Study on the review of the list of Critical Raw Materials

Critical Raw Materials Factsheets

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Raw Materials

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Contents

1. ANTIMONY

Key facts and figures

Material name and element symbol	Antimony, Sb	World / EU production (tonnes)[1]	42,833 / 0
Parent group	n.a.	EU import reliance[1]	100%
Life cycle stage /material assessed	Processing/ Sb metal	Substitution index for supply risk [SI(SR)][1]	0.93
Economic importance (EI) (2017)	4.3	Substitution Index for economic importance [SI(EI)][1]	0.91
Supply risk (SR) (2017)	4.3	End of life recycling input rate (EOL-RIR)	28%
Abiotic or biotic	Abiotic	Major global end uses in 2014	Flame retardants (43%) Lead-acid batteries (32%) Lead alloys (14%)
Main product, co-product or by-product	Main product or co or by product of Au, Pb, Zn	Major world producers[1] (Sb metal production)	China (87%) Vietnam (11%)
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] average for 2010-2014, unless otherwise stated.

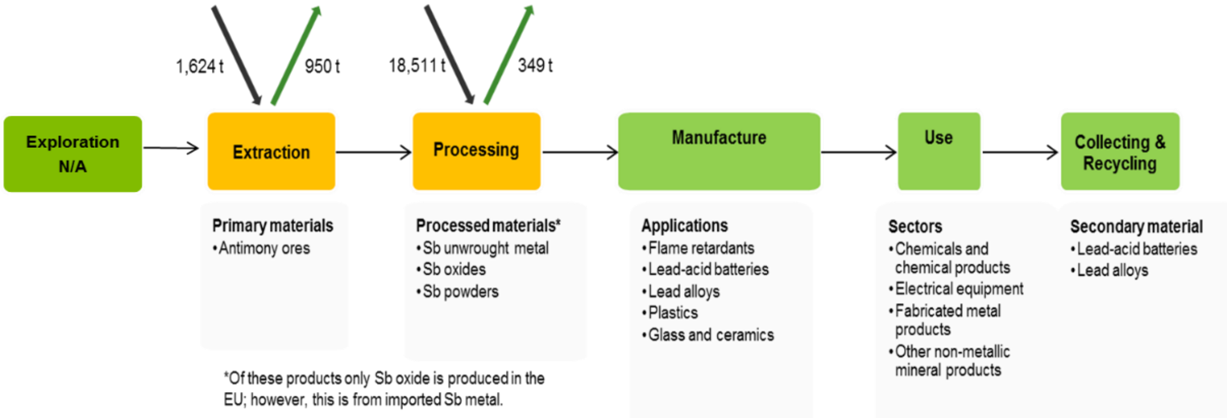

Figure 1: Simplified value chain for antimony

The orange boxes of the production and processing stages in the figure above suggest that activities are not undertaken within the EU. The black arrows pointing towards the extraction and processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

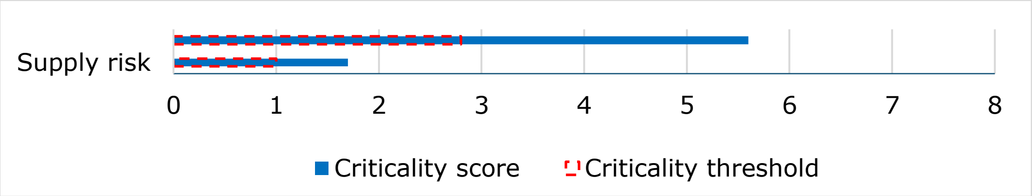

Figure 2: Economic importance and supply risk scores for antimony

1.1 Introduction

Antimony (chemical symbol Sb) is a soft, lustrous, silver-grey metalloid. It is stable in air at room temperature, but reacts with oxygen when heated to form antimony trioxide (Sb_2O_3). It has a relatively low melting point of 630°C and a density of 6.697 g/cm^3. Antimony is rare in the Earth's crust having a (upper)crustal abundance of only 0.4 ppm (Rudnick and Gao, 2003). Antimony is found in over 100 different mineral species, typically in association with elements such as mercury, silver and gold. The principal ore mineral of antimony is stibnite (Sb_2S_3). The main applications for antimony are as a flame retardant and in the manufacture of lead-acid batteries. It also has relatively minor uses in the production of plastics, glass and pigments. Antimony metal poses few environmental or human health problems; however, it has been suggested that antimony dusts and some antimony compounds can cause dermal irritation and respiratory-related problems.

Although trade data are available for antimony ores and concentrates the criticality assessment for antimony is based on the production and trade of unwrought antimony metal. This is because unwrought metal is the most significant form in terms of trade volume and therefore represents the most likely bottleneck in the EU supply chain. Primary extraction of antimony ores and concentrates does not take place in Europe, nor does the production of unwrought antimony metal. However, the EU does produce antimony trioxide (ATO). The EU is therefore entirely reliant on imports of unwrought antinomy metal to meet current demand from the European antimony trioxide industry. Apparent consumption of unwrought antimony metal in Europe (2010–2014) was on average about 18,200 tonnes per annum, the majority of which was used in the production of antimony trioxide primarily for the manufacture of flame retardants.

1.2 Supply

1.2.1 Supply from primary materials

1.2.1.1 Geological occurrence

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

Greenstone-hosted antimony deposits are of particular economically importance. They may be many tens of millions of tonnes in size and typically contain between 1.5 and 25% Sb_2S_3. These deposits typically comprise a stockwork of gold-antimony-quartz-carbonate veins hosted by metavolcanic and/or metasedimentary rocks. Carbonate replacement deposits are also found in some of these metasedimentary sequences (e.g. Xikuangshan, China), which are thought to form by hydrothermal alteration of the host material (Schwarz-Schampera, 2014).

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

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

1.2.1.2 Exploration

The Minerals4EU project identified that antimony exploration in Europe, in 2013, was primarily taking place in Portugal, Spain and Slovakia (Minerals4EU, 2015). However, according to Dail (2014) there are many more antimony prospects in other European countries, including France, Italy, Poland, Germany and the Czech Republic.

1.2.1.3 Mining, processing and extractive metallurgy

Antimony is extracted as a primary product from stibnite-bearing ores in some parts of the world (e.g. China), but also as a by-product of gold and base metal mining. Therefore, the mining methods employed to extract antimony will largely depend on the deposit type. For example, near-surface ore deposits may be exploited by open-pit mining methods, whereas deeply-buried ore bodies are likely to be mined underground by conventional mining methods.

Regardless of the mining method employed primary antimony ores are first crushed and milled, before the ore minerals are separated from the gangue (non-ore minerals) by physical (e.g. gravity) and/or chemical (e.g. froth flotation) separation techniques. Importantly, these separation techniques do not necessarily result in any chemical modification of the ores themselves. The particular process used depends on the composition and grade of the ore being mined.

Typically antimony concentrates are further refined by either pyrometallurgical methods, whereby concentrates are smelted in a high temperature furnace, or hydrometallurgical methods that rely on a combination of alkaline leaching and electrowinning. The choice of refining method will ultimately depend on the mineralogy and grade of the antimony concentrate (Schwarz-Schampera, 2014).

1.2.1.4 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of antimony in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[1], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for antimony. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for antimony, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable

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[1] www.crirsco.com

datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for antimony at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015). Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

World antimony known resources have been estimated at 5 million tonnes of contained Sb metal in 2011 (Bio Intelligence Service, 2015). Principal identified world resources are in Australia, Bolivia, China, Mexico, Russia, South Africa, and Tajikistan. Additional antimony resources may occur in Mississippi Valley-type lead deposits in the Eastern United States (USGS, 2016).

In Europe six countries are known to have antimony resources, including: France, Germany, Sweden, Finland, Slovakia and Greece. Most resources in Europe are based on historic estimates and are of little current economic interest. Data for these are also not reported in accordance with the UNFC system of reporting. Data for Germany are not reported at all because data collection in that country is the responsibility of sub-national level authorities (Minerals4EU, 2015).). Resource data for some countries in Europe are available in the Minerals4EU website (see Table 1) (Minerals4EU, 2014) but cannot be summed as they are partial and they do not use the same reporting code.

Table 1: Resource data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2014)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
France	None	26,250	t	Metal content	Historic Resource Estimates
Greece	UGSG	90	kt	2.5%	Indicated
Serbia	Russian Classification	2.83	Mt	2.34%	A
Slovakia	None	3.206	Mt	1.71% sub-economic	-
Finland	none	0.3	Mt	0.41%	Historic Resource Estimates
Sweden	Historic	17	Mt	0.06%	Historic Resource Estimates

According to the USGS world antimony reserves amounts 2 million tonnes and are concentrated in three countries, with China (48 %), Russia (18 %) and Bolivia (16 %) accounting for more than 80 % of global production - see Table 2 (USGS, 2016). It is worth noting that sizeable reserves are also found in Thailand (525,000 tonnes) and Kyrgyzstan (385,000 tonnes) (Schwarz-Schampera, 2014). Reserve data for some countries in Europe are available in the Minerals4EU website only for Serbia (0.085 Mt of Sb ores at 2.95% of metal contained, anticipated reserves Z3).

Table 2: Global reserves of antimony in year 2016 (Data from USGS, 2016).

Country	Antimony Reserves (tonnes)	Percentage of total (%)
China	950,000	48
Russia	350,000	18
Bolivia	310,000	16
Australia	140,000	7
United States	60,000	3
Tajikistan	50,000	3
South Africa	27,000	1
Other countries	100,000	5
World total (rounded)	*2,000,000*	*100*

1.2.1.5 World production

1.2.1.5.1 World mine production

The world mine production of antimony is about 175,500 tonnes on average in 2011-2014 (BGS, 2015). About 86 % of global antimony extraction takes place in only three countries, China (78 %), Russia (4 %) and Tajikistan (4 %) (Figure 3). A minor amount of antimony is also extracted in countries such as Bolivia, Kyrgyzstan and South Africa, and as a by-product of gold and base metal refining in Australia, Peru, Mexico, Canada and the United States of America; however, it is difficult to fully quantify the amount of antimony recovered as a by-product of metal refining (Schwarz-Schampera, 2014). There is currently no primary extraction of antimony ores and concentrates in the EU.

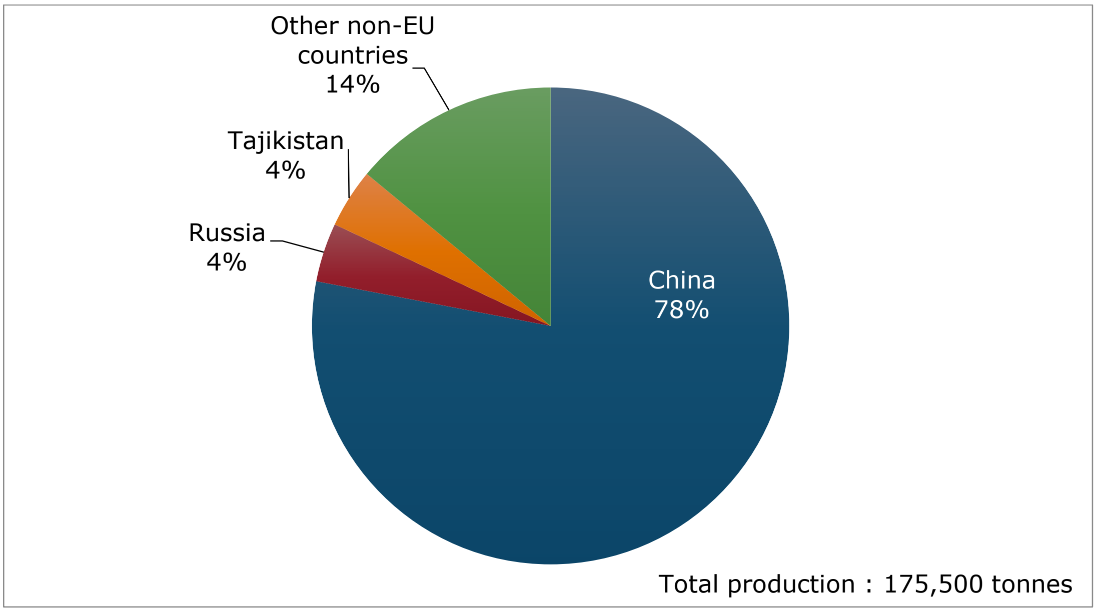

Figure 3: Global mine production of antimony, average 2010–2014 (Data from BGS, 2015)

1.2.1.5.2 World refinery production

The production of unwrought antimony metal (about 42,000 tonnes) is similarly heavily concentrated, with China and Vietnam accounting for about 98 % of global production. Small amounts are also produced in Russia, Kyrgyzstan and Bolivia (Figure 4).

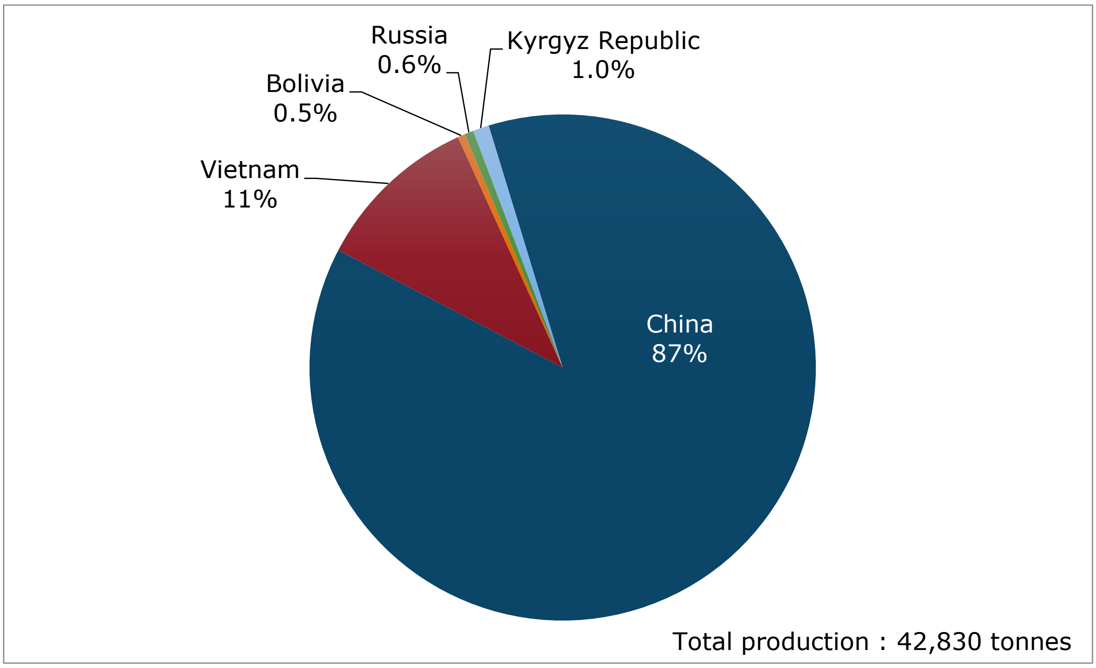

Figure 4: Global production of unwrought antimony metal, average 2010–2014 based on reconstructed trade data (Data from UN Comtrade database)

1.2.2 Supply from secondary materials

The End of Life (EoL) recycling rate for antimony is estimated to be between 1 and 10 % (UNEP, 2013). However, the Raw Materials Supply Assessment (RMSA) study, undertaken by BIO by Deloitte in 2015, suggests that the EoL recycling rate for antimony is as high as 28 % (BIO by Deloitte, 2015). Secondary antimony is chiefly recovered from lead-acid batteries. Therefore the availability of secondary antimony is almost entirely dependent on the extent of lead recycling and the market conditions for lead and lead-acid battery scrap. Supply of primary antimony is heavily concentrated in only a few countries, meaning the recovery of secondary antimony is an important part of the supply chain in some countries, for example the United States of America, Japan, Canada and the EU. Antimony used in the manufacture of plastics and flame retardants is generally not recovered because antimony is dispersed in these products (Schwarz-Schampera, 2014). However, antimony could potentially be recovered from the bottom ash resulting from the incineration of some of these products at their end of life stage, but this currently does not appear to be economically viable (Caroline Braibant *pers. Comm.,* 2017).

1.2.3 EU trade

Antimony is traded in a number of forms (e.g. ores and concentrates, antimony trioxide (ATO) and unwrought antimony metal and powders). Primary antimony ores and concentrates are not extracted in the EU. Similarly, unwrought antimony metal is not produced in Europe. However, the EU is a significant producer of antimony trioxide, although this is largely produced from imported unwrought antimony metal, meaning the EU is heavily reliant on antimony metal imports for its supply. During the 2010–2014 period the EU imported just over 1,600 tonnes of antimony ores and concentrates; however, during the same period the EU imported almost three times as much ATO (ca. 5,900 tonnes) and more than ten times as much unwrought antimony metal (ca. 18,500 tonnes). The trade of antimony trioxide and unwrought antimony metal is dominated by China, which accounts for almost 65 % of European antimony trioxide imports and almost 90 % of European unwrought antimony metal imports (see Figure 5).

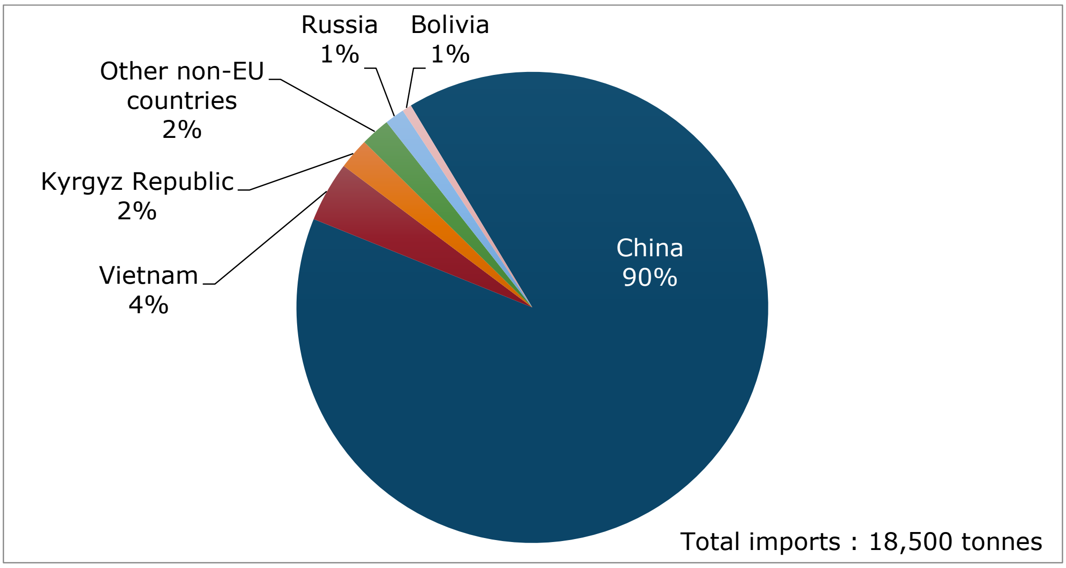

Figure 5: EU imports of unwrought antimony metal, average 2010-2014 (Data from Eurostat COMEXT database)

The majority of these imports end up in Spain, Belgium, France and Italy. Since 2010 imports of unwrought antimony have generally decreased from a high of ca. 23,000 tonnes in 2010 to ca. 17,000 tonnes in 2014. This decrease in import volumes is likely due to restriction of Chinese supply in 2010 and 2011, due to mine closures and export quotas. Exports of unwrought antimony metal from the EU have remained fairly constant over the 2010–2014 period (Figure 6).

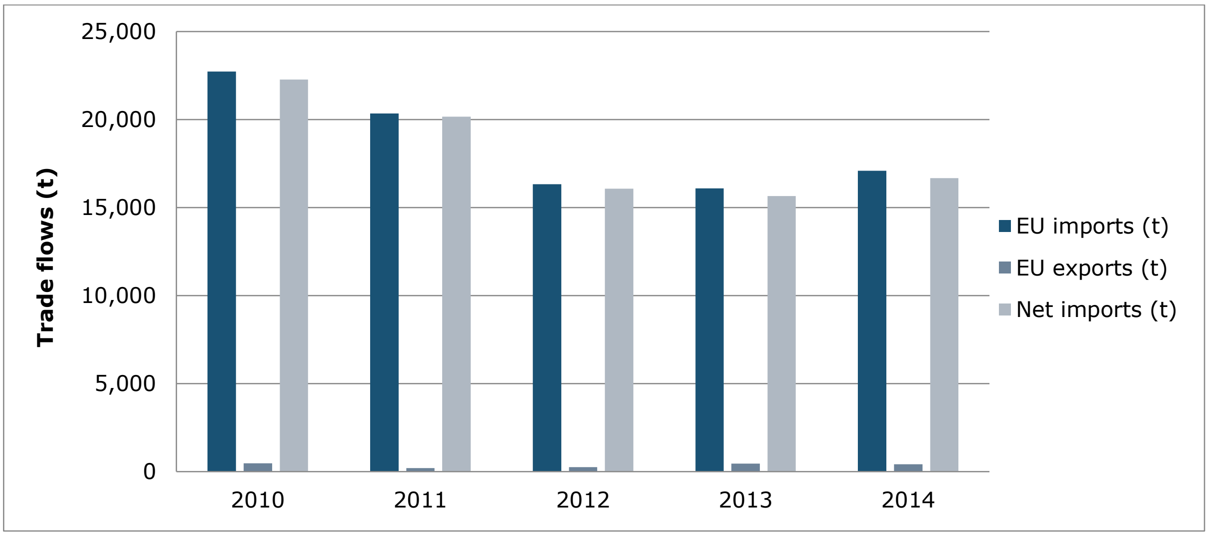

Figure 6: EU trade flows for unwrought antimony metal (Data from Eurostat COMEXT database)

1.2.4 EU supply chain

Primary antimony ores are not extracted in the EU. Unwrought antimony metal in not produced in the EU, meaning the EU is entirely reliant on unwrought antimony metal imports to meet demand. However, the EU does produce antimony trioxide, mainly in Belgium, France, Spain and Italy. The production of European ATO is heavily reliant on the availability of unwrought antimony metal and therefore on imports. Secondary antimony recovered from lead-acid batteries also contributes to the European antimony supply chain. It is difficult to quantify the volume of ATO that is actually produced in

Europe because data are unavailable via the Eurostat Prodcom database. However, it is assumed that flame retardants and the manufacture of PET plastics are the main end-uses of ATO in Europe.

There is currently an export quota placed on unwrought antimony metal and antimony trioxide exports from China. There is also an export tax of up to 25 % on these exports (OECD, 2016).

1.3 Demand

1.3.1 EU consumption

EU consumption of unwrought antimony metal was just over 18,000 tonnes per annum during the 2010–2014 period. However, none of this came from within the EU, which explains why the calculated import reliance figure is 100 % for unwrought antimony metal.

1.3.2 Applications/end-uses

Global end-uses of antimony in 2014 are shown in Figure 7 and relevant industry sectors are described using the NACE sector codes in Table 3.

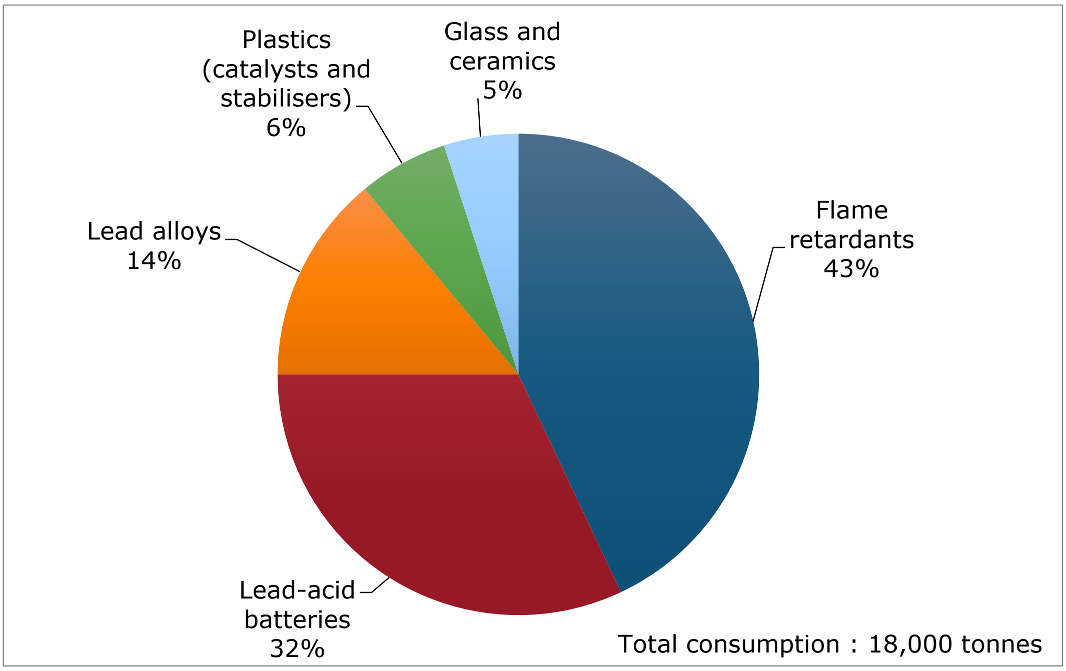

Figure 7: Global end uses of antimony. Figures for 2014. (Data from EC, 2014)

Approximately 43 % of antimony (in the form of antimony trioxide, or ATO) is used in the production of flame retardants. Antimony trioxide is not a flame retardant in itself but when combined with halogenated (i.e. brominated or chlorinated) flame retardant compounds it constitutes a highly-effective flame retardant synergist. Halogenated antimony compounds are effective dehydrating agents that inhibit ignition and pyrolysis in solids, liquids and gases. They also promote the formation of a char-rich layer on the substrate, which reduces oxygen availability and volatile-gas formation (Schwarz-Schampera, 2014). Antimony-based flame retardants are used in plastics, cable coatings, upholstered furniture, car seats, fabrics and household appliances (i2a, 2014).

Table 3: Antimony applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016c).

Application	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit NACE sector
Flame retardants	C20 - Manufacture of chemicals and chemical products	110,000	C2059 - Manufacture of other chemical products n.e.c.
Lead-acid batteries	C27 - Manufacture of electrical equipment	84,609	C2720 - Manufacture of batteries and accumulators
Lead alloys	C25 - Manufacture of fabricated metal products, except machinery and equipment	159,513	C2599 - Manufacture of other fabricated metal products n.e.c.
Plastics	C20 - Manufacture of chemicals and chemical products	110,000	C2016 - Manufacture of plastic in primary forms
Glass and ceramics	C23 - Manufacture of other non-metallic mineral products	59,166	C2311 - Manufacture of flat glass

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

The production of lead alloys accounts for about 14 % of global antimony use. For example, ternary Babbitt metals (i.e. tin-copper-antimony alloys) contain between 4–14% antimony and are used in the manufacture of low-load bearings used in the automotive sector. For applications that require heavy-load bearings (e.g. railway engines) quaternary Babbitt metals (i.e. tin-copper-lead-antimony alloys) are used instead. These alloys typically have higher antimony contents (between 8–15% antimony) and have greater fatigue resistance. The addition of antimony in Babbitt metals improves both corrosion resistance and anti-seizure properties. Britannia metal (i.e. tin-copper-antimony) and Pewter (i.e. tin-copper-antimony ± lead and bismuth) typically contain 7–20% antimony and are used in the manufacture of household and decorative items such as teapots, vases and lamp stands. Tin-lead-antimony solders are used extensively in the electronics industry (Schwarz-Schampera, 2014; CRM_InnoNet, 2015).

About 6 % of antimony, in the form of antimony trioxide (ATO), is used as a catalyst in the production of polyethylene terephthalate (PET), which is used in the manufacture of plastic bottles. It is also used as a heat stabiliser in polyvinyl chloride (PVC) (Schwarz-Schampera, 2014).

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

1.3.3 Prices

United States antimony metal prices rose from about US$1,300 per tonne in 2004 to a high of over US$14,000 per tonne in 2011. Prices have been declining over the last five years from the peak in 2011 to just under US$7,000 per tonne in 2015 (Figure 8). The peak in antimony price in 2010–2011 occurred in response to Chinese mine closures and the introduction of Chinese export quotas (Schwarz-Schampera, 2014). Antimony prices have generally declined since 2011 because of reduced global consumption. This is in response to substitution of antimony where economic performance would drive the choice of material, following supply disruption and associated price increases (USGS, 2014).

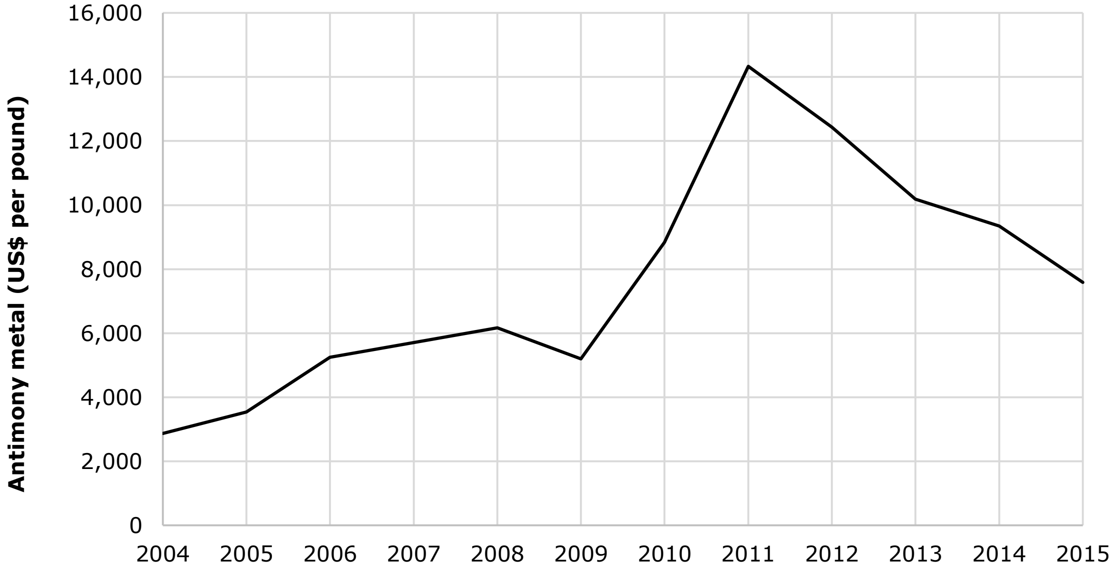

Figure 8: United States antimony metal price trend. (Data from USGS, 2015; 2016)

1.4 Substitution

According to published information (e.g. CRM_InnoNet) antimony is reasonably easy to substitute in some of its applications. For example, compounds of chromium, tin, titanium, zinc and zirconium can substitute for antimony in the manufacture of pigments and glass. However, in its main application (i.e. as a flame retardant) antimony is much harder to substitute. Compounds such as alumina trihydrate, magnesium hydroxide and zinc borate may substitute for antimony in flame-retardant materials, but their performance is inferior to antimony-based flame retardants. Various combinations of cadmium, barium, calcium, lead, tin, zinc and germanium may substitute for antimony in the production of plastics (e.g. as stabilisers or catalysts), but there is typically a price penalty in moving away from the use of antimony in these applications. Potentially there are several metals that may substitute for antimony in the production of lead alloys (e.g. cadmium, calcium, selenium, tin and copper); however, assuming 1:1 substitution in alloys is overly simplistic, for the simple reason that the properties of a given alloy are not controlled by a single metal, but rather by several metals. In addition each metal may produce a range of effects in the alloy (Schwarz-Schampera, 2014); CRM_InnoNet, 2015).

Any substitution would be associated with a price and/or performance penalty. In general there appears to be little economic or technical incentive to substitute antimony in its principal applications.

1.5 Discussion of the criticality assessment

1.5.1 Data sources

Production data for unwrought antimony metal was based on trade data from the UN Comtrade database, assuming that Chinese and Vietnamese exports account for more than 95 % of global production (Michael Schmidt *pers. comm.,* 2016). EU trade data were taken from the Eurostat COMEXT online database (Eurostat, 2016) using the Combined Nomenclature (CN) code 811 010 (unwrought antimony metal and powders). Data were averaged over the five-year period 2010–2014 inclusive. Other data sources used in the assessment are listed in section 1.7.

1.5.2 Calculation of economic importance and supply risk indicators

The calculation of Economic Importance (EI) was based on the 2-digit NACE sectors shown in Table 3. For information about the application share of each sector see section 1.3.2. Figures for value added were the most recently available at the time of the assessment (i.e. 2013) and are expressed in thousands of Euros. The supply risk was assessed on unwrought antimony metal using both the global HHI and the EU-28 HHI as prescribed by the revised methodology.

1.5.3 Comparison with previous EU criticality assessments

A revised methodology was introduced in the 2017 assessment of critical raw materials in Europe and both the calculations of economic importance and supply risk are now different; therefore the results with the previous assessments are not directly comparable. The results of this review and earlier assessments are shown in Table 4.

Table 4: Economic importance and supply risk results for antimony in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Antimony	5.84	2.56		7.07	2.54		4.3	4.3

The economic importance of antimony has reduced between 2014 and 2017 due to the change in methodology. The value added in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a 'megasector', which was used in the previous assessments. The economic importance result is therefore reduced. The supply risk score is higher compared to the previous assessments, which is due to the revised methodology and the way the supply risk is calculated. Therefore, differences between the assessment results are largely due to changes in methodology and the form of the commodity that has been assessed. The most recent assessment was based on the production and trade of unwrought antimony metal rather than the extraction and trade of antimony ores and concentrates as was done on previous EC criticality assessments.

1.6 Other considerations

Halogenated antimony trioxide is still highly regarded as an effective flame retardant and therefore this is likely to remain the principal market for antimony in the EU, although its use in the manufacture of PET plastics is likely to increase. The continued use of ATO in flame retardants is also likely to be driven by increasingly stringent fire regulations. The use of antimony in lead-acid batteries is perhaps less certain: it may increase if developing countries continue to grow their automotive sectors, but the antimony-lead alloys used in the production of these batteries are being increasingly substituted on environmental grounds in many developing nations (Schwarz-Schampera, 2014).

Table 5: Qualitative forecast of supply and demand of antimony

Material	Criticality of the material in 2017		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Antimony	x		+	+	+	+	+	+

A range of antimony-bearing substances fall within the EU's Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) which came into force in 2007 albeit with a phased implementation.

1.7 Data sources

1.7.1 Data sources used in the factsheet

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1.8 Acknowledgments

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2. BARYTE

Key facts and figures

Material name and chemical formula	Baryte (Barytes, Barite) $BaSO_4$	World/EU production (tonnes)[1]	9,200,000/117,000
Parent group (where applicable)	N/A	EU import reliance[1]	80%
Life cycle stage assessed	Extraction/ Ore	Substitution index for supply risk [SI (SR)][1]	0.94
Economic importance (EI) (2017)	2.9	Substitution Index for economic importance [SI(EI)][1]	0.93
Supply risk (SR) (2017)	1.6	End of life recycling input rate	1%
Abiotic or biotic	Abiotic	Major end uses in the EU[1]	Weighting agent (60%), Filler (30%), Chemicals (10%)
Main product, co-product or by-product	Main product	Major world producers[1]	China (44%), India (18%), Morocco (10%)
Criticality results	2011	2014	2017
	Non-critical	Non-critical	Critical

[1] average for 2010-2014, unless otherwise stated.

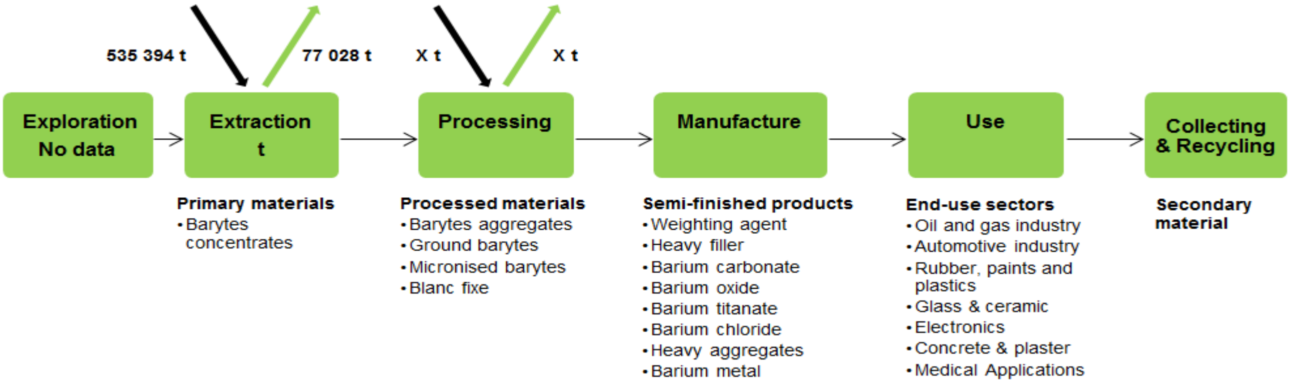

Figure 9: Simplified value chain for baryte

Green boxes represent stages of the supply chain which take place in the EU-28. The black and green arrows represent imports and exports to and from the EU respectively. EU reserves are displayed in the exploration box.

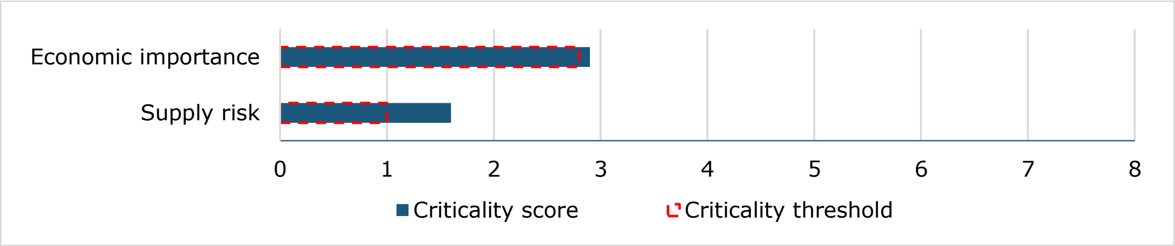

Figure 10: Economic importance and supply risk scores for baryte

2.1 Introduction

Baryte (or barite) is a naturally occurring barium sulphate mineral ($BaSO_4$). It is inert, non-toxic and almost insoluble in water. Baryte has a high density of 4.5 g/cm^3, high fusion point (1,580°C) and brightness, and a low oil adsorption. Baryte is white, grey or black in colour depending on the presence of any impurities. It is mainly used as a weighting agent in drilling fluids by the oil and gas industry. Baryte and barium compounds are also used as a fillers or additives in industrial products including rubber, paint, ceramics and glass, high density concrete and plaster, dielectrics, medical application.

2.2 Supply

2.2.1 Supply from primary materials

2.2.1.1 Geological occurrence

Baryte deposits are classified into three major types: stratiform, vein, and residual deposits. Stratiform (or bedded) deposits are the dominant source of industrial baryte. They are formed by the precipitation of baryte at or near the seafloor of sedimentary basins (sedimentary-exhalative or ‘SEDEX’ deposits). These are often associated with volcanic-hosted massive sulphide mineralization (mainly zinc-lead). Individual beds are massive to laminated, fine-grained and may contain from 50% to 95% baryte which is often greyish to dark-grey in appearance. In veins deposits, baryte forms by precipitation from hydrothermal fluids or deep-seated brines in faults, fractures and cavities. This type of baryte varies in colour from white to yellowish and is often iron-stained. Residual deposits are formed by the dissolution of the host rock of the stratiform or vein deposits, leaving irregular masses of baryte in a clay matrix (BGS, 2005; NSW Department of Industry, 2009).

2.2.1.2 Mining, processing and extractive metallurgy

Baryte is extracted by both surface and underground mining, generally followed by simple physical processing – crushing, grinding, and heavy media separation – to remove gangue. Flotation is sometimes necessary to upgrade the baryte for use in filler or chemical applications, but it is often not preferred for oil-well applications (Huxtable, 2017). Bedded baryte deposits are commercially the most significant because of their large size and more consistent grades. They can be exploited by large-scale open pit methods, followed by relatively simple processing. Mining vein deposits can be difficult and expensive because they have complex geometry. These deposits are generally smaller than the stratiform deposits and are often extracted from surface or underground as a co-product of lead or zinc mining. Residual deposits are shallow enough to be worked by opencast method (Scogings, 2014).

2.2.1.3 Resources and reserves

There is no single source of comprehensive evaluations of resources and reserves that apply the same criteria to deposits of baryte in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by

application of the CRIRSCO template[2], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for baryte. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for baryte, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for baryte at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2014). Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

The USGS (2016) estimated around 740 million tonnes of (identified) resources and 380 million tonnes of reserves, of which China and Kazakhstan would account for half (Table 6).

Table 6: Global reserves of baryte in year 2015 (Data from USGS, 2016)

Country	**Estimated Baryte Reserves (tonnes)**	**Percentage of total (%)**
China	100,000,000	26
Kazakhstan	85,000,000	22
Turkey	35,000,000	9
India	32,000,000	8
Iran	24,000,000	6
USA	15,000,000	4
Morocco	10,000,000	3
Mexico	7,000,000	2
Pakistan	1,000,000	0.3
Other countries	66,000,000	17
World Total (rounded)	*380,000,000*	*100*

Resource/Reserve data for some countries in Europe are available in the Minerals4EU website (Minerals4EU, 2014) but cannot be summed as they are partial and they do not all use the same reporting code (Table 7 and Table 8).

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[2] www.crirsco.com

Table 7: Resource data for the EU compiled in the European Minerals Yearbook (Minerals4EU, 2014)

Country	Reporting code	Quantity	Unit	Code Resource Type
Czech Republic	National reporting code	0.57	Mt	Potentially economic
France	None	8.8 ($BaSO_4$)	Mt	Historic Resource Estimate
Hungary	Russian Classification	86	Mm^3	C2
Ireland	None	1.65	Mt	Historic Resource Estimate
Italy	None	3.5	Mt	Historic Resource Estimate
Poland	National reporting code	5.66	Mt	A+B+C1+C2
Serbia	JORC	1	Mt	Total
Slovakia	None	3.45	Mt	Verified (Z1)
Spain	None	9.99	Mt	Historic Resource Estimate
United Kingdom	None	22	Mt	Total

Table 8: Reserve data for the EU compiled in the European Minerals Yearbook (Minerals4EU, 2014)

Country	Reporting code	Quantity	Unit	Code Reserve Type
Croatia	National reporting code	185.9	kt	No code
Slovakia	None	633	kt	Verified (Z1)
Spain	N/A	Reserves known to exist		N/A
United Kingdom	N/A	Reserves known to exist		N/A

2.2.1.4 World mine production

World production is broadly linked to oil-well drilling activity and has increased from around 6.0 to 6.5 million tonnes/year in the early 2000s to 9.3 million tonnes in 2014. During the period 2010-2014, 9.2 million tonnes of baryte were produced on average annually in the world. China was the largest producer and accounted for 44% of global production, contributing 4 million tonnes/year on average over the period 2010-2014.

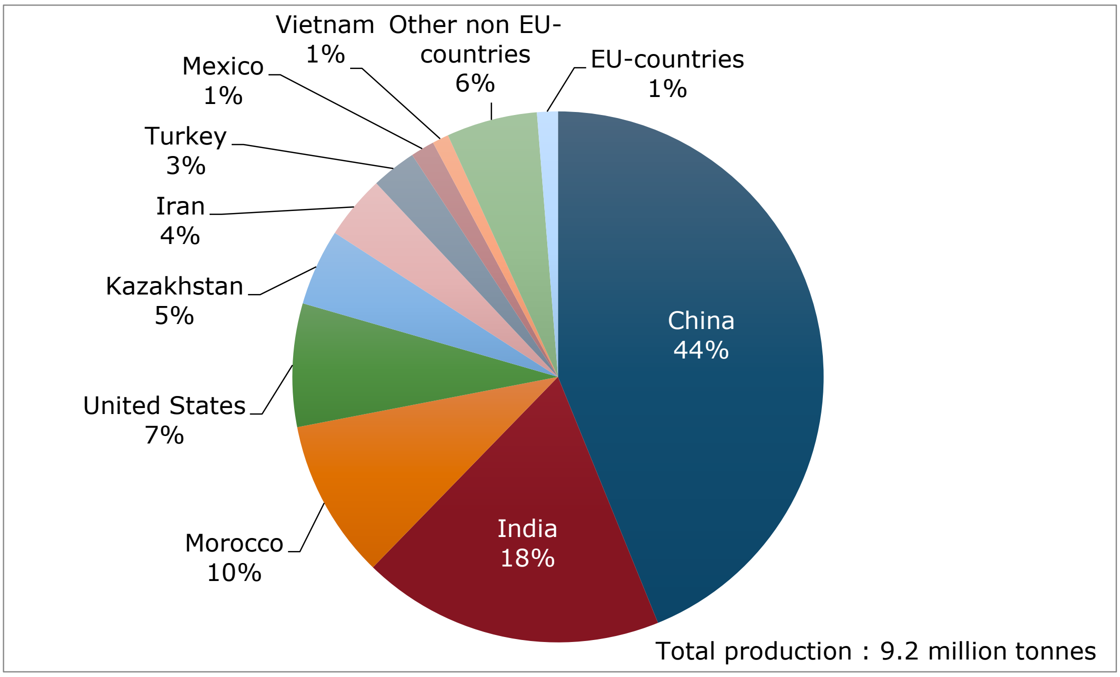


Figure 11: Global mine production of baryte, average 2010–2014 (Data from BGS, 2016)

India, Morocco, USA and Kazakhstan accounted for a further 41% altogether. India's sharp production decrease (-0.9 million tonnes) over the same period was more than offset by an increase in Morocco output (+0.4 million tonnes), China, Turkey, Iran and Thailand.

2.2.2 Supply from secondary materials

Baryte is barely re-used. As it is a small percentage of any drilling project total cost, little baryte is recycled for re-use beyond that recovered at a drill site (U.S. Department of the Interior & USGS, 2014). In most other applications, baryte is not recovered (fillers etc.) and cannot be recycled.

2.2.3 EU trade

Imports of baryte totalled 535,394 tonnes per year over the period 2010-2014. However, net imports declined sharply by 30% from 2010 to 2014 due to an important drop in UK imports according to Eurostat data (Figure 12).

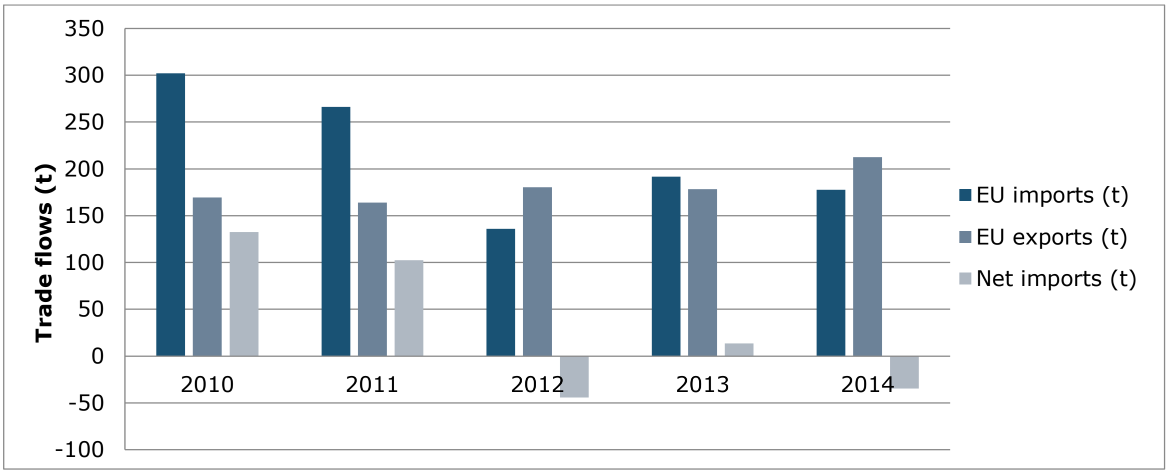


Figure 12: EU trade flows for baryte. (Data from Eurostat, 2016a)

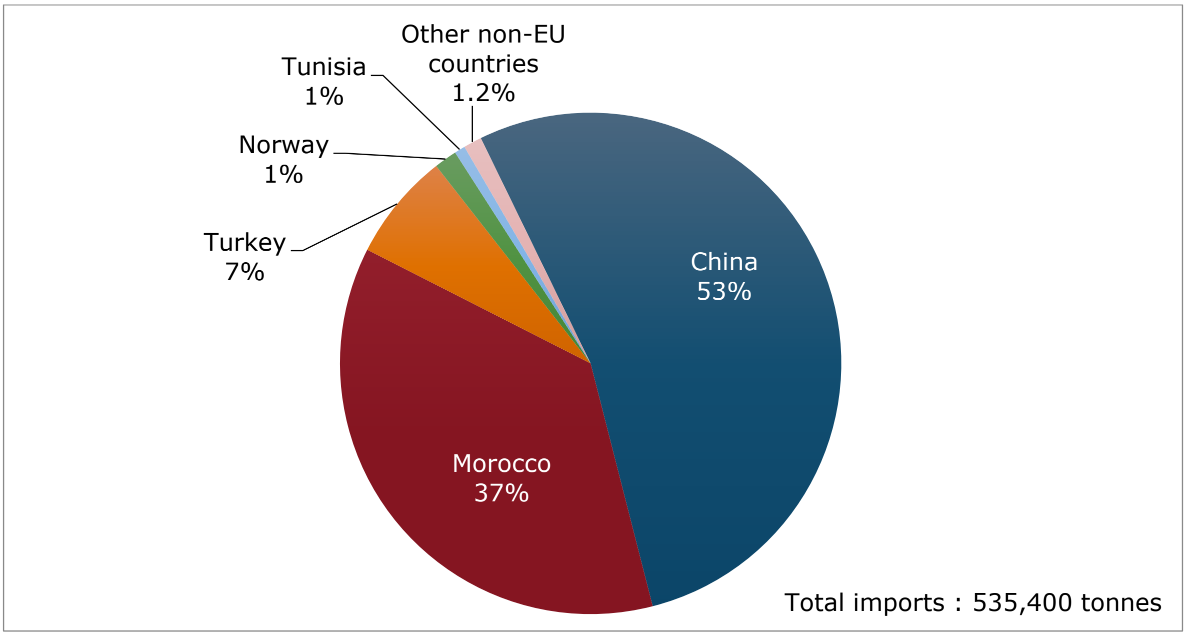


Figure 13: EU imports of baryte, average 2010-2014. (Data from Eurostat, 2016a)

China continued to be the largest EU supplier (Figure 13) but its share has steadily decreased from 61 % in 2010 to 53% in 2014, whereas Morocco and Turkey registered an increase in market share during this period (+6 % and +2%, respectively).

China and Morocco, the two main suppliers of the EU for baryte, have imposed export taxes less than 25% (OECD, 2016). Several EU free trade agreements are in place with other suppliers such as Turkey, Norway and Tunisia (European Commission, 2016).

2.2.4 EU supply chain

Baryte is extracted and processed into different products in the EU. Baryte production amounted to 116,964 tonnes/year on average, during the period 2010-2014, contributing 1.3% of the global production. Germany is the largest producer with almost half of the EU production (49%), followed by the UK (30%), Slovakia (17%) and Bulgaria (4%) (BGS, 2016). The EU production registered a 40% increase from 2010 to 2014 thanks to an increase in Germany output (+26%) which reached 70,665 tonnes in 2014 and a new production in Bulgaria (about 20,000 t) (BGS, 2016). The EU was a net importer of baryte and its import reliance was estimated at 80%. Figure 14 presents the EU sourcing (domestic production + imports) for baryte.

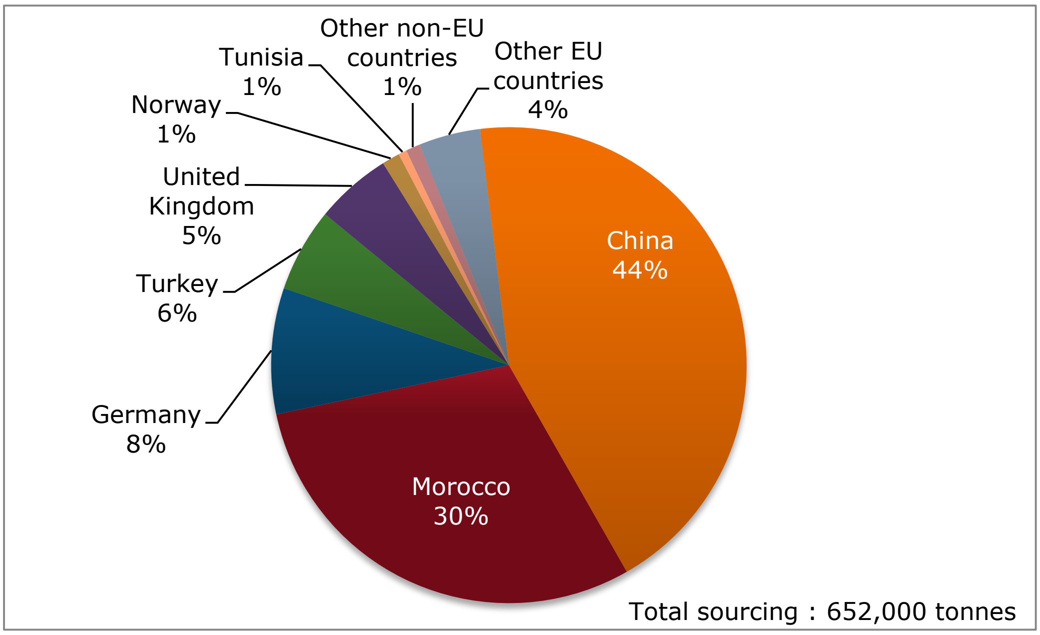


Figure 14: EU sourcing (domestic production +imports) of baryte, average 2010-2014. (Data from Eurostat, 2016a; BGS, 2016)

Plans to develop a baryte mine at Duntanlich, in Scotland, have been approved by local authorities in September 2016 (Duntanlich Mine, 2014). The Duntanlich deposit has a baryte resource in excess of 7.5 million tonnes.

European processors of baryte are into added-value markets so a significant proportion is an export earner (The Barytes Association, 2017).

2.3 Demand

2.3.1 EU consumption

The EU net consumption amounted to about 575,000 tonnes per year on average during the period 2010-2014.

2.3.2 End uses

Figure 15 presents the main uses of baryte in the EU.

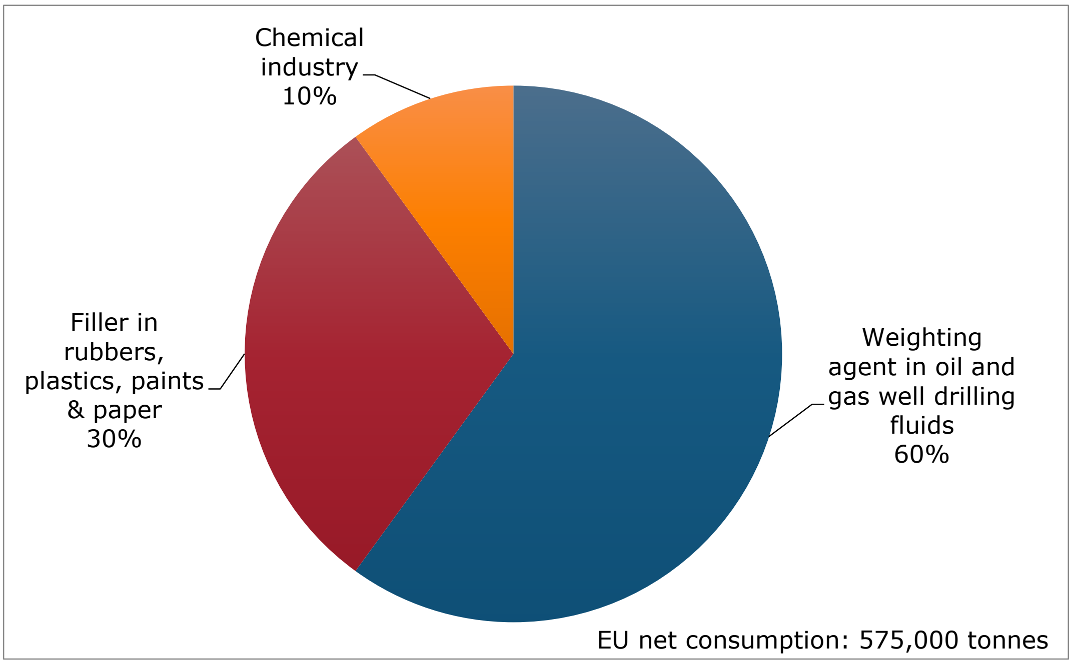


Figure 15: EU end uses of baryte. Average figures for 2010-2014. (Data from the Barytes Association, 2017)

Baryte is primarily used as a weighting agent in drilling fluids or "muds" for oil and gas wells where baryte high specific gravity assists in containing pressures and preventing blowouts. Ground baryte is combined with bentonite, water, and other materials to manufacture "mud" which is pumped down the drill hole. Drillings muds remove cuttings up to the surface while cooling and lubricating the drill bit (Schlumberger, 2013). In drilling muds the standard is the API (American Petroleum Institute) specification 13A 4.1 or 4.2.

Baryte is used as heavy filler in rubber, paint and plastics applications. It is used within the automotive industry mostly as a soundproofing material in moulded components, floor mats, and in friction products such as breaks and clutches pads. In the construction sector, baryte is used for the production of building materials or concrete with special features, like x-ray protection and sound insulation. Baryte is used as filler in asphalt, in high quality primers and anti-corrosion coatings, resistant to abrasion paint such as bituminous paints etc. (Mineralia, 2016).

In the chemical industry, baryte is used for the preparation of barium compounds, notably barium carbonate ($BaCO_3$) that is used in the production of special glass, as an ingredient in high-fire glazes, and in the brick and tile industry (BRGM, 2014). $BaCO_3$ is increasingly used in electronic components, such as electronics ceramics and capacitors. Barium meal (barium sulphate) is used in radiodiagnosis.

Baryte demand is linked to oil and gas-well drilling activity and around 80% of the baryte produced globally was used as a weighting agent for drilling fluids in oil and gas exploration. The filler and the chemical industry accounted for 10% each. The USA is the largest consumer, followed by China and the Middle East. Nearly 95% of the 3.4 tonnes of baryte sold in the USA in 2014 was for the oil industry (USGS, 2015). In contrast, the chemical and filler industries accounted for half of the European baryte consumption, the remaining going into oil and gas production (The Barytes Association, 2016).

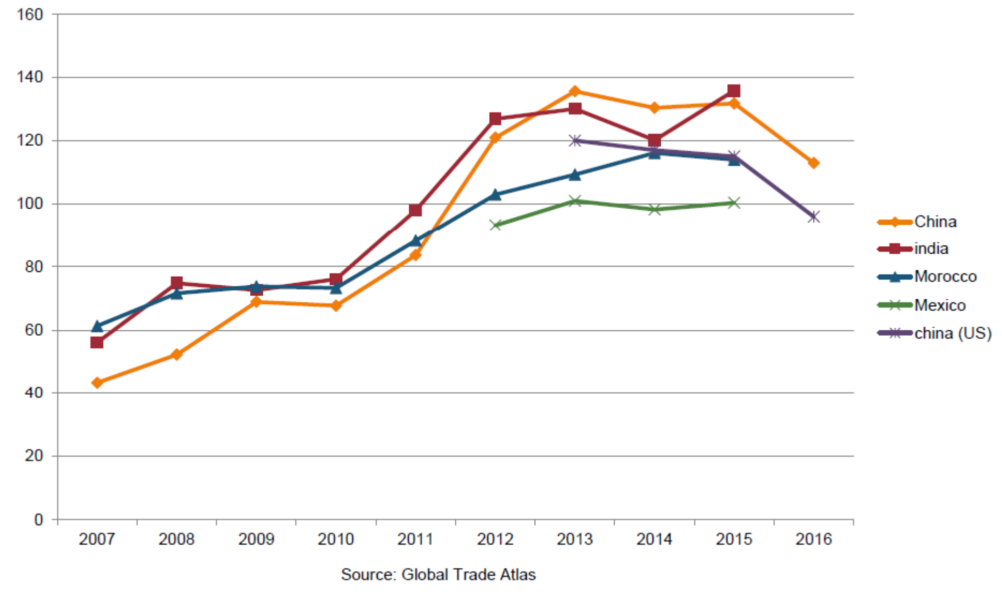
Corresponding industry sectors described using NACE sector codes (Eurostat, 2016b) are shown in Table 9.

Table 9: Baryte applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016b)

Applications	2-digit NACE sectors	Value added of sector (millions €)	4-digit NACE sectors
Weighting agent in oil and gas well drilling fluids	C23 - Manufacture of other non-metallic mineral products	59,166	C23.9.9 - Manufacture of other non-metallic mineral products n.e.c.
Filler in rubbers, plastics, paints	C22 - Manufacture of rubber and plastic products	82,000	C22.1.1 - Manufacture of rubber tyres and tubes; retreading and rebuilding of rubber tyres
			C22.2.1 - Manufacture of plastic plates, sheets, tubes and profiles
Chemical industry	C20 - Manufacture of chemicals and chemical products	110,000	C20.1.3 - Manufacture of other inorganic basic chemicals

2.3.3 Prices

Baryte prices depend on the amount of processing needed which is determined by the end-use and the quality required. Drilling grade baryte attracts the lowest prices. Filler applications command higher prices following physical processing by grinding and micronising, and there are further premiums for whiteness and brightness and colour (The Barytes Association, 2016).



Source: Global Trade Atlas

© THE BARYTES ASSOCIATION

Figure 16: Baryte prices (US$/t FOB) from January 2007 to March 2016 (Courtesy of The Barytes Association)

Prices for Chinese drilling grade baryte have decreased over the past five years, from US$131-135/tonne FOB China in 2012 to US$85-90/t in 2016 (Figure 16). This is largely due to the decline in US demand as a consequence of lower oil drilling activity in response to weaker oil prices. Chinese white baryte prices had been relatively stable during the period 2010-2014, due to limited production. The 2015-2016 price decrease is partly due to the depreciation of Chinese yuan against US dollar (Industrial Minerals, 2016).

2.4 Substitution

Substitutes for baryte used as a weighting agent for the oil and gas industry include hematite (Fe_2O_3), ilmenite ($FeTiO_3$), calcium carbonate ($CaCO_3$), but they are economically less attractive. Baryte has currently over 99% of the market. Hematite has a higher density and can be used to reduce solids percentage for rheology control, and ilmenite can be used when drilling activities take place close to a cheap supply source (Schlumberger, 2014; Huxtable, 2016).

For fillers, the main substitutes are calcium carbonate and clays (kaolin, talc) which are widely used for general purpose fillers where quality or technical considerations are less stringent. They do not match quality aspects for heaviness, sound proofing and radiation shielding.

There are various acceptable substitutes for barium carbonate in several applications in the chemical sector. Strontium carbonate is sometimes used as a substitute in ceramic glaze. There is no alternate for barium carbonate in dielectrics and no safe substitute for medical applications.

2.5 Discussion of the criticality assessment

2.5.1 Data sources

Production data for baryte are from BGS (2016). Trade data were extracted from the Eurostat Easy Comext database (Eurostat, 2016a). Data on trade agreements are taken from the DG Trade webpages, which include information on trade agreements between the EU and other countries (European Commission, 2016). Information on export restrictions are derived from the OECD Export restrictions on the Industrial Raw Materials database (OECD, 2016).

For trade data, the Combined Nomenclature CN8 code 25111000 'Natural barium sulphate (baryte)' has been used.

2.5.2 Economic importance and Supply Risk Calculation

The calculation of economic importance (EI) was based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 9). The value added data correspond to 2013 figures. The calculation of the Supply Risk (SR) was carried out at the extraction stage (i.e. baryte ore) of the life cycle, using both the global HHI and the EU-28 HHI.

2.5.3 Comparison with previous EU assessments

A revised methodology was introduced in the 2017 assessment of critical raw materials in Europe and both the calculations of economic importance and supply risk are now different, therefore the results with the previous assessments are not directly comparable. The results of the 2011, 2014 and 2017 assessments are shown in the following table.

Table 10: EI and SR Economic importance and supply risk results for baryte in the assessments of 2011, 2014 and 2017 assessments (European Commission, 2011; European Commission, 2014)

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Baryte	3.7	1.7		2.8	1.7		2.9	1.6

The shift to a lower Economic Importance (EI) score which is expected when applying the revised methodology based on 2-digit NACE sector instead of 'megasector' in the previous assessments has been cancelled out in this current assessment by using end-use sectors on the European market instead of the US market. The calculation of Economic Importance (EI) in the 2014 assessment was based on applications market share in the USA (weighting agent in oil and gas well drilling fluids: 95%; fillers and chemical industry: 5%) instead of European end uses of baryte.

2.6 Other considerations

2.6.1 Forward look for supply and demand

The consumption in drilling "mud" - and therefore of baryte - fluctuates from year to year, as it is dependent on the amount of exploration drilling for oil and gas, which in turn depends on oil and gas prices. World baryte production fell to 7.5 million tonnes in 2015 as a result of low oil prices and reduced drilling activity (The Barytes association, 2017). No reliable demand and supply forecasts for the next 5, 10 and 20 years have been obtained from industry experts or literature. However general trends on the world baryte market are expected to follow global energy trends during the next 20 years.

According to the OPEC (2016), total primary energy demand is set to increase by 40% to 2040, with combined oil and gas expected to supply around 53% of the global energy demand by 2040. There is a projected major shift towards gas and renewables at the expense of coal. The majority of demand growth is expected to come from natural gas, at some 2.1% p.a. growth to 2040. This is expected to drive the global baryte market growth over the forecasted period. China, which is currently the largest baryte supplier to world markets, could require more baryte for its own needs and begins to compete for baryte supply (Willis, 2017).

Increasing demand in the construction sector and the automotive industry in the developing countries will also support baryte demand in coming years (see Table 11).

Table 11: Qualitative forecast of supply and demand for baryte

Material	**Criticality of the material in 2017**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Baryte	x		+	+	+	+	+	+

2.6.2 Environmental and regulatory issues

The naturally occurring mineral baryte is not subject to EU REACH regulations (ECHA, 2017). However the re-precipitated blanc-fixe (barium sulphate) and also the barium salts are subject to REACH.

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2.8 Acknowledgments

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3. BERYLLIUM

Key facts and figures

Material name and Element symbol	Beryllium, Be	World/EU production (tonnes)[1]	320 / 0
Parent group (where applicable)	n/a	EU import reliance[1]	n/a
Life cycle stage/material assessed	Extraction/ Be ores	Substitute index for supply risk[1] [SI (SR)]	0.99
Economic importance (EI) (2017)	3.9	Substitute Index for economic importance[1] [SI(EI)]	0.99
Supply risk (SR) (2017)	2.4	End of life recycling input rate	0%
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Electronic & tele-communications equipment (42%), Transport and Defence (44%), Energy applications (8%), Industrial components (6%)
Main product, co-product or by-product	Main product (from bertrandite); By-product (from beryl)	Major world producers[1]	*Ores*: US (90%), China (8%) *Refined*: US (75%), Japan (25%)
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] Data for 2012;

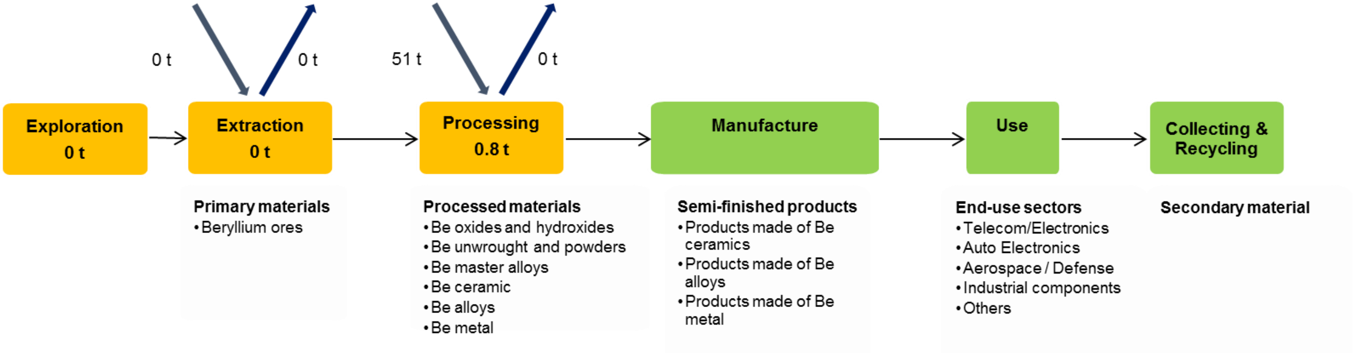

Figure 17: Simplified value chain for beryllium

The orange boxes of the production and processing stages suggest that activities are not undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

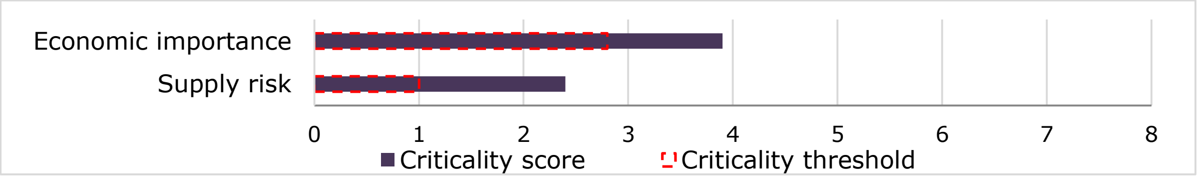

Figure 18: Economic importance and supply risk scores for beryllium

3.1 Introduction

Beryllium (Be, atomic number 4, formerly also known as glucinium) is an alkaline metal that occurs naturally only in combination with other elements. Beryllium is a light, bluish-white, shiny, hard and brittle metal with hexagonal-close-packed structure. A very low density combined with strength, high thermal stability and conductivity, flexural rigidity and resistance to acids make beryllium a useful material for structural parts that are exposed to great inertial or centrifugal forces, in aerospace and defence applications (European Commission, 2014).

After extraction, beryllium ore is processed into beryllium oxides and hydroxides, master alloys, beryllium unwrought and powders that are used to produce mainly of Be alloys, metals and ceramics (Bio Intelligence Service, 2015). Then, these Be products are used in finished products in various applications such as electronic equipment, road transport, moulds for industry, etc. (Bio Intelligence Service, 2015). Its main uses in the EU and in the world are electronic and telecommunications equipment, transports and defence components, industrial components and energy applications notably. Because of the toxicity of inhaled beryllium-containing dusts causing berylliosis, a chronic life-threatening allergic disease, industrial risk mitigation measures are implemented (European Commission, 2014).

All quantities are provided in Be content.

3.2 Supply

3.2.1 Supply from primary materials

3.2.1.1 Geological occurrence

Beryllium is a relatively rare element with a concentration of about 2.8-3 ppm (0.0003%, 5th tier) in the earth's crust, and 2.1 ppm in the uppercrust (Rudnick, 2003). Nevertheless it is concentrated in some minerals, predominantly in beryl and bertrandite (BeST, 2016b; European Commission, 2014).

Until the late 1960s the only beryllium mineral commercially exploited was beryl ($Be_3Al_2Si_6O_{18}$). Beryl contains between 3 and 5% of Be but the material is harder than bertrandite ($Be_4Si_2O_7(OH)_2$) leading to difficulties to refine to beryllium. Today the most important commercial beryllium mineral is bertrandite (over 95% of mining operations for beryllium) which is extracted from ores containing 0.2-0.3-1.5% beryllium. Beryllium extracted from bertrandite ore is a main product although beryllium extracted from beryl is a byproduct of small scale emerald gemstone mining operations in Brazil, Argentina and other countries in South America and Africa (BeST, 2016b).

3.2.1.2 Resources and reserves of beryllium

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of beryllium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[3], which is also consistent with the United Nations

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[3] www.crirsco.com

Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for beryllium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for beryllium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for beryllium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

World resources and reserves are respectively estimated as about 150,100 tonnes and 23,400 tonnes of Be content (Bio Intelligence Service, 2015). Both US resources and reserves account for 65% of the global estimates (Bio Intelligence Service, 2015), in only one deposit (Spor Mountain) (BRGM, 2016). No information is available for the breakdown of world reserves by country.

The Minerals4EU project reports no data about beryllium resources and reserves in the EU (Minerals4EU, 2014). However, according to experts, there are no reserves of beryllium in Europe and very limited resources (about a dozen of tonnes) (Bio Intelligence Service, 2015). There are known resources of beryllium, in the form of beryl crystals, usually found in a matrix of granitic pegmatite rock, in several locations in Europe, notably the Bordvedaga deposits at Rana in the north of Norway, with smaller deposits in Germany, Czech Republic and Ireland (Bio Intelligence Service, 2015). According to BRGM, there are some known resources in France in 6 deposits, including one evaluated at 2.4 ktonnes of contained beryllium (BRGM, 2016).

Investment in EU for exploration of new Beryllium ores is less than 1 million of Euros per year (Bio Intelligence Service, 2015).

3.2.1.3 World mine production

The world annual production of beryllium ores in average between 2010 and 2014 is around 254 tonnes of Be content, mainly in the US, China and Mozambique (see Figure 19).

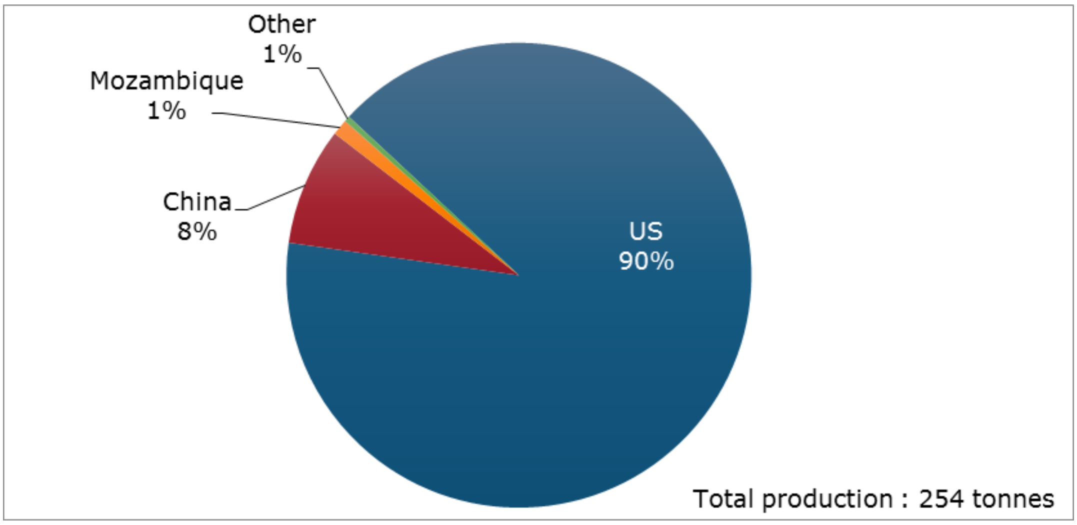

Figure 19: Global mine production of beryllium in tonnes and percentage. Average for the years 2010-2014. (USGS, 2016)

According to USGS, the 2015 world production is 300 tonnes, with 90% of the global production for the US, and 8% for China (USGS, 2016). There is no mining of beryllium ores in the EU (Bio Intelligence Service, 2015).

3.2.1.4 Refining of beryllium

The extraction of beryllium from its main sources beryl and bertrandite involves several stages. After mining the ores they are first converted to an acid-soluble form by fusion. To obtain comparatively pure beryllium hydroxide or oxide, and in a further step beryllium chloride or fluoride, complex chemical processes are used. These halogenides are then reduced to metallic beryllium with other metals or by melt electrolysis. The beryllium metal obtained is subject to one or more refining processes and finally to further treatment by powder metallurgy or in some cases fusion metallurgy. The metal or other product is then incorporated into the end product, before being sent on for use (BeST, 2016b).

Only four countries currently have the resources and capability to commercially mine and process beryllium ores and to manufacture beryllium products (hydroxides, oxides and powders). These are the USA, Kazakhstan, China and India (Bio Intelligence Service, 2015). However, even if they have the capacity, there is no production of refined beryllium in Kazakhstan, China and India (Freeman, 2016).

At present, the US possesses the only fully integrated beryllium producer in the world, involved in the mining, ore processing, manufacture, sale and recycling of beryllium-bearing products. Japan does not extract Be ores but refine it from imports (Freeman, 2016); for examples from stockpiled ores in Kazakhstan and smaller contributions from mines in China, together with beryl sourced from Brazil, Nigeria, Namibia, Zambia, Mozambique, Madagascar - none of which countries have any capabilities to convert the ores into beryllium hydroxide or any other downstream forms (BeST, 2016c).

Annual worldwide production / consumption of beryllium (in alloys, metal or ceramics) in 2014 is estimated as 300 tonnes, with alloys representing about 90%. The US and Japan are the main producers of Be processed materials (see Figure 20), with respectively 75% and 25% of the global production (Freeman, 2016). Older data before 2012 gives another picture of world producers of refined beryllium with 50% for the US, 25% for Kazakhstan, 17% for Japan and 8% for China (BGRM, 2016).

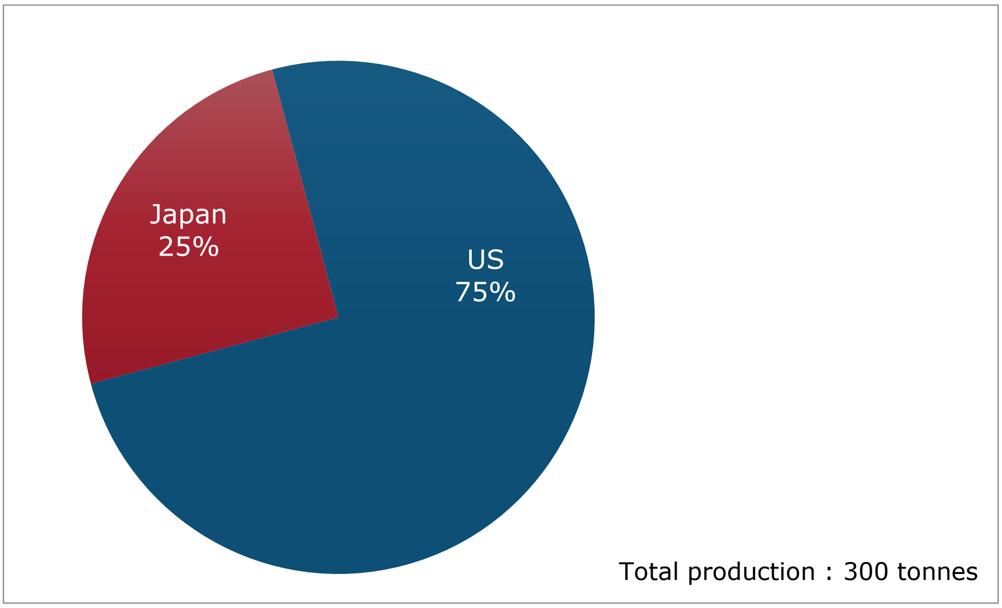

Figure 20: Global production of beryllium products. (BeST, 2016b), year 2014

The EU is only involved on a limited scale in this supply chain, except for the manufacturing of products made of pure beryllium and copper beryllium (CuBe) alloys (BeST, 2016c).

3.2.2 Supply from secondary materials

3.2.2.1 Post-consumer recycling (old scrap)

Beryllium is not recycled from end finished products (BeST, 2016b), therefore the end of life recycling input rate is set to 0%. The recuperation of pure metal of beryllium from end finished products is extremely difficult because of the small size of components and the tiny fraction of Beryllium contained in appliances (less than 40 ppm in appliance having the highest amount of Be) (BeST, 2016b).

3.2.2.2 Industrial recycling (new scrap)

However, beryllium can be recovered from new scrap generated during the manufacture of beryllium products and from old scrap. Quite all the new scrap (between 94% and 100%) is sent back to the producer and recycled (Freeman, 2016). In 2013 secondary beryllium production from new scrap recycling was between 100 and 135 tonnes, i.e. about 20% of global demand (BRGM, 2016).

3.2.3 EU trade

The EU does not import any beryllium ores as there is no processing activities undertaken in the EU.

Europe imports 100% of the refined beryllium used in the EU (about 50 tonnes per year) (Freeman, 2016).The forms of beryllium that are imported are mainly Be alloys and master alloys (80% of imports), but also Be metal and oxides (Bio Intelligence Service, 2015):

- Beryllium containing master alloys: e.g. For foundries and recycling
- Beryllium copper alloys: e.g. Strip; Rod; Bar; Tube; Plate
- Beryllium metal: e.g. near shapes; finished components
- Beryllium aluminium alloy metal: e.g. near shapes; finished components
- Beryllium Oxide: e.g. raw material for pressing and firing into ceramic shapes.

As Eurostat data are unusable to assess the EU imports and exports of refined beryllium (no codes for several types of refined beryllium), the trade flows over the period 2010-2014 cannot be displayed in this factsheet.

The main suppliers of the EU are the US (60%), Kazakhstan (23%) and Japan (17%) (Freeman, 2016) (see Figure 21).

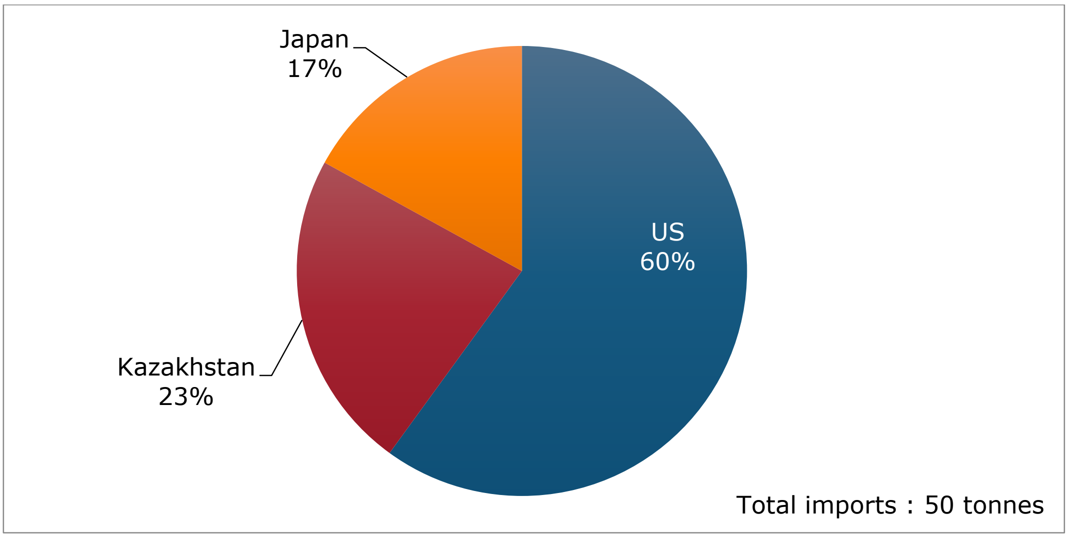

Figure 21: EU imports of Be processed materials. (BeST, 2016b)

No free trade agreements exist at this time between the EU, Kazakhstan and the US or Japan (European Commission, 2016). There were no exports taxes, quotas or prohibition of Be products from those counties for the EU (OECD, 2016). However, if the end use is the defence sector, there is was a need of export licenses from the US, which were never refused for European countries. To the contrary, the US were not allowed to export Beryllium to China (Freeman, 2016).

3.2.4 EU supply chain

The EU is only involved on a limited scale in this supply chain of beryllium, except for the manufacturing of products made of pure beryllium and copper beryllium (CuBe) alloys.

The first stages of the value chain of beryllium take place outside Europe. As there are no reserves of beryllium in the EU, there is consequently no production of beryllium ore. There are also no imports of beryllium ore in Europe and this primary material is totally processed into Be oxides and hydroxides outside the EU (Bio Intelligence Service, 2015). The EU import reliance cannot be calculated for the extraction stage, as there is no production and trade for beryllium ores and concentrates in the EU.

The EU entirely depends on imports of processed and semi-finished products, mainly under the form of beryllium master alloys and alloys (around 40 tonnes of Be per year) and beryllium metal (around 10 tonnes of Be per year). There is no production of alloys or metal but reprocessing (cutting) of imported bars (Bio Intelligence Service, 2015). Some Be ceramics are produced in the EU, from imported Be oxides. The EU is clearly a net importer of beryllium as its import reliance has been estimated at 100%. The European industry uses these processed materials to manufacture various finished products. Some beryllium-copper alloy castings strip, rod, bar and plate products are produced in France, Germany and Switzerland. During this manufacture step, the European industry generates a lot of scrap (around half of the beryllium input) which is totally sent back to suppliers outside Europe for recycling (Freeman, 2016). The EU also imports a large quantity of finished products containing beryllium (Bio Intelligence Service, 2015).

The beryllium contained in the waste ends up in landfill or is downcycled with a large magnitude material stream. However, there is no post-consumer functional recycling of beryllium in Europe and in the world (no recovery of beryllium from old scrap displacing primary production of beryllium) (Bio Intelligence Service, 2015).

3.3 Demand

The world global market of beryllium (concentrates and refined) is about 440 t worth 500 millions of dollars (Bio Intelligence Service, 2015). Annual worldwide production / consumption of refined beryllium (in alloys, metal or ceramics) in 2014 is estimated as 300 tonnes.

3.3.1 EU demand and consumption

The annual EU consumption of beryllium ores is null. In the EU, the consumption is about 50 tonnes in Be content of processed beryllium materials (Bio Intelligence Service, 2015; Freeman, 2016). About 80% of the beryllium used in the EU goes into copper beryllium alloys (0.1 – 2.0%) for the manufacture of high performance electrically conductive terminals and mechanical components; and 15% of the beryllium used is in the form of pure metal, as a metal matrix containing over 50% beryllium. The remaining 5% are Beryllium Oxide Ceramics are used to produce components with extremely high thermal conductivity while providing electrical insulation (BeST, 2016d).

Beryllium's superior chemical, mechanical and thermal properties make it a favourable material for high technology equipment (e.g. in aerospace) for which low weight and high rigidity are important qualities. A large share of the world beryllium production is used for military purposes. Due to the high price, only small amounts of beryllium are used in the civilian sector (European Commission (2014); Freeman, 2016).

3.3.2 Uses and end-uses of Be in the EU

Figure 22 presents the main uses of baryte in the EU.

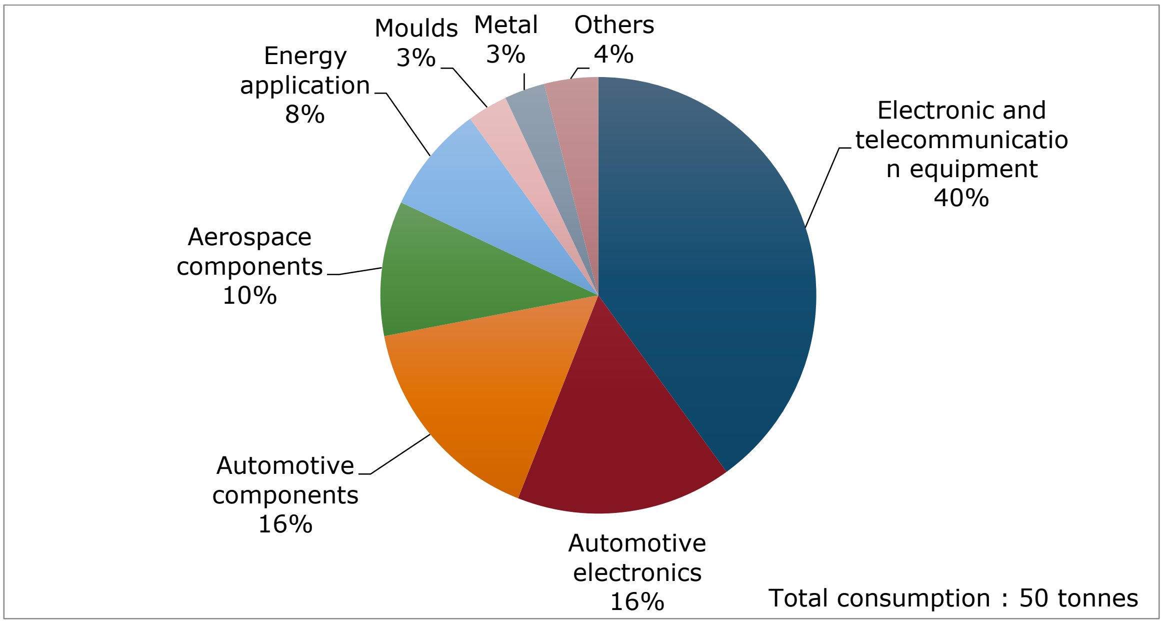

Figure 22: EU end uses of Beryllium. (Data from BeST, 2016b; and Bio Intelligence Service, 2015)

The end-uses of beryllium products in the EU are (European Commission, 2014); Bio Intelligence Service, 2015):

- Electronics and telecommunication equipment: Beryllium is used as an alloying element in copper to improve its mechanical properties without impairing the electric conductivity. Copper beryllium is used in electronic and electrical connectors, battery, undersea fibre optic cables, chips (consumer electronics + telecommunications infrastructure)
- Transport and Defence :
  - Automotive electronics : connectors in vehicle components (CuBe) for air-bag crash sensor and deployment systems, airbags, anti-lock brake systems and many other life safety applications, for weather forecasting satellites, undersea earthquake tsunami detection monitors, air traffic control radar, fire sprinkler systems, power steering and electronic control systems, etc.
  - Other light metal vehicle components (Be used in <10 ppms): car body panels, seat frames, car steering components and wheels, etc.
  - Aerospace components: landing gears, engine for aircraft, mirrors for satellites, etc.
- Industrial components:
  - Moulds for rubber, plastics and glass, made of Be ceramics
  - Metals : Bar, plate, rod, tube, and customized forms
- Energy application: copper-beryllium is used to stop the leaking during the Oil spills, non-magnetic equipment component used to improve extraction equivalent of energy applications
- Others: among others, Be in medical application is used as beryllium foil for high-resolution medical radiography, including CT scanning and mammography; Be in explosives; beryllium oxide ceramic in lasers; beryllium as components to analyse blood and in X-ray equipment, etc.

Relevant industry sectors are described using the NACE sector codes (Eurostat, 2016c) in Table 12.

Table 12: Beryllium applications, 2-digit and associated 4-digit NACE sectors and value added per sector [Data from the Eurostat database, (Eurostat, 2016c)]

Applications	2-digit NACE sector	Value added of 2-digit NACE sector (M€)	4-digit NACE sectors
Electronic and telecommunications equipment	C26 - Manufacture of computer, electronic and optical products	75,260	C2610 - Manufacture of electronic components, C2630 - Manufacture of communication equipment
Transport and Defense : Vehicle electronics	C26 - Manufacture of computer, electronic and optical products	75,260	C2651- Manufacture of instruments and appliances for measuring, testing and navigation, C2670 - Manufacture of optical instruments and photographic equipment:
Transport and Defense : Auto components	C29 - Manufacture of motor vehicles, trailers and semi-	158,081	C2930 - Manufacture of other parts and accessories for motor

	trailers		vehicles
Transport and Defense : Aerospace components	C30 - Manufacture of other transport equipment	53,645	C3030 - Manufacture of air and spacecraft and related machinery
Energy application	C26 - Manufacture of computer, electronic and optical products	75,260	C2651 - Manufacture of instruments and appliances for measuring, testing and navigation
Industrial components : Moulds	C28 - Manufacture of machinery and equipment n.e.c.	191,000	C2823 - Manufacture of machinery for metallurgy
Industrial components : Metal	C24 - Manufacture of basic metals	57,000	C2420 - Other non-ferrous metal production: Bar, plate, rod, tube, and customized forms

3.3.3 Prices

Beryllium is not traded on any metals exchange: there is no quotation on stock market, and prices are established by direct contract negotiation between primary producers and refiners or users (BRGM, 2016). There is no publication of beryllium prices neither on Metal Pages nor Metal Bulletin. Only USGS publishes an annual average estimated price. According to market exerts, the price of beryllium is dependent on the form (BeST, 2016b):

- As a fully machined aerospace component of pure beryllium: €300 – 1,500/kg
- As a cast aluminium 39% beryllium alloy aerospace component: €200 – €500/kg
- As a copper 2% beryllium alloy: €20 – 50 /kg
- As a copper 0.3% beryllium alloy in strip form: €12 – 20 /kg

3.4 Substitution

Substitution of beryllium always leads to a loss of performance. As beryllium is extremely expensive, it is used only when it is absolutely needed (Freeman, 2016). For example, copper-beryllium is only used when absolute reliability is essential to ensure safe operation in the defence, transport or energy sector. Pure beryllium and Al-Be (62% Be) alloys are used only in applications where the unique property combinations are essential for mission capabilities. In this way, when beryllium is used to ensure high performance and reliability in life safety related applications (transport and defence and energy application), it cannot be substituted (BeST, 2016a).
No other alloys offer the same combinations of CuBe alloys, AlBe alloys or pure beryllium properties. In all cases, there is a reduction in performance which can be significant particularly when the combination of properties is for the benefit and safety of society.
However, alternate materials for copper beryllium alloys could include (BeST, 2016a):

- Copper nickel silicon alloys (Corson alloys)
- Copper iron alloys
- Copper titanium alloys
- Copper Nickel Tin Spinodal Alloys (Cu-Ni-Sn)
- Phosphor bronzes (Cu-Fe-P)
- High Performance Bronzes (Cu-Pb-Sn + Al / Fe / Mn)

Alternate materials for the mechanical properties provided by beryllium could include (BeST, 2016a):

- Titanium alloys
- Magnesium alloys

- Aluminium alloys
- Carbon fibre composite

Alternate materials for the thermal properties provided by beryllium:

- Aluminium metal matrix composites with Silicon Carbide / Boron Nitride
- Carbon Reinforced Composites

In all cases, the share of applications in which the beryllium can be substituted by these materials is extremely low (less than 10%), and especially for some applications in the defence, transport and energy sector.

In parallel to substitution, reduction in the quantity of beryllium used in applications is also not feasible, since in practice beryllium is only used where absolutely necessary, due to its high price relative to other metals. Furthermore, the most prevalent use of beryllium occurs in copper beryllium alloys, which only contain between 0.5% – 2% beryllium (BeST, 2016a). Discussion of the criticality assessment

3.4.1 Data sources

Data for Be ores extraction was also not available from World mining data (Austrian Federal Ministry of Science, Research and Economy, 2016) and World Mineral Production (BGS, 2016), so data from the USGS (USGS, 2016) was used for the 2010-2014 period.

As Eurostat data was not usable for beryllium refined products (only Be oxide and powders, and no master alloys) (Eurostat, 2016a; Eurostat, 2016b), we use data from MSA study (Bio Intelligence Service, 2015), and BeST experts for Be oxides, hydroxides powders, unwrought, master alloys, alloys, metal and ceramics production quantities and imports. In this way, results are not based on a 2010-2014 average, but on the most recent single-year data (most of the time 2012 or 2014).

3.4.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 12). The value added data correspond to 2013 figures.

The life cycle stage assessed in for the SR indicator is the extraction step (Be ores and concentrates). The Supply Risk (SR) is calculated using only the HHI for global supply, as the HHI for EU supply was not calculable due to the absence of trade at the extraction stage. The United States is the major producer of beryllium ores (90%).

If the SR indicator was assessed for the processing stage, it would have been lower (1.8) as the share of the US as main producer and EU supplier was slightly lower : the United States and Japan accounted for, respectively, 75% and 25% of both the global and the EU supply for refined beryllium.

3.4.3 Comparison with previous EU assessments

The results of this review and earlier assessments are shown in Table 13.

Table 13: Economic importance and supply risk results for beryllium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Beryllium	6.17	1.32		6.74	1.45		3.9	2.4

Although it appears that the economic importance of beryllium has reduced between 2014 and 2017 this is a false impression created by the change in methodology. The value added in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a 'megasector', which was used in the previous assessments. The economic importance result is therefore reduced. No remarkable changes in the market of beryllium occurred during the three exercises, the shift observed is due to the methodology (in 2014, the recycling rate – not only for end of life recycling- was considered as 19%, reducing the supply risk).

3.5 Other considerations

3.5.1 Forward look for supply and demand

The market outlook forecast for world beryllium demand is increasing from the current baseline, rising to 500 tonnes by 2020, at an overall rate of 1.8% per year (Bio Intelligence Service, 2015). It is not possible to split the forecast by major end-market, due to the lack of available data. However, the larger increases are expected in defence applications and in commercial applications such as (nonmedical and industrial) X-ray products, semiconductor processing equipment and new types of beryllium alloys. Beryllium annual consumption is expected to grow to 425 tonnes / year by 2020 and to >450 tonnes/year by 2030, driven by such applications as the construction of the ITER fusion reactor (BeST, 2016b).

According to experts (Freeman, 2016), the demand for beryllium product will increase for the next 10 years, as well as for the supply (see Table 14). Forecast on 20 years is impossible.

Table 14: Qualitative forecast of supply and demand of Beryllium (Data from Freeman, 2016)

Materials	Criticality of the material in 2017		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Beryllium	x		+	+	?	+	+	?

3.5.2 Environmental and regulatory issues

Beryllium can be toxic and is classified under the European regulation as a cancerous material of 1B category under the Guidance on Labelling and Packaging. It is highly toxic if inhaled in dust form during some operational steps, leading to chronic respiratory disease called berylliosis (European Commission, 2014). A check-up of workers need to be implemented in production and use of beryllium. In different industries a limitation of exposure to beryllium has been implemented, the global Occupational Exposure Limit is 0.6 $\mu g/m^3$ Inhalable (BeST, 2016c). The potential tightening regarding the regulation of beryllium, notably to include the material as a hazardous substance in the REACH legislation, is still discussed and considered as a threat to the beryllium industry (Freeman, 2016).

3.6 Data sources

3.6.1 Data sources used in the factsheet

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3.7 Acknowledgments

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4. BISMUTH

Key facts and figures

Material name and Element symbol	Bismuth, Bi	World/EU production (tonnes)[1]	Refining: 8,180 / 0.8
Parent group (where applicable)	n/a	EU import reliance[1]	100%
Life cycle stage /material assessed	Processing/ Bi metal: 99.8%	Substitute index for supply risk [SI(SR)][1]	0.94
Economic importance (EI) (2017)	3.6	Substitute Index for economic importance [SI(EI)] [1]	0.96
Supply risk (SR) (2017)	3.8	End of life recycling input rate[1]	1%
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Chemicals: 62%, Low-melting alloys: 28%, Metallurgical additives: 10%
Main product, co-product or by-product	By-product of lead and tungsten	Major world producers (refined Bi)[1]	China (82%), Mexico (11%), Japan (7%)
Criticality results	2010	2014	2017
	Not assessed	Not assessed	Critical

[1] Average for 2010-2014, unless otherwise stated.

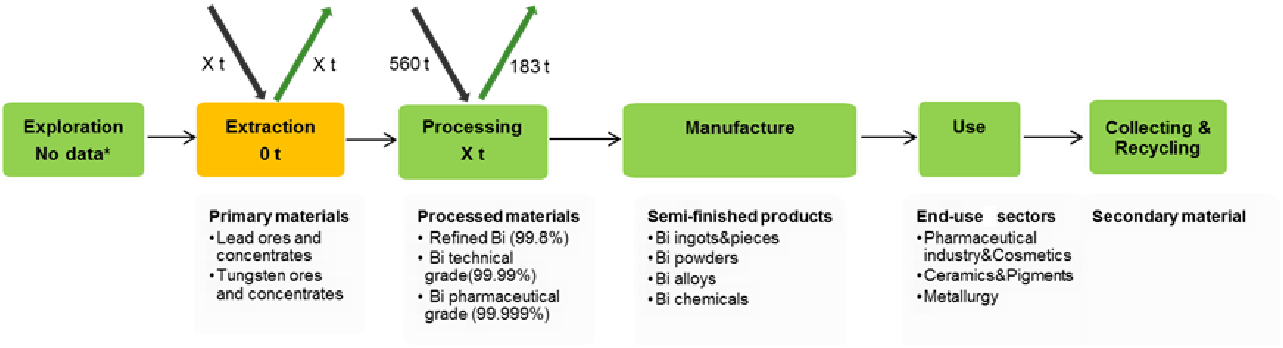

Figure 23: Simplified value chain for bismuth

The green boxes suggest that activities are undertaken within the EU. The black arrows represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%.*EU reserves data is partial and cannot be summed (cf.2.1.2).

Figure 24: Economic importance and supply risk scores for bismuth

4.1 Introduction

Bismuth (chemical symbol Bi) is a very brittle metal with a pinkish metallic lustre. Its concentration in the upper continental crust is 0.16 ppm (Rudnick, 2003). It occurs naturally in the minerals bismuthinite (sulfide), bismutite (carbonate) and bismite (oxide), but is very rarely extracted as main metal. It is mainly a by-product of lead and tungsten extraction and processing. Bismuth shares chemical properties with arsenic and antimony. Its main physical properties are a low melting point (271.3°C) and the second lowest thermal conductivity after mercury. It also has the capacity to expand on freezing, which makes it an important component notably in low-melting alloys. Its main uses in recent years in the world and in the EU are in pharmaceutical and cosmetics products where its non-toxicity is highly valuable.

EU highly relies on imports of primary refined materials for transformation into Bi-containing finished products.

4.2 Supply

4.2.1 Supply from primary materials

4.2.1.1 Geology, mining and processing

Bismuth mineralization can occur in various geological settings. Main occurrences are notably in tungsten, copper, gold and lead skarn deposits, as a by-product in tin pegmatites, and in magmatic-hydrothemal mineralization related to granites (Pohl, 2011). As a by-product, extraction methods depend on the type and mineralogy of the ore. Bismuth has been mined as a main product only in the Cerro Tasna mine (Bolivia) and also currently in China (Shizhuyuan). In this country, artisanal mining for bismuth also exists, with manual separation of bismuth-rich mineralization contributing significantly to global production of concentrates (Blazy, 2013).

Currently, the two main sources for the recovery of bismuth metal are known to be lead and tungsten extraction and processing, with 50 to 60% coming from lead processing according to industry experts. Minor recovery of bismuth can also come from metallurgy of tin and copper, for instance in Japan, although in most cases it is seen as a penalizing impurity in those treatments (Blazy, 2013; Krenev, 2015).

4.2.1.1.1 Recovery as a by-product of lead extraction

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

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

4.2.1.1.2 Recovery as a by-product of tungsten extraction

Not much is known concerning Chinese operations to recover bismuth from tungsten. An important part comes from artisanal mining and uses standard gravity concentration equipment including jigs and shaking tables. At the industrial scale, one example is the

Xihuashan plant, where the ore is composed of scheelite, wolframite, cassiterite, bismuthinite, molybdenite, copper sulphides and REE-bearing minerals. A commercial concentrate of bismuthinite is obtained through various flotation processes and sold for further transformation (Blazy, 2013). In Vietnam, first commercial production of bismuth concentrates occurred in September 2014 at the Nui Phao mine. These concentrates are also obtained through bismuth flotation, followed by leaching and cementation (Masan Resources, 2015).

4.2.1.1.3 Refining and purification of bismuth

Refining is needed to obtain bismuth metal of a purity of at least 99.8%. Most of the time, the thermal route is preferred. During this process, caustic soda and potassium nitrate are added to the molten bismuth to remove impurities (As, Sb, Se, Te, Sn). An addition of Zn metal can be necessary when impurities include Cu, Ag and Au (Blazy, 2013). Final treatment with soda ash can bring purity to 99.99% Bi (technical grade).

Others processes exist depending on the nature of the impurities and the required quality of final products. Electrolytic refining is preferred to obtain higher purity, up to 99.999 % (pharmaceutical grade). Bismuth can be commercialized in the form of high purity ingots, pieces, pellets, or even as powdered oxide.

4.2.1.2 Bismuth resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of bismuth in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template4, which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for bismuth. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for bismuth, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for bismuth at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

During the Minerals4EU project, resources of Bi were reported only in Bulgaria in the category "No statistical data available but resources known or believed to exist". Exploration projects were mentioned in Portugal and Slovakia with no further information (Minerals4EU, 2014).

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[4] www.crirsco.com

For reserves, the only reference at the global level is from USGS (USGS, 2016). However, these estimations have been unchanged for many years (except for Vietnam) and are likely to be incomplete since they are based on bismuth content of lead ores only, forgetting bismuth content in copper and tungsten ores.

Table 15: Global reserves of bismuth (USGS, 2016)

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

4.2.1.3 World refined bismuth production

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

The criticality assessment was performed at the refining stage because of the high import reliance of the EU on refined Bi products. There are only a few producers in the world at this stage (Figure 25). The main one is in China, responsible for 82% of total world production, the main company being Hunan Jinwang Bismuth Industrial Co Ltd (www.en.jin-wang.com.cn) with capacities of 8,000 tonnes. In Mexico, it is the company Peñoles which controls all Bi production (www.penoles.com.mx) and accounted for 10% of total production (average 2010-2014). And in Japan, the company Mitsui (www.mitsui-kinzoku.co.jp).

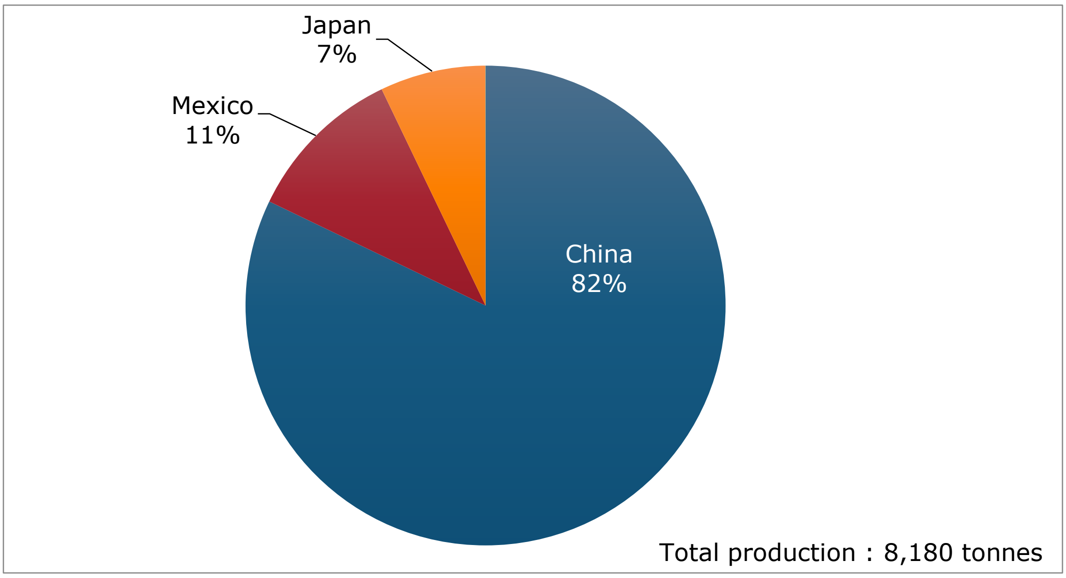

Figure 25: Global production of refined bismuth. Average 2010-2014. (Data based on World Mining Data, 2016)

In the EU, the company 5N Plus is a huge player on the bismuth market and specialty products (refined bismuth, bismuth chemicals, and low melting point alloys) and has a subsidiary in Belgium. It could have refining capacities there, although no data on production is available at all (5NPlus, 2015).

Regarding mine production, China is also the main producer in the world, although figures vary according to different sources (BGS, 2016; USGS, 2016), partly due to the difficulty of assessing the part of artisanal/illegal production. Another important producer is Vietnam, where commercial production of bismuth concentrates started in September 2014 at the Nui Phao mine. Objectives of the company are to produce 2,000 tonnes/year and to become the second most important producer in the world (Masan Resources, 2015).

In Europe, BGS Minerals Statistics mention mine production in Armenia (3.6 tonnes Bi per year on average for 2010-2014), and as far as EU-28 is concerned, in Bulgaria (3 tonnes per year) with higher uncertainty. In Italy, although bismuth production was reported at 5 tonnes a year (USGS, 2016), this figure could not be verified in any other source and is no longer relevant.

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

4.2.2 Supply from secondary materials

The rate of recovery of bismuth from end-of-life products is under 1% (UNEP, 2011). Bismuth is difficult to recycle because it is mainly used in many dissipative applications, such as pigments and pharmaceuticals. The most likely candidates for the recycling of bismuth are where bismuth is used in solder alloys found in electronic equipment. The recycling process could be relatively straight forward due to the low melting point of the metal and the solders it is used in. However, it is usually not the primary metal to be recycled in such alloys so far.

4.2.3 EU trade

EU is a net importer of refined bismuth. Imports for 2013 and 2014 were 3 times higher than in 2010-2012. Such increase could be linked with a reaction to the speculative accumulation of stocks in the Fanya Metal Exchange or to intra-company material transfer from 5N Plus subsidiary in Belgium.

EU import reliance on refined bismuth is almost 100% (average of 2010-2014) due to the predominant part of China in the EU supply for this period, which represents 84% of the total EU imports (Figure 26 and Figure 27).

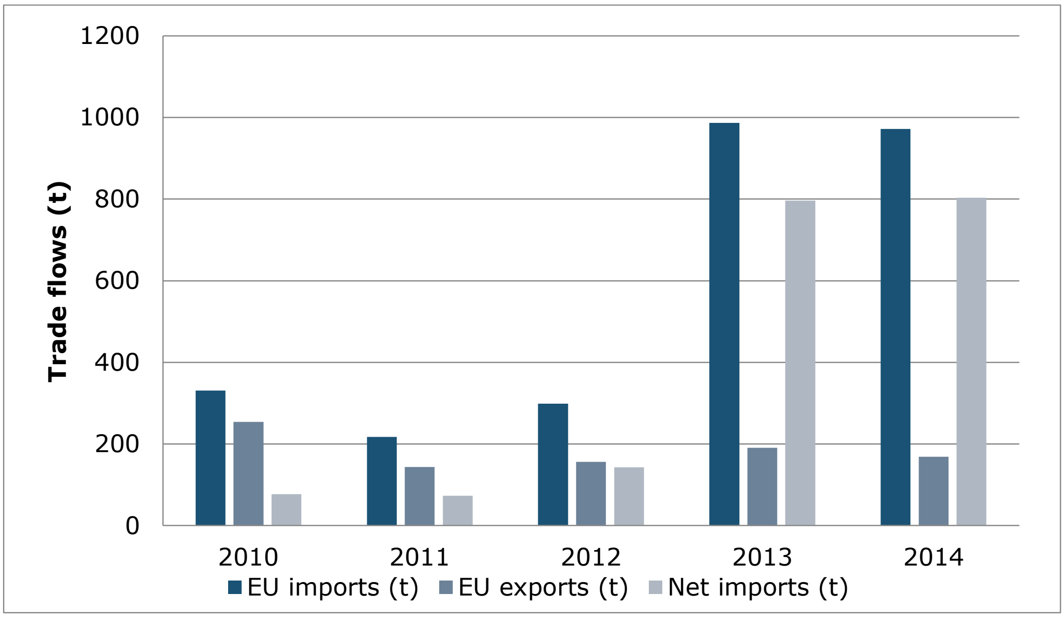

Figure 26: EU trade flows for unwrought Bi (Eurostat, 2016)

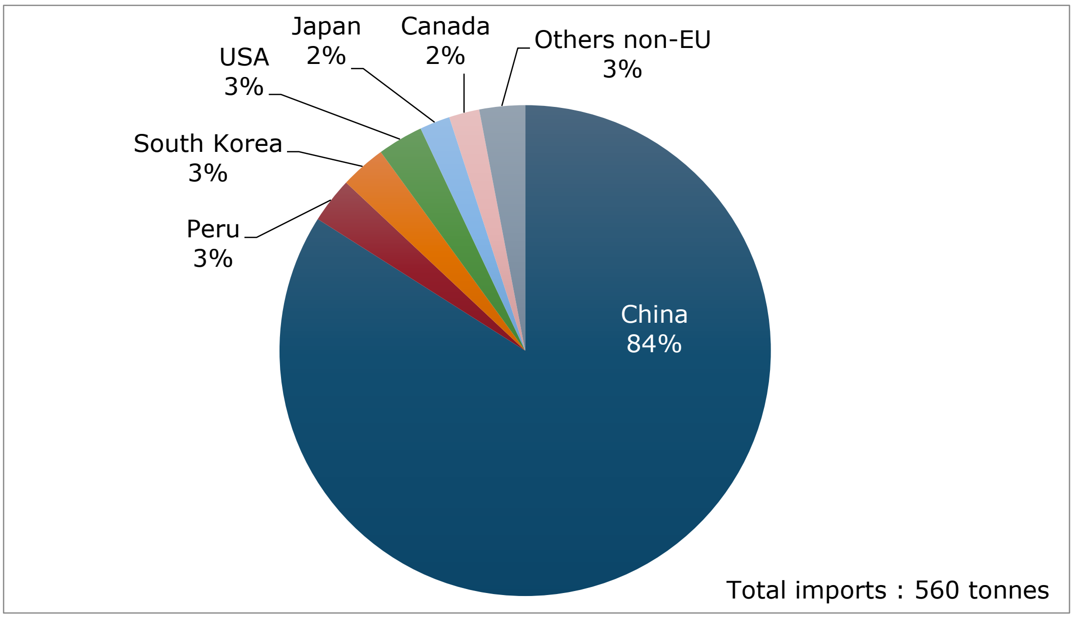

Figure 27: Main sources of extra-EU28 imports of Bi, average 2010-2014 (Eurostat, 2016)

4.2.4 EU supply chain

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

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

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

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

No trade restrictions were identified for bismuth (OECD, 2016). The only stocks that are known to exist on bismuth where at the Fanya Stock Exchange.

Domestic production in the EU is located in Bulgaria, and represents about 0.1% of the total EU sourcing (domestic production + imports). Therefore the EU sourcing can be considered identical to EU imports (see Figure 27). The import reliance is 100%.

4.3 Demand

4.3.1 EU consumption

Apparent consumption figures derived from adding EU production and imports and subtracting exports are not reliable for bismuth because of the uncertainties related to current levels of production in the EU and the number of dissipative applications in which it is used. The main company active in Bi transformation in the EU is likely to be 5N Plus subsidiary in Belgium, with many intra-company material transfers. A number of companies producing pharmaceutical products and low-melting alloys may use bismuth integrated in finished goods. It is very difficult to assess consumption precisely, which is of the order of a few hundred tonnes.

4.3.2 Applications/end uses

Bismuth is considered as an “eco-friendly” material. As a result, its first sector of application is in the pharmaceutical and animal-feed industries (62% of total uses for Bi chemicals – see Figure 28). In modern medicine, compounds of bismuth are mainly applied clinically for gastrointestinal disorders as anti-ulcer agents. Examples are De-Nol and Pepto-Bismol used to treat and prevent gastric and duodenal ulcers. The use of bismuth (III) is also seen in nuclear medicine, anticancer, antitumor and antimicrobial studies (Yang, 2007).

Fusible alloys represent the second most important use (28%). Bismuth is notably used as a replacement for more harmful metals (on top of which is lead) in solders. Other uses include metallurgical additives and a number of other industrial applications such as coatings, pigments, and electronics (Ecclestone, 2014).

Relevant industry sectors are described using the NACE sector codes in Table 16.

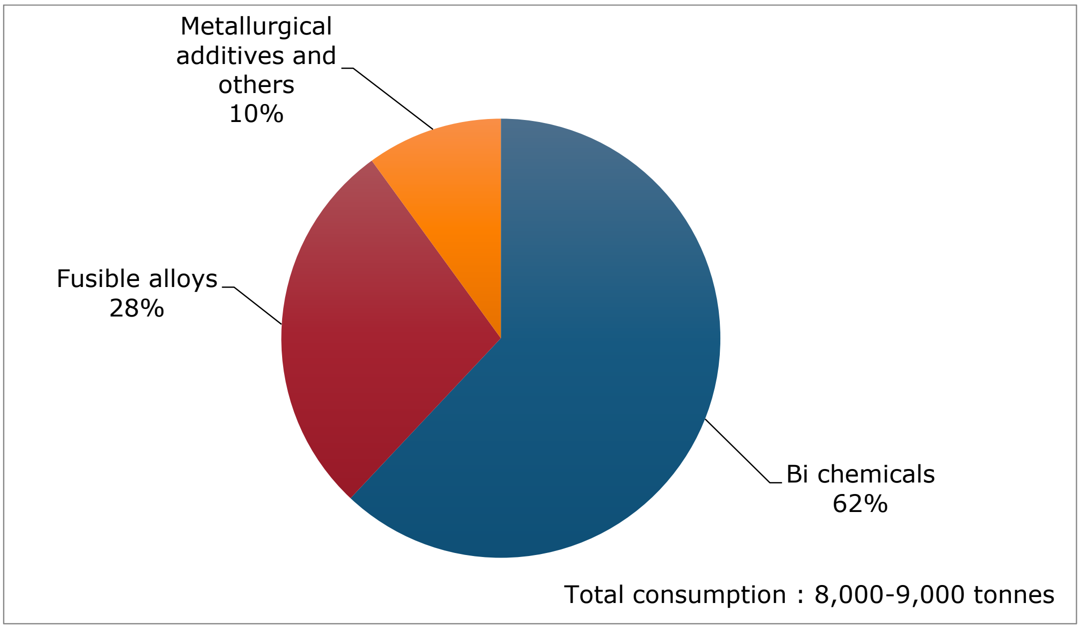

Figure 28: End uses of bismuth. Data from Blazy (2013)

Table 16: Bismuth applications, 2-digit NACE sectors associated 4-digit NACE sectors and value added (Data from Eurostat, 2016)

Applications	**2-digit NACE sectors**	**Value added of NACE 2 sectors (millions €)**	**4-digit NACE sectors**
Chemicals	C20 - Manufacture of chemicals and chemical products	110,000	C2029 - Manufacture of other chemical products n.e.c.
Fusible alloys	C32 – Other manufacturing	41,613	C3290 - Other manufacturing n.e.c.
Metallurgical alloys	C24 - Manufacture of basic metals	57,000	C2431 – Casting of iron

4.3.3 Prices and markets

Bismuth is not traded on any metals exchange, and there are no terminal or futures markets where buyers and sellers can fix an official price. References for prices are obtained through averages of past deals between private parties, generally available through paid subscription (e.g. Asian Metal, Metal Pages).

Figure 29: Bismuth prices (99.99% Bi) in $/kg. Data from DERA, 2016

Over the past decade, the bismuth price has highly fluctuated. Prices rose dramatically in 2007 following a state-directed effort to concentrate bismuth production in China. This led to the closure of numerous smelters in the country, which accounts for 80 to 90% of global refined bismuth production. The global financial crisis brought bismuth back to prices close to 15 US$/kg. Between 2010 and 2014, speculative investment in bismuth metal by the Fanya Metal Exchange - which claimed to have bought over 18,000 tonnes in about a two year period - brought prices back up, until investigations into activities at the Exchange resulted in an abrupt end to these purchases and prices falling dramatically to around 10 US$/kg by 2015 and 2016(Wilburn et al., 2016).

4.4 Substitution

Substitutes exist for bismuth in many applications as in some of them it is primarily used for its non-toxicity as a replacement for already existing materials (metals).

In pharmaceutical applications, it can be replaced by antibiotics. In pigment uses, by titanium dioxide-coated mica flakes or fish-scale extracts, and in devices such as fire sprinklers, by glycerine-filled glass bulbs (USGS, 2016). Other types of low-melting alloys also exist, with other properties or prices, which are the main drivers for substitution.

4.5 Discussion of the criticality assessment

4.5.1 Data sources

The choice of data source for production data was BMWFW (World Mining Data, 2016) as this source compiles figures reported either from national statistics or companies, which seem of acceptable quality and more homogeneous than others; for instance in 2014, it ranges from 3,400 tonnes (BGS, 2016) to 13,600 tonnes (USGS, 2016). However, like other sources, production data from BMWFW may contain confusions between pure “mine producers” and “refiners”. For instance, it reports figures from Japan and Vietnam, but in the first country there is no mining of bismuth and in the second, there is no refining (only bismuth concentrates are sold). Although corrections may be applied using a conversion factor to express all quantities in Bi content, the choice in this factsheet was to distinguish clearly refining production and exclude mining producers (Figure 25). Trade data were extracted from the Eurostat Easy Comext database for the Combined

Nomenclature CN8 code 81011000: 'unwrought bismuth; bismuth powders; bismuth waste and scrap (excl. ash and residues containing bismuth)'. Data on trade agreements are taken from the DG Trade webpages, which include information on trade agreements between the EU and other countries (European Commission, 2016). Information on export restrictions are derived from the OECD Export restrictions on the Industrial Raw Materials database (OECD, 2016).

4.5.2 Economic Importance and Supply Risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 16). The value added data correspond to 2013 figures. The supply risk was assessed using the global HHI and the EU-28 HHI as prescribed in the revised methodology.

4.5.3 Comparison with previous EU assessments

Bismuth is being assessed for the first time in 2017 with the EI and SR results presented in the following table. Bismuth was not assessed in 2011 or in 2014, therefore, it is not possible to make any comparisons with the previous assessments.

Table 17: Economic importance and supply risk results for bismuth in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Bismuth	Not assessed			Not assessed			3.6	3.8

4.6 Other considerations

4.6.1 Forward look for supply and demand

On the demand side, global demand for bismuth is estimated to grow at 4-5% by year, thanks to high demand in pharmaceutical applications. There may also be growth in applications where there is a requirement for very low temperature solders, where bismuth is competitive. Another emerging market could come from the substantial interest in developing new classes of semiconductor, thermoelectric materials and topological insulators. Such trend is driven by their potential applications in the development of low power and energy efficient optoelectronic, thermoelectric, and electronic devices, including laser diodes, light-emitting diodes, solar cells, transistors, and spintronic devices. It could lead to the development of emerging semiconductor compounds and alloys that contain bismuth (BIWS, 2017).

On the supply side, Fortune Minerals Ltd. in Canada (London, Ontario) was granted final approval for a Type A water license for the NICO gold-cobalt-bismuth-copper mine in the Northwest Territories in 2014. The water license was one of the final steps in the permitting process, allowing construction to begin once financing had been received. Output was expected to be 40,500 troy ounces per year of gold, 1,600 metric tons per year (t/yr) of cobalt, 1,700 t/yr of bismuth, and 250 t/yr of copper (USGS,2016).

Table 18: Qualitative forecast of supply and demand of bismuth

Material	Criticality of the material in 2017		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Bismuth	x		+	?	?	+	?	?

4.6.2 Environmental and regulatory issues

Several bismuth-containing substances are registered with REACH. However, none of them is on the list of substances of very high concern. Even though the REACH dossier indicates that data is lacking on the physical, health and environmental hazards of bismuth, this element is generally acknowledged for its non-toxicity in many of its uses.

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4.8 Acknowledgments

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5. BORATES

Key facts and figures

Material name and Formula	Borates, variable	World/EU production (tonnes)[1]	1 million / 0
Parent group (where applicable)	-	EU import reliance (%)[1]	100%
Life cycle stage/ material assessed	Mine production/ Ore	Substitution index for supply risk [SI (SR)][1]	1.00
Economic importance (EI) (2017)	3.1	Substitution Index for economic importance [SI(EI)][1]	1.00
Supply risk (SR) (2017)	3.0	End of life recycling input rate	0%
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Glass (49%), Frits and Ceramics (15%), Fertilizers (13%)
Main product, co-product or by-product	Main product	Major world producers[1]	Turkey (38%), Unites States (23%), Argentina (12%)
Criticality results	2011	2014	2017
	Non critical	Critical	Critical

[1] average for 2010-2014, unless otherwise stated;

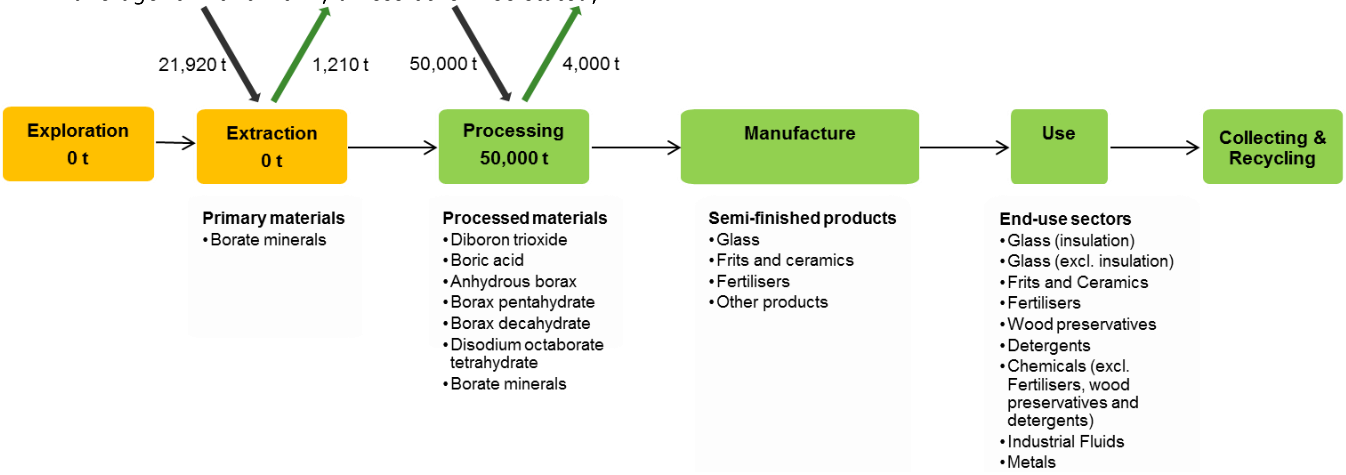

Figure 30: Simplified value chain for borates

The orange boxes of the production stage suggest that activities are not undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

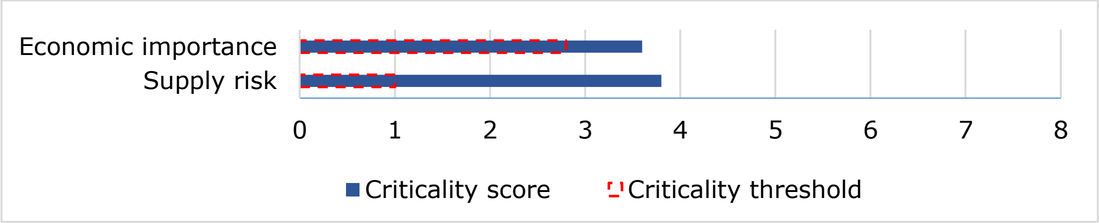

Figure 31: Economic importance and supply risk scores for borates

5.1 Introduction

Borates are naturally-occurring minerals containing boron (B). Boron occurs in nature as borates, such as borate minerals and borosilicates. Borates are thus inorganic salts of boron, and refers to a large number of chemical compounds that contain borate anions. Borates are defined by industry as any compound that contains or supplies boric oxide (B_2O_3). They have metabolizing, bleaching, buffering, dispersing, vitrifying properties. Borates are important ingredients in a variety of household and commercial products, chief among them: insulation fiberglass, textile fiberglass and heat-resistant glass; detergents, soaps and personal care products; ceramic and enamel frits and glazes, ceramic tile bodies; agricultural micronutrients; other uses including wood treatments, polymer additives and pest control products (European Commission, 2014).

5.2 Supply

5.2.1 Supply from primary materials

5.2.1.1 Geological occurrence

Borates are naturally-occurring minerals containing boron (B). Boron occurs in nature as borates, such as borate minerals and borosilicates. The abundance of boron in the upper crust is 17 ppm (Rudnick, 2003). Borates are thus inorganic salts of boron, and refers to a large number of chemical compounds that contain borate anions. Boron does not occur naturally in the environment as a native element, but is rather found in boric acids and inorganic salts called borates. Borates are defined by industry as any compound that contains or supplies boric oxide (B_2O_3). There are over 150 borate minerals known, with 4 of these making up 90% of the minerals used in the industry: sodium borates tincal and kernite, calcium borate colemanite, and the sodium-calcium borate ulexite. Borate deposits are associated with volcanic activity, with the largest being found in Turkey and California (Bio Intelligence Service, 2015). About 70% of all deposits in Turkey are colemanite (USGS, 2016a).

5.2.1.2 Resources and reserves of borates

There is no single source of comprehensive evaluations that apply the same criteria to deposits of Borate in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[5], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for Borate. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for Borate, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition,

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[5] www.crirsco.com

translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for Borate at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

Deposits of Borates are generally linked with dry climate and volcanically active areas. As a result, the largest known deposit of Borates can be found in the Mojave Deserts in California, Andean belt of South America and the Alpide belt in southern region of Asia (USGS, 2016a). The global known resources of borates are about 807 million tonnes of borates (250 million tonnes of B content) (Bio Intelligence Service, 2015).

There are no known resources of borates in the EU28 but a large deposit of lithium-borates has been recently discovered in Serbia, with estimated resources at 18 million tonnes of borates (Rio Tinto, 2015). The Minerals4EU website (Minerals4EU, 2014) also reports only resources of borates in Serbia, of 18 million tonnes (JORC). The global borate known reserve are estimate to be around 380 million tonnes of B content (USGS, 2016a); it is important to note that there are no known reserve of borate in the EU (European Commission, 2014). The Minerals4EU website (Minerals4EU, 2014) reports also no reserves of borates in EU member states.

Table 19: Global reserves of boron in 2015 (Data from USGS, 2016a)

Country	Boron Reserves (tonnes)
Turkey	230,000
Unites States	40,000
Russia	40,000
Chile	35,000
China	32,000
Peru	4,000

5.2.1.3 Mine production of borates

The global mine production is about 1 million tonnes of borates (World Mining Congresses, 2016; BGS, 2016). Turkey is the main producer of borates, followed by the US, Argentina and Chile (see following figure)

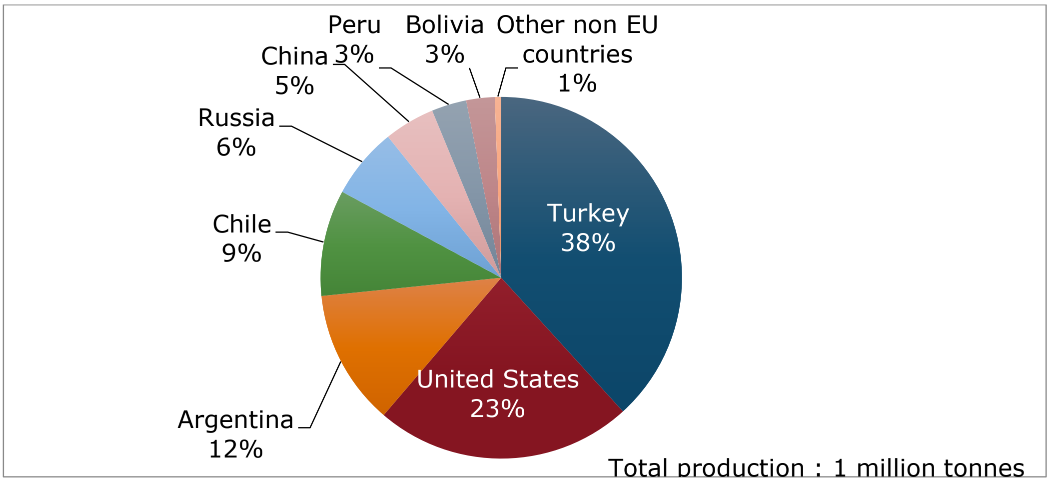

Figure 32: Global mine production of borates, in tonnes and percentage (Data from World Mining Congresses, 2016)

5.2.2 Supply from secondary materials

Secondary materials result mostly from non-functional recycling. There is no way to separate borosilicate glass from boron-free container and flat glass. It means that waste borosilicate glass is likely to end up in the manufacture of new glass containers or glass wool and it does not replace primary boron in the new production of borosilicate glass (Bio Intelligence Service, 2015). The functional recycling of boron is thus null.

5.2.3 EU trade

The EU imports about 21,890 tonnes of natural borates and exports only about 1,200 tonnes on average on the 2012-2014 period (Eurostat, 2016a) (see Figure 33). No data were recorded in the Comext database for the year 2010 and 2011. The Comext code used was 25280000 (20% B contained).

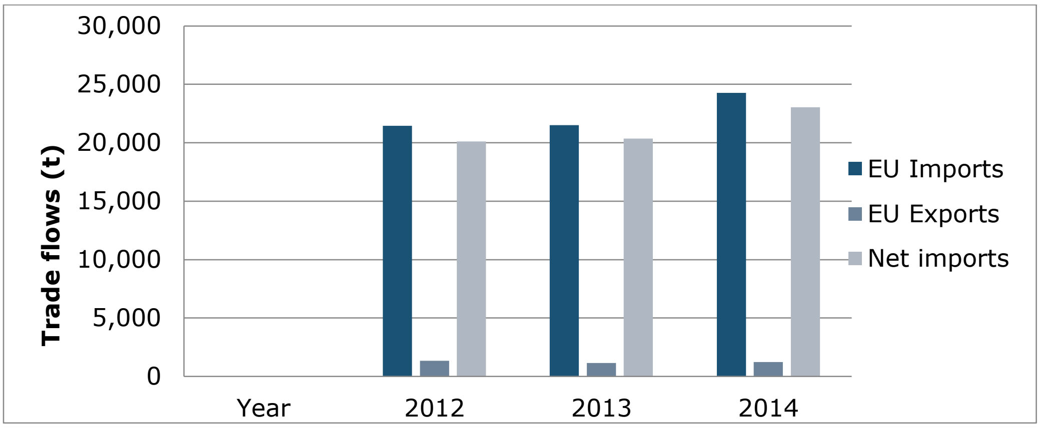

Figure 33: EU trade flows for natural borates. (Data from Eurostat, 2012-2014 - Eurostat, 2016a)

Turkey is quite the only supplier of the EU for natural borates, with 98% of the total imports in average on the 2012-2014 period, see Figure 34 (Eurostat, 2016a). The EU imports also small quantities of natural borates from Argentina and Peru. Turkey and the EU have a customs union agreement in force since 1996 (European Commission, 2016). Argentina is the only supplier to put an export tax of 10% on natural borates (OECD, 2016).

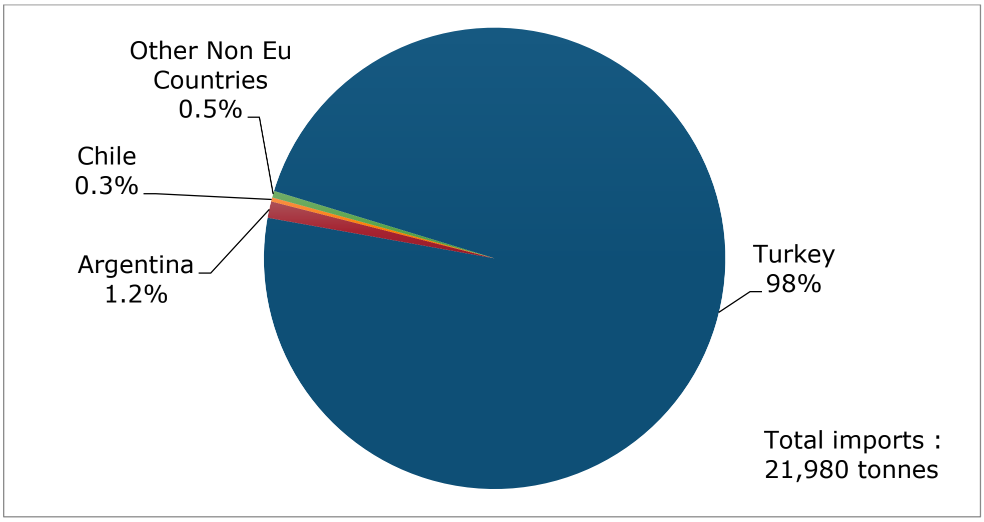

Figure 34: EU imports of natural borates, average 2012-2014. (Data from Eurostat, 2016a)

According to Comext, the EU imports about 50,000 tonnes of refined borates and exports only about 4,000 tonnes per year on average on the 2010-2014 period (Eurostat, 2016a) (see Figure 35). The codes used in Comext were: boric acid (CN8 code 28100090), boric oxide (CN8 code 28100010), disodium tetraborate (anhydrous) (CN8 code 284011), disodium tetraborate (other than anhydrous) (CN8 code 284019), other borates (CN8 code 284020). However, according to industry experts, the EU imports of refined borates are higher than the Eurostat value, reaching about 65,000 tonnes (IMA-Europe, 2016).

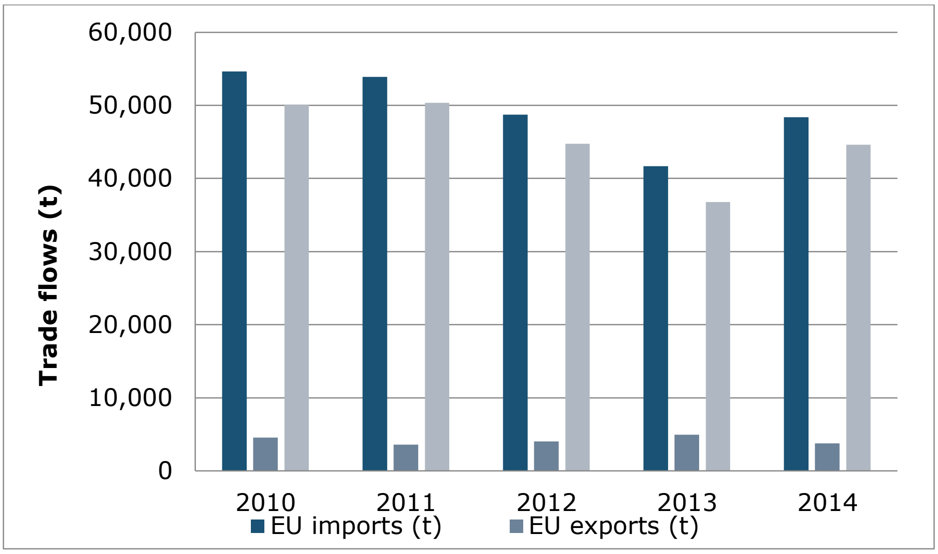

Figure 35: EU trade flows for refined borate. (Data from Eurostat, 2010-2014 - Eurostat, 2016a)

According to Eurostat, Turkey is the main supplier of the EU for refined borates, with 83% of the total imports in average on the 2010-2014 period (see Figure 36). The US are the only other notable supplier with 7% of the imports (Eurostat, 2016a). According to industry experts, the share of the main supplier Turkey is slightly lower (55%) whereas USA's contribution to EU imports is substantial (35%), with the remaining 10% from other countries (mainly Latin America) (IMA-Europe, 2016).

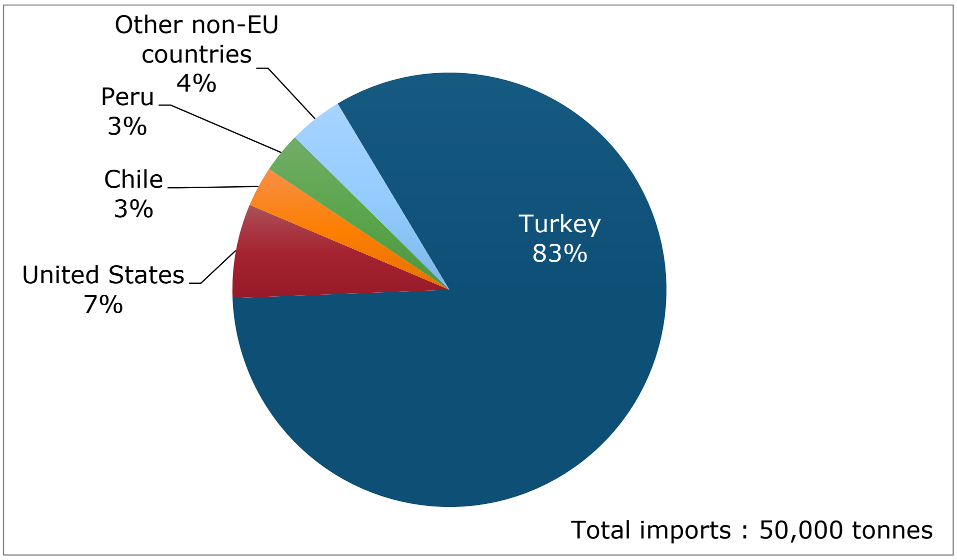

Figure 36: EU imports of refined borates, average 2010-2014. (Data from Eurostat, 2016a)

5.2.4 EU supply chain

The EU does not extract borates (BGS, 2016; Eurostat, 2016b) and has no known reserves (Bio Intelligence Service, 2015). Therefore the EU is 100 % reliant on imports for primary products (import reliance of 100%). For most applications, borates require refining as the ores are not of sufficient quality. There is actually no manufacturing/processing plants to refine borates in the EU (IMA-Europe, 2016), and that explains the fact that the imports of refined borates are two-three times larger than the imports of natural borates (European Commission, 2014).

The main supplier of the EU for natural and refined borates is Turkey, with which a free trade agreement is in place (European Commission, 2016).

5.3 Demand

5.3.1 EU demand and consumption

For borates, EU consumption is estimated at approximately 285,000 tonnes (borate equivalent), which represents around 15% of world consumption (European Commission, 2014).

Over three quarters of borates are used in glass and fibreglass applications, ceramics and agriculture (fertilizers) (Bio Intelligence Service, 2015). They also have several other applications within the construction and chemicals industries (Bio Intelligence Service, 2015). The borate imported in the EU is mostly embodied into glass. Second single most common use of borates includes frits and ceramics followed by fertilizers. The other products such as construction materials, abrasives, catalysts, coatings, detergents, etc.

5.3.2 Uses and end-uses of Borates in the EU

Global end-uses of borates in 2014 are shown in Figure 37 and relevant industry sectors are described using the NACE sector codes (Eurostat, 2016c) in Table 20.

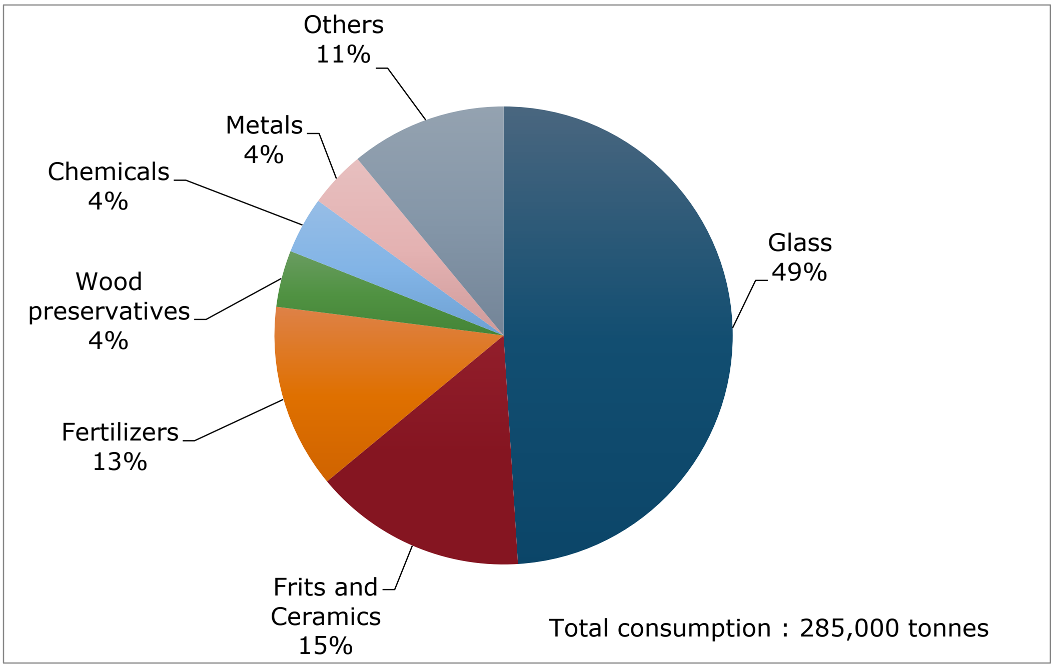

Figure 37: EU end uses of borates. Average figures for 2010-2014. (Data from IMA-Europe, 2016)

The end-use of borates products in the EU are (Bio Intelligence Service, 2015; IMA-Europe, 2016):

- Glass (insulation): Used in insulation fiberglass (IFG) for thermal and acoustic insulation; and textile fiberglass (TFG).
- Glass (excl. insulation): Used in Pyrex cookware, laboratory glassware, pharmaceutical packaging, lighting and domestic appliances (borosilicate glass) in LCDs used in tablets and televisions.
- Frits and Ceramics: Added to ceramics and enamel frits in order to enhance chemical, thermal and wear resistance.
- Fertilisers: an essential micronutrient for plant growth, crop yield and seed development.
- Wood preservatives: Borates are used to treat wood to ward off insects and other pests.
- Detergents: Used in laundry detergents, household and industrial cleaning products. Borates enhance stain removal and bleaching, provide alkaline buffering, soften water and improve surfactant performance.
- Chemicals (excl. Fertilisers, wood preservatives and detergents): Used for chemicals such as fire retardants.
- Industrial Fluids: Used for metalworking fluids, and other fluids used in cars, antifreeze, braking fluid etc.
- Metals: Used as an additive for steel and other ferrous metals as its presence ensures higher strength at a lower weight

Table 20: Borate applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016c)

Applications	**2-digit NACE sector**	**Value added of NACE 2 sector (M€)**	**4-digit NACE sectors**
Glass (insulation)	C23 - Manufacture of other non-metallic mineral products	59,166	C2314 - Manufacture of glass fibres
Glass (excl. insulation)	C23 - Manufacture of other non-metallic mineral products	59,166	C2319 - Manufacture and processing of other glass, including technical glassware
Frits and Ceramics	C23 - Manufacture of other non-metallic mineral products	59,166	C2331 - Manufacture of ceramic tiles and flags
Fertilisers	C20 - Manufacture of chemicals and chemical products	110,000	C2015 - Manufacture of fertilisers and nitrogen compound
Wood preservatives	C16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	29,585	C1610- Sawmilling and planing of wood
Detergents	C20 - Manufacture of chemicals and chemical products	110,000	C2041- Manufacture of soap and detergents, cleaning and polishing preparations
Chemicals (excl. Fertilisers, wood preservatives and detergents)	C20 - Manufacture of chemicals and chemical products	110,000	C2059- Manufacture of other chemical products n.e.c.
Industrial Fluids	C20 - Manufacture of chemicals and chemical products	110,000	C2059- Manufacture of other chemical products n.e.c.
Metals	C24 - Manufacture of basic metals	57,000	C2410- Manufacture of basic iron and steel and of ferro-alloys

5.3.3 Prices

Borate prices are continuously decreasing since the beginning of 2000's as can be seen in Figure 38 (USGS, 2016b). In 2008 – 2009, the price cut was a reflection of an imbalance between supply and demand created by the global economic crisis (European Commission, 2014). The price increase from 2010 to 2011 is a result of stabilisation in market conditions but as dropped again since 2011.

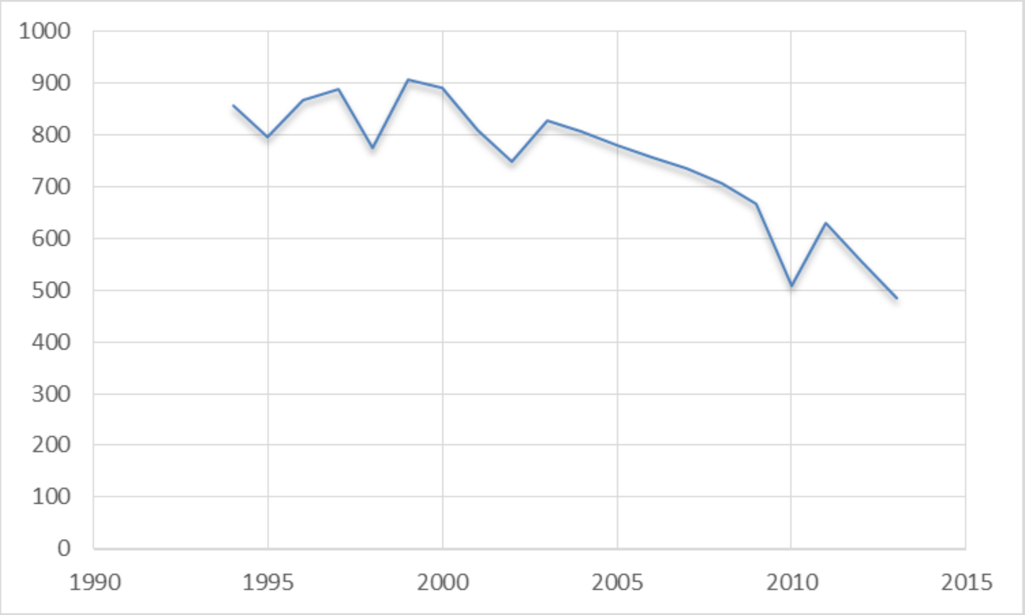

Figure 38: Borates prices in $/tonne (USGS, 2016b). Figures are indexed to 1998 values

5.4 Substitution

In terms of substitutes, the substitution of boron is feasible in insulation (by using stone wools and polymer foams), soaps (potassium salts and sodium) and detergents (sodium percarbonate) (USGS, 2016a). According to experts (IMA-Europe, 2016), there are no existing substitutes of borates for glass insulation, for glass resistant to thermal shocks, for many frits, and for fertilizers.

5.5 Discussion of the criticality assessment

5.5.1 Data Sources

To perform this criticality assessment, data from Eurostat (Eurostat, 2016a), World Mining Data (World Mining Congresses, 2016) as well as MSA study (Bio Intelligence Service, 2015) were used. Data provided in this factsheet are an average over 2010-2014, unless specified in comment.

5.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 20). The value added data correspond to 2013 figures.

The stage assessed for the assessment of the supply risk is the extraction stage. The Supply Risk (SR) is calculated using both the HHI for global supply and the HHI for EU supply as prescribed in the revised methodology. Turkey is the main supplier of the EU with 98% of the natural borate imported.

5.5.3 Comparison with previous EU assessments

A revised methodology was introduced in the 2017 assessment of critical raw materials in Europe and both the calculations of economic importance and supply risk are now different; therefore the results with the previous assessments are not directly comparable.

The results of this review and earlier assessments are shown in Table 21.

Table 21: Economic importance and supply risk results for borates in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017.

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Borate	5.0	0.6		5.7	1.0		3.1	3.0

Although it appears that the economic importance of borate has reduced between 2014 and 2017 this is a false impression created by the change in methodology. The value added in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a 'megasector', which was used in the previous assessments. The economic importance result is therefore reduced. The supply risk score is higher compared to the previous assessments, which is due to the revised methodology and the way the supply risk is calculated. In terms of EU supply, Turkey (with a high WGI) is clearly dominant (98%) compared to the global supply breakdown (38%).

5.6 Other considerations

5.6.1 Future Supply and Demand Outlook

The consumption of borates is anticipated to increase in the coming years, mainly to increase in demand in the ceramic, glass and agricultural sector in South America and Asia. As a result of improvements in the building standards, in Europe and majority of the developing countries, an increase of demand for borates used in fiberglass building insulations is expected (USGS, 2016a), see Table 22.

The Jadar project in Serbia is a potentially world-class lithium-borate deposit discovered by Rio Tinto in 2004. If developed, it could supply a significant proportion of global demand for lithium and borates (Rio Tinto, 2015).

Table 22 : Qualitative forecast of supply and demand of tungsten (Data from Baylis, 2014)

Materials	Criticality of the material in 2017		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Borate	x		+	+	?	+	+	?

5.6.2 Environmental and regulatory issues

Diboron trioxide, tetraboron disodium heptaoxide(hydrate) (disodium tetraborate), boric acid, and lead bis (tetrafluoroborate), have been identified as Substances of Very High Concern (SVHC) under REACH legislation and were added to the candidate list in 2010 (European Commission, 2014). These compounds have also been classified as toxic for reproduction under category 1B of the EU CLP legislation (European Commission, 2014). In 2013, borates was added to the Registration, Evaluation, Authorization, and Restrictions of Chemicals (REACH) Restricted Substances List (RSL) in the European Union. As a result, the detergent makers are required to minimize their use of boron.

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5.8 Acknowledgments

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6. COBALT

Key facts and figures

Material name and Formula	Cobalt, Co	World/EU production (tonnes)[1]	135,497 / 1,233
Parent group (where applicable)	-	EU import reliance [1]	32%
Life cycle stage/ material assessed	Mine production/ Ore	Substitution index for supply risk [SISR)][1]	1.00
Economic importance (EI) (2017)	5.7	Substitution Index for economic importance [SI(EI)][1]	1.00
Supply risk (SR) (2017)	1.6	End of life recycling input rate	0%
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Battery chemicals (42%); Superalloys, hardfacing, high speed steel and other alloys (23%); Hard materials (10%).
Main product, co-product or by-product	Mostly a by-product or co-product with nickel or copper; less than 6% mined as a main product	Major world producers[1]	Democratic Republic of Congo (64%); China (5%); Canada (5%)
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] average for 2010-2014, unless otherwise stated;

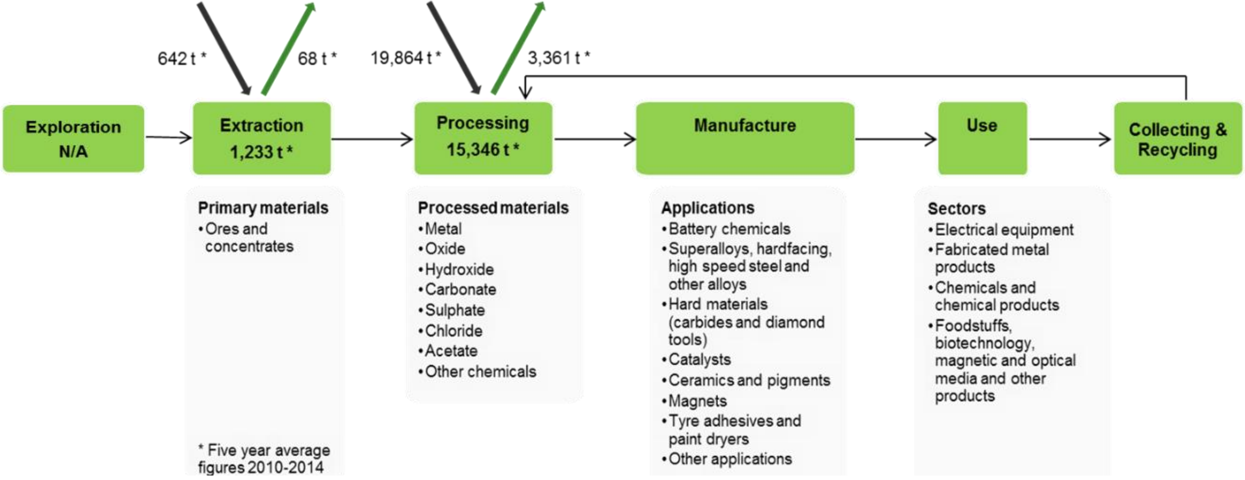

Figure 39: Simplified value chain for cobalt

The green boxes of the production and processing stages suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. EU reserves are displayed in the exploration box.

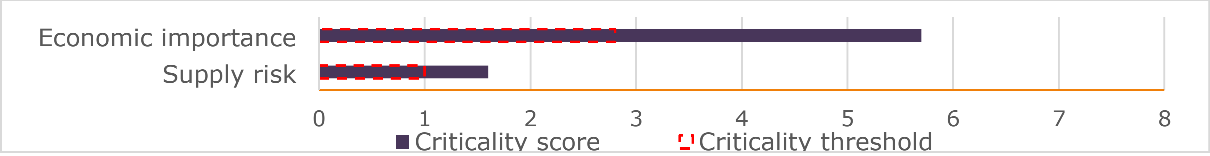

Figure 2: Economic importance and supply risk scores for cobalt

6.1 Introduction

Cobalt (chemical symbol Co) is a hard-wearing, ferromagnetic, silvery-blue metal with a hardness of 5.0 on Mohs scale and a melting point of 1495°C (1768 K). It has a thermal conductivity of 100 W m-1 K-1 and is both stable in air and unaffected by water. Cobalt has a relatively minor abundance in the Earth's crust, 26.6 parts per million, which is slightly more than lithium or niobium. In the upper crust, the abundance of Cobalt is 17.3 ppm (Rudnick, 2003). It is not found as a pure metal in nature but the element forms part of minerals such as cobaltite (CoAsS), skutterudite ($(Co,Ni)As_{3-x}$) and erythrite ($Co_3(AsO_4)_2 \cdot 8H_2O$). Most cobalt is produced as a by-product of nickel or copper refining. The main uses of cobalt are in battery chemicals (for Ni-Cd, Ni-metal hydride and Li-ion types), superalloys (for use in applications such as jet engines), hard materials (in carbides used for cutting tools), catalysts, ceramics and pigments (where it imparts a bright blue colour), magnets, tyre adhesives and paint dryers, and a number of other smaller applications (including foodstuffs, biotechnology, anodising, recording media and electrolysis). Cobalt is an essential trace element for human health, where it forms part of vitamin B12. Cobalt also has some hazardous properties including lung carcinogenicity for fine cobalt powders and some cobalt compounds, and therefore requires appropriate measures for safe handling and use.

Cobalt is mined as a by-product of nickel and copper mining in Finland but this represents approximately 1% of the annual worldwide total. Globally most cobalt is also mined as a by-product of nickel or copper and is only obtained as the main product in one deposit in Morocco. Refined cobalt products are produced in Finland, Belgium and France and the combined quantities of these countries represent 18% of the total produced in the world. The majority of the source material for this EU-28 refined production is imported.

6.2 Supply

6.2.1 Supply from primary materials

6.2.1.1 Geological occurrence

Cobalt can be found in economic concentrations in four main geological settings (Hannis & Bide, 2009): sediment hosted deposits; hydrothermal and volcanogenic deposits; magmatic sulphide deposits; and laterite deposits. Significant concentrations of cobalt also occur on the sea floor within manganese-rich nodules and cobalt-rich crusts although to date no cobalt has yet been extracted from these.

Sediment hosted deposits consist of organic-rich pyritic shales or sandstones that were deposited under reducing conditions in a near-shore lagoonal environment. They are primarily worked for copper with cobalt as a by- or co-product (Hannis & Bide, 2009). In some classifications these deposits are included within the following category because it is likely that hydrothermal fluids are also involved in the mineralisation process (Roberts & Gunn, 2014). The most significant example is the Central African Copperbelt which extends for 500 kilometres across north-western Zambia and south-eastern parts of the Democratic Republic of Congo.

Hydrothermal and volcanogenic deposits are actually a range of deposit styles, which involve the concentration of minerals by hydrothermal fluids usually as a result of by volcanic activity. Ore minerals occur along fault planes, fissures or cracks, in veins or as metasomatic replacement (Hannis & Bide, 2009). Significant examples occur as polymetallic deposits in Finland, Sweden, Norway, USA, Canada and Australia. The Bou

Azzer deposit in Morocco, where cobalt is currently extracted as a main product, also falls within this category.

Magmatic sulphide deposits are formed by a mafic or ultramafic magma where an immiscible sulfide phase has been formed which scavenges nickel and cobalt from the residual magma. These are subsequently deposited in discrete layers or lenses usually at or near the base of igneous intrusions. Significant deposits of this type include the Noril'sk deposit in Russia, the Sudbury deposit in Canada and the Kambalda deposit in Australia, all of which are primarily worked for nickel with cobalt as a by-product (Roberts & Gunn, 2014).

Laterite deposits are formed by intense weathering of ultramafic rocks in tropical or sub-tropical environments. If cobalt existed as silicates and sulphides within the host rock, it will be remobilized by these weathering processes and deposited, together with nickel, in surficial residual deposits (Hannis & Bid, 2009). Significant examples are found in New Caledonia (France) and Cuba.

6.2.1.2 Exploration

It is rare for cobalt to be the only objective in exploration activities. More usually it is one of a suite of metals identified during exploration for polymetallic deposits. During the Minerals4EU project it was identified that in 2013 exploration for polymetallic deposits, possibly containing cobalt, were undertaken in Poland, Portugal, Spain, Sweden and Greenland. However, cobalt may also have been the subject of exploration in other countries where no information was provided during the survey (Minerals4EU, 2015).

6.2.1.3 Mining, processing and extractive metallurgy

Cobalt is mainly extracted as a by-product or co-product with nickel or copper and consequently the techniques used for mining and the initial stages of beneficiation will depend on the processes required to extract those base metals. As with other metal mining, extraction can take place either in surface mines, if the ore deposit is not buried too deeply, or underground using standard mining methods. Due to increases in demand for cobalt and recent advances in processing technology it is also possible to extract cobalt from the mine tailings of current or former copper mines, where cobalt was present in the original ores but was not previously extracted (Hannis & Bide, 2009).

In all cases, the extraction processes will involve crushing the primary ore, separating the metal-bearing material from gangue using either physical or chemical techniques as appropriate and subsequent refining stages. The selection of the actual processes used will depend on the type and individual composition of ore being treated (as described more fully in Roberts and Gunn, 2014).

The metallurgical process that can be used, individually or in combination, for the production of pure cobalt metal can be classified broadly into hydrometallurgy or pyrometallurgy.

Hydrometallurgical processes rely on the differences in solubility and electrochemical properties between different materials. For cobalt extraction this generally includes some form of leaching often using hydrochloric or sulphuric acid, sometimes (but not always) at high pressures and temperatures. It can also include solvent extraction and electrowinning.

Pyrometallurgy uses the differences in the melting points and densities of different materials to separate them. The ore is heated together with a reducing agent to facilitate chemical reactions that separates the metals from other compounds. Some impurities are driven off in gaseous form and others are separated into a slag. After smelting, cobalt is normally still combined with nickel and the two are subsequently separated using electrolytic processes.

6.2.1.4 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of cobalt in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[6], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for cobalt. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for cobalt, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for cobalt at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

Within Europe, resources of cobalt are known to exist in Finland, Germany, Norway and Sweden but data for these are not reported in accordance with the UNFC system of reporting. Data for Germany is not reported at all because data collection in that country is the responsibility of sub-national level authorities. Resources may also exist in other European countries but no information is available (Minerals4EU, 2015).

Globally, the United States Geological Survey estimates resources to be approximately 25 million tonnes with the majority located in Democratic Republic of Congo, Zambia, Australia, Cuba, Canada, Russia and the U.S.A. Manganese nodules and cobalt-rich crusts on the sea floor are estimated as more than 120 million tonnes (USGS, 2016). Resource data for some countries in Europe are available in the Minerals4EU website (see Table 23) (Minerals4EU, 2014) but cannot be summed as they are partial and they do not use the same reporting code.

Global reserves of cobalt, estimated by the United States Geological Survey at about 7.1 million tonnes, are shown in Table 24. These are not necessarily reported in accordance with any internationally recognised system of reporting. Reserve data for some countries in Europe are available in the Minerals4EU website (see Table 25) but cannot be summed as they are partial and they do not use the same reporting code.

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[6] www.crirsco.com

Table 23: Resource data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2014)

Country	Reporting code	Value	Unit	Grade	Code Resource Type
Finland	JORC	507	Mt	0.021% Co	Measured
	NI43-101	81	Mt	0.014% Co	Measured
Ukraine	Russian Classification	9.15	kt	-	P1
Norway	NI43-101	4.625	Mt	0.02% Co	Indicated

Table 24: Estimated global reserves of cobalt in 2015 (Data from USGS, 2016)

Country	Estimated Cobalt Reserves (tonnes)	Percentage of total (%)
Democratic Republic of Congo	3,400,000	48
Australia	1,100,111	15
Cuba	500,000	7
Zambia	270,000	4
Philippines	250,000	4
Russia	250,000	4
Canada	240,000	3
New Caledonia (France)	200,000	3
Madagascar	130,000	2
China	80,000	1
Brazil	78,000	1
South Africa	30,000	<1
United States of America	23,000	<1
Other countries (unspecified)	610,000	9
World total (rounded)	*7,100,000*	*100*

Table 25: Reserve data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2014)

Country	Reporting code	Value	Unit	Grade	Code Reserve Type
Ukraine	Russian Classification	683	t	-	A
Finland	JORC	1.51	Mt	0.16% Co	Proved
	NI43-101	75	Mt	0.014% Co	Proven

6.2.1.5 World cobalt production

Cobalt is predominantly extracted as a by- or co-product of nickel or copper mining. The Cobalt Development Institute states that approximately 50% of global supplies of cobalt come from the nickel mining industry, whilst 44% is sourced from copper mining and only 6% from mining operations where cobalt is the primary objective (CDI, 2016).

Globally, cobalt is mined in 19 countries, as shown in Figure 40, with the largest producers being the Democratic Republic of Congo (with 64% of the global total, based on a five-year average over 2010-2014), China (6%) and Canada (5%). The world mine production of cobalt is about 135.5 thousand tonnes in average over the period 2010-2014 (BGS, 2016). Within the EU, cobalt is mined in New Caledonia (France) and Finland (respectively 2% and 1% of the global total) (BGS, 2016).

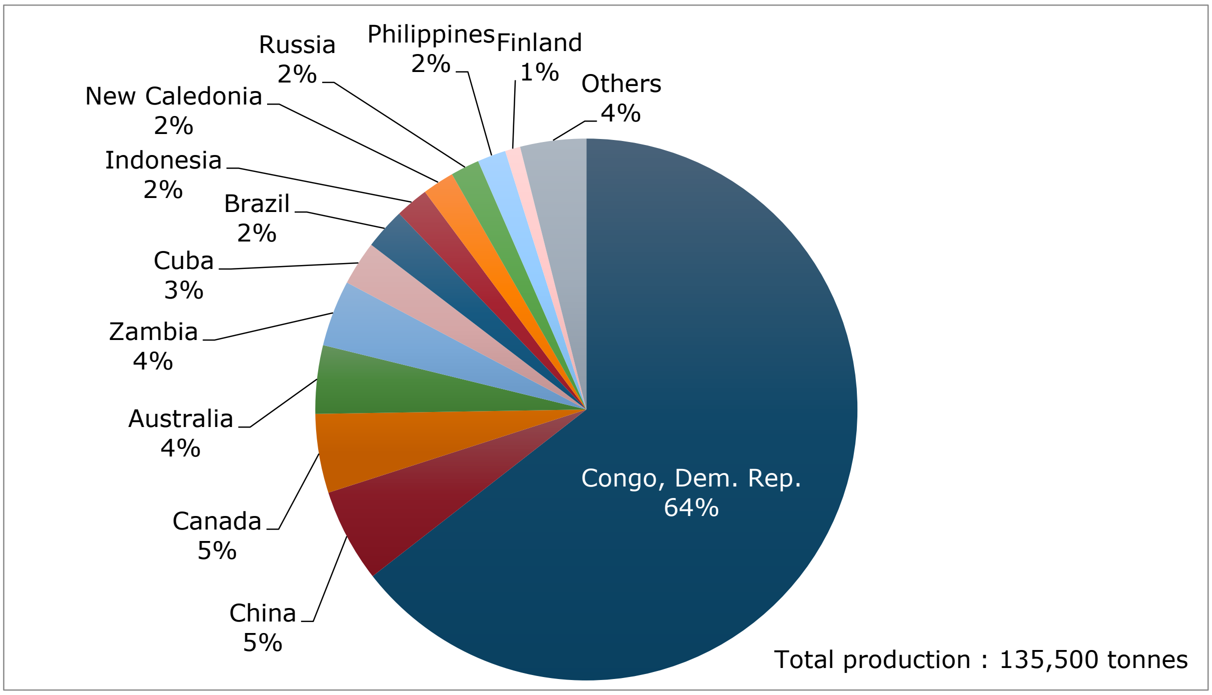

Figure 40: Global cobalt mine production, figures are percentage of global total, based on average production during 2010–2014 (Data from BGS World Mineral Statistics database; BGS, 2016). Other countries include (in order of production size) Morocco, South Africa, Madagascar, Papua New Guinea, Uganda, Botswana and Zimbabwe.

Refined cobalt (including both metal and chemicals) is produced, from domestic and/or imported ores, in 17 countries worldwide. The relative share of the global total held by the top producing countries, based on a five year average over 2010-2014, is shown in Figure 41. Other countries include (in order of production size) Brazil, Morocco, South Africa, Madagascar, India, Uganda and France. Within the EU, refined cobalt is produced in Finland (13% of the global total), Belgium (5%) and France (<1%) (BGS, 2016). The world production of refined cobalt is about 83.4 thousand tonnes in average over the period 2010-2014 (BGS, 2016).

The majority of the feed material for China’s production of refined cobalt is sourced from the Democratic Republic of Congo (DRC). According to data on the United Nations Commodity Trade database, between 92% and 99% of China’s imports of cobalt ores and concentrates came from that country in the years 2010–2014 (UN, 2016). Although the DRC is the largest global producer of mined cobalt, output from that country has declined from more than 99,000 tonnes in 2011 to 76,500 tonnes in 2014 (BGS, 2016), albeit production is believed to have increased in 2015. With China’s imports of cobalt ores and concentrates from DRC increasing this means that a smaller quantity will be available to other countries from this source.

The formula used in this review incorporates a calculated figure based on the Worldwide Governance Indicators developed by the World Bank. The figure calculated for DRC is the equal third highest (i.e. worst) of all the 210 countries included, on a par with North

Korea and Sudan and only better than Afghanistan and Somalia. DRC is widely considered to be one of the riskiest countries to do business and a source of so called 'conflict minerals'. However, within the DRC cobalt is mined, as a by-product of copper, in the southern province of Katanga and this region is not associated with the well-publicised armed conflicts that have taken place in the North and South Kivu provinces of eastern DRC. Consequently, and similarly to copper, cobalt is not one of the defined 'conflict minerals' because this term generally includes only gold, tantalum, tungsten and tin (CDI, 2011). Cobalt is produced in the South-Eastern province of Katanga where there is no armed conflict but where human rights abuses such as child labour have been observed. However, it should be noted that child labour is linked with illegal or poorly regulated artisanal mining, rather than with the large-scale mining industry.

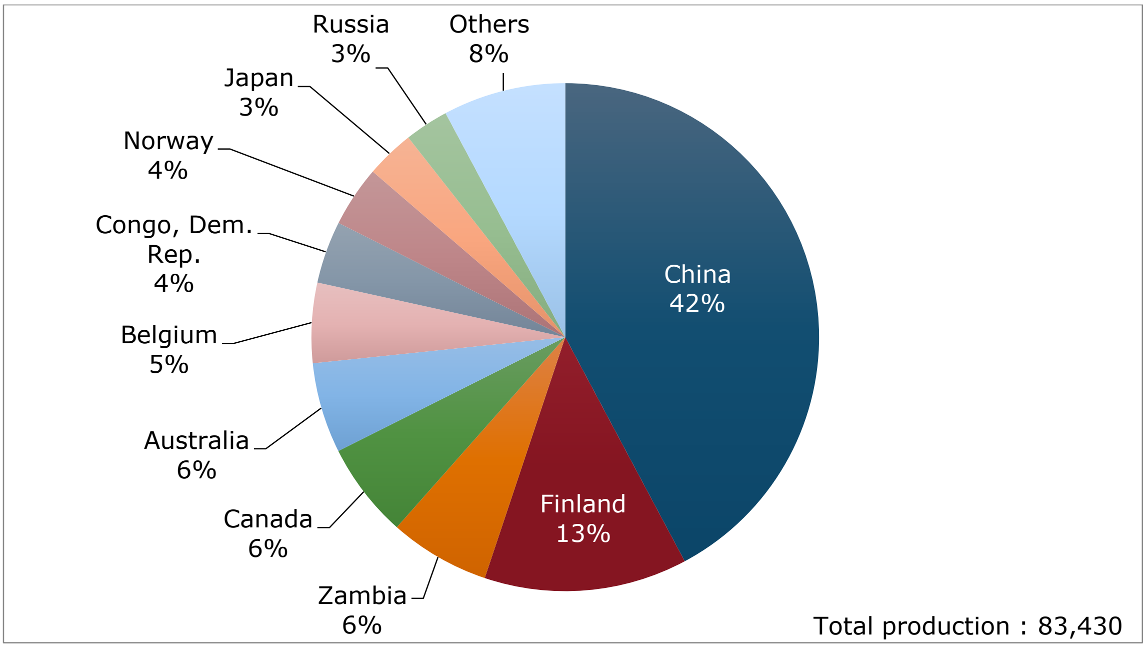

Figure 41: Global refined cobalt production, figures are percentage of global total, based on average production during 2010–2014 (Data from BGS World Mineral Statistics database - BGS, 2016)

Note: the term 'coltan' which is often associated with the issue of 'conflict minerals' relates to the minerals columbite and tantalite, which are sources of niobium and tantalum, not cobalt.

6.2.2 Supply from secondary materials

The end uses of cobalt are described more fully in section 6.3.2. Some of these uses are dissipative, e.g. as pigment in glass, ceramics, paints, etc., meaning that the cobalt is not available for recycling. However, cobalt used in other applications, such as superalloys, hard metals, batteries and even spent catalysts can be collected and either reused or recycled.

End-of-life scrap (sometimes termed 'old scrap') is defined as scrap arising from products that have been used but are no longer required because they have been worn out or become obsolete. Cobalt-bearing end-of-life scrap can be in the form of used turbine blades or other used parts from jet engines, used cemented carbide cutting tools, spent rechargeable batteries, magnets that have been removed from industrial or consumer equipment, spent catalysts, etc. (USGS, 2004).

The most significant factors in determining the quantity of 'old scrap' that is recycled is the efficiency of collection systems for the discarded products and the economics of recovering particular elements from the scrap. Usually cobalt is not the only metal contained within the scrap and the economics of recycling will be affected by the presence or absence of other metals of interest and the prices associated with those metals. For example the price of tungsten affects the quantity of hard metal scrap that is recycled and consequently the amount of cobalt that is recovered from this source. In certain circumstances cobalt-bearing alloys can be remelted and recast into new products without the different elements being separated, for example with aero-engine parts that are cast from certified content alloys. However, within Europe, alloys containing cobalt are predominantly recycled into stainless steel and the cobalt content is not recovered.

In addition, scrap metal is also generated during the manufacture of cobalt-bearing alloys and products (sometimes referred to as 'new scrap' or 'processing scrap'). This could be in the form of metal that did not meet required specifications, excess metal removed during pressing or forging, grinding sludge or turnings generated during machining processes, baghouse dust collected from the cleaning of gaseous emissions, loose material generated from powder metallurgical processes, etc. (USGS, 2004). Because of the cost of purchasing of raw materials, it is clearly in the manufacturer's interest to minimise the generation of 'new scrap' and wherever possible to reuse them within the manufacturing process.

There are many different indicators that can be used to assess the level of recycling taking place for any material. The United Nations Environment Programme (UNEP) estimated the end-of-life recycling rate for cobalt as 68% (UNEP, 2011), meaning that for every 100 tonnes of cobalt contained in end-of-life products 68 tonnes is recycled and available for reuse (i.e. 'old scrap'). This does not include scrap metal produced during manufacturing processes (i.e. 'new scrap'). The same report also estimated that for cobalt the recycled content of fabricated metal is 32% (UNEP, 2011), i.e. the total scrap, both 'old scrap' and 'new scrap', contained within the total quantity of cobalt metal used by manufacturers. It should be noted that the source of these percentage estimates was a report by the United States Geological Survey, which was based on data for 1998 and related to the U.S.A. only (USGS, 2004). The position is likely to have changed in the intervening period and, in any case, the position in Europe could be different to the U.S.A.

For this criticality assessment, a slightly different indicator has been used: end-of-life recycling input rate (EOL-RIR). This measures the quantity of end-of-life scrap (i.e. 'old scrap') contained within the total quantity of metal available to manufacturers (which would also include primary metal and 'new scrap').The end-of-life recycling input rate for cobalt ores is 0%.

6.2.3 EU trade

Due to the relatively small quantity of cobalt mined in the EU, the EU is reliant on imports for its supply. Whilst some imports of cobalt ores and concentrates do take place (as shown in Figure 42), a much larger quantity of cobalt is imported in other forms.

The criticality assessment for ores and concentrates used the trade code CN 2605 0000 'cobalt ores and concentrates' and assumed a cobalt content of 10%. Figure 42 illustrates the imports and exports of this material to and from the EU-28 collectively and demonstrates that the EU-28 is a significant net importer of cobalt ores and concentrates, even though the imports have drastically decreased over the 2010-2014 period.

The analysis for refined cobalt used data for 'oxides and hydroxides' (CN code: 2822 000); 'chlorides' (CN code: 2827 3930) and 'mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders' (CN code: 8105 2000). Cobalt is also traded as sulphate, carbonate, nitrate, acetate and other forms but data for these are not available. Each of these forms has a different cobalt content. For the 2017 criticality assessment 'oxides and hydroxides' was assumed to contain 72% cobalt and 'chlorides' 24% cobalt.

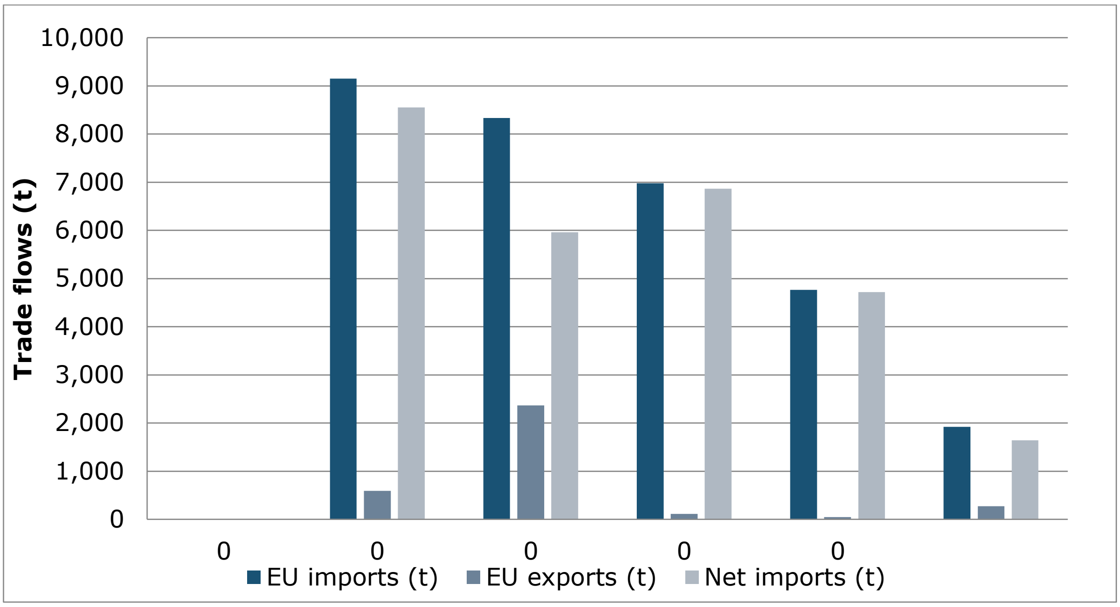

Figure 42: EU trade flows for cobalt ores and concentrates. (Data from Eurostat database (Comext, 2016a); assuming 10% cobalt content)

The third trade code used creates a significant problem in that the 'mattes and other intermediate products' may contain only 20% cobalt while the 'unwrought cobalt' or 'powders' are likely to be 100% cobalt and there are no data available to allow the user to distinguish the quantity of each within that one trade code. This makes it very difficult to track the exact flows of cobalt around the world.

Following discussions with the Cobalt Development Institute and the World Bureau of Metal Statistics, the trade data recorded against this code was adjusted for cobalt content in the 2017 criticality assessment by taking account of the value recorded in the trade statistics. If the value divided by the quantity resulted in an average price of less than €10 per kilogram the trade quantity was assumed to be predominantly 'intermediate' and a cobalt content of 20% was used. If the calculated average price was between €10 and €20 per kilogram it was assumed that the trade quantity was split 50:50 between intermediate forms and pure metal or powder. If the calculated average price was greater than €20 per kilogram it was assumed the traded quantity had a cobalt content of 100%. Other organisations conducting a similar exercise may use different cut-off values and/or different cobalt contents for intermediate products and as a consequence the results will be different.

Figure 43 illustrates the import and export flows of these materials to and from the EU-28 collectively and demonstrates that the EU-28 is a significant net importer of cobalt-bearing materials. Unsurprisingly, the import reliance calculated in this review was high with 52% of EU-28 consumption being supplied by imports.

The originating countries for these EU-28 imports are shown in Figure 44 for ores and concentrates and Figure 45 for refined cobalt. Figure 44 illustrates that the EU-28 is dependent on imports from Russia for cobalt ores and concentrates amounting to approximately 580 tonnes per year, the majority of which is imported by Finland. In average over the 2010-2014 period, the EU has imported about 642 tonnes of cobalt ores and concentrates.

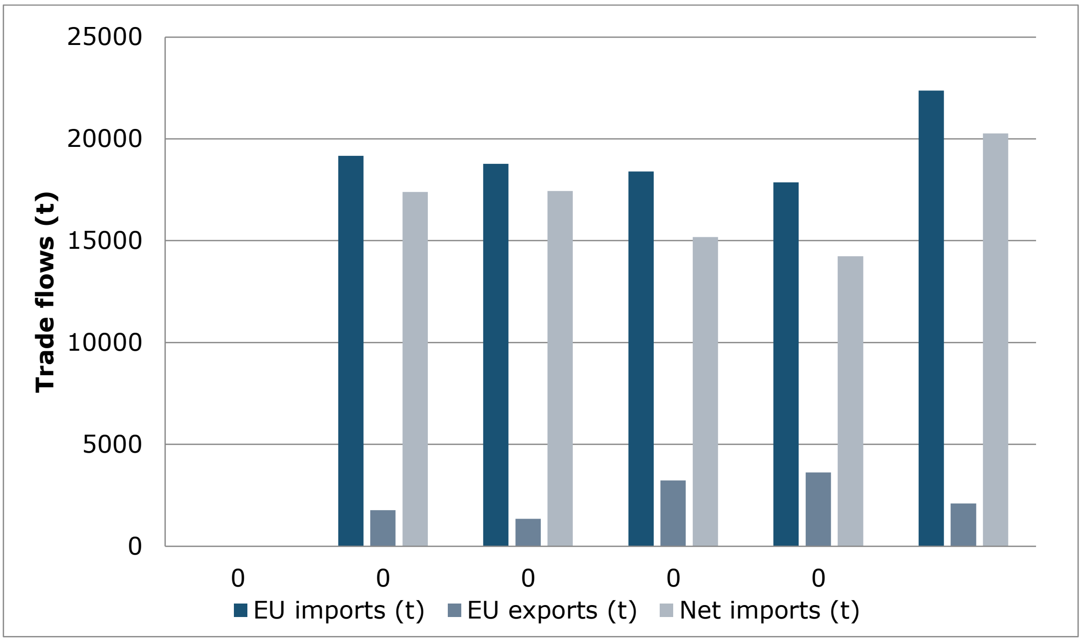

Figure 43: EU trade flows for cobalt oxides, hydroxides, chlorides, mattes, intermediate products, unwrought metal and powders. (Data from Eurostat database (Comext, 2016a); adjusted for cobalt content)

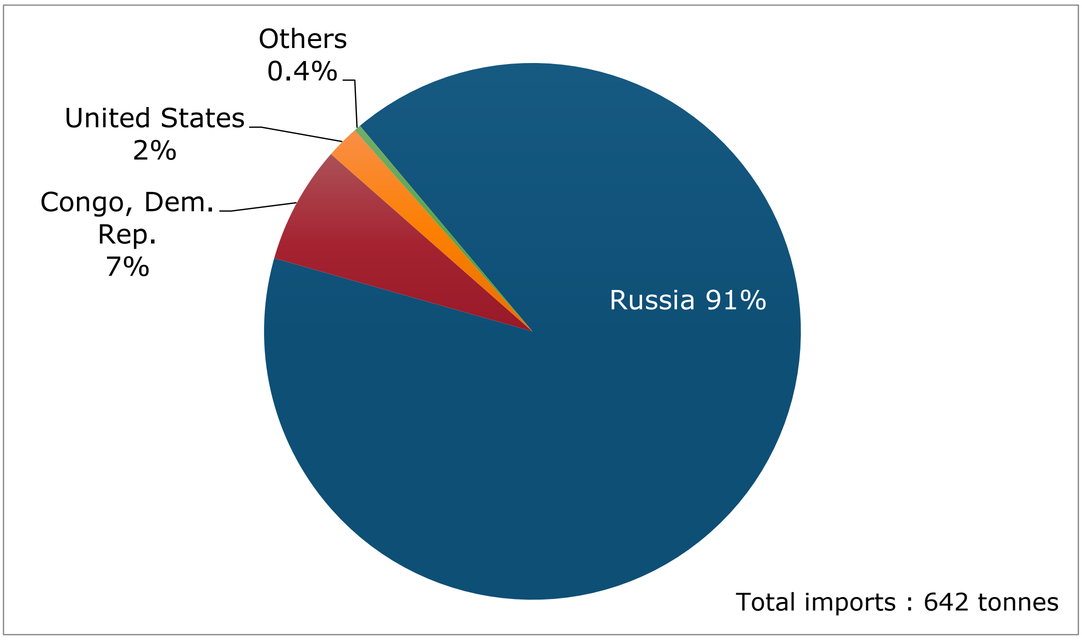

Figure 44: Originating countries for EU imports of cobalt ores and concentrates, average 2010–2014. (Data from Eurostat database (Comext, 2016a); adjusted for cobalt content)

Figure 45 illustrates that the EU-28 are dependent on imports of refined cobalt-containing materials from the Democratic Republic of Congo. This amounted to 48.2% of all imports to the EU-28 based on the calculated cobalt content of these materials or an average of more than 9,000 tonnes per year over the 2010–2014 period. By comparison, imports from Norway, the United States, Russia, South Africa and Canada amounted to 1,000–1,700 tonnes per year each and imports from all other countries were less than 1,000 tonnes per year each. In average over the 2010-2014 period, the EU has imported about 19,700 tonnes of refined cobalt-bearing materials.

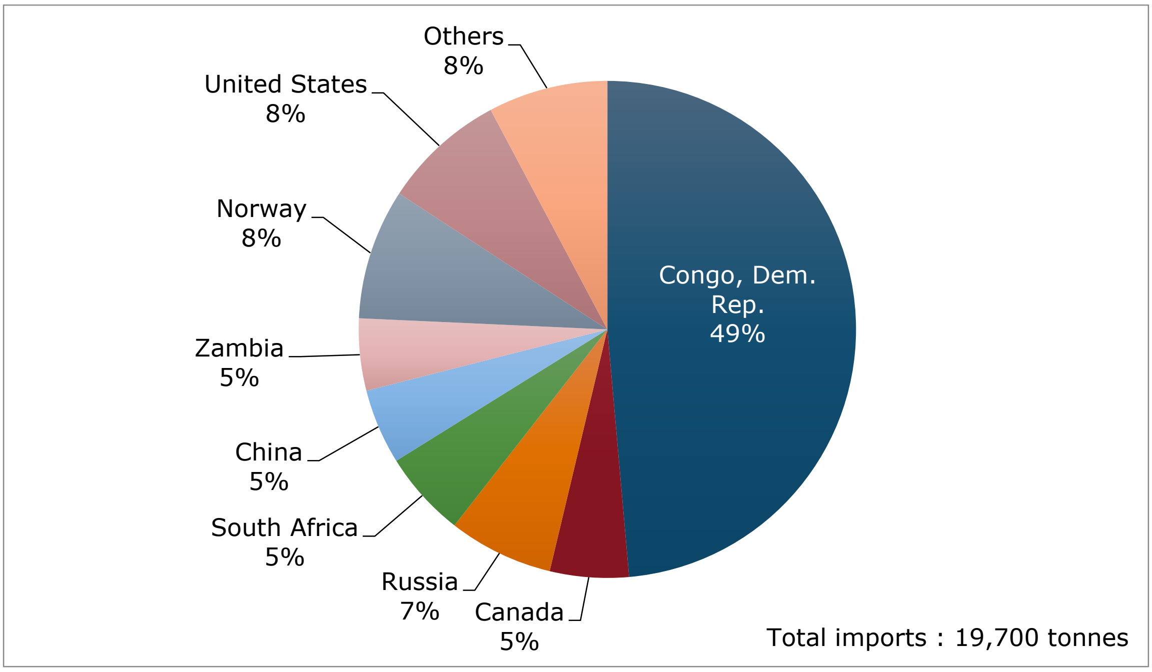

Figure 45: Originating countries for EU imports of cobalt oxides, hydroxides, chlorides, mattes, intermediate products, unwrought metal and powders, average 2010–2014. (Data from Eurostat database (Comext, 2016a); adjusted for cobalt content)

Over the same time period, China imported significantly larger quantities of cobalt. Whilst the oxides and hydroxides originated from a variety of different countries, the 'mattes, intermediate products, unwrought metal and powders' predominately come from the Democratic Republic of Congo (DRC). China's imports of the latter have increased from approximately 22,000 tonnes in 2010 to 28,000 tonnes in 2014 (adjusted for cobalt content) and the proportion of this sourced from DRC has also increased from 55% in 2010 to 70% in 2014 (UN, 2016). This trend increases the risk of supply disruption to other importing countries, including the EU-28, as a result of competition for material from China.

Regarding export restrictions, the Democratic Republic of Congo and China have imposed export taxes of up to 25% on cobalt ores and concentrates over the period 2010-2014 (OECD, 2016). Some EU free trade agreements are in place with minor suppliers such as South Africa and Turkey (European Commission, 2016).

6.2.4 EU supply chain

Cobalt is mined only in one EU-28 country, Finland, where it is a by-product of nickel or copper mining in 4 mines (Sotkamo, Kevitsa, Hitura and Kylylahti); however, on a global scale this production is relatively small (1,200 tonnes). New Caledonia (France) is a significant producer but cannot be considered as part of the EU even if it is a French overseas territory. As noted in Figure 42, based on averages over the period 2010–2014, just over 640 tonnes per year of cobalt is imported to the EU-28 contained within ores and concentrates. The EU import reliance for cobalt ores and concentrates is 32%. The Figure 46 presents the EU sourcing (domestic production + imports) for cobalt ores and concentrates.

According to data available from Eurostat, the vast majority of this also goes to Finland for processing with small amounts also going to Belgium, Netherlands and Germany and less than one tonne each to the United Kingdom, France, Portugal, Italy, Ireland, Czech Republic and Spain. The flow of material within the EU-28 was not been examined within the context of the 2017 criticality assessment, therefore it is possible the material was imported to a major port in one EU-28 Member State and then shipped to a processing plant in another EU-28 Member State. The majority of these imports are from Russia with smaller quantities from Democratic Republic of Congo, the United States and Canada and less than one tonne each from China, Turkey, Philippines, Uganda, India, South Africa and Hong Kong (Eurostat, 2016).

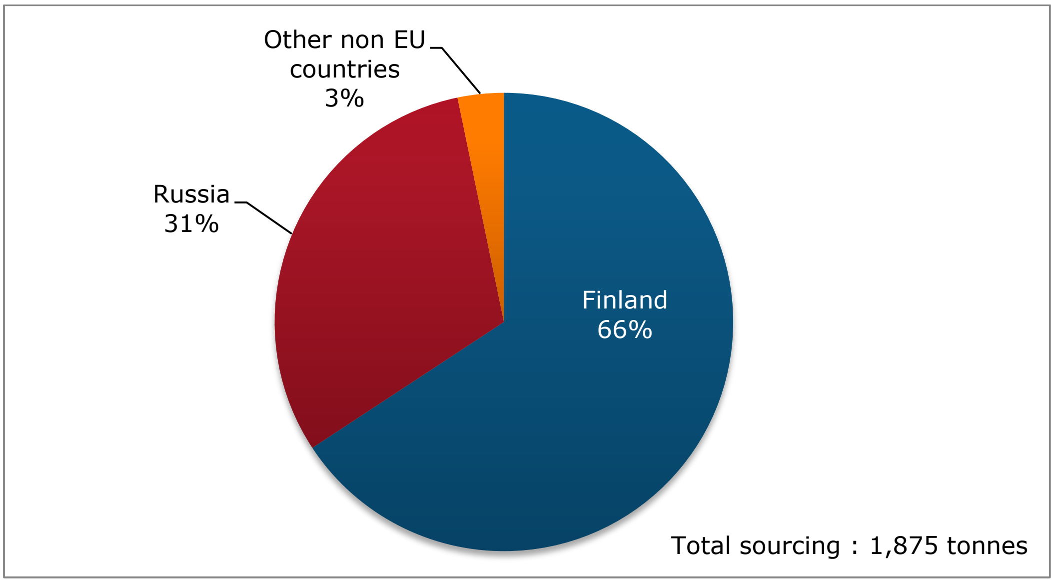

Figure 46: EU sourcing (domestic production + imports) of cobalt ores and concentrates, average 2010–2014. (Data from Eurostat database (Comext, 2016a; BGS, 2016); adjusted for cobalt content)

Refined cobalt is produced in three countries within the EU-28: Finland, Belgium and France (BGS, 2016). The Cobalt Development Institute lists output from Freeport Cobalt in Finland, Umicore in Belgium and Eramet in France. The figure for Umicore is footnoted as being their global total and will therefore include production in non-European countries (CDI, 2016). Freeport Cobalt is a joint venture company that purchased the Kokkola smelter in western Finland from OM group in 2013. Umicore processes precious and specialty metals, including cobalt, both from primary and secondary sources at five locations in Belgium. At its Sandouville-Le Havre refinery, Eramet produces cobalt as a by-product from refining nickel matte imported from New Caledonia (France).

Nearly 18,000 tonnes per year of cobalt contained in "cobalt mattes and other intermediate products, unwrought cobalt metal and cobalt powders" were imported to the EU-28 (again averaged over the 2010–2014 period), nearly 55% of which was delivered to Finland. More than 28% was imported by the Netherlands and over 8% by the United Kingdom. Also more than 400 tonnes of cobalt contained in "oxides and hydroxides" were imported, of which almost 58% went to Spain, 18% to Italy and nearly 17% to the Netherlands. In addition, more than 800 tonnes of cobalt contained in "chlorides" were imported, of which almost 99% went to Denmark (Eurostat, 2016). The originating countries for these imports are shown in Figure 45. These figures will not include nickel matte imported to the EU-28 which may also contain cobalt, as noted in the previous paragraph. In 2014, France imported more than 12,000 tonnes of nickel matte from New Caledonia (France); the cobalt content of this material is not recorded.

6.3 Demand

6.3.1 EU consumption

For mined cobalt, the EU consumption is approximately 1876 tonnes per year, on average over the 2010–2014 period. Of this 1233 tonnes per year (averaged over 2010–2014) came from within the EU (calculated as EU production – exports to non-EU countries) and the remaining nearly 642 tonnes was imported from outside the EU-28. In reality the picture is more complicated because it is believed that the cobalt that is mined in Finland is not recovered within the EU and it does not appear in export statistics because it is a by-product of other materials. It is also not clear whether the cobalt mined in the EU is actually recovered during processing of the copper or nickel concentrates in other countries or whether it is lost to tailings.

Apparent consumption of refined cobalt in the EU amounts to nearly 32,000 tonnes per year on average during 2010–2014. Of this only 12,000 tonnes per year (again averaged over 2010–2014) came from within the EU (calculated as EU production – exports to non-EU countries) and the remaining nearly 20,000 tonnes was imported from outside the EU-28. Other organisations have calculated different figures for apparent consumption in the EU-28 and this is probably because they have access to more detailed trade data which are not publically available through Eurostat. For example, during the stakeholder review process for the 2017 criticality assessments the Cobalt Development Institute advised that calculations performed on their behalf indicated EU-28 apparent consumption should be in the order of 10,500 tonnes per year (CDI, personal communication). These detailed calculations are commercially confidential, therefore it is not possible to replicate this figure and consequently it has not been incorporated into the criticality assessment.

In this review, import reliance is calculated as ('imports' – 'exports') / 'apparent consumption'. For cobalt ores and concentrates this was calculated as 32% and for refined cobalt as 52%.

6.3.2 Applications / end uses

All of the cobalt mined globally is either used as cobalt metal or for a variety of cobalt-bearing chemicals. For the criticality assessment on cobalt ores and concentrates it was assumed that 60% of mined cobalt was used in chemicals and 40% in metal applications.

The main categories of end uses for refined cobalt, sourced from the Cobalt Development Institute (2016), are shown in Table 26. Relevant industry sectors are described using the NACE sector codes in Table 26.

In batteries, cobalt is used in the positive electrode (cathode) in nickel-cadmium batteries and lithium-ion batteries and in both the positive and negative electrodes (cathode and anode) in nickel-metal hydride batteries. The electrodes in nickel-cadmium and nickel-metal hydride batteries each contain between 1% and 5% cobalt whereas electrodes in lithium-ion batteries can contain up to 50% cobalt although it depends on the precise composition used (CDI, 2006a). The significant increase in the numbers of portable electronic devices, most of which contain lithium-ion batteries, has driven considerable growth in demand for cobalt in recent years. In 2005, battery chemicals represented just 25% of global end uses of cobalt (CDI, 2006a), compared to the 42% in 2015 shown in Table 26 (CDI, 2016).

Superalloys are alloys that have been developed specifically to withstand elevated temperatures and cobalt is used in them because of its high melting point and superior corrosion resistance at high temperatures. The term 'hardfacing' refers to corrosion resistant, high temperature resistant coatings applied to protect other materials, and often these are alloys between cobalt, chromium and tungsten. High speed steels are steel alloys used for cutting tools and cobalt is used in several types where high temperature strength is required. Other alloys include cobalt-chromium alloys used in medical applications, controlled expansion alloys in which a proportion of nickel is replaced by cobalt and specialty steels for niche markets (CDI, 2006b).

The category 'hard materials' includes cemented carbide substances, which are used to cut metal, diamond grinding wheels, which are used to grind gem quality diamonds and diamond saws for stone cutting. Most carbides are manufactured from tungsten or molybdenum with cobalt used as a binding material. Cobalt is used to cement industrial diamonds in place on grinding wheels or is blended with industrial diamonds in the segments of a diamond saw (CDI, 2006c).

Cobalt oxides are used in desulphurisation catalysts during oil and gas refining, in combination with molybdenum trioxide and aluminium oxide. Cobalt acetate is mixed with manganese bromide as a catalyst in the production of chemicals used to manufacture certain plastics. Cobalt is also used in the synthesis of alcohols and aldehydes for the manufacture of detergents or plastics (CDI, 2006d).

One of the earliest known uses for cobalt is as a pigment to produce an intense blue colour in glass, porcelain, ceramics, paints, inks and enamels. In reality there is a variety of compounds containing cobalt that can be used to create a range of colours including purple, violet, green, pink, brown and yellow as well as blue, light blue and turquoise. Cobalt can also be used as a decolouriser to suppress yellow tints that originate from iron contamination (CDI, 2006d).

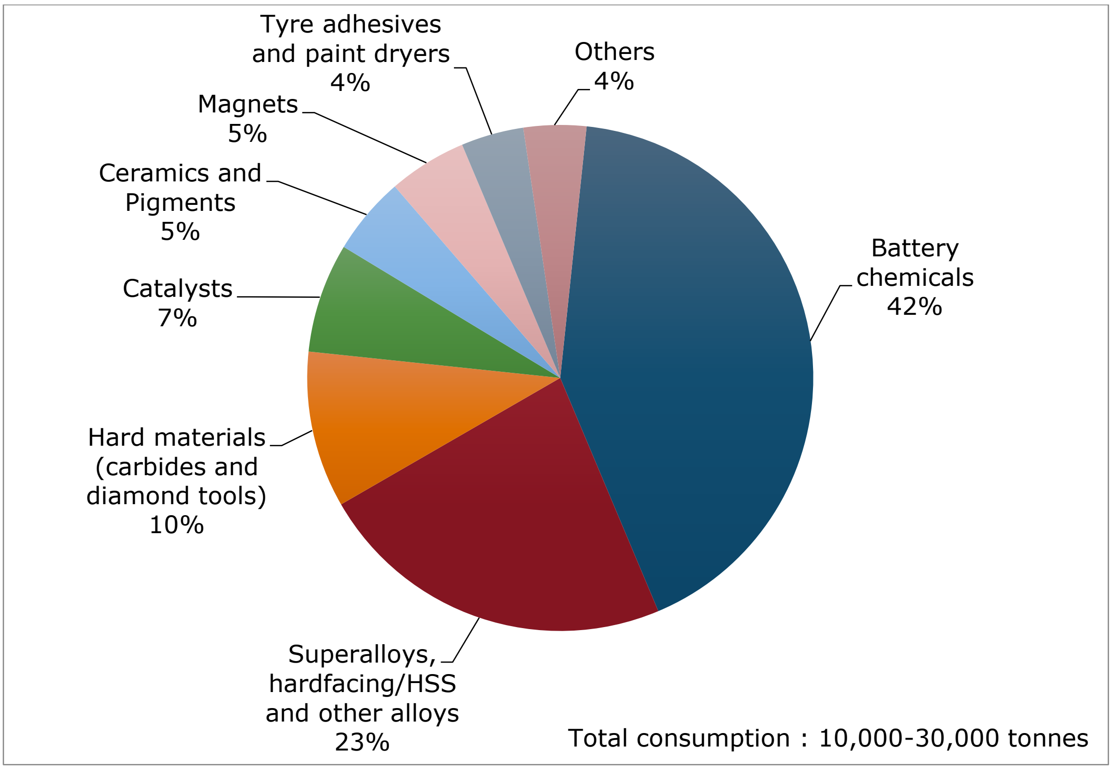

Figure 47: Global end uses of cobalt in 2015. (Data from the Cobalt Development Institute (CDI, 2016))

Table 26: Cobalt applications, 2 digit and examples of associated 4-digit NACE sectors, and the value added of those sectors (Data sourced from Eurostat, 2016c)

Applications	2-digit NACE sector	Value added of NACE2 sector (M€)	Examples of 4-digit NACE sector(s)
Battery chemicals	C27 – Manufacture of electrical equipment	84,609	C2720 – Manufacture of batteries and accumulators
Superalloys, hardfacing, HSS, other alloys	C25 – Manufacture of fabricated metal products	159,513	C2511 – Manufacture of metal structures and parts of structures; C2550 Forging, pressing, stamping and roll-forming of metal, powder metallurgy; C2561 – Treatment and coating of metals; C2573 – Manufacture of tools; also possibly C3030 – Manufacture of air and spacecraft and related machinery
Hard materials (carbides, diamond tools)	C25 – Manufacture of fabricated metal products	159,513	C2573 – Manufacture of tools
Catalysts	C20 – Manufacture of chemicals and chemical products	110,000	C2013 – Manufacture of other inorganic basic chemicals; C2059 – Manufacture of other chemical products n.e.c.
Ceramics and pigments	C20 – Manufacture of chemicals and chemical products	110,000	C2012 – Manufacture of dyes and pigments
Magnets	C27 – Manufacture of electrical equipment	84,609	C2711 – Manufacture of electric motors, generators and transformers; C2790 – Manufacture of other electrical equipment; also possibly C2620 – Manufacture of computers and peripheral equipment; C2680 – Manufacture of magnetic and optical media
Tyre adhesives and paint dryers	C20 – Manufacture of chemicals and chemical products	110,000	C2030 – Manufacture of paints, varnishes and similar coatings, printing ink and mastics; C2052 – Manufacture of glues

Cobalt is an essential element in many different types of magnet because it has the highest known Curie Point of 1121°C (this is the temperature at which permanent magnetism is lost). Cobalt is also added to improve thermal stability and corrosion resistance. Magnets containing cobalt are used in electric motors, generators, magnetic resonance imaging (MRI), microphones, loudspeakers, sensors, computer hard disk drives and many other applications (Hannis & Bide, 2009).

In a steel braced radial tyre, cobalt is used in a complex adhesive that bonds the rubber of the tyre to the steel bracing. Cobalt salts are used to accelerate drying in printing inks, varnishes and oil-based paints. The use of cobalt also increases the stability, resistance and flexibility of the dried material. Other metals can be used for this purpose, but using cobalt means that the inks, varnishes and paints dry several times faster (CDI, 2006d).

Cobalt forms part of vitamin B12 which is essential for metabolic processes and the production of red blood cells. Most herbivore animals obtain vitamin B12 from bacteria living in their intestines, but humans have to obtain it from food. Cobalt is of vital importance to all animals, albeit in tiny quantities and consequently it is sometimes added to animal feeds (CDI, 2006d). Cobalt underpins the high-value biotechnology industry in its use as an essential element for fermentation processes for the production of bio-medical devices (urine, blood test kits), antibiotics and other bio-medicines, as well as biogas.

6.3.3 Prices

For many years cobalt prices were only available from the London Metal Bulletin free-market quotation and this is still commonly used. The London Metal Exchange (LME) began trading in cobalt in 2010. Prices are available for two main grades 99.80% (high grade) shown in Figure 48 and 99.30% (low grade).

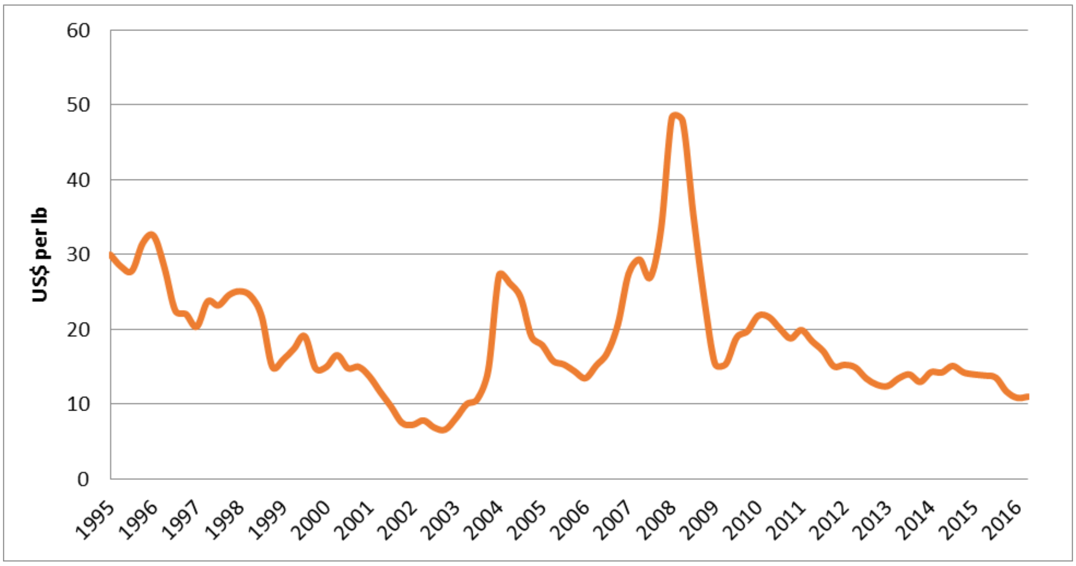

Figure 48: Global cobalt price trend, London Metal Bulletin Quarterly Average 99.80% grade. (Data from the Cobalt Development Institute (CDI, 2016))

According to the DERA raw materials price monitor and the LMB Bulletin, cobalt (high grade, 99.8%) prices have decreased since 2015 as it cost 31,86 US$/kg in average on the period 2011-2015 but only 25,67 US$/kg in average on the period December 2015 - November 2016, i.e. a price drop of 19.4%. The same trend can be observed for the cobalt low grade (99.3%), with a price drop of 17.2%, from 30,05 US$/kg in average on the period 2011-2015 but only 24,87 US$/kg in average on the period December 2015 - November 2016.

6.4 Substitution

Substitution has been included in this review of the criticality assessment in a completely new way. Each application has been considered in turn with both product to product and material to material substitute included in the assessment. Consideration has been given to the cost and performance of each potential substitute in each application, relative to that of cobalt, together with the level of production, whether or not the substitute was previously considered to be 'critical' and whether the potential substitute is produced as a by-, co- or main product.

Specific data relating to all of these criteria are often difficult to find and a number of assumptions have had to be made to complete the calculations. Consequently a significant degree of uncertainty is associated with the results. The level of precision shown for the Substitution Indices does not fully reflect this uncertainty.

With regards to cobalt ores and concentrates, no substitutes were included in the assessment because its direct applications (i.e. cobalt metal and cobalt chemicals) all require the element itself. Substitutes for refined cobalt were considered in the separate criticality assessment.

There are a wide range of different battery technologies available and all of these could be considered as potential substitutes for the varieties that contain cobalt. The most commonly known type is lead-acid batteries, but the following types have also been considered in the assessment: lithium-nickel-oxide, lithium-manganese-oxide, lithium-iron-phosphate and lithium-titanate. In all of these potential substitutes the performance is considered to be lower than for the battery types that contain cobalt and this has significant consequences for particular end uses of batteries. For example, it is possible to power electric vehicles or hand tools using lead-acid batteries, but to obtain the same level of performance as lithium-ion the battery pack would need to be so large that it would be impractical.

In the ‘superalloys, hardfacing, high speed steel and other alloys’ category potential substitutes that have been considered include composites (e.g. metal matrix composites, reinforced carbon-carbon composites), titanium-aluminides, nickel-based single crystal alloys, iron-based alloys and ceramic matrix composites. Not all of these can substitute for cobalt alloys in all applications and all these alternatives are considered to have reduced performance compared to cobalt alloys. Research has been undertaken in recent years with the aim of reducing weight and thereby increasing the efficiency of gas turbines (i.e. jet engines). However, the lead time required to certify new materials for the aerospace industry is long and as a consequence the rate at which cobalt is substituted in this application is low.For the ‘hard materials’ category consideration was given to nickel, nickel-aluminium, iron and ruthenium as potential substitutes for cobalt. As with the other application categories, all of these potential substitutes would result in reduced performance compared to cobalt. The cost of ruthenium would also inhibit substitution.

Substitutes for the other application categories were not considered in detail during the criticality assessment because their application shares were less than 10% of the total cobalt used. Whilst there are substitutes available for cobalt in many of these applications, the use of alternative materials normally results in a loss of performance. For example, cobalt complex dyes have a high light-fastness which cannot be achieved by using alternative dyes resulting in colour fading; an aspect which is particularly important in the automobile industry.

There is no substitute for cobalt in vitamin B12 and no substitute for vitamin B12 in human and animal health. The use of cobalt in biotechnology is largely connected with the bacterial synthesis of vitamin B12 and other pharmaceutical products and biomolecules. Consequently there is no substitute for cobalt in biotechnology.

6.5 Discussion of the criticality assessment

6.5.1 Data sources

Production data for cobalt ores and concentrates and refined cobalt were taken from the British Geological Survey’s World Mineral Statistics dataset (BGS, 2016). Trade data was extracted from the Eurostat COMEXT online database (Eurostat, 2016a) and used the

Combined Nomenclature (CN) codes 2605 0000 'cobalt ores and concentrates', 2822 0000 'cobalt oxides and hydroxides', 2827 3930 for 'cobalt chlorides' and 8105 2000 'cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders'. These data were averaged over the five-year period 2010 to 2014 inclusive and adjusted to take account of differing cobalt contents (as described in the previous sections). Other data sources have been mentioned elsewhere in this factsheet and are listed in section 6.7.

6.5.2 Calculation of economic importance and supply risk indicators

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 26). For information relating to the application share of each category, see section on applications and end-uses. As required by the methodology, the application shown as 'others' was distributed among the remaining applications. The figures for value added were the most recently available at the time of the assessment, i.e. 2013, and are expressed in thousands of Euros.

Two criticality assessments were carried out. For the first, the calculation of the Supply Risk (SR) was carried out at the ores and concentrates stage and for the second, the calculation of the Supply Risk (SR) was carried out at the refined material stage of the life cycle. In both cases the assessment used both the global HHI and EU-28 HHI calculation as prescribed in the methodology.

6.5.3 Comparison with previous EU criticality assessments

The results of this review and earlier assessments are shown in Table 27.

Although it appears that the economic importance of cobalt has reduced between 2014 and 2017, this is a false impression created by the change in methodology for calculating this indicator. In the 2014 assessment, the 'megasector' selected for the batteries application was listed as "electronics" which had a value added of 104,900 thousand Euros. In the 2017 assessment, the 2-digit NACE sector identified as the most appropriate for batteries was "manufacture of electrical equipment" which has a lower value added of 84,610 thousand Euros. If the 'megasector' was used instead of the 2-digit NACE sector then the EI indicator would have increased rather than the decrease suggested in Table 27. This illustrates exactly why a direct comparison between this review and the previous assessments should not be made.

Table 27: Economic importance and supply risk results for cobalt of the assessments performed in 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011		2014		2017	
Indicator	EI	SR	EI	SR	EI	SR
Cobalt	7.2	1.1	6.69	1.63	5.7	1.6

6.6 Other considerations

A range of cobalt-containing substances fall within the EU's Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) which came into force in 2007 albeit with a phased implementation. The future supply and demand for cobalt is presented in Table 28.

Table 28: Qualitative forecast of supply and demand of cobalt

Material	**Criticality of the material in 2017**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Cobalt	x		+	+	+	+	+	+

6.7 Data sources

6.7.1 Data sources used in the factsheet

Bio by Deloitte. (2015). Study on Data for a Raw Material System Analysis. Background data (unpublished)

BGS (2016). World Mineral Production 2010-2014 [online]. Keyworth, Nottingham British Geological Survey, Available at: http://www.bgs.ac.uk/mineralsuk/statistics/home.html

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Cobalt Development Institute. (2006c) Cobalt Facts – Cemented carbides. http://www.thecdi.com/cobaltfacts.php

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6.7.2 Data sources used in the criticality assessment

Bio by Deloitte. (2015). Study on Data for a Raw Material System Analysis. Background data (unpublished)

BGS (2016). World Mineral Production 2010-2014 [online]. Keyworth, Nottingham British Geological Survey, Available at: http://www.bgs.ac.uk/mineralsuk/statistics/home.html

Cobalt Development Institute. (2006) Cobalt Facts – Metallurgical uses. http://www.thecdi.com/cdi/images/documents/facts/COBALT_FACTS-Metallurgical_%20uses.pdf

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6.8 Acknowledgments

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7. FLUORSPAR

Key facts and figures

Material name and Formula	Fluorspar, CaF_2	World/EU production (ktonnes)[1]	6,615 / 290
Parent group	-	EU import reliance[1]	70%
Life cycle stage/ material assessed	Mine production / Fluorspar AG and MG	Substitution index for supply risk [SI (SR)][1]	0.97
Economic importance (EI) (2017)	4.2	Substitution Index for economic importance [SI(EI)][1]	0.98
Supply risk (SR) (2017)	1.3	End of life recycling input rate (EOL-RIR)	1%
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Steel and iron making (33%), Refrigeration and air conditioning (17%), Aluminum making and metallurgy (14%)
Main product, co-product or by-product	By product: fluorosilicic acid	Major world producers[1]	China (64%), Mexico (16%), Mongolia (5%)
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] average for 2010-2014, unless otherwise stated;

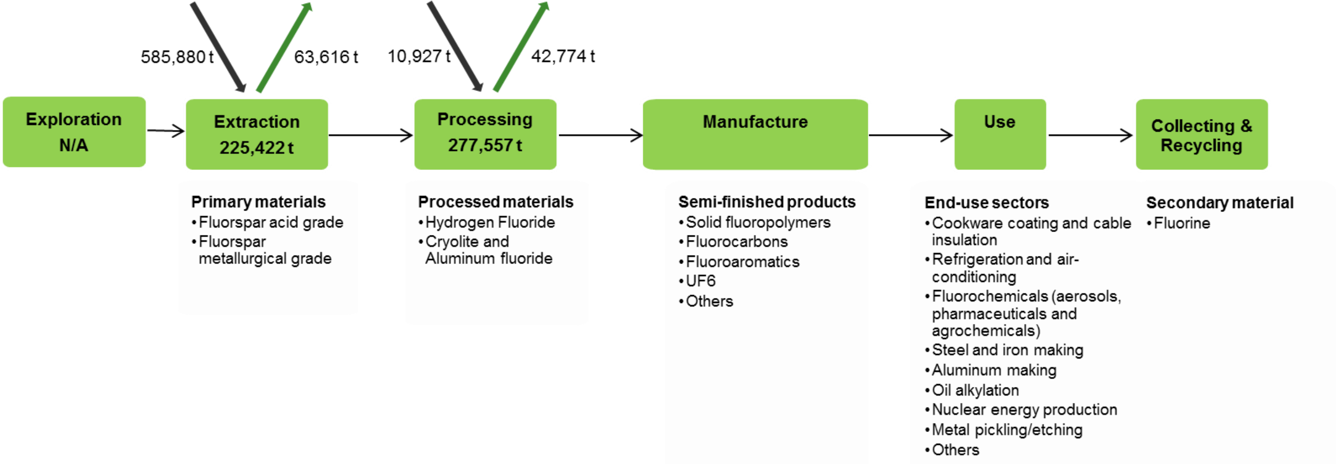

Figure 49: Simplified value chain for fluorspar

The green boxes of the production and processing stages in the figure above suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

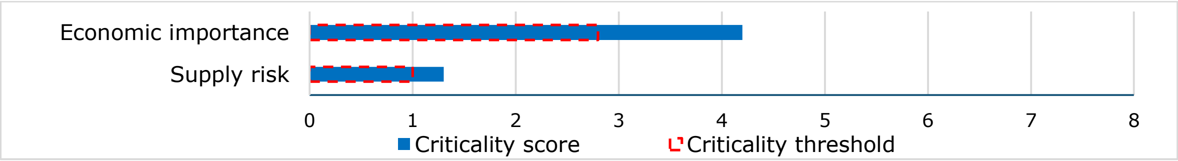

Figure 50: Economic importance and supply risk scores for fluorspar

7.1 Introduction

Fluorspar is the commercial name for the mineral fluorite (calcium fluoride, CaF_2). Fluorite is a colorful, widely occurring mineral that occurs globally with significant deposits in over 9,000 areas. Fluorspar is commonly produced in the form an acid grade (97% CaF_2 contained) or a metallurgical grade (84% CaF_2 contained). Fluorspar is mainly used to produce hydrofluoric acid, fluoropolymers as well as fluorochemicals for the refrigeration, air-conditioning, heat-pump, pharmaceutical and agrichemical industries. Fluorspar is furthermore used to produce welding fluxes and rods, metal casting additives, glass and glass fibre and as supplement in the cement industry.

The bulk of remaining fluorspar consumption is due to its low melting point, as a result it is used as flux in aluminum, steel and ceramics production processes.

In this factsheet, all the quantities are given in CaF_2 content.

7.2 Supply

7.2.1 Supply from primary materials

7.2.1.1 Geological occurrence

Most fluorspar (also known as fluorite) occurs as vein fillings in rocks that have been subjected to hydrothermal activity (BGS, 2011). These veins often contain metallic ores which can include sulfides of tin, silver, lead, zinc, copper and other metals. Fluorite is also found in the fractures and vugs of some limestones and dolomites (BGS, 2011). Fluorite is a common mineral in hydrothermal and carbonate rocks worldwide.

7.2.1.2 Fluorspar resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of fluorspar in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[7], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for fluorspar. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for fluorspar, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for fluorspar the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not

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[7] www.crirsco.com

always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

Identified world fluorspar resources were approximately 500 million tonnes of contained fluorspar (USGS, 2016). Fluorspar resources are widespread globally and major deposits can be found on every continent. About 4 million tonnes of contained fluorspar are located in the EU (Bio Intelligence Service, 2015). Resource data for some countries in Europe are available in the Minerals4EU website (see Table 29) (Minerals4EU, 2014) but cannot be summed as they are partial and they do not use the same reporting code.

Table 29: Resource data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2014)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
Spain	Adapted version of the USGS Circular 831 of 1980	4,794	kt	-	Measured
France	-	9.6	Mt (CaF_2 content)	-	Historic Resource Estimates
UK	-	25	Mt (CaF_2 content)	-	Historic Resource Estimates
Sweden	JORC	25	Mt	10.28%	Indicated
Norway	JORC	4	Mt	24.6%	Inferred
Poland	Nat. rep. code	0.54	Mt	-	C2+D
Ukraine	Russian Classification	18,500	kt	-	P1
Hungary	Russian Classification	?	Million m^3	2.9t/m^3	-
Serbia	-	0.8	Mt	27.01%	Historic Resource Estimates
Czech Republic	Nat. rep. code	2,033	kt	-	Potentially economic

World known reserves of fluorspar are estimated at around 250 million tonnes (as 100% equivalent CaF_2, equivalent to ores reserves of 406 million tonnes) (USGS, 2016). South Africa has the world's largest fluorspar reserves, followed by Mexico and China (See Table 30). There are about 10 years of reserves of fluorspar in the EU at the current rate of consumption (Bio Intelligence Service, 2015). Some data are available for Ukraine in the Minerals4EU website (Minerals4EU, 2014), with 8,779 kt of fluorine ores (Russian classification – RUS A), 199 Mt (Russian classification – RUS B) and 697 Mt (Russian classification – RUS C1) (Minerals4EU, 2014).

Table 30: Global reserves of fluorspar in year 2010 (Data from (BGS, 2011))

Country	Fluorspar Reserves (million tonnes)
South Africa	41
Mexico	32
China	24
Mongolia	12
Spain	6
Namibia	3
Kenya	2
Other countries	110

7.2.1.3 Mine production

After extraction, fluorspar ore is directly transformed into fluorspar acid grade (AG, 97% of CaF_2 contained) and metallurgical grade (MG, 84% of CaF_2 contained) (Bio Intelligence Service, 2015). The world annual production of primary material is around 6.62 million tonnes, mainly originating China and Mexico (USGS, 2016).

The European production of primary material is around 290 kt (BGS, 2016) and is entirely in the form of fluorspar AG (no production of fluorspar MG in the EU). Between 2010 and 2014, the EU production mainly took place in the UK, Spain, Germany and Bulgaria (Bio Intelligence Service, 2015), since the production ceased in France and Italy in 2006 (BGS, 2011). It must be noted that the fluorspar mine in Bulgaria was closed in early 2016, so Bulgaria is not a producing country for fluorspar anymore (Euromines, 2016; CRM Alliance, 2016).

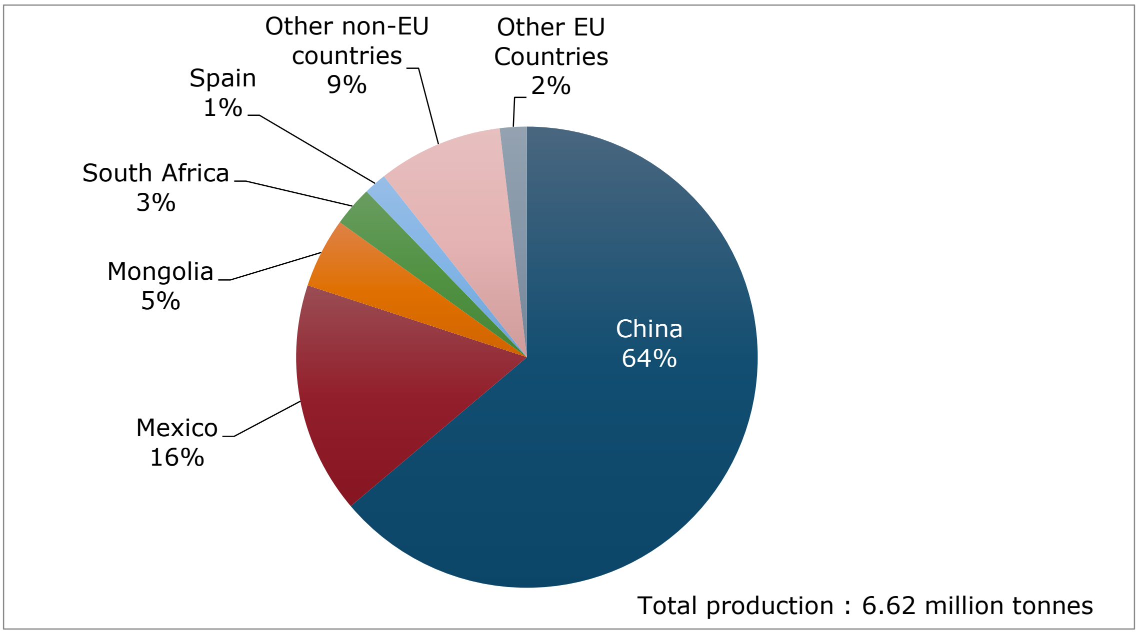

Figure 51: Global mine production of fluorspar, average 2010–2014 (Data from BGS, 2016)

7.2.1.4 Refining of fluorspar

The fluorspar acid grade (AG) and metallurgical grade (MG) are processed into hydrogen fluoride (HF), cryolite (Na_3AlF_6) and aluminum fluoride (AlF_3) (Bio Intelligence Service, 2015). Fluorspar MG is also used in iron and steel making, but is not incorporated in the iron and steel products. The processed material HF is converted into semi-finished products such as fluorocarbons, fluoropolymers, fluoroaromatics and uranium hexafluoride (UF_6, used in nuclear energy production) or is directly converted into finished products such as inorganic fluorine compounds. HF is also used for etching and pickling of metals and for alkylation process in oil refining but for these 2 applications there is no F element in the final products (Bio Intelligence Service, 2015). In the same way, cryolite and aluminum fluoride are used for aluminum processing but are not incorporated in aluminum alloys (Bio Intelligence Service, 2015). Fluorocarbons, fluoropolymers and fluoroaromatics are used in finished products in various applications such as cable insulation, fire protection, refrigerants, pharmaceuticals, etc. (European Commission, 2014).

7.2.2 Supply from secondary materials

Fluorspar is not recyclable (European Commission, 2014). The fluorspar contained in the waste mainly ends up in landfill (Bio Intelligence Service, 2015).

Although fluorspar itself is not recyclable, a few thousand tons of synthetic fluorspar are recovered each year during the uranium enrichment (as well as stainless steel pickling and petroleum alkylation. In the case of aluminum producers, during the smelting operations, HF and fluorides are recovered (USGS, 2015). In the air-conditioning and refrigeration sector, close to 60-70% of the fluorochemicals are recycled (The Chemours Company, 2016).

7.2.3 EU trade

According to Comext (Eurostat, 2016a), about 63 kt of fluorspar AG and MG (CaF_2 content) is exported from the EU, but there are no net exporters of fluorspar in Europe and all EU Member States are reliant on imports. Indeed, the quantities of fluorspar AG and MG imported are almost ten times higher, with about 586 kt (CaF_2 content) imported in average on the period 2010-2014 (see Figure 52). The import reliance is 70%.

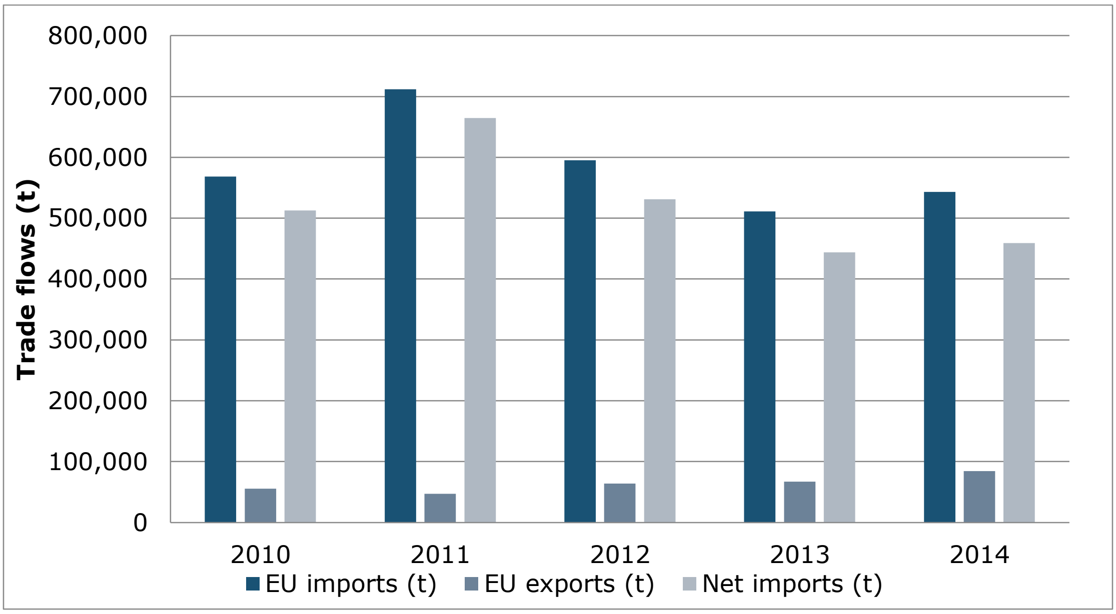

Figure 52: EU trade flows for fluorspar (Eurostat, 2016a)

The main suppliers of the EU are Mexico (38%), China (17%), South Africa (15%) and Namibia (12%) as shown in Figure 53 (Eurostat, 2016a). Currently there are EU free trade agreements in place with South Africa, Mexico and Morocco (European Commission, 2016). At the moment, there are no exports, quotas or prohibition in place between the EU and its suppliers of CaF_2 (OECD, 2016).

It must be noted that the fluorspar mine in Namibia was closed in 2014, taking approximatively 80,000t capacity out of the market. This will have an impact of the supply dynamic into Europe (CRM Alliance, 2016).

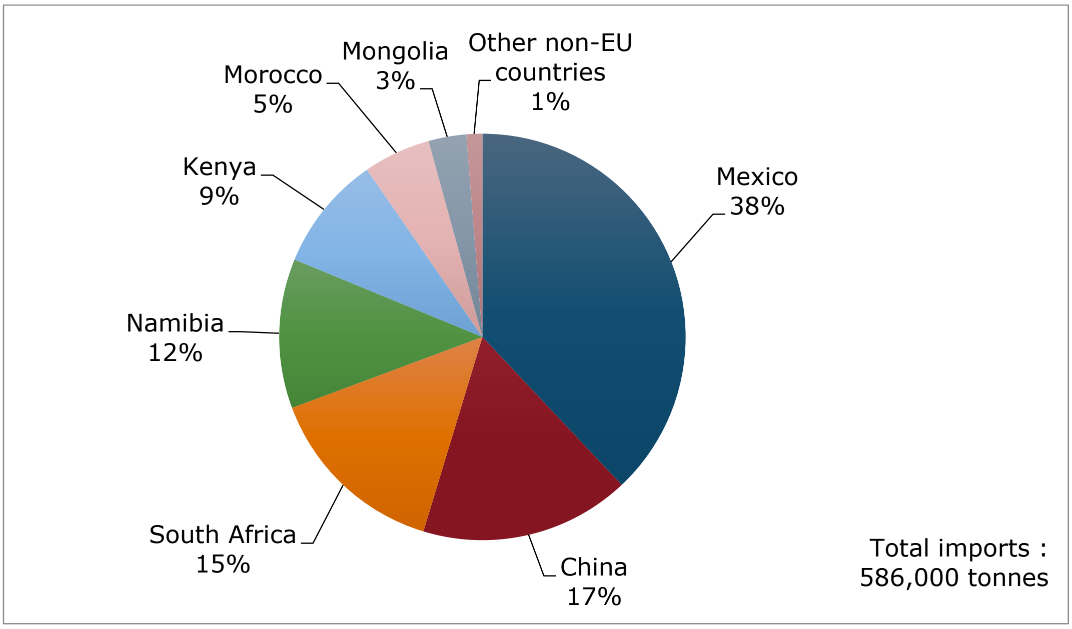

Figure 53: EU imports of fluorspar, average 2010-2014. (Data from Eurostat, 2016a).

7.2.4 EU supply chain

The European production of primary material is around 290 kt (CaF_2 content) (BGS, 2016) and is entirely in the form of fluorspar AG (no production of fluorspar MG in the EU). Between 2010 and 2014, the EU production mainly takes place in the UK, Spain, Germany and Bulgaria (Bio Intelligence Service, 2015), since the production ceased in France and Italy in 2006 (BGS, 2011). The fluorspar mine in Bulgaria was closed in early 2016, taking approximatively 30,000t capacity out of the market. This will have an impact on the import reliance in Europe (CRM Alliance, 2016)

Despite its production of fluorspar, the EU remains dependent on its foreign imports, with an import reliance of 70%. The Figure 54 presents the EU sourcing (domestic production + imports) for fluorspar.

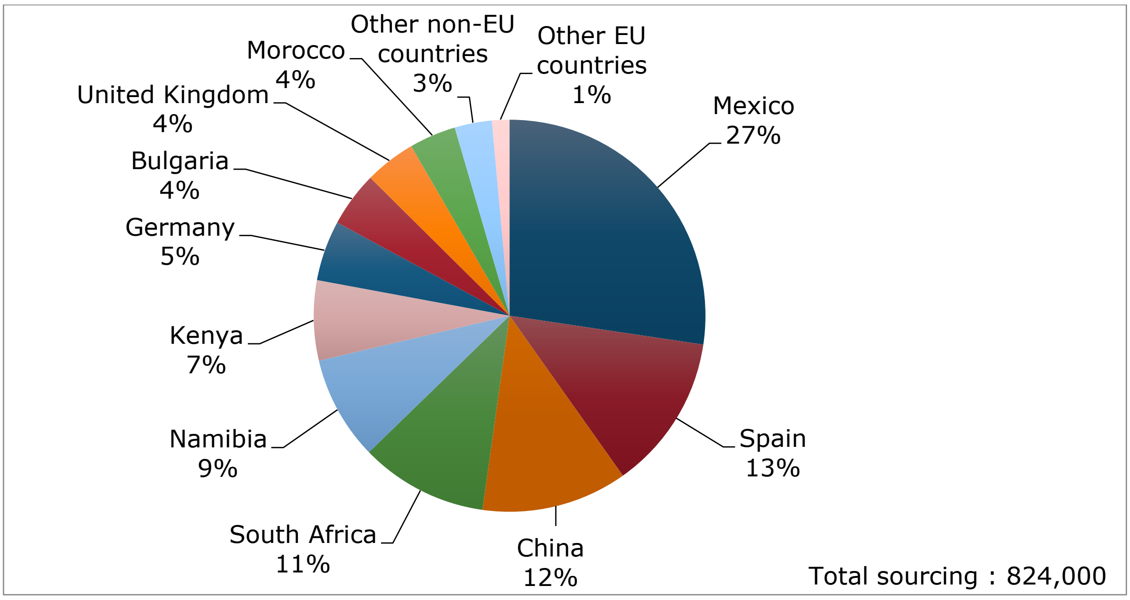

Figure 54: EU sourcing (domestic production + imports) of fluorspar, average 2010-2014. (Data from (Eurostat, 2016a; BGS, 2016))

China export quotas (550 000 t) ended in 2010 and export taxes (15%) in 2013 (OECD, 2016).

7.3 Demand

7.3.1 EU demand and consumption

The primary uses are in the metallurgical, ceramics and chemical industries; however, optical, lapidary (cut gems) and other uses (ornamental objects) are also important (European Commission, 2014). The majority of the world annual consumption is for the production of hydrofluoric acid (HF) and aluminum fluoride (AlF_3). The remainder of fluorspar consumption is utilized as a flux in steelmaking, in iron and steel casting, primary aluminum production, glass manufacture, enamels, welding rod coatings, cement production, and other uses and products (Bio Intelligence Service, 2015). There are many other uses for fluorspar including: fluoropolymer used in cookware, lubricants, building materials, and many other fluorine chemicals, but the main use of the mineral is to increase the fluidity of slags used in smelting flux (Bio Intelligence Service, 2015). Fluorspar, or calcium fluoride, is the principal source of fluorine, an essential ingredient in many industrial processes. Around half of all production ends up in fluorocarbons, the refrigerant gases used in refrigerators, air-conditioning units, and heat pumps, as heat transfer fluid, as blowing agent, as propellant in aerosols and pharmaceutical sprays, as fire extinguish ant and as solvent (The Chemours Company, 2016).

7.3.2 Uses and end-uses of fluorspar in the EU

Overall Europe consumes about 810 kt (CaF_2 content) of fluorspar for its industries, mainly from imports.

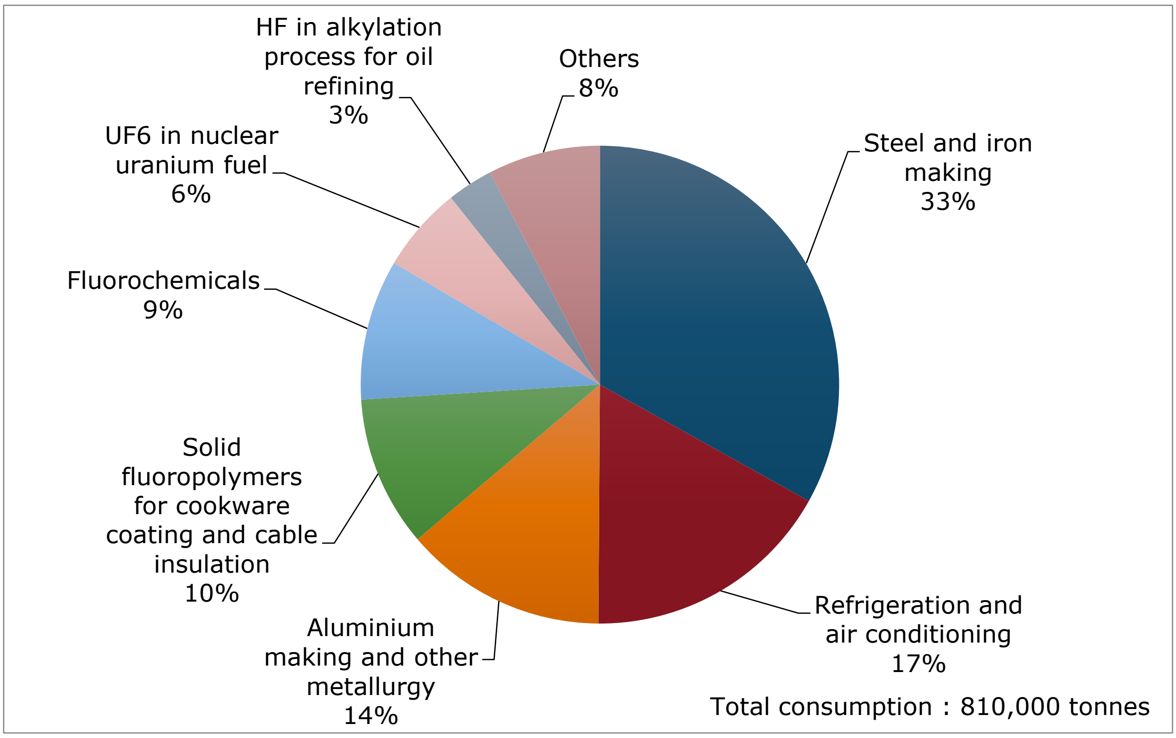

Figure 55: EU end uses of fluorspar. Average figures for 2010-2014. (Bio Intelligence Service, 2015)

Relevant industry sectors are described using the NACE sector codes (Eurostat, 2016c) in Table 31.

The end-use of fluorspar products in the EU are provided in the Figure 55 and can be summarised as follows (Bio Intelligence Service, 2015):

- Solid fluoropolymers for cookware coating, cable insulation and membranes: Solid fluoropolymers is used for cookware coating and cable insulation in household electrical appliances, lighting industry, telecommunications, aeronautics, nuclear, military, fuel-cells
- Refrigeration, air conditioning and heat-pumps: fluorochemicals are used for the production of refrigerants for refrigeration (refrigerator) and air conditioning in automobiles or other vehicles (military) and heat-pumps
- Steel and iron making: Metspar in Iron & Steel making (internal process use)
- Fluorochemicals: Used as Inorganic fluorine compounds, as well as in in the form of Fluoroaromatics in pharmaceuticals and agrochemicals industry and Aerosols (dissipative)
- UF6 in nuclear uranium fuel
- HF in alkylation process for oil refining
- Aluminium making and other metallurgy: fluorspar is used for aluminum processing (internal process use of AlF3 and cryolite), as well as Aqueous HF for pickling/etching applications (internal process use)

Table 31: Fluorspar applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016c)

Applications	**2-digit NACE sector**	**Value added of NACE 2 sector (M€)**	**4-digit NACE sectors**
Solid fluoropolymers for cookware coating and cable insulation	C27 - Manufacture of electrical equipment	84,609	C2750- Manufacture of electric domestic appliances; C2740- Manufacture of electric lighting equipment
Refrigeration and air conditioning	C27 - Manufacture of electrical equipment	84,609	C2750- Manufacture of electric domestic appliances; C2819- Manufacture of non-domestic cooling and ventilation equipment; C2750- Manufacture of electric domestic appliances
Refrigeration and air conditioning	C29 - Manufacture of motor vehicles, trailers and semi-trailers	158,081	C2920- Manufacture of electrical and electronic equipment for motor vehicles
Steel and iron making	C24 - Manufacture of basic metals	57,000	C2410- Manufacture of basic iron and steel and of ferro-alloys
Fluorochemicals	C20 - Manufacture of chemicals and chemical products	110,000	C2011- Manufacture of other organic basic chemicals; C2021- Manufacture of pesticides and other agrochemical products; C2029- Manufacture of other chemical products n.e.c.
UF6 in nuclear uranium fuel	C24 - Manufacture of basic metals	57,000	C2420- Processing of nuclear fuel
HF in alkylation process for oil refining	C19 - Manufacture of coke and refined petroleum products	13,547	C1920 - Manufacture of refined petroleum products
Aluminium making and other metallurgy	C24 - Manufacture of basic metals	57,000	C2420- Aluminium production; C2029- Manufacture of other chemical products n.e.c.

7.3.3 Prices

The majority of fluorspar is traded on annual contracts and only small amounts are sold on the open market (BGS, 2011).

After remaining relatively constant for many years, fluorspar prices rose rapidly between 2007 and 2009, due to a tightening of supply as a result of increased consumption within China and the implementation of Chinese export quotas (BGS, 2011). In 2009, there was a rapid decrease in prices from the 2008 peak due to weakened demand from fluorochemical sector; however prices remained higher than those of 2007 (see Figure 56). According to the DERA raw materials price monitor and the LMB Bulletin, acidspar prices have decreased drastically since 2015 as it cost 462,5 US$/t in average on the period 2011-2015 but only 277,1 US$/t in average on the period December 2015 - November 2016, i.e. a price drop of 40.1%.

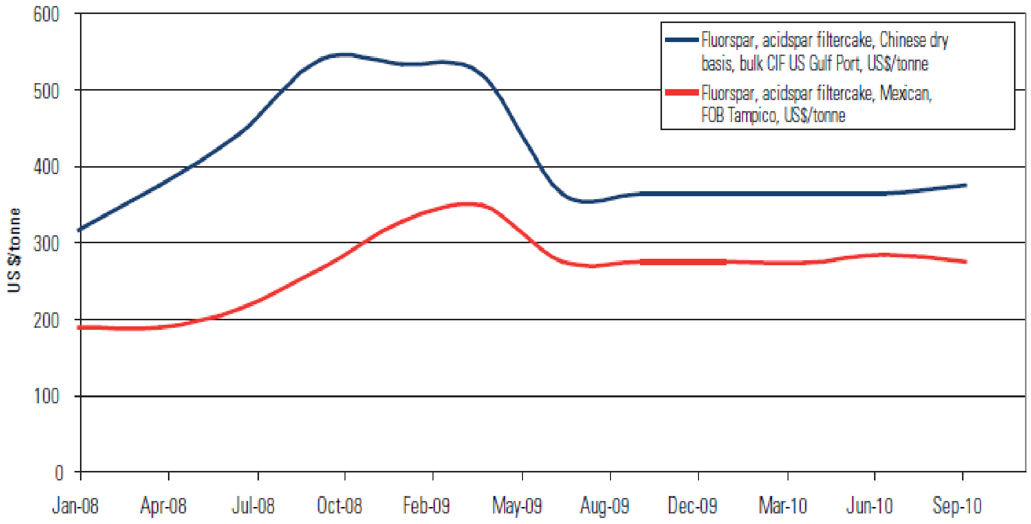

Figure 56: Prices of fluorspar (US$ per tonne) from 2008 to 2010 (Data from BGS, 2011)

7.4 Substitution

In the past, borax, iron oxides, aluminium smelting dross, silica sand, calcium chloride and titanium dioxide have been used as a possible substitutes for fluorspar (USGS, 2015). Especially, ammonia and CO_2 were used for replace fluorine-based air conditioning and refrigeration compounds, but they can be hazardous in terms of security of use (risk of explosion so they are used only in very limited applications (The Chemours Company, 2016). At the moment, there is a major push to substitute fluorine used in many industries (especially in the air condition and refrigerator sector) for a more environmentally friendly option (BGS, 2011). These alternative materials could include hydrocarbons such as propane.

Alternative material for solid fluoropolymers could include, but with a loss of performance (The Chemours Company, 2016):

- Plastics
- Stainless steel
- Ceramics
- Aluminum

In the iron and steel making sector alternatives could include, but with a loss of performance:

- Calcium aluminate
- Aluminum smelting dross

7.5 Discussion of the criticality assessment

7.5.1 Data Sources

To finalize this criticality assessment, data from Eurostat (Eurostat, 2016a; Eurostat, 2016b), as well as MSA study (Bio Intelligence Service, 2015) were used. Data provided in this factsheet are an average over 2010-2014, unless specified in comment. CN8 codes used for the EU supply, based on: 25292200 (97% CaF2 contained) and 25292100 (84% CaF2 contained).

7.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 31). The value added data correspond to 2013 figures.

The life cycle stage assessed in for the SR indicator is the extraction step; CaF_2 processed materials under study are: Fluorspar Acid Grade, and Fluorspar Metallurgical Grade. The Supply Risk (SR) is calculated using both the HHI for global supply and the HHI for EU supply as prescribed in the revised methodology.

7.5.3 Comparison with previous EU assessments

The results of this review and earlier assessments are shown in Table 32.

Table 32: Economic importance and supply risk results for fluorspar in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Fluorspar	7.5	1.63		7.18	1.72		4.2	1.3

Although it appears that the economic importance of fluorspar has reduced between 2014 and 2017 this is a false impression created by the change in methodology. The value added in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a ‘megasector’, which was used in the previous assessments. The economic importance result is therefore reduced. The supply risk has slightly decreased from the two previous exercises but as no major changes in the fluorspar market occurred during the period 2010-2014, we assumed that this change is due to the methodology, and in particular to the consideration of the EU supply.

7.6 Other considerations

In terms of future outlook, there are number of concerns regarding the safety of HF, future supplies and the environmental issues that could arise with the use of fluorochemical-based products. Due to the economic downturn in China during 2012-13 global fluorspar consumption was reduced, resulting in low-capacity-utilization rates of HF and AIF_3 operations in China (USGS, 2015).

In the coming years the future demand for fluorspar will highly depend on the development and use of fluorocarbon substitutes; considering that the use of fluorocarbon in refrigeration will be phased down, especially for HFCs with high GWP (F Gas Regulation EU 517/ 2014; The Kigali Amendment to the Montreal Protocol). Currently hydrofluoroolefins (HFO-1234ze, HFO-1234yf, HFO-1233zd), due to their low GWP, and mixtures based on HFOs are considered to be the most likely replacement

(The Chemours Company, 2016). It is important to mention that due to the high amount of fluorine used in the manufacturing process, the fluorspar industry will be able to take advantage of such new developments (USGS, 2016). No reliable forecast for the EU demand and supply for the next 5, 10 and 20 years have been obtained from market and industry experts (Table 33).

Table 33: Qualitative forecast of supply and demand of fluorspar

Materials	Criticality of the material in 2017		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Fluorspar	x		?	?	?	?	?	?

On the global level, due to the shift of fluorocarbons and HD production to China as well as transfer of aluminum smelting industries to areas with lower-energy cost, the market for fluorspar in the developed nations has become stagnant. In the coming years, China is expected to remain the leading consumer of fluorspar globally (USGS, 2015).

7.7 Data sources

7.7.1 Data sources used in the factsheet

BGS (2011). Mineral Planning Factsheet - Fluorspar, [online] Available at: https://www.bgs.ac.uk/downloads/start.cfm?id=1405 [Accessed August 2016].

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Eurostat (2016)b. Statistics on the production of manufactured goods (PRODCOM NACE Rev.2). [online] Available at: http://ec.europa.eu/eurostat/data/database

Eurostat (2016)c. Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E). [online] Available at: http://ec.europa.eu/eurostat/en/web/products-datasets/-/SBS_NA_IND_R2

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7.7.2 Data sources used in the criticality assessment

BGS, (2010). Mineral Planning Factsheet - Fluorspar, [online] Available at: https://www.bgs.ac.uk/downloads/start.cfm?id=1405 [Accessed August 2016].

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7.8 Acknowledgments

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8. GALLIUM

Key facts and figures

Material name and Element symbol	Gallium, Ga	World/EU production (tonnes)[1]	Refining : 340 /30
Parent group (where applicable)	N/A	EU import reliance[1]	34%
Life cycle stage/material assessed	Processing / Ga metal (99.99%)	Substitute index for supply risk [SI (SR)]	0.96
Economic importance (EI) (2017)	3.2	Substitute Index for economic importance [SI(EI)]	0.95
Supply risk (SR) (2017)	1.4	End of life recycling input rate (EoL-RIR)	0%
Abiotic or biotic	Abiotic	Major end uses in the EU	Integrated circuits (70%), LED lighting (25%), CIGS solar cells (5%)
Main product, co-product or by-product	By-product of aluminium production and partly zinc	Major world producers (refined Ga production capacity)[1]	China (85%), Germany (7%), Kazakhstan (5%)
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] 2010-2014 average unless otherwise stated

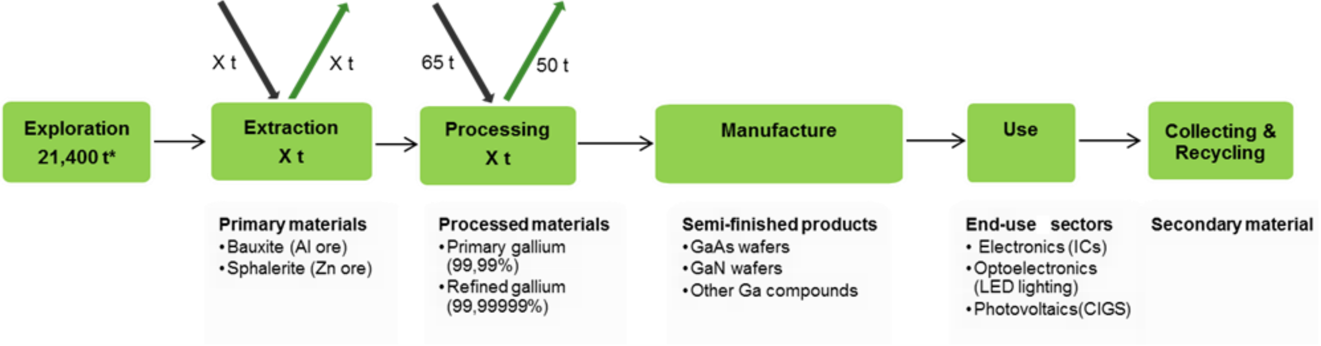

Figure 57*: Simplified value chain for gallium*

The green boxes in the above figure suggest that activities are undertaken within the EU. The black arrows represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR below is. 70%. *Estimates for EU resources of gallium need to be interpreted with caution.

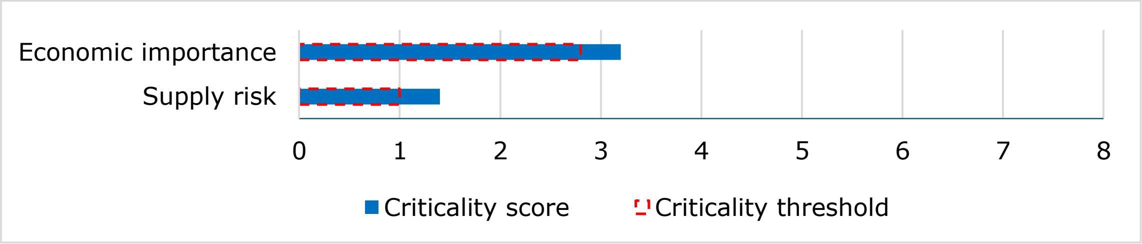

Figure 58: Economic importance and supply risk scores for gallium

8.1 Introduction

Gallium (chemical symbol Ga, from Gallia, the ancient Latin name for France) is a soft, silvery-white metal. It is an excellent conductor of both electricity and heat, has a very low melting point (30°C), and is a magnetic material. Gallium's abundance in the upper continental crust is 17.5 ppm, which is comparable to the one of lead (Rudnick, 2003). However, gallium does not occur in its elemental form in nature and mostly substitutes for other elements in certain minerals such as gallite ($CuGaS_2$) (Butcher, 2014). Gallium is rarely found in sufficient quantities by itself to enable economic extraction and is currently almost exclusively extracted as a by-product of aluminium production (and to a much a lesser degree of zinc production).

Gallium arsenide (GaAs) and gallium nitride (GaN) are the main intermediary compounds for Ga end-uses because they display exceptional semiconductor properties, with electron mobility six times higher than in silicon. They are mainly employed in integrated circuits (ICs), light emitting diodes (LEDs), and to a lesser extent in solar cells (CIGS technology).

There is a quite mature supply chain in the EU, with production capacities in Germany and Hungary, and various manufacturers of Ga-based products.

8.2 Supply

8.2.1 Supply from primary materials

8.2.1.1 Geology, mining and processing

8.2.1.1.1 Introductory note

Gallium is almost exclusively obtained as by-product during the processing of other metals. Therefore, the term "primary gallium" (or its synonyms "virgin gallium", or "crude gallium", also found in the literature) must be used with caution. There is no mining extraction of gallium per se. "Primary gallium" refers to the Ga metal of a purity of 3N (99.9%) or 4N (99.99%) obtained after the first steps of processing. "Refined gallium" refers to a purity of 6N or 7N obtained after further processing.

8.2.1.1.2 Recovery as a by-product of aluminium processing

The production of gallium from bauxite remains by far the primary source of supply. Gallium is present in bauxite, the main ore of aluminium, as a trace element. It would originate from minerals such as feldspar or nepheline (Deschamps et al., 2002). Both aluminium and gallium are released from these minerals during weathering processes and their similar geochemical properties result in the enrichment of both elements in bauxite (Dittrich et al., 2011). The ratio of gallium to aluminium, and therefore the concentration of gallium, in bauxite increases with greater intensity of weathering. Gallium also appears to be more abundant where the bauxite was derived from alkali source rocks (Weeks, 1989). The gallium content in bauxite can vary from 10 to 160 ppm (Mordberg et al., 2001; Bhatt, 2002). On average, it is reported to be 57 ppm (Schulte, 2014).

About 90% of bauxite mined in the world is converted into alumina using the Bayer process. The 'Bayer liquor' is formed during this process as a result of the reactions of aluminium trihydroxide and aluminium oxide hydroxide with aqueous caustic soda. This sodium aluminate solution is recycled on a continuous basis. It contains equilibrium concentrations of 100–125 ppm of gallium.

To recover gallium from the Bayer liquor, the stream of liquid is tapped and the crude gallium metal is extracted by electrodeposition or electrolysis employing ion-exchange resins, most usually using proprietary techniques specific to companies. Gallium at this stage has a purity of up to 99.9% (3N), with impurities occurring in the surface oxide or as finely dispersed phases in the metal. Filtration of the liquid gallium and heating under vacuum remove such impurities. Then, either electrolytic refining, or washing with hydrochloric acid will bring the metal up to 4N purity. It is the main commercial form of Ga.

An important consideration for an alumina producer is that both the types of resin used for electrolysis and their longevity have an important bearing on the cost of extracting the gallium from the Bayer liquor, as does the purity of the liquor itself. Extraneous and/or unexpected impurities in the liquor can drastically reduce the life of resins and drive up costs, which is a reason why only a fraction of gallium’s total resources in bauxite has traditionally been recovered (Moss et al., 2011).

8.2.1.1.3 Recovery as a by-product of zinc processing

Gallium concentrations in the zinc ore, sphalerite, are known to increase as the temperature of deposition decreases, although it can still be present in intermediate and higher-temperature deposit types (Stoiber, 1940; Cook et al., 2009).

In the hydrometallurgical route for zinc production, zinc oxide is first produced by roasting the zinc sulphide (sphalerite). The gallium-bearing zinc oxide is then leached with sulfuric acid to produce a zinc sulphate solution. The impurities, which include gallium, are removed through the addition of antimony or arsenic trioxide, zinc dust or proprietary reagents. The gallium is then extracted from the resulting separated solids or ‘cement residues’ by electrolysis (Butcher, 2014). In 2011, this source accounted for less than one per cent of total Ga supply (Roskill, 2011). It is likely to be still the case.

8.2.1.1.4 Refining and purification of gallium

Optoelectronic applications generally require gallium (and arsenic) of at least 6N purity (99.9999%) and electronic applications require 7N purity metal. Purities of 6N or 7N are achieved by gradual crystallization of liquid gallium. Two methods exist and rely on the fact that impurities tend to remain in the liquid phase and cannot contaminate the growing crystal. There are many impurities of concern such as Ca, C, Cu, Fe, Mg, Ni, Se, Si, Sn, Te. Concentrations of these elements should be less than 1 ppb in the gallium (and arsenic) used for GaAs semiconductors manufacture. Lead, mercury and zinc concentrations must also be lower than 5 ppb. Mass spectrometry is used to analyse final high purity gallium for such impurities (Roskill, 2011).

8.2.1.2 Gallium resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of gallium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[8], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are

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[8] www.crirsco.com

changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for gallium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for gallium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for gallium the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

In the Minerals4EU project, no data was reported concerning gallium. However bauxite resources are reported as being present in many countries such as Bulgaria, France, Germany, Greece, Hungary, Italy, or Romania (Minerals4EU, 2014) representing potential gallium resources.

The only existing estimates of European gallium resources are provided in the 2014 criticality assessment (European Commission, 2014a) at 21,400 tonnes. This number should be interpreted with appropriate caution though, as it does not comply with international standards of reporting (UNFC) and is very likely to be overestimated, as well as being uneconomic in current market conditions.

According to USGS estimates, gallium contained in world resources of bauxite would exceed 1 million tonnes, with a considerable quantity also potentially contained in world zinc resources (USGS, 2015). In 2011, Indium Corporation estimates of gallium resources were more conservative with 760,000 tonnes worldwide (European Commission, 2014a).

Globally, supply risks weighing on gallium’s availability are not related to its natural abundance but rather to industrial capacities for its recovery.

8.2.1.3 World refined gallium production

Total production of primary gallium (4N) is of the order of a few hundred tonnes per year, which is quite modest. As for many other minor metals, obtaining production figures is quite difficult because of the nature and size of the market, and estimations can vary greatly from on source to another. For instance, for the year 2014, it ranges from 74 tonnes (World Mining Data, 2016) to 440 tonnes (USGS, 2015). Therefore, it is more accurate to express **capacities** of production worldwide (Table 34).

Primary gallium production is known to have increased between 2010 and 2014, in large part due to major expansion of both capacity and output in China. In 2010, Chinese capacities were estimated at 141 tonnes (Roskill, 2011). In 2015, they would have amounted to at least 400-500 tonnes (Mikolajczak, 2016) thanks to great investments from aluminium producing companies in this country, supported by the central government. However, such increase in production exceeded the growth in consumption, as many promising markets such as photovoltaic panels using Copper-Indium-Selenium-Gallium (CIGS) technology, did not develop as expected. A major consequence was high oversupply of the market and a significant drop of gallium prices.

Table 34: Gallium global production capacities (European Commission, 2014; Mikolajczak, 2016)

Country	Estimated production capacity of 4N Ga (tonnes)
China	400 - 500
Germany	25 - 40
Kazakhstan	25
Ukraine	15
South Korea	10 - 15
Japan	6 - 10
Hungary	6 - 8
Russia	5 - 10
Total	*450 - 600*

It led many producers other than Chinese to stop their gallium operations during this period. According to company reports production would have stopped in 2013 in Hungary (MAL Magyar Alumínium Termelő, www.mal.hu), as well as in Germany in 2016 (Dadco Alumina www.dadcoalumina.com). USGS does not report any production from Kazakhstan since 2013 (USGS, 2015). The situation in other countries is less clear but is likely to have similarly reduced or stopped. In China, output has also been cut to levels of the order of 150-170 tonnes (Mikolajczak, 2016).

Capacity for refined high-purity gallium (6N or 7N) is less important (around 160 tonnes according to USGS) and less concentrated in China. It is only mastered by a few companies worldwide, some of them located in the EU.

8.2.2 Supply from secondary materials

The rate of recovery of gallium from end-of-life products is near 0% (UNEP, 2011). It is due to the difficulty and cost to recover gallium in items where it is highly dispersed. Indeed, semiconductor devices such as integrated circuits (ICs) and light emitting diodes (LEDs) represent the highest volumes of gallium consumption but they consist of a few microns thick deposition layer on top of a much thicker substrate and therefore require very little gallium per device (Weimar, 2011). Current recycling processes of waste electrical and electronic equipment in which they are contained rather favour the recovery of precious metals or copper, while gallium ends up as an impurity in recycled metals or in waste slags (UNEP, 2013).

However, as for many other metals, pre-consumer recycling (i.e. from industrial scrap) is more common and a consequent source of secondary supply for gallium. The manufacture processes of gallium arsenide (GaAs) and gallium nitride (GaN) wafers are estimated to be the metal's most important secondary source, with some 60% scrap generated and recycled in a 'closed loop' (Butcher, 2014). As for gallium used in thin film photovoltaic production, CIGS technology in particular, material yields assuming sputtering deposition is typically 30-60%, which also allow material recovery and recycling (Marwede, 2014).

There are a few companies in the EU with operations in Ga recycling, notably in Germany and Slovakia.

8.2.3 EU trade

EU import reliance on primary gallium is only 34% (average of 2010-2014) thanks to the presence of two producers in Germany and Hungary. However, this situation has changed since, with operations temporarily stopped in 2013 in Hungary and in 2016 in Germany due to high operating costs and cheap Chinese material available. It explains why EU's situation has changed from being a net exporter in 2011-2012 to a net importer in 2013-2014 (Figure 59).

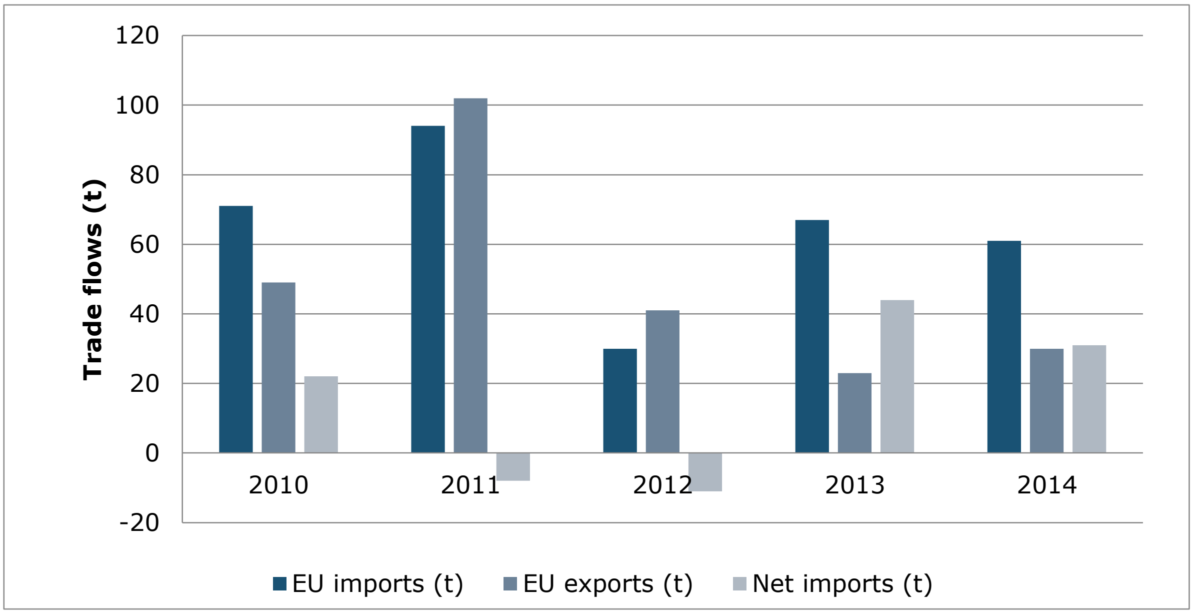

Figure 59: EU trade flows for gallium (Data from Eurostat Comext, CN8 code 81129289)

China was by far the first source of EU supply for this period (Figure 60). For some countries like United States, Canada or Russia, imports include quantities of secondary gallium (new scraps) for treatment within the EU.

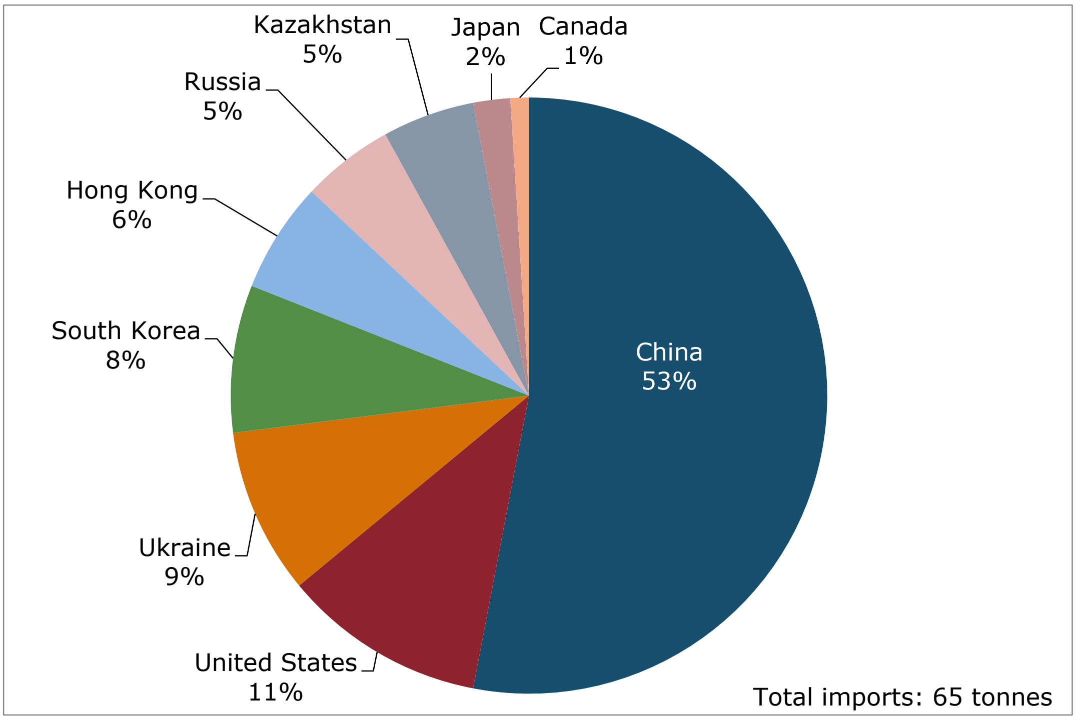

Figure 60: EU imports of gallium from extra-EU countries, average 2010-2014 (Data from Eurostat Comext)

China has imposed an export tax on gallium as well as an export quota of 230 tonnes (OECD, 2016). The only existing EU free trade agreement is with South Korea (European Commission, 2016).

8.2.4 EU supply chain

All levels of the gallium supply chain are present in the EU:

- Alumina production in Germany and Hungary can lead to the production of up to 50 tonnes of primary gallium (4N), if economic conditions are favourable;
- The import reliance is 34%. The Figure 61 presents the EU sourcing (domestic production + imports) for gallium.
- Some of the only companies in the world producing refined high-purity gallium (6N or 7N) are located in the EU, notably in Slovakia (CMK, http://cmk.sk/) and in Germany (PPM Pure Metals, www.ppmpuremetals.de, 5N Plus, www.5nplus.com);
- There are processors and wafer manufacturers in Germany (such as Freiberger Compound Materials, www.freiberger.com) and in Belgium (Umicore, which commercializes trimethylgallium, http://pmc.umicore.com/) which are suppliers of downstream European microelectronic and optoelectronic industrials.

This supply chain is quite mature and players adapt to market conditions. Some manufacturers are also active in recycling with closed-loop facilities, sometimes located abroad (intra-companies material transfers are frequent). Some Ga consumption also occurs in the form of imported manufactured products.

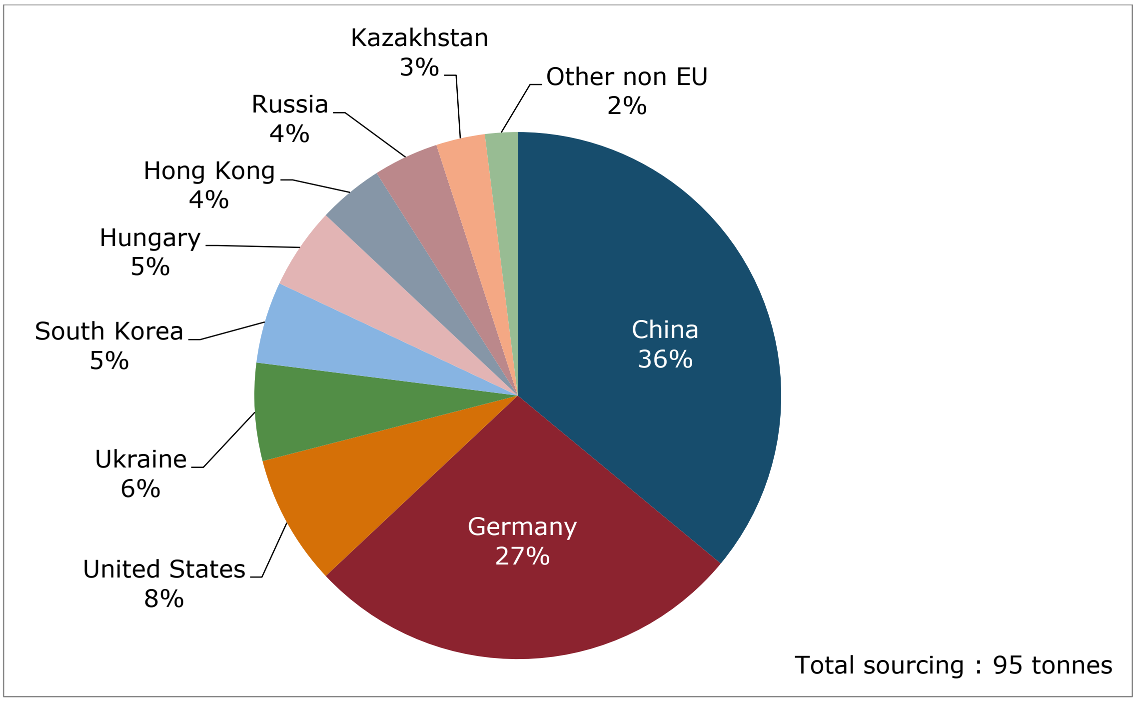

Figure 61: EU sourcing (domestic production + imports) for gallium, average 2010-2014 (Data from Eurostat Comext)

8.3 Demand

8.3.1 EU consumption

Apparent consumption figures derived from adding EU production and imports and subtracting exports are not reliable because of uncertainties related to the share of gallium produced, traded, or integrated in finished goods at every level. It is very difficult to assess these numbers precisely, which are of the order of 10-50 tonnes.

8.3.2 Applications/End uses

Currently, the greatest consumption of gallium is in semiconductors, the most popular being gallium arsenide (GaAs), followed by gallium nitride (GaN) with respective shares of 92% and 8% (BRGM, 2016). One of the reasons why GaN is produced in reduced quantities is that GaAs is composed of two metals whereas GaN is formed from a metal and a gas, which is much more difficult and costly to make.

In the simplest terms, a semiconductor consists of a substrate on which one, or more, very thin surface layers (epitaxial layers) are deposited. Ultrahigh-purity single crystals of GaAs are first grown and then sliced into wafers (the basis of electrical components) upon which the requisite epilayers are grown. Different end-uses require different qualities of substrate crystal, with integrated circuits (ICs) and microwave devices requiring the highest quality.

In terms of final end-uses, on average during 2010-2014, it can be estimated that 70% of gallium consumption has been for Integrated Circuits (ICs), 25% for lighting applications (mostly LED technology) and around 5% in the Copper-Indium-Selenium-Gallium photovoltaic technology (USGS, 2015; Mikolajczak, 2016) (Figure 62).

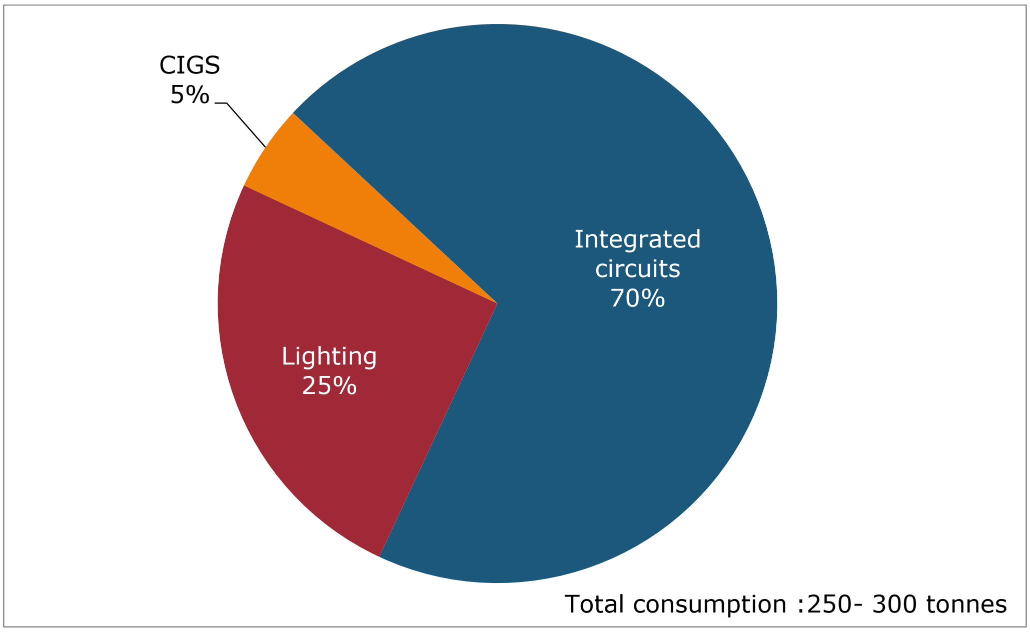

Figure 62: End uses of Gallium. Data from (Roskill, 2014)

A few examples of electronic devices where Integrated Circuits are critical components include:

- Cell phones; mostly in Power Amplifiers (PAs). The PAs in a cell phone are the vital components that amplify signals, both voice and data, to the appropriate power level for them to be transmitted back to the network base-station. The more advanced the generation used (3G, 4G), the more PAs it needs;
- Wireless communication systems; where semiconductors are employed in a number of different contexts (fibre optics, sensors, etc.);
- Military applications; for radar, satellite, night vision or communication high performance devices.

In lighting, semiconductors are used in an optoelectronic capacity, because of their ability to convert electrical input into light output. Some of their main applications are Infrared Emitting Diodes (IREDs), Laser Diodes (LDs) and Light Emitting Diodes (LEDs); the latter being one of the fastest growing markets in the past few years (Grady, 2013).

For a few examples: GaAs-based LEDs (red, orange, yellow) are used in automotive dashboards and exterior lights, traffic lights, full-color displays and many other signage and display applications. GaN-based LEDs (violet, blue, green, and mostly white) are used in general lighting, automotive and as backlighting for liquid crystal displays (LCD) in televisions, monitors, and digital appliances (Butcher, 2014).

In photovoltaics, gallium's main use is Copper-Indium-Selenium-Gallium (CIGS) technology. It is a thin-film technology that involves the deposition of a thin layer, only a few micrometres deep, of semiconducting material on various different surfaces. However, since 2010, the market for this technology has dropped, the vast majority of solar cells for terrestrial applications using crystalline silicon (c-Si, both mono- and multi-crystalline) technology (Fraunhofer, 2016). CIGS technology is preferred for specific terrestrial applications where flexibility is required (Butcher, 2014). Quantities of gallium currently used in solar-cell production thus remain small.

Other end-uses for gallium metal or chemicals include eutectic alloys, pharmaceutical compounds (gallium nitrate) or NdFeB magnets (wher Ga can be added in small quantities to improve magnetic properties and corrosion resistance), which remain minor at the industrial level.

The calculation of economic importance of gallium is based on the use of the NACE 2-digit codes. Relevant industry sectors are the following:

Table 35: Gallium applications, 2-digit NACE sectors and associated 4-digit NACE sectors [Data from the Eurostat database, (Eurostat, 2016)]

Applications	**2-digit NACE sector**	**Value added of sector (millions €)**	**4-digit NACE sectors**
Integrated Circuits	C26 - Manufacture of computer, electronic and optical products	75,260	C2610- Manufacture of electronic components
Lighting	C27 - Manufacture of electrical equipment	84,609	C2740-Manufacture of electric lighting equipment
CIGS solar cells	C26 - Manufacture of computer, electronic and optical products	75,260	C2610- Manufacture of electronic components

8.3.3 Prices and markets

Gallium is not traded on any metals exchange, and there are no terminal or futures markets where buyers and sellers can fix an official price. References for prices are obtained through averages of past deals between private parties, generally available through paid subscription (e.g. Asian Metal, Metal Pages). The main commercial form of gallium is 4N Ga metal. After a spike in prices in 2011 (up to almost 1,000 US$/kg), there was a chaotic and progressive ten-fold decrease for gallium prices (150-200 US$/kg) until the beginning of 2017, in great part due to huge oversupply in China (see Figure 63).

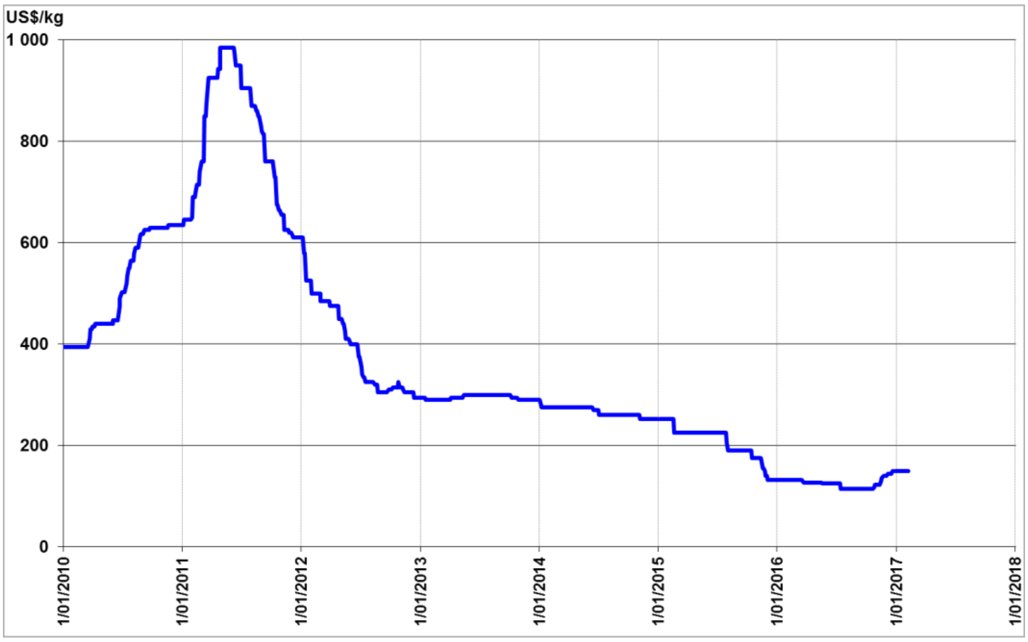

Figure 63: Gallium prices (min. 99.99 % FOB China). Data from (DERA, 2016)

8.4 Substitution

As for many minor metals, gallium has specific properties which make it unique in its main applications. Nevertheless, in case of disruption or price constraints, some alternative technologies or materials can usually substitute, often at lower cost but with loss of performances.

In semiconductors, many different types exist. Silicon or silicon-based substrates are usually the main substitutes for GaAs or GaN substrates, such as SiGe (CRM InnoNet, 2015). But it can only be for a limited number of applications, as silicon presents a lesser electron mobility and is therefore significantly less efficient. GaAs-based semiconductors also operate at higher breakdown voltages and generate less noise at high frequencies (>250 MHz). Pure GaAs substrates finally have the great advantage of being semi-insulating, whilst silicon substrates are semiconducting.

In lighting, LEDs present many advantages such as their low-energy consumption, non-toxicity, and longevity (up to 100,000 hours). Organic LED (OLED) could be a substitute to solid state LED but so far, they are not competitive in terms of price and durability (CRM InnoNet, 2015).

In photovoltaics, other technologies compete with CIGS. As mentioned before, for terrestrial applications, crystalline silicon technologies currently represent more than 90% of the market, even though conversion efficiency is reduced from 18-22% to 8-15% when silicon is used rather than CIGS in photovoltaic cells. Other thin film technologies include cadmium telluride (CdTe) and copper indium selenide (CIS) (Fraunhofer, 2016).

8.5 Discussion of the criticality assessment

8.5.1 Data sources

Market shares and production data are particularly difficult to obtain due to the size and nature of the market, information coming from public sources (USGS, 2015, World

Mining Data, 2016) were completed based on expert consultation (Mikolajczak, 2016). Data on imports and exports are taken from Eurostat Comext, data on trade agreements are taken from the DG Trade webpages, which include information on trade agreements between the EU and other countries (European Commission, 2016). Information on export restrictions are derived from the OECD Export restrictions on the Industrial Raw Materials database (OECD, 2016).

8.5.2 Economic Importance and Supply Risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 35). The value added data correspond to 2013 figures. The supply risk was assessed using the global HHI and the EU-28 HHI as prescribed in the revised methodology.

8.5.3 Comparison with previous EU Criticality Assessments

Both Economic Importance (EI) and Supply Risk (SR) scores are lower than in the previous assessments. Part of the explanation comes from the change in methodology. To evaluate EI, the value added in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a 'megasector', which was used in the previous assessments. The way the supply risk is calculated in the new methodology (taking into account global HHI and the EU-28 HHI, for instance) also explains why the SR score is lower than in the previous assessments, together with the current situation of oversupply of the global gallium market.

Table 36: Economic Importance and Supply Risk results in the assessments of gallium in the 2011, 2014 and 2017 assessments (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Gallium	2.5	6.5		1.8	6.3		1.2	3.2

8.6 Other considerations

8.6.1 Forward look for supply and demand

Between 2010 and 2013 Chinese capacity for production of primary gallium tripled, in expectation of growing demand for GaN LEDs for backlighting in tablet computers, mobile phones and TVs. While there was considerable growth in demand from this sector, the supply of gallium far out grew requirements (Roskill, 2014; Mikolajczak, 2016). Global conversion to LED general lighting and wireless communication systems is expected to continue in the period up to 2020-2030, which is likely to restore some balance to the gallium market, but supply could still remain more than adequate. No further reliable forecast for demand and supply for the next 10 and 20 years could have been obtained from market and industry experts (see following table).

Table 37: Qualitative forecast of supply and demand of gallium

Material	Criticality of the material in 2017		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Gallium	x		+	?	?	+	?	?

8.6.2 Environmental and regulatory issues

Since 2014, gallium arsenide is mentioned in Annex XVII to REACH regulations in the category carcinogenic, mutagenic or reprotoxic substances. However, none of gallium compounds is on the list of substances of very high concern (ECHA, 2014).

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8.7.1 Data sources used in the factsheet

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8.8 Acknowledgments

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9. GERMANIUM

Key facts and figures

Material name and Element symbol	Germanium, Ge	World/EU production (tonnes)[1]	Extraction : 760 / 0 Refining: 136 / 13
Parent group (where applicable)	N/A	EU import reliance[1]	64%
Life cycle stage/ material assessed	Processing/GeCl$_4$, GeO$_2$, Ge metal	Substitution index for supply risk [SI(SR)][1]	1.00
Economic importance (EI)(2017)	3.5	Substitution Index for economic importance [SI(EI)][1]	1.00
Supply risk (SR) (2017)	1.9	End of life recycling input rate (EoL-RIR)	2%
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Optical fibres (40%); Infrared Optic (47%); Satellite solar cells (13%)
Main product, co-product or by-product	By-product of zinc ores and coal ashes	Major world producers[1]	Extraction: China (56%), US (16%), Australia (13%) Refining: China (67%), Finland (11%), Canada (9%), US (9%)
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] 2010-2014 average, unless otherwise stated.

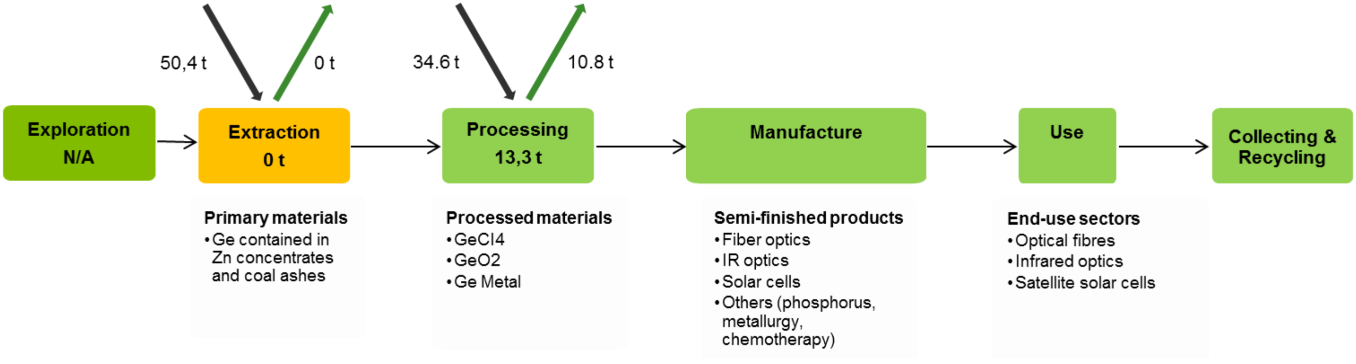

Figure 64: Simplified value chain for germanium

The orange box of the production stage in the above figure suggests that activities are not undertaken within the EU, to the contrary of green boxes. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

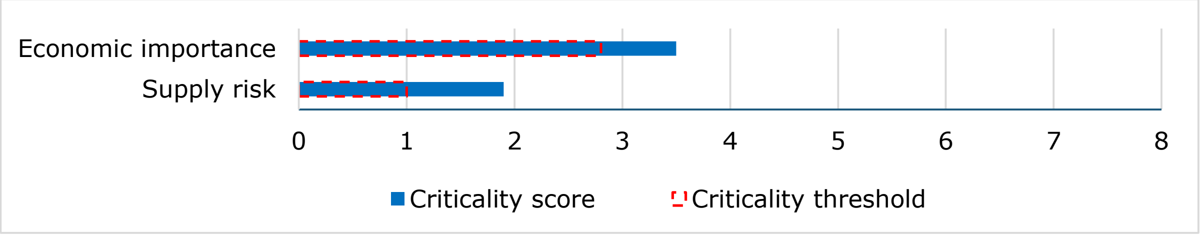

Figure 65: Economic importance and supply risk scores for germanium

9.1 Introduction

Germanium is a chemical element with symbol Ge and atomic number 32. It is a lustrous, hard, brittle, crystalline and greyish-white metalloid in the carbon group, chemically similar to its group neighbours tin and silicon. It resembles a metal; however, it also displays non-metal characteristics, such as semi conductivity. Indeed, purified germanium is a semiconductor, with an appearance most similar to elemental silicon. Like silicon, germanium naturally reacts and forms complexes with oxygen in nature. Unlike silicon, it is too reactive to be found naturally on Earth in the free (native) state.

Germanium is contained in zinc ores and coal ashes. Germanium primary production is heavily dependent on zinc production (given that it is mostly recovered as a by-product of zinc refining). Only 12% of germanium mined outside of China and Russia is refined; this is considered to be a major bottleneck in world germanium supply (European Commission, 2014). Around 30% of worldwide germanium production is accounted for by recycling of new scraps and tailings (USGS, 2016a).

Germanium is used in several applications such as optical fibres, IR optics, wafers for satellites solar cells, IT applications, PET catalyst etc. Some of these end-uses, such as PET catalysts and IT applications, are not occurring in the EU (Bio Intelligence Service, 2015).

9.2 Supply

9.2.1 Supply from primary materials

9.2.1.1 Geological occurrence

Germanium is a silvery metallic element with the same crystalline structure as diamonds when formed under standard conditions. In this form it is very hard and brittle and can break like a piece of glass if dropped or mishandled. It is a rare metal, with an average concentration in the Earth's crust of 1.6-2 parts per million, and 1.4 ppm in the upper crust (Rudnick, 2003).

As is the case for many minor metals, germanium does not occur in its elemental state in nature, but is found as a trace metal in a variety of minerals and ores (European Commission, 2014). Only a few minerals of germanium have been identified, the major one being germanite ($Cu_{13}Fe_2Ge_2S_{16}$). This was the principal source of germanium in the past; however, no ore bodies with commercially viable contents of germanite are known at present (European Commission, 2014). Germanium is also contained in zinc ores and coal ashes.

Some exploration activities are undertaken within the Eu for germanium, in particular in Portugal and Slovakia according to the Minerals4EU website (Minerals4EU, 2014)

9.2.1.2 Mining, processing and extractive metallurgy

Today, germanium is extracted as a by-product of zinc production and from coal fly ash (European Commission, 2014). It is estimated that 60% of worldwide production of germanium is sourced from zinc ores, mainly the zinc sulphide mineral sphalerite, and 40% from coal. China and Russia are the only countries to recover germanium from coal fly ash (European Commission, 2014).

About 760 tonnes of germanium were present in 2012 in zinc ores mined, but only a small proportion is effectively recovered (European Commission, 2014).

Germanium recovered from the leaching of zinc residues or coal fly ash and is precipitated into germanium concentrates and crude germanium dioxide (GeO_2). Crude GeO_2 is then converted into germanium tetrachloride ($GeCl_4$) and hydrolysed to produce high grade GeO_2. $GeCl_4$ is also partly used to produce high grade GeO_2. A fraction of high grade GeO_2 is then reduced and refined into Ge metal (Bio Intelligence Service, 2015).

Those processed materials are used to manufacture various finished products: $GeCl_4$ is mainly used to manufacture optical fibres, high grade GeO_2 is transformed into PET catalyst and Ge metal serves in several applications such as IR optics, wafers for satellites solar cells, IT applications, etc. Some of these end-uses are not occurring in the EU, such as PET catalysts and IT applications (Bio Intelligence Service, 2015).

9.2.1.3 Resources and reserves of germanium

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of germanium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[9], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for germanium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for germanium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for germanium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

The available resources of germanium are associated with certain zinc and lead-zinc-copper sulfide ores (USGS, 2016a), as well as coal ashes. Global known resources of germanium are estimated at 11,000 tonnes in zinc ores and 24,600 tonnes in coal in 2013 (European Commission, 2014). Around half of total known resources are located in Russia (17,500 tonnes, all from coal ashes) and one quarter is located in China (10,860 tonnes, including 4,200 tonnes in zinc ores and slag, the remaining in coal ashes) (European Commission, 2014). The USA and Congo have also significant resources of Ge in zinc ores (respectively 2,300 and 3,750 tonnes), while Canada, Mexico, Namibia, Ukraine and Uzbekistan account for the rest of Ge resources (European Commission, 2014). Some resources of Ge in Zn mines exist in the EU but they are not quantified. They have been estimated at less than 1,000 tonnes using the low Ge content (0-10 ppm) in EU Zn resources (Bio Intelligence Service, 2015). Resource data for some member state are available in the Minerals4EU website (see Table 38) (Minerals4EU,

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[9] www.crirsco.com

2014) but cannot be summed as they are partial and they do not use the same reporting code.

Table 38: Resource data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2014)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
Ukraine	Russian Classification	5493.9	t	-	P2
Czech Republic	Nat. rep. code	473	t	0.01% Ge	Potentially economic

World known reserves for germanium are estimated at 8,600 tonnes in 2012 (Bio Intelligence Service, 2015), including 3,500 tonnes of proven reserves of germanium in China (European Commission, 2014). There are no reserves of germanium in the EU actually because historic European deposits (St Salvy, Bor, Bleigerg, Freiberg, Sardaigne) are drained (Bio Intelligence Service, 2015).

The investment in exploration for germanium is null, because companies are exploring for zinc, not for germanium (Bio Intelligence Service, 2015). Statistics on metal exploration do not mention germanium as it is not an important material for exploratory activities (Bio Intelligence Service, 2015). The Minerals4EU website only reports 41147.24 tonnes of germanium contained in coal in Ukraine (Minerals4EU, 2014).

9.2.1.4 World mine production

There is only one zinc mine very rich in germanium (400 g/t) within the world (located in Tennessee, USA), but it has been closed temporarily in the last years (Bio Intelligence Service, 2015). Several Zn mines with medium germanium content (50 g/t) are located in Alaska and Australia, and there are also plenty of Zn mines with low germanium content (0-10 ppm) located in China, Congo, India, Bolivia, etc. (Bio Intelligence Service, 2015). There were some very rich germanium mines in France and Austria but they all closed in the 1990's once empty (Bio Intelligence Service, 2015).

Most of the germanium is extracted from zinc ores as a by-product, mainly in China, the United States, Australia and India (see Figure 66) (Bio Intelligence Service, 2015). It is important to note that only a small fraction of the germanium contained in the zinc ore extracted worldwide is effectively recovered and further used in the value chain of germanium. The main fraction is not valued and is considered as lost (in tailings, as impurities in zinc products, etc.) (Bio Intelligence Service, 2015). About 760 tonnes of Germanium were present in 2012 in zinc ores mined worldwide, but only a small proportion is effectively recovered (European Commission, 2014).

There are no reserves of germanium in the EU and consequently there is no extraction of germanium, neither from zinc ores nor from coal ashes (Bio Intelligence Service, 2015).

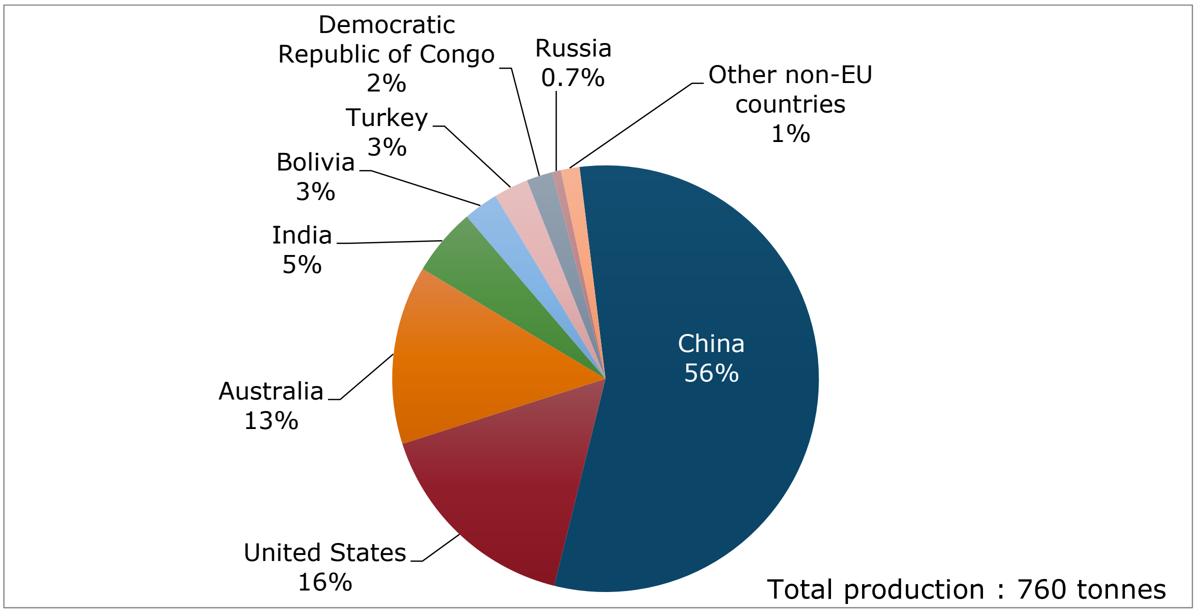

Figure 66: Ge contained in global mine production of zinc ores (not necessarily recovered), 2012 (Data from (Bio Intelligence Service, 2015))

9.2.1.5 World refinery production

Approximately 336 tonnes of germanium were contained in zinc mined in the USA, Australia and India in 2011 (European Commission, 2014). However only 40-45 tonnes of those were actually refined into germanium concentrates, meaning approximately 12% of the germanium mined in the USA, Australia and India was refined (European Commission, 2014). On a global scale (including China production), as little as 3% of the germanium contained in zinc concentrates is recovered (USGS, 2016a).

There are several reasons why such a low percentage of germanium is refined from zinc concentrates. Firstly, it was reported that germanium recovery can have a negative impact on zinc recovery, detracting from the core business for these refineries (European Commission, 2014). As a consequence, except the Chinese refineries, only two zinc refineries (located in the USA and Canada) currently extract germanium as part of their operations (European Commission, 2014). Secondly, high germanium zinc concentrates must be sourced in order to make recovery of germanium economic; this may increase the cost of sourcing the concentrate, making it prohibitive. This is of particular importance given that germanium production only accounts for a low percentage of the business’s turnover. For example, in the Canadian zinc refinery, germanium accounts for at most 2% of total revenues. Therefore, the investment may not be profitable unless germanium prices are sufficiently high (European Commission, 2014).

Significant amounts of germanium are contained in ash and flue dust generated in the combustion of certain coals for power generation (USGS, 2016a). However, due to the low concentration of the Ge in such ashes and dust, recovery of this germanium has a low or even negative value (Industrial player, 2016). Higher Ge concentration in ash or flue dust is required for a viable recovery and can only be reached by incineration of these coals without recovery of the energy released by this process. Such operation has clearly a high ecological footprint and negative impact on the environment (Industrial player, 2016). China and Russia are the only countries where such operations to recover germanium from coal fly ash exist (European Commission, 2014).

In 2012, total production of refined germanium was estimated to be around 136 tonnes (Bio Intelligence Service, 2015). It was estimated that 60% of this was produced from zinc ores and 40% from coal fly ash (European Commission, 2014). In 2012, China was the main producer (about 66%), as presented in Figure 67. In 2015, total production of refined germanium was estimated to be around 165 tonnes (USGS, 2016a). This comprised germanium recovered from zinc concentrates, fly ash from burning coal, and recycled material.

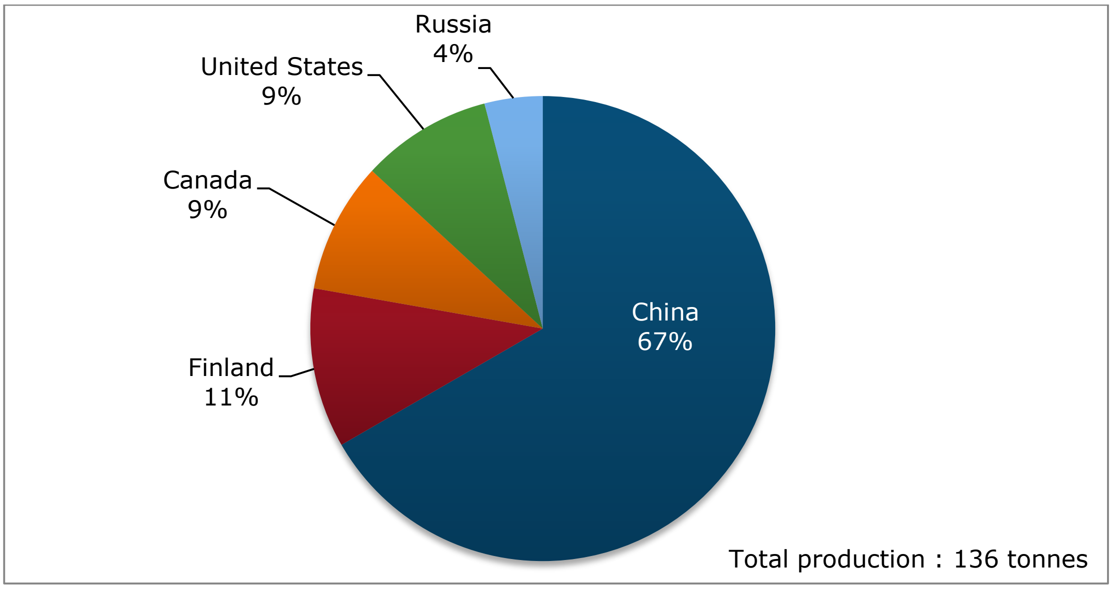

Figure 67: Global refinery production of germanium, 2012 (Data from (Bio Intelligence Service, 2015))

In 2015, China accounted for 72% of global supply for refined germanium, and Russia, the US, Belgium, Canada and Germany are the other producers (USGS, 2016a). Note that there is no more Ge refining activity (from Cobalt ores) in Finland since 2015 (Bio Intelligence Service, 2015).

9.2.2 Supply from secondary materials

It is estimated that around 30% of global germanium production is supplied by recycling, mostly from scrap generated during the manufacture of fibre-optic cables and infrared optics. Due to the value of refined germanium, this scrap is reclaimed and fed back into the production process (European Commission, 2014).

9.2.2.1 New scrap recycling

As Ge products usually need to be of a very high purity, a lot of production scrap is generated all along the manufacturing chain. However, the high price of refined germanium encourages recycling: the huge majority of the new scrap generated during the manufacture of germanium processed materials and products is recycled by being fed back into the manufacturing process.

All the waste generated during the conversion of GeO_2 and the production of $GeCl_4$ and Ge metal is internally recycled (Bio Intelligence Service, 2015). The manufacture of optical fibres generates about 75% of waste, and about 80% of this new scrap is reprocessed (Bio Intelligence Service, 2015). The waste produced during the manufacture of IR optics amounts about 30% of the germanium input, of which 100% is internally recycled. The cutting (from large high purity mono-crystals) and gridding of Ge wafers during solar cells manufacture produces a lot of production scrap (e.g. Ge dust from sawing the wafers) - almost 50% if the Germanium input - which is fully recycled internally (Bio Intelligence Service, 2015). Downstream producers of solar cells or infrared optics also generate a lot of production scrap on the way to the final product, which is also collected and recycled with high efficiency (Industrial player, 2016).

9.2.2.2 Old scrap recycling

However, once the final products are sold into the market, there is very little recycling at end of life of "old scrap" (Industrial player, 2016). Recycling of old scrap has increased over the past decade (European Commission, 2014) but is still low. The functional recycling rate has been estimated at about 12% (Bio Intelligence Service, 2015) and the end-of-life recycling input rate is assessed at 2% only. Indeed, very few used end-products are collected separately to be recycled: all used optical fibres go into non-functional recycling in C&D waste, solar cells for satellites are not recovered and only some Ge is recycled from old crap of IR optics such as used mobile phones (Bio Intelligence Service, 2015). According to experts, this situation will not improve in future due to dissipation and low grade uses, as well as extra-terrestrial applications (solar cells for satellites) that cannot be collected, etc. (Industrial player, 2016) Moreover, in most of the products and devices containing germanium the metal is present in trace amounts, making it technically and economically difficult to recover secondary germanium (European Commission, 2014).

9.2.3 EU trade

Overall, the EU is a net importer of germanium, importing around 35 tonnes per year of Ge contained in unwrought germanium and germanium powders (Eurostat, 2016a) (CN8 code 81 12 92 95, see Figure 68), Germanium dioxide and Germanium tetrachloride GeO_2 accounts for about 15.3 tonnes, $GeCl_4$ about 5.1 tonnes (Bio Intelligence Service, 2015) and Ge metal for about 14.3 tonnes (Eurostat, 2016a). The EU does not import any germanium concentrates (Bio Intelligence Service, 2015). In average, the EU imports 34 tonnes of germanium contained in refined products.

The major source of imported germanium is China, which exported 21 tonnes of germanium to the EU in average on the period 2010-2014; followed by Russia and the United States.

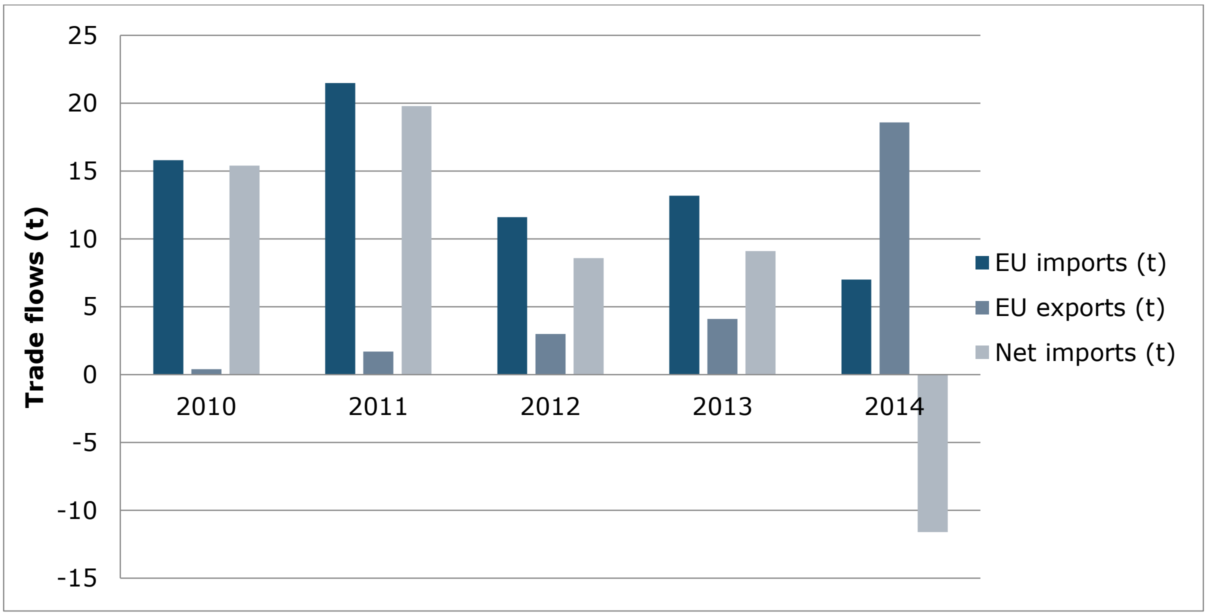

Figure 68: EU trade flows for germanium unwrought and powders (Data from (Eurostat, 2016a) unwrought germanium and germanium powders CN8 code 81 12 92 95)

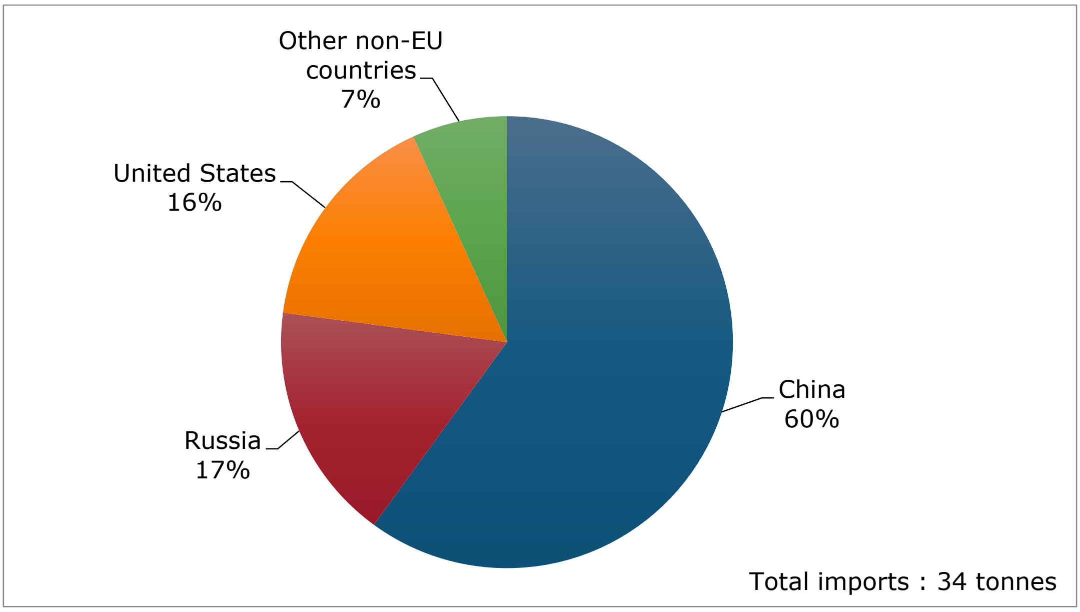

Figure 69: EU imports of germanium, average 2010-2014. (Data from Eurostat, 2016a; Bio Intelligence Service, 2015)

9.2.4 EU supply chain

As there are no reserves of germanium in the EU, there is no extraction of Ge ores. There is no germanium concentrates recovered neither from a European mine in activity, nor from coal ashes in the EU.

Between 2010 and 2014, some crude GeO_2 is produced in Finland from cobalt concentrates (mined in Congo by the owner of the Finnish refinery) (Bio Intelligence Service, 2015). The Finnish plant stopped the production of germanium in 2015 (Bio Intelligence Service, 2015).

This crude GeO_2 is used in the EU to produce Ge processed materials (GeO_2, $GeCl_4$ and Ge metal), with most of them (80%) being exported outside the EU (Bio Intelligence Service, 2015). The EU net production of refined Ge is then only few tonnes (about 2.5 tonnes) of Ge contained, whereas it imports about 35 tonnes of Ge. The import reliance reaches 64%.

Figure 70 presents the EU sourcing (domestic production + imports) for germanium products.

The major supplying country, China, has put in place exports restrictions for a group of nonferrous minor metals (germanium, vanadium, gallium, hafnium, indium, niobium, rhenium), such as export taxes of 5% and export quotas of about 230 tonnes between 2009 and 2014 (OECD, 2016). Russia has put in place licensing requirements for exports of germanium (OECD, 2016). No free trade agreements exist at this time between the EU and the US or Japan (European Commission, 2016).

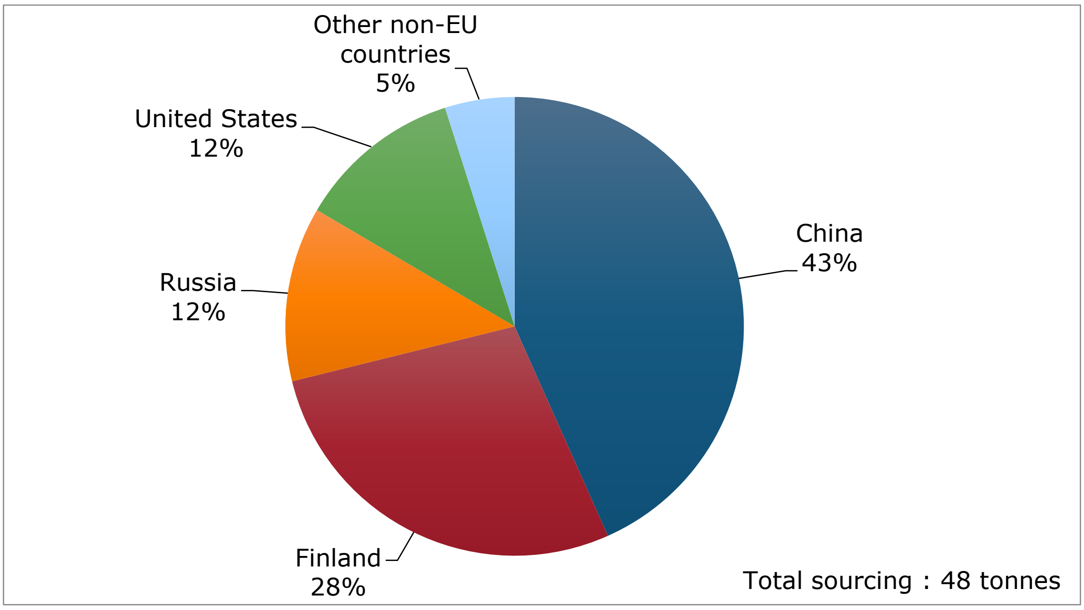

Figure 70: EU sourcing (domestic production + imports) of germanium, average 2010-2014. (Data from Eurostat, 2016a; Bio Intelligence Service, 2015)

9.3 Demand

9.3.1 EU demand and consumption

The demand for Ge processed materials in the EU is about 37 tonnes in average on the period 2010-2014, about 25% of the world consumption. This consumption of 37 tonnes of germanium is destined to the manufacture of germanium end-products. As mentioned before, those processes generates a lot of scrap which is quite fully internally recycled.

9.3.2 Uses and end-uses of germanium in the EU

The three major global uses of germanium are in fibre optics, infrared optics and polymerisation catalysts for PET plastics. Use in electronic applications and satellite solar cells also play and important role at the global scale. The other applications are mainly for phosphors, metallurgy, and chemotherapy (European Commission, 2014).

However, it must be noted that in the EU, Germanium is not used as PET polymerisation catalysts as well as in the electronic industry (Bio Intelligence Service, 2015).

The end-uses applications of germanium in the EU are (see Figure 71):

- Fibre-optics*:* Germanium oxide is used as a dopant in within the core of optical fibre. Small quantities of this compound are added to the pure silica glass to increase its refractive index; this prevents light absorption and signal loss. This type of fibre is used for high-speed telecommunication. Over the past years there has been substantial growth in this sector with increasing demand for more bandwidth (European Commission, 2014).
- Infrared optics: Germanium is transparent to infrared radiation (IR) wavelengths, both as a metal and in its oxide glass form. For this reason it is used to make lenses and windows for IR radiation. These are mainly used in military applications such as night-vision devices. Uses outside of the military are in advanced firefighting equipment, satellite imagery sensors and medical diagnostics.
- Solar cells: Germanium-based solar cells are principally used in space-based applications but also in terrestrial installations. Demand for satellites has

increased steadily from 2007 due to commercial, military, and scientific applications. The advantage of germanium substrates over the more common silicon based solar cells are the smaller size and weight and higher efficiency (over 25%). These solar cells are not common in terrestrial applications because of the cost of their manufacture. However these are considerably more efficient at converting solar energy into electricity, so fewer cells are required in a panel to produce equivalent amounts of power. It is thought that germanium-based cells will compete for a portion of the terrestrial market in the future (European Commission, 2014).
- Other uses in the EU include gamma-ray detectors and organic chemistry, phosphors, metallurgy, and chemotherapy.

Germanium is also used in the following applications outside the EU:

- Polymerisation catalysts: Germanium dioxide is also used outside the EU (and particularly in Japan) as a catalyst in the production of PET plastics which is used, for instance, for plastic bottles, sheet, film and synthetic textile fibres. There is a drive to move towards different catalysts given the increasing price of germanium (European Commission, 2014).
- Electronic components: Germanium is used as a semiconductor in several electronic applications. Some examples are high brightness Light Emitting Diodes (LEDs) in devices such as cameras and smartphone display screens. Silicon germanium transistors have been replacing other silicon based components in high speed wireless telecommunications devices due to the higher switching speeds and energy efficiency (European Commission, 2014).

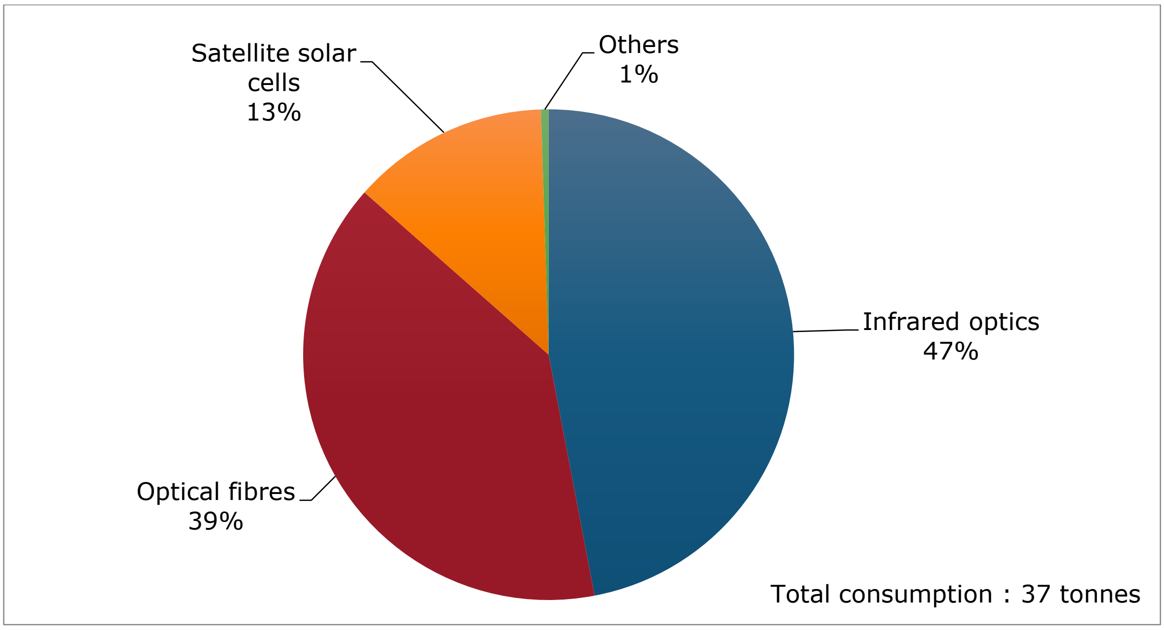

Figure 71: EU end uses of germanium. Figures for 2012. (Data from Bio Intelligence Service, 2015)

Relevant industry sectors are described using the NACE sector codes (Eurostat, 2016c) in the following table.

Table 39: Germanium applications, 2-digit and associated 4-digit NACE sectors and value added per sector (Eurostat, 2016c)

Applications	2-digit NACE sector	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
Optical fibres	C27 - Manufacture of electrical equipment	84,609	C2731 - Manufacture of fibre optic cables; C2630- Manufacture of communication equipment;
Infrared optics	C26 - Manufacture of computer, electronic and optical products	75,260	C2670- Manufacture of optical instruments and photographic equipment
Satellite solar cells	C26 - Manufacture of computer, electronic and optical products	75,260	C2611- Manufacture of electronic components

9.3.3 Prices

Historical prices for germanium are shown below in Figure 72. Germanium prices have been variable between 2000 and 2014 (USGS, 2016b). Germanium prices have decrease from 2000 to 2004 due to a slight decrease in demand, increased supply through recycling and stockpile releases and due to a lower than expected demand for satellite applications. Prices increased until 2008 due to increased use of germanium in infrared equipment and solar cells for satellites for military reasons. Increases in late 2006 and 2007 are reported to be due to the construction of fibre optics networks throughout the world. The global economic crisis in 2008 resulted in a reduction in prices; however, these showed recovery since 2010. In early 2012, three Chinese germanium dioxide plants were shut down because of environmental concerns. Global supply was also tightened by the export tax on germanium dioxide from China. Finally, in mid-2012, one of the major Chinese producers announced it would supply 375 tonnes of germanium dioxide over a period of six years to a single consumer that specialises in solar and hydro projects. This contributed to the perceived supply tightness thus resulting in increased prices (European Commission, 2014). The germanium prices have been very high (metal at about \$1,800/1,900 kg) from 2012, which incites processors to increase collection and recycling of new scrap (Bio Intelligence Service, 2015). Prices in the period 2012 - mid 2015 have remained high due to a combination of strategic government stockpiling of germanium metal and a speculative investors' demand organized by a Chinese minor metals trading platform (Fanya) (Industrial player, 2016). The huge speculative demand by financial investors drove prices of minor metals such as Indium, Germanium, and Bismuth to unprecedented levels in 2013-2014. After the collapse of this trading platform in first half of 2015, prices significantly dropped. Currently, germanium prices are less than half of their value in 2013-2014 (Industrial player, 2016).

According to the DERA raw materials price monitor and the LMB Bulletin, GeO_2 prices on the MB free market have decreased drastically since 2015 as it cost 1,253 US\$/kg in average on the period 2011-2015 but only 812 US\$/kg in average on the period December 2015 - November 2016, i.e. a price drop of 35.2%.

Figure 72: Germanium historical price volatility (US$/tonne). Figures for 2000-2016. (Data from USGS, 2016b; Industrial player, 2016)

9.4 Substitution

Research on efficient germanium substitutes is currently under progress (Industrial player, 2016).

Various alternatives are available for the substitution of germanium in some its applications (mainly the IT applications and catalysts applications, not relevant for the EU scope). However, many of these substitutes result in a loss of performance and are therefore not optimal. Silicon can be a less-expensive substitute for germanium in some electronic applications such as transistors (USGS, 2016a). However, there has recently been a shift back to the use of germanium, albeit in materials with silicon, as this will allow the miniaturization of electronics (USGS, 2016a). Some metallic compounds can be substituted in high-frequency electronics applications and in some light-emitting-diode applications (USGS, 2016a). Antimony and titanium are substitutes for use as polymerization catalysts (USGS, 2016a).

For infrared optics, zinc selenide and zinc sulphide can be used as substitutes of germanium, but with a reduced performance (Industrial player, 2016). Tellurium is also a substitute as part of chalcogenide glasses for infrared optics (Industrial player, 2016).

Substitutes of germanium in optical fibres are not really used because of performance losses, but fluorine and phosphorus can be mentioned, with a low probability of industrial use (Industrial player, 2016).

There is actually no substitute for germanium in satellite solar cells, even if some research are ongoing on semiconductor materials based on gallium and indium such as InGaP, AlGaInP, InGaAsP, InGaAs (Industrial player, 2016).

9.5 Discussion of the criticality assessment

9.5.1 Data sources

The data source used for the world production of refined germanium is the MSA study (Bio Intelligence Service, 2015), based on years 2011-2012. Some experts noticed that the figure for Canada is some underestimated (it could be 30-50% higher), and that China have meanwhile taken control over the Finnish feed (Industrial player, 2016).

Supply data for the EU comes from Comext for Ge unwrought and powder (Comext, 2016a - CN8 code 81129295, average 2010-2014), and from the RMSA study (Bio Intelligence Service, 2015)for $GeCl_4$ and GeO_2 as no data is recorded under the Comext CN8 code 28256010 for Ge oxide.

9.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors. The value added data correspond to 2013 figures.

The life cycle stage assessed in for the SR indicator is the processing step. The Supply Risk (SR) is calculated using both the HHI for world production and the HHI for EU supply as prescribed in the revised methodology. China accounts for about 67% of the global supply, and is also the main supplier for the EU. Over the period 2010-2014, the EU production is exclusively performed in Finland, but has stopped in 2015.

9.5.3 Comparison with previous EU assessments

The results of this review and earlier assessments are shown in Table 40.

Table 40: Economic importance and supply risk results for germanium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Germanium	6.28	2.73		5.54	1.94		3.5	1.9

Although it appears that the economic importance of germanium has reduced between 2014 and 2017 this is a false impression created by the change in methodology. The value added in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a ‘megasector’, which was used in the previous assessments. The economic importance result is therefore reduced. The calculations of the Supply Risk (SR) for 2011 and 2014 lists have been performed for the processing step considering only Ge unwrought and powders whereas the SR in 2017 assessment is calculated for the processing step considering all processed Ge forms : Ge unwrought and powders + Ge dioxide and Ge tetrachloride. However, the SR score has not changed a lot between the three exercises.

9.6 Other considerations

9.6.1 Forward look for supply and demand

The outlook on germanium supply depends largely on future demand of germanium and its price. As a by-product, germanium production is heavily dependent on zinc production. For this reason, the germanium market is slow to respond to demand and tends to be volatile. A higher price may result in increased interest shown by zinc refineries. As mentioned above, only a small proportion of germanium extracted outside of China and Russia is refined (note: there are no germanium mining operations outside of China and Russia; outside of these two countries, Germanium is only recovered as a by-product of other metal refining operations); therefore there is considerable opportunity to increase capacity in the future (European Commission, 2014). Zinc refineries in the USA are becoming more interested in germanium recovery. In Australia greater germanium output may be possible; however, the largest germanium-containing mine has closed in 2015. It was also reported that some zinc concentrates are currently exported from Australia to China, therefore germanium might be recovered. In 2010, a zinc mine in Canada stopped production; however, the restart of Gordonsville mine in 2011 at Tennessee, USA, should bring new supply to the market. Furthermore, a facility was opened in Canada in 2010 which has capacity for semiconductor processing, purification, and recycling of several metals including germanium. In India lower germanium concentration in zinc ores makes recovery less likely (European Commission, 2014). In fact in most cases, the Ge concentration in these by-products is very low and recovery is only viable when prices are at a high level (which is currently not the case) (Industrial player, 2016).

Recovery from coal fly ash could also be increased; however, a declining germanium content of germanium-containing fly ash has been observed in China, triggering a lower recovery rate (European Commission, 2014).

The market outlook forecast for world germanium supply and demand a moderate overall growth rate in demand, at around 4.4% per year. The largest increases are actually in germanium’s largest end-market: infrared and fibre optics, where demand is anticipated to grow at 5.6% per year. Solar and electronics are also expected to witness good rates of market growth at over 4% per year, although the market for PET catalysts is only expected to be flat (European Commission, 2014). On the supply-side, there currently exists a small market surplus. However, this is expected to narrow over the coming decade, as supply growth will not quite keep up with demand growth. However, this will depend on the willingness of zinc refiners and coal-fired power plants to engage in germanium market. Given that there are plenty of germanium reserves worldwide, as well as germanium arising in certain waste streams, the supply-demand picture for germanium should be relatively secure (European Commission, 2014).

Table 41: Qualitative forecast of supply and demand of germanium

Material	**Criticality of the material in 2017**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Germanium	x		+	+	?	+	+	?

9.6.2 Trade restrictions

Two of the major germanium producing countries currently impose taxes upon the export of germanium; Russia imposes a tax on the export of germanium waste and scrap (6.5%) and China imposes a tax on the export of germanium oxides (5%) (OECD, 2016). With the introduction of such tax in 2010, the Chinese Government attempted to limit exports of raw materials (European Commission, 2014). In order to protect germanium resources, China has taken multiple measures in recent years, including purchase and storage of germanium by the country and increase in tariffs, which resulted in significant decline in export of germanium and products thereof, falling by 21.8% year on year to about 25.8 tonnes in 2013, according to data from China Customs. At the same time China encouraged the export of more processed products through export tax rebates on products such as germanium ingots and optical lenses (European Commission, 2014).

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9.8 Acknowledgments

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10. HAFNIUM

Key facts and figures

Material name and Element symbol	Hafnium, Hf	World/EU production (tonnes)[1]	72 /30
Parent group (where applicable)	N/A	EU import reliance[1]	9%
Life cycle stage assessed	Processing	Substitution index for supply risk [SI (SR)][1]	0.97
Economic importance (EI)(2017)	4.2	Substitution Index for economic importance [SI(EI)][1]	0.93
Supply risk (SR) (2017)	1.3	End of life recycling input rate (EOL-RIR)	1%
Abiotic or biotic	Abiotic	Major end uses in the EU[1]	Base metal alloys (45%) Machinery parts (26%), Chemical products (13%)
Main product, co-product or by-product	By-product	Major world producers[1]	France (43%), United States (41%), Ukraine (8%), Russia (8%)
Criticality results	2011	2014	2017
	Not assessed	Not critical	Critical

[1] 2010-2014 average, unless otherwise stated.

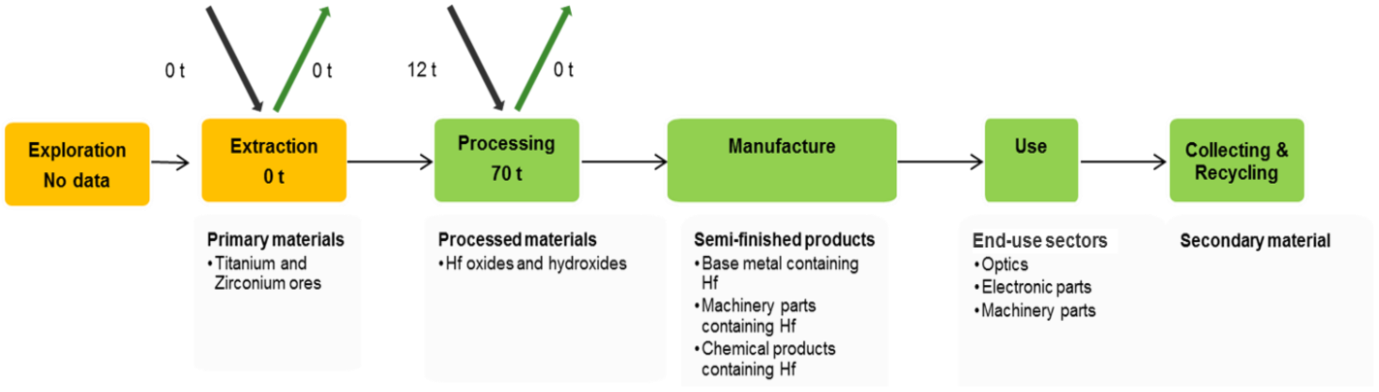

Figure 73: Simplified value chain for hafnium

The green boxes of the production and processing stages in the above figure suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. Eu reserves are displayed in the exploration box.

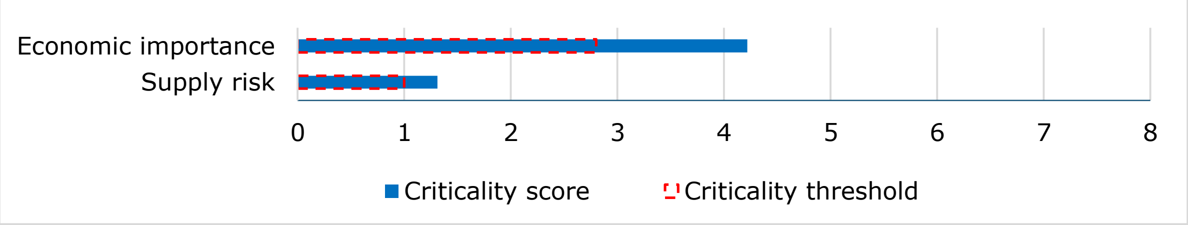

Figure 74: Economic importance and supply risk scores for hafnium

10.1 Introduction

Hafnium is a chemical element with symbol Hf and atomic number 72. Hafnium is a hard, ductile metal similar to stainless steel in its appearance and chemically very similar to zirconium. For this reason, zirconium is discussed in several instances in this factsheet. In nature, hafnium is always found with zirconium and its main commercial sources are zircon and baddeleyite; these are available as by-products from the extraction of titanium minerals (Nielsen & Wilfing, 2010).

Commercial production of hafnium is driven by demand in the nuclear industry for high purity zirconium metal alloys (Moss et al., 2011). Major uses of hafnium are super alloys and nuclear reactor control rods. Hafnium is used in high-temperature alloys and ceramics, since some of its compounds are very refractory: they will not melt except under the most extreme temperatures (Lenntech, 2016).

10.2 Supply

10.2.1 Supply from primary materials

10.2.1.1 Geological occurrence/exploration

The presence of hafnium in the earth’s crust is somewhat rare, with 5.3 parts per million (ppm) upper crustal abundance (Rudnick & Gao, 2003). Compared to hafnium, zirconium occurs in 132ppm.

Hafnium is not present in nature in its elemental form. Its ores are rare, however two of these are known: hafnon ($(Hf,Zr)SiO_4$) and alvite [$(Hf,Th,Zr)SiO_4 \cdot H_2O$]. Hafnium is always found with zirconium and is retrieved as a by-product of its extraction. The two major sources of zirconium and hafnium are zircon ($ZrSiO_4$) and baddeleyite (ZrO_2), in which it is normally present between 1.5-3.0% by weight, and is typically found in a zirconium to hafnium ratio of approximately 50:1.

10.2.1.2 Processing

Hafnium is firstly found in the minerals extracted for zirconium. Zircon sand in their turn is obtained from the processing of heavy mineral sands to recover the titanium minerals rutile and ilmenite.

The separation of the pair zirconium and hafnium is difficult due to the similarity of their chemical properties such as atomic radius, ionic radius and electronegativity. Several methods have been used to separate this ionic pair. Such methods include fractional crystallization, ion exchange, fractional distillation, thermal diffusion, solvent extraction and electrochemical separation (Felipe et al., 2013).

10.2.1.3 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of hafnium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by

application of the CRIRSCO template[10], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for hafnium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for hafnium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for hafnium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

Data on hafnium supply, demand and reserves are not recorded; the figures available are generally estimates (European Commission, 2014). Deposits of heavy metals sands, which are commercially recoverable, are found in China, Malaysia, Thailand, India, Sri Lanka, Australia, South Africa, Madagascar, and the USA. World reserves for hafnium are not recorded, but can be estimated from those of zirconium. Table 42 shows the estimated world reserves of zircon. USGS estimates world resources of hafnium associated with those of zircon and baddeleyite as exceeding 1 million tonnes, which is consistent with the figures shown in Table 42.

Table 42: Global reserves of zircon reserves in year 2016 (Data from Bedinger, 2016)

Country	Zirconium Reserves (tonnes)	Percentage of total (%)
Australia	51,000,000	65
South Africa	14,000,000	18
Other countries	7,200,000	9
India	3,400,000	4
Mozambique	1,100,000	1
China	500,000	1
United States	500,000	1
Indonesia	N/A	N/A
World total (rounded)	*78,000,000*	*100*

10.2.1.4 World refinery production

The global production of Hafnium between 2010 and 2014 was annually 70 tonnes on average. Most of the global production of hafnium (i.e. refining of zirconium) is done in France and the United States (Figure 75), where the production of high purity zirconium for nuclear applications is dominating. It is believed that the Ukraine is not certain about the future of its hafnium production. Alternatively, raw materials used in hafnium production would be merely exported to Russia.

Hafnium production is in anyway highly concentrated, although within countries of low political risk.

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[10] www.crirsco.com

India and China have some low-volume hafnium production for domestic use but do not export (Lipmann Walton & Co Ltd 2012).

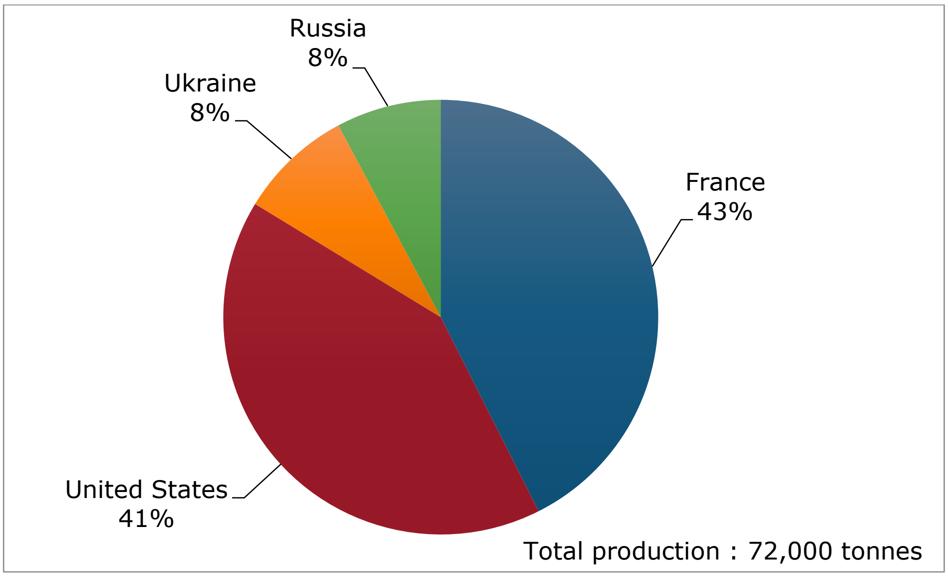

Figure 75: Global refinery production of hafnium, average 2010–2014 (Data from Lipmann Walton & Co Ltd 2012)

10.2.2 Supply from secondary materials

The end-of-life recycling input rate for hafnium is estimated to be 1%. No reliable information on hafnium recycling is currently available. According to USGS, hafnium metal recycling is insignificant in the United States (Bedinger, 2016). UNEP reports that the end-of-life recycling rate is lower than 1% (UNEP, 2011). It is likely that little to no post-use recycling is being carried out currently, given its contamination in the nuclear industry and the low percentage content in super alloys.

Given the existence of hafnium as a by-product of titanium and zirconium, it is likely that waste hafnium from production processes are reintroduced in the process.

10.2.3 EU trade

The volumes of internationally traded hafnium are small and volatile, as can be seen in Figure 76. However, compared to the annual production of hafnium, traded volumes are five times higher; a ratio that is surpassed arguably by only a few other metals or processed minerals.

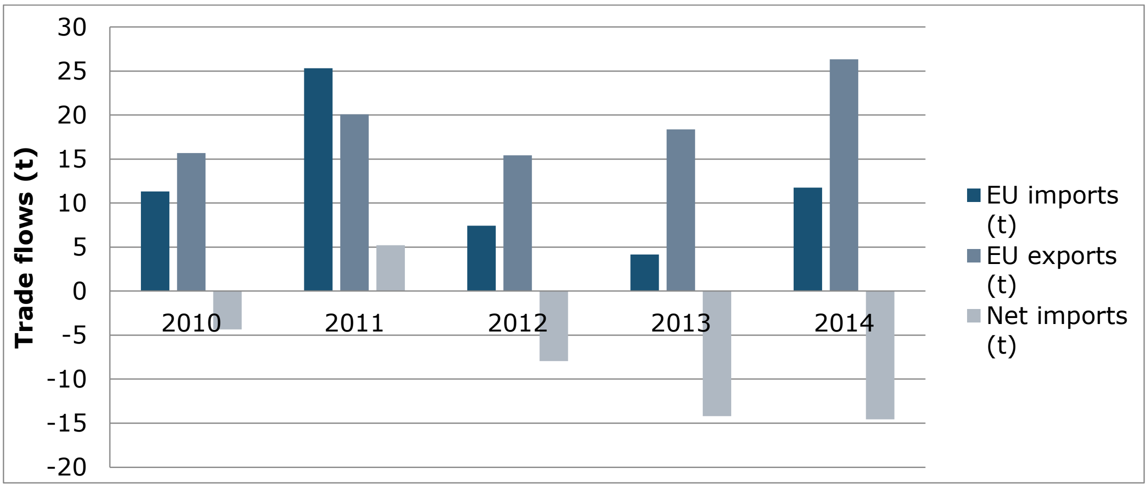

Figure 76: EU trade flows for hafnium (Data from Eurostat Comext 2016)

The imported hafnium metals to the EU come from two countries only: China and Canada (Figure 77).

EU trade is analysed using product group codes. It is possible that materials are part of product groups also containing other materials and/or being subject to re-export, the "Rotterdam-effect". This effect means that materials can originate from a country that is merely trading instead of producing the particular material.

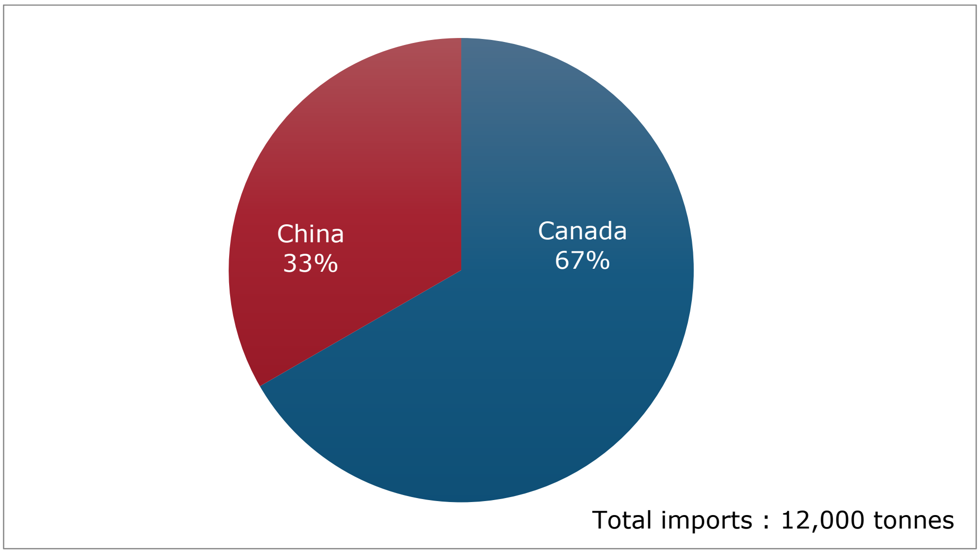

Figure 77: EU imports of hafnium, average 2010-2014 (Data from Lipmann Walton & Co Ltd 2012; Eurostat Comext 2016)

10.2.4 EU supply chain

France is the world major producer of hafnium, with 30 tonnes of annual production. The EU relies for the supply of hafnium for 9% on its imports. Figure 78 presents the EU sourcing (domestic production + imports) data for hafnium.

Supply of hafnium is heavily dependent on the nuclear industry and its demand for pure zirconium. This is because production of zirconium requires separation of the two metals. Following the Fukushima accident many countries, such as Germany, Belgium and Switzerland, have reconsidered their nuclear energy policies. However, most countries remain committed to their energy programs (Hayashi & Hughes, 2012).

Given the concentrated production of hafnium, it is remarkable that export restrictions that might affect hafnium are widely recorded by OECD (2016). This has to do with the CN product group code 8112 92, that on 6-digit detail level also contains niobium, gallium, indium, vanadium and germanium. According to the trade database of the OECD, Jamaica, Rwanda, Burundi, Indonesia, Kenya issue a prohibition for 8112 92. Export taxes are issued by Morocco (7.5%), Russia (6.5%), Argentina (5%) and also licensing requirement. Vietnam even has a tax rate around 30% on average between 2010 and 2014 of the abovementioned unwrought metals.

The restrictions on CN 6 digit level might affect hafnium supply, but also might be a statistical anomaly that is not relevant in international trade in the coming years.

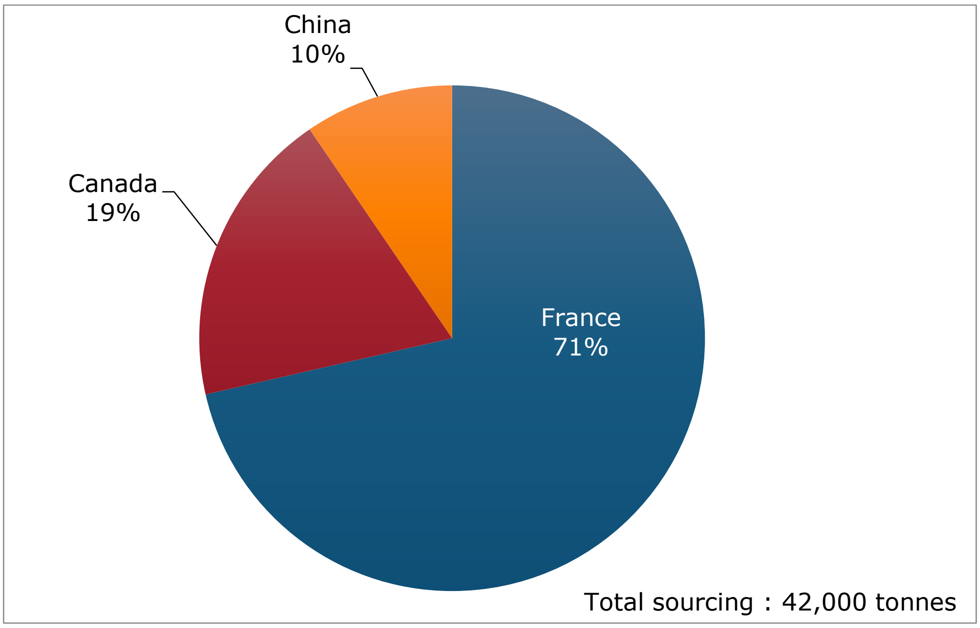

Figure 78: EU sourcing (domestic production + imports) of hafnium, average 2010-2014 (Data from Lipmann Walton & Co Ltd 2012; Eurostat Comext 2016)

10.3 Demand

10.3.1 EU consumption

The EU consumption is on average 33 metric tonnes between 2010 and 2014.

10.3.2 Applications / End uses

Figure 79 shows the uses of hafnium metal; super alloys used in the aerospace industry are the major output (Lipmann Walton & Co Ltd 2012). The nuclear applications are listed as "machinery parts", as they are allocated to NACE 28, manufacturing of machinery.

The major applications for hafnium can be described in more detail as follows:

- Super alloys: the major application for hafnium is as an alloy addition in polycrystalline nickel-based super alloys; for example, MAR-M 247 alloy contains 1.5% hafnium. These alloys are used in the aerospace industry both in turbine blades and vanes but also in industrial gas turbines. The super-alloy industry requires the purest form of hafnium, crystal bars, with low zirconium content. Demand and supply for this form of hafnium approximately equal, making the sector volatile.
- Nuclear control rods: hafnium and zirconium are both used in nuclear reactors and nuclear submarines. Both hafnium and zirconium must be in the pure form in order to work effectively, this leads to the production of hafnium-free zirconium and, as a result, hafnium as a by-product. Hafnium is used in nuclear control rods due to its high thermal neutron absorption cross section (Bedinger, 2016).

Other uses of hafnium are refractory ceramic materials, microchips and nozzles for plasma arc cutting.

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 43). The value added data correspond to 2013 figures.

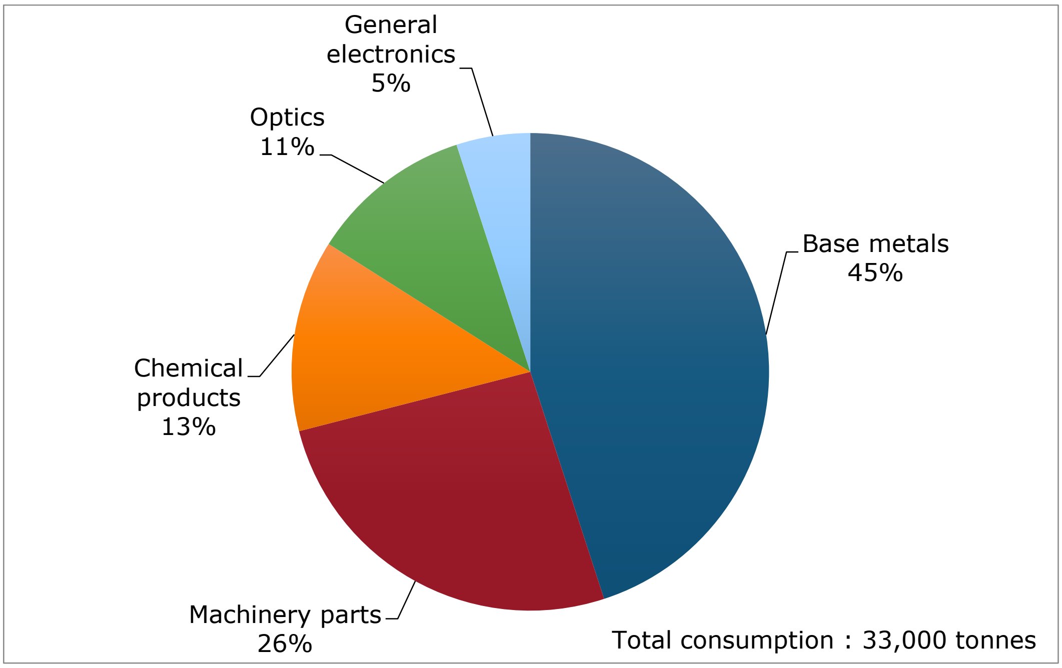

Figure 79: Global end uses of hafnium, projected on EU consumption. Average figures for 2010-2014. (Data from Lipmann Walton & Co Ltd 2012)

Table 43: Hafnium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Data from the Eurostat database, Eurostat, 2016)

Applications	**2-digit NACE sector**	**4-digit NACE sector**	**Value added of sector (millions €)**
Chemical products	C20 - Manufacture of chemicals and chemical products	20.13 Manufacture of other inorganic basic chemicals	110,000.0
Base metals	C24 - Manufacture of basic metals	24.45 Other non-ferrous metal production	57,000.0
General electronics	C26 - Manufacture of computer, electronic and optical products	26.60 Manufacture of irradiation, electromedical and electrotherapeutic equipment	75,260.3
Optics	C27 - Manufacture of electrical equipment	27.31 Manufacture of fibre optic cables	84,608.9
Machinery parts	C28 - Manufacture of machinery and equipment n.e.c.	28.99 Manufacture of other special-purpose machinery	191,000.0

10.3.3 Prices and markets

Hafnium metal is not traded publicly, therefore worldwide data and price trends are not readily available. Figure 80 shows that there has been a significant increase in price since the early 2000s, following a long decline in prices since 1970 given the maturation of the hafnium market. The average price between 2011 and 2015 of bulk zirconium shipped from Australia was 1.511,00 US$/t (DERA, 2016).

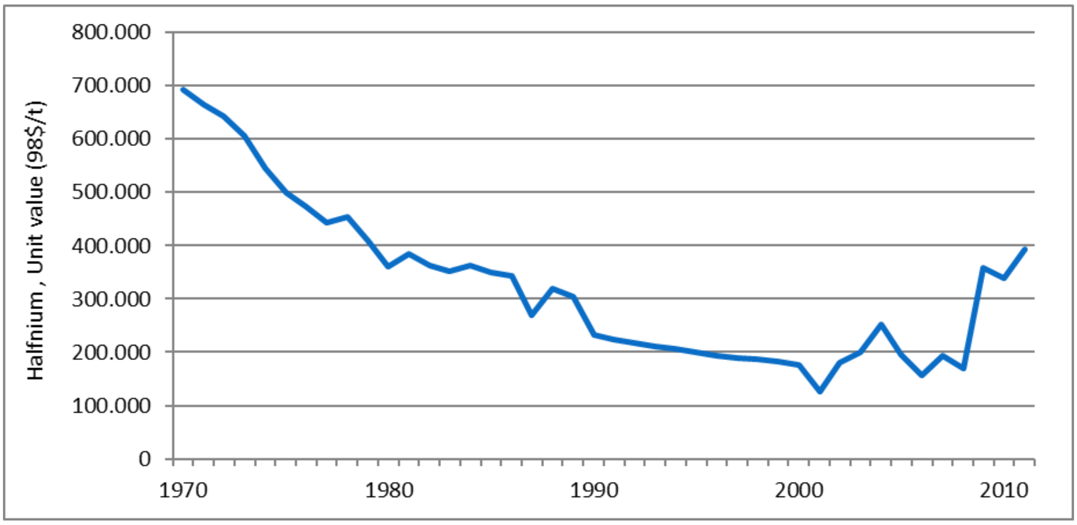

Figure 80: Global developments in price of hafnium. Average figures for 1970-2013. (Data from USGS, 2016)

10.4 Substitution

The applications of hafnium in steel alloys can generally be substituted by other alloy metals, such as magnesium, niobium, tantalum, cobalt and chromium. The performance (corrosion resistance, thermal stress) of these other metals is similar (Bedinger, 2016). For example, in nuclear applications, it is a long standing option to substitute hafnium with silver-cadmium-indium control rods (Graves, 1962).

Zirconium is self-evidently a possible substitute of hafnium (Schemel, 1977), resulting in the maximum numerical value of 50% for all hafnium applications.

10.5 Discussion of the criticality assessment

10.5.1 Data sources

The CN product group code covering hafnium metal is 8112 9210, and labelled “Unwrought hafnium "celtium"; hafnium powders; hafnium waste and scrap (excl. ash and residues containing hafnium)”.

The data has a very strong coverage. It is available on EU level, is available for time series and updated at regular intervals and is publicly available.

10.5.2 Calculation of Economic Importance and Supply Risk indicators

Hafnium is only obtained as a by-product during the processing of other metals. Therefore, data at the extraction (mine) level cannot exist. All data is a representation of materials obtained after processing.

The economic importance allocation is relatively easy to determine for the nuclear applications, which are clearly identified in products produced by the manufacturing of machinery NACE2 sector. The applications of hafnium in base metal is less accurately allocated to end-uses, since some of the applications of hafnium alloys are used in small quantities in equipment that is listed under several NACE2 sectors (metal products, transport equipment, electronics etc.)

The supply risk indicator is heavily influenced by the limited amount of reported suppliers of hafnium. This in spite of the fact that a large share of the EU supply comes from France (43% of the world production on average between 2010 and 2014). The supply risk was assessed on hafnium using both the global HHI and the EU-28 HHI as prescribed in the revised methodology.

10.5.3 Comparison with previous EU assessments

The results for hafnium are significantly different in the 2017 criticality assessment compared to the previous assessments (see Table 44). In addition to the influence of the revised methodology on the overall decrease in economic importance and increase in supply risk scores compared to the previous assessments, the economic importance is also influenced (i.e. reduced) by the fact that the energy sector is not considered to be dependent on hafnium. The Supply Risk indicator is particularly influenced by the limited number and amount of reported suppliers of hafnium. It must be noted that the supply risk is dependent on monopoly or quasi-monopoly situations, independent from the fact that the monopoly is in a European or an extra-European country. Furthermore, the actual SR score is based on the inclusion of actual EU sourcing, which takes into account the EU supply shares from France (71%), Canada (19%) and China (10%). Indeed, in the previous (2014) assessment, the SR was calculated using a share of 50% for France and for the US. In the 2017 assessment, the higher share of France in the EU supply drives up the SR score.

Table 44: The results of Economic Importance and Supply Risk for hafnium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Hafnium	N/A	N/A		7.8	0.4		4.2	1.3

10.6 Other considerations

10.6.1 Forward look for supply and demand

Overall it is estimated that hafnium demand for nuclear applications will increase by 4% annually (Moss et al., 2011). China plans to increase its nuclear power development, this is likely to result in an increase in demand for nuclear-grade zirconium and hafnium (Bedinger, 2016). It must be noted that, given the interdependency of supply and demand of zirconium and hafnium from the nuclear industry, an expansion of the nuclear energy industry should also result in increased production.

Demand is expected to increase by 3.6% for alloys in aerospace and by 5% for non-aerospace super alloys (Moss et al., 2011). For nuclear control rods, demand is expected to increase by 4%; a 3% increase is expected for all other applications.

Table 45: Qualitative forecast of supply and demand of hafnium

Material	**Criticality of the material in 2017**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Hafnium	x		+	+	?	+	+	?

10.7 Data sources

10.7.1 Data sources used in the factsheet

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10.8 Acknowledgments

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11. HELIUM

Key facts and figures

Material name and Element symbol	Helium He	World/EU production[1] (million m^3)	167.1/0.9
Parent group (where applicable)	n/a	EU import reliance[1]	96%
Life cycle stage assessed	Processing	Substitution index for supply risk [SI (SR)]1	0.96
Economic importance (EI)(2017)	2.8	Substitution Index for economic importance [SI(EI)][1]	0.94
Supply risk (SR) (2017)	1.6	End of life recycling input rate	1%
Abiotic or biotic	Abiotic	Major end uses in EU (2012)	Cryogenics (29%), welding (17%), semiconductors & optical fibres (14%)
Main product, co-product or by-product	By-product	Major world producers[1]	United States (73%), Qatar (12%), Algeria (10%)
Criticality results	2011	2014	2017
	Not assessed	Not assessed	Critical

[1] Average for 2010-2014, unless otherwise stated.

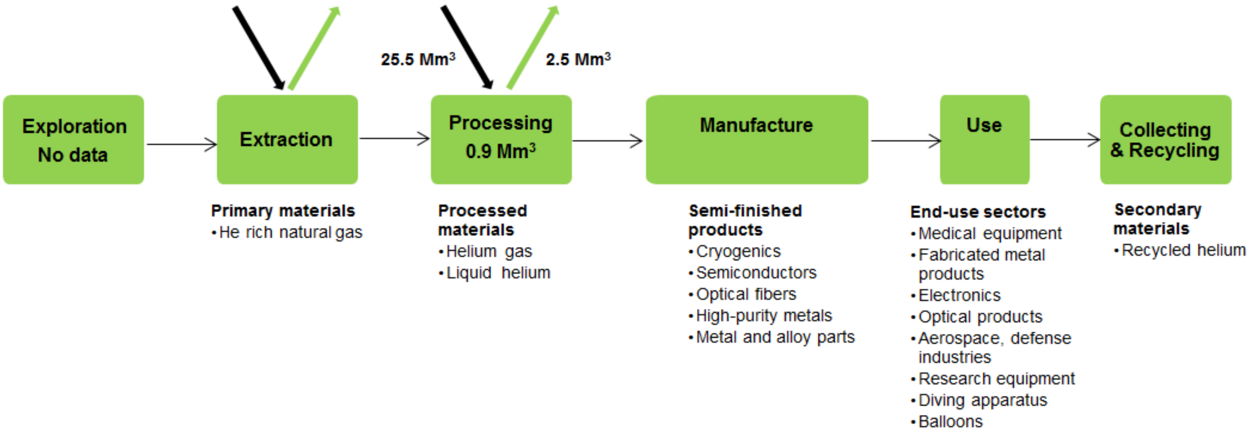

Figure 81: Simplified value chain for helium

Green boxes in the above figure represent stages of the supply chain which take place in the EU-28. The black and green arrows represent imports and exports to and from the EU respectively. EU reserves are displayed in the exploration box.

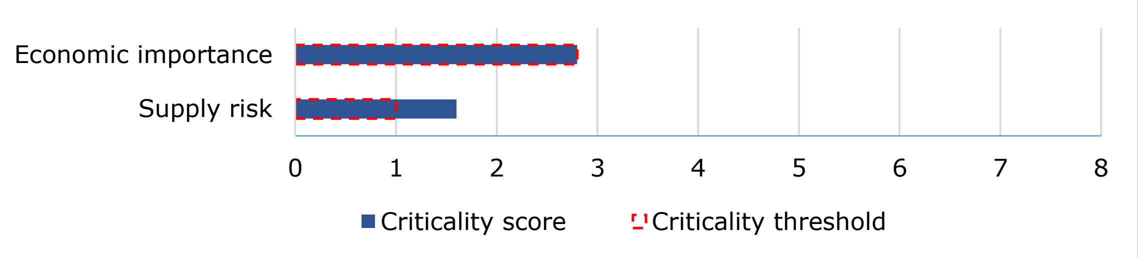

Figure 82: Economic importance and supply risk scores for helium

11.1 Introduction

Helium (chemical symbol He) is a chemical element with symbol He and atomic number 2. It is a colourless, odourless, tasteless, non-toxic, inert, monatomic gas that heads the noble gas group in the periodic table. Its boiling point is the lowest among all the elements (–269° Celsius). Chemically inert, helium does not form compounds, and its molecules consist of single atoms. The second lightest element after hydrogen, helium constitutes about 23% of the mass of the universe and is thus second in abundance to hydrogen in the cosmos. Below 2.17 kelvins, the isotope helium-4 (^{4}He) becomes a superfluid (its viscosity nearly vanishes). Most helium on Earth is ^{4}He, which is produced by radioactive decay deep inside the planet. Over hundreds of millions of years, it migrates up to the crust, where it is released during periods of tectonic activity.

The helium that is found in large quantities on Earth consists of a mixture of two stable isotopes: helium-4 (99.99987%) and helium-3 (0.00013%).

Helium is used as a coolant liquid in cryogenics, as an inert gas atmosphere for welding metals, in the manufacturing of semiconductors and optical fibre cables, in rocket propulsion to pressurize fuel tanks, as a lifting gas, and in high-pressure breathing operations.

11.2 Supply

11.2.1 Supply from primary materials

11.2.1.1 Occurrence

Helium is concentrated in stars, where it is synthesized from hydrogen by nuclear fusion. Helium occurs in the Earth's atmosphere only to the extent of 1 part in 200,000 (0.0005 %), and small amounts occur in radioactive minerals, meteoric iron, and mineral springs. Great volumes of helium are found as a component in natural gases. The helium that is present on Earth is not a primordial component of the Earth but has been generated by radioactive decay. Helium is produced in the natural environment continually by the radioactive decay of uranium specifically within uranium and thorium-rich sedimentary sequences in the earth's crust (e.g., black shales) (Selley, 1985) and escapes into the atmosphere. Since the concentration of helium in air is very minimal, extraction of helium from air is not economically viable. Helium is mainly extracted from helium-bearing natural gas.

11.2.1.2 Exploration

There are several exploration projects worldwide:

- In Canada, in southern Saskatchewan, where the gas can be found in the Precambrian basement. The province issued 59 helium leases in 2016 alone; it didn't issue any in 2015.
- Discovery of a world-class helium gas field in in the Tanzanian East African Rift Valley in 2016 (Danabalan et al., 2016). Helium One Ltd has 3 exploration projects in the area, namely Rukwa, Eyasi and Balangida in Central-North Tanzania.

11.2.1.3 Extraction

Helium is extracted from natural gas of average content 0.1%-0.5%. Helium is usually produced as a by-product of natural gas processing. Natural gas contains methane and other hydrocarbons and smaller quantities of nitrogen, water vapour, carbon dioxide, helium and other non-combustible materials. Crude helium containing about 50-70% helium is extracted from the stream of natural gas usually using a cryogenic distillation method after removing the impurities which might solidify during the process. Once separated from the natural gas, crude helium which contains nitrogen along with smaller amounts of argon, neon, and hydrogen is purified to commercial grades (99.99+%). This is typically done using either activated charcoal absorbers at liquid-nitrogen temperatures and high pressure or pressure-swing adsorption (PSA) processes (U.S. National Research Council, 2010).

For natural gas fields with sufficient concentrations of helium and other nonfuel gases such as CO_2 and sulphur, helium may be directly processed.

Helium is also recovered during the production of liquefied natural gas (LNG) which consists mainly of liquefied methane. The helium is extracted from the gases that remain after the methane has been liquefied. These tail gases, which have a high helium concentration similar to that of crude helium, are then purified. The end product of the purification process is liquefied helium. In this case, helium can be economically recovered from natural gas with very low helium content (U.S. National Research Council, 2010).

The entire helium supply depends on roughly 20 liquefaction plants. The main manufacturers are Air Liquide, Air Product, ExxonMobil, Linde, Gazprom, PGNiG, Praxair and RasGas. The helium distribution business is a highly consolidated sector, with about 10 companies, mostly industrial gas companies, having direct access to sources of helium.

11.2.1.4 Resources and reserves

There are no recent and reliable global or EU resource and reserve estimates for helium. Existing data should be treated with caution as direct comparison between countries may not be possible due mainly to different reporting systems.

In December 2006, the total helium reserves and (probable, possible and speculative) resources in the United States were estimated to be 20,600 million cubic metres (Mm^3). Updated domestic data should be available by the end of 2017. Helium resources in the rest of the world were estimated at about 31,300 Mm^3, with the third of these resources located in Qatar (10,100 Mm^3) followed by Algeria (8,200 Mm^3), Russia (6,800 Mm^3), Canada (2,000 Mm^3) and China (1,100 Mm^3) (USGS, 2016). The USA reserves data have been revised in 2014.

Within the EU, Poland helium reserves are estimated at 25 Mm^3 (Polish Geological Institute, 2016; USG, 2017). Global reserves are displayed in Table 46.

Table 46: Global reserves of helium (Data from USGS, 2016)

Country	**Helium Reserves (million cubic metres, Mm^3)**
USA	3,900
Algeria	1,800
Russia	1,700
Poland	25
Other countries: Australia, Canada, China, Qatar	Not available
World	Not available

11.2.1.5 Helium production

The world annual supply of helium was approximatively 167 Mm^3 on average on the period 2010-2014, with 73% of the supply coming from the USA, followed by Qatar

(12%), Algeria (10%), Russia (3%), Australia (2%) and Poland (1%), the only EU producer (USGS, 2016; Polish Geological Institute, 2016; Gazprom, 2016), see Figure 83.

The USA supply came from active natural gas wells and from the federal government National Helium Reserve which is an underground stockpile known as the Bush Dome Reservoir in the Cliffside gas field, in Texas. Large amounts of helium had been stored in this reservoir from the early 1960s to the mid-1990s. The Helium Privatization Act of 1996 and the Helium Stewardship Act of 2013 mandated the resell of most of the federal stockpiles. The Bureau of Land Management (BLM) manages the federal helium reserve (U.S. National Research Council, 2010; Garvey, 2014).

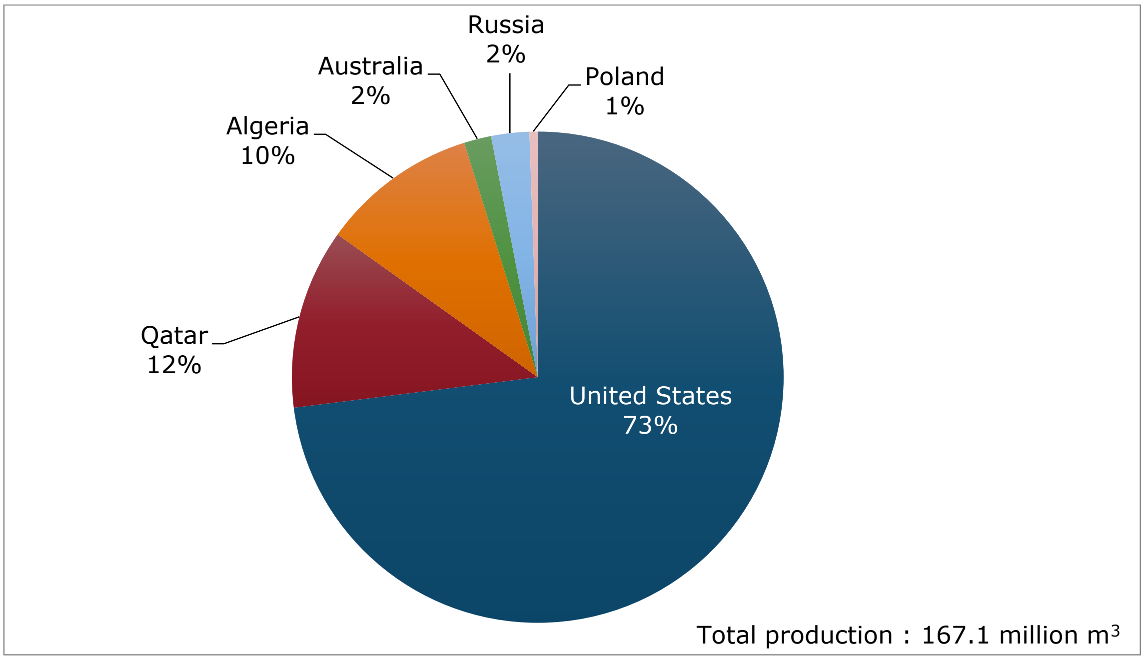

Figure 83: Global helium production, average 2010–2014 (Data from USGS, 2016; Polish Geological Institute, 2016; Gazprom, 2016)

World global supply saw major changes during the period 2010-2014:

- The USA share of worldwide helium supply declined from 78% to 62% between 2010 and 2014;
- The BLM share of the USA supply decreased from 70-80% during the period 2010-2013 to 35% in 2014. The BLM share of world output decreased from 35% in 2012 to 16% in 2014;
- Qatar became the second world largest helium producer in 2013 when the Qatar 2 plants started commercial production and provided 22% of the global supply in 2014 (35 Mm^3).

The three years of severe shortage during the 2011-2013 period caused by the curtailed production of helium from the helium refining facilities tied to the BLM Pipeline in the USA, came to an end early in 2014 when new supply came into the market from several sources: the Qatar II plant, an expansion of the Skikda source in Algeria and a new Gazprom liquefier in Orenburg in Russia (Kornbluth, 2016).

11.2.2 Supply from secondary materials

Cost issues and uncertainties about helium supply have led to the development of recovery and recycling technologies in certain end-user applications and an increasing usage of helium recovery and purification systems in both scientific R&D and industrial applications. However USGS (2015) reports that helium used in large-volume applications is seldom recycled. The end-of-life recycling input rate has been estimated at 1%.

11.2.3 EU trade

The EU was heavily reliant on imports of helium during the period 2010-2014. The EU imports which amounted to 29 Mm^3 in 2010 and 2011 declined to 21 Mm^3 in 2013 in response to a global helium shortage during the 2011-2013 period (see Figure 84). The shortage was caused by curtailed production of helium in the USA, Algeria and Russia (Kornbluth, 2015). Imports picked up again in 2014 as the shortage came to an end with new supply coming into the market, most notably from the Qatar II plant (Kornbluth, 2016).

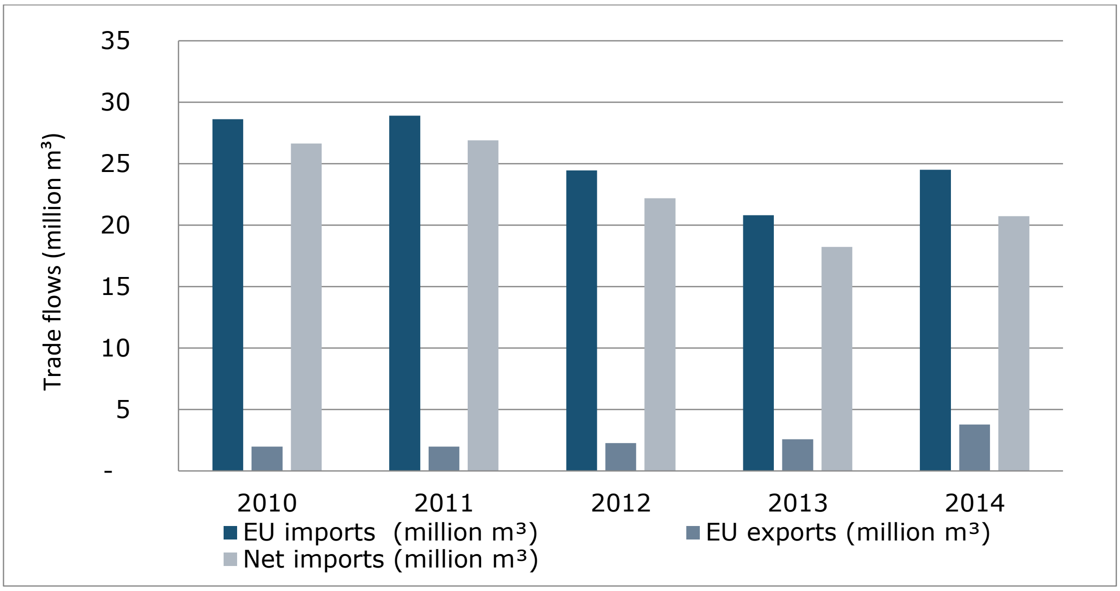

Figure 84: EU trade flows for helium (Data from Eurostat, 2016a)

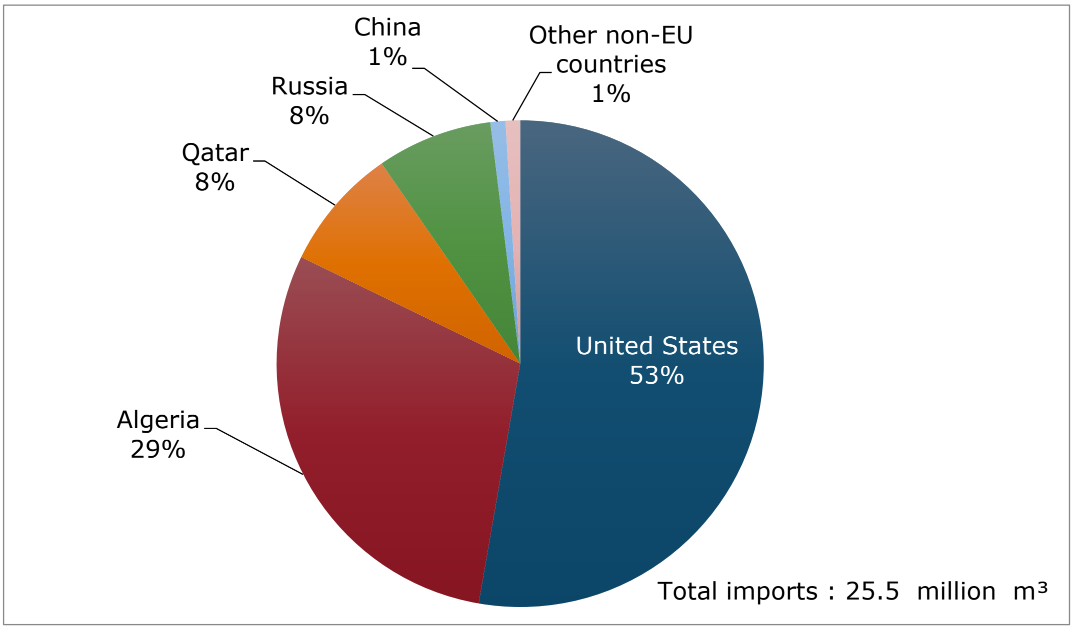

Figure 85: EU imports of helium, average 2010-2014. (Data from Eurostat, 2016a)

About half of the EU-28 imports came from the USA, 30 % from Algeria and 8% from both Russia and Qatar on average during the period 2010-2014 (Figure 85). In 2014, imports from the USA accounted for only 35% of the EU imports whereas those from Qatar were representing 29% of the total imports. Imports from Algeria stayed more or less stable over that period.

No export restriction was in place for helium over the period 2010-2014 (OECD, 2016). A free trade agreement exists between the EU and Algeria (European Commission, 2016).

11.2.4 EU supply chain

EU import reliance is high (96%). Poland is the only EU helium producer. The Figure 86 shows the EU sourcing (domestic production + imports) for helium.

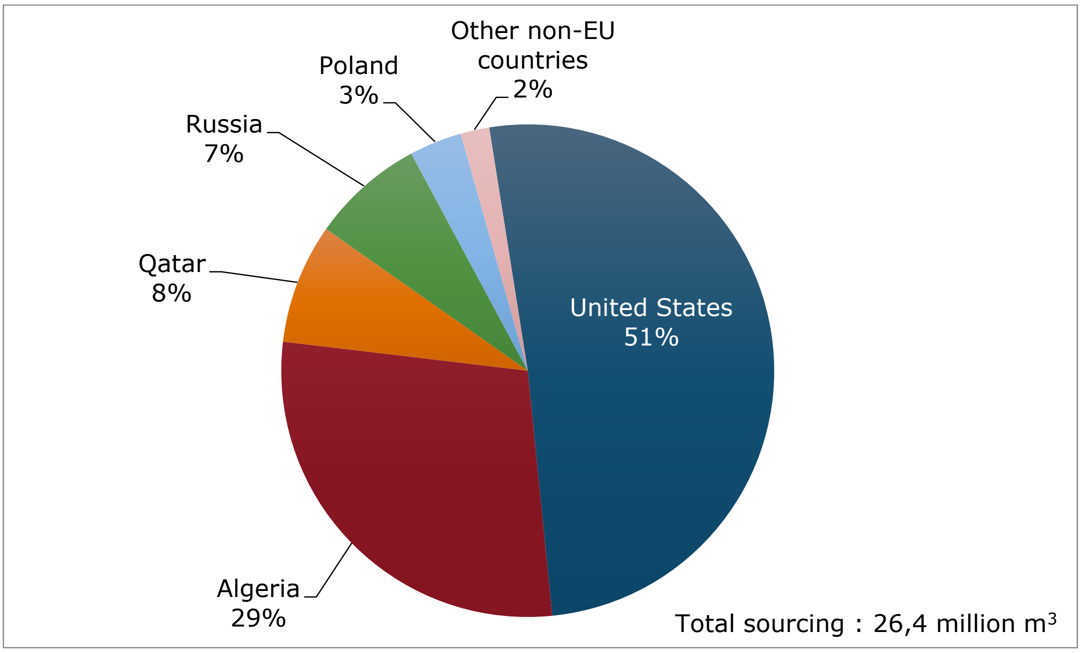

Figure 86: EU sourcing (domestic production + imports) of helium, average 2010-2014. (Data from Eurostat, 2016a; Polish Geological Institute, 2016)

Polskie Górnictwo Naftowe i Gazownictwo SA (PGNiG) owns and operates a helium production facility in Odolanów that extracts and refines helium from gas produced by its domestic natural gas fields, which are located in the Zielona Góra-Rawicz-Odolanów. The natural gas concentration of helium ranges from 0.02% and 0.45% (Polish Geological Institute, 2016). The company has been consistently producing helium from this plant since the late 1970s. Poland produced 0.9 Mm^3 per year on average during the period 2010-2014.

11.3 Demand

11.3.1 EU consumption

The EU net consumption amounted to about 23.8 Mm3 per year on average during the period 2010-2014 (Data from USGS, 2016; Polish Geological Institute, 2016; Gazprom, 2016; Eurostat, 2016a).

11.3.2 End uses

The main categories of end uses for selenium are shown in Figure 87 and relevant industry sectors are described using the NACE sector codes in Table 47.

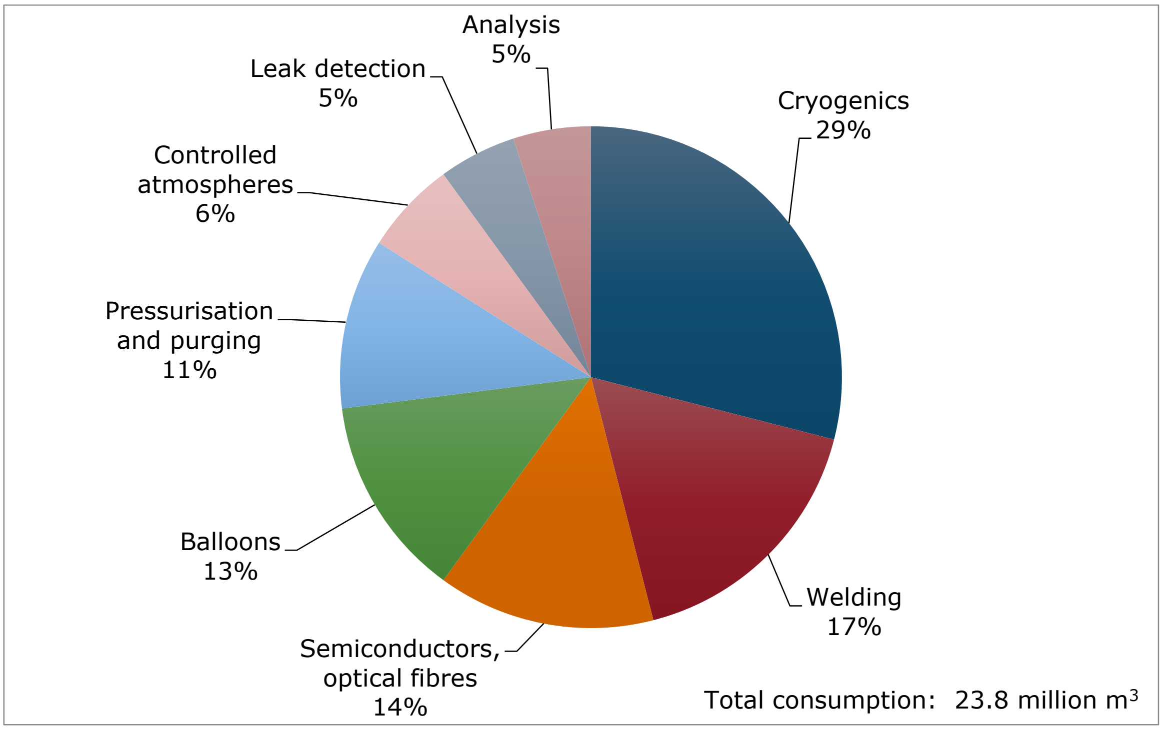

Figure 87: Global end uses of helium. Average figures for 2010-2014. (Data from Nuttall et al., 2012)

The largest use for liquid helium is in cryogenics where it is used mostly to cool superconductive magnets of MRI (magnetic resonance imaging) scanners and, to a much less extent, in particle physics research facilities.

The largest use for gaseous helium is in arc welding, where it provides an inert gas shield to prevent oxidation during welding of aluminium, magnesium, copper, and stainless steels. Depending on the type of weld and the metal, helium will usually be blended with argon. For metal inert gas welding (MIG), helium might make up from 25% to 75% of the gas mix in a helium/argon blend. Pure helium is generally only used for some specialized tungsten inert gas (TIG) welding applications (Air liquide, 2017).

Helium gas is also used:

- In semiconductor wafer and chip fabrication for its inertness, heat conducting and cooling properties. It is used as a cooling gas in the strand spinning operations in the manufacture of optical fibre cables.
- As purging and/or pressurizing gas in aerospace, defence, and nuclear industries (e.g. NASA, Ariane).
- To create controlled atmospheres when gas inertness is necessary: heat treatment and manufacture of high-purity metals etc. It is a component of breathing gas in deep diving activities in offshore oil and gas exploration and underwater pipe maintenance.
- In leak detection as a tracer gas to check for leaks in containers, pressure vessels etc. because of the He atom small size.
- As a lifting gas in party balloons, weather balloons, advertising blimps, balloons for upper atmosphere studies.

The US was the largest market for helium worldwide in 2013, consuming about 32% of the total volume, followed by Asia (31%) and Europe (21%).

Table 47: Helium applications, 2-digit NACE sectors and associated 4-digit NACE sectors, and added value [Data from the Eurostat database, (Eurostat, 2016b)]

Applications	2-digit NACE sector	Value added of NACE 2 sector (millions €)	4-digit NACE sector
Cryogenics	C32 - Other manufacturing	41,613	C32.5.0 - Manufacture of medical and dental instruments and supplies
Controlled atmospheres	C24 - Manufacture of basic metals	57,000	C24.4.5 - Other non-ferrous metal production
Welding	C25 - Manufacture of fabricated metal products, except machinery and equipment	159,513	C25.1.1 - Manufacture of metal structures and parts of structures
Pressurisation and purging	C32 - Other manufacturing	41,613	C32.9.9 - Other manufacturing n.e.c.
Leak detection	C33 - Repair and installation of machinery and equipment	60,879	C33.1.2 - Repair of machinery
Semiconductors, optical fibres	C26 - Manufacture of computer, electronic and optical products	75,260	C26.1.1 - Manufacture of electronic components C26.3.0 - Manufacture of communication equipment
Lifting gas	C32 - Other manufacturing	41,613	C32.9.9 - Other manufacturing n.e.c.
Analysis	C32 - Other manufacturing	41,613	C32.9.9 - Other manufacturing n.e.c.

11.3.3 Prices

The US Bureau of Land Management (BLM) started to sell crude helium from the federal helium reserve on the open market in 2005, at a formula-driven price. This price became the de-facto crude helium price, and the basis of the price of refined liquid and refined gas in the US and worldwide. The BLM crude helium price rose sharply (40%) from October 2011 to October 2014 in response to the supply constraints during the period 2011-2013. BLM crude helium price over the period October 1997-October 2015 is show in Figure 88. The USGS (2017) indicates that the BLM crude helium average price was US$3.75 per cubic metre in 2016 (i.e. similar to 2015 level).

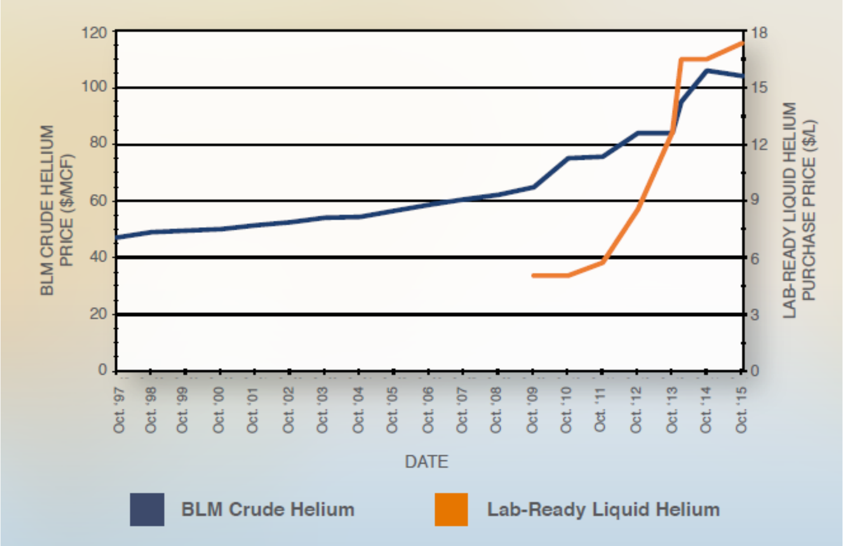

Figure 88: Bureau of Land Management open market price of crude helium from October 1997 to October 2015 (American Physical Society, 2016)

11.4 Substitution

For some applications, helium can be replaced by others gases, but other uses rely on helium unique properties and there are no existing alternatives.

- **Cryogenics**: There is no substitute for liquid helium in cryogenic applications if temperatures below 17°K (-256°C) are required. Other cryogenic substances are used in other temperature conditions.
- **Purge and pressurization:** There is no substitute for applications requiring inertness and ultra-low temperature.
- Welding: Argon can be used for both gas metal arc welding and gas tungsten arc welding.
- **Semiconductor and optical fibre manufacturing:** At the present time only argon seems to be a marginal substitute for helium in the semiconductor industry (Campbell et al., 2013). There is presently no substitute for helium in optical fibre production process (Boersen, 2013).
- **Lifting gas:** Hydrogen is sometimes substituted if safety concern can be met (Chan, 2013).
- **Controlled atmospheres and breathing gas:** Argon can be used as a substitute. There is no substitute for breathing mixtures.
- **Leak detection:** Some helium users could use a mix of 5% hydrogen and 95% nitrogen -which is classified as non-flammable - as an alternative.
- **Analysis:** Hydrogen and nitrogen are used as carrier gas for chromatography. Hydrogen provides the fastest analysis time over a broad linear velocity range, but safety concerns must be addressed. Nitrogen is a slow carrier gas, so its use is limited to situations where longer analysis times are acceptable (Wallace and Sidisky, 2011).

11.5 Discussion of the criticality assessment

11.5.1 Data sources

Production data for helium are from USGS (2016), the Polish geological institute (2016) and Gazprom (2016). Trade data were extracted from the Eurostat Easy Comext database (Eurostat, 2016a). Data on trade agreements are taken from the DG Trade webpages, which include information on trade agreements between the EU and other countries (European Commission, 2016).

For trade data, the Combined Nomenclature CN8 code 28042910 'Helium' has been used.

11.5.2 Economic importance and supply risk calculation

Helium was not assessed in 2011 or in 2014. Therefore, helium is being assessed for the first time in 2017, with the EI and SR presented below in Table 3. The 2017 assessment was performed using a revised methodology.

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 47). The value added data correspond to 2013 figures.

11.5.3 Comparison with previous EU assessments

The calculation of the Supply Risk (SR) was carried out at the refining stage of the life cycle using both the global HHI and the EU-28 HHI. The effect of substitution is incorporated both in the calculation of the economic importance and the supply risk by estimating the substitution indexes SI_{EI} (in economic importance calculation) and SI_{SR} (in supply risk calculation). Finally, the effect of recycling is incorporated into the supply risk calculation. The results of this review are shown in Table 48.

Table 48: Economic importance and supply risk results for niobium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Helium	Not assessed			Not assessed			2.8	1.6

11.6 Other considerations

11.6.1 Environmental and regulatory issues

Helium is listed in Annex IV/V of REACH, and is exempted from registration (ECHA, 2017).

11.6.2 Forward look for supply and demand

Despite the current over-supply in the market, some significant developments are under development including: (1) The new Qatar Helium 3 (RAsGas) plant in Qatar that is expected to produce up to about 11 Mm^3 per year starting in 2018 (Arabianindustry, 2015); (2) Plans to develop a 20 Mm^3 per year helium plant in the Dry Piney Creek (Wyoming) in the USA; (3) Gazprom's project to produce helium at the Amur Natural Gas Processing Plant in Siberia which is under construction. Helium production is expected to commence by early 2021, with capacity increasing in stages to about 64 Mm^3 per year, eventually making this the world's largest source of helium (Kornbluth, 2016).

The future growth of helium is expected to be driven by demand from electronics manufacturers in China, South Korea, and Taiwan. Semiconductor manufacturing, flat-panel display manufacturing, and optical fibre manufacturing are all significant consumers of helium in Asian markets. While worldwide demand is expected to grow only 2% per year, demand in these countries is expected to grow close to double that rate. With high-tech manufacturing shifting to Asian countries, the US and Western European share of worldwide demand is expected to continue to decline (IHS Markit, 2016).

Table 49: Qualitative forecast of supply and demand of Helium

Material	**Criticality of the material in 2017**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Helium	x		+	+	+	+	+	+

11.7 Data sources

11.7.1 Data sources used in the factsheet

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11.8 Acknowledgments

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12. INDIUM

Key facts and figures

Material name and Element symbol	Indium, In	World/EU production[1] (tonnes)	689/47.8
Parent group (where applicable)	n/a	EU import reliance[1]	0%
Life cycle stage assessed	Processing / Refined indium	Substitution index for supply risk [SI(SR)][1]	0.97
Economic importance score (EI)(2017)	3.1	Substitution Index for economic importance [SI(EI)][1]	0.94
Supply risk (SR) (2017)	2.4	End of life recycling input rate (EOL-RIR)	0%
Abiotic or biotic	Abiotic	Major end uses[1]	Flat panel displays (56%) Solders (10%), PV cells (8%)
Main product, co-product or by-product	By product of zinc refining	Major world producers[1]	China (57%); South Korea (15%), Japan (10%)
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] average for 2010-2014, unless otherwise stated.

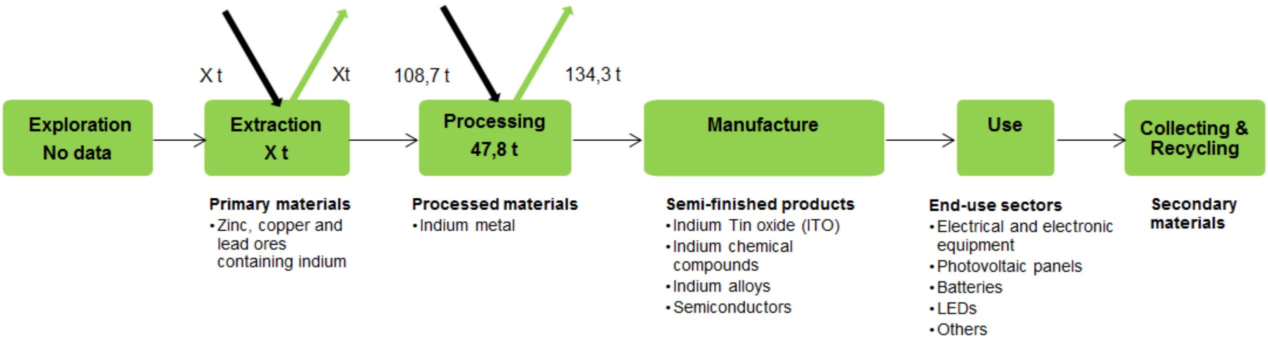

Figure 89: Simplified value chain for indium

Green boxes in the above figure represent stages of the supply chain which take place in the EU-28. The black and green arrows represent imports and exports to and from the EU respectively. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

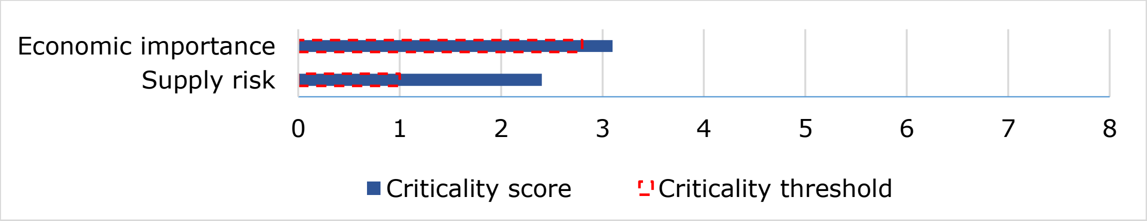

Figure 90: Economic importance and supply risk scores for indium

12.1 Introduction

Indium (In, atomic number 49) is a very soft, ductile and malleable silvery metal with a hardness of 1.2 on Mohs scale. It has a density of 7.31 g/cm^3 (similar to tin's), a low melting point of 156.6°C, a high boiling point of 2072°C and becomes superconducting at 3.37 K. Indium an abundance in the Earth continental upper crust is estimated at 0.056 ppm (Rudnick & Gao, 2003). The most important commercial source of indium is the zinc mineral sphalerite. The major use of indium is as indium-tin oxide (ITO) in flat panel devices (FPDs). Other applications include alloys and solders, thin film solar panels, thermal interface materials, light emitting diodes (LEDs) and laser diodes.

12.2 Supply

12.2.1 Supply from primary materials

12.2.1.1 Mineral occurrence

Indium is found as a trace element in some zinc, copper, lead and tin minerals but is mostly recovered from the zinc-sulphide mineral sphalerite. Approximatively 95% of the refined indium produced in the world comes from the processing of zinc ores.

The most important deposits are volcanic- and sediment-hosted base-metal sulphide deposits, which are generally characterised by high metal abundance and large tonnages. The concentration of indium in these ores is in the range 20–200 parts per million (ppm). Other types of deposits containing significant and recoverable amounts of indium include polymetallic vein-type deposits, vein-stockwork deposits of tin and tungsten and epithermal deposits (Schwarz-Schampera, 2014).

12.2.1.2 Exploration

Deposits with high indium concentrations have been reported from the Mount Pleasant porphyry tin-tungsten deposit in New Brunswick, Canada, and from several deposits in Argentina (Pinguino), Australia, Bolivia, Finland, Peru, Portugal, and the United States.

12.2.1.3 Mining, processing and extractive metallurgy

Indium is not concentrated enough to be a major commodity in deposits, but is recovered as a by-product mainly from residues generated during zinc ore processing. A small amount (about 5%) is produced as a by-product of lead, tin and copper production. Indium recovery from the total indium bearing ores mined annually is approximatively 30% according to the Indium Corporation (Mikolajczak, 2009) because the ore is either processed in smelters which cannot recover indium (30% of the ore) or either not fully recovered in indium-capable smelters. However indium contained in smelting wastes is potentially available for recovery in the future. Today zinc is mostly produced by hydrometallurgical treatment of its concentrates in electrolytic plants. Indium is produced mainly by leaching with hydrochloric acid (HCl) or sulphuric acid (H_2SO_4) of dusts, fumes, residues, and slag from the zinc and lead-zinc smelting. The solutions are concentrated, and indium recovered and refined to standard grade (99.99% In or 4N). Virgin indium can further be refined to 6N or 7N purity, or manufactured into products such as indium-tin oxides, alloys, and compounds (Alfantazi et al, 2003; Lokanc et al, 2015; Roskill, 2010).

12.2.1.4 Resources and reserves

Indium being mainly recovered as a by-product of zinc production, indium resources and reserves are generally derived from zinc resources and reserves data using an average indium content of zinc ores.

There is no single source of comprehensive evaluations of resources and reserves that apply the same criteria to indium deposits in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[11], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for indium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for indium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for indium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2014). Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

A study undertaken by the Indium Corporation (Mikolajczak, 2009) estimated that primary indium resources and reserves in identified base metal mines amounted to approximatively 50,000 tonnes of indium, with some 47% in China and the Commonwealth of Independent States (CIS), and 53% in other countries.

Global resources and reserves of indium calculated from global zinc resources and reserves reported by USGS (2012), using an average zinc ore indium content of 50g/t, have been estimated at 95,000 tonnes and 12,500 tonnes, respectively (Schwarz-Schampera, 2014). When also considering recoverable indium in copper deposits and using an average indium content of 10g/t, total resources and reserves amounted to 125,000 tonnes and 18,800 tonnes in 2012 (Table 50).

Table 50: World indium resources and reserves calculated from global zinc and copper resources and reserves reported by USGS in 2012 (Data from Schwarz-Schampera, 2014)

Estimated world indium resources and reserves (tonnes of indium)	
Resources in zinc ores	95,000
Reserves in zinc ores	12,500
Resources in copper ores	30,000

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[11] www.crirsco.com

Reserves in copper ores	6,300
World total indium resources	125,000
World total indium reserves	18,800

There is no mineral resource and reserve data for indium reported in the Minerals4EU project (Minerals4EU, 2014). In Europe, most of the indium mineralisation is located in Variscan units and, to a small extend, in Proterozoic (Sweden), Caledonian and Alpine formations. The largest indium anomalies on the Iberian Peninsula overlap with known metallogenic districts which include deposits such as Neves-Corvo copper-zinc mine in Portugal (Ladenberger, 2015).

12.2.1.5 World indium production

The world production of primary indium was approximatively 690 tonnes per year on average on the period 2010-2014. More than half of global refined indium is produced in China (57%). The remaining production was predominantly in South Korea, Japan, Canada, Belgium, France, Peru and Russia (Figure 91). Kazakhstan was also producing a small amount of indium as a by-product of zinc production by Kazzinc. Global annual production capacity amounted to about 800 tonnes (Les Echos, 2014).

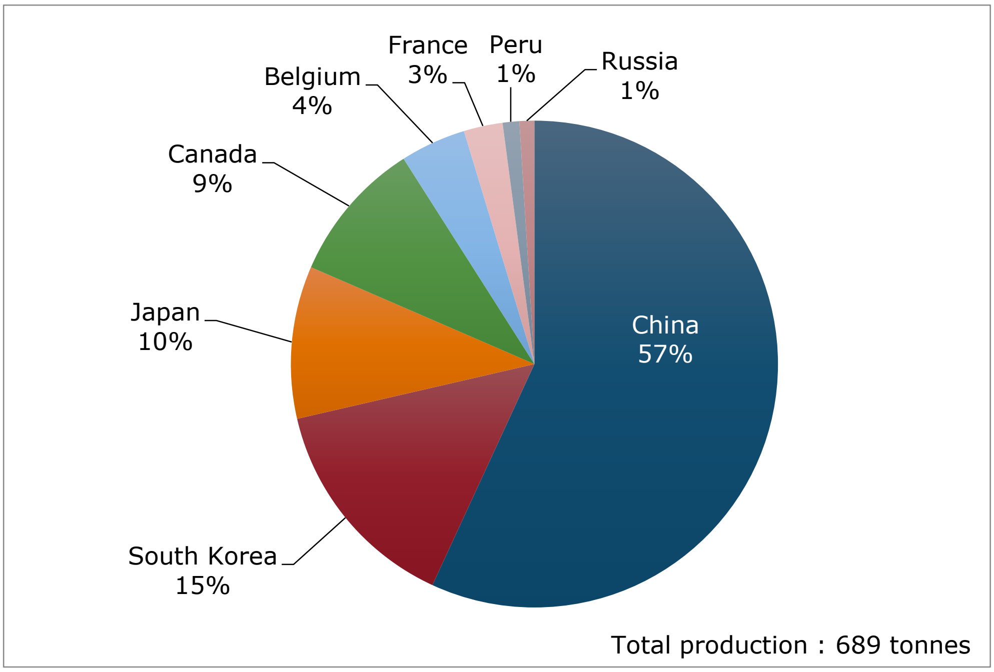


Figure 91: World production of indium, average 2010–2014 (Data from BGS World Mineral Statistics database; Nyrstar, 2015)

12.2.2 Supply from secondary materials

12.2.2.1 Secondary production from pre-consumer scraps

World secondary refined indium production resulted almost exclusively from the recycling of manufacturing waste (new scrap) rather than recovery from end-of-life (EOL). Precise data on the amount of secondary indium recovered annually from scrap are not available, but are estimated to exceed virgin indium production. According to the Indium Corporation (Jackson, 2012), approximatively 1,500 tonnes of refined indium was produced in 2011, including 950 tonnes of recycled indium. Most of the indium produced in the world is used in ITO (tin-doped indium oxide) thin-film coating on flat-panel liquid-crystal displays (See section on global end uses). New scrap used in the secondary production of indium consists mainly of spent ITO sputtering targets which are used as ITO source material to produce thin films. Only 30% of the ITO target material is actually deposited onto the substrate when using planar sputtering targets, which are the dominant form of targets. The thin film production efficiency is now however greatly improved by the use of rotary sputtering targets. What is left of the target is recycled into indium metal. It is estimated that over 70% of the indium from the starting targets is recovered (Mikolajczak, 2009). ITO recycling is concentrated in Japan, South Korea and China where ITO production and thin film manufacturing take place.

12.2.2.2 End of life recovery and recycling

Very little old scrap (1%) is recycled worldwide (UNEP, 2011) because of minor indium concentrations in final products, a lack of appropriate technology, or low economic incentives compared to recycling costs (Ylä-Mella and Pongrácz, 2016).

12.2.3 EU trade

The EU was a net indium exporter over the period 2010-2014. EU imports of indium rose 75% in 2011 before declining sharply (-70%) in 2012 and stabilizing around 65 tonne/year (see Figure 92). The EU was a net indium exporter (128 tonnes) in 2011 thanks to a very high level of exports (388 tonnes) in 2011.

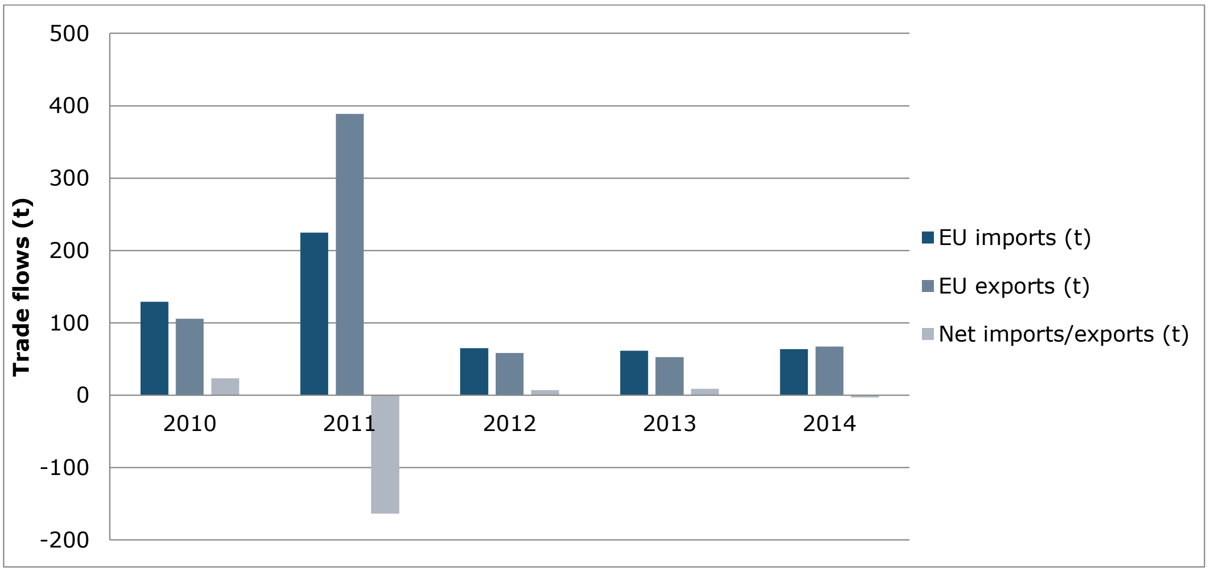


Figure 92: EU trade flows for indium (Data from Eurostat COMEXT database)

The EU imported a total of 544 tonnes of indium metal during the period 2010-2014, exported 672 tonnes, and produced 239 tonnes of refined indium. The EU import reliance was 0%. The imports and exports values suggested that the EU imported standard refined indium and exported higher purity indium or other types of indium with higher added value.

China and Kazakhstan were the EU main indium suppliers, accounting for nearly 60% of EU average annual imports over the period 2010-2014 (Figure 93). However, imports pattern changed drastically during that period: imports from Kazakhstan - which has a small production of indium as a by-product of zinc production by Kazzinc - stopped in 2012 and imports from China were accounting for only 11 % of the total imports in 2014. South Korea became the main supplier with 30% of the imports in 2013. Indium exports from China, which had been a traditional indium exporter, tumbled in 2012 while Chinese imports soared on booming investment demand (Shanghai Metals Market, 2013) when the Fanya Metals Exchange started to trade and stockpile indium. Chinese exports quotas were maintained over the period 2010-2014 (about 240 tonnes/year on average) but have been removed in 2017.

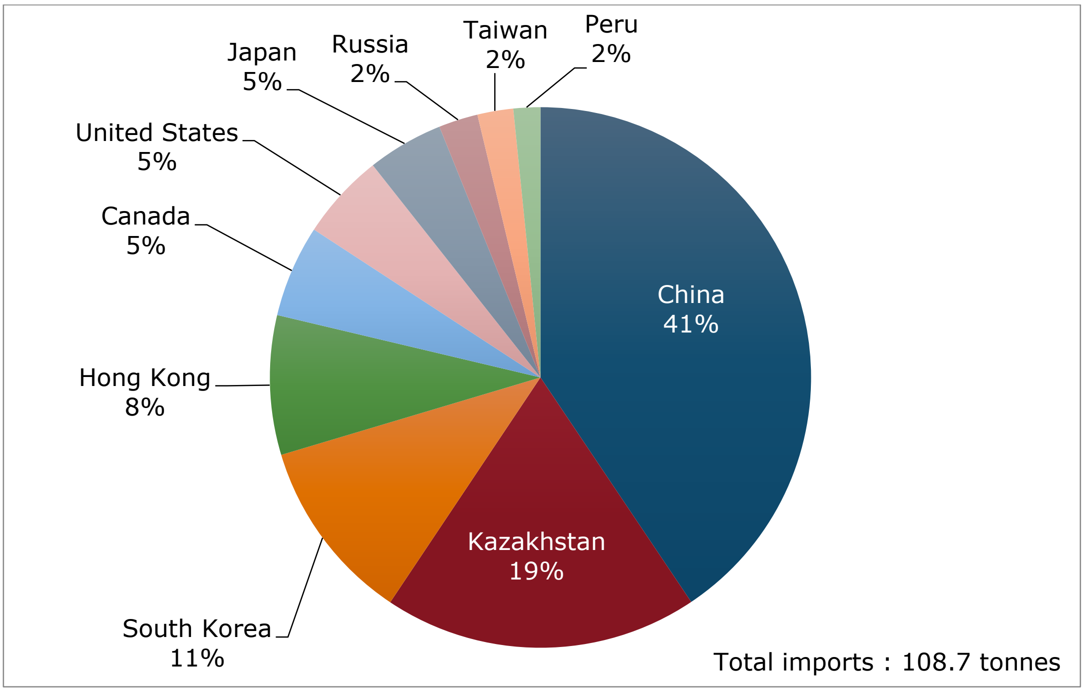


Figure 93: EU imports of indium, average 2010-2014. (Eurostat, 2016a)

China export tax on indium was reduced from 5% to 2% in 2014 before being cancelled in 2017. Exports quotas were maintained over the period 2010-2014 (237 tonnes on average) but have been removed in 2017. China has switched to using export licences rather than quotas to control the export of the minor metal from January 2017. The EU-28 applies a 2% import duty on indium metal and a 5.5% duty on indium compounds imports such as indium nitrate.

12.2.4 EU supply chain

12.2.4.1 Indium bearing ore production

Some of the zinc concentrates produced in the EU present significant indium contents. At Neves Corvo mine in Portugal, indium grades vary within the range 20 to 1,100 ppm/tonne in the massive zinc and lead-zinc ores of the deposit (Pinto et al., 2014). However it is not known if indium was recovered from concentrates produced within the EU during the period 2010-2014.

12.2.4.2 Refined indium production

The EU production of refined indium amounted to 47.8 tonnes per year on average on the period 2010-2014 and represented around 7% of the world production. Figure 94 presents the EU sourcing (domestic production + imports) for refined indium. The EU production more than doubled from 2010 to 2014. The two producers, Belgium and France, refined indium from imported concentrates, residues and slags. In France, Nyrstar commissioned a new virgin indium plant at Auby in 2012 which produced 43 tonnes of metal in 2014. Auby's zinc concentrates were sourced from suppliers world-wide (Nyrstar, 2016). There was no indium production in 2016 due to a fire at the indium cement plant that occurred in late 2015. The indium plant has since been re-built with additional capacity, bringing total production capacity to 70 tonnes/year, and is expected to resume production in 2017. The other major producer was Umicore in Belgium. Umicore produced refined indium at its Hoboken plant from dusts and residues generated by its lead-copper processing plant. Umicore Precious Metals Refining has a capacity of 30 tonnes per year (Nyrstar, 2015). Germany small production which consisted into upgrading 4N indium (99.99 In) to very high purity indium (up to 7N) (PPM Pure Metals) was not included in the EU primary production.

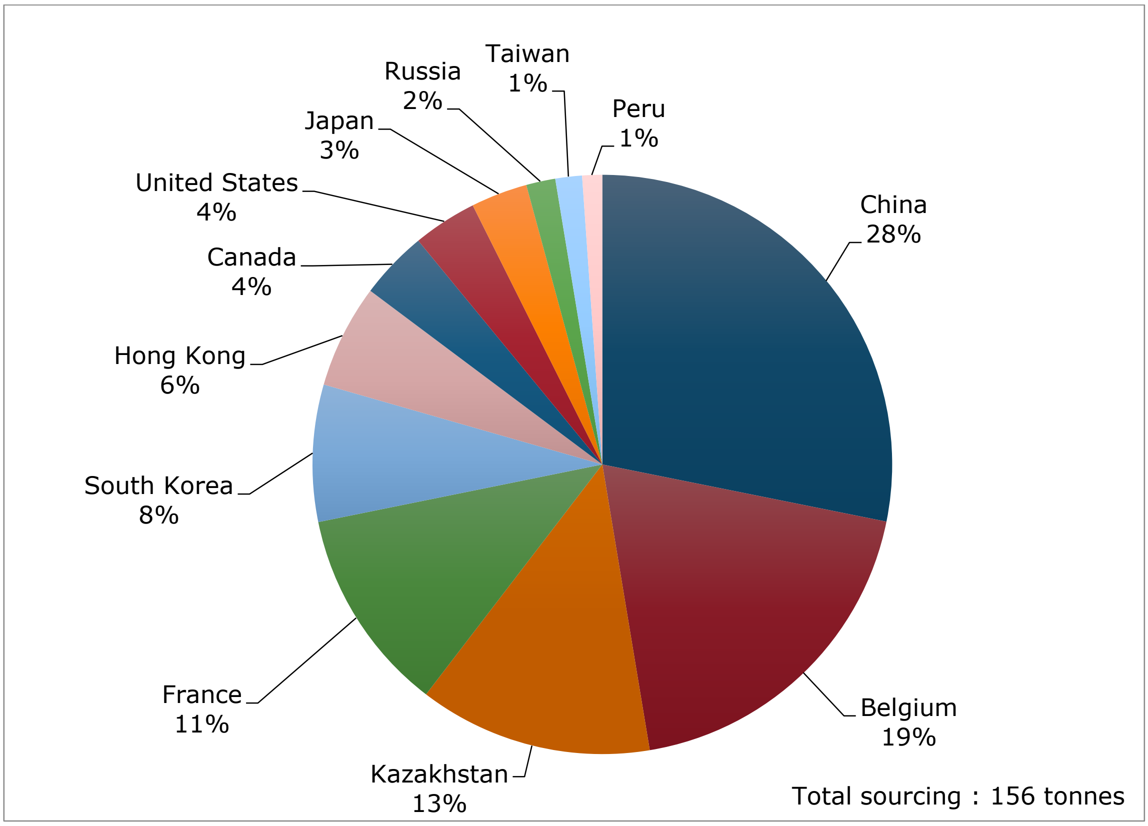


Figure 94: EU sourcing (domestic production + imports) of indium, average 2010-2014. (Eurostat, 2016a; BGS, 2016; Nyrstar, 2015)

12.2.4.3 Semi-finished and finished products

There was no ITO production in the EU. There was a small production of CIS (copper indium selenide) solar cells in Germany until 2013 at the AVANCIS GmbH factory in Torgau which had an annual production capacity of 20 MW. The production line was converted into a research facility in 2013 and the production was moved to China (Jäger-Waldau, 2015). A number of small companies produced specialty low indium alloys in Germany, compound semiconductor material [e.g. Wafer Technology Ltd in the UK, (Wafer Technology; 2016)], batteries (2 plants in the UK), thin films (Heraeus in Germany) and other indium products.

12.2.4.4 Collecting and recycling

The annual addition of indium to stock in landfill in the EU has been estimated at around 56 t by the Study on Data for a Raw Material System Analysis (Bio by Deloitte, 2015).

12.3 Demand

12.3.1 World and EU consumption

In the EU, indium metal apparent consumption (i.e. 'production' + 'imports' – 'exports') amounted to 22.2 tonnes per year on average during 2010–2014 which represents about

3% of the global production and less than half (46%) of the EU indium production during that period. The EU was self-sufficient regarding to its indium metal supply.

Nearly 80% of the production of ITO sputtering targets for thin film coating (FPDs and PV solar cells mainly) is concentrated in Japan and in South Korea (e.g. JX Nippon Mining & Metals, Samsung etc.). There is also a handful of smaller scale producers in China and USA. Global ITO sputtering target demand mainly comes from Japan, South Korea, China other Asian countries of which China accounts for more than 35% of the total (Research In China, 2016). All flat panel displays (FPDs) manufacturing takes place in Japan, South Korea and China. Ex-Asia, indium was mostly used in the manufacturing of non-ITO applications such as solders, alloys, and compound semiconductors.

12.3.2 End uses

The main categories of end uses for refined indium are presented in Figure 95 and corresponding industry sectors described using NACE sector codes (Eurostat, 2016c) are shown in Table 51.

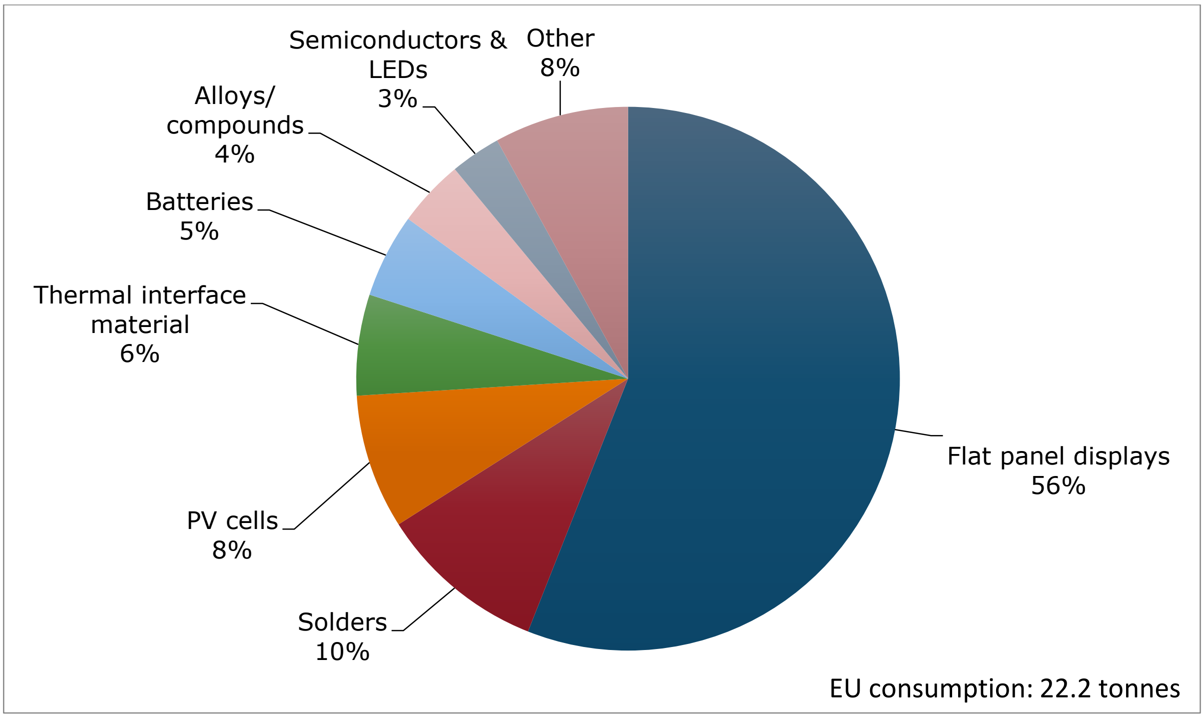


Figure 95: Global end uses of indium. (Data from Indium Corporation, 2013)

Indium is predominantly used in the form of indium tin oxide (ITO or tin-doped indium oxide) as a transparent conductive oxide (TCO) material. ITO is a mixture of indium (III) oxide (In_2O_3) and tin (IV) oxide (SnO_2), typically 90% In_2O_3, 10% SnO_2 by weight. When deposited as a thin film on glass or clear plastic it functions as a transparent electrode.

Indium finds its primary application as ITO thin films in flat-panel displays (FPDs) - whether liquid crystal displays (LCDs), plasma display panels (PDPs) or OLED displays (organic light emitting diodes) - for televisions, laptops, notebooks and mobile phones. ITO thin films are also applied to car and aircraft windshields for defogging and deicing. They were still used to make touch screen cathode ray tubes (CRTs) found, e.g., in some banks ATMs, although these are slowly being phased out (Vulcan, 2013). All flat panel displays are made in Japan, South Korea and China. This application accounted for 56% of the global indium use in 2013 (Indium Corporation, 2013).

Indium is used as a low-temperature solder and a lead-free solder, either as alloys or as pure metal. Indium reduces the melting point in solder alloys and can improve the thermal fatigue performance of solders used in the electronics industry, even in a small amount. Its ductility and malleability are retained at cryogenic temperatures so that an assembly can maintain an effective seal, even in harsh environments. Indium solders are also used for glass-to-glass or glass-to-metal joints.

Indium semiconductor compounds ($CuIn1\text{-}xGaSe_2$) are used as a light absorber material in CIGS (Copper indium gallium diselenide) and CIS (without gallium) thin film solar cells. ITO (indium tin oxide) is used as a top transparent electrode of CIGS, amorphous silicon and CdTe cadmium telluride PV cells. The transparent conductive oxide (ITO) maximizes light transmission of the incoming light into the solar cell absorber materials (CIGS, amorphous silicon or cadmium telluride layers).

Because of its excellent thermal conductivity and ductility, indium metal, alloys and composites are used as thermal interface materials (TIMs) in electronics devices. TIMs transfer heat generated by semiconductors to a heat sink to prevent the device from overheating. The extreme malleability of indium allows it to fill in any microscopic gaps between the two surfaces, thereby increasing heat flow.

Indium is one of many substitutes for mercury in alkaline batteries to prevent the zinc anode from corroding and releasing hydrogen gas. Indium functions like mercury by forming zinc alloy to inhibit zinc corrosion.

Indium is a component of low melting-point alloys which can be used for glass-to-glass or glass-to-metal joints and in a variety of other applications: in semiconductor compounds in LEDs (e.g. indium gallium nitride-InGaN), laser diodes (indium phosphide InP), etc.

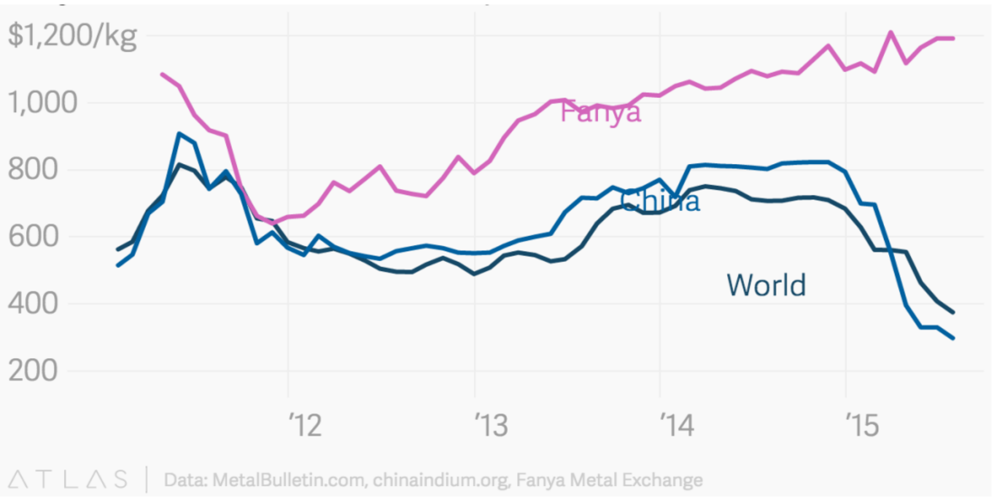
Table 51: Indium applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016c)

Applications	**2-digit NACE sector**	**Value added of sector (millions €)**	**4-digit NACE sectors**
Flat panel displays	C26 - Manufacture of computer, electronic and optical products	75,260	C26.2.0 - Manufacture of computers and peripheral equipment
Solders	C26 - Manufacture of computer, electronic and optical products	75,260	C26.1.1 - Manufacture of electronic components
PV cells (CIGS, CIS and CdTe)	C26 - Manufacture of computer, electronic and optical products	75,260	C26.1.1 - Manufacture of electronic components
Thermal interface material	C26 - Manufacture of computer, electronic and optical products	75,260	C26.1.1 - Manufacture of electronic components
Batteries	C27 - Manufacture of electrical equipment	84,609	C27.2.0 - Manufacture of batteries and accumulators
Alloys/compounds	C24 - Manufacture of basic metals	57,000	C24.4.5 - Other non-ferrous metal production
Semiconductors & LEDs	C26 - Manufacture of computer, electronic and optical products	75,260	C26.1.1 - Manufacture of electronic components

12.3.3 Prices

Indium price which was just US$65 per kilogramme in 2002 climbed to its record high of US$1,000 in 2005 supported by rising ITO demand from TVs manufacturers. Price started to fall in 2006, marking the beginning of a period of fluctuations with prices falling to about US$350 per kilogramme during the financial crisis before climbing again to US$800 per kilogramme in 2011. Prices were thereafter supported by stockpiling at the Fanya Metals Exchange which was established in 2011 in Kunming, in China until its collapse in August 2015. Indium prices have since dropped to their current levels of about US$200 per kilogramme.

The Fanya Metals Exchange stockpiled and traded 14 metals, including indium, rapidly becoming the biggest minor metals market in the world. Prices for the metals traded on the exchange rose sharply and became increasingly disconnected from world and domestic prices. Indium price on the Fanya Metals Exchange more than doubled between 2012 and 2015 to US$1,200 per kilogram (Figure 96). Prices kept rising from the end of 2014 despite tumbling global prices (Reuters, 2015). The exchange's trading volume grew quickly and prior to its collapse in August 2015, Fanya reportedly held 3,629 tonnes of indium, which is more than the amount of indium needed globally for several years combined (Metal Bulletin, 2017).



Data: MetalBulletin.com, chinaindium.org, Fanya Metal Exchange

Figure 96: Indium prices from 2011 to 2015 (theatlas.com, 2016)

12.4 Substitution

In transparent conducting oxides (TCOs) used in flat panels displays and in amorphous silicon and CdTe PV cells, indium can be replaced by other TCOs such as aluminium doped zinc oxide (AZO) and fluorine doped tin oxide (FTO), which are cheaper, but their performance is lower (conductivity and/or transparency) (Jackson, 2012). Other TCOs alternatives include silver nanowires which are used in touch-sensitive display screens (Cambrios, 2016).

There is no commercially available substitute for indium in semiconductor compounds (CIGS and CIS) used in thin-film solar cells. However, CIGS and CIS technologies currently account for only 2% of the total global PV production (in GWp) (Fraunhofer, 2016). Crystalline silicon technologies which hold more than 90% of the PV market, and thin-film technologies such as CdTe and Amorphous silicon (a-Si) are available substitutes for CIGS.

Tin-indium alloys can be replaced by tin-bismuth alloys in a number of low temperature bonding and soldering applications. Lead-based alloys could replace indium and indium-tin alloys used in sealing at cryogenic temperatures.

12.5 Discussion of the criticality assessment

12.5.1 Data sources

Production data for indium are from BGS (2016) and Nyrstar (2015). Trade data were extracted from the Eurostat Easy Comext database (Eurostat, 2016a). Data on trade agreements are taken from the DG Trade webpages, which include information on trade agreements between the EU and other countries (European Commission, 2016). Information on export restrictions are derived from the OECD Export restrictions on the Industrial Raw Materials database (OECD, 2016). For trade data, the Combined Nomenclature CN8 code 81129281 'Unwrought Indium; Indium powders' has been used.

12.5.2 Calculation of EI and SR parameters

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors. The value added data correspond to 2013 figures.

The calculation of the Supply Risk (SR) was carried out at the refining stage (i.e. refined indium) of the life cycle using both the global HHI and the EU-28 HHI.

12.5.3 Comparison with previous EU assessments

A revised methodology was introduced in the 2017 assessment of critical raw materials in Europe and both the calculations of economic importance and supply risk are now different; therefore the results with the previous assessments are not directly comparable.

The results of this review and earlier assessments are shown in Table 52.

Table 52: Economic importance and supply risk results in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014a) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Indium	6.7	2.0		5.6	1.8		3.1	2.4

The lower economic importance indicator in 2017 is mostly due to the revised methodology. The value added in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a 'megasector', which was used in the previous assessments. The economic importance figure is therefore reduced.

The supply risk score is higher than in the previous assessments, which is also due to the methodological modification. However this result is misleading because the EU is self-sufficient in its refined supply.

12.6 Other considerations

12.6.1 Forward look for supply and demand

Indium consumption is expected to be supported by the continued ITO demand for LCD screens and the growth of the emerging IGZO (Indium Gallium Zinc Oxide) display market. The IGZO technology provides high resolution, low power consumption and a fine touch sensitivity.

Demand from the energy sector for thin films PV cells did not live up to expectations as the market share of all thin film technologies has instead been decreasing since 2009 from 16% to about 7% of the global annual production (Fraunhofer Institute for Solar Energy Systems, 2016).

Indium supply is available to support the market growth and could be increased by improving indium recovery rate during ore processing and recycling, extracting indium from smelting wastes etc. Within the EU-28, virgin indium annual production capacity has now been doubled with the new Nyrstar plant extension (70 tonnes/year) in France.

Table 53: Qualitative forecast of supply and demand of indium

Material	**Criticality of the material in 2017**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Indium	x		+	+	?	+	+	?

12.6.2 Environmental issues

Indium metal is not subject to registration under the EU REACH regulations (ECHA, 2017).

12.7 Data sources

12.7.1 Data sources used in the factsheet

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13. MAGNESIUM

Key facts and figures

Material name and Element symbol	Magnesium, Mg	World/EU production (thousand tonnes)[1]	846 / 0
Parent group (where applicable)	N/A	EU import reliance[1]	100%
Life cycle stage/ material assessed	Processing stage/ Refined material	Substitution index for supply risk [SI(SR)]1	0.91
Economic importance (EI) (2017)	7.1	Substitution Index for economic importance [SI(EI)][1]	0.91
Supply risk (SR) (2017)	4.0	End of life recycling input rate (EOL-RIR)	9%
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Transportation (58%), Packaging (16%), Desulfurization agent (12%),
Main product, co-product or by-product	Main product	Major world producers[1]	China (87%)
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] average for 2010-2014, unless otherwise stated

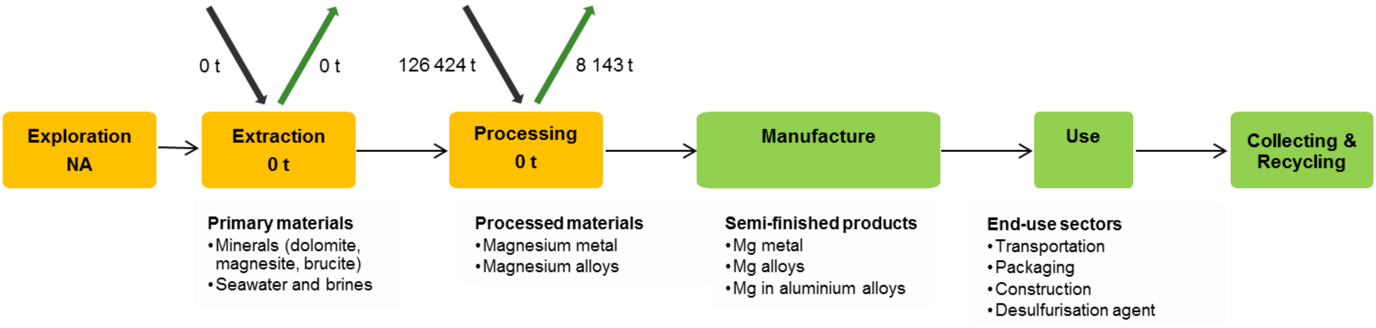

Figure 97: Simplified value chain for magnesium

The orange boxes of the Extraction and Processing stages in the above figure suggest that no activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

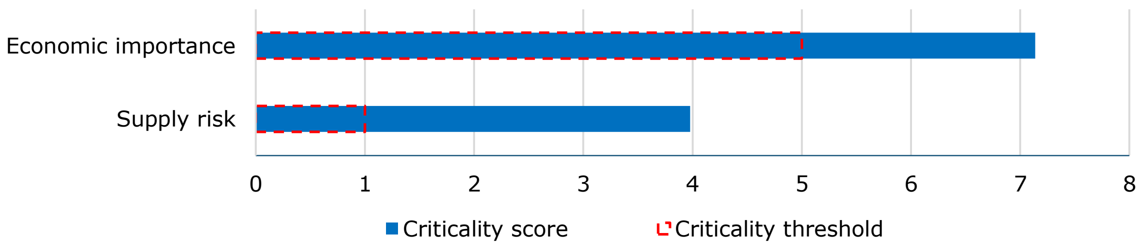

Figure 98: Economic importance and supply risk scores for magnesium

13.1 Introduction

Magnesium (symbol Mg) is the eighth most abundant element in the Earth's crust (2.1% in weight) and the third most abundant element in solution in seawater. Magnesium is a metal which does not occur in its elemental form in nature, but is found in different forms in minerals (dolomite, magnesite, carnallite) as well as in seawater and brines. Although seawater was a major source of magnesium during the second half of the twentieth century, closure of seawater magnesium plant and increase in output from China led to a magnesium supply now dominated by mineral sources. Magnesium is the lightest of all commonly used structural materials.

Magnesium is commercialised under the form of pure metal or as casting alloys. The former may be used as such, for instance in the steel industry (as a desulfurization agent), or in aluminium alloys. On the overall, 40% of magnesium is used in the EU in magnesium casting alloys, and 39% in aluminium alloys over the 2010-2014 period. Due to its lightness and mechanical strength, magnesium alloys are used in transportation; and due to its ability to improve the aluminium properties, aluminium alloys for transportation, packaging and construction also contain magnesium. Other applications include pharmaceutical and agricultural chemical production. The use of magnesium in the manufacture of electronic devices (laptop, mobile phone, etc.) is not significant in the EU (IMA, 2017).

There is no production of pure magnesium in the EU: the supply for the manufacturing industry entirely relies on imports from China and a few other non-EU countries (Israel, Russia, and Turkey). The EU apparent consumption of magnesium represents around 15% of the consumption worldwide.

13.2 Supply

13.2.1 Supply from primary materials

13.2.1.1 Geological occurrence

Magnesium is a relatively common element with a concentration of about 2.1% in the Earth's crust, and of about 46.7 ppm in the uppercrust (Rudnick, 2003). It is found in more than 60 distinct minerals. The most important minerals containing magnesium are rock-forming minerals: the chlorites, the pyroxene and amphibole group minerals, dolomite and magnesium calcite. Magnesium is also present in magnesite and hydrated carbonates (e.g. nesquehonite, lansfordite) as well as in brucite. In addition, a series of basic magnesium carbonates exist (e.g. hydromagnesite, artinite) (Shand, 2006).

Natural minerals supply the majority of commercialised magnesium (i.e. magnesium oxide): dolomite, magnesite and carnallite (respectively 47%, 19% and 13% of commercialised output). Other commercial sources of magnesium include seawater and brines (22% of volumes) (BGS, 2004). Brucite is no longer used as a raw material for primary magnesium production (IMA, 2017).

Dolomite mineral ($CaMg(CO_3)_2$) is found in sedimentary rocks such as dolomite rock and limestones. It can occasionally be found in high-temperature metamorphic rocks and low-temperature hydrothermal veins. Dolomite is the raw material for the majority of the magnesium plants in China; it is also used in Turkey and Brazil (BGS, 2004).

Magnesite mineral ($MgCO_3$) exist as cryptocrystalline (amorphous) magnesite or macrocrystalline (bone) magnesite. Four types of magnesite deposits exist: as a sedimentary rock, an alteration of serpentine, as a vein filling or in replacement of limestone and dolomite (Shand, 2006). Magnesite deposits are fairly widespread but high-purity deposits of adequate size are uncommon (BGS, 2004).

Carnallite ($KCl.MgCl_2.6H_2O$) is the main source of magnesium in Russia and was significant in Chinese production. It is normally delivered as brine produced by the solution-mining of the solid carnallite deposits.

13.2.1.2 Mining of magnesium ores and refining of magnesium

Magnesium-bearing ores are worked by open pit methods, although narrow and deep deposits may be worked by underground drifts and stopes. (United States International Trade Commission, 2012).

Magnesium can be produced through electrolytic methods or thermal-reduction methods such as the Pidgeon process.

The electrolytic method has dominated magnesium production from the 1970s to 1990s – the various processes consist of electrolysis of molten magnesium chloride (produced with different methods), the magnesium produced is liquid (molten). The source of magnesium can be seawater, brine or carnallite, among others (Wulandari et al., 2010). For instance, carnallite is used as raw material for the electrolysis process in Russia (BGR, 2017).

In the thermal-reduction method, calcined dolomite and calcined magnesite are broken down through the use of reducing agents. The mixture is heated in a vacuum chamber forming magnesium vapors which later condense into crystals. The crystals are melted, refined and poured into ingots for further processing (IMA, 2016).

The Pidgeon process is the most commonly used thermal-reduction method for production of magnesium due to the fact that its operation is relatively easy, versatile and has low capital cost; however it is energy intensive and has low productivity. The largest producers of magnesium through the Pidgeon process are China, Brazil and Turkey (IMA, 2016). The process is based on silicothermic reduction of magnesium oxide from calcined dolomite. Dolomite calcination takes place at temperature ranges of 1,000 to 1,300°C. Calcined dolomite and ferrosilicon are mixed; at specific temperatures and pressure, the reduction of calcined dolomite by ferrosilicon produces magnesium vapor. High purity magnesium is obtained from condensation of the vapor; the potential impurities (Ca, Fe and Si) are low at these conditions (Wulandari et al., 2010).

New processes such as Carbothermic and the Mintek process are high productivity alternatives to the existing technologies that still require further development; they could achieve lower energy usage.

13.2.1.3 Magnesium resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of magnesium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[12], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are

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[12] www.crirsco.com

changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for magnesium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for magnesium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for magnesium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

It is acknowledged that reserves of magnesium are large enough to meet the worldwide consumption needs for the next decades – either from dolomite and other magnesium-bearing evaporate minerals, or from magnesium-bearing brines.

13.2.1.4 World production of processed magnesium metal and alloys

World refined production of magnesium is summarised in Figure 99, and totals 843,000 tonnes (average 2010-2014). Primary magnesium is commercialised as pure magnesium (99.8% purity - which may later be used in aluminium alloys) and magnesium alloys (estimated 90% magnesium content in average). Global supply of magnesium is dominated by China with about 87% of the total refined production, equivalent to 733,500 tonnes (average 2010-2014). The United States and Israel are the second and third largest producing countries respectively accounting for 5% (40,000 tonnes; average over 2010-2014) and 3% (26,000 tonnes; average over 2010-2014) respectively of worldwide primary magnesium production. It is thought that production statistics for China may include production figures based on capacity rather than actual production and that some primary magnesium may be double counted when it is sold to local magnesium alloy producers (Roskill, 2013).

Production of primary magnesium jumped from 443,000 tonnes in 2000 to 957,000 tonnes in 2015, the first year with a slight decline (983,000 tonnes in 2014) in the past years. The worldwide sourcing of primary magnesium significantly evolved since 2000: at that time, China represented 32% of worldwide refined production, whereas the USA produced up to 21% of primary magnesium (Data from BGS World Mineral Statistics).

China's dominance of global magnesium production increased in recent years, whereas there was little or no growth in other producing countries, despite some capacity expansion (e.g. Brazil) and new primary production units (e.g. in Malaysia, South Korea and Turkey). These capacity increases remained small compared to total global production (Roskill, 2013).

There are more than 50 magnesium smelting operations in China, most of them in the provinces of Shaanxi and Shanxi, which accounted for 61% and 28% of production respectively in 2015. On a company basis, the largest productive capacity is held by Shanxi Yinguang Huasheng with 80,000 t/y. This is followed by Ningxia Hui-Ye Magnesium with 60,000 t/y (International Mining, 2016).

There is no production of pure magnesium metal in the EU since 2001. However magnesium alloys are processed in the EU based on primary magnesium (e.g.

magnesium alloys) imported from extra-EU countries or from secondary magnesium production (IMA, 2017).

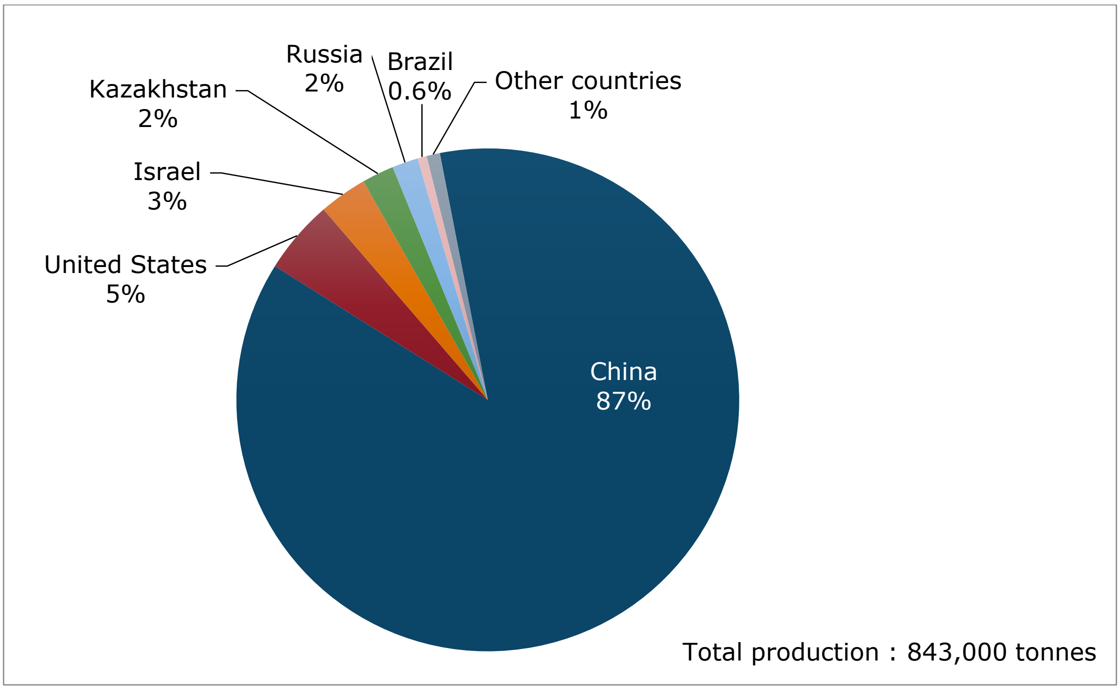

Figure 99: Global production of primary magnesium, average 2010–2014 (Data from BGS, 2016)

13.2.2 Supply from secondary materials

Secondary magnesium is an important component in global magnesium supply, with production estimated to be between 200,000 t and 250,000 t/y, 125,000 t/y of which is in the USA (International Mining, 2016). The amount of secondary material used in the magnesium industry depends on various factors, among others: amount of material lost in the melting cycle, quantity of different cast components, quality of process scrap, or recycling operation efficiency (IMA, 2016). At the EU level, the magnesium recycling capacity is about 75,000 t/y (mostly for new scrap). The main European players are in Austria (Non ferrum), Czech Republic (Magnesium Elektron), Germany (Magontec, Real Alloy Germany GmbH), Hungary (Salgo-Metal), Romania (Magontec), and in the UK (Magnesium Elektron) (Roskill, 2013). In the EU, the EoL-RIR for magnesium is assessed at 9% level (estimate calculated based on EoL-RIR for aluminium).

Various recycling methods exist and are currently used to **re-melt magnesium scrap**: a common process is the remelting and refining of heavy scrap. In order to ensure the same quality criteria (in terms of chemical composition, oxide content) for secondary and primary materials, **other recycling methods** may be required, in particular for old scrap. For instance, the addition of manganese reduces the levels of iron; distillation or dilution allow for nickel and copper control (IMA, 2016).

In the EU, a large share of magnesium is used as an alloying element in the production of aluminium alloys and derived applications; therefore most of end-of-life magnesium scrap is recycled as part of the aluminium value stream. In addition, magnesium alloys are entirely recyclable once they are collected from end-of-life products.

Recycling or reuse of **new scrap** is common in the magnesium industry; the scrap kept within a close loop system reduces the demand of primary magnesium by up to 50%. Die casting foundries recycle scrap internally or externally. Lower grade arising is used as reagents in steel desulfurization or other markets, as replacement to primary magnesium (IMA, 2016). There is no recycling of magnesium from steel desulfurization applications.

13.2.3 EU trade

With no extraction of magnesium nor processing of pure magnesium, the EU supply entirely relies on imports of primary magnesium, as well as on production of secondary magnesium (from post-consumer recycling) although less significantly.

The average annual net import figure in the period 2010-2014 is of 118,000 tonnes (Figure 100). The main supplier of the EU is China, with 94% of the imports to the EU (Figure 101) – which is consistent with China being the largest worldwide producer. The Chinese prevalence in EU imports started in the past decade: in 2000, only 27% of EU magnesium imports originated from China, behind Norway (36% of imports in the same year – Norway production of primary magnesium stopped since then).

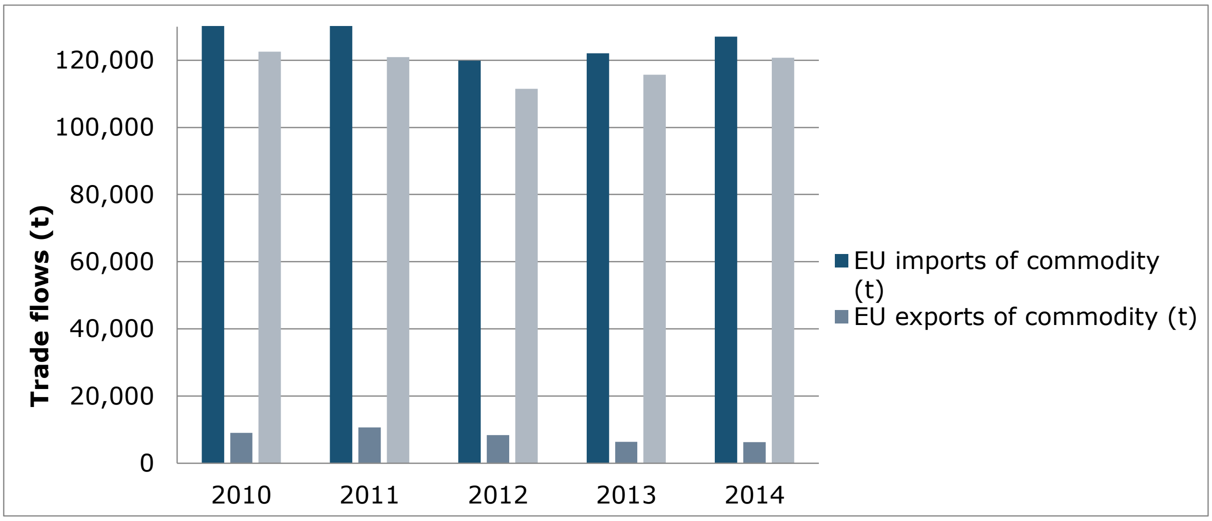

Figure 100: EU trade flows for primary magnesium. (Data from Eurostat, 2016a)

Imports of magnesium to the EU increased regularly until 2007, with a 7% annual rise between 2000 and 2007. In 2009, EU trade of magnesium with extra-EU countries collapsed mainly due to reduced primary magnesium production. From 2010 to 2014, EU trade remained stable. Around 57% of magnesium imports in 2015 are under the form of pure metal ('Unwrought magnesium, containing >= 99.8% by weight of magnesium'); the rest is under the form of magnesium alloys ('Unwrought magnesium, containing < 99.8% by weight of magnesium'). The breakdown remained similar in the past years. The Eurostat statistics partly include magnesium processed from secondary material (e.g. imports from Serbia, since there is no primary magnesium production in the country); once processed, there is no distinction between primary and secondary magnesium.

Exports of magnesium from the EU are not significant compared to imported volumes, with an average of 8,000 tonnes over the 2010-2014 period. Most of exported volumes are under the form of magnesium alloys, either processed in the EU or previously imported to the EU. Major destinations for exported magnesium are the United States and Switzerland.

Since 2013, there is no restriction on commercial trade of magnesium metal and magnesium alloys (i.e. no export tax, export quota or export prohibition of magnesium from extra-EU countries) with the EU Member States. Until end of 2012, China had established a 10% tax on magnesium exports from the country. In July 2011, the World

Trade Organisation ruled that China violated global rules by restricting exports of nine materials including magnesium, thus leading to the removal of the tax.

The EU trade of magnesium scrap is not included in the factsheet, however large volumes are traded to US companies as source of low-cost metal, in competition with US magnesium. The US anti-dumping duties on Chinese magnesium causes price differential between the two markets (IMA, 2017).

Export restrictions apply to magnesium waste and scrap imports to the EU. There are export taxes in Argentina (5%), Jordan (5%), Morocco (7.5%), Russia (20%), Vietnam (22%) and Zambia (25%); there is an export prohibition in Burundi, Kenya and Rwanda. Licensing requirements apply in many countries, for magnesium waste and scrap as well as unwrought magnesium.

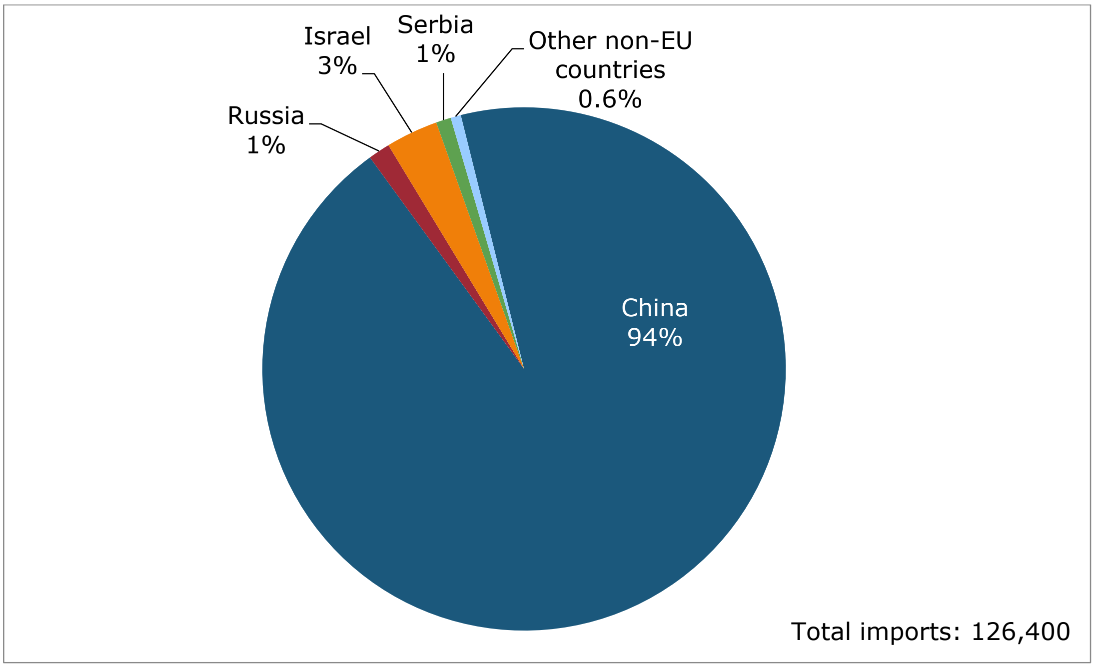

Figure 101: EU imports of magnesium from extra-EU28 countries, average 2010-2014. (Data from Eurostat, 2016a)

13.2.4 EU supply chain

The EU supply chain of magnesium can be described by the following key points:

- The first stages of the value chain of magnesium (extraction, processing) take place outside of the EU, although there are reserves of magnesium in the EU. There are no imports of magnesium ores in Europe and all primary magnesium is processed outside the EU (except from very small volumes of magnesium alloys).
- The EU supply of magnesium entirely relies on imports of primary magnesium, as well as on production of secondary magnesium (from post-consumer recycling) although less significantly. The 5 year average European net imports of magnesium between 2010 and 2014 was 118,000 tonnes per year (Eurostat, 2016a).
- The EU import reliance for magnesium is therefore estimated at 100%.
- Magnesium can be cast, rolled, extruded, machined, and forged similar to any other metal. Magnesium is the lightest structural metal: one quarter the weight of steel, two thirds the weight of aluminium, and has same light weighting potential as carbon fibre.

- Europe imports primary magnesium in the forms of pure metal or alloys. In addition, the EU relies on imports of intermediate and final products, in particular in the electronics sector.
- At the EU level, the magnesium recycling capacity is about 75,000 t/y (mostly for new scrap).
- The European Union is a net exporter of magnesium scrap, with net gross volumes of 6,500 tonnes in 2015. Up to 67% of scrap exports are now directed to the USA, mainly due to price difference with primary magnesium (increased prices from anti-dumping measures, which were implemented in 2001). For comparison, 76% of scrap was exported to Norway in 2000 (Eurostat, 2016a).

The EU sourcing (domestic production + imports) for magnesium is presented in Figure 101 in the previous section since there is no domestic production of magnesium in the EU.

13.3 Demand

13.3.1 EU demand and consumption of magnesium based products

Annual worldwide consumption of magnesium for end-use applications in 2014 is estimated as 900,000 tonnes. In the EU, the consumption is about 130,000 tonnes of processed materials. Almost all of magnesium is imported in the EU as pure magnesium or magnesium alloys; swarf, granules and powders represent gross volumes of about 14,000 tonnes (IMA, 2017).

Magnesium casting alloys and aluminium alloys represent respectively 40% and 39% of magnesium use in the EU over the 2010-2014 period. It can be considered that all magnesium alloys are used in transportation applications; some castings are alloyed with rare earth elements to improve creep and corrosion resistance (International Mining, 2016).

On the other hand, aluminium alloys are used in packaging, transportation and construction sector. Magnesium is present in aluminium alloys in distinct proportions: transportation aluminium alloys contain around 1% of magnesium, while there is around 2% of magnesium in packaging and 0.5% in construction aluminium alloys. Magnesium as alloying element is essential for the aluminium industry.

13.3.2 Uses and end-uses of magnesium in the EU

The major end-uses of magnesium in the EU are in the transportation sector. In addition, magnesium in aluminium alloys is used in packaging and construction. Magnesium is also used in non-structural applications such as desulfurization agent (European Commission, 2014; IMA, 2017):

- Automotive industry: Magnesium casting alloys is mainly used in vehicles to lower the overall weight, e.g. in replacement of steel or aluminium. Magnesium is used in many vehicle parts from gearbox, steering column and driver’s airbag housings to steering wheels, seat frames and fuel tank covers. The use of magnesium as one single cast piece in vehicles may also increase the strength of the material compared to various steel components.
  In addition to being used in terrestrial vehicles such as cars, vans and trucks, magnesium is also used in aerospace applications both civil and military: for instance in thrust reversers, as well as in engines and transmission casings of aircrafts and helicopters. Spacecraft and missiles also contain magnesium as it is capable of withstanding exposure to ozone and impact of high energy particles and matter (IMA, 2016).

- Desulphurisation of steel: Due to its high affinity for sulfur, magnesium is injected in molten iron or steel to reduce the sulfur content. The process prevents sulfur from damaging steel as it causes brittleness in steel; low sulfur facilitates modern production processes (IMA, 2016; International Mining, 2016).
- Packaging applications represent 35% of magnesium use in aluminium alloys (European Commission, 2014). Magnesium improves aluminium strength without removing the material workability. In addition to aluminium beverage can, magnesium is also used in aluminium alloys in food cans and trays. Further detail may be found in the aluminium factsheet.
- Construction equipment: Magnesium in aluminium alloys is used for doors, windows, cladding, roofing, staircases, air conditioning units, among other components. Further detail may be found in the aluminium factsheet.
- Other uses: Medical applications, sport applications, among others. Magnesium can be used in electrochemical applications: magnesium anodes prevent from galvanic corrosion of steel. It is also used in industrial synthesis such as the Grignard reaction in organic chemistry applications (IMA, 2016).

Magnesium alloys are used in small and portable electronic applications such as camera, cell phone and laptop for its lightness combined to strength and durability, e.g. in replacement of plastics. Many electronics require parts or casings with complex shapes which are possible with magnesium. The use of magnesium in electronic applications manufacturing is not significant in the EU (IMA, 2017). Finally, magnesium is used as a reducing agent in the production of beryllium, titanium, etc. – although not in the EU since there is no titanium or beryllium production.

The end-use shares provided in Figure 102 were calculated based on existing studies and stakeholders' feedback (Bio Intelligence Service, 2015; IMA, 2017) and relevant industry sectors are described using the NACE sector codes in Table 54.

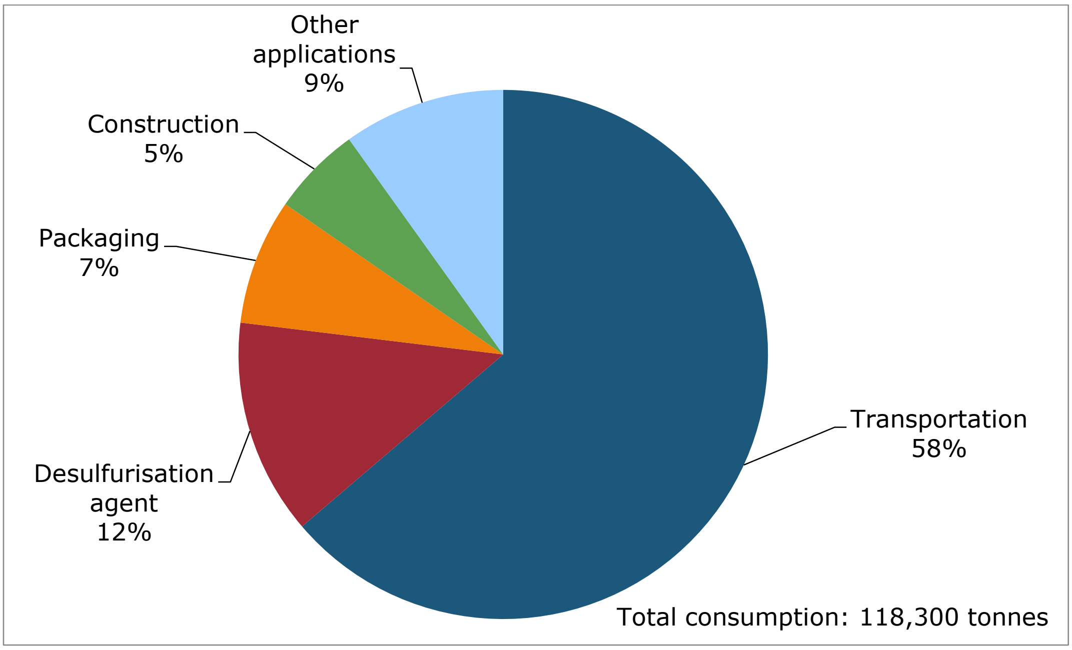

Figure 102: EU end uses of magnesium. Average figures for 2010-2014. (Data from IMA, 2017)

Table 54: Magnesium applications, 2-digit and associated 4-digit NACE sectors, and value added per sector. (Data from the Eurostat, 2016c)

Applications	**2-digit NACE sector**	**Value added of NACE 2 sector (M€)**	**4-digit NACE sectors**
Transportation	C29 - Manufacture of motor vehicles, trailers and semi-trailers C30 - Manufacture of other transport equipment	158 081.4 53.644.5	C2910 - Manufacture of motor vehicles; C2920 - Manufacture of bodies for motor vehicles; C2932 - Other parts for motor vehicles; C3030 - Manufacture of air and spacecraft; C3011 - Building of ships and floating structures; C3020 - Manufacture of railway locomotives and rolling stock; C3092 - Manufacture of bicycles
Packaging	C25 - Manufacture of fabricated metal products, except machinery and equipment	159 513.4	C2592 - Manufacture of light metal packaging
Construction	C25 - Manufacture of fabricated metal products, except machinery and equipment	159 513.4	C2511 - Manufacture of metal structures and parts of structures; C2512 - Manufacture of doors and windows of metal; C2599 - Manufacture of other fabricated metal products n.e.c.
Desulfurisation agent	C24 - Manufacture of basic metals	57 000.0	2410 - Manufacture of basic iron and steel and of ferro-alloys

13.3.3 Prices and markets

Prices for magnesium metal are primarily cost driven, reflecting supply overcapacity (particularly in China). In 2008, magnesium plants were shut down for environmental concerns during Beijing Olympics game, which led to a price hike on the global market up to $6/kg of metal since China is the major supplier of magnesium worldwide (IMA, 2017).

Figure 103: Magnesium metal prices (EUR/kg) between 2006 and 2016. (InfoMine, 2017)

Since 2008, magnesium prices remained more stable, and gradually decreased down to $2/kg until the first quarter of 2016 (see Figure 103). As prices moved below this level at the end of 2015, resistance from producers coupled with firming coal prices and better than expected performance in the Chinese economy pushed the price of magnesium up by 11% in April 2016 (International Mining, 2016).

There is an antidumping-duty in the USA for magnesium from China, therefore the price of magnesium metal is higher in the USA compared to the EU (antidumpingpublishing.com, 2017).

13.4 Substitution

Substitution has been included in this review of the criticality assessment in a refined way. Each application has been considered in turn with both product to product and material to material substitute included in the assessment. Consideration has been given to the cost and performance of each potential substitute in each application, relative to that of the material in question, together with the level of production, whether or not the substitute was previously considered to be 'critical' and whether the potential substitute is produced as a by-, co- or main product.

Specific data relating to all of these criteria are often difficult to find and a number of assumptions have had to be made to complete the calculations. Consequently a significant degree of uncertainty is associated with the results. The level of precision shown for the Substitution Indices does not fully reflect this uncertainty.

Magnesium in casting alloys as well as in aluminium alloys may be partially substituted, e.g. to lower the need for magnesium. Possible substitutes are composites such as carbon-fibre reinforced plastic, as well as steel and titanium alloys. The information provided below for transportation, construction and packaging applications may also be found in the factsheet on aluminium substitution.

In transportation applications, reinforced plastics provide similar performance in vehicles and the latest aircraft but at much higher cost than aluminium alloys containing magnesium. Steel and titanium are possible substitutes in this sector; with steel being the only one of these were costs are similar to aluminium alloys. However, steel is heavier than aluminium and consequently lesser performing for certain applications.

In the construction sector, steel, plastics (such as PVC or vinyl) and wood were considered as possible substitutes. In all cases the cost and performance were considered to be similar to aluminium alloys containing magnesium. For packaging, steel, glass and plastics were identified as potential substitutes for aluminium alloys and again for all of these the costs and performance were considered to be similar.

The steel desulfurization process allows the use of several reagents such as lime (carbon oxide, CaO), calcium carbide (CaC_2) and magnesium (Mg), which remove the sulfur in the hot metal by chemical reaction and convert it to the slag. The performance of lime and calcium carbide provide is lower than with magnesium: the latter is soluble in hot metal and reacts with sulfur in solution; unlike the formers, magnesium is not subject to layer formation on steel, which would impede the desulfurizing reaction. Although more expensive, magnesium has approximately 20 times the capacity of removing sulfur as lime; calcium carbide, 8 times the capacity as lime (IspatGuru, 2013). Other substitutes such as ZnO are experimented but are not currently commercialized.

13.5 Discussion of the criticality assessment

13.5.1 Data sources

Market shares are based on existing studies (Bio Intelligence Service, 2015) and stakeholders' feedback (IMA expertise, 2016). Production data for magnesium metal and alloys are from BGS World Mineral Statistics dataset. Additional feedback was received from stakeholders and included in the assessment to obtain data best representative of the global supply from 2010 to 2014. Trade data were extracted from the Eurostat Easy Comext database (Eurostat, 2016a). Data on trade agreements are taken from the DG Trade webpages, which include information on trade agreements between the EU and other countries (European Commission, 2016). Information on export restrictions are derived from the OECD Export restrictions on the Industrial Raw Materials database (OECD, 2016).

For trade data the Combined Nomenclature (CN) codes 81041100 'Unwrought magnesium, containing >= 99.8% by weight of magnesium' and 81041900 'Unwrought magnesium, containing < 99.8% by weight of magnesium' have been used. These data were averaged over the five-year period 2010 to 2014. Other data sources used in the criticality assessment are listed in section 13.7.

The EoL-RIR for magnesium was estimated considering that recycling of magnesium metal and alloys are similar to recycling of aluminium alloys.

13.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 54). The value added data correspond to 2013 figures.

The supply risk was assessed at the processing stage of magnesium value chain using both the global HHI and the EU-28 HHI as prescribed in the revised methodology.

13.5.3 Comparison with previous EU criticality assessments

The results of this review and earlier assessments are shown in Table 55. A revised methodology was introduced in the 2017 assessment of critical raw materials in Europe and both the calculations of economic importance and supply risk are now different; therefore the results with the previous assessments are not directly comparable.

Table 55: Economic importance and supply risk results in the magnesium assessments of 2011, 2014 (European Commission, 2010; European Commission, 2014a) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Magnesium	6.45	2.62		5.48	2.53		7.14	3.98

The economic importance of magnesium has increased between 2014 and 2017, despite using the value added of 2-digit NACE sectors rather than 'megasectors' as in the previous assessments. Unlike most of other metals assessed, this methodological change did not reduce the EI figure because of significant changes in the choice of sectors compared to the previous assessments:

- Better representativeness of end-use applications based on magnesium alloys and aluminium alloys by using the associated sectors (transportation, packaging, construction) instead of intermediate applications (“aluminium based alloys”, “magnesium die casting”)

- Inclusion of all 2-digit NACE sectors rather than only the most representative. For instance for aluminium alloys, only the “Beverages” megasector was selected in the 2014 criticality assessment; the project team here included the three end-use applications (see Table 55).

Moreover, the supply risk score is higher than in the previous assessments, which is partly due to the evolution in the global supply, in particular the growing share of magnesium production from China (85% of global supply in 2014).

13.6 Other considerations

13.6.1 Forward look for supply and demand

Global growth in the magnesium demand in the short term is expected to average 3.4%/y reaching almost 1.2 Mt/y by 2020. Aluminium alloys and magnesium die casting are predicted to be the fastest growing markets at about 4%/y each. Transportation will probably be the main applications affecting magnesium demand because of greater unit consumption and increased vehicle production.

Worldwide demand is expected to increase at a CAGR between 6.5% and 7.1% in the next decade (IMA, 2017; Future Market Insights, 2016). In particular, the development of R&D technologies could significantly impact the long-term demand for magnesium, such as: incorporation of nanoparticles in magnesium alloys to improve its properties (e.g. strength, stiffness, plasticity and high temperature stability), magnesium-ion rechargeable batteries (with twice the capacity and energy density of lithium-ion batteries) (International Mining, 2016).

On the supply side, leading players in the magnesium metal market are expected to continue expanding in the coming years, for instant in China, South Korea and Turkey. New projects are under progress, for instance Qinghai Salt Lake in China – due on stream in 2017, which will probably be confined to its first phase of 100,000 t/y (International Mining, 2016). Other planned projects aiming at production before 2020 include Alliance Magnesium in Canada (50,000 t/y); Latrobe in Australia (40,000 t/y); SilMag in Norway (65,000 t/y).

On the overall, it is anticipated that global primary capacity will expand in line with over 42% of underutilised capacity in China and other Western smelters expanding capacity or creating new plants (IMA, 2017). Dead Sea Magnesium in Israel is a high cost producer with capacity for 35,000 t/y; which may terminate operations in 2017 (International Mining, 2016).

Regarding magnesium prices after 2017, no major change is expected assuming continuation of stable supply from China; therefore magnesium prices will probably remain in the $2 to $3/kg range (International Mining, 2016).

The estimations for the outlook for supply and demand of magnesium are shown in Table 56.

Environmental and legislative influences are expected to promote the use of magnesium compared to steel and aluminium. As lightweight and fuel-efficient vehicles gain centre stage in the automotive landscape, magnesium is gaining traction as a preferred manufacturing material (Future Market Insights, 2016).

Table 56: Qualitative forecast of supply and demand of magnesium

Materials	Criticality of the material in 2017		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Magnesium	x		+	+	+	+	+	+

13.7 Data sources

13.7.1 Data sources used in the factsheet

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13.8 Acknowledgments

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14. NATURAL GRAPHITE

Key facts and figures

Material name and formula	Natural graphite, C	World/EU production[1]	1.1 million tonnes/ 562 tonnes
Parent group (where applicable)	N/A	EU import reliance[1]	99%
Life cycle stage assessed	Extraction/ore	Substitution index for supply risk [SI(SR)][1]	0.97
Economic importance (EI)(2017)	2.9	Substitution Index for economic importance [SI(EI)][1]	0.95
Supply risk (SR) (2017)	2.9	End of life recycling input rate in the EU in 2012	3%
Abiotic or biotic	Abiotic	Major end uses in EU (2014)	Refractories for steelmaking (52%), refractories for foundries (14%), batteries (8%)
Main product, co-product or by-product	Main product	Major world producers[1]	China (69%), India (12%), Brazil (8%)
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] 2010-2014 average, unless otherwise stated.

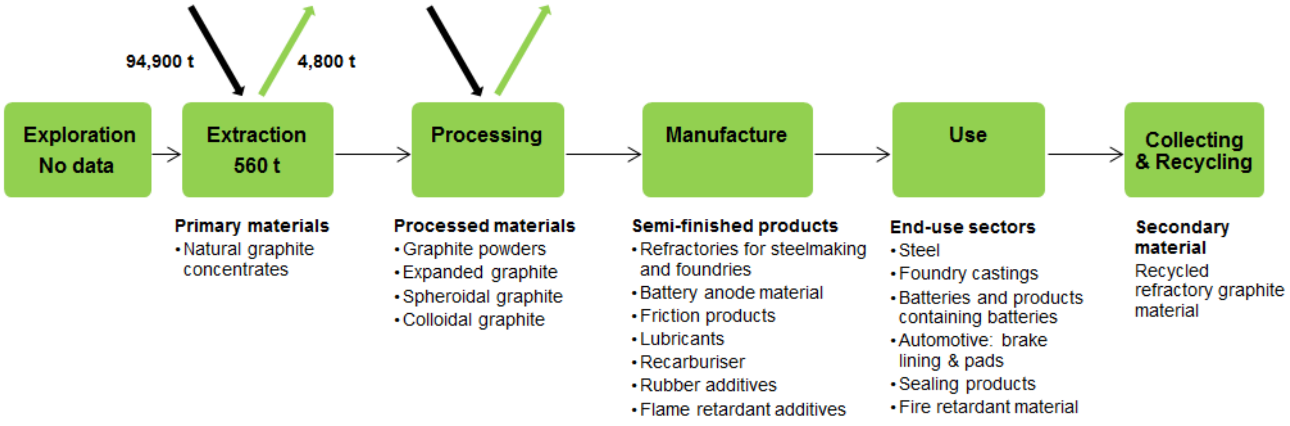

Figure 104: Simplified value chain for natural graphite (average 2010-2014)

Green boxes in the figure above represent stages of the supply chain which take place in the EU-28. The black and green arrows represent imports and exports to and from the EU respectively. EU reserves are displayed in the exploration box.

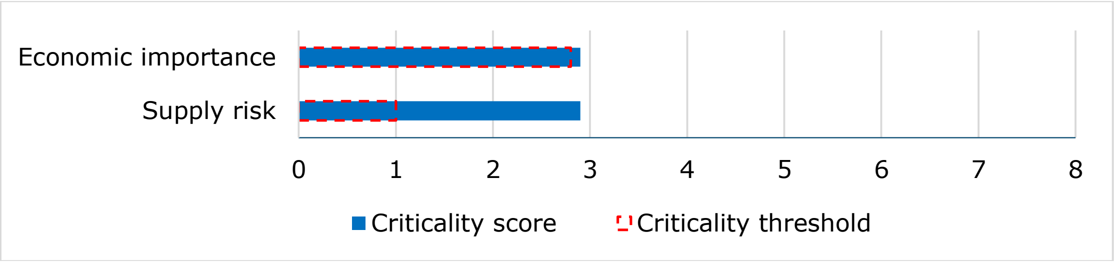

Figure 105: Economic importance and supply risk scores for natural graphite

14.1 Introduction

Natural graphite (chemical symbol C) is a carbon allotrope which exhibits both metallic and non-metallic properties. It is a soft (hardness: 1-2 on Mohs scale), grey-black mineral with a perfect basal cleavage. It consists of planar sheets formed from three-coordinated carbon atoms. Intra-planar bonding is very strong, but forces holding these sheets together are weak so the layers can easily slide over each other. Free electrons between the layers allow graphite to conduct electricity and heat. It is a good thermal and electrical conductor and has a high melting point (3,650ºC). It has a high thermal resistance and lubricity, is resistant to corrosion, chemically inert and non-toxic. These properties make it a mineral with a wide range of uses.

The main uses of natural graphite are in refractories for steelmaking and foundries, lubricants, friction materials, batteries, brushes for electrical motors, sealing applications, fire retardants, and pencils etc.

14.2 Supply

14.2.1 Supply from primary materials

14.2.1.1 Geological occurrence

Three types of natural graphite are mined for commercial use: (1) flake graphite, (2) "amorphous/microcrystalline" graphite, and (3) vein/lump graphite (BRGM, 2012; Simandl et al., 2015).

Flake graphite occurs in high-grade metamorphic rocks (e.g. marbles, schists, gneisses), where it was generated by either fluid deposition or graphitisation. Flake graphite is found as crystals generally larger than 100 micrometres and is disseminated in rocks with bulk carbon contents generally in the range 5–40 wt%.

Amorphous or microcrystalline graphite is a fine grained graphite which also occurs in metamorphic rocks, with bulk carbon contents in the range 15–80 wt%. This type is made of small graphite grains, generally below 1 micrometre in size.

Vein or lump graphite is much rarer and accounts for only 1% of the world production. The degree of crystallization ranges from very fine crystals to coarse flakes up to 1 centimetre across. Vein graphite is fluid-deposited, and is generally pure and perfectly crystallized. It occurs in veins present in high-grade metamorphic or magmatic rocks (Luque et al., 2014). Vein graphite sole point of production today is in Sri Lanka.

14.2.1.2 Exploration and mining projects

With rising prices in 2011-2012 and perspectives of a growing demand fuelled by the Li-ion batteries sector, there has been an increase in graphite exploration projects around the world. According to Technology Metals Research (2015), 17 projects could start production by 2020, mainly in Africa (Tanzania, Mozambique), North America and Australia, depending on market conditions.

14.2.1.3 Mining and processing

The ore can be either quarried or shaft mined depending on the proximity of the ore body to the surface. Graphite crude ore with a typical content of 3 to 20% is crushed and then processed to increase the carbon content using grinding and flotation. Further purification of the material can be carried out by chemical or thermal treatment to achieve high purity grade. Commercial flake graphite available for further processing is available in three primary sizes: coarse (+80-mesh, i.e. >180 micrometres), medium (+

100-mesh, i.e. >150 micrometres) and fine (-100-mesh, i.e. <150 micrometres) and are in a range of purities from around 80% carbon up to 99+ percent carbon (Asbury, 2016).

14.2.1.4 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of natural graphite in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[13], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

The USGS (2016) estimated global natural graphite resources to be in excess of 800 million tonnes of recoverable graphite and world reserves at 230 million tonnes (Table 57).

Table 57: Estimated global reserves of natural graphite in 2015 (USGS, 2016)

Country	Estimated natural graphite reserves (thousand tonnes)
Turkey	90,000
Brazil	72,000
China	55,000
India	8,000
Mexico	3,100
Madagascar	940
Other countries	960*
Total	230,000

*Other countries include Canada, North Korea, Norway, Russia, Sri Lanka, Ukraine, USA, Zimbabwe.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for natural graphite. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for natural graphite, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for natural graphite at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2014).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts. The Minerals4EU available resource and reserve data for natural graphite are shown in Table 58 and Table 59.

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[13] www.crirsco.com

Table 58: Resource data for the EU-28 compiled in the European Minerals Yearbook (Minerals4EU, 2014)

Country	Reporting code	Code resource type	Quantity	Unit	Weighted average grade
Czech Republic	National reporting code	Potentially economic	10.447	Mt	-
		P1	3.997	Mt	-
		P2	5.279	Mt	-
Slovakia	None	Not specified	0.290	Mt	3.4%
Sweden	JORC	Indicated	9	Mt	18.1%
		Inferred	2.9	Mt	18.5%

Table 59: Reserve data for the EU-28 compiled in the European Minerals Yearbook (Minerals4EU, 2014)

Country	Reporting code	Code reserve type	Quantity	Unit	Weighted average grade
Czech Republic	National reporting code	Economic explored	1,106	Mt	-
		Economic prospected	2,606	Mt	-

"-": not known

14.2.1.5 World mine production

World natural graphite ore production data can vary greatly depending on the sources but most agree to a figure close to 1 million tonnes per year (Leguérinel and Le Gleuher, 2017). Annual production of graphite ore (concentrates) amounted to 1,114,894 tonnes on average during the period 2010-2014 (World Mining Data, 2016). China is the world leading supplier (flake and amorphous graphite) with approximately 70% (770,000 tonnes) of the global production (Figure 106), followed by Brazil contributing 91,206 tonnes/year, and India (133,258 tonnes). Indian production might be closer to 25,000 tonnes/year according to some sources (Benchmark Mineral Intelligence, 2016). Sri Lanka is a small producer (0.3% of global production) but is the only major producer of vein graphite in the world (3,000 tonnes/year). There is a very small production in the EU in Austria and Germany accounting for 0.05% of the global output.

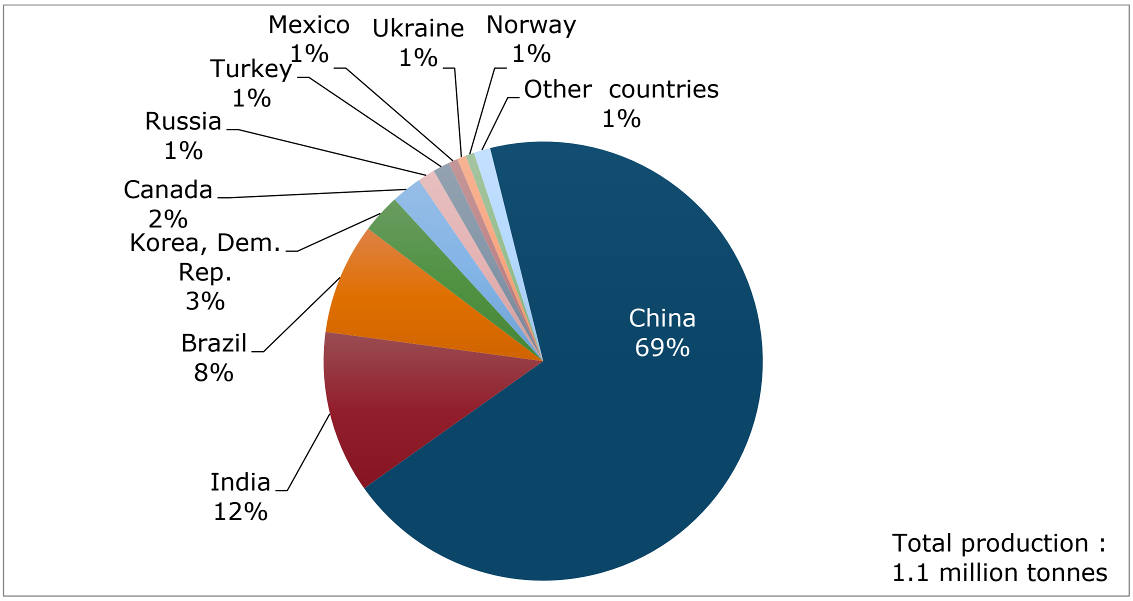

Figure 106: Global mine production of natural graphite, average 2010–2014 (Data from World Mining Data, 2016)

14.2.2 Supply from secondary materials

A significant amount of material containing natural graphite is lost during use (lubricants, friction materials, and to some extent refractories) and therefore cannot be recycled. Efforts toward recycling post-consumer products containing natural graphite are dampened by oversupply and low prices. There is some recycling of used refractory material.

14.2.3 EU trade

The EU was heavily reliant on its imports of natural graphite for its supply. Imports amounted to about 95,000 tonnes per year on average during the period 2010-2014. Imports which surged in 2011 in response to a strong demand from the steel industry declined sharply since (23% from 2011 to 2014) (Figure 107).

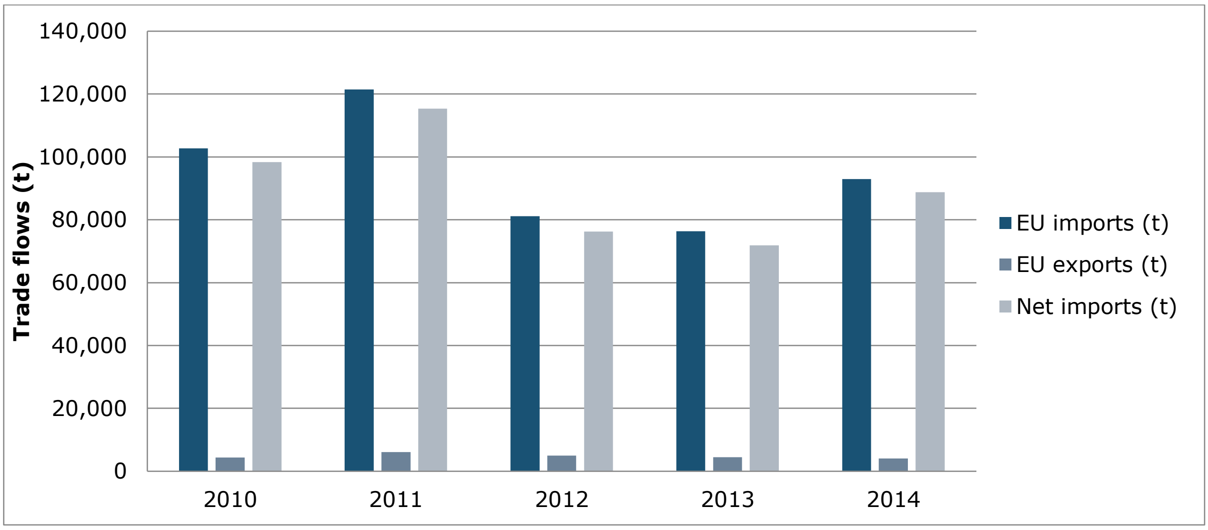

Figure 107: EU trade flows for natural graphite (Data from Eurostat, 2016a)

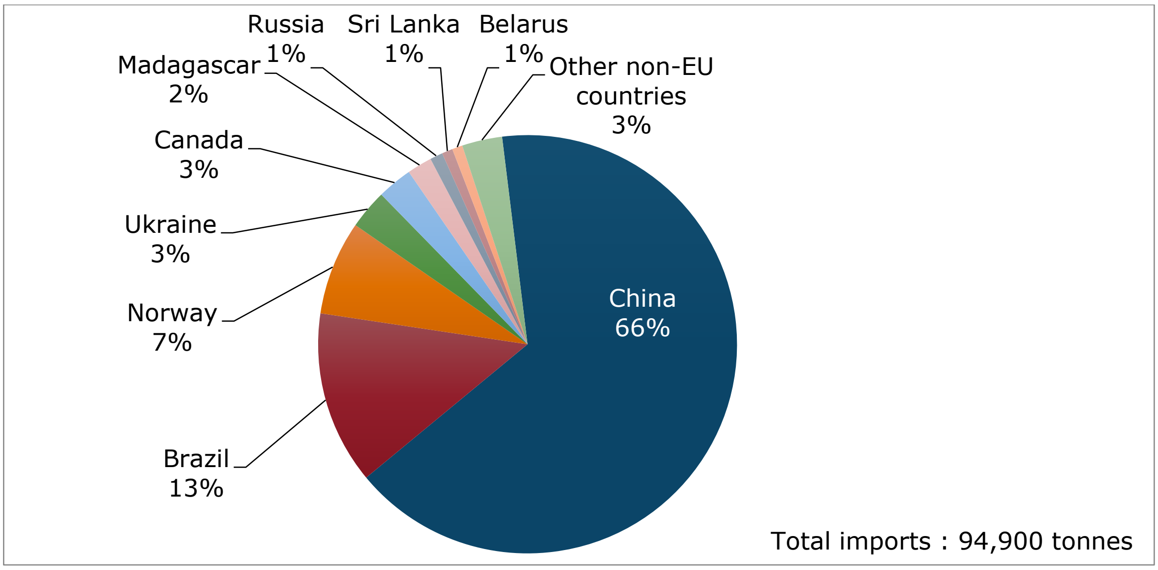

Figure 108: EU imports of natural graphite, average 2010-2014 (Data from Eurostat, 2016a)

Two-thirds of the EU-28 imports came from China and 20 % from Brazil and Norway (Figure 108). China introduced a temporary 20% export tax on natural graphite in 2009 which has been renewed every year until 2016. This export tax has been cancelled from

January 2017. EU exported small amounts of natural graphite (4,800 tonnes), mainly to South Korea.

14.2.4 EU supply chain

The EU-28 produced 561.8 tonnes per year of natural graphite (C content) on average, during the period 2010-2014. There were 3 active mines in the EU-28: the Kaisersberg mine in Austria (Grafitbergbau Kaisersberg GmbH), the Kropfmüh mine (Graphit Kropfmühl, a subsidiary of AMG Advanced Metallurgical Group) in Germany, and the Woxna Mine (Leading Edge Materials) in Sweden which operated only a few months during 2014 producing about 500 tonnes (Benchmark Mineral Intelligence, 2016). Due to low prices, production at the Woxna mine has been suspended 2015.

Because EU domestic production represents less than 1% of total EU sourcing (domestic production + imports), data on EU sourcing can be considered identical to EU imports (see Figure 108).

Recycling and processing of spent graphite based refractories started more than 30 years ago in the EU. Recycled materials are used in a number of applications including as a full or partial replacement to virgin materials in monolithic and shaped refractories (LKAB Minerals, 2017). The end of life recycling input rate was estimated at 3% in 2012 (Bio by Deloitte, 2015).

14.3 Demand

14.3.1 EU consumption

With an apparent consumption of natural graphite of about 91,000 tonnes per year on average over the period 2010-2014 and a very limited mining production, the EU is heavily dependent on external sources of supply (import reliance of 99%). All flake graphite was imported.

14.3.2 Global end uses

Refractories are the largest single market for natural graphite, although only a small proportion of refractories contain graphite (Figure 109). They are used for steel making and hot metal-forming which put together represented 70% of the world consumption in 2014 (Roskill, 2015). The natural graphite used in refractories is selected for its high temperature stability and chemical inertness. The important properties are flake size, carbon content and ash or, impurity level. Large flakes help to increase the brick mechanical strength (Engel, 2013). Graphite flakes are primarily used is in the production of magnesia-carbon bricks (MgO-C) which are used as a lining material in basic oxygen furnace (BOF) and electric arc furnaces (AEF), and in high wear areas in ladle slaglines. The bricks consist of fused magnesia and flake graphite (15-25%) bonded with synthetic resin. Large flakes (>150 micrometre) with a carbon content of at least 85% are preferred. Alumina-carbon refractories are used as functional components (e.g. stopper rods and ladle shrouds) in continuous steel casting operations.

Natural graphite-based foundry coatings and washes are used to protect refractory linings, troughs, and other foundry equipment.

Natural graphite is used as anode material in lithium-ion batteries for electric vehicles, portable electronics and large-scale domestic and commercial energy storage. Battery-grade graphite requires high purity (>99.95 wt% C) spheroidal particles with sizes in the range of 10-25 µm for effective operation. Spherical graphite is made by micronizing, purifying, and rounding flake graphite. The uncoated spherical graphite material is then coated with carbon by thermal vapor decomposition (Northern Graphite, 2016).

Natural amorphous and fine flake graphite are components of many lubricants as a dry powder in solid dry lubricants in many applications or as an additive to greases, water, solvents, and oils to improve lubrication under conditions of extreme friction and heat.

Natural graphite is added to friction products including brake linings, brake pads, clutch facings and other specialty friction applications to provide lubrication and increased thermal transfer in order to improve operation at higher temperatures. Graphite good thermal stability helps to eliminate "hot spots" (Asbury, 2016).

Amorphous graphite is used to rise the carbon content (recarburising) of steel while it is still liquid before casting and in other various applications including in electric motor brushes, pencils etc. Emerging applications for natural graphite include: fuel cells, pebble bed nuclear reactors (PBNRs).

High purity natural graphite is an important raw material for the production of expanded natural graphite and flexible graphite which are used in a wide range of industrial applications. Expandable graphite is manufactured by inserting compounds between the graphite layers. When heated, intercalated compounds vaporize and create pressure causing expansion (exfoliation) of the graphite layers and an increase of the initial volume. Graphite foil (or flexible graphite) is produced by rolling and compressing expandable graphite into thin sheets. