalny deposits in Tajikistan's northeastern Sughd Province. China has acquired rights to a number of major mineral deposits and exploration concessions in Tajikistan in exchange for Chinese loans and investment. Chinese investment has been facilitated by the state-owned Export-Import Bank of China, to which Tajikistan reportedly owes more than $US1.2 billion, equivalent to nearly a fifth of its GDP for Talco projects alone. In 2018, another Chinese company, TBEA, acquired the rights to operate another small-scale antimony mine in Tajikistan's northern Sugd region as partial compensation for its construction of a power plant. The status of this project of uncertain.

COMSUP COMMODITIES/ANZOB (TAJIKISTAN)

A New Jersey based company, Comsup Commodities Inc. (via Anzob LCC) owns approximately 50% of the Jizhikrut antimony-mercury deposit in Tajikistan; the mine is estimated to be producing at a rate of 4,500-7,500 tonnes per annum of contained antimony-mercury concentrates albeit with high mercury (0.6%-1.0%) which limits its downstream sale and use (USGS, 2015). Previously, the concentrate was shipped to the Kadamjai smelter in Kyrgyzstan but, for the last decade, has been sold to China. A smelter was built in 2013 near the mine using Chinese technology, but the smelter has proven uneconomic to operate and the bulk of mine production is exported to third-party smelters. Comsup has been involved in the antimony business in Tajikistan since 2005. However, recently there have been disruptions in Comsup's activities due to alleged corruption in the government and mining sector. Chinese investment in the mining sector in Tajikistan has been significant in the last decade and China owns over half of the country's US$3.2 billion debt and has been taking hard assets such as mines and processing plants in exchange for the debt and routing output to Chinese government-owned or operated companies. Thus, output from Comsup's Tajik operations is likely to remain unstable and unavailable to western buyers.

AFRICA

MURCHISON BELT

The Consolidated Murchison mines in South Africa which make up the famous "Antimony Line" had been operating since the 1930s. The operations are situated in the Murchison greenstone belt of the north-eastern Kaapvaal craton. South Africa was for many years one of the free world's largest antimony producers with gold as a co-product (Pearton and Viljoen, 1988). Historical production starting in 1942 during WWII up through 2015 was 605 kt of antimony (in both sulphide and oxide form) averaging 3.3% Sb and 44.7 tonnes (1.5 Moz) of gold from 24 million tonnes of ore at a grade of 2g/t Au. Both gold and antimony values were typically required in the ores to support the underground mining and processing costs in the post WWII era. Since the mid-1970s, the area has had declining production and grades and most of the region's deposits are worked out, and the major mines were shut down in 2014 and processing facilities closed in 2015. Masetlana et. al. (2019) reports reserves of antimony total 27kt as of the end of 2018. No significant antimony production has occurred since that closure. Between 2015-2017 Chinese interests have bought the major former antimony-producing mines in the District and have not reported antimony production, but it is likely that if operations do restart the antimony-gold concentrates will remain under Chinese control.

MEXICO

Mexico became a significant producer of antimony prior to and during WWI and WWII, with numerous mines supplying Mexican smelters and U.S. smelters and roasters in Texas and Utah with feedstock (Seal et al., 2018). Typical, but not all Mexican antimony concentrates contain large amounts of impurities such as arsenic, mercury, copper and lead making them unsuitable for many industrial and defense needs. Most antimony is recovered from base metal rich (copper, lead, zinc) carbonate replacement deposits or from simple quartz-stibnite veins.

There are several former past-producing antimony districts in Mexico including: The El Antimonio District in Sonora (White and Guiza, 1949); the Tejocotes District in Oaxaca; the Wadley District in San Luis Potosi (White and Gonzales, 1946); and the Soyatal District in Queretaro (White, 1948). Many of the deposits in these areas were discovered and first produced in the 1500s-1900s where silver was the targeted material. After the industrial revolution and use of antimony in industry increased antimony was recovered either as a primary commodity or as a by-product of silver mining and beneficiation operations. Many of these old mines were reopened and active during WWII feeding smelters in Mexico and in Texas which provided war materials to the U.S. Government during the war. Although cumulative production from these areas is significant, individual mines within the respective Districts were quite small. Today many of the former Mexican antimony mines and districts are considered worked out or are considered uneconomic.

UNITED STATES ANTIMONY CORPORATION

United States Antimony Corporation (USAC), a Thompson Falls, Montana-based company operates several small mines, mill facilities and a smelter in Mexico. Other operations include additional refining and processing facilities in Montana. In 2019 USAC reported significant upgrades to the processing facilities in Mexico. Five Mexican properties supply direct shipping ore or mill feed for the Mexican smelter. The company controls a large property position including the San Luis Potosi, one of the largest past-producing antimony mines in Mexico during the WWII era (White and Gonzales, 1946). The founder and CEO of U.S. Antimony passed away in 2020 disrupting operations for a short period, but new management is in place and attempting to continue and expand operations. The company recently completed a significant financing to address long term debt and expand their Mexican plant. In February 2019, USAC announced it had signed a non-binding letter of interest regarding the potential supply of antimony with AMBRI, a company that utilizes antimony in its novel off-grid storage batteries.

BOLIVIA

Historic production of antimony from Bolivia is second only to Chinese production. Some of the largest known antimony deposits in the world outside of China and the Russian Far East occur in Bolivia. The largest mines were those that contained significant silver and often tin and where mercury amalgamation methods were used in 16th to 18th centuries to recover silver and gold. During WWII many of the operations provided antimony to the axis powers. Over 500 known antimony occurrences are found along a 600km long belt of deposits in Eastern Cordillera of Peru, Bolivia and Argentina (Haeberlin et, al., 2002). Several of the deposits are world class in terms of past production including Karma, Caracota and several others. Bolivia mined about a fifth of the world's antimony in the late 1980s and was the leading producer among market economies. Private companies were responsible for all antimony production (Hudson and Hanratty, 1989). The largest output came from the United Mining Company (Empresa Minera Unificada), which controlled the two largest antimony mines, located at Chilcobija and Caracota, both in Potosí. Medium and small miners generated an average of 9,500 tons of antimony a year in the mid-to late-1980s, all of which was exported. By the early 2000s this output had dwindled to a third. In 2010, the Bolivian government nationalized Empresa Metalúrgica Vinto Antimonio, an antimony smelter owned by Sinchi Wayraa, a Glencore subsidiary (Metals Bulletin, 2010). Litigation in the case continues into 2021. Despite significant resources, most of the known larger deposits have not been worked since the mid- to late-1980s. In 2014, Amalgamated Gold and Silver attempted to reopen one of the larger former antimony mines and shortly after shuddered the attempted restart. Current production from Bolivia is almost exclusively from small scale miners. There are currently significant reserves in Bolivia, estimated to be around 350,000kt, but production is inefficient and irregular from numerous small mines and artisanal operations.

