Towards responsible and resilient mineral supply chains, with case studies on cobalt, antimony, and zinc

Brink, S. van den

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Chapter 4. Resilience in the antimony supply chain

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Authors
Susan van den Brink, René Kleijn, Benjamin Sprecher, Nabeel Mancheri and Arnold Tukker

Abstract

Antimony is considered a critical and strategically important metal and is used in a wide range of products. This study examines major antimony supply chain disruptions from 1913 to 2018 and analyses how resilience mechanisms and price feedback loops contributed to supply chain resilience. We found that the antimony diversity of supply of both mining and refining is low, but is enhanced by recycling, around 25% of global antimony supply is produced via recycling of antimony bearing metal alloys. Based on production volume, almost 70% of antimony was mined as by- or co-product in 2018, indicating a high supply risk. However, the presence of unrecovered by-products can also make the supply more elastic. Substitution is possible for some antimony applications, but for one of the main applications, flame retardants, performance of substitutes is still considered inadequate. Overall, stockpiling played a significant role in both dampening and exacerbating supply disruptions. It is recommended that the mined production and processing capabilities are diversified, stockpiles are explored as a mechanism to absorb sudden shortages, and, most importantly, recycling of antimony (trioxide) should be further improved.

Keywords
Resilience, antimony supply chain, metals criticality, companion metal, sustainable resource management

Highlights

- The antimony diversity of supply of both mining and refining is low.
- Almost 70% of Sb is mined as by- or co-product.
- Companion metals can both have higher and lower resilience.
- An additional 25% of Sb production comes from post-consumer recycling.
- Stockpiling has played a role in dampening and exacerbating supply disruptions.

4.1 Introduction

Antimony is one of the 30 raw materials listed as critical for the European Union, which is 100% import reliant for antimony (European Commission, 2020a). Various national governments also designate antimony as a strategic and critical material, including the governments of Australia, Russia, the United Kingdom, and the United States (Chakhmouradian et al, 2015). Panousi et al. (2020), concluded that the supply risk for antimony was the highest of seven specialty metals over the medium-term (i.e. 5 to 10 years) and the second highest over the long term.

The high criticality of antimony was illustrated in 2021, when the price of Chinese antimony reached a seven-year high, caused by a shortage in ore supplies following a fall of imports due to Covid-19, as well as a production suspension at the country's largest mine after its license expired. This resulted in a production delay in China's refineries for several months (Argusmedia, 2021). Since 60% of global supply originates from China, this caused a large supply disruption.

Antimony is of high importance for a wide range of products. Its main applications are as a flame retardant in electrical and electronic equipment and textiles, in alloys (lead-acid batteries), wires and cables, ceramics, and glass (Tercero Espinoza et al., 2018). In addition, there are some future technologies related to the energy transition in which antimony may play a significant role. For example, antimony is a promising potential anode material for rechargeable lithium-ion batteries (used in electric vehicles). Compared with graphite, it has a much higher theoretical capacity and safer reaction potential. Antimony also seems to be a promising electrode material for liquid metal batteries due to its relatively low melting point. With the requirement of higher energy density, liquid metal batteries have attracted researchers' attention for large scale energy storage technology (He, 2018). Finally, in solar energy applications antimony selenide is emerging as a new photovoltaic absorber material, combining abundant, low toxicity materials with rapidly improving efficiencies (Hutter et al., 2018).

Current estimates of future antimony demand vary, according to Mordor Intelligence (2021) the antimony market is expected to grow by 5% annually until 2026, while according to a report in Perpetua Resources (2021), an additional annual 18 kt of annual mine production (or 12% of production in 2018) will be required through 2030.

The high risk of supply chain disruptions causes concern. Therefore, insight into how the supply chain can respond to disruptions is essential. In this paper, we analyse to what extent the supply chain can manage disruptions using the resilience framework developed by Sprecher et al. (2015). While antimony has been analysed in traditional criticality studies (e.g. Hayes et al. 2018, Panousi et al, 2020, Gemechu et al., 2015, Chakhmouradian et al., 2015, Nuss and Blengini, 2018, Sverdrup et al., 2017, Henckens et al., 2016), it has not been studied from a resilience perspective. Traditional criticality studies mainly look at static parameters such as diversity of supply and stability of regimes in source countries. Resilience adds a dynamic (i.e. time-dependent) perspective, by also analysing how supply chains of critical materials can cope with disruptions through feedback loops and other mechanisms such as material substitution and stockpiling. Furthermore, criticality studies often under-address recycling as a sources of material supply, while the resilience framework explicitly includes recycling in the analysis of diversity of supply.

To understand which factors, play a role in the supply chain resilience of antimony, we first make a historical analysis of ten major antimony supply chain disruptions, occurring between 1913 and 2021. We then analyse the supply chain structures of antimony through the lens of the resilience framework.

We chose 2018 as base year, as for this year the most complete data set was available when we started this study.

The original Sprecher et al. (2015) framework analyses diversity of supply in the mining stage and at country level. However, for minor metals a disruption at even a single mine can have an outsized impact on the overall price of the metal (van den Brink et al. 2020). Furthermore, concentration of supply may not only occur in the mining stage, but also in the refining stage. In addition, links between companies and countries can also influence concentration of supply, for instance when a company owns various mines in different countries. Therefore, this study examines the supply concentration not only on the country level, but also on the level of individual mines and SoRs (Smelters or Refineries). Detailed information is collected on individual antimony mines and SoRs, their annual production, geographic location, operator and parent companies and mine host or by-product metals. When there is a supply disruption at a specific location, a timely switch between (international) suppliers is required. Therefore, the links between private companies in the supply chain as well as the geographical trade flows are examined.

Key innovative features of this study are that this is the first study in which the supply chain of antimony is studied from a resilience perspective based on the analysis of four resilience mechanisms. Secondly, this study provides an in-depth overview of the antimony supply chain and particularly its diversity of supply covering not only mining, but also the next step in the supply chain (refining), involving the supply concentration on a geographic and company level, illustrated with a map of the antimony mines and refineries, and antimony global trade flows.

4.2 Methods and materials

4.2.1 Resilience framework

Criticality studies can point to supply disruptions that economic systems may undergo, but what they do not offer systematically is insights on how an economic system responds to disruptions and how it is able to mitigate or absorb them (DeWulf et al., 2016). According to Dewulf et al. (2016) criticality assessments calculate criticality of raw materials while resilience addresses the way an entity is able respond to criticality.

Resilience can be defined as the capacity of a system to tolerate disruptions while retaining its structure and function. Four resilience mechanisms can be identified that mitigate supply disruptions: feedback loops through price mechanism, diversity of supply, material substitution (and improved material) and stockpiling (Sprecher et al, 2015). These mechanisms are interlinked in the resilience framework through feedback loops. To examine the resilience of the antimony supply chain the following data is collected about these four mechanisms.

The first part of the study is an historical analysis (1913-2017) of major antimony supply chain disruptions. The supply chain disruptions are based on literature review and linked to the antimony price and production. The real price is calculated based on the nominal antimony price in U.S. dollar per tonne, corrected by the annual rate of inflation of the U.S. dollar based on the consumer price index, starting from index year 1983 (Argusmedia, 2021, US Antimony, 2020, Federal Reserve Bank of Minneapolis, 2021, USGS, 2011, USGS, 2012), the antimony production is based on USGS data (2017b). In the analysis is described how the resilience mechanisms help to absorb the disruptions based on literature review. In the second part of the analysis, the resilience mechanisms are evaluated in more detail for our base year 2018.

