Resilience in the Tin supply chain:

From the COVID-19 crisis to future developments

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Summary

Resilience has been gaining importance as a key element that prepares the supply chains to respond after disruptions. In this thesis, the material supply chain resilience framework is used to study the supply chain of tin before and during the disruption caused by the COVID-19 pandemic. Tin is a small-scale market compared to other major metals but its importance is increasing thanks to its possible applications in the next-generation lithium-ion batteries, fundamental for the energy transition. Besides, Tin is one of the main elements used in the semiconductor industry which is at the centre of the trade war between the US and China. In order to increase its potential and be used in “next-gen” batteries, tin supply chains must show resilience. Using qualitative and quantitative data and modelling, this paper aimed to explore the resilience of the supply chain of tin. The research showed that Tin demonstrated considerable resilience during the COVID-19 disruptions ,thanks to the semiconductors and Chinese demand, both of which increased during the second quarter of 2020. Currently, almost half of tin production goes to solders, which explains the high dependency between the tin market and the semiconductor market. China is the biggest producer and consumer of tin, which makes the demand for tin dependent on Chinese demand. The analysis of the resilience mechanisms showed stockpiling and diversity of supply are integrated into the supply chain but their contribution to resilience remain low. Substitution could not be considered a resilience mechanism due to the lack of substitutes for tin solders. The resilience mechanisms would gain importance in the future of tin if it would be used in new technologies. The model presented in this thesis estimates the amount of tin that will be used by 2030. With this in mind, recycling of tin must be increased to support the future demand. Consequently, Governments and companies must invest in technologies in order to increase the recycling of E-waste. Lastly, the development of the relations between the US and China will also interest the tin supply chain. In this regard, three different sub scenarios are analysed: complete decoupling, partial decoupling, and no-decoupling.

1.Introduction to Tin "The spice element"

Tin is called "the spice element" due to its hidden presence in everyday life. In fact, tin can be found in every electronic compound, steel can, PVC, glass coating, cement, and many other products. In nature, the sole source with economic importance is an igneous rock called cassiterite, where tin is contained in the oxidized form Sn_2O. This mineral is only found in alluvial and lode deposits in association with other metallic minerals that can contain by-products of Tin.

The biggest producers and smelters of Tin can be found in China, Indonesia, and Myanmar, which account for more than half of the world supply. Other important supplier's countries are Peru, Bolivia, Brazil, and the Democratic Republic of Congo, while potential resources for the future supply are also found in Russia and Australia. In particular, Russia has potentially the second-largest share in reserves and resources (ITA 2020a)(Appendix A).

In a broader view, Tin has a concentration of 2 ppm in the Earth's crust and is the 49^{th} most abundant element, which makes it a relatively scarce but not rare (Appendix A). Since 2013, along with tantalum, tungsten, and gold, it has also entered the list of "conflict metals"[1]. This list includes those metals that are mined to finance guerrilla and illegal armies, as it happens mainly in the Democratic Republic of Congo.

On the other edge of the supply chain, end-products of Tin are many, which in order of importance are: solders, chemicals, tinplate, lead-acid batteries, bronze, and others. (Malqueen 2018) Solders controls half of production and finds its main use in semiconductors. Tin chemicals have many applications, the most important is for PVC stabilizers. In 2015, new legislations in Europe[2] and the US[3] are starting to put pressures on Tin chemicals. Lead-acid batteries are expected to be substituted by more sustainable options like lithium-ion batteries from 2025 onwards. (Liu et al. 2016)

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[1] The term "Conflict minerals" indicates those elements whose purchase goes to financing militias and illegal armies in any stage of the supply chain. The main area impacted is the Democratic Republic of Congo and its surroundings. The first legislation that used the name "conflict minerals" was the US Dodd-Frank Act, section 105 in 2010, which set the base for future regulations. Later on, the Organisation for Economic Co-operation and Development (OECD) published "Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas" which explains in detail why it is necessary to take action to empower the supply chain.

[2] Dangerous Substances Directive 67/548 EEC Directive of 2015, introducing the Globally Harmonised System of Classification and Labelling of Chemicals (GHS)

[3] US food and drug administration, Code of federal regulations (CFR)

The last big share of Tin demand goes to the bronze industry, an old alloy that still finds many applications.

Since 2018 tin solders supply chain is being affected by the trade war between the US and China[4]. The trade war has had a main repercussion on the high-tech market, which reduced Chinese demand. The reduction in Chinese demand had a big impact also on tin solders demand during the year 2018 and 2019. (Colback 2020) (Willoughby 2019)

In 2020, combined with the consequences of the trade war, the spread of COVID-19 has created a new disruption among the tin supply chain. Supply of tin has been reduced drastically, accounting for a 10% drop in prices during the first trimester of 2020. In response to that, all producers has seen a reduction in their primary output, i.e. the world's largest tin producer, the Indonesian PT Timah, announced that it is also cutting the production ('Indonesian Tin Sales Fall after PT Timah Announces Production Cuts' 2020).

The information on the Tin market and its disruptions is scarce due to the small scale of its market compared to other important metals. The modest size of the market does not attract many big investors and lack of institutional interest discourages analysts to focus on tin. However, it could be time to rethink about this tiny metal. An MIT study showed that tin could be the metal most impacted by new technologies (Home 2020b). The main potential use for tin is in the next-gen batteries, many types of researches are being conducted using tin as an anode in lithium-ion batteries (Lehao Liu, 2016). The International Tin Association is monitoring these new possibilities for tin and it has been tracking publications and patents detailing the development of tin in at least four generations of lithium battery technology over the last year (Pearce 2017). Due to the increasing demand for lithium-ion batteries, used in electric vehicles, in the upcoming future Tin could be an excellent substitution to be used as an anode in the next-gen batteries.

The first impact of new uses for tin is the growth in demand, which leads to concerns about its supply. In recent years tin showed supply shortage problems. The supply of tin is vulnerable for four main reasons. (Willis and Adina 2019) Firstly, Asian alluvial production is costly and occurs in short life cycles. Secondly, China, known for its material protectionism, dominates production and consumption of tin. Thirdly, since 2013, along with tantalum, tungsten, and gold, it has also entered

[4] The former president of the US Donald Trump accused China of unfair trading practices and intellectual theft. His administration put three rounds of tariffs on more than 550 billion $ of Chinese goods, including more than 90 line tariffs central to the semiconductor industry. China has retaliated with tariffs on 185 billion $ of US goods, accusing the US of stopping their rise as a global economic power. (BBC 2020)

the list of “conflict metal”. At last, Tin is on the edge of becoming a critical material (CM) for most of the major economies.

The concept of critical material has grown strong in the last decade and all the major economies want to reduce their reliance on imports of CM or increase their access. (Schuyler 2019) Tin is considered a CM in China and the US while in the European Union it is close to becoming one (Figure 1). The difference of assessment between countries is given by different interpretations of the criticality indicators.

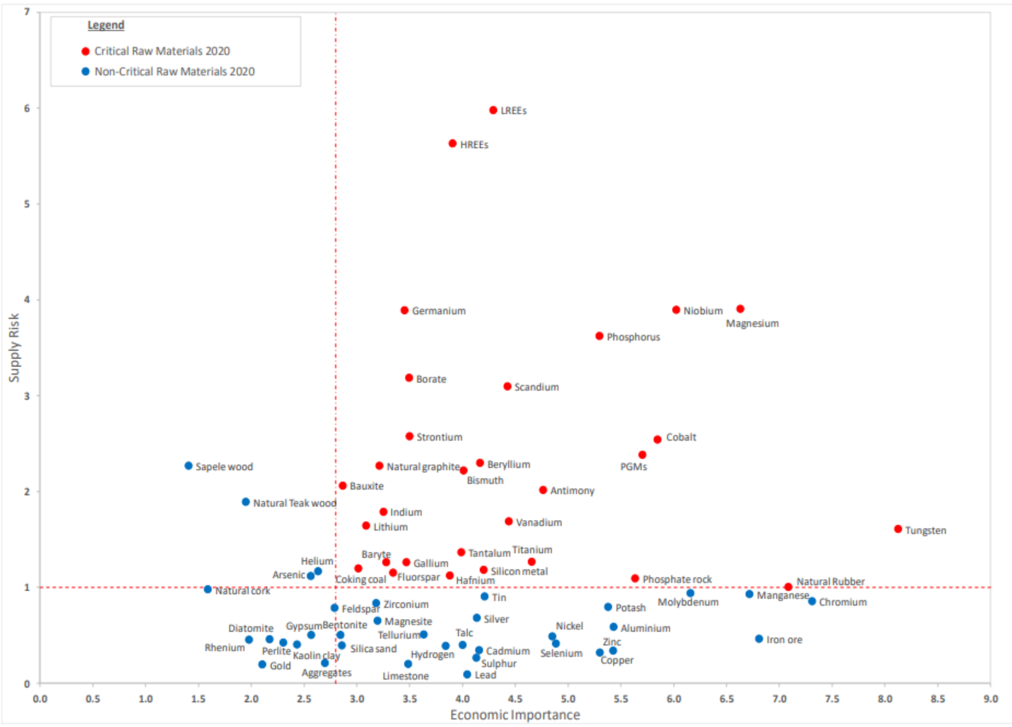


Figure 1: EU 2020 critical raw materials table. Materials above a supply risk of 1 are considered CRM and tin has a value of 0,9. (European Commission 2020)

In general, critical materials are assessed on the static indicators supply risk and economic importance. The use of statics indicators restrict criticality assessments to a fixed spatial and temporal reference system. These indicators do not address the dynamics of the supply chain. (Ioannidou et al. 2019)

In this context, Dewulf et al. highlighted how current methods do not offer insights on how a system responds to disruptions and how it is able to mitigate them, what they call resilience to criticality. They propose a difference between criticality calculation based on recent past/present characteristics and resilience that can be based on future potential characteristics, that is given by a dynamic approach (i.e. time-dependent) (Mancheri et al. 2018) (Dewulf et al. 2016). Concerns about security of supply is a problem regarding the resilience of the tin supply chain.

Resilience in the supply chain is gaining more and more importance. In 2019, almost 70% of companies had experienced at least 1 disruption, of which 13% reported a loss of over 1 M Euros (E. Staff 2019). The nature of disruptions ranged from equipment malfunctions, unforeseen discontinuities in supply, information technology, to breakdowns to natural hazards and disasters. Hence, a concept that reduces the impact of disruption by proactively identifying strategies that allow the supply chain to react while recovering to its original state is gaining importance (Jüttner and Maklan 2011). In the context of the supply chain, resilience is defined as 'the capacity (of a system) to supply enough of a given material to satisfy the demands of society and to provide suitable alternatives if insufficient supply is available' (Sprecher et al. 2015). This means that in a supply chain, supply and demand need to have elasticity in order to absorb any kind of disruption without letting the price plunge or rocket. The framework for supply chain resilience studies was developed by Sprecher et al. (2015; 2017). They introduced and researched resilience mechanisms: diversity of supply, recycling, stockpiling, and substitution. So far, this framework has been applied to neodymium (Nd), tantalum (Ta), Platinum Group Metal, and Cobalt (Sprecher et al. 2015; (Sprecher et al. 2017; Mancheri et al. 2018; van de Camp 2020).

In this thesis, this supply chain resilience framework is used to analyze the tin supply chain. The potential of tin in future technologies and next-gen batteries expose the supply chain to future disruptions, which makes interesting and important the study of its resilience. Moreover, the application of the framework to tin supply chain is academically interesting, because it demonstrates the framework to a new material and a major metal (not a companion). In this thesis, the COVID-19 disruption is used to study the resilience of the tin supply chain. Moreover, the main results are used to assess two more future disruptions given by the next-gen batteries and the possible results of the US-China trade war.

The main research question is:

"Is the Tin supply chain resilient and how do the resilience mechanisms respond to disruptions?"

In order to answer the research question, different sub-questions will be developed.

1. How the resilience mechanisms performs in the supply chain?
2. How is the supply chain responding to the COVID-19 disruption?
3. How could the supply chain respond to a possible future change in demand or supply?

2. Market and supply chain history

Following the words of Dr. Carl Sagan (1980) "You have to know the past to understand the present.", the first section of the report will be dedicated to describing the history of the Tin supply chain since understanding its history can be extremely useful to discern the current actors and the main common events. The starting point of the chapter will be the Tin crisis that took place during 1985 due to the collapse of the International Tin Agreement (ITA) and consequently of the International Tin Council (ITC). This event changed the Tin industry from the roots because the International Tin Agreement had been a key arrangement between Tin producers and consumers in order to control the fluctuations of Tin in the market after the Second World War . The collapse of the Council left the Industry exposed to the market fluctuations.

2.1 International Tin Agreement collapse (1985)

As stated before, a preliminary Tin agreement was first signed after the Second World War by six producers and nine consumers. The goals of the agreement were mainly to avoid big fluctuations in the market and ensure supplies of Tin at reasonable prices. It was decided to renew the agreement every five years.

The International Tin Council, who was in charge of keeping the well-functioning of the agreement, had the power to introduce quotas for the exports, used at the end of the '70s, and trade buffer stocks in order to keep the price-controlled. In the '80s, during the time of the sixth revision of the agreement, the ITA was counting a high number of Tin consumers but few producers. In the same period the group of metals traded in the London Metal Exchange (LME) was having a strong span of fluctuations caused by a shortage of supply, which made the increase dramatically. In 1984 the Tin price reached a historical top and the consequences grew out of the control of the Council.

Three main events can be identified that caused the price collapse during 1985 and were out of control by the ITC, which are:

- The United States started to sell a significant quantity of its strategic stockpile
- Brazil increased exports by 50% due to the discovery of a new deposit
- The number of smugglers that were selling Tin in South East Asia rose dramatically

Due to these new flows of tin introduced in the market, the prices started to fall down. The Council tried to protect the floor price by buying buffer stocks while the price was still high, which increased the debts. The council tried to introduce new quotas but it was ineffective due to the few numbers of producers in the agreement.

The high debts brought legal problems with the creditors, in this situation the ITC couldn't defend the price floor anymore and at the beginning of 1986, it plunged definitely. Tin prices collapsed from 12,389 $US per ton in October 1985 to 5,485 $US per tonne in June 1986, to the point that not even the costs of production could be paid.(UNCTAD secretariat 1995) As a result, various mines were closed and a number of producers reduced their production, i.e. Malaysia – 30%, Thailand -40% mines, Bolivia -40%.

To bring order in the tin industry another international association intervened, the Association of Tin Producing Countries (ATPC), which established again quota exports in order to raise the price. What made the new quotas more effective was that the ATPC and its partner countries controlled about 85% of the world Tin supply.

The result of this cooperation not only raised the prices but also gave trust to the creditors. Along with the demand, also the production rose, as can be seen in figure 2. The tin producers began to change the focus of their concern, they were fearing that the quick price recovery would encourage substantial additional production, leading to a disruption of the market and the export control scheme. This fear was well-founded, as the price of tin slid during the second half of 1989. This new drop in the prices had two main reasons: the increase of China's production and exports, and the fall of the URSS that cut off part of consumption. (Thoburn 1994)

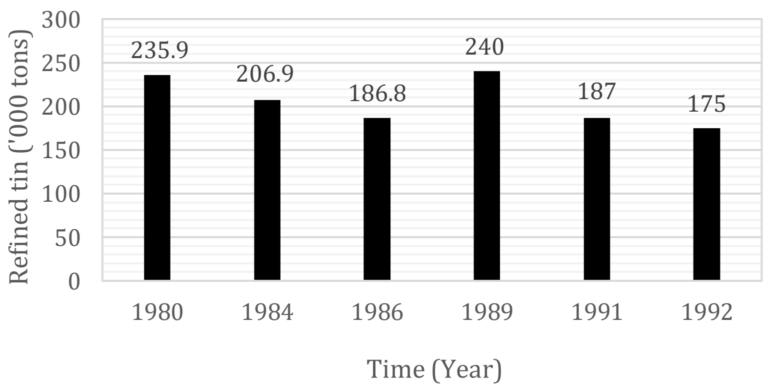


Figure 2: World Tin production(USGS 1980-1992)

2.2 "Dot-com bubble" Crisis (2001)

During the '90s there weren't notable events that occurred in the Tin industry. The decade was marked by low prices and growth in production in the response to an increase in demand. The supply-side saw the rise of new leading producing countries such as China, Indonesia, and Peru, while other historical producers such as Malaysia and Thailand switched to become consumers. On the demand side, solders changed into the biggest products of tin, overtaking tin plates.

The "dot-com bubble" was a period of exaggeratedly high speculations on high-tech companies between the years 1997-2000. There was a lot of capital invested in the sector that brought a lot of overvaluation and bad investments. When the bubble exploded during 2000-2001 the demand for high tech fell. The result for the Tin industry was a drastic reduction in demand from electric solders which made the prices drop. (CFI 2017)

This fall was worsened by the oversupply of China, where mining and export regulations were only introduced in 2001, and new legislation in the Indonesian government, which removed Tin from the strategic commodities list. As a strategic commodity, only a few companies had an official license to export and trade the metal. The liberalization policy set no limit on tin exports and exempted tin ore producers from paying royalties to the Government, which increased the legal but also illegal production of Tin.

2.3 The Rise of China (2003-2011)

The years between 2003 and 2008 saw the industrialization of China as the main driving event. The industrialization process brought growth in demand in every sector, including metals. The world economic slowdown after the burst of the Dot-com bubble left the investor skeptical for new investment. Low investments meant low production which increased the prices, but the growth of Chinese demand limited this increment.

In the EU and the US, more and more lead-free regulations were increasing the demand for lead substitution, i.e. in 2006 the EU's Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) regulation was published. This opened the way for more Tin uses in electrical solders, leading to higher demand.

In 2008 the world experienced one of the biggest recessions of the previous 100 years and almost all the markets were affected, and Tin was not an exemption. Tin consumption reflected the crisis and dropped as much as 15% in 2009, while the production already started to decline from 2006 and intensified during the crisis. The Tin industry started recovering in 2010 thanks to the Chinese domestic demand. China attested itself as a key actor in the industry, being the biggest producer and consumer.

In spite of the increase in demand, during 2010 China shifted from being a net exporter to a net importer. A new phase of supply deficit was starting.

2.4 The "black swan" Myanmar and Indonesian export laws (2011-2016)

During 2011 the tin industry entered a supply deficit moment. Aside from China being a net importer, the deficit was driven by different events, such as lack of investment, outdated mines, conflict minerals, and political risks.(Gardiner and Sykes 2015)

This supply deficit increased the prices but lowered ore grades of new projects in the alluvial mines of South-East Asia, since they were not encouraging investments in new yet costly renewals . Without investments, the sector could only rely on the existing mines, which in some cases started to reduce their output due to the lack of other projects , as it has happened in Peru where production is decreasing since 2006.

Moreover, in order to reduce the phenomena of the "conflict metals", which Tin is part of, legislations in consumer countries were starting to oblige companies to trace the supply chain of different minerals. The goal of this process was to cut off the supply from countries where the trade of Tin was used to finance illegal activities. Unavoidably, it had an influence on the export of the producers' countries.

For instance, the Indonesian government , hampered multiple times the production of artisanal and small-scale mining (ASM) in order to prevent illegal mining. These actions have had a great impact on global production because Indonesia is the biggest Tin exporter and ASM has a big share in the tin extraction. In 2014 during a period of low demand, the Indonesian government started to constrain the Tin ingot exports in order to keep the price high. This caused a disadvantage for China, which was the customer of ingots from Indonesia. To counteract, China started to buy Tin Ore and refined it within its national border. The tin ore was bought from Myanmar, who started to produce it in 2011. In only three years, Myanmar became the third-largest producer of Tin ore, thanks also to the Chinese investments. In 2015 China turned into a net exporter. (Gardiner and Sykes 2015)

Thanks to the new supply of Tin, the prices of this metal fell again. This situation was also worsened by a loophole in the Indonesian legislation, and the exports of tin in solders and chemicals increased. Moreover, the continuous drop in the price of crude oil was making production costs lower while the strengthening of the dollar was making imports more expensive, reducing demand further. Rustam Effendi, the governor of the Bangka Belitung province - the region with the largest tin production, called a reduction in production but received little response form the largest producer, who stated that they would continue fulfilling contracts. Only at the beginning of March 2015 the government and the producer found an agreement to reduce production in order to not let the price drop. (Taylor 2011)

This year the Shanghai Future Exchange increased its importance in trading by buying tin stocks.

2.5 Pre-COVID 19 tin supply chain and the trade war (2016-2020)

From the previous historical chapters five factors emerged to influence the supply chain more than others. These factors are:

- Solders demand
- Global stocks
- Country legal framework
- Input prices
- Chinese tin supply chain

Most of these factors are analyzed in the results. In this part, I only introduce solders demand and the Chinese supply chain because they are important for the timeframe of this section.

Solders has half of the demand for tin (figure 3), therefore, changes in solders demand directly influence the tin prices. The solders demand showed to be tied with the semiconductors demand, if the latter is resilience it would reflect on the solder market. (Home 2020a) To show this interdependence figure 4 represents the tin prices with the semiconductor sales.

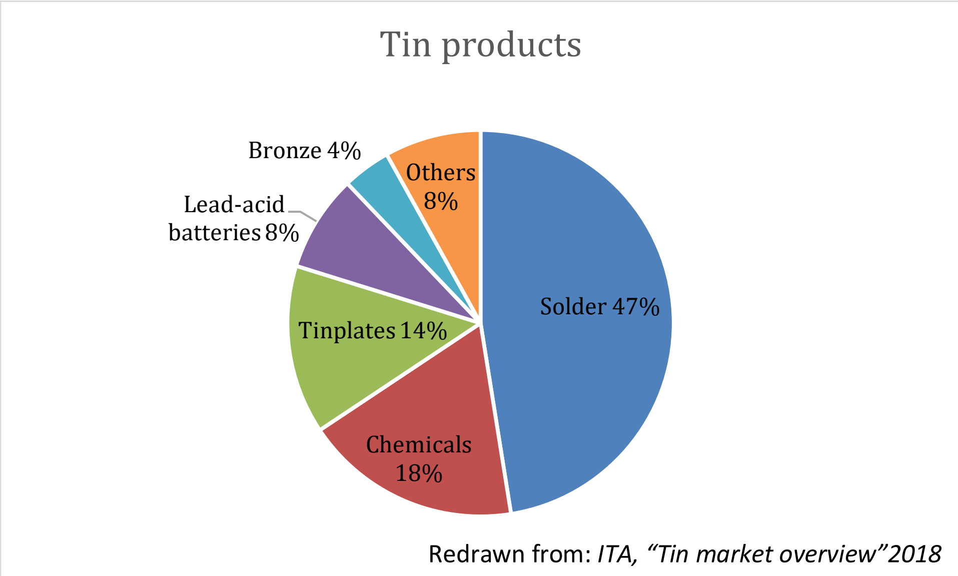


Figure 3: products of tin with shares 2018

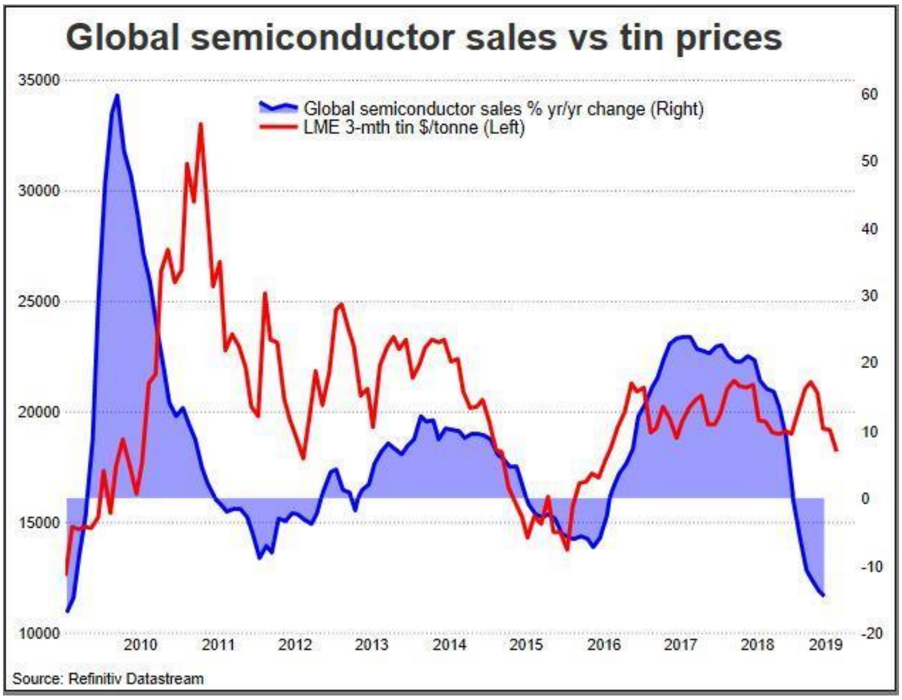


Figure 4: Prices trends of tin compared with the semiconductor sales

The correlation between semiconductor sales and solders demand is important because during the trade war between China and US, one of the most hit sectors was semiconductor production. The trade war started in 2018 when the former administration of the US imposed tariffs on many Chinese products.

The first effect was a reduction in Chinese demand that brought disruption among supply chains on a global level. In the tin supply chain, China represents the biggest producer and consumer. The reduction of its demand during 2019 resulted in a decrease in tin prices for more than 5% in the YoY. This indicates the importance of China in the tin supply chain. (BBC 2020) To counteract that, China also imposed tariffs on US products. Tariffs on both sides intensified the process of economic decoupling which, according to experts started before 2018. However, from that year onwards the relations between the two countries have worsened, moving toward a hard decoupling. Despites this, for China expert Arthur Kroeber a complete decoupling is hard to achieve in a few years because the two countries have built relations for 40 years. US companies have more than 700 billion US$ of assets in China. The latter produces 45% of the global export of computers and tablets and 54% of all phones worldwide. On the other side, China is still severely behind American technological leaders and it continues to command the largest dollar foreign exchange reserve outside the United States.

On January 2020 a first agreement called "Phase one"[5] was signed. The agreement layed a foundation to enhance the relations between the parties but the spread of the COVID-19 made the deal unattainable within the two-years deadline. To this date, the future of the agreement is still uncertain.

Tin is considered a critical material for both the US and China. The position of the two administrations is clear. The US wants to stop its reliance on critical materials from other countries, as is stated by the executive order 13953 of September 2020: "Executive order on addressing the threat to the domestic supply chain from reliance on critical minerals from foreign adversaries". The election of November 2020, where the democratic party won over the republican party, does not change this political line toward critical materials. (Alden 2020)

On the contrary, China has supplies for critical materials but lacks technological developments. The Chinese Communist Party (CCP) created the so-called "Made in China 2025" campaign, which seeks to engineer a shift for China from being a low-end manufacturer to becoming a high-end producer

[5] The "Phase one" deal includes commitments by China to purchase an additional $200 billion worth of U.S. products over 2017 levels in four sectors (manufactured goods, services, agricultural products, and energy) over the next two years. China also protects foreign intellectual property (IP), and refrain from forcing foreign companies to transfer technology. On the other side the US promised to reduce its tariffs on Chinese goods (Bisio et al. 2020)

of goods. This program is based on the “dual circulation” strategy, that combines an internal circulation of production, distribution, and consumption with an external circulation that consists of opening the market to foreign companies.

The effects of the decoupling of these two economies will be studied in the scenarios of this thesis.

3. Methodology

The objective of the thesis is to research the resilience of the tin supply chain and to analyse its characteristics for two different future scenarios.

The methodology used in this thesis is straightforward. It is based on literature review, conceptual framework, data collection, analysis of the results and visualization of future scenarios for the tin supply chain (static and dynamic). These steps will lead to the conclusion and the answer of the research question.

3.1 Conceptual Framework

The framework used in this thesis follows the supply chain resilience introduced by Sprecher et al. (2015;2017). In their papers, resilience, in the context of material supply chains, is defined as “The capacity (of a system) to supply enough of a given material to satisfy the demands of society, and to provide suitable alternatives if insufficient supply is available” (Sprecher et al. 2015). This can be described in a framework that divides resilience into three main characteristics (Sprecher et al. 2015):

- Resistance: the system maintains its function
- Rapidity: the system is able to recover in a short period of time
- Flexibility: the system is capable of meeting the supply needs subsystem

These concepts were connected with the different mechanisms that influence resilience. Stockpiling, meaning to prepare for supply disruptions by storing (refined) materials (products obtained from the processing and refining of ores) in order (Sprecher et al., 2015). Substitution takes into account the ability to replace a given material with a certain application with a different material, without it losing its functionality (Sprecher et al., 2015). Diversity of supply refers to the availability of multiple supply sources and the option to switch to other supply sources in time (Day, 2014; Sprecher et al., 2015). These mechanisms are analyzed during a disruption, which are events that are difficult or impossible to predict. Disruption types are categorized on the axis of supply-demand and low-fast. (Sprecher et al.2015) It follows a description of these axes:

- Supply-fast: includes disruptions caused by catastrophic events disrupting major production facilities. For instance, the disruption caused by the Covid-19 pandemic and the generalised quarantine period that followed has reduced production worldwide.
- Supply-slow: Change in processing that leads to a change in recovery for a by-product or change in the supply system. This type of disruption could be shown by a possible decoupling of two economies as it is happening with China and the US.
- Demand-fast: Regulations that shrink the metal used. For example, the REACH regulations introduced in the European Union put pressure on Tin chemicals to be substituted for less toxic metals.
- Demand-slow: Collapse in demand caused by a technological breakthrough for primary metal. Tinplate has experienced this kind of disruption with the substitution of steel cans with plastic or aluminum.

In this thesis, the supply-fast disruption of COVID-19 is analyzed along with the resilience mechanisms described above.

The first mechanism described is diversity of supply. The approach used divides diversity of supply into diversity of primary and secondary (recycling) production. Diversity of primary production is split between Tin ore production and refined tin production. The supply diversity is indicated by the Herfindahl-Hirschman index (HHI): the market shares of governments or companies are squared and summed, providing a score between 0 and 10,000 (Sprecher et al.,2017)[6]. An HHI above 2,500 indicates a highly concentrated supply with high market power of larger producers. At last, Tin ore production is analyzed from an Artisanal and small-scale mining (ASM) point of view and from a large company point of view. Due to lack of data, an extensive analysis of company level as diversity of supply will not be present.

For the resilience mechanism of substitution, the main substitutes for tin are analyzed in its main products during pre-COVID and COVID-disruption periods.

The last mechanism described is stockpiling, it can act like a buffer that can lessen the impact of temporary supply disruptions (Sprecher et al. 2017). It can benefit the resistance of a system, because it can absorb price fluctuations (Sprecher et al. 2015). Stockpiling has been important in

[6] An HHI of 10,000 indicates a single producer monopoly (Sprecher et al., 2017). In contrast, low HHI values indicate that market shares are evenly distributed among a great diversity of producers.

the history of the tin supply chain and It will be analysed with the feedback loop represented by the price. In general, price represents a global feedback loop for the supply chain resilience (Mancheri et al. 2018). An increase in demand would lead to an increase in prices, while an increase in prices would reduce demand. Overall, feedback loops are important for resilience because they provide non-linearity in the system (Sprecher et al. 2017). Aside from the price, two other feedback loops are identified: by-products(companion metals) and legal framework for materials. By-products are identified as the companion metals mined with Tin. Tin is normally a major and a host metal but it is dependent on its by-products. (ITRI 2016) Legal framework of materials can also directly influence feedback loops. Control's laws influence the production of the metal.

3.2 Supply chain dynamics before and during covid-19

The supply chain dynamic is achieved by an extensive literature review of annual reports, market analysis websites (such as Reuters), and academic papers. The literature review included qualitative and quantitative data regarding the period pre-COVID-19 and during the COVID-19 disruption. The pre-COVID period is considered as the 2010-2020 decade. However, more attention was set on the two years period 2017-2018 for it was a period without big disruption and represented a good measure of comparison with the current date. The COVID-19 disruption data covers the first two quarters of 2020.

Forecasts and Expert future projections are also part of the data collection and, in case the specific year was missing, it is indicated with three different time frames: short- (before 2025), medium- (2025-2030), and long-term (after 2030).The data collection was conducted with more attention for the resilience mechanisms: stockpiling, substitution, and diversity of supply. Furthermore, data on the tin supply chain appeared to be fragmented or expensive, leaving gaps in the data collection. In order to avoid miscalculations and unreal results, an holistic and general approach was used.

It is also worth mentioning that the literature review was intended to be complemented by interviews made to actors of the supply chain. However, due to the little number of responses, they are integrated with the literature review and can not be considered as an additional source. Besides this, two interviews have been conducted. The first with two members of the International Tin Association (ITA). The ITA is the organisation dedicated to supporting the tin industry and expanding tin use, which count on big producers' companies as members. The second interview was conducted with the supplier expert of TATAsteel Netherland, the company produces tinplate.

3.3 Future scenario model

3.3.1 Next-gen Batteries boost tin demand

To study how the supply chain of Tin can evolve in the future, two scenarios will be developed. These scenarios provide a possible vision of how the supply chain could respond to future disruptions.

The first scenario will represent a demand-slow disruption with the opening of new markets for Tin in the Lithium-ion battery technology and 5G electronics. In order to create it, the Vensim software was used to create a basic model (figure 3) has been developed with the Vensim software to analyze three possible tin demand growth scenarios until 2030. All three scenarios represent a future in which Tin is being used in the next-generation batteries. The article published by the ITA in 2019 is used as a basis. In this article, the ITA claimed that there are three possible technologies that could increase tin demand by 10.000-20.000 tons each by 2030. The scenarios are divided as follows: one technology is used, two technologies are used, and three technologies are used.

Three main assumptions are made for this analysis: tin demand will recover from the current disruption by 2021 (ITA), 5G diffusion will increase the semiconductor market by 4,6% per year (newswire) and the new technologies will start to be used between 2023 and 2025.

In figure 5 the overview of the Vensim model created for calculating the demand of tin is shown.

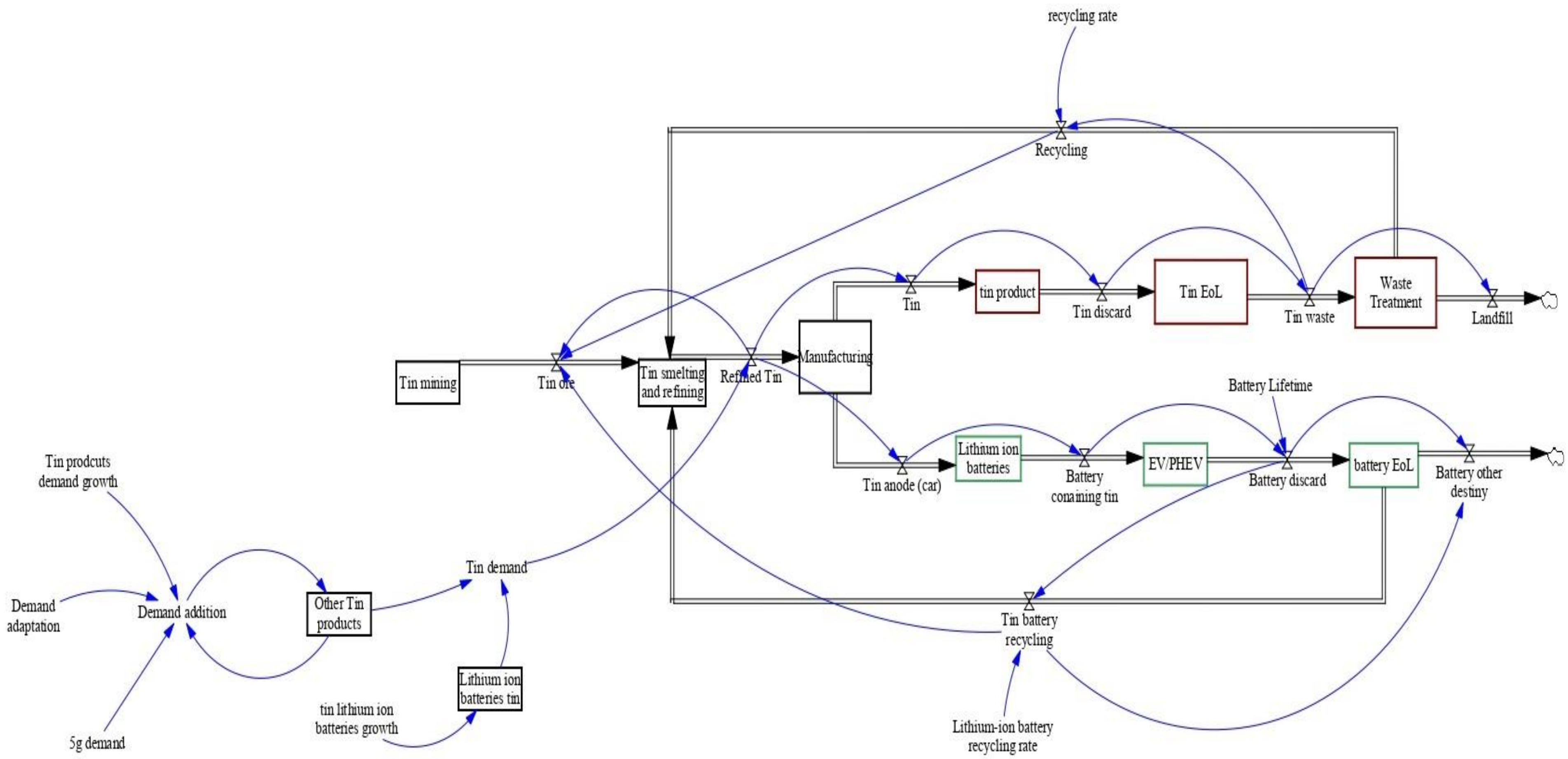


Figure 5: Conceptual demand system dynamics for the tin supply chain. The supply chain has been split in two segments: "Classic" tin products (red) and the new product Lithium-ion batteries (green).