AUSTRALIA

Australia has two small, but significant antimony-gold deposits that in 2018 accounted for 2% of global production but, by 2020 declined to 1% of total world production (USGS, 2021). Both deposits have complex mineralogy and metallurgy, and ores and concentrates are high in both arsenic and mercury making them unsuitable for some end uses.

MANDALAY RESOURCES - COSTERFIELD

Mandalay Resources produced approximately 3,903 tonnes of contained antimony in gold-antimony concentrates from the Costerfield underground mine operations in Victoria in 2020 (Mandalay Resources, 2021). Reported proven and probable reserves total 217,000 tonnes of contained antimony and total measured, indicated, and inferred resources reported in 2020 total 12,000 tonnes of contained antimony. Costerfield is currently producing approximately 10,000mt of gold-antimony flotation ore per month with approximately 5,000 tpa antimony. The concentrate contains approximately 53% antimony and 60 g/t gold and is sold to Chinese smelters and, at times, U.S. Antimony Corp. The operations are underground, high cost and involve mining of narrow discontinuous veins. Only a few years of reserves are drilled out at a time. Typically, both gold and antimony values are required in the ores to support the cost of underground development, mining, and processing.

RED RIVER RESOURCES - HILLGROVE

Red River Resources recently acquired and restarted the shuddered past producing Hillgrove gold-antimony Mine in New South Wales, Australia in 2019. Since 2004, over US$126.4M has been invested in underground development, surface infrastructure and the processing plant by the previous owners. The mine was briefly operated in 2014-2015 and was put on care and maintenance in 2016. The operation has a reported potential production capacity of 4,000 to 5,000 tonnes of contained antimony per year. However, since the 2021 restart the company has only reported gold production and no antimony output. JORC compliant total measured, indicated and inferred mineral resources include 75,000 tonnes of antimony in concentrates (Red River Resources, 2021).

CANADA

Canada formerly produced antimony from several deposits in eastern Canada - a deposit in New Brunswick and another in Newfoundland. There are no primary antimony processing facilities in Canada, but there are two lead smelters that can take antimony-bearing feed: Teck's smelter at Trail, British Columbia, and Xstrata plc's smelter at Belledune, New Brunswick. Both process concentrate feeds that contain antimony, supplemented by recycled lead-acid batteries. Secondary lead smelters in Canada depend upon recycled lead-acid batteries from Canadian users supplemented by imports from the United States.

LAKE GEORGE

The past producing Lake George antimony deposit consists of narrow stibnite-bearing quartz veins near and associated with a granitic intrusive complex near Fredrickton that also has been a significant source of tungsten, molybdenum and tin (Scratch et al, 1984; Seal et al, 1988). Historic production was approximately 1 million short tons of ore grading 3.0 to 3.5% antimony mined from Hibbard, the dominant vein. The mine was an underground operation and it closed in 1996 due to depletion of economic ores. Attempts to restart Lake George, the second largest past antimony producer in North America (behind Stibnite, Idaho) in the early-mid 1990s were also unsuccessful and more recent exploration has focused on tungsten and gold.

BEAVER BROOK

Another former producer in Newfoundland is the Beaver Brook deposit (Lake and Wilton, 2006). The Beaver Brook Antimony Mine is owned by Chinese Hunan Nonferrous Metals (HNC), the largest antimony company in the world, itself a part of China Minmetals Nonferrous Metals. The former producing mine was originally suspended in 2012 and reopened in Q1/2019. However, with growing supply from Russia to China, ore was exported to various non-China-based ingot producers in Vietnam, India and Oman. Oman had been the major destination in 2020, with the Oman Antimony Roaster accounting for nearly all the mine's output. Although both deposits have antimony mineralized material remaining, they are narrow vein type deposits and unlikely to provide significant feed or meet U.S. demand at current or projected metal prices.

MYANMAR

Over 30 occurrences of stibnite and other antimony-bearing minerals are known in Myanmar and there is active exploration, as of 2018, in at least 18 of the prospects (Myanmar Ministry of Mines, 2018). However, out of the 30 mineral occurrences noted in a survey by Goossens (1978), only four have been developed as small mines. These are Thabyu, Lebyin, Natsan and Painchit mines and, in recent years, significant investment in exploration and development has occurred via state-owned Chinese companies partnering with the Myanmar government. Production has been steadily increasing from these mines, all located in the State of Kayha within the Eastern Highland Belt. Concentrates are reportedly shipped to Chinese roasters and refiners. As a result, China also effectively controls this source of supply.

TURKEY

Turkey has seen an increase in antimony production over the last few decades as the country has experienced an overall increase in foreign and Turkish investment in exploration and development. Reported reserves from 14 small-scale antimony mines in Turkey was reported to be 313kt in 2013 (Uysal,2013). Political unrest in portions of Turkey may influence the stability of these supplies. Concentrates are shipped to China and Belgium with a small processing facility located at one of the mines.

U.S.

STIBNITE-YELLOW PINE

The Stibnite Gold Project in Valley County, Idaho is a major past producer of tungsten and antimony and is currently in permitting by Perpetua Resources (formerly Midas Gold) for a resumption of commercial production. The former stibnite mine was the largest producer of antimony for the U.S. prior to and during WWII. Significant antimony reserves and resources remain, according to Perpetua Resources' feasibility study. The complex contains some of the largest known reserves and resources of antimony outside of China and Russia (Dail, 2014). In 2020, the company released a positive feasibility study to extract over 4.8 million ounces of gold and an estimated 67,400 metric tonnes of antimony in its reserves included within a larger reported measured and indicated resource of 93,400 metric tonnes and inferred resources of 13,300 metric tonnes of antimony (M3, 2021). The company is in the process of permitting under the National Environmental Policy Act (NEPA) to re-develop the large gold-antimony deposits and restore the environment after mining during the WWII era left many legacy impacts in the district. A recent and ongoing study by the USGS, Minerals Resources Branch and the Idaho Geological Survey has provided significant new information as to the nature of the District's geological setting and ore deposits that may eventually lead to future discoveries.