Sprecher et al. (2015) describe several price feedback loops, these are illustrated in Figure 4.1 and summarized in Figure C1 of Appendix III. To measure if production changes correspond to price changes on a global level (and vice versa), the correlation between price and production is evaluated. To take into consideration the time lag in the production, the correlation between price and production is measured during the price cycle following a disruption (see also Figure C4 in Appendix III), from the lowest price point to the end of lowest price point. This assumes that the price decreased, because supply shortage was met by a higher production. The time lag could take longer on a national scale. A correlation >0 is a positive correlation between price and production and <0 a negative correlation. Note that next to ore production, other supply can influence price as well, such as supply from recycling or stockpiles. The historic antimony demand is unknown and therefore not included in the price analysis. Only the events causing demand disruptions are described.

Diversity of supply is based on the production concentration of mined and refined antimony, which is analysed on four levels: countries, mines, refineries and companies. In addition, data is collected on artisanal supply and recycling. Production concentration is measured with the Herfindahl-Hirschman Index (HHI), which is a commonly used indicator for the concentration in commodity markets. An HHI of between 1500 and 2500 signals a ‘moderately concentrated’ market, while an HHI above 2500 indicates a ‘highly concentrated market’ (Silberglitt et al. 2013). The HHI will be used in this study as an indicator for supply diversity and will measure the concentration of supply, instead of the market concentration.

In addition to the HHI, network theory is used to analyse the links between actors in the Sb supply chain. Today's resource criticality assessments do not generally account for risk aspects related to the topology of the supply chains (Nuss et al., 2016). Network analysis is used for understanding, designing, and managing supply chains (Bellamy and Basole, 2012). The network is visualised with the software tool Gephi (Gephi, 2021). The analysis of the resilience mechanism substitution/improving material properties and stockpiles are based on a qualitative analysis of literature review.

4.2.2 Data sources

Country level mining and refining statistics are taken from the United States Geological Survey (USGS, 2020) and the British Geological Survey (BGS, 2020). To identify the individual antimony mines and smelters or refineries (SoR), as well as operators and shareholders involved, we used the following sources: company (annual) reports, reports on antimony from geological surveys, media articles, and reports of operators and websites that collect information on mines globally.

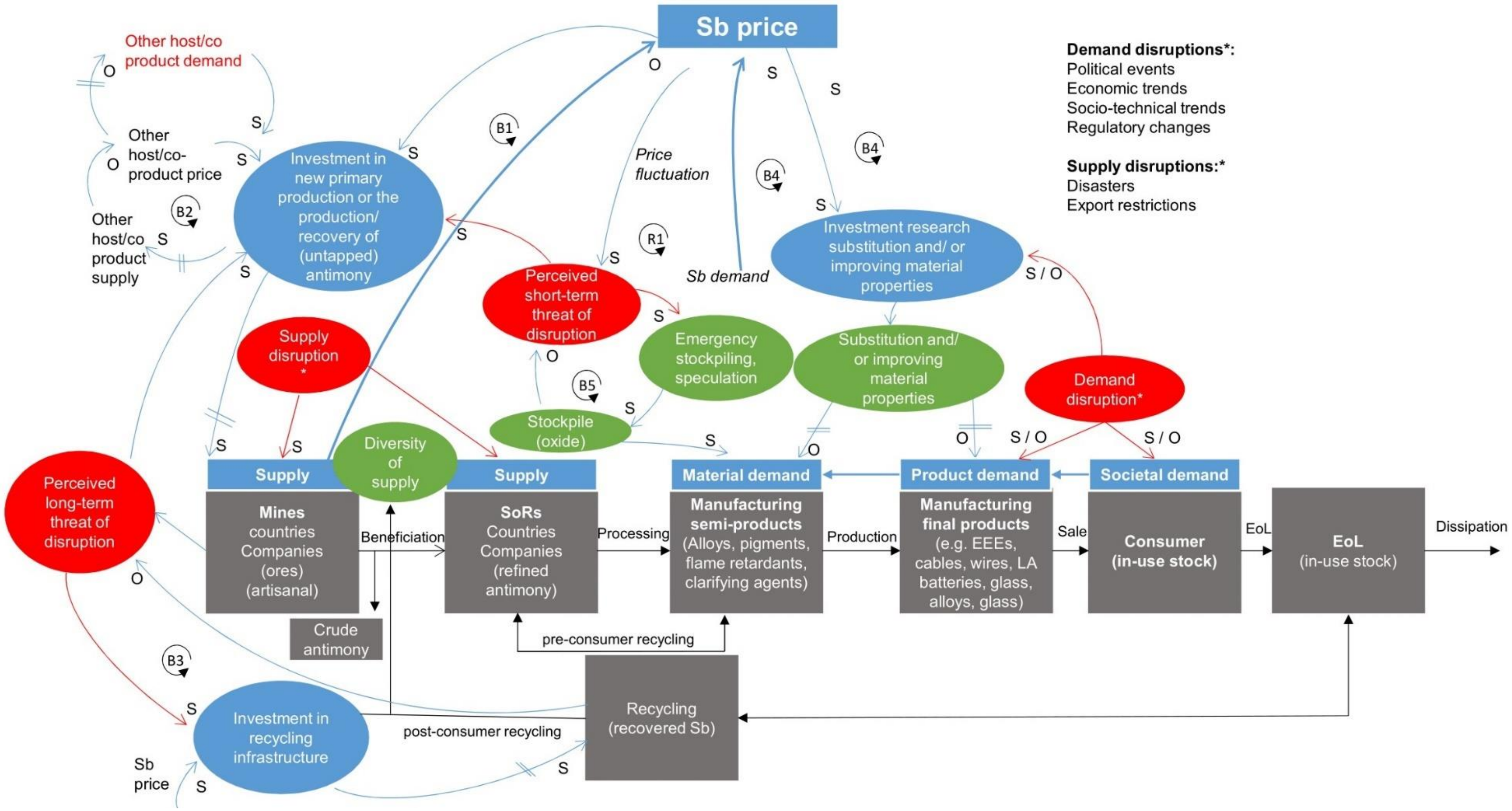


Figure 4.1: System dynamics of the antimony supply chain based on Sprecher et al. (2015). The blue arrows represent how the elements in the system influence each other: the arrowheads indicate the direction of the influence, the S or O next to the arrowhead indicate whether the connected parameters change in the Same or Opposite direction. The double dashed blue lines indicate a delay in the influence. The green ovals represent the four resilience mechanisms. The red ovals represent the supply chain and disruptions and perceived threats of disruptions. The arrow circles represent feedback loops: B1-B4 are balancing feedback loops and R1 is a reinforcing feedback loop. Added elements to Sprecher’s framework are Smelters or Refineries (SoR) as part of the diversity of supply and the production/recovery of an (untapped) companion metal.

The trade of antimony between mines and refineries was mapped with trade data from UN Comtrade (UN Comtrade, 2021). The data as reported by import countries are often different from those reported by export countries. Import data is considered to be more reliable, because imports may usually generate tariff revenues while exports generally do not (Worldbank, 2010). We therefore base our analysis on import data. The trade flows “antimony ores and concentrates” (HS261710), “antimony and articles thereof; unwrought antimony, powders” (HS 811010) and “antimony oxides” (HS282580) are assessed.

4.2 Results

An historical analysis of prices and production of antimony is used to generate insights in the dynamics within the antimony supply chain including four different resilient mechanisms. Figure 4.2 shows a timeline of antimony prices and production. The main historic antimony supply chain disruptions were identified and used to determine factors increasing or decreasing supply chain resilience.

4.2.1 Analysis of resilience in the antimony supply chain: 1913-2017

During the First World War (WWI) a sudden increase in the demand of antimony for military applications (mainly artillery shells and shrapnel bullets) caused the price to triple within one year (Bräuninger et al. 2013). This high price led to a rapid increase in primary production (or the production/recovery of an (untapped) companion metal), which absorbed the supply shortage (see Figure 4.2). This so-called balancing price feedback loop is illustrated in Figure 4.1 (B1). There was little diversity of supply, as mining companies in China produced 80% of the global use from 1908 to 1914, together with a handful of other countries (Amspec, 2009) (for more information on the ten largest producers between 1929 and 2018, see Figure C2 in Appendix III). Most supply was coming from the Chinese stibnite mines (mainly the Xikuangshan mine), stibnite is the most common antimony ore mineral, though more than 100 other minerals also contain antimony (USGS, 2017a).

Following WWI, in the 1930s, the upcoming automobile industry created a demand for lead-acid batteries, made of lead-antimony alloys. This resulted in period of price increase leading up to the Second World War (WWII), when the shortage was absorbed by a production increase. In 1936, China established a government antimony administration, which created a government monopoly of antimony production by artificially restricting output and basing the purchase prices on foreign market conditions rather than domestic influences (Amspec, 2009). In 1949 the Xikuangshan mine was completely converted to state management. During the same time, production increased in Bolivia and Mexico (USGS, 2004).

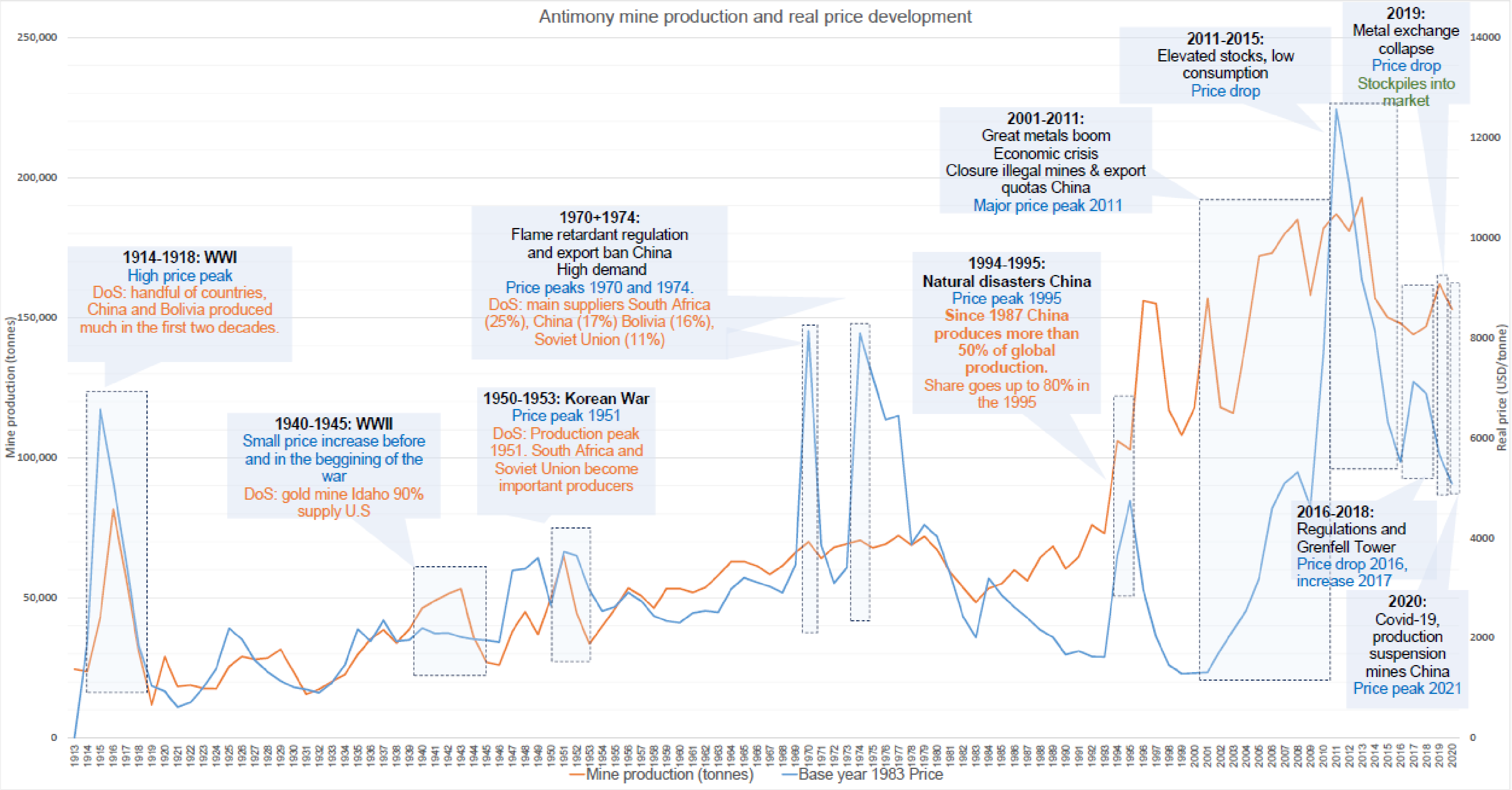


Figure 4.2: Overview of the mine production (tonnes of metal content) and antimony real price development between 1913 and 2021, calculated from index year 1983 (Argusmedia, 2021, US Antimony, 2020, USGS, 2011, USGS, 2012, USGS, 2017b). In addition, descriptions are added related to diversity of supply (DoS - orange) and price (light blue) during the disruption period.

During WWII a smaller fraction of antimony went into ammunition, most was used in lead-acid batteries in military vehicles and as flame retardants in textiles such as tents (USGS, 2004). When the Chinese supply in the United States was cut off by Japan, a gold-stibnite mine in Idaho rapidly increased its antimony production. The mine site and equipment for milling and floatation were already there, but the mine site had to be partly reconstructed to get to the antimony orebody that was identified. The mine was owned by a company, but all production was under allocation of the governmental war production board (United States Department of the Interior, 1987). The mine ended up producing 90% of America's demand for antimony for the duration of the War (Forbes, 2021). The government of the United States was also using their existing industrial base for processing and manufacturing, which further decreased their dependence on other countries. While on a national scale, owning both mining and processing companies increases the security of supply, on a global scale, the concentration of mining and processing in certain countries can increase supply risks.

There were also a few smaller sources of antimony in Europe. Germany was able to get some antimony from Austria and Czechoslovakia (Bidwell, 1940). Another important factor for resilience on a national level during WWII, was that due to perceived short-term threat of a disruption, stockpiles were accumulated in the period leading up to the war. Especially Germany built stockpiles from 1933 onwards, though no exact estimates are available on the size of the stockpiles as they constituted a military secret (Bidwell, 1940). This contributed to the price peaks before the war. In Figure 4.1 this process is illustrated by feedback loop B5.

During the beginning of Korean war there was also a price increase, presumably caused by a higher demand of materials needed related to the war-effort (from 1950 to 1951). During this time production increased in China, but also in South Africa and former Yugoslavia. The production increase was followed by a decrease in price. Overall, between 1937 and 1990 there was a high diversity of supply and the supply concentration (HHI) remained below 2500 (see also an overview of the historic HHI values in Figure C3 in Appendix III). The price-production correlation varies by year, but on average, as illustrated in Figure 4.2, between 1913 to 1970 there was a positive correlation between the price and production (the overall correlation coefficient during this period is 0.7), meaning that when the price increased or decreased, production corresponded.