Figure 6 represents the left side of the model, where the demand of tin is calculated; for “other tin products” the demand is calculated with an yearly addition in demand given by two main factors: a generic annual growth and the 5G addition. “Demand adaptation” is the alignment of the 5g with others tin products. The resulting demand is then added to the increment given by the tin used in the lithium-ion batteries. The final tin demand, called “Tin demand” influence the refined tin production and it is connected with the rest of the model.

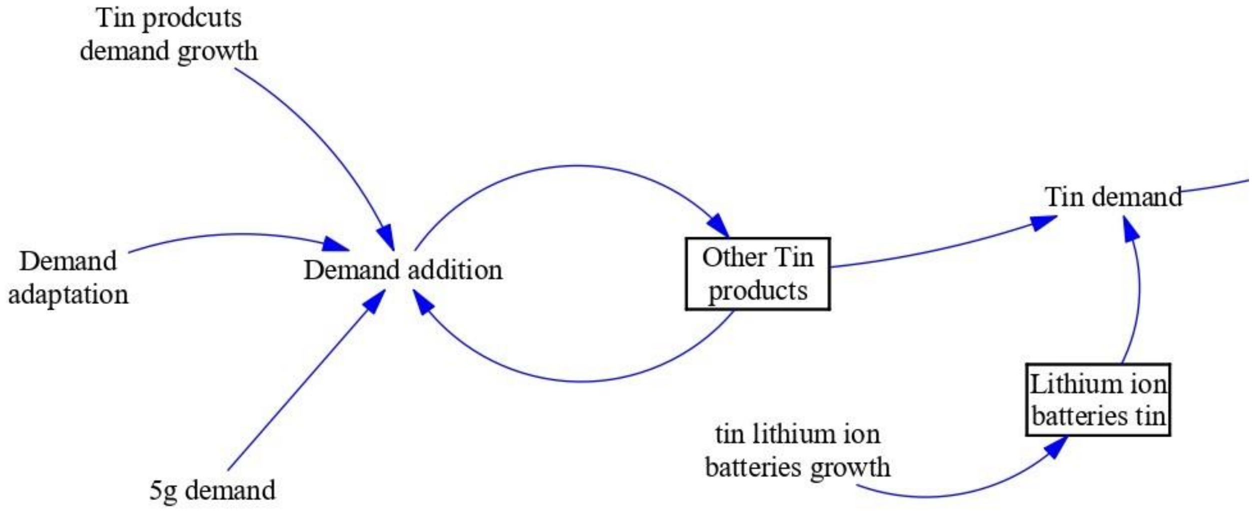


Figure 6: Model section calculating tin demand

Figure 7 shows the main part of the model that represents the supply chain, from tin mining to waste treatment, including recycling. Connected with the “manufacturing” process there is the Lithium-ion battery supply chain. This supply chain is added to understand the possibilities of tin recycling from Lithium-ion batteries and its possible contribution to secondary sources of tin.

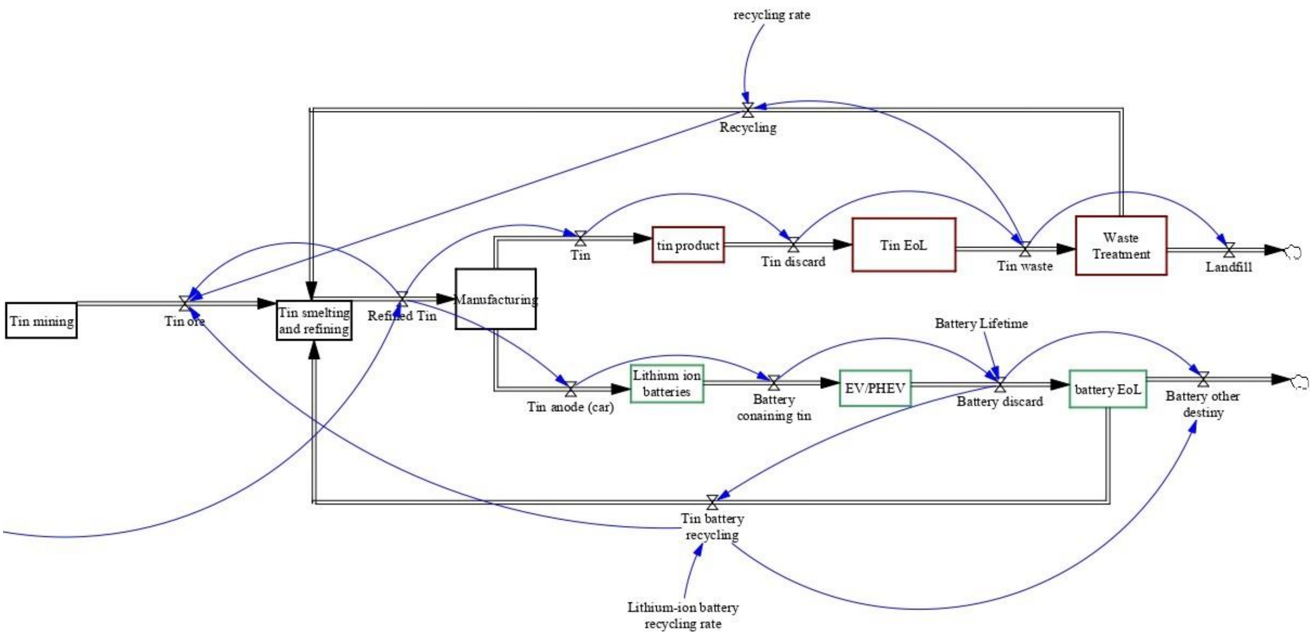


Figure 7: Model part representing tin supply chain with lithium ion batteries

3.3.2 Possible developments of the trade war

In the second scenario, the possible developments of the current trade war between China and the US is explored in a supply-slow disruption scenario. The scenario is based on the events that started in 2018 when the former US administration started to impose tariffs on Chinese goods. The third section of the results will introduce the current situation of the trade war. For this purpose, a desktop research was used. It was based on Experts website articles (ITA website), reports (Reuters) and news from reliable sources (such as BBC).

With the literature review, the possible outcomes of the trade war were explored. Three possible outcomes were found: complete decoupling, partial decoupling and no-decoupling[7].

Complete decoupling represents the scenario in which the US and Chinese economy are completely separated and resulted in two different tin supply chains. In order to study them individually, another literature review was conducted. Quantitative data were collected from geological databases (USGS) and others (OECD databases) to structure the supply chains. The software STAN was then used to visualize the results.

[7] "Decoupling" started to be used by experts since the beginning of the trade war to indicate the process of economical and supply chain separation between the US and the Chinese economies.

The Partial decoupling outcome is represented by the relocations of most US production from China toward a third country and the development of Chinese technology to satisfy internal demand. The data collection for the supply chain scheme consisted of quantitative and qualitative analysis, using the same method of the complete scenario. The visualization of the supply chain was made with the software STAN.

Non decoupling outcome consists of the current supply chain scheme. Therefore, only a qualitative analysis has been conducted. The sources of data for this outcome were the same as previous parts.

Little quantitative data were found for the Chinese production, consumption, import/export. 2017 is the year with the most data collected. Thus, in order to achieve the most comparable results between China and The US, the production of tin during 2017 was set as a quantitative base for the development of the supply chains in the first and second outcomes. During this year no big disruptions of the supply chain have been registered, which makes it reliable to set as a base.

4. Results

This chapter discusses the results. I firstly introduce the supply situation of tin, which is more sensible to disruptions. Then I discuss the Feedback loops of the supply chain pre- and during-COVID-19 disruption. Then, the resilience mechanisms Stockpiling, substitution and diversity of supply are discussed. At last, the study of the two scenarios.

4.1 Tin supply, sensible to disruptions

At the end of section 2 it was stated that the demand for tin follows the trend of the semiconductor sales and, therefore, its demand. The demand for tin will be discussed in different parts of this thesis while this section will focus on the most vulnerable part of the tin supply chain, the supply. Tin is already suffering from a general supply/demand problem. In the last five years, this ratio has been met the demand only once, as it is shown in table 1.

Table 1: supply and demand balances (Willoughby 2019; Onstad 2020)

World supply/demand Balances for refined tin ('000 ton)

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
Refined tin production	335,8	340,1	365,1	358,2	353,9	333,7
Refined tin consumption	336	344,9	362,4	369,1	359,6	338,9
Total	**-0,2**	**-4,8**	**2,7**	**-10,9**	**-5,7**	**-5,2**

This general supply shortage has different causes, I will now explain them.

First of all, Tin has two main deposits: alluvial and hard rock deposits. The alluvial deposits are typical of South East Asia and they are formed by clay/gravel/silt that is carried by rushing streams until they slow down. The main costs of alluvial deposits goes to energy and fuel.

Hard rock deposits, which are divided into an open pit or underground, are more vulnerable to labor costs. These deposits are more typical in Central Africa and South America. Figure 8 gives an approximation of the main costs for different types of deposits.

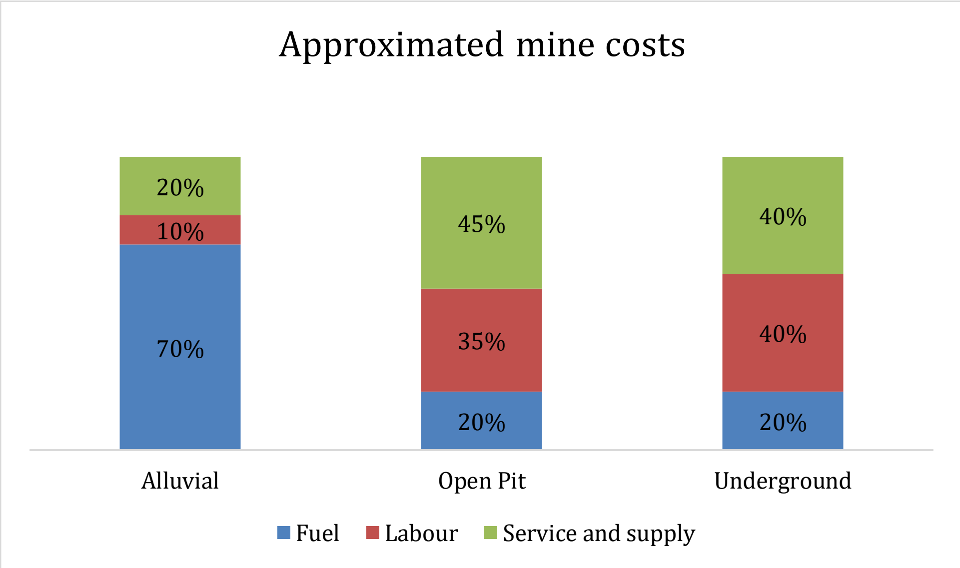


Figure 8: Approximation of tin mine costs given three different deposits. The costs refers to a primary tin, open pit mine in Australia grading 0.5%, producing 7,500 tonnes of tin per year, with a 75% recovery (Sykes 2013)

The Tin grade in the alluvial deposits is approximately between 0,2/0,4 kg/m^3 [8] . Lower grades have higher costs, for a grade of 0,4 kg/m^3 has a theoretical cost of around 10.000 $US/ ton while a grade of 0,2 kg/m^3 has a theoretical cost of 15.000 $US/ ton. (Sykes 2013) The decrease in Tin ore grades in alluvial deposits represents a problem for the tin industry because discourage new investments (Moore 2018).

To encourage new investments and reduce the cut-off grade[9] of new projects, by-products of tin must be taken into account. Interesting for the future energy transition are the increasingly Lithium mine projects that have tin as a by-product. The future demand for Lithium in the battery sector could also increase the supply of tin. In table 2 the two most important projects are shown.

Table 2: Two of the most important lithium mine projects that have Tin as a by-product.

Mine projects	Country	Grade	Production per year	Opening
Weilasituo	China	0,8% Sn 1,3% Li_2O	7000 tons Sn 550 ktons Li	late 2020
Manono	DRC	772 ppm Sn 1,65% Li2O	3000 tons Sn 700 ktons Li	2021

[8] Theoretical change in ore grade for a primary tin, alluvial mine in Indonesia, producing 7,500 tonnes of tin per year, from a team of gravel pumps, with a 100% recovery
[9] Cut-Off grade is the minimum grade of a mineral or metal that makes it economically mineable. Material found to be above this grade is considered to be ore, while material below this grade is considered to be waste.

Other by-products of tin are tungsten, tantalum, copper, zinc, and silver. (ITA 2020) No quantitative data have been found on the percentages of by-products.

The geographical distribution of tin supply is heavily unbalanced toward Asia with China, Indonesia, and Myanmar that control the mining production. These three countries control more than 70% of the total tin output. This unbalancing makes the supply chain more sensible to disruptions, as most of the supply comes from only one geographical area. Myanmar is the third world tin ore producer. Tin is mined in the mining areas of Man Maw which have been spotted by Reuters as a possible high-risk area. The mines are situated in the auto-proclaimed independent region of Wa State, which is only recognized as a State by China. There are 7 big mines in the area which are controlled by the Wa treasury department. The department gave control of some of these mines to the United Wa State Army (UWSA), which was blacklisted by the United States for alleged narcotics trafficking. Due to the little information that comes out of the mining area, it is difficult to understand whether it can be considered a conflict area or not, but it is undeniable that it is a high-risk region. (Slodkowski 2016) Further investigations are needed but if Man Maw mines would go against the OECD 'due diligence guide' would represent a problem for the supply line. Moreover, production in Myanmar may have reached its peak already in 2016 (ITRI 2016), with an yearly output reduction of around 10% (Malqueen 2018).

This reduction in output made China, Myanmar's main buyer, to look for other suppliers such as Australia. Nevertheless, Myanmar represents the 95% of Chinese tin ore imports. This one line of supply makes Chinese supply chain highly sensitive to disruptions, which have effects on the tin market. These effects are related to the unique position of China, it controls half of the refined tin production and the majority of the consumption. The Chinese position on the tin supply chain will be discussed more in the primary production paragraph.

Besides using one supply line, China has a well-known protectionist policy. For example, in 2010 the Chinese authorities introduced a quota of 10% in order to control the national production toward sustainable economic growth. The repercussion that this decision had in the global market was of such relevance during 2016, that the EU and the US started two parallel legal procedures against China, arguing that its export quotas were against WTO rulings. (EU 2016) This is only one of the legal actions taken against China by other countries (Mancheri et al. 2018), another important but more economic example is given by the trade-war, which is widely discussed in this thesis.

The last big supplier of tin is Indonesia, where 90% of the tin is mined in the Bangka-Belitung province. This area is known for Artisanal and Small-scale Mining (ASM) and illegal mining, which had brought over the years environmental and social issues, i.e. such as destructions of the reef and local fauna and flora or unsafe workplaces and child exploitation. (Hodal 2012) Since 2011 the government and the largest Indonesian company, the public PT-Timah, have been trying to combat illegal mining by blocking export of tin ore and providing less mining license[10]. In order to control the ASM in the Indonesian region, PT TIMAH gave concessions for artisanal mining, which contributes 50% of TIMAH's production.(Prakoso 2015) This situation had increased control over environmental and social issues but has not resolved the underlying root cause. In particular, environmental and social problems had raised the attention of NGOs which accused big consumers supply chains such as Apple, Microsoft, and Samsung.

At last, exploration activities follow a "boom and bust" pattern and follow mineral price cycles. Between the price crashes of 1985 and 2016, only 4 greenfield tin deposits were discovered, despite the small increase in exploration in 2011 after the price peak. The feedback loop of price is discussed in the next paragraph.

4.2 Feedback loops of pricing and price fluctuations

Tin price is essential as a feedback loop for the supply chain. In this section I discuss the tin market and pricing, firstly using examples of past disruptions and ,secondly, analysing the fluctuations during the COVID-19 disruption.

Tin has two main markets, the London Metal Exchange (LME) which is the historical trading base, and, since 2015, also the Shanghai Future Exchange (SHFE) for the Asian market. Since there are two markets, the volatility of Tin increased due to the different timeframe in which they operate. Although LME is still leading the market of Tin, they influence each other (London Metal Exchange 2017). Table 3 shows the volatility of prices for different combinations of supply and demand while figure 9 describes the volatility of tin prices in the period between 2011-2019.