COEUR D'ALENE

The Silver Valley area of Idaho has produced significant antimony as a by-product of silver mining from the mineral tetrahedrite, a chemically complex mineral containing antimony, copper, arsenic, silver iron, and often zinc and lead. Historic production was treated at the Sunshine Refinery or shipped to the Stibnite complex up until the late-1950s. There are several operations that currently mine tetrahedrite-bearing silver ores, but antimony is not recovered in the mills and is either discarded or shipped elsewhere to smelters and the production is insignificant. Within the overall Coeur d'Alene District, the antimony-rich veins occur in a distinct belt that trend into the Thompson Falls area in Montana.

THOMPSON FALLS

The U.S. Antimony Mine in western Montana is a simple quartz-stibnite vein deposit with limited production in the past and was closed in 1983; the former mine's production and in situ mineralization are estimated to be approximately 17kt of antimony (Hofstra and others, 2013). The mine is associated with a processing facility owned by the same company that produces antimony oxide product lines from imported feedstock. The facility produces specialty antimony oxide products and reportedly has a capacity of 6,800 tpa of antimony trioxide and 2,300 tpa of antimony metal according to the company's promotional literature. However, the plant has never produced that much product according to the company's regulatory filings. Typical output over the past decade has ranged from 450 tpa up to 750 tpa of antimony trioxide.

BACKGROUND ON ANTIMONY

Antimony is an under-appreciated, rare, critical element widely used in basic manufacturing processes, the defense sector and has numerous existing and new emerging uses in the energy and technology sectors. Its most prevalent application is within various fire-retardant formulations used in wire sheathing and compounds used to make fabric and plastics more fire resistant. Another major use is in strengthening alloys, which is important for lead batteries, electrical applications, nuclear reactor shielding, and ammunition and other defense applications. An important use is in primers for conventional small arms and larger weaponry ammunition. During wartime, there is typically a significant increase in consumption of antimony due to its military applications. It has long been used in various electronics and exciting new uses are being developed in the next generation of energy production and storage applications.

Physical Properties

Antimony is a brittle, silver-white, shiny metalloid that has a specific gravity of 6.68 and a melting point of 630.5 degrees Celsius (°C) (Miller, 1973). It is a poor conductor of heat and electricity, but it has other unique electrical properties when alloyed with other metals and metalloids and is often used as a dopantin various technical applications.

Antimony metal itself is brittle, but it imparts strength, hardness, and corrosion resistance to numerous alloys (Miller, 1973). It does not readily oxidize and keeps its luster even in moist air, and even does so at elevated temperatures in the range of 100 to 250 °C. At temperatures above its melting point, powdered antimony metal ignites and burns with a white-green flame. It is resistant to attack by alkalis, dilute hydrochloric and concentrated hydrofluoric acids, unlike many metals and metalloids, and these properties make it a very important constituent in process plants in the petroleum and chemical industry, where it is often used in specialty applications as a catalyst. Antimony metal also expands upon cooling, one of only a few metals or metalloids to do so, and one of the reasons it is critical for smelting and fabrication of certain alloys and in various types of metallurgical processes.

Antimony is not abundant in the earth's crust and average crustal abundance is approximately 0.2 part per million (ppm), about as rare as Indium and some of the heavy rare-earth elements (HREEs) (Eyi, 2012). Antimony rarely occurs as the native metal because of its strong affinity for sulfur and other metals such as copper, lead, and silver; it is typically found in sulfides, sulfosalts, oxides, antimonates, and antimonites (Boyle and Jonasson, 1984). This strong affinity to bind with other metals has traditionally made it a collector of impurities in certain types of hydrometallurgical and alloy refining plants (Anderson, 2012).

Geology and Deposit Types

The most significant antimony mineral deposits occur in geologic environments with a thick sequence of siliciclastic or carbonate sedimentary rocks in areas with significant fault and fracture systems.

Despite its low crustal abundance, antimony is a common constituent of many rocks and minerals but not in concentrations for extraction recovery. The most common antimony ore contains the mineral Stibnite (Sb_2S_3), but more than 250 other minerals also contain antimony (Boyle and Jonasson, 1984; Anderson, 2012). Ore deposits of sufficient size and grade to be exploited for primary antimony production are rare and concentrated in only a few locations worldwide (Figure 11).