In the early 1970s, many countries made the use of flame retardants in textiles and other products mandatory. At the same time there was a sharp increase in production of plastic products in which these flame retardants are used, e.g., plastics in electronics (Bräuninger, Leschus and Rosse, 2013). In 1970 the price more than doubled and in 1974, China as one of largest antimony producers, banned antimony export, resulting in a second price peak (Bräuninger, Leschus and Rosse, 2013). During this period the production remained at a relatively high level compared to previous years and there was a high diversity of supply. The main producing countries were Bolivia, China and South Africa (above 10 kt), but there was also high production in former Yugoslavia and the Soviet Union, Morocco, Serbia and Montenegro, Thailand and Turkey (each produced 2 to 8 kt). This nevertheless could not prevent two exceptionally high price peaks. The global production did not increase in line with price, therefore there was a moderate, though positive price-production correlation between 1972 and 1978 (see Figure 4.2).

In the 1980s and early 1990s companies in China increased production very rapidly and their production accounted for more than 80% of world production in 1995 (BGS, 2020). Since the 1990s there has been globally a highly concentrated supply. Figure 4.2 illustrates that while the production continuously increased from 1984 to 1993 (particularly in China), the price continuously decreased. The existing link of price signals resulting in a higher or lower mine production broke down. Production in China was presumably still being coordinated on a national level since the establishment of the antimony industry association in 1936. There can be different reasons why companies in China did not decrease their production while the price decreased. Possibilities include the introduction of subsidies or a decrease in production costs. In 1993 and 2000 two antimony companies (Jiefu Corporation and Hunan Gold Corporation) were founded, with less than 50% of state-owned shares (DGJiefu, 2022, Emis, 2021 and Marketscreener, 2021).

In 1993 the price shortly increased again until 1995, this was during widespread floods in Southern-China in 1994-1995. These floods did not affect the production of antimony in China, but caused transport disruptions and shipment delays, which was causing uncertainty on the market and hence price increases. In 1996 the antimony production in China reached a peak of 129 kt (USGS, 2017b). From 1996 onwards the price drops steadily again and during this time China begins to scale back production. The price kept decreasing and as a result, in 2000, China imposed export restrictions due to the low price (Bräuninger et al., 2013).

The period between 2001 and 2008 is often referred to as “the great metals boom” in which the demand for and price of metals increased very rapidly (Humphreys, 2010). This boom in demand was mainly a result of the rapid build-up of infrastructure in emerging countries, most notably China (Kleijn, 2012). This increase in demand together with the export restrictions in China, resulted in a rapid price increase. During the great metals boom China’s production increased further and reached a new production peak of 166 kt (USGS, 2021). During this period there was a strong correlation between price and production again. The availability of producer stocks in China and a lower–than-expected consumption of antimony between 2011 and 2015 resulted in a price decrease followed by a production decrease (USGS, 2016). Between 2008 and 2018, production in China decreased while production in Russia and Tajikistan increased, though the supply remained highly concentrated.

In 2016, a bill was passed in the United States prohibiting the use of antimony in children’s products, such as textiles (Qima, 2016), which incentivized substitution. However, flame retardants remained an important application of antimony. In 2017 the Grenfell Tower fire in London re-confirmed the importance of the use of antimony in flame retardants in plastics and increased demand (InvestorsIntel, 2021). There was an antimony nominal price peak of 8333 U.S. dollar per tonne, that decreased again in 2018.

The analysis of the supply chain disruptions between 1913 and 2017 demonstrated how the different resilient mechanisms helped to absorb supply shortages. Particularly the diversity of supply and the price mechanisms (primarily balancing feedback loop 1) increased the supply chain resilience between 1913 and 1983. From 1983 until 2017 production highly increased. However, production temporarily did not respond to price signals, and became concentrated in one region, resulting in high price volatility during the disruptions. Overall, stockpiling played a significant role in both dampening and exacerbating the disruptions.

4.2.2 Analysis of resilience in the supply chain: 2018

Price feedback loops (balancing feedback loop 1 and 2)

During the price cycle of 2016 until 2018 the production in China decreased, while the antimony price increased, resulting in a negative correlation. By contrast, Russia doubled its production between 2017 and 2018, responding to the price increase with a delay. This corresponds with the delay after investment in new primary production. In the same year the price decreased. As illustrated in Figure 4.1, the primary production feedback loop is complicated by the demand for by-products. Of the 24 mines, half (12) are primarily antimony mines, 9 are gold mines that produce antimony as by-product, 2 mines co-mine different minerals (e.g. Anzob produces a Hg-Sb concentrate) and one mine produces antimony as by-product of lead processing. By production volume, 56% of antimony is produced as by-product of gold, 32% is produced as host metal and 12% of antimony is produced a co- or by-product (lead, tin, silver, mercury) in 2018.

The production of a mine that produces both host metals and by-products will in most cases be dominated by the demand for the host metal since most economic revenues will come from production of the host. That means that the supply of the by-product cannot easily respond to price increases (inelastic supply). A high price of the host metal can result in new production of antimony, depending on the technology required to recover those metals (Mudd et al., 2014), but it can also result in lower production, making the by-product more vulnerable (see also balancing feedback loop 2 in Figure 4.1). However, the fact that a metal is mined as a by-product can also make the supply of the metal more elastic. If there are mines where the companion metal is not extracted, because this is not profitable, a price increase can rapidly lead to additional production. The rapid transformation of the Idaho mine in WWII is a good example where the fact that antimony was mined as a companion metal actually increased resilience. Globally, 13% of all mercury deposits, 5% of all tungsten deposits, 5% of all silver deposits, 4% of all lead deposits and 2% of all gold deposits contain antimony (Mindat, 2021). There are also mines in which antimony is not yet recovered as a by-product or mines that are closed that contain antimony that can potentially be re-opened.

Diversity of supply

Mining

In 2018, antimony was mined in 17 countries (USGS, 2020), with a total production of 147 kt (USGS, 2020), of which around 90 kt was mined in China, 30 kt in Russia and 14 kt in Tajikistan, resulting in a highly concentrated supply (see Figure 4.3). Though China remains to be the leading producer, declining reserves, market consolidation and regulatory inspections have led to a closure of facilities and caused a decrease of the Chinese production. As a result, China had to resort to importing antimony (Roskill, 2018). There has been a slow increase in the diversity of supply as Russia and Tajikistan have both increased their production in recent years. In addition, a company in Oman is expected to produce 20 kt of Sb (metal and trioxide) from 2021 onwards (Oman daily Observer, 2020, SPMP, 2020).

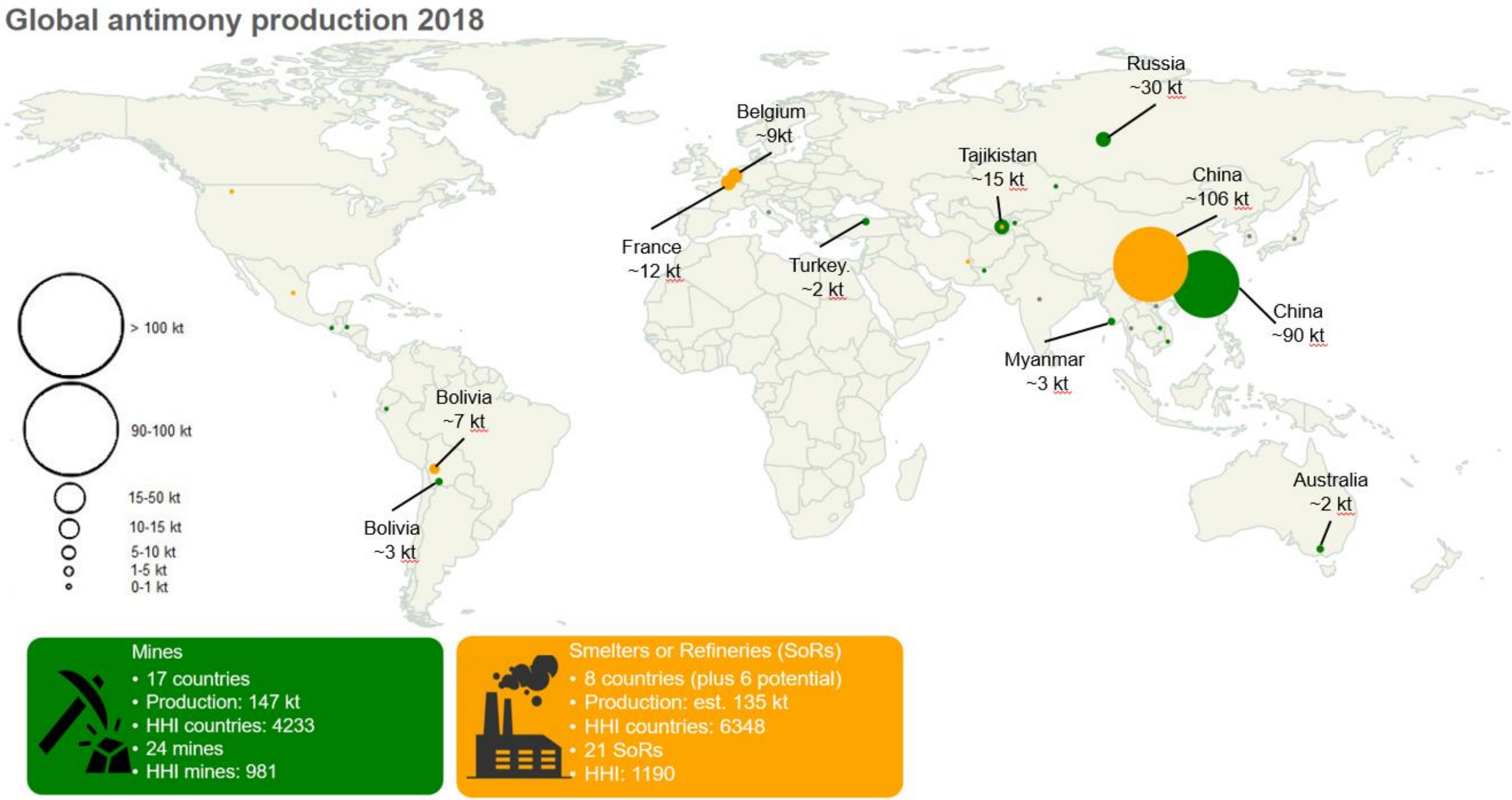


Figure 4.3: Global antimony production 2018 and diversity of supply

To meet future demand, there are several significant potential sources of antimony concentrates in Europe, North America, Africa and Oceania that could add up to 14 kt of antimony to mine capacity in the next four years (Roskill in Perpetua Resources, 2021). In 2018, 24 antimony mines (or collection of mines with one operator) were identified with an estimated production of total 149 kt of the identified individual mines, which is close to the production of 147kt reported by the USGS (2020), see table C1 and Figure C2 in Appendix III. The concentration of supply of individual mines in 2018 is low with a HHI of 981 as most countries have multiple mine sites, which makes the supply more diversified. However, some of the major mines can still cause a disruption. In 2020, there was a production suspension in Hsikwangshan Twinkling Star, one of the China's largest (collection of) mines, which caused a major disruption. There are also large mines in Russia (in 2018 the Olympiada mine was the largest mine globally) and in Tajikistan, though both Russia and Tajikistan export their antimony to China for refining. Therefore, there is still significant dependence on China for processing capabilities.

Processing

The HHI of the processed supply on the country level is an extremely high 6348, as the majority, an estimated 80%, is processed in China. Other important producers in 2018 were Belgium, France and Bolivia. Unwrought antimony and powder (antimony ingots) are imported from China by Belgium, France, and the United States. This material serves as feedstock for the production of high-purity antimony oxides (European Commission, 2020b and Roskill, 2018). These countries are therefore also dependent on China for the pre-processing of the ores. The HHI of the individual SoRs is more diversified (1190) as there are multiple SoRs in China. An estimated 135 kt of primary antimony metal was produced from ores and concentrates in 2018, while the mined production in that year was reported at 147 kt. Total antimony production could therefore also be higher than the estimated 135 kt, possibly because 12 kt is not refined. Crude antimony is also used, e.g. in low flash point ingredients such as matches, detonators and explosives (Perpetua Resources, 2021). Table C2 of the SI gives an overview of the antimony SoRs, and companies and the quantity of antimony refined. In Figure C5 of Appendix III more information can be found on the geographic locations of individual mines and refineries.

Recycling

Figure 4.1 illustrates how supply chain disruptions and perceived long-term price risks can result in investment in recycling, which will increase the diversity of supply (balancing price feedback loop B3). In addition to the 135 kt produced from primary processing, approximately 50 kt or 25% of global antimony is produced via recycling of antimony bearing metal alloys, primarily of lead-acid batteries. Another ~20 kt is produced from antimony bearing residues from lead smelting (confidential report in Perpetua Resources, 2021). The quantity recycled is significantly larger than the commonly quoted global end-of-life recycling rate between 1% and 10% of UNEP (2013). According to the OECD (2015) a recycling rate of over 60% is necessary to mitigate criticality.

No data was available on the facility level split of antimony produced from recycling and from primary antimony, and therefore is not included separately in the production data. The recycling company Campine has introduced recycled antimony trioxide in 2018 and aims to source at least 20% of its antimony metal from regional waste streams. This antimony is extracted from lead-acid batteries (Campine 2021). While most recycling is of lead acid batteries, there is also research done to separate and recover antimony trioxide from plastics from Waste Electrical and Electronic Equipment, where antimony trioxide is mixed with a lot of impurities (Plast2bcleaned, 2020). To achieve high recycling rates, this avenue of research is important as most of the antimony (40%) is used in flame retardants in electrical and electronic equipment and textiles (Graedel and Erdmann, 2012) and only around 20% of antimony is used in lead-acid batteries, though this percentage is higher (32%) within the European Union (European Commission, 2014).

Trade flows

To allow companies to switch to other suppliers during a national disruption, good infrastructures and diversified trade flows are required. The concentration of countries that export of ores and concentrates is high with a HHI 3119, and the concentration of countries that export unwrought antimony is even higher with a HHI of 4013. Countries who export oxides are similarly concentrated with HHI of 4421. A visualization of the trade flows is presented in Figure 4.4, see for more information on the flows also table C3 in Appendix III.

Artisanal antimony ores are mined in Ecuador, Honduras, Laos, Morocco, Mozambique, Pakistan and South Africa to China (Roskill 2018, in Perpetua Resources, 2021). Formally there is only mining from small scale cooperatives in Bolivia reported, but no artisanal mining. Based on the exports of ores and concentrates from these countries (with a min grade of 60% based on USGS, 2004) minus the formally mined antimony, around 1600 tonnes is artisanal mined, equivalent to 1% of total mined production. In accordance with the production concentration, the trade flows in Figure 4.4 illustrate the export and import of antimony is concentrated in one country, China. If we compare this to the map of trade flows of the cobalt supply chain (van den Brink et al., 2020), the cobalt map illustrates production is concentrated in two regions (mine production in Central/South Africa and processing in China). Therefore, the antimony supply chain is even more prone to supply disruptions.