[10] 2017 revision of the raw material and coal law and revision of the law n 4 in 2020.

table 3: price trends depending on supply and demand

Supply	Demand	Price trend
Low	High	Upward
High	Low	Downward
Low	Low	Steady
High	High	Steady

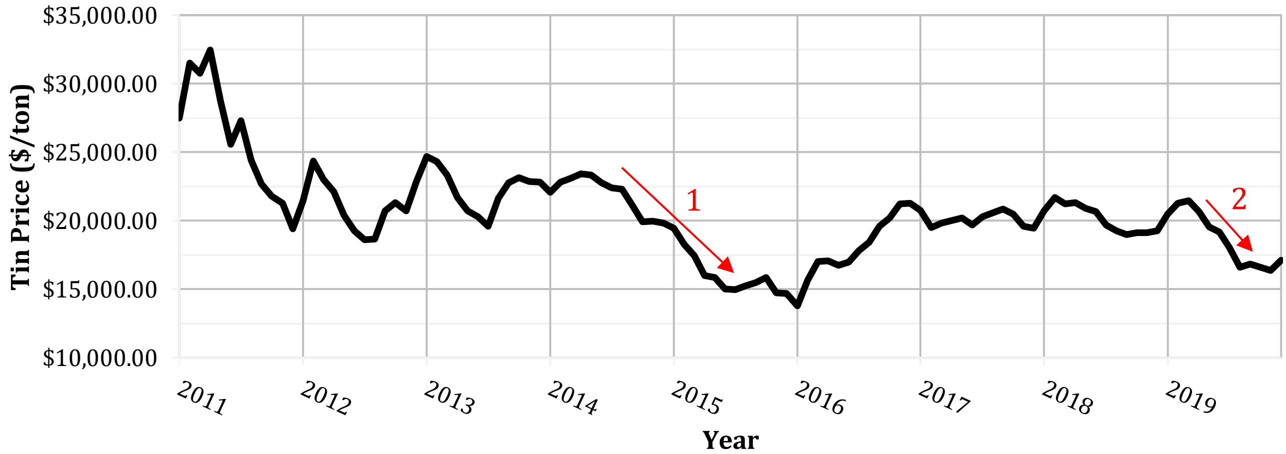


Figure 9: London Metal Exchange Tin prices in dollar per tonnes between 2011-2019 (https://www.westmetall.com/en/markdaten.php?action=show_table&field=LME_Sn_cash)

The decade started with historical high prices of tin caused by a rebound in consumption after the 2008-2009 crisis and selected government restrictions in Indonesia. The price in 2011 peak was 32 000 $/ton. (USGS 2010; 2011) After the peak, the price started to decrease again. In figure 7 two different disruptions are highlighted, the Myanmar disruption in 2015 (1) and the trade war between US-China (2). The Myanmar disruption was already explained in the historical background and it caused a fall in tin price due to a combination of oversupply, a strong dollar, and cheap oil prices (Slodkowski 2016). It is a supply-fast disruption and the only example of over-supply in recent years for tin. The prices dropped for almost a year, reaching a new low of 14 000 $/ton in January 2016. In order to stop this negative trend the Indonesian government introduced a new mining license that reduced the exports. Thanks to this intervention the price increased up to 20000 $/ton at the end of 2017. The little price drop that occurred at the end of 2015 was mainly caused by a crash in the Chinese stock market, impacting all the metals.

The second disruption highlighted is a supply-slow disruption caused by a more protectionist policy from the US at the expense of China. This decision started at the end of 2018 and caused a trade war between the two countries (section 2.3). The repercussions on the Chinese demand are tangible, the reflection on the price started with a slight depression in 2018 and a drop in 2019. The weak Chinese solder demand combined with low supply had caused tin prices to fall for almost a year, only the “Phase one” agreement between the US and China stopped this falling. This disruption highlights how China has a big influence on the tin supply chain.

I now turn to analyse the price volatility during the first two quarters of 2020, during the COVID-19 pandemic.

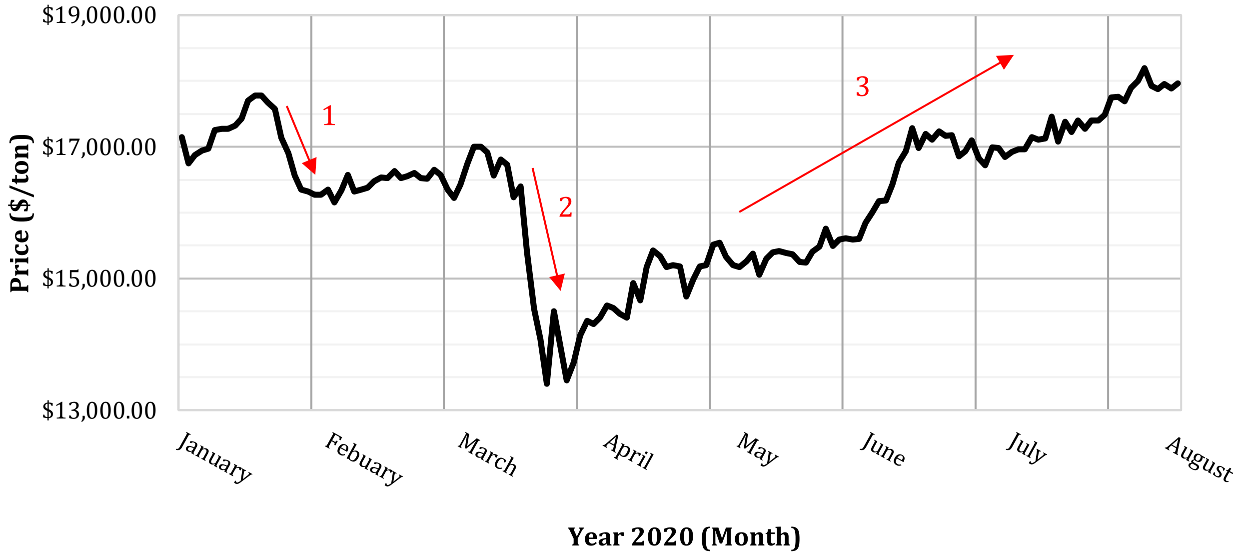


Figure 10: LME tin-settlement prices from January to august 2020. The numbers represent: 1- Chinese lockdown after the first Chinese death, 2- Pandemic declaration and Worldwide lockdowns, and 3- the price recovering after the demand growth.

Figure 10 shows the price fluctuations in the LME market during the first half of the year. The price path follows the diffusion of the pandemic and the main decision taken by governments. On the price basis, it dropped in two different moments: the first covid related death in China and the consequential lockdown of the country (1) and the declaration of a pandemic by the World Health Organization (WHO) which lead to several lockdowns all over the world (2). In the early stage, the supply disruption started to strike in the Chinese production, when the governments started to put in quarantine mining areas. This situation was worsened by logistics difficulties at the border with Myanmar, creating a bottleneck with its main supplier. The supplying problems reflected in the Chinese manufacturing sector, which struggled to get raw material. This brought an international rebound effect due to the numerous companies which rely on the Chinese manufacturer for different parts of their production, as it happened for the automotive sector. This can be seen with the first drop in prices (1). Despite this, the first sentiments of the markets were optimistic toward the confinement of the virus in Asia. Nevertheless, when the first cases started to arrive in the western world and the WHO declared the pandemic, the prices plunged. Worldwide lockdowns, pessimistic sentiments, and the reduction in demand for electronics contribute to the price drop until a new historical low, which was 13 450 $/ton in March 2020. In April, prices started to rise again thanks to a restored Chinese semiconductor demand. The analysis of the price feedback loop confirms two important characteristics of the tin supply chain introduced at the end of section 2: the recover of Tin demand is related with the Chinese and semiconductors demand.

Experts say that the tin price would increase in the short-term and stabilize around 18 000-20 000 $/ton during 2021, when the supply will recover from the COVID-19 disruption and the supply/demand deficit will narrow.(Onstad 2020) Two disturbances are expected in the tin supply chain, given by use of tin in Lithium-ion batteries and the future relations between China and US. These will be analyzed later.

4.3 Stockpiling

Stockpiling has been reduced during the last decades due to tin high prices. Nowadays, a smaller number of stocks are exchanged in the LME market, which fluctuate depending on changes in supply and demand. Low demand would increase stockpiling, while high demand would decrease it. Low supply would decrease stocks, while high supply would increase them. As a consequence, selling stocks is a strategy to reduce prices in a period of high demand while accumulating stocks and waiting for a better market situation is a strategy in periods of low prices. In this thesis I mainly discuss two types of stockpiling: strategic and company-level.

A strategic stockpile is held by governments to assure supply during disruptive events. Tin strategic stockpiling has been reduced in the last decades but, considering the potential of new tin uses and supply shortages, it probably will increase in the upcoming future. (Home 2020) The most noticeable strategic stockpiles known are held by the US and South Korea but their contribution to resilience is low. The US governments held an amount of 5000 tons in 2019. (Schuyler 2019) Considering the total imports of around 83 000 ton/y, the strategic stockpile represents only 6% of the total. This small percentage is insignificant for resilience. In 2016 South Korea started to purchase tin with the goal of stockpiling, after a reduction in Indonesian outcome. The amount held by South Korea is around 3000 tons, which is less than the US but has a bigger impact on the country's tin resilience because stocks represent around one third of the yearly import. (ITA 2016) No information has been found on Chinese stockpiling but, after COVID-19 disruption highlighted problems on Chinese supply line, a stockpiling program started in the Yunnan province, the richest tin region in China. The Yunnan governments set aside 1 billion yuan (141,22 $US million) to help business stockpiling a total of 800 000 tons of non ferrous metal, where tin would account for 40 000 tons. (Daly 2020, ITA 2020) This program is in line with the national raw material program that wants to assure critical material supply to China. This renewed stockpiling would represent the 22% of total Chinese production and the 57% of the imports, which would have a significant contribution to Chinese supply chain resilience and, therefore, global resilience.

No data has been found for other countries but it is possible that, given tin supply shortage, some are building up strategic stockpiling.

On a company level, the stock held by producers and consumers in 2017 was 21,1 kt, which represents around 5% of the total 2017 production.(Mulqueen and Xia, 2017) There is no data on how the stocks are divided but, generally, tin is an expensive metal and stocks are not common in downstream companies. Stocks are mainly held by producers, indicating that suppliers contributes more to resilience. There are mechanisms for stock use but price analysis shows that they are commonly used during disruptions.

To better understand the influence of stockpiling on disruptions, I now will discuss the stock exchange compared with the price feedback loop. In order to understand this, figure 11 represents the fluctuations of LME from 2011 to the end of 2019.

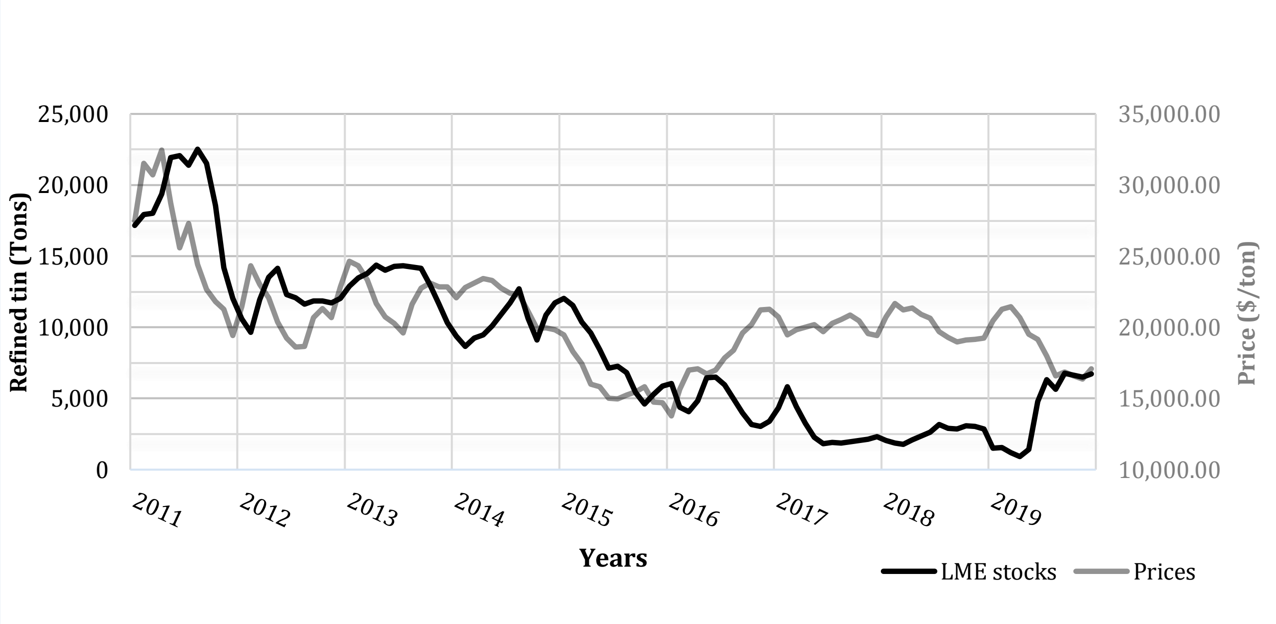


Figure 11: London Metal Exchange stocks in the period 2011-2019
*(*https://www.westmetall.com/en/markdaten.php?action=show_table&field=LME_Sn_cash)

The graph shows a correlation between prices and stocks. Stocks exchange in the LME market followed the general reduction in prices until the beginning 2016, after the boom of Myanmar supply was passed. This year showed the evidence of the supply deficit, prices started to increase and stocks reduced. The stocks exchanged at the LME reached historical lows during the period 2018 and 2019. In 2019, when tin prices drop after the reduction in Chinese solders stocks started to rise again. Taking in consideration that the annual production of tin is around 360 000 tons the really small amount traded at the LME market is insignificant to contribute to resilience.

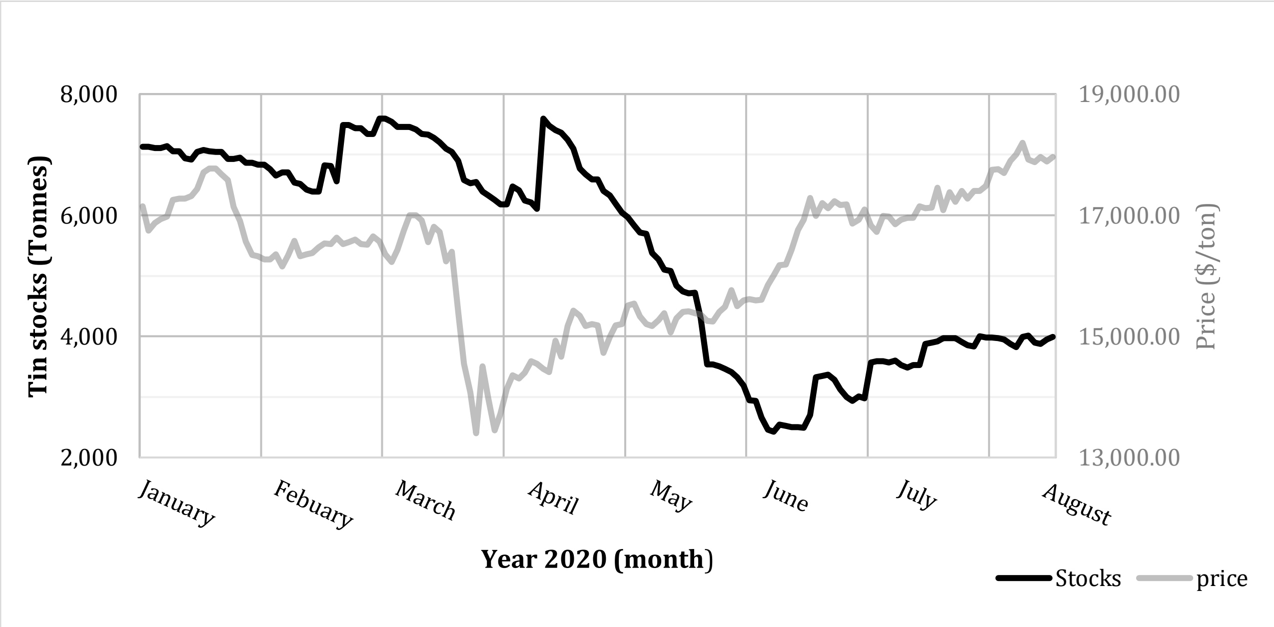


Figure 12: LME stocks in tonnes from January to august

In figure 12 a comparison between the LME stocks and the LME prices is shown. At a first glance, the stocks followed the price trend, yet with a delay. During the first months of the year, stocks increased probably due to the uncertainty of what was happening in China and the possibility of a disruption. The supply disruption resulted in the first quarter has led to a massive use of stockpiles, which translated into a drop of stocks in both the London and Shanghai markets from March to June. (Koh and Baffes 2020) In July, stocks have been rising again thanks to the rebound effects on demand and prices. In spite of the low quantities of tin stocks held by the LME market compared with the total production, they represented an important element in the first months of this disruption. Thanks to its immediate availability, Stockpiling has been a first and effective price control. Moreover, from this analysis, stockpiling showed to contribute to the supply chain resilience but to which extent is unknown due to the little information collected on the supplier's company level.

4.4 Substitution

Two causes lead to the substitution of tin: changes in legislation and high prices. These two causes lead companies to look for cheaper or less problematic materials. Table 4 shows the main substitution threat that tin products are facing.

Table 4: The main threat of the tin products demand

Position	Product	Share	Main threat	Main substitution
1	Solders	47%	Miniaturization	None
2	Chemicals	18%	Substitution	Calcium-zinc stabilizer
3	Tinplate	14%	Substitution	Aluminium, Plastic
4	Lead-acid Batteries	8%	substitution	Lithium-ion batteries
6	Others	12%	\	\

Solders demand is directly related to the semiconductor demand, which are used in every electronic compound Although the demand for electronics is increasing every year, with revenues that grew by 12% at the beginning of 2020 (Statista), the solders share in the total tin demand lost almost 5%. This decrease is directly caused by the miniaturization of electronics components, which is counteracting the possible growth of the sector. Miniaturization has been driven from what is called the “Moore’s Law” [11], which says that the density of components on chipboards increases constantly. There are beliefs that the shrinking of semiconductor will stop in 2021 in a different view of the Moore law. In 2015 the International Technology Roadmap for Semiconductors (ITRS) predicted the following 15 years of the industry. The report stated that by 2020-2025 devices features would be reduced to a few nanometres and it would become impossible to reduce any further dimension. It is predicted that from 2021 these devices will start to develop in vertical instead of horizontal, by adding different layers of transistors. (International roadmap committee 2015) There are studies that are being conducted to continue miniaturizations but no data has been found on studies that have passed the experimental phase.

Tin-lead alloys have been the main products for solders but in recent years new regulations are pushing towards lead-free solders. (Shangguan 2005) This supported the development of solders that only used tin, which increased the demand of tin and reduced the effects of miniaturization. It is expected that tin will continue to substitute lead for the next decade. In 2030 the substitution will reach 90% of the total lead solders. This substitution process increases the importance of tin in the

[11] The “Moore’s Law” was articulated in 1965 by Gordon Moore, co-founder of intel. Moore said that the numbers of transistors incorporated on a chip would double every two years. The decreasing surface of chipboards broughts the necessity to create smaller cheap components, which increased miniaturization. (Keyes 2006)

soldering sectors and reduces the study for tin substitutes. Nevertheless, there are examples of phone companies that are substituting tin solders, i.e. the South Korean company "Samsung'' started to build its electronic boards without the use of solders. (Onstad 2014)

Tin chemicals have the second-largest demand share and it has been increasing in the past years. Tin chemicals consist of a big range of products: PVC stabilizer, Catalysts, glass coating, electroplating, and other minor uses. Their use has been increasing strongly in the past decades' thanks to the PVC stabilizers that substituted lead. Organotins are the compounds used in the PVC stabilizer sector, but they are losing ground in the EU market due to the REACH[12] regulation. For example, the REACH classification has started to put more pressure on some tin-based chemicals[13], and companies already started to look for substitutes. Tin is starting to be substituted by zinc or calcium, a cheaper and less problematic option. In 2012 in Europe calcium stabilizers already had 65% of the market share, Tin stabilizer only represented the 8%. Although the demand for these products is decreasing in Europe, it remains strong overseas, mainly in the US and Canada, where regulations are less strict and the substitution in favour of tin is increasing in the defence sector. China is where tin PVC stabilizers have the most potential because there is a lot of lead to be substituted. (Pearce and Wallace 2016)

In spite of the possible substitutions, this is probably the sector with the biggest potential for the future, thanks to the different possibilities in the energy sector such as anode for the Lithium-ion batteries, sodium-ion batteries, solar cells, and other minor projects.

Lead-acid batteries are the main battery type used in vehicles and their market is expected to grow steadily until 2023 when there will be strong signals that they will start to be substituted by lithium-ion batteries. There will probably be a market for lead-acid batteries for many years in the future, mainly in the developing countries, but its share in the tin demand will diminish due to the substitution caused by the energy transition.

[12] REACH regulation: Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC. (European Union)

[13] Butyl tin products were banned in the EU in 2012. In 2013 also the di-octyl tin products. The only usable tin PVC stabilizers used in Europe are the mono-octyl tin.

Tinplate used to be the first tin product but, in the last decades, its demand has decreased to the third position in the share of tin demand. Nowadays, tinplate demand is steady or saturated in developed countries like the EU and the US. In these states, a strong substitution for plastic and aluminium has reduced the demand for tinplate. In the steel cans, the use of tin has been reduced to a really thin layer, therefore less material is needed, which leads to less demand. Although in Europe and the US the market could be considered saturated, in China and the developing countries the use of steel packages is increasing. Besides the future of tinplate is not bright, it is still representing a fair percentage of tin demand, and its strength is given by two factors: its high recyclable rate (over 70% worldwide), which makes it a valuable and sustainable option, and the lack of substitutes for tin plates.

This resilience mechanism is influenced by the complexity to find a substitution for tin in its products. Interviews with different stakeholders showed that tin does not have real substitutes for solder, the main tin product. This lack of substitutes can be again explained by the fact that tin has been the main substitute for lead in the last decades. This state of irreplaceability and the constant technological development increases its demand recover, and it could be expected that, without valuable substitutes, it would probably help the supply chain during disruptions.
No information has been found for other tin products, the COVID-19 disruption has not altered enough this indicator to find evidence.

4.5 Diversity in supply

4.5.1 Diversity on primary production

Supply problems have been already introduced in section 4.1. Low diversity of supply is true for primary refined tin production but not for tin mining production. ASM also represents a fair percentage of the tin supply but information on it is hard to find. At a company level diversity also has low results as the production is concentrated on a group of less than 10 companies. In the following paragraphs diversity of supply is discussed in comparison with the enormous supply disruption caused by COVID-19 disruption.

4.5.2 Mining production

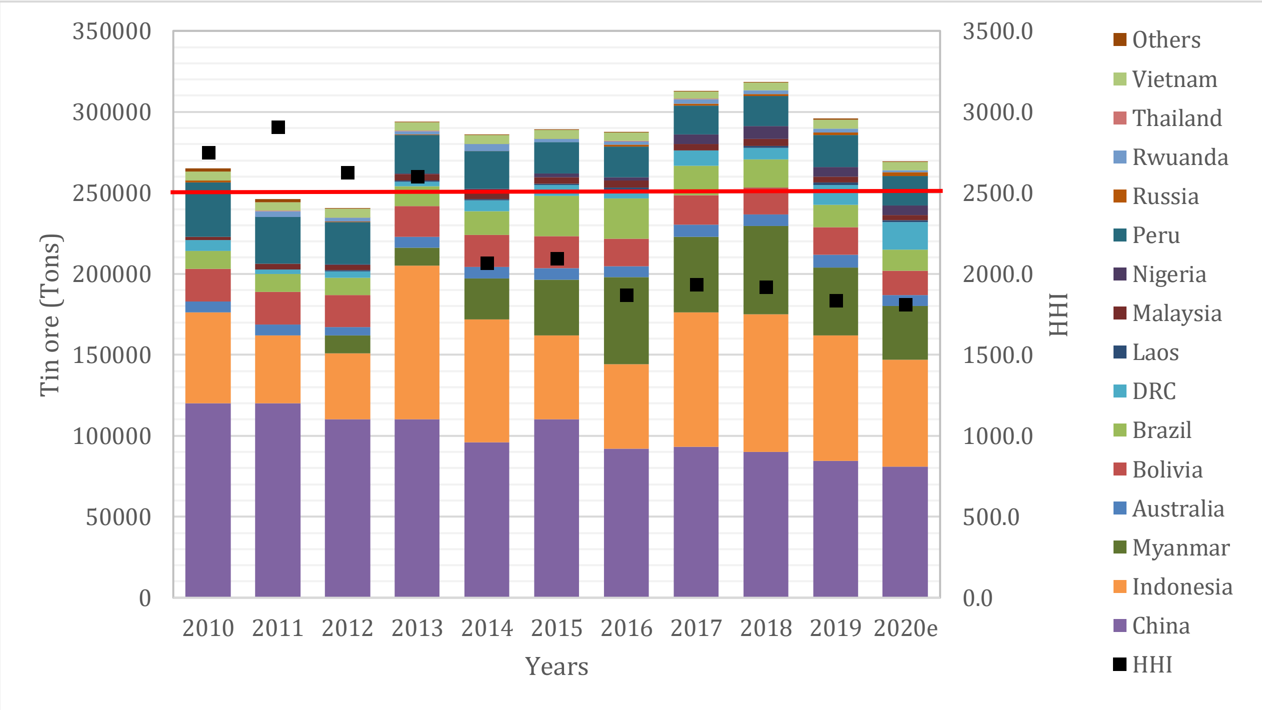


Figure 12: Tin mining production by country in the period 2011-2019, before the COVID-19 disruption. The black squares represent the HHI production index. The red line indicates the value of HHI 2500,above this value the production is highly concentrated. (source: (USGS 2010; 2011; 2012; 2013; 2014; 2017; 2019; 2020; 2021)

Tin mine production shows diversity of suppliers with a prevalence in the Asian regions. In particular, China, Indonesia, and Myanmar are dominant. This geographic production considers both ASM and large-scale producers.

The timeline shows a good diversity of tin mine production (figure 12) with an HHI_{mine} of 1839 in 2019. This indicates a well-diversified tin ore supply, values above 2500 are considered high. The HHI_{mine} decreased concurrently with the growth of Myanmar mine production. Besides the Covid disruption, estimation for 2020 mine production does not show a significant change in the index.

China, Myanmar and Indonesia share respectively 29%, 14% and 26% of total mine production. This makes a diversified mining production, which increases resilience of this stage. The main difference between these suppliers is that China and Indonesia refine most of their tin ore locally, while Myanmar exports most of it (>99%). This information is important in the context of tin ore consumption. Supply problems related to these three countries were already introduced in section 3.1, I now discuss their behaviour during the COVID-19 disruption.

From figure 12 the outcome of 2020 shows only a drop of 5% in a YoY. This is an outstanding result considering the first quarter of the year, when mines were closing worldwide after mandatory quarantines imposed by the governments to control the pandemic.

The Indonesia PT-Timah, the only Large-scale producer in the country, announced in march 2020 a cut in production between 20-30%. (Post 2020) In South America mining operations in Peru stopped for two whole weeks. In China the only open supplier was the public Yunnan tin, this brought a reduction in tin ore imports of 7%. (ITA 2020b)

Overall, as already mentioned above, tin mine supply is resilient in terms of diversity of supply on a global level but it also showed a big problem in the Chinese supply line. In 2014 China started to import tin ore from neighbouring Myanmar and then refined it in the country. Myanmar accounts for more than 95% of Chinese tin ore imports, making the Chinese supply chain a one line supplier. This one line supplier system entered in crisis during the Covid-19 disruption where logistic problems arose between the two countries. Due to regulations, Chinese workers could not cross the border to load trucks with tin. In 2020 the imports from Myanmar dropped 10%, representing now 85% of total imports. This issue pushed China in the search of alternative sources, among which Australia (+70%), DRC (+34%), and Southeast Asia (+30%) were on the top of the list. (ITA 2021) The increment of Chinese diversity of supply is positive for the global tin ore diversity of supply because it will increase the diversity of producers.

Future of tin mining will bring more diversification of supply as the big Asian mines are reducing their tin ore grade and output (section 3.1). Important tin reserves can be found in Russia, DRC, China, Australia and UK.

Russia has the second largest reserves after China and the main mining company Seligdar is aiming to increase its tin production already in 2021 with the construction of a new mine at the Pravourmiysk deposit. The company announced a total production of 6 000 ton of tin concentrate by 2024. ('Seligdar's Pravourmiysk Nears Construction' 2020)

In the DRC the Manono project will start in 2021 adding a new tin ore supply line of 3 000 ton with a reservoir of 400 Mt of tin ore. (ITA 2020a)

At last, in the UK there are investments studies such as the one of the Canedian firm "strongbox exploration" to reopen the South Crofty mine, although costs to reopen a 300 hundred metres depth mine are high. Other potential tin mining sites are present in the old Cornwall mine. Currently there are no projects that entered the construction phase but the future tin demand will increase prices and, therefore, investments.

4.5.3 Artisanal and Small-scale mining

Quantitative data on ASM are difficult to be found. In the tin supply chain ASM represents the 40% of the total tin mining production, around 118 400 tons in 2019. This percentage is a fair amount in the total mine production but data are scarce on small-scale mining. Normally, communities of ASM are sensitive to disruptions as they are exposed to price fluctuations. The Covid-19 disruption had a significant impact on the mining communities in Indonesia and Africa.

In Indonesia, where ASM accounts for 50% of PT-Timah tin ore production (Prakoso 2015) , artisanal miners, who normally have to sustain an entire family, have seen their income reduced due to the government COVID-19 restrictions. An Indonesian miner said during an interview for a local newspaper "Help us little people governor. We only want to be able to mine", while another miner commented "We ask to please pay attention to people who rely on the tin as a livelihood", adding that the village market is very quiet because there is no money. (Pratama 2020) This explains the precarious situation of artisanal mining in Indonesia ,where the government's restrictions left these miners without the possibility of working and getting the only income they have.

In the past years, the regional government have started a process to reduce the economic dependence of the Bangka-Belitung province on the tin industry, but it is a long process and at the moment a lot of communities and families still depend on tin for their survival.

In Africa the COVID-19 disruption had a worse effect, increasing child exploitation and the conflict minerals effect. In the DRC, after the closing of the borders, the processing houses could not export their products but only stock them until exports could start again. This situation made stocking houses to stop buying tin from artisanal miners. Without mine trades, the inflows to the local economy stopped and essential goods prices started to increase. An artisanal miner from the South Kivu region in DRC interviewed by IPIS said that in 4 months the selling price for cassiterite halved, going from 5$ per kilo to 2,63$ per kilo. (Matthysen et al. 2020) On one hand, this situation has made several artisanal miners leave their mines to return to their places of origin or change to a more profitable business. On the other hand, the abandoned mines became a target for other Congolese people that had lost their jobs. However, those unemployed are sadly not the only newcomers. After the school closure for the pandemic, child labour has dramatically increased. The Business and Human Rights Resource Centre said that the COVID-19 could lead to the first increase in child labour after 20 years. Moreover, less cash flow opened the doors to barter, which miners use to exchange cassiterite for essential goods. This practice renders very difficult the traceability of production, increased by the fact that most of these new buyers do not know how to sell the mineral legally. To complete this scenario, it is relevant also to mention the possibility of armed groups taking advantage of the precarious economic situation in order to make new recruitments and increase their financial income by the selling of minerals (conflict minerals).

Given the critical situation arising from artisanal miners, different actions are being taken by external actors. First of all, the OECD made a call for action for a responsible mineral supply chain, which said that the gains made in the supply chain due diligence could be lost as all the stakeholders are impacted by the pandemic. A significant amount of on-the-ground due diligence projects could be suspended or closed due to a lack of funds. Focusing on tin, a similar call for action was written by the ITSCI[14], the ITA due diligence program for tin, to all stakeholders and actors in order to continue the program. Thanks to funding from downstream companies the program could survive but with a reduced operational budget of about 50%, limiting support to stakeholders and on-field activities. (Cleland 2020)

The important effects that disruptions bring to ASM regards the environmental performances, which ASM does not take in consideration. A good example is the Indonesian coal and mining law 2020 revision, which was published uncontested during the pandemic. The main critics against the law concern the freedom that the reform gives to mining companies to explore new regions and guarantee continued operations to big coal companies. On the environmental side, the revision law states that miners failing to complete land restorations projects will face a pecuniary fine or up to five years of imprisonment. Miners are also obliged to allocate funds to environmental

[14] ITSCI focuses on avoiding conflict financing, human rights abuses, and other related risks in the tin supply chain. ITSCI is based in four countries, which are Burundi, the Democratic Republic of Congo, Rwanda, and Uganda. It was founded in 2010 and now involves more than 2000 mine sites with more than 300 participating companies.(Schuyler 2017)

rehabilitation, whose sum will be decided by the government. Nevertheless, miner watchdogs have criticized it because it is failing to create limits to mine expansion, leaving the natural environment undefended toward degradation. (Harsono 2020) In the particular case of tin, the "Minerba law" would give more freedom to the company PT-Timah to explore new off-shore deposits, leading to an intensification of the existing conflict between mining companies and the coastal fishermen. Considering that 50% of PT-Timah is represented by artisanal mining, a possible expansion of mining activities would bring more problems to the environment. In this context, the governor of Bangka-Belitung provinces officially challenged the Minerba law accusing it of lack of transparency, because when it was drafted the regional government was not present and had no influence on the law saying that "We simply want the regions to be involved in drafting this law. This is necessary because the matter of natural resources is very sensitive". The governor also added that the regions would not have any power in decision making regarding supervision, licensing, and conflict resolution, accusing the law of setting aside the local government without the possibility of defending its interests. (Randika 2020)The biggest fear for local administration is that in case of bad governance from the central government the mining area would be exploited in an unsupervised manner, which in turn would lead to more environmental, economic, and social problems for the region.

At last COVID-19 had increased the threat of illegal mining and the environmental problems related. In the region of Altamira, in Brazil, there was a growth in mining activity already in 2019, which intensified in the last year. Illegal mining is leading to massive deforestation and water pollution. About 300 hectares were lost between January and October 2019 ('Illegal Tin Mining Leaves Trail of Ruin in Protected Brazilian Rainforest' 2019) Illegal mining is also increasing due to the political line of the central government that not increasing forest protection but it is aiming to develop the mining sector.

4.5.4 Refined tin production

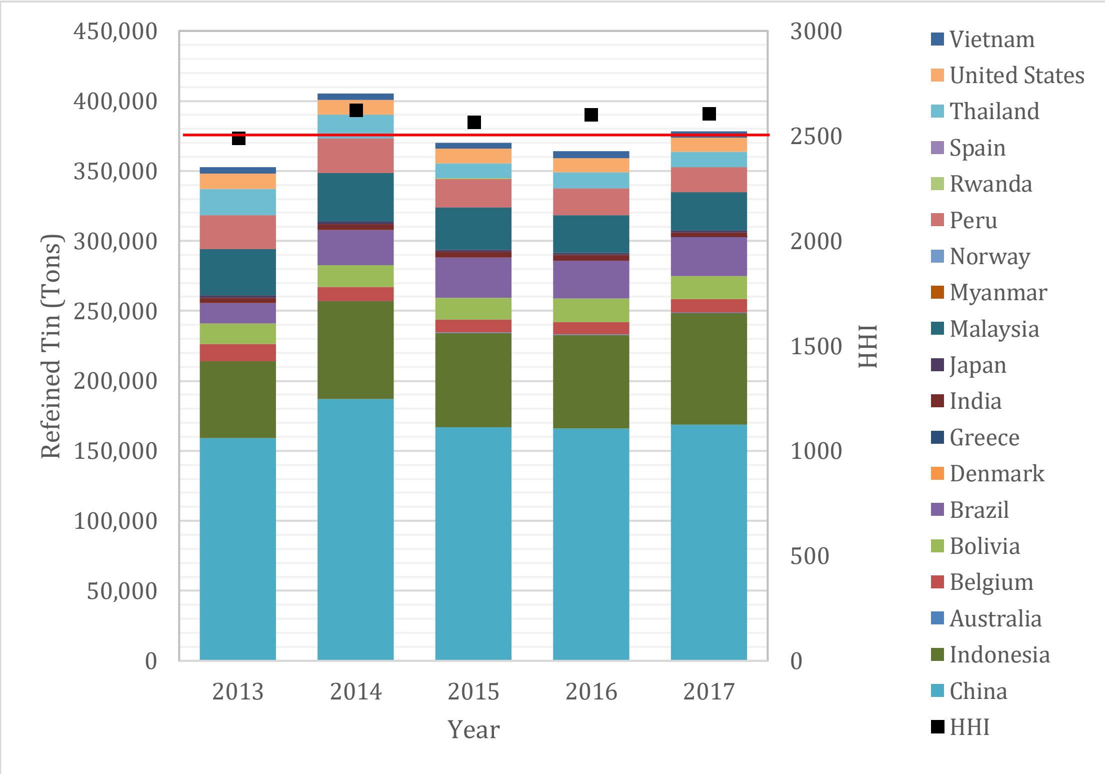


Figure 13: Refined tin production by country in the period 2011-2019, before the COVID-19 disruption. The black squares represent the HHI production index. The red line indicates the value of HHI 2500,above this value the production is highly concentrated. (Source: (USGS, 2017)

Refined tin production shows a different reality compared with mine production, refined tin has low diversity. The historical analysis indicates a $HHI_{refined}$ above 2500 from 2014 onward. An index >2500 indicates a highly concentrated market. From 2013 to 2017 the $HHI_{refined}$ increased from 2491 to 2607,giving a slightly upward trend. Between 2017 and 2020 there is no available data for each producer but there is evidence that the $HHI_{refined}$ remained above 2500. China, the main refined tin producer, had a production of 168 500 tons in 2017, which accounted for 46% of total production. In 2019 Chinese produced around 160000 ton of refined tin while the world production was 333 000 tons.