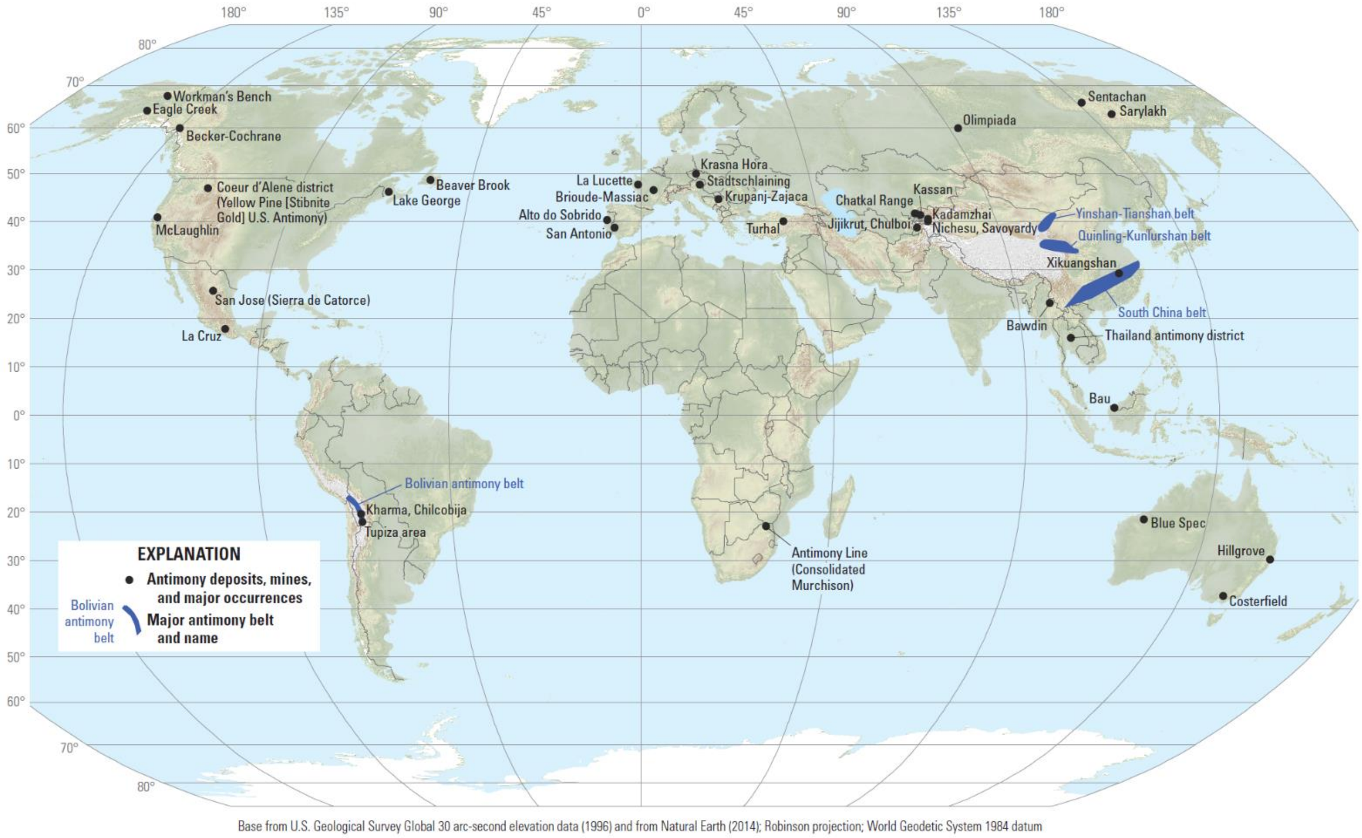


Figure 11: World map showing locations of selected antimony deposits, mines, and major occurrences. Some symbols represent a single mine or resource, whereas others represent a cluster of deposits in one area. Also shown are major antimony belts in China (Wu, 1993) and the Bolivian antimony belt, which has approximately 500 antimony-gold deposits (Arce-Burgoa and Goldfarb, 2009)

Many of the countries where antimony deposits are found are hostile to U.S. political, industrial, economic and defense interests. Deposits occur as simple intrusive-related vein systems such as Woxi (Jiada, 1993), as disseminated type deposits such as Stibnite-Yellow Pine (Dail, 2014) and as replacement deposits in carbonate rocks such as Xikuangshan (Yang et al, 2006). The largest deposits in the world are those of the carbonate replacement and disseminated styles (Miller, 1973; Dail, 2014).

USES: ANTIMONY IN THE ENERGY SECTOR

Thermoelectric cells (convert heat to electricity)

Thermoelectric cells convert heat to electricity. Research and commercial applications indicate there are promising antimony alloys, particularly those with zinc compounds (for instance TEGnology's patented Zn_4Sb_3 alloys) that can operate at, and stay stable under, high temperature situations, allowing for prolonged use without degradation due to thermal cycles and extending the operating time.

Various industry, university, and government research centers are rapidly developing nanoparticle thermoelectric energy generation technologies. For example, European investigators have developed high electrical conductivity antimony selenide nanocrystal assemblies and demonstrate antimony selenide to be a promising thermoelectric material (Mehta et al, 2010). Nanocrystal assemblies also show high electrical conductivity, making the nanocrystals attractive building blocks to realize nanostructured thin film and bulk forms of this material for thermoelectric device applications.

Scientists based in Bengaluru, India have developed a silver-antimony-telluride compound that is able to take waste heat generated by appliances and reuse it. For instance, the heat from an oven could then be captured and used to power a television. This new silver-antimony-telluride material would be able to capture the waste heat from power plants and other devices and convert it into electricity that could then be used to power other appliances, machines, or processes more efficiently than previous thermoelectrical conversion methods (Sinha, 2021). Typically, energy conversion is not very efficient. As a result, the extra energy that is not captured is wasted and normally released as heat. Industrial processes and conventional power plants generate copious amounts of waste heat. With current technology, this heat can be trapped and converted to electrical energy using various types of heat exchangers, however the current methods are also inefficient.

Scientists have known about the thermoelectric phenomenon for over 200 years. However, the inefficiency of energy capture using this method stems from the fact that most metals that conduct electricity well also conduct heat well. As a result, scientists have been looking for a material that is a good conductor of electricity but not heat. And the Bengaluru-based scientists discovered it in the silver-antimony-telluride compound they created. This opens doors for the future of thermoelectric heat generation and provides an important and significant new use for antimony.

Antimony Use in Lithium-Ion Batteries

Antimony has long been regarded as a promising potential anode material for high-performance lithium-ion and sodium-ion batteries as this metalloid exhibits a high charging capacity, by a factor of two higher than that of commonly used graphite. Extensive research has shown that antimony anodes constructed using antimony nanoparticles can be used equally well with lithium-ion or sodium-ion batteries, which makes antimony particularly promising for sodium batteries because the best lithium-storing anode materials (graphite and silicon) do not operate with sodium (Kovalenko, 2012).

As with lead-acid batteries, antimony is also widely used in the insulation around copper wiring that connects these batteries to their end users.

Antimony Use in Liquid Metal Batteries

Consortiums from various institutions, such as the business group at Ambri Corporation, funded by DOE's Advanced Research Projects Agency-Energy (ARPA-E) program, the French energy company Total, Bill Gates, the Deshpande Center, the Chesonis Family Foundation and many others (Bradwell et al, 2012; Kim et al., 2013; Wang et al., 2014) have conducted extensive research into both magnesium–antimony and more recently lead-antimony liquid metal batteries. The electrode and electrolyte layers are heated until they are liquid and self-segregate due to density and immiscibility. Research has demonstrated that these battery systems may have significantly longer lifetimes than conventional batteries, as the electrodes go through a cycle of creation and destruction during the charge-discharge cycle which makes them immune to degradation affecting conventional battery electrodes. In addition, the speed with which these systems recharge is much faster than conventional solid-material battery systems. Antimony was selected as the positive electrode in these systems due to its low cost and high discharge voltage, as well as the alloy's ability to withstand higher temperatures and its chemical characteristics. Although still not truly cost effective for portable battery systems, the technology shows exceptional promise and could lead to large scale grid-scale energy storage systems like that described in Wang et al (2014).

Wang et al (2014) describe a Li-Sb-Pb battery comprised of a liquid lithium negative electrode, a molten salt electrolyte and a liquid antimony–lead alloy positive electrode, which self-segregate by density into three distinct layers owing to the immiscibility of the contiguous salt and metal phases. The all-liquid construction confers the advantages of higher current density, longer cycle life and simpler manufacturing of large-scale storage systems potentially suitable for grid-type electrical storage because no membranes or separators are involved relative to those of conventional batteries.

The market for using various battery storage units for the power grid is rapidly growing in the U.S. There was an estimated 220 megawatts of energy storage projects installed in 2016, mostly using lithium-ion batteries, which is the equivalent in energy stored to the power required for about 220,000 homes. However, since that time the demand for large scale energy storage capacity has skyrocketed with an estimated 23.2 GW of capacity developed as of 2020 (US EIA, 2020; DoE Power Monthly 2020). It is anticipated that, as there is a larger push away from fossil fuel energy sources in the U.S. and abroad, there will be significant increases in battery energy storage capacity due to the variable reliability and sometimes off-cycle generation nature of non-fossil fuel type energy sources. This could lead to a significant increase in demand for antimony, lithium and other materials used in both conventional battery systems and new technologies as they reach the commercial development stage. The cost to develop and install grid-scale lithium-based battery storage systems is significantly higher than antimony-based liquid battery systems and they are expected to last longer and provide faster recharge times (Ambri, 2021).

Antimony Uses in Low Emissivity Coatings

Low emissivity coatings, which operate by keeping heat inside a building and therefore reduce energy consumption, are seeing increased use, particularly in the commercial building sector to meet U.S. and EU energy saving construction specifications. Not only is the antimony used as a clarifier in the glass making, but it is also used in the formulations in glass coatings to promote energy conservation. The coatings include various combinations containing fluorine, tin, indium and antimony (EC, 2013).

Antimony Compounds in Solar Energy Applications

Antimony is also used as a decolorizing agent in optical glass. When added to glass, it is a critical component and anti-solarant (the glass will not change color in sunshine) and, when combined with nitrate compounds, helps reduce oxidation. Anti-solarant glass made with antimony oxide has excellent light transmitting properties near the infrared range of the light spectrum, a very important component in some solar energy systems as well as in various defense applications. It typically is used in amounts ranging from 0.1% to 2%, depending upon the application.

Other uses for antimony related to solar energy include doping various compounds in the electrodes for silicon solar cells. Antimony is often the dopant of choice because of its high solubility in silicon, its low-cost relative to many other specialty metals products, and the fact that an alloy of antimony and silver exists as a single, uniform phase for low antimony concentrations, providing a number of benefits. In these applications, antimony may be used in amounts from 2% up to 5% by weight.

Antimony Uses in Passivation Additives in Petroleum Refineries

Contaminant metals such as nickel and vanadium in an oil stream can deposit themselves on the catalyst in fluid catalytic cracker units (FCCU) fouling the catalytic cracking of hydrocarbons. These contaminants have the detrimental effects of reducing catalyst activity, decreasing the yield of gasoline and promoting catalyst attrition. Passivation additives such as antimony pentoxide and tin oxide compounds suppress these detrimental effects and thereby extend the useful life of the catalyst and improve refinery yields and capacity. Quantities of materials used in these additives range from 25-50% by weight antimony pentoxide (Sb_2O_5).

Antimony Uses in the Nuclear Industry

Antimony is typically utilized with lead in nuclear reactor shielding to provide hardness to the lead and allow it to be built into free standing walls and shells, both in commercial nuclear reactors and in mobile reactor vessels in military applications such as nuclear-powered submarines and aircraft carriers. Alloys of lead, tin and antimony are utilized to construct shielding bricks for construction of nuclear shielding for storage of high energy materials and in shielded transportation vessels for transport of nuclear materials and waste products. Typically, the alloys will contain 1% to 18% by weight of antimony metal in shielding applications. It also is mixed with lead and barium in making glass with radioactive shielding and in paint additives and coatings for shielding purposes as well.

An antimony compound is a primary constituent in radioactive waste clean-up in effluent stream water treatment plants in uranium mines, nuclear reactors, waste storage sites and reprocessing facilities, as it is an excellent material for capture of radioactive strontium from the wastewater streams.

Antimony is also often used as a bearing material or sealing material for pumps in the coolant circulation plumbing of nuclear reactors due to some of its unique chemical and physical characteristics, with antimony contents between 1% and 12%, and used very widely in the petroleum industry for pumps and valves in refinery and chemical plants.

Antimony, alloyed with beryllium (SbBe), is fabricated into pellets, and is utilized in nuclear start-up fuel rod assemblies at reactor start-up and fuel scanners in nuclear applications. This is also the formulation used as an activator to start up research reactors and submarine reactors as well as in various portable x-ray fluorescence spectrometers used in chemical analysis, metal, and alloy testing and in pipeline leak detection test equipment.

Antimony is also widely used in the insulation around copper wiring that is ubiquitous in all aspects of the nuclear energy sector, from generating stations to transformers to distribution lines.

USES: MILITARY APPLICATIONS

Antimony has an extremely wide variety of military uses and has had for over a century, as so eloquently stated by Rousch (1937), "*…Antimony is the last of the non-ferrous group of strategic metals, but it by no means the least important, for it has more uses of direct military character than any other member of the group…*" This is truer today than it was in 1937 given its use in high tech electronics that are found in night vision googles, communications equipment, infrared sensors, explosives formulations, ammunition primers, military clothing (both for its fire retardant and infrared absorption characteristics) and numerous other uses (USGS, 2018). It is used in hardening lead in bullets and shrapnel, in armor piercing projectiles, as a reaction activator with beryllium in nuclear weapons and reactors and in the production or tritium (used in hydrogen bombs). In addition, it has a critically important use in manufacturing high quality glass (as a clarifier to remove impurities) used in military binoculars, precision optics and laser sighting and survey equipment. It is a primary ingredient in many explosives formulations as well as in tracer ammunition and flares. Antimony oxides are often used in many military specifications for paints, plastics, and coatings due to its fire-retardant properties. This use was well documented in WWII when aircraft carrier decks were coated with paints and stains containing antimony trioxide to prevent fires when kamikaze pilots crashed their planes into decks attempting to ignite the wooden decks but is still as important today with our modern high technology weaponry.

USES: ANTIMONY IN THE MANUFACTURING SECTOR

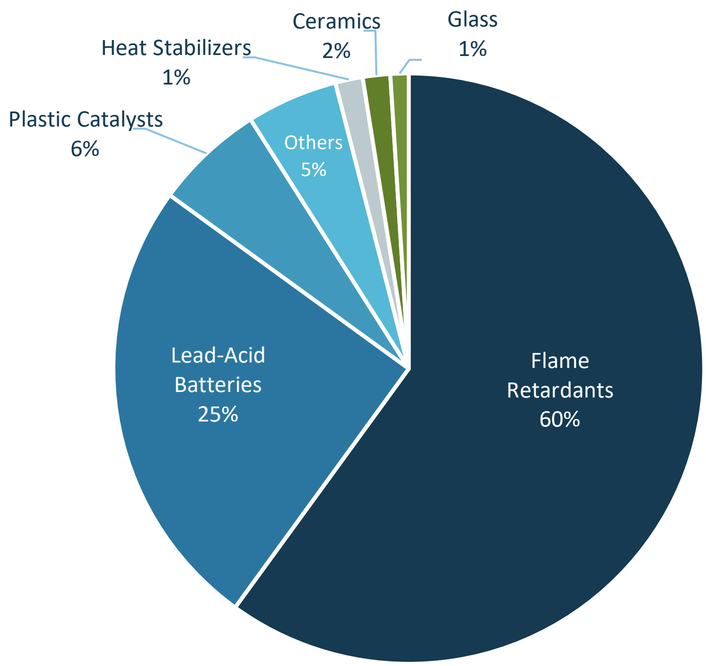


Figure 12: Antimony End-Uses (Sources: USGS, 2018; Roskill, 2018; Unpublished industry reports)

Antimony's biggest use is in fire retardant formulations, followed by use in lead-acid batteries (Figure 12). Numerous other manufacturing sectors utilize antimony compounds, and, in many cases, there are no practical substitutes due to the element's unique properties.

Flame Retardants

The largest use of antimony oxide is in a synergistic system with a halide (generally chlorine or bromine) flame retardant system for plastics and textiles. Normal applications for these products include coatings on electrical components, housings and cabinets, electrical cable insulation and sheathing, electrode and shielding laminates, fire resistant adhesives, as fire retardants in circuit boards, in switches, motors, transformers in electrical appliances and in various chips, semiconductors, sputtering targets and as dopants. An obvious, but perhaps underappreciated use of antimony, is as a flame retardant in the plastic insulation around copper wiring that is found in every aspect of the energy sector as well as buildings, vehicles, and equipment (military and civilian), without which fires, system failures and other issues would be much more widespread. Around 90% of flame-retardant production ends up in electronics and plastics (including wire insulation), while the remaining 10% ends up in other uses.

The importance of this less glamourous element (as compared to the more well-known seemingly exotic elements like REEs) as a component in electrical applications can be shown by its use in the resins for semiconductor chip boards (often up to 8-10% by weight antimony trioxide) to prevent them from igniting, or in various components mounted on the circuit boards. Yet a casual review of various published "snapshots" of critical materials used in devices with circuit boards often fails to show the presence of this volumetrically major component, probably because the quantity and formulations of the resins and epoxies containing the antimony trioxide are often considered proprietary components.

Antimony is also a commonly used component in the semiconductor industry, where antimony is used as a dopant for ultra-high conductivity silicon wafers in the production of diodes, infrared detectors, and Hall-effect devices. Alloyed with silver, antimony is typically employed in bearing assemblies (used in wind turbines, generators, and motors), ballast, casting, step soldering and radiation shielding. It is in widespread use in electrical and energy related technologies and new uses are constantly being developed as evidenced by over 1,000 U.S. patents utilizing antimony in the electrical applications over the last decade.

Antimony Compounds in Coatings and Paints

Paints and numerous metallic or plasticized coatings in many energy-related electrical generation, transmission and storage components must be resistant to fire. Antimony trioxide added in amounts ranging from 10% to 25% by weight is typically compounded and added to paints and coatings to provide this protection. In addition, antimony oxides are insoluble in water and thus they have an advantage over other flame retardant coatings additives for exterior uses. These are especially important applications in coatings used in fire-resistant electrical transmission lines.

Metal casings for electrical equipment afford fire safety, but pose electrical risks, as well as being heavier, more expensive and less design flexible than modern plastics. Even where non-flammable materials (such as steel) are used, flame retardant antimony intumescent coatings, containing 10 to 25% antimony trioxide compounds by weight, can provide valuable heat protection for these to limit or delay mechanical deterioration in the case of fire.

Antimony Compounds in Glass Making

Antimony in the form of sodium hexahydroxy antimonate, is used in the manufacture of high-quality clear glass. This use accounts for about 5% of global antimony consumption. In this 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 coloration (Schwarz-Schampera, 2014).

Antimony as a Catalyst in Manufactured Goods

Antimony is a commonly used catalyst in the manufacture of polyester resins for fibers which have numerous basic uses in the manufacturing sector across the line of consumer goods. Numerous patents exist for different catalysts, catalyst supports, and processes, including the use of antimony pentafluoride (SbF5) as catalyst reaction of Lewis acids during the alkylation reaction. It is also utilized as a catalyst in the manufacturer and esterification of high molecular weight polyethylene terephthalate (PET). Although commonly known for its widespread use in the plastic container for food and drink storage, PET is a very common and important component in numerous electrical products related to the energy sector, such as in electronic thermoplastic encapsulation production for items like solenoids, toroid's, sensors, bonded coils, motors and in transformers. In addition to the use antimony as a catalyzer in resins and powders it also is typically added to these plastics in variable percentages as a fire retardant as noted in the earlier section. Antimony pentafluoride content in catalysts may range from several percent up to 10% or more depending on the product being produced. It is unknown how much, if any, of this material is lost during the reaction nor the life span of such materials in reactor vessels.