Diversity of companies

There are 59 companies identified in the antimony supply chain (including 5 government owned companies). The HHI of the mine and SoR operator companies is low (1162 and 1116) as well as the HHI of the mine and SoR parent companies (1116 and 1301). Most of the mines and SoRs have the same operator as parent company, this is also included in the data if no parent company was identified. While only six parent companies and two government owned companies were identified that own both mine(s) and SoR(s), together these companies produce more than 50% of both the mined and refined supply. Most production of these vertically integrated companies is in China.

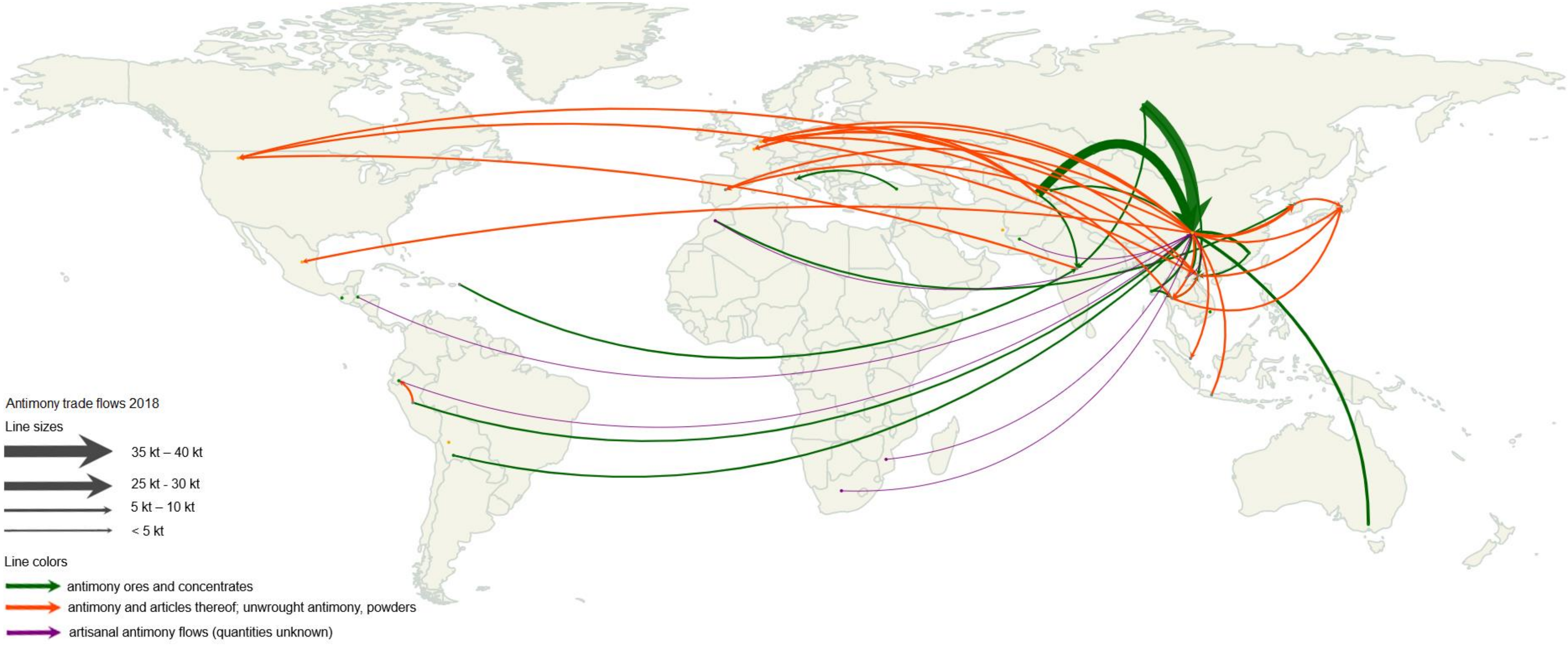


Figure 4.4: Global antimony trade flows > 500 metric tonnes antimony ores and concentrates" (HS261710) and "antimony and articles thereof; unwrought antimony, powders" (HS 811010) (UN Comtrade, 2021). Nodes are included in the countries with mines (dark green) and SoRs (orange). Artisanal antimony flows quantities unknown (flows are based on Roskill in Perpetua Resources, 2021).

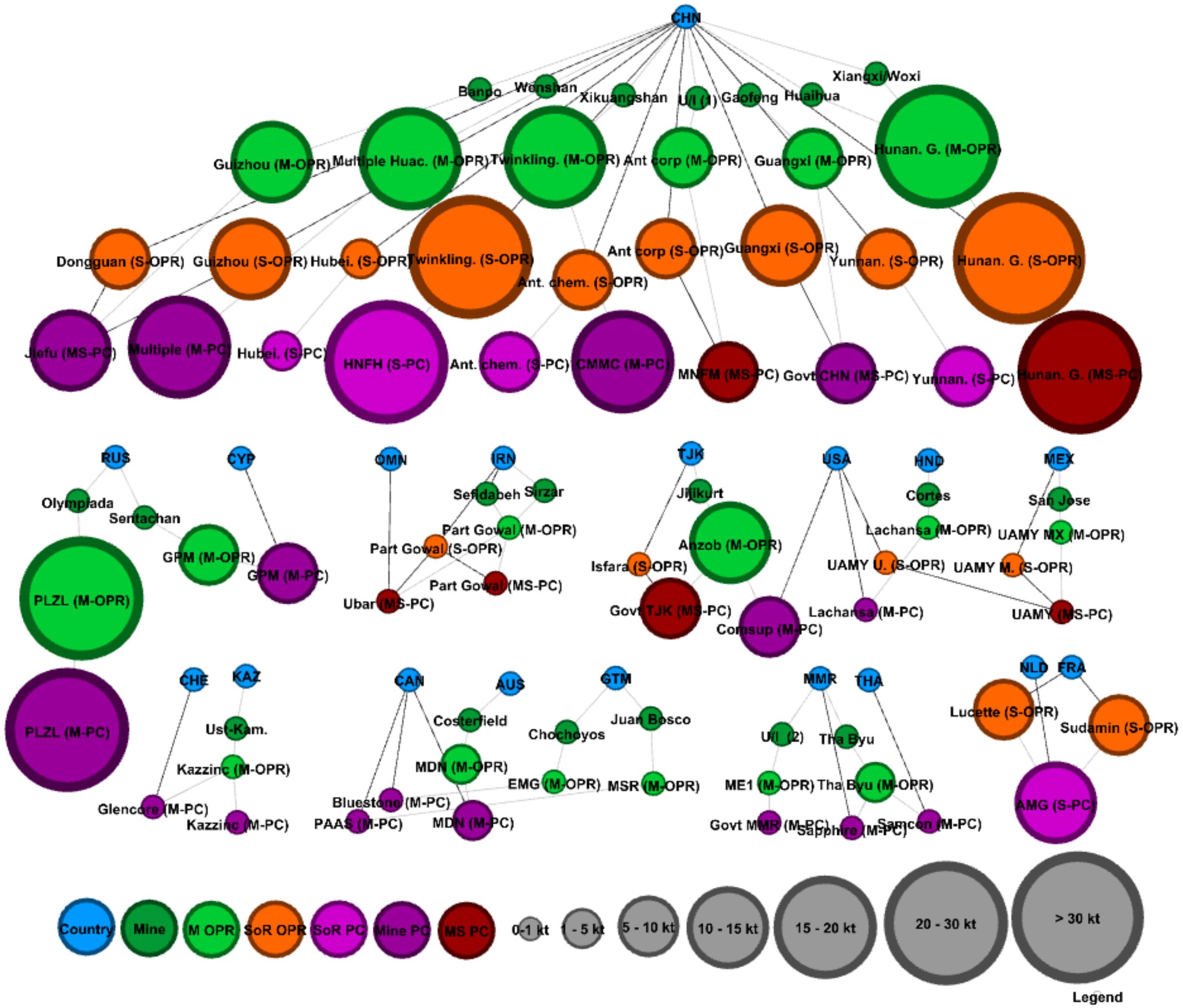


Figure 4.5: Part of the antimony supply chain links between companies (for a complete overview see Figure C6 in Appendix III). On the top of the graph are the companies in China, no links to other countries were identified. Below China are the companies that are linked to two to four countries. The size of the company nodes is linked to their production, the size of the countries and mines is not linked to production (all minimum). M=Mine, S=SoR, OPR=operator, PC=parent company. The abbreviations and references for the links can be found in table C1 and C2 in Appendix III.