China is the largest producer of refined tin, it accounts for almost half of the world production and has the highest imports of tin ore (around 70 000 tons in 2017). This makes the refined tin production highly concentrated and relatively sensitive to disruption, given also the one line Chinese tin ore supply. Another important characteristic is that China also represents the main consumer of refined tin, accounting for half of the total production (Yang et al. 2018). This position reflects on price fluctuations depending on changes in the Chinese supply and demand. For example, the drop in tin prices during 2018 and 2019 was caused by a reduction in the Chinese demand.

The main Chinese smelting region is the Yunnan province which produces tin ingot, tin materials, organic tin and inorganic tin chemical products, tin-based alloys. These products go mainly into the domestic market while a small part goes overseas markets, i.e. the silicon valley in California.

Supply shortages and the COVID-19 disruption made China a net importer. In the first six month of the year refined tin imports reached an growth of 1762% compared to the same period of 2019.(ITA 2020c) The rocketing of the imports was caused by the closing of all Chinese smelters, except for Yunnan tin. In the second half of the year, when all suppliers resumed normal services, tin imports remained high suggesting that the country is still not able to meet the demand. Net refined imports in July were 9 262 ton, which doubled from the same period of 2019 when it was 4 175 ton.

Indonesia, which is the main exporter of refined tin, also shows a restrain in exports and production during the COVID-19 disruption. In the first 11 months of 2020 the exports were 59 100 ton, down 3,6% 2019 and the lowest value since 2016. In South America the impact of the disruption had a similar effect. In November 2020, the refined tin production was down 6% compared to 2019.

At a global level, the production of refined tin had a drop of 8% compared to 2019, which increased the deficit between supply and demand (5 200 ton). This drop in production leaves vulnerable countries as the US, which rely on imports.

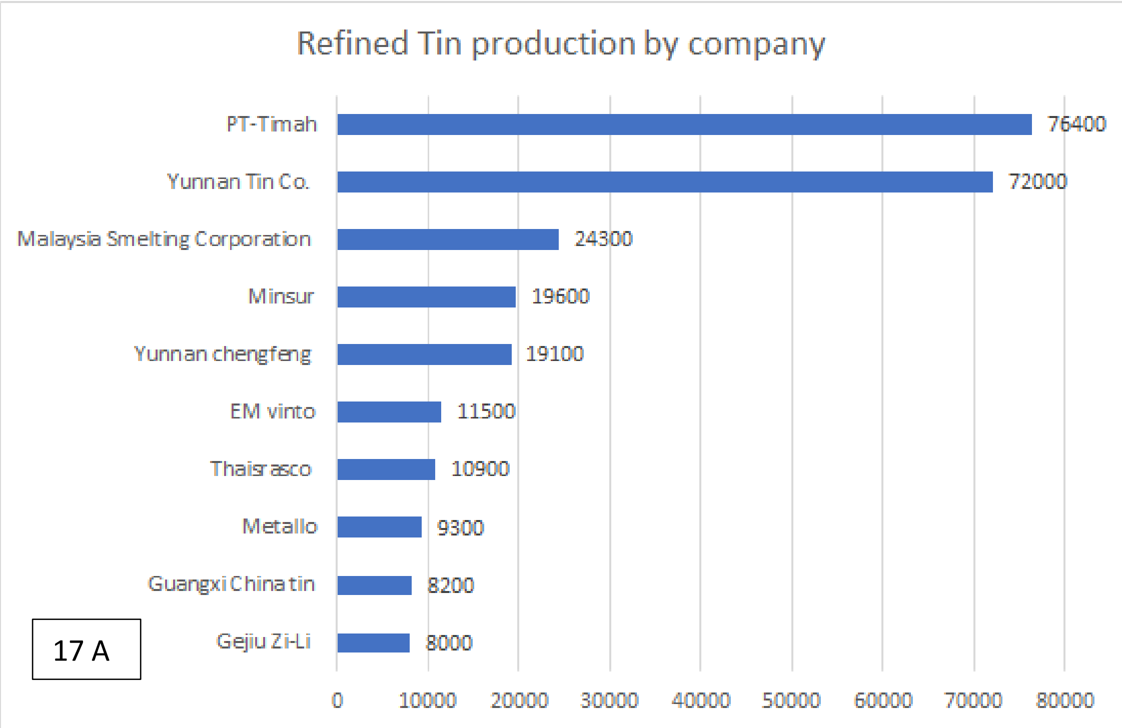
The supply-fast disruption of the Covid-19 hit the world tin refined supply, increasing the gap deficit between production and consumption. Moreover, it showed that low diversity on the refined level are impacted by disruptions.

4.5.5 Company level refined tin production

In the industry sector, the market is highly consolidated, with the 10 major refined tin producers accounting for more than 70% of the global market. Table 5 shows the major producers while figure 14 shows their refined tin production in 2019.

Table 5: Largest refined Tin producers in 2019 (ITRI)

Order	**Name**	**Country**	**Share(%)**
1	PT Timah	Indonesia	22,8
2	Yunnan Tin Co.	China	21,5
3	Malaysia Smelting Corporation	Malaysia	7,3
4	Minsur	Peru	5,9
5	Yunnan chengfeng	China	5,7
6	EM vinto	Bolivia	3,4
7	Thaisarco	Thailand	3,3
8	Metallo	Belgium	2,8
9	Guangxi China tin	China	2,5
10	Gejiu Zi-Li	China	2,4



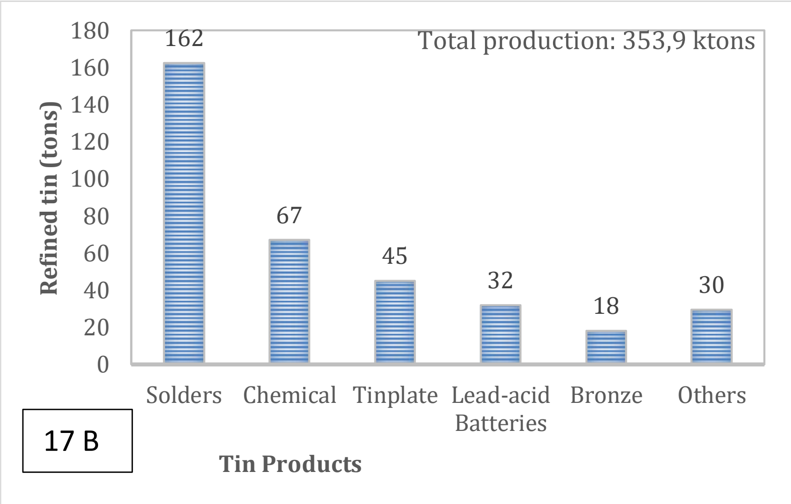


Figure 14 A and B: refined tin production in tonnes by the top 10 companies (2019) (A). Refined tin production divided in the main products (2019) (B)

The company level analysis confirms what explained in the previous chapter, low diversity of supply. Due to the lack of data it can not be possible to calculate the HHI at a company level but it is noticeable that two companies account for 40% of total production, these are: Yunnan tin (China) and PT-Timah (Indonesia). Yunnan tin has been the historical top tin producer but in 2019 reduced the production as an effect of the trade war and the reduction of Chinese demand.

In 2019 thanks to enforcement in export regulations in Indonesia, which brought a reduction in competition for concentrates. Most private smelters could not comply with the new government requirements and had to close or reduce production, making the public company PT-Timah a quasi-monopoly in Indonesia (ITRI 2016). This monopoly position in the first exporter country has direct effects on the market. For example, price feedback loops changes depending on Indonesian exports which are directly related to PT-Timah exports. During COVID-19 disruption the company registered a loss of almost 27 million in the period from January to June and announced the reduction of its output by 30%, these actions had effects on the total Indonesian exports. (Post 2020)

The disruption had also changed the top 10 tin producer classification as figure 15 shows.

2020 Top 10 Refined Tin Producers

Refined tin production (tonnes)

Order	Company	2019	2020	YOY Change (%)
1	Yunnan Tin (China)	75,900	74,800	-1.4%
2	PT Timah (Indonesia)	76,400	45,700	-40.2%
3	Malaysia Smelting Corp (Malaysia)	24,300	22,400	-7.8%
4	Minsur* (Peru)	19,600	19,600	0.0%
5	Yunnan Chengfeng (China)	19,100	16,500	-13.6%
6	Thaisarco (Thailand)	10,900	11,300	3.7%
7	Guangxi China Tin (China)	8,200	10,100	23.2%
8	Jiangxi New Nanshan (China)	7,200	10,100	40.3%
9	Metallo (Belgium)	9,300	8,100	-12.9%
10	Gejiu Zi-Li	8,000	7,000	-12.5%

Data: Provisional data reported to ITA and rounded to the nearest 100t. One company excluded from the top 10 on request.
**Excludes production from Minsur's Brazilian subsidiary, Taboca*

FIgure 15: top 10 companies of refined tin, before and after the covid-19 disruption.

In 2020 these 10 companies produced 69% of total refined tin, down from 76% of 2019. In China, after a rough start of the year, the major companies were able to ride out the disruption thanks to a increasing demand and the government actions.

Most of the companies in South America had to shut down for two month in the early part of 2020. This length made the Bolivian company EMVinto to move out of the list while the Peruvian Minsur afford to maintain production steady. (ITA,2020)

4.5.6 Secondary sources

The Recycling input rate (RIR) of tin was 31% in 2018, where re-refined tin contributed 13% while the remainder was reused or reformulated alloy (ITA,2020). Although it represents a high percentage it varies greatly depending on the product that is taken into account, it will follow a brief description of the recycling characteristics for every end-use product:

- Solders: solders are the main product of Tin and its recycling rate is directly related to the collection and processing of e-waste. In 2016, only 20% of the worldwide e-waste was recycled (UN 2019). Considering that the use of electronics is in constant growth of around 4%, more effort must be made to increase their recycling rate, which is fundamental for a circular economy. The main recycling challenges for tin are the complexity of the products and the small amounts used, which is between 1% and 6% in an electronic board. Different companies are trying to overcome the technical issues that impact the solders' recycling but it does not seem that the RR will increase in the short term.

- Chemicals: It is the most varied sector with products that range from PVC to energy and coating components, making the evaluation of its recyclability really difficult. The biggest market for tin chemicals is PVC stabilizers and catalysts. PVC stabilizer is directly related to the PVC recycling rate.
- Tinplate: This is the biggest contributor to the Tin recycling rate, with an EU rate of more than 80% and a world rate of 70%.
- Lead-acid batteries: the overall recyclable rate of batteries is more than 90% but tin is mainly lost in the process due to its tiny amount present.

4.6 Scenario Analysis

The supply side is still recovering from the current disruption while the demand showed good resilience for tin solders. Besides this, the future for the tin supply chain is uncertain. In the next section, two different scenarios are presented that could interest the supply chain of tin in the upcoming years. The first scenario is more focused on the medium-term and long-term and will explore the possibility of tin demand to increase in the upcoming years after the spread of 5G mobiles and the use of tin in the energy transition technologies. The second scenario will start from the possible winner of the US election and it will develop into three possible consequences of the trade war between the US and China.

4.6.1 Scenario 1: Lithium-ion batteries

As already explained in section 3.3, the energy transition will increase the use of lithium-ion batteries in the transportation sector, which needs improvements to equal the current carbon-engines. In this context, different studies are exploring the use of tin as anode for different next-generation batteries (ITA 2020e), such as lithium- and sodium-ion batteries. The substitution of graphite with tin or tin alloys would increase the overall battery capacity (Kapacyr 2018). Thanks to the introduction of tin in new energy technologies, the ITA estimated tin demand to increase up to an extra 60 000 tons by 2030 (section 3.4). Figure 16 shows the results given by the Vensim model, using the ITA increment in tin demand prediction and the increment given by the 5G diffusion in the electronics sector.

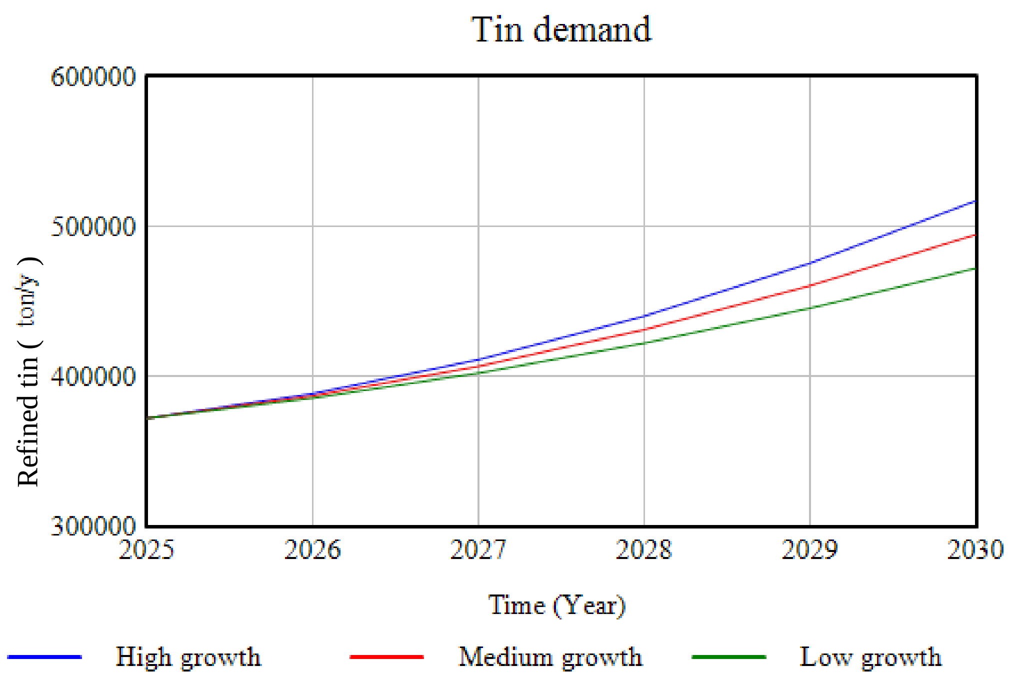


Figure 16: Increase of Tin demand from 2025 to 2030 with the modelling calculations. (Created with the software Vensim)

High growth represents the most optimistic scenario where tin is being used in all three anodes materials (60000 tons); Medium growth, a middle ground where tin is being used as an anode in two different battery technologies (45000 tons); low growth, the less favourable where tin is used in one new battery technology (30000 tons).

The demand projections shown in figure 16 do not represent a real trend due to the high volatility of prices, disruptions, and other variables not included in this model. It gives an indication of the possible growths for the upcoming years if tin would find new uses for new technologies. Depending on how many of them will use tin, the demand growth could be more or less sharp. Still, the model shows that the demand could overcome the amount of 400 000 tons/year around 2027.

Using the same model, it is calculated that there are no relevant differences in the depletion of reserves. Although there is no difference between the three predictions, the depletion of the reserves will accelerate in the next decade, accelerated by the growth of tin demand. It is expected to consume 1 M Tons of the current reserves. In order to keep up with the demand and avoid another disruption, producers have to make more investments in mining explorations. Explorations that will take years before new mines can be operative. Therefore, the tin supply chain will enter again in a low supply period as before the crisis of 2019 and 2020. The short-term will then see an increase in prices which could lead to new investors interested in tin. New explorations could also increase the number of reserves of tin, which keep stakeholders interested in Tin without spreading the sentiment that the world is running out of tin. For example, in 2015 the ITA counted an amount of 2,2 M tons reserves of tin, while in a similar document they counted an amount of 5,5 M tons by the end of 2019. The discrepancy between the two years could be explained as growth in explorations due to high prices and high demand. A similar situation could occur again in the scenario described in this chapter. New explorations and mining activities could also consist of rehabilitating old mine sites such as the old English tin mine of Cornwall, which is expected to reopen in 2021. (Kent and dos Santos 2019)

The short-term could benefit from new investment in the mining sector but the constant depletion of tin global reserves could endanger the market in the medium and long-term, reducing reserves to less than 2 M tons by 2050. In order to avoid possible disruptions, the supply chain should focus on circularity with secondary sources becoming an important source. The recycling rate of tin was around 30% in 2019 while the recycling of E-waste, which contains tin solders, was only 17,4% (UN 2019). If the e-waste collection and treatment would improve in the upcoming years also the tin recycling input rate(RIR) would increase. Figure 17 shows how the depletion of reserves would be reduced in the medium growth prediction if the RIR of tin could reach 40% or 50% by 2025.

Figure 17: Tin reserve depletion with different Recycling input rate (RIR) extracted from the model. (Created with the software Vensim)

The graph shows that the depletion in reserves would significantly reduce with an improvement of the recycling rate, with a difference of around 40 000 tons between each recycling input. A higher RIR would also extend the lifetime of the current reserves. The model estimates that with the current recycling rate they would last between 12 and 14 years which could be extended up to 20 years with a recycling rate of 50%. Secondary sources could also create less stress on mine extraction by controlling the demand for tin ore, which is in constant growth. In order to satisfy demand, the model estimates to overcome the 300 000 tons by 2027 keeping the recycling rate at 30%. Taking into account that the global mine production in 2018 was 310 000 tons (Schuyler 2019), the tin supply chain could face serious supply problems by the end of the decade. In order to keep tin ore demand below 300 000 tons by 2030, the RIR should increase by 5% by 2025. An RIR of 35% could already reduce the possibilities of big supply disruptions in the short-term.

In the medium-term and long-term how hard the disruption becomes will depend on the resilience of the supply chain. The three resilience mechanisms are analysed trying to understand where companies should focus more in order to not face a shortage of supply:

- **Stockpiling:** It will maintain its importance in the supply chain to fill gaps between supply and demand during disruptions. Down-stream companies will continue to not keep stockpiles due to the high prices of tin and buy only the amount they need. On the contrary, upstream suppliers will always keep stockpiles in order to avoid disruption and control the price market. The Yunnan government announced in July that it would give incentive to producers that decide to stockpile up to 40 000 tons of tin for the upcoming year. (ITA 2020d) This behaviour will give more control to suppliers on a price level but it will probably tighten the other market such as the European and American. In a broader, low supply and high demand will push upstream actors to use their stockpiles. Resulting in a reduction of total stockpiles.