USES: ANTIMONY IN THE TECHNOLOGY AND ELECTRONICS SECTOR

Antimony Compounds in Phosphors for Fluorescent Lighting

Numerous patents describe the use of various antimony oxide compounds of various valence states for use as phosphorescent agents in fluorescent light bulbs and other lighting applications (for example, US Patents US 3639253 A, US 3468812 A, US 2755254 A, US 3539857 A, and references therein).

Various antimony-doped pyrophosphates are used as the antimony-supplying ingredient in the manufacture of calcium yttrium-terbium and other REE phosphors activated with antimony or antimony plus manganese and other materials. The extreme fineness and high reactivity of the antimony-supplying materials and their low volatility at lower temperatures are significant advantages in the manufacture ofthe phosphors. In addition, the antimony containing yttrium-terbium phosphate phosphors exhibit longer decay times than their non-antimony containing counterparts and, accordingly, these phosphors are advantageous for energy conservation. The antimony content of these compounds can range from 0.7% to over 20% by weight as expressed as antimony oxide, trioxide or tetroxide, depending upon the application. When considering criticality, it is unfortunate to note, that with all the concerns and efforts directed at REE supply chains, that antimony, a critical component of most REE-based formulations, is rarely discussed and is much rarer than REEs and the antimony market more tightly controlled by China and Russian interests.

Antimony Compounds in Electrical Switching Apparatus

Antimony is commonly used in semi-conductors and many electrical components in trace to percentage level amounts. Switches may contain antimony alloyed with silver or other metals and can be utilized in amounts up to several percent by weight. Many kinds of thermally activated electrical switches that employ bimetallic actuators with antimony as one of the alloys used have been patented (US Patents US 5939970 A, US 5428336 A, and references therein). These heat-activated switches and thermocouples are critical and irreplaceable components in commercial and residential fire alarm systems and heat-activated emergency devices used across the industrial and defense sectors.

Although there are issues for conventional electrical systems, one potential key future growth area for antimony use could be in high-speed electrical switching systems which will likely involve the use of antimony due to its metalloid electrical properties. Alloys based on germanium, antimony, and tellurium (GST) can change phase between crystalline and amorphous states in response to laser or electrical energy and could be faster, smaller and more efficient than the present generation of switches.

Antimony Used in Sputtering Targets

Antimony is a very common constituent in sputtering targets used in the manufacture of semiconductors, for chemical vapor deposition and physical vapor deposition applications in electronics manufacturing due the high density and smallest possible average grain sizes and chemical properties associated with many antimony formulations. It is often utilized in large area coatings for solar energy or fuel cells and flip-chip applications. "Sputtering" allows for thin film deposition of an ultrahigh purity sputtering metallicor oxide material onto another solid substrate by the controlled removal and conversion of the target material into a directed gaseous/plasma phase through ionic bombardment. There are numerous uses in the energy sector and emerging renewable and “green” energy applications. Typical formulations for sputtering targets often contain from 30% to 60% antimony by weight.

Antimony Oxides and Trioxides Used in Printed Circuit Boards

Printed wiring boards are typically made of plastic laminates with metal circuitry and electronic components soldered onto the circuitry. The type of wiring board used in an electronic product depends on the material and the sophistication of the application (i.e., cell phone vs. high-speed digital applications). The trend in today’s electronic manufacturing sector leans toward smaller, yet more powerful, devices. This translates into a higher concentration of heat sources and the possibility of electronic components overheating. Electrical faults, in addition to possible external sources of ignition, only increase the potential for fire hazards. For this reason, most printed wiring boards are designed to meet flammability standards set by organizations such as Underwriters Laboratories or the European Commission of the European Union, which standards often can only be met using antimony-based flame retardants.

Antimony oxides (antimony trioxide and antimony pentoxide) are effective synergists for imparting flame retardancy to brominated epoxy resins. The major application for this type of epoxy is in FR-4 epoxy-glass laminates used for printed circuit boards, the most common circuit board substrate used in computers and electronics applications including numerous control panel components, etc. in energy systems. Using such a synergist allows significant reductions in bromine levels to achieve equal or better fire retardancy characteristics. Other metal oxides may be mixed in with the antimony oxides, depending upon the specific end use application, and can include aluminum and zinc oxides. Depending upon the application and the desired fire retardancy characteristics antimony pentoxide (Sb_2O_5) can range from 25% to up to 80% by weight in the epoxy resin material and may be utilized in powdered form (ranging from nanoparticles to granular pelletized material), in gels or colloidal solutions. Examples of products, such as DuPont™ Rynite® and Hytrel® thermoplastic polyester elastomers or DuPont™ Minlon® and Zytel® nylon resins and various products by other manufacturers can be found on manufacturers' websites and in their technical literature.

Many of these same antimony materials are utilized in solar panel encapsulants and in glass laminating interlayers often in large quantities. Other uses of antimony include compounding with halogen and non-halogen plastic polymers in low- and high-voltage wire and thermoplastic jacketing and insulation and in semi-conductive layers and many major manufacturers utilize antimony compounds in their formulations. For instance, polyethylene (PE) and low-density polyethylene (LDPE) typically contain 8% to 16% antimony oxide combined with other synergists as flame retardants.

USES: ANTIMONY IN THE AUTOMOBILE, SHIPBUILDING AND HEAVY EQUIPMENT SECTOR

Alloys in Lead-Acid Batteries

Antimony is a major component of conventional lead-acid batteries, normally as a hardening agent for the lead terminals and plates, which typically contain from 8% to 11% antimony, but content can be as high as 15%. Besides acting as a hardening agent, specific antimony-bearing alloys display particularly high corrosion resistance as compared to the customary hard-lead alloys, as well as considerably higher discharge values of the batteries than attained with the grids made of conventional alloys. This usage is particularly evident in larger lead-acid batteries, such as that used in large vehicles and ships, including those used by the military. Without it, batteries would be less resilient and more susceptible to failure. There are literally hundreds of patents utilizing antimony metal alloys in battery storage systems. For instance, recombinant electric storage batteries include separators of multiple fiber electrolyte absorbency that retain a balanced amount of absorbed electrolyte, for controlled recombination and which are in contact with positive and negative plates. The positive plates containing antimony in amount of 2% to 4% of total alloy weight provides considerably greater capacity and cycling life (US patent US 4873157 A, EC, 2013). Various maintenance-free battery systems utilize antimony alloys with 1% to 3% antimony by weight in electrode grids (US patent US 4166155 A, US 4401730 A) providing long battery life and improved performance. Antimony is also widely used in the insulation around copper wiring that connects these batteries to their end users.