Figure 4.5 illustrates the companies in the antimony supply chain with the company links between parent company and operator companies. The overview is very different compared to the analysis of the company links in the cobalt supply chain (van den Brink et al., 2020), which is visualized as a network. In the antimony supply chain network, there are few links identified between companies. In the cobalt supply chain network there were more links, as operator companies have multiple shareholders that connect them to other companies. The supply chain could be more resilient if there are overall short supply chain paths i.e., on average less ‘hops’ to get from one actor to another’ and it is therefore less likely that a disruption in physical or information flows occurs (Nuss et al., 2016). Also, companies that connect other companies and countries in the network can function as bridges. The resulting shorter (indirect) links to other companies can make the supply chain more resilient. In addition to ownership, supplier-buyer relations play an important role in absorbing a supply disruption by switching to other supplier, but these links are confidential and therefore unknown. It should be noted though that competing companies can also use a disruption as opportunity to increase their prices. Compared to the cobalt supply chain, there are only few mine operators and SoR operators with headquarters in other countries. Headquarters abroad diversify the supply chain network, but likely have little impact on disruptions (e.g. natural disasters, political issues) as they are not located in the production country.

Material substitution and improved material properties

In addition to investments in primary production or recycling, a high antimony demand can also lead to investments in research on substitution and/or improving material properties, which can reduce the demand for antimony with a delay (see price feedback loops B4 in Figure 4.1). Conversely, a low antimony price can also lead to inefficient material use and cheaper production techniques that yield lesser material properties. Regulatory changes can both lead to an increase and decrease in substitution and improving material properties (Sprecher et al. 2015). As discussed in section 4.2.1, regulatory changes incentivized substitution in 2016, in 2017 the Grenfell Tower fire in London re-enforced the use of antimony in flame retardants (InvestorsIntel, 2021). In 2019, there were expectations for restrictions in regulation in the European Union, but these have been postponed.

Substitution is not a very promising antimony resilience mechanism on the short term, due to the difficulties in the substitution of antimony flame retardants. Substitution of antimony in lead-acid batteries is possible while retaining performance, combinations of calcium, copper, selenium, sulfur, and tin are substitutes for alloys in lead-acid batteries (Graedel et al. 2015; Tercero Espinoza et al. 2015; and USGS,2020). In other antimony products such as antimony chemicals in enamels, paint and pigments, there are also possibilities for substitution with chromium, tin, titanium, zinc, and zirconium (USGS, 2020). However, for some applications, including flame retardants, substitution can have undesirable consequences, such as weakening of the polymer (Australian Government, 2019), therefore antimony is still considered to have superior performance (Graedel et al. 2015; Tercero Espinoza et al. 2015). According to a manufacturing company the development of viable substitutes in flame retardants can take ten more years (Antimony, 2019).

Overall, in 2018 there was potential for substitution for 35% of the antimony uses (global use of lead-acid batteries is 20% and certain antimony chemicals 15%), while the use in flame retardants is 40% and thus remains a factor that decreases the resilience of the supply chain (Graedel and Erdmann, 2012). Options could be explored for material substitution, whereby a lower grade of the same material is used (Sprecher et al., 2015). This would also result in a decrease in demand (Mancheri et al., 2018).

Stockpiling

The antimony disruption case studies demonstrate that stockpiles can increase the resilience of the supply chain, however, it can also *cause* supply chain disruptions. In 2019, when the Fanya metal exchange was liquidated, around 19 kt of antimony stocks were auctioned and were said to be bought by China Minmetals (Reuters, 2019). The additional supply resulting from the FANYA stock liquidation flooded the market, this supply surplus decreased threats of disruptions and contributed to price drop in 2019 (see also balancing feedback loop 5 in Figure 4.1). Alternatively, when worries about changing regulations disappeared in the EU (in 2020), a strong competition arose to buy antimony stocks (Investors Intel, 2021). The competition for emergency stockpiling, resulted in an even higher demand and contributed to a strong price increase, this is illustrated with the reinforcing feedback loop 1 in Figure 4.1.

The relation of stockpiles and resilience is contingent to the strategy and position of the stakeholder who holds the stockpile (Van de Camp, 2018). In 2013, the US Department of Defense recommended strategic stockpiling of 11 kt, the agency has been stockpiling antimony at a rate of around 1,1 kt annually (Perpetua Resources, 2021). Apart from stocks bough by China's State Reserve Bureau, the company China Minmetals is understood to have maintained a stockpile of around 20 kt of metal and oxide in Guangxi. If it remained unused, together this would form a strategic stock of 30 kt, or 20% of the production in 2018, but particularly with recent competition and unknown stocks in other countries, global stocks are expected to be higher. The stockpiles held by companies are unknown. Therefore, it's not possible to estimate the extent to which the stockpiles contributed to the overall supply chain resilience in 2018.

4.3 Conclusion

This is the first study that examined the antimony supply chain from a resilience perspective. Using this theoretical framework, the different interactions between parts of the supply chain were analysed, as well as the supply chain as a whole. The individual mines, refineries, companies, and links between companies as well as trade flows were mapped, both in terms of the geographic location as well as in terms of annual production. Between 1913 and 1983 there was a positive correlation between price and production, and presumably the price incentivized rapid production increase to absorb supply chain shortages. Also stockpiles and a high diversity of supply increased supply chain resilience. In 1980 production rapidly increased in China, resulting in a highly concentrated supply. In the 1980s and early 1990s the production did not correlate anymore with price changes, however, during this period production was mostly increasing while the price decreased, indicating there was sufficient supply. During the periods of the great metals boom both demand and price increased rapidly and correlated again with the continuous growth in production.

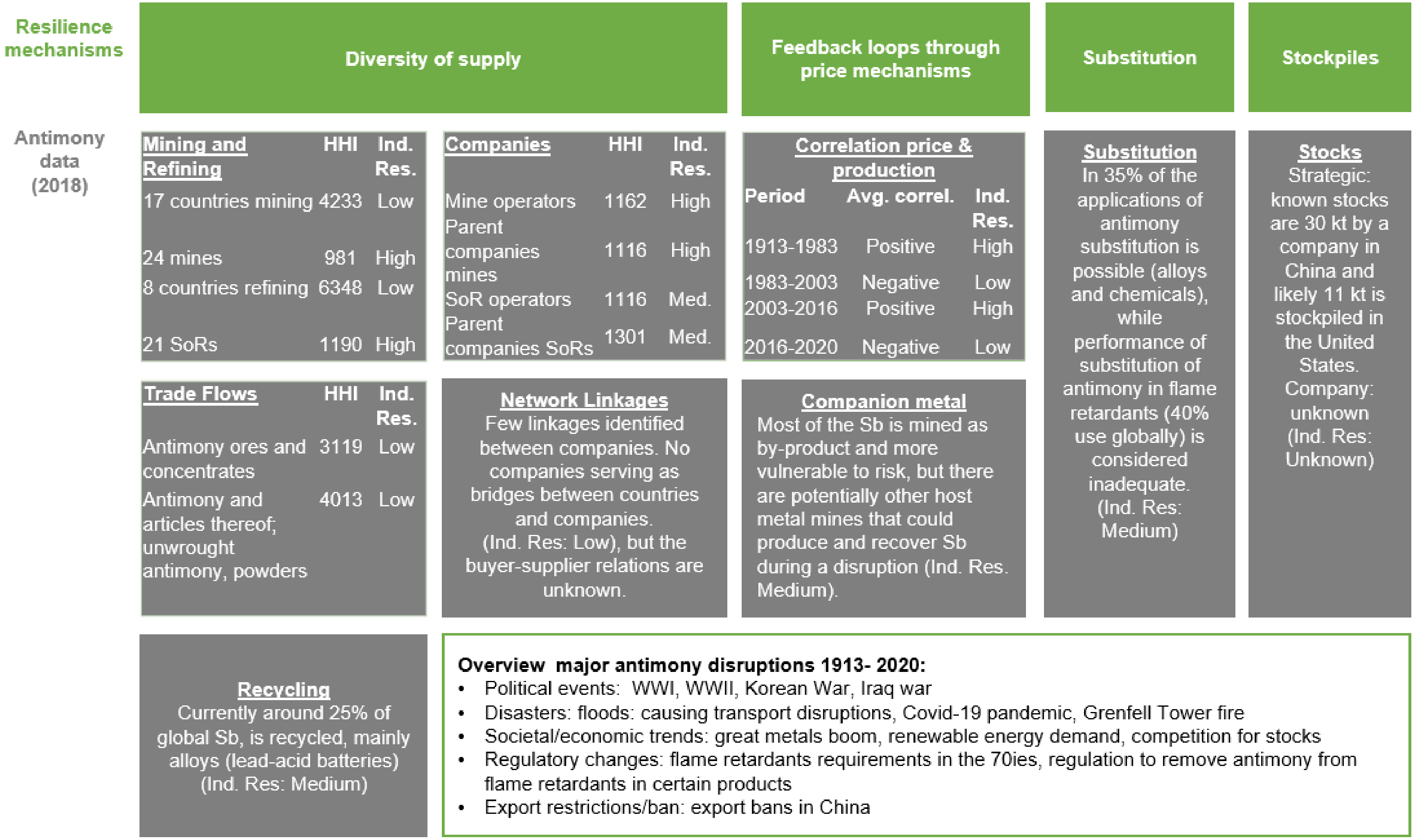
From 1990 to 2018 antimony mining was highly concentrated. The vertical integration of the largest mining and refining companies in 2018 also indicated a lower diversity of supply on a company level. We found that based on production volume, most antimony is mined as a by-product, which increases the vulnerability to supply disruptions. However, the presence of unrecovered by-products can also make the supply of a by-product more elastic. For this feedback loop to function, there will need to be clear price signals from the market. Further research is recommended into the availability of antimony in existing gold, silver, mercury, lead and tungsten mines. If the EU would want to reduce its import dependency, there are also several antimony deposits within the Europe that could be developed.

However, mining alone is not enough. Mining and processing capacity should be developed simultaneously, because processing is also concentrated in China. Together with the development of new primary sources, secondary sources could also provide significant amounts of antimony. One example of a significant source of secondary antimony is lead-acid battery recycling. Some recycling capability already exists in Europe, and it is recommended to increase this by developing dedicated policies.

This study finds that in 2018 all production and trade flows of antimony were concentrated in one region. This is a bottleneck for resilience as it can cause logistical disruptions and hamper switching between suppliers. On a company level, there are few links between companies (parent companies) in different countries, which could be an indication that switching between alternative suppliers is problematic. The substitution of antimony in flame retardants could take years (flame retardants representing ~40% of the overall market), resulting in lower overall supply chain resilience, while for lead-acid batteries and chemicals substitutes seem readily available (together representing ~35% of the total market). In conclusion, most of the discussed resilience mechanisms for antimony were relatively weak in 2018, particularly the diversity of supply and price mechanisms, see Figure 4.6. It is therefore recommended that the mined production, processing capabilities and supplier networks are diversified, stockpiles explored to absorb sudden shortages and recycling be increased.

4.4 Discussion

We listed different measures to increase antimony supply chain resilience. However, it should be considered that antimony is a heavy metal that can have a negative impact of human health and can cause significant environmental pollution, both by mining (Wang et al., 2010) and disposal (e.g. disposal of PV panels will become a salient environmental issue in the next decades, Chowdhury et al., 2020). The need for resilience and particularly substitution should therefore be considered not only from an economic perspective, but also from an environmental and health perspective. This study also highlighted the data gap for antimony production. There are limited sources available on the antimony mines and processing facilities and their annual production. No public data was found on global antimony oxide production per country or facility. This study includes the production of the largest players in the supply chain, but greater transparency and better data reporting is highly recommended, particularly at the processing stage. A complete overview of the resilience of the antimony supply chain can only be provided when downstream flows are included, which was out of scope in this study. This would also create a quantitative link between recycling and secondary supply. Material flow analysis methods can add knowledge about the manufacturing and sourcing practices, to quantify the whole supply chain. Although there are several projections for antimony demand, the available information about the future demand for antimony is limited and does not provide details on the material flows. More detailed future demand scenarios are therefore recommended, particularly on the need for antimony in the energy transition.



Resilience mechanisms

Diversity of supply | **Feedback loops through price mechanisms** | **Substitution** | **Stockpiles**

Antimony data (2018)

Mining and Refining	**HHI**	**Ind. Res.**
17 countries mining	4233	Low
24 mines	981	High
8 countries refining	6348	Low
21 SoRs	1190	High

Companies	**HHI**	**Ind. Res.**
Mine operators	1162	High
Parent companies mines	1116	High
SoR operators	1116	Med.
Parent companies SoRs	1301	Med.

Correlation price & production

Period	**Avg. correl.**	**Ind. Res.**
1913-1983	Positive	High
1983-2003	Negative	Low
2003-2016	Positive	High
2016-2020	Negative	Low

Substitution
In 35% of the applications of antimony substitution is possible (alloys and chemicals), while performance of substitution of antimony in flame retardants (40% use globally) is considered inadequate. (Ind. Res: Medium)

Stocks
Strategic: known stocks are 30 kt by a company in China and likely 11 kt is stockpiled in the United States. Company: unknown (Ind. Res: Unknown)

Trade Flows	**HHI**	**Ind. Res.**
Antimony ores and concentrates	3119	Low
Antimony and articles thereof; unwrought antimony, powders	4013	Low

Network Linkages
Few linkages identified between companies. No companies serving as bridges between countries and companies. (Ind. Res: Low), but the buyer-supplier relations are unknown.

Companion metal
Most of the Sb is mined as by-product and more vulnerable to risk, but there are potentially other host metal mines that could produce and recover Sb during a disruption (Ind. Res. Medium).

Recycling
Currently around 25% of global Sb, is recycled, mainly alloys (lead-acid batteries) (Ind. Res: Medium)

Overview major antimony disruptions 1913- 2020:
- Political events: WWI, WWII, Korean War, Iraq war
- Disasters: floods: causing transport disruptions, Covid-19 pandemic, Grenfell Tower fire
- Societal/economic trends: great metals boom, renewable energy demand, competition for stocks
- Regulatory changes: flame retardants requirements in the 70ies, regulation to remove antimony from flame retardants in certain products
- Export restrictions/ban: export bans in China

Figure 4.6. Summary of the resilience mechanisms with an indication of supply chain resilience (Ind. Res.) and an overview of major supply chain disruptions between 1913 and 2020

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