- **Diversity of supply:** Tin is not currently considered a critical material in Europe thanks to the presence of big tin producers such as "Metallo" in Belgium, but there are chances that the high prices, supply shortage, and high demand, of the upcoming future, will make the European Union label tin as a critical material. It is known that the US, China, and the EU have plans to ensure supply lines of critical raw materials as part of the sustainable development goals (SDG), making the diversity of supply an even more important resilience mechanism. The unbalanced supply scheme toward Asia would probably keep the actual characteristic but high prices will create new investment opportunities in other parts of the world. At the moment the most suitable areas for new mines are Africa, Australia, and old mines that could be reopened, i.e. Cornwall in England. Siberia is also rich in tin deposits but exploration and mining in this area are expensive due to the climate condition, and could also bring considerable environmental disruptions. In general, downstream actors and manufacturers could ensure a strong supply line by getting their supplies from different geographical areas . In this context, the relations between consumer and producer will become more important, also considering the possible future geopolitics scenarios. The obligation derived from different suppliers will acquire more importance in the optic of a sustainable supply chain.

- **Substitution:** There will be an increase in substitution for some sectors while others will see a growth of substitution in favour of tin. Different end-stream companies could look for cheaper materials due to the high prices of tin and the possible supply shortage. The tin sectors that will face a stronger substitution will be the lead-acid batteries and Tin chemicals sectors. The latter because it will be substituted by the next generation of lithium-ion batteries while the former because there are cheaper products such as zinc and calcium, the same substitution explained in 4.4 which will intensify in the upcoming years. Substitutions that will benefit the tin market are the next-generation batteries. In general, the tin demand share will maintain the current division but lithium-ion batteries will substitute the share of lead-acid batteries while solders could gain a bigger share thanks to the diffusion of 5G technologies if the miniaturization will phase out (section 4.4).

4.6.2 Scenario 2: Trade war US-China developments

The results are that a complete decoupling in all sectors in a short time is not possible but it would be interesting to see the possible futures for the tin supply chain depending on the future US-China relations.

In section 2.5 it was said that both countries want to assure their supply of critical materials. It was stated that the US government published at the end of September an executive order called "Executive order on addressing the threat to the domestic supply chain from reliance on critical minerals from foreign adversaries", where Tin is considered a critical material and China an adversary. .

Complete Decoupling scenario

In a complete decoupling scenario, represented by a "Tin cold war", both parts have developed two different supply chains with no contact between them. Even if this scenario is the most unlikely to happen, it is possible to try to understand how the two supply chains would look like. In general, both countries would point to the diversity of supply to improve their resilience.

Possible US supply chain

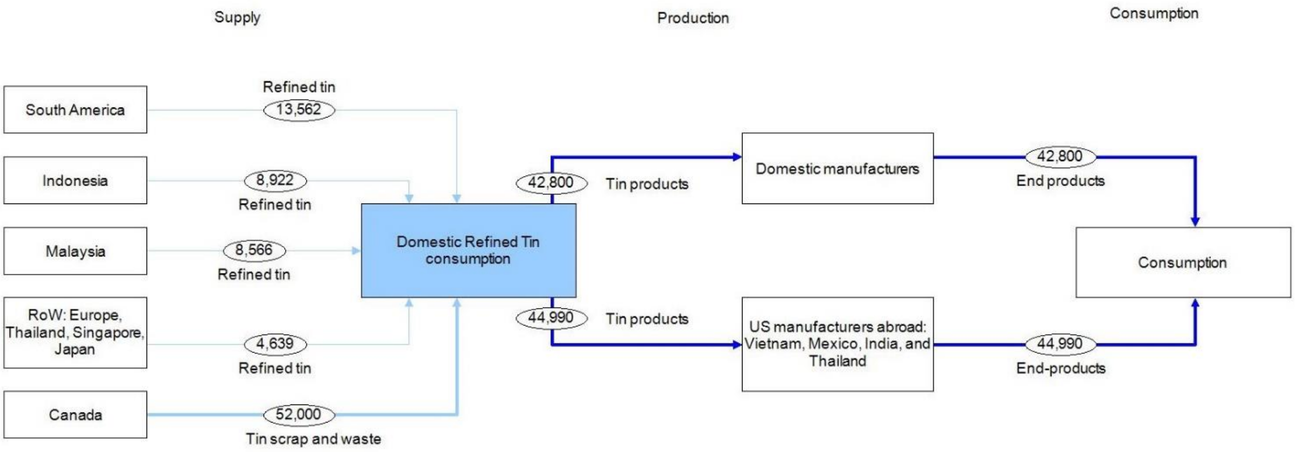


Figure 18: possible US supply chain without China using as source for data the USGS 2020 report, flows (arrows) are in tons/year created with the software "stan". Light blue indicates the supplies line while dark blue the consumption flows.

Figure 18 shows a possible US supply chain decoupled from China. The US has not mined tin since 1993 so they rely for 100% on imports from foreign countries. It does not import tin ore as China but only refined tin, in 2017 were imported 35 689 tons, divided as shown in table 7. (USGS, 2020)

Table 7: US tin suppliers without China. Numbers are using the year 2017 as base. USGS 2020)

Refined Tin	**Quantity (tons)**	**Share (%)**
Indonesia	8922	25
Malaysia	8566	24
Peru	7138	20
Bolivia	6424	18
RoW	4639	13
Total	35689	100
Tin waste and scrap		
Canada	52000	99

Supply of tin would be divided into different suppliers. The imported tin is mainly consumed in the following tin products: tinplate, 21%; chemicals, 17%; solder, 14%; alloys, 10%; babbitt, brass, and bronze, and tinning, 11%; and other, 27%. The US is not relying on China in the level of refined tin imports and a complete decoupling would be possible. All the tin would be imported to the US in form of refined tin or tin products and then would leave the United States for further manufacturing or assembly. In this new supply line, the manufacturers of semiconductors, the first tin solder product, would represent the first problem level for the US supply chain.

The US leads the global sales of semiconductors with a share of 47%, but Asia and China lead the production with 80% of manufacturers. In addition to this, US manufacturing capacity has been cut in half to just 12% over the past 20 years and is forecast to fall to 10% by 2023. (SIA 2020) Therefore, the first phase of the US for a complete decoupling would be to bring the manufacturer process back in the US with policies that incentives new local production. Moreover, the US would have to stop relying on Chinese manufacturers such as Semiconductor Manufacturing International Corp. (SMIC) and create stronger alliances with other non-Chinese companies such as the world leader Taiwanese chipmaker Taiwan Semiconductor Manufacturing Co. (TSMC), which already announced the construction of a production facility inside the US. Another problem that US companies would face is the relocation of production outside China, which is a slow and costly process that can cost millions of dollars before it starts to give results. Due to the high labor costs, the production will not be relocated to the US but several countries look to have the characteristics to welcome the new American production. (Zhu 2020)

The biggest country targets for new manufacturers' relocations are Vietnam, Mexico, Taiwan, South Korea, India, and Thailand.(Netherl 2020) Among the new possible destinations, Vietnam is the most appealing thanks to its cheap labour costs compared to China, 2.99 $/hour against 6.5 $/hour. In 2019 the imports of goods from Vietnam increased by 35% and many companies announced to move part of their production to Vietnam. (Lee 2020) Mexico would be another winner in a possible complete decoupling, as US companies could take profit of the Mexican 4.82$/hour wage. It is estimated that the production of electronic components could increase by 17% (Netherl 2020). Taiwan has always been a strategic point for both China and the US. Taiwanese companies started to relocate their production in Taiwan and they might be an important US alliance thanks to new deals with TSMC. Thailand and India would benefit less than other countries due to their small production of electronic products but, in case of a complete decoupling, they could see an increase in their high-tech production. Once the new manufacturer countries would be found, half of the tin would be exported again to be assembled in the final product.

Stockpiling: Tin is not present anymore in the US strategic national stockpiling and it is unlikely that it could collect enough stockpiles in the upcoming years given also the possible increase in demand. It is more plausible that the US would count more on the stockpiles of its suppliers.

Diversity of Supply: The resilience of the US tin supply chain would be based on its diversity of supply as it can count different suppliers around the world that even contribute to US tin supply.

Substitution: Substitution would still not contribute significantly to resilience.

Possible Chinese supply chain

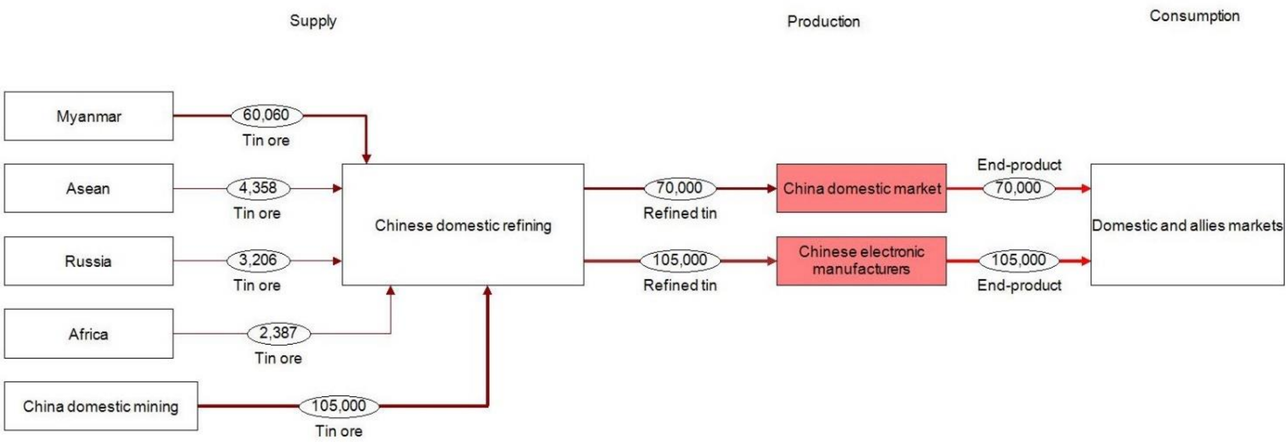


Figure 19: Possible basic sketch of the Chinese tin supply chain, created with the software "stan". In dark bred are highlighted the production flows, in light red the consumption flows.

Figure 19 shows a possible only Chinese supply Chain, where tin ore imports from Australia have been divided between Russia, Africa, and ASEAN. China is the biggest producer and consumer of tin, accounting for 40% of tin reserves worldwide. It also has been an exporter of tin for many years before switching into a net importer. Thanks to this characteristic, China would have fewer problems on a supply level than the US. A good supply line would need to be created to sustain the demand, with new local investments and importing tin ore from a third country, figure 14.

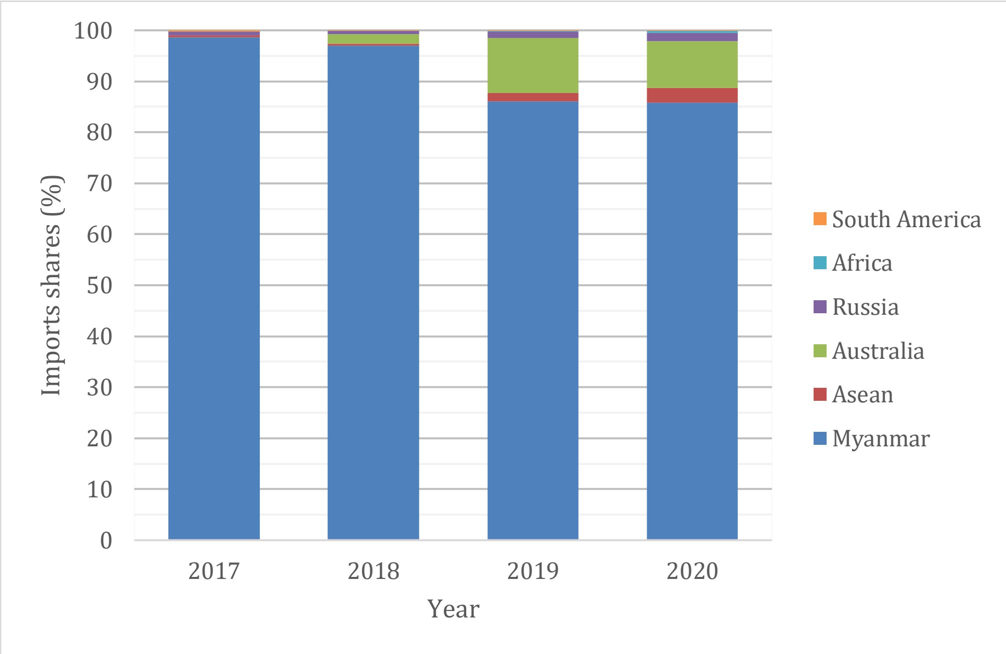


Figure 20: Shares of Chinese tin ore imports in the period 2017-2020
https://oec.world/en/visualize/tree_map/subnational_chn/import/show/show/52609/2017/.

Figure 20 shows the shares in tin ore imports to China from 2017. The timeline shows that until 2017 China was only importing from Myanmar. The depletion of Myanmar mines has made China look for new suppliers. Since 2018, it increased its import from other parts of the world such as Australia. In a possible complete decoupled scenario, Australia would tend more to trades with the US, making China to deal with other countries. During the crisis, China imported huge amounts of tin ore (section 3.2.1), and a possible new supplier could be its neighbour Russia. Even if Russia is not directly interfering in the trade war, China and Russia relations have increased (Ignatova, Gorbunova, and Tereshina 2019). Russia is also increasing its tin production, the company JSC Rusolovo increased by 48% on a year to year basis during 2019 while in august 2020 bough the old Pyrkakay stockwork deposit, making the company the fourth-largest company in the world when measured by their contained tin resource (ITA 2020f). At the moment import from Russia accounts only for 1,58% but is constantly increasing. Table 8 showed the possible Chinese tin supplier after cutting out all potential US allies.

Table 8: possible share in Chinese tin suppliers

Refined Tin	Quantity (tons)	Share (%)
China	105000	60
Myanmar	60060	34
ASEAN	4358	2
Russia	3206	2
Africa	2387	1
Total	175011	100

On a manufacturer level, China would also be in advantage thanks to its cheap and specialized labor and to its in-land facilities with no need in relocating. The biggest impact that China would face is the loss of high technology products such as high-tech semiconductors, for which the US is the world leader. A possible ban to SMIC, the biggest chip company in China, would bring a loss in the Chinese semiconductor market that will rebound on the tin demand as already happened in 2019. To avoid this possible disruption the Chinese government must invest in high-tech, which currently only covers 12% of domestic demand but it is looking forward to closing this gap by 2030 (Hodiak and W. Harold 2020). With the beginning of the trade war, funds toward this industry had risen dramatically and in the model, China would continue to invest in high tech production as it can be seen in figure 13 with the flow of refined tin entering “Chinese high-tech manufacturers”. First of all, to complete the decoupling, it would increase the investment in high-tech technology and probably the foundation of a Chinese “silicon valley”, which is already happening in the “The Great Bay Area'', located on the Pearl River Delta (Bork 2019).

Stockpiling: The decoupling from the US would initially bring a decrease in semiconductor Chinese demand, which would also affect tin. This will have effects on imports but also on stockpiling, as China could increase its stocks more than the US could do.

Diversity of Supply: China mostly rely on domestic production and few importers. This lack of diversity of supply is already a problem and would probably keep being in a Chinese supply chain. It would still count on Myanmar and domestic production for more than 90% of supply, leaving the supply chain sensible to disruptions.

Substitution: It is unlikely that China would look for substitutes, given the high amount of tin deposits in China.

General considerations

Both supply chain outcomes have common points that are difficult to predict. Firstly, common suppliers of both countries will probably have to take sides deciding who is the most profitable client. Big African companies, ruled by westerners, will be more favourable in making deals with US but tin miners located in southeast Asia such as Indonesia could find themselves in a more problematic situation. Secondly, the island of Taiwan could become the field for political or real conflicts, maybe turning it into another "Cuba". On one hand, China does not want to give complete independence to the island. On the other hand, it could represent an important strategic point for the new US supply chain.

Resilience mechanisms would work differently for China and the US. The former would count more on stockpiling to counteract disruptions thanks to its domestic tin deposits, while the latter would focus its resilience in the diversity of supply.

The complete decoupling would lead to a cold war between China and the US while the rest of the world would need to take sides and support one or the other. The European Union, UK, Japan, and Australia would increase their deals with the United States, while Russia would intensify its relations with China. Russia could also become a strategic ally if it would start exploring the tin deposits in Siberia.

A complete decoupling is unlikely to happen in the short-term or medium-term because the two parts are deeply bonded together and a possible hard rupture would bring hard times for the US semiconductor market. (Capri 2020) A complete decoupling will then bring a loss in demand for tin in the short-term. Moreover, the implication of a complete decoupling would be devastating for the global economy and sustainable development goals. In particular, the latter would be probably set aside to reach the global order.

Partial Decoupling scenario

A partial decoupling would consist of a special deal with the two countries where they do not stop to make business together but the relocation of production would continue to happen. Probably the semiconductor market would still be affected by a push towards decoupling as both countries are looking to reach complete technological independence. Still, the US and China semiconductor market is deeply bonded together, making the process harder. In this possible hybrid scenario, the tin supply chain could probably be maintained as usual for primary production and smelting, but it could change on a manufacturer level where both countries are trying to gain independence. Figure 21 shows a schematic possible tin supply chain in the case of partial decoupling.

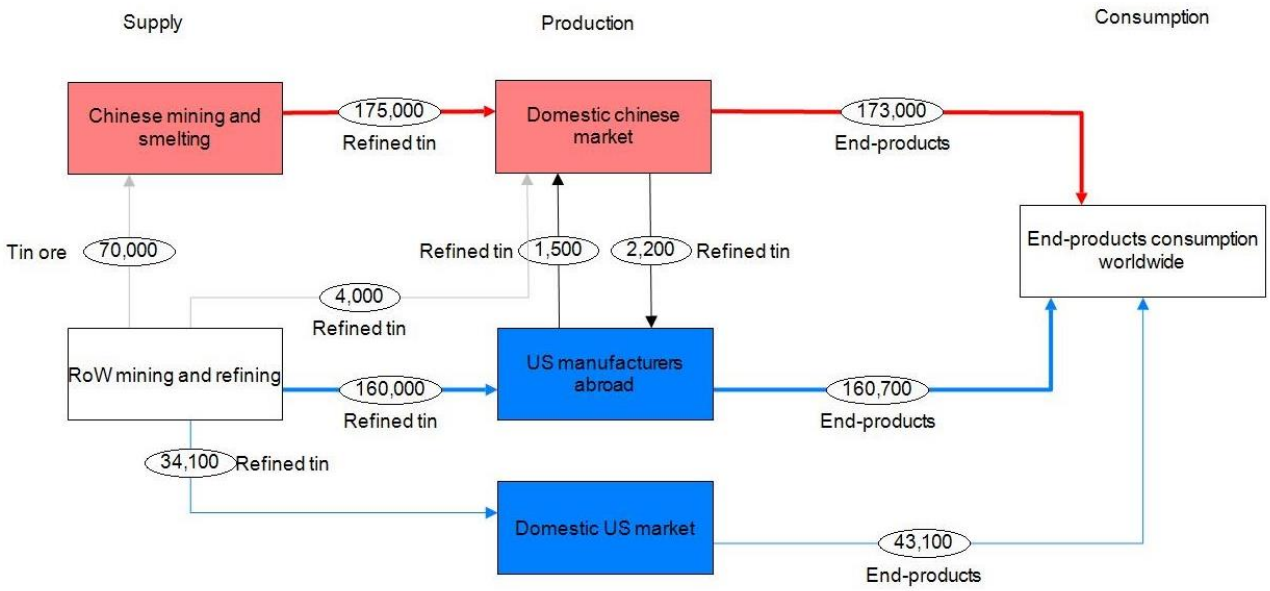


Figure 21: accounting model of a possible semi-decoupled supply chain between the US and China, using data from the year 2017 where global production was 373,4 kt, created with the software "stan". In blue is highlighted the US supply chain, in red the Chinese supply chain, in black their exchanges and in grey the suppliers.

In this scenario what would change from the usual trade system is the amount exchanges between US-China. On the supply side, China would completely try to be independent of foreign suppliers and find a possible tin ore loyal supplier such as Myanmar, which will continue to be the main and only supplier. The downsizing of Chinese demand caused by the relocation of some US manufacturers could help China in reinforcing its domestic demand. The US will continue to rely on foreign suppliers for the domestic market and companies located abroad, which will increase its demand due to the reduction in buying Chinese products. In this context, diversity of supply will be a key element for resilience in the US supply chain. The refined tin will then enter the different end-product manufacturers, where most secondary tin products can be produced in the internal market of the two countries. A special position would be occupied by tin solders producers which will continue to make deals with both countries because the semiconductor market will continue to have links between Chinese and US companies. In particular, US companies would slowly lose their dependency on China by relocating most of their products to other countries such as Vietnam, Mexico, Taiwan, South Korea, India, and Thailand. On the other side, China will continue to buy US semiconductors while developing its high-tech technologies. Both countries will continue to sell their products to the rest of the world.

The resilience mechanisms in this scenario would not be greatly interested by the semi-decoupling but the tin supply chain would lose its reliance on China and increasing its resilience.

This scenario could only happen if an agreement is reached between the two parties to stop the hard decoupling put in motion with the trade war but still following the politics of supply chain independence of both countries.

No Decoupling scenario

The third scenario is that China and the US find an agreement to continue cooperating despite some antagonism. A possible future deal could start from the dust of the current "Phase one" agreement if China shows real efforts to accomplish the previous deal and the US starts to reduce tariffs. This situation could lead to reopening the stage for a possible "Phase two" deal, although Donald Trump said in July that he is not thinking of a "phase two" (R. Staff 2020). A possible new agreement could touch more delicate cases such as data protection or a Chinese fair trade. China from his side could create stronger data protection policies for foreign users or create a more fair environment for both domestic and foreign companies while increasing competitiveness. On the other side, the US could reduce the tariffs imposed on Chinese products and create more agreements. The antagonism with both countries would not completely stop, mainly at the technological level where both countries would still push toward possible technological supremacy. Besides this, a middle ground should be found to maintain a "status quo" in their relationship. China would emerge as a global power economy without attempts to push to supremacy while the US would accept China as a new global power and push toward cooperation instead of distancing. In this scenario, probably as good as unlikely to happen, both countries could push together toward technological development and sustainability for a better future. The global economy would benefit from this renewed optimism and markets could rise again.

For the tin supply chain, this would represent the best scenario possible as it would not bring direct disruptions either on the supply or the demand. The current structure would be maintained but demand would rocket thanks to the technological developments of both China and the US. In this possible future, the development of new technologies could open the market to new products for tin, i.e. next-generation batteries, improving tin demand. The tin supply chain would then face scenario 1 already explained previously in this thesis.

5. Discussion

This thesis has tried to give a qualitative analysis of such a complex and broad system as a full supply chain while focusing on its resilience. The supply chain has been analyzed with an holistic approach that successfully manages to show the current problems of the supply chain. Tin is considered a small market compared to other major metals but worth understanding due to its importance in the semiconductor sector and its possible future applications.

5.1 General discussion

The first part of the results, from section 4.1 to 4.5, discussed the supply chain dynamics and resilience mechanisms before and during the COVID-19 disruption. These paragraphs lead to the answer of the first two sub-questions, where the first was: *How the resilient mechanisms performs in the supply chain?.* Overall, the resilience mechanisms showed low performances for the short-term, but they has potential for the medium and long-term.

Substitution is the mechanism with the lowest contribution to resilience. Besides the little information available, no economic substitute has been found that could substitute tin solders that could increase the performance of this resilience mechanism. It was shown at the end of section 2 that the solders occupy half of the tin demand and this share would not change in the medium-term. The lack of substitutes for tin has a double face medal for the supply chain. On one hand, this increases its essentiality and maintains high prices, which is good for new investments. On the other end, down-stream companies can not rely on substitutes during disruptions, making the supply chain more sensible to disruptions. The only product of tin that has economic valuable substitute is represented by tin chemicals. In this sector tin has been substitute with cheaper option after changes in government legislation and metal prices, which could increase resilience during disruption but not enough data has been found. Furthermore, during the covid-19 disruption, no information regarding substitution in the resilience context was found. In general, Tin has been substituting lead in solders and chemicals for many years, which means that there is a smaller possibility to find a substitute for tin at this moment. As long as lead can be substituted by tin there is no willingness in looking toward substitutions for tin. Nevertheless, in the medium or long-term this situation could change thanks to new technological developments.

Stockpiling has an immediate response during disruption, as the price feedback suggests, but its contribution to resilience is low due to the small amounts of strategic and company stockpile. Stocks mainly increased during periods of low demand, i.e., during 2019 (section 4.3), and decreased in periods of low supply, i.e. covid-19 disruption.

A possible fast-demand disruption such us the use of tin in lithium-ion batteries, would drastically reduce stockpiling. In the short-term stockpiling would increases thanks to new stocks projects but in the medium-term it will go down again due to the boost in tin demand.

Diversity of mining supply provide resilience to the primary production after the surge of Myanmar as one of the biggest tin mine producers. In the short-term diversity of mining supply is expected to be maintained thanks to new projects that will increase the output in African countries. The resilience provided by diversity of mining supply is lost in the refined production. Diversity of refined production is low on both a geographical and company perspective, which provides low resilience to disruptions.

The second research sub-question focuses on the resilience mechanisms' performances during the COVID-19 disruption: *How is the supply chain responding to the COVID-19 disruption?* This unprecedented crisis has affected all suppliers, which registered a decrease in production and a loss in revenues. Many facilities had to close during the first period of the pandemic. The tin supply chain has overall shown a fair resilience in the short term thanks to the resilience of semiconductor supply chain.

Stockpiling responded rapidly to the COVID-19, as the feedback price suggested. It indicates that stockpiling has a good performance as resilience mechanism but its contribution to overall resilience is low due to the low amount of stocks. However, the apparent correlation between the upward trend of prices and the sharp decrease in stocks can be explained by the increase in demand and the decrease of supply.

No information has been found on tin substitution as a resilience mechanism during the covid-19 disruption, but not having substitutes for tin solders has helped the demand.

For the diversity of supply, the Covid-19 pandemic was an unprecedented fast-supply disruption that put to the test at the same time all tin suppliers, both ASM and large-scale mining companies. The disruption highlighted the importance of having a diversity of supplier in the supply chain when China has been cut out from its main supply line. Nevertheless, a high diversity of mining production helped China in finding new suppliers.

On the level of refined tin production there were not many changes in its contribution to resilience as the disruption hit all suppliers at the same time. Only the company level showed some adjustments depending on the impact that the crisis had on every company.

The disruption and price drops highlighted also another problem related to ASM communities which relies on mining for living.

The third and last sub-question analyses the changes in the tin supply chain in two possible disruption scenarios. The question is: *How could the supply chain respond to a possible future change in demand or supply?* The two scenarios analyzed in the results showed different possible futures for the tin supply chain. The first scenario represents a demand-low disruption where the tin market would expand in the future to new uses in new technologies such as different Lithium-ion batteries. The increase in demand would bring more pressure on the supply sector which was already struggling before the current disruption. Moreover, the increment in demand would also increase the depletion of the current tin reserves, which in turn would need new investments and years before getting a new one. The first solution to this demand growth comes from secondary sources of tin which could help to fill the gap between supply and demand and increase the lifetime of the reserves.

In this future scenario, resilience mechanisms will play an important role.

- Stockpiling: it will be used as usual in the short-term to control prices during periods of low supply.
- Substitution: it will probably increase for some sectors such as chemical and lead-acid batteries as in the previous year. Thus, there will be more tin for the products.

- Diversity of supply: in the short-term current project could sustain the increase in demand in the first stages. In the medium- and long- term technological development is needed to increase secondary sources of tin.

The second scenario explores the possible outcomes of the current trade war between China and the US. Recently, Joe Biden has been elected as the 46th President of the United States after his predecessor Donald Trump, under whose legislature the trade war started. The new President has not stated his position regarding the trade-war yet but it seems his policies will continue with the economic decoupling already in place. On the other side, China seems to pursue technological supremacy and is investing money in its “made in China 2025” plan. Considering the economic decoupling of the two countries, the scenarios analyzed three possible futures for the tin supply chain

· Complete decoupling: Two different supply chains are developed where China relies mostly on its own domestic production and stockpiling as resilience mechanisms while the US would rely on diversity of supply. This scenario would bring the world on the edge of a new cold war.

· Partial decoupling: Most of the US manufacturers are relocated to other states and only a small percentage would be left in China. This scenario would profoundly change the tin supply chain as Chinawould lose part of its supremacy in the supply. The resilience would completely rely on the semiconductors’ demand, which market will be boosted by the rivalry of both countries.

· No decoupling: An agreement would be found by the US and China. There will not be any major changes in the supply chain of tin and its resilience mechanisms.

5.2 Limitations and Further research

It has to be said that the main limitation of this research is the lack of data from actors in the supply chain. It seems that getting in contact with companies is complex and they are reluctant to give information. The tin supply chain represents a niche in the group of the major metals that is difficult to approach. The lack of specific data from actors made the literature review the only source of data available. Free data available on open sources are scarce and difficult to access. There is a big gap between data available on tin ore production and refined tin production because most of the data regarding ASM and Myanmar production is hard to find. There is also a few free data available for tin products. The only reliable data is coming from the ITA, Reuters, and government publications. Given the limitations described above, this thesis tried to give a general analysis of the tin supply chain and its resilience but further research is needed.

All in all, further research with more resource availability should focus on getting enough data for creating an MFA model for the tin to which this thesis could be related. The same theoretical framework could be then used to study other major metals and their resilience. Understanding the work of the resilience mechanisms in the supply chain could bring benefits to stakeholders. Also, this thesis showed that there are discrepancies between the mining community and resilience, further resources could focus on the resilience of these mining communities and ASM. At last, the tin supply chain is in a changing phase that will last for a decade and this work should be repeated in the future to understand the development of the supply chain and its projection in the future.

6. Conclusions

The main research question was: *"Is the Tin supply chain resilient and how do the resilience mechanisms respond to disruptions?"*

The tin supply chain proved to be resilient during the current disruption but also showed supply issues that must be taken into account due to the use of tin in Lithium-ion batteries. Tin demand is influenced by two factors: Chinese demand and solder demand. China is first for both production and consumption of tin, and consequently, a reduction in Chinese demand has effect on tin demand as it happened during 2019 with the US-China trade war. Solders demand for tin represents half of the total and it is directly related with the semiconductor sales. It can be stated that Tin demand is dependent on the semiconductors demand and, therefore, its resilience. This conclusion is driven by the resilience showed during the COVID-19 disruption compared with the low performances of the resilience mechanisms.

Stockpiling had responded immediately during the analyzed disruption, indicating that it is well integrated in the supply chain, but the number of stocks is too low to make a difference in a large disruption. New regulations may increase the amount of stocks in some countries, i.e. China, which could also has an impact on resilience. Due to the high price of tin, it is expected that down-stream companies will not continue to keep tin stocks.

Substitution as a resilience mechanism could not be evaluated from the COVID-19 disruption perspective, as too little information on companies has been collected. In a general view, tin chemicals are the only product to have substitutes that can be used during disruptions. Tin solders and tinplate has no feasible substitutes. The lack of substitutions leaves the supply chain sensitive to possible demand disruptions. Therefore, substitutes coming from technological development are needed.

Diversity of supply has different results for mining production and refined tin production. The former has a good diversity while the latter has a low diversity. This division is explained by the importance of China, as it is the largest importer of tin. The big quantity of imports to China also make it the biggest refined tin producer, reducing diversity of supply. The company level is also impacted by this low diversity of supply for refined tin. Low diversity of supply leaves the supply chain exposed if one of the major suppliers would be affected by a disruption. New projects in diverse geographical areas are needed to increase diversity of supply.

At the current level, the supply of tin would not be enough if a new growth in demand would occur. Companies and Governments should invest in projects in the medium-term while increasing secondary supply during the short-term. In particular, investments must be made in new technologies that increase the recyclability of solders in the E-waste while collection programs must be improved.

Important for the tin supply chain are the relations between China and the US, since the former is the biggest producer and consumer of tin while the latter is the biggest semiconductors producer. A possible economic decoupling between the two countries would have effects on the tin supply chain and would profoundly change it.

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Appendices

Appendix A

Important in attracting new investment is a report of the reserve and resource of a new mineral deposit, but these reports are commonly adapted from the country or company that is making the report. The Committee for Mineral Reserves International Reporting Standards (CRIRSCO) is an inter-organizational body that brings together international reporting standards around the globe. Australasia, Canada, Chile, Europe, Mongolia, Russia, South Africa, and the United States of America have been members for some time, while India and Kazakhstan have recently joined. China and Turkey are looking to join in the future.

CRIRSCO produced a set of agreed standard definitions for the reporting of Exploration Results, Mineral Resources and Mineral Reserves. These definitions can be found below:

"A 'Mineral Resource' *is a concentration or occurrence of material of economic interest in or on the Earth's crust in such form, quality, and quantity that there are reasonable prospects for eventual economic extraction"*

"A 'Mineral Reserve' *is the economically mineable part of a Measured and/or Indicated Mineral Resource."*

A study conducted by the International Tin Association (ITA) in 2019, showed that the global resource of Tin is approximately 15,4 Mt, of which 6,0 Mt (38.9%) was CRIRSCO-compliant. From this number, the tin reserves are estimated to be 5,5 Mt of which less than one third (1,6 Mt) was reported to CRIRSCO standards. The CRIRSCO fraction will increase in the following years when china will join. (ITA 2020)

Comparing these numbers with the annual consumption of Tin in 2019, 305,8 kt, present global tin reserves will last a minimum of 18,0 years, while resources will last a minimum of 50,4 years. The shares of global resource and reserve are shown in figure 22.

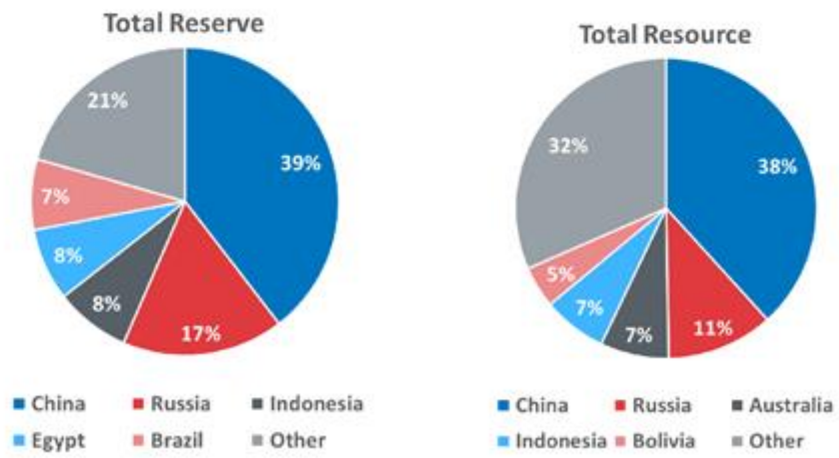

Figure 22: shares of resource and reserves worldwide (ITA 2020a)

The Analysis showed that there is potentially enough supply for the upcoming years, although the real situation is more complicated. Understanding the real content of Tin in a new reserve and its possible revenue is very complicated because the economy is what drives new explorations. During these, a cut-off grade is used to determine the minimum metal content that is economical to extract. There are different methods to calculate the cut-off grade. From that calculation, which goes beyond the scope of this thesis, the current metal price shows to be very important in determining new investments. High prices reduce the cut-off grade and bring new investments, while low prices work the other way around. Given this general rule, cut-off grade varies greatly also depending on different variables such as by-products prices and inputs costs. These economic assumptions could lead to an underestimation or overestimation of the reserve. (ITA 2020a)

Tin extraction and processing

A report of the USGS of 2017 describes in detail the refined tin production process, from cassiterite deposit to the final product. Cassiterite can be found in two different types of deposits: alluvial or hard-rock mines. Alluvial deposits are common in southeast Asia, where the cassiterite is normally dredged by either high-pressure water or an excavator. Hard-rock mining is normally situated underground and the mineral is extracted by rock shredding. After the extraction, the ore is concentrated through a combination of processes that result in cassiterite with a concentration of 70% of Tin. The mineral is then smelted in the presence of carbon at a temperature of 1.200 °C, which reduces the cassiterite in Tin metal and releases carbon dioxide.

The next step in the tin production is the refining process, usually carried out at the smelter site. Here the Tin is heated up just above its melting point, which allows impurities to remain solid and drop from the tin in the liquid state. In order to refine tin, two processes are available: heat or electrolytic treatment. Heat treatment is the more common but produces less pure tin, it uses a furnace and it is based on carbon-based fuel as a heat source. The Electrolytic process is more expensive but can provide pureness of tin close to 100%, it consists of running electricity through electrodes in order to heat up the tin concentrate until the melting point.(Schuyler 2019)