Alloys Used in Renewable Energy Generation, Shipbuilding, and Heavy Equipment Manufacturing

Antimony is a key ingredient in "babbitt" bearings (named after the inventor Isaac Babbitt who developed alloys in 1839) which utilize various combinations of metals typically tin and copper, but always antimony to produce strong, corrosion resistant, self-lubricating bearings for equipment requiring high strength materials such as the bearings in ship and submarine propellers and engine crank shafts, in propeller bearings for aircraft and for bearings in wind generation (U.S. Patent 1252, 1839). Key characteristics of babbitt metal include its resistance to galling and its low coefficient of friction that combined with its corrosion resistance are irreplaceable uses in marine shipbuilding.

POTENTIAL FUTURE USES

Antimony is under intense study because of its unique and physical properties such as in investigations as a potential new nanocomposite (consisting of Sb_2O_3 and Fe_3O_4) for use as new anode materials for lithium-ion batteries and for other high technology applications. For instance, infrared photodetectors (IRPDs) have become extremely important devices in various military applications such as night vision, missile tracking, medical imaging, industry defect imaging, environmental sensing, and remote sensing. Semiconductor technologies using older material-based photodetectors have been dominating the industry. However, in the last few decades, efforts to improve IRPD performance of IRPDs by lowering fabrication cost, simplifying fabrication, increasing production yield, and increasing device operating temperature by making use of advances in nanofabrication and nanotechnology using antimony doped materials as a key ingredient (Tan and Mohseni, 2018).

Both fluorescent bulbs and LED lighting contain antimony in various components. In LED lighting and chips, there are often large quantities of metals such as antimony and gallium, tellurium and selenium. Most LEDs have more contained metal than conventional fluorescent and incandescent lamps, so the expected transitions will likely increase demand for these specialty materials.

Current fuel cell designs and compositions vary considerably. Many of the designs currently under development and in, or heading towards, commercial development includes the use of significant quantities of antimony in the molten anodes or in solid oxide electrode formulations. In addition, significant amounts of antimony are expected to be utilized in flame retardant coatings, wire sheathing and insulation and other ancillary components, so there is little doubt that, as these technologies develop, there will be a much larger demand for these materials.

Recent investigations into the application of potassium-ion and other metal oxide battery technologies represent new approaches to energy storage beyond the well-evolved lithium-ion sector. Research into alternative technologies has included use of antimony-based electrodes exhibiting high reversible storage capacity cyclicities, good charge and discharge kinetics, high operating voltages and low overpotentials demonstrating the effectiveness of the use of antimony in anodes and its applicability to the field of metal oxygen batteries (McCulloch, et al, 2015). As these advancing technologies develop into commercial applications they could result in substantial increases in demand for antimony.

The development of new classes of materials utilizing antimony that can convert ambient indoor light into electricity may soon power wireless smart devices (Warburton, 2021). These materials will help reduce energy consumption since it will allow some of the energy used to illuminate indoor environments to be recycled. While individually the energy save would seem small, given the sheer volume of small handheld electronics in use today, the overall energy savings could be substantial.

Other emerging technologies reported in the literature relate to the use of antimony porphyrins as photocatalysts for solar fuel production from halide solutions in solar cells systems (Ertl, et al., 2015) and there are numerous studies showing the potential use of antimony in anodes in Na-ion and Li-ion battery systems as could contribute to additional demands as these applications develop.

REGULATORY HURDLES

The single largest challenge in developing a robust supply chain, including domestic production, for critical minerals is the regulatory process. A recent 2018 survey (AEMA, 2018) by the American Exploration & Mining Association (AEMA), a large industry trade organization with over 2,000 members representing mining interests across 42 states and multiple countries noted that, of 16 larger mining projects currently in the permitting process in the U.S., the average permitting time anticipated to completion is more than eight years. Some have been extended for over 20 years.

A set of six recommendations in the recent Department of Commerce report titled "*A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals*" outlines important steps to be taken by Federal agencies to comply with the 2017 Executive Order 13817. Recommended overarching goals included:

1. **Advance Transformational Research, Development, and Deployment Across Critical Mineral Supply Chains:** Assesses progress toward developing critical minerals recycling and reprocessing technologies, technological alternatives to critical minerals, source diversification, and improving processes for critical mineral extraction, separation, purification, and alloying.
2. **Strengthen America's Critical Mineral Supply Chains and Defense Industrial Base:** Discusses ways to improve critical mineral supply chains, which could help reduce risks to U.S. supply by increasing domestic critical mineral resource development, building robust downstream manufacturing capabilities, and ensuring sufficient productive capacity.
3. **Enhance International Trade and Cooperation Related to Critical Minerals:** Identifies options for accessing and developing critical minerals through investment and trade with America's allies, discusses areas for international collaboration and cooperation, and ensures robust enforcement of U.S. trade laws and international agreements that help address adverse impacts of market-distorting foreign trade conduct.
4. **Improve Understanding of Domestic Critical Mineral Resources:** Provides a plan to: improve and publicize the topographical, geological, geophysical, and bathymetrical mapping of the United States; support mineral information collection and analysis of commodity-specific mitigation strategies; focus and prioritize interagency efforts; and conduct critical mineral resource assessments to support domestic mineral exploration and development of conventional sources (minerals obtained directly through mining an ore), secondary sources (recycled materials, post-industrial, and post-consumer materials), and unconventional sources (minerals obtained from sources such as mine tailings, coal byproducts, extraction from seawater, and geothermal brines) of critical minerals.
5. **Improve Access to Domestic Critical Mineral Resources on Federal Lands and Reduce Federal Permitting Time Frames:** Provides recommendations to streamline permitting and review processes related to developing mining claims or leases and enhancing access to domestic critical mineral resources.
6. **Grow the American Critical Minerals Workforce:** Discusses the activities related to critical minerals needed to develop and maintain a strong domestic workforce to foster a robust domestic industrial base.

Whether these recommendations lead to concrete changes in the permitting structure in the U.S. and will help reestablish Critical Minerals raw materials mining remains to be seen.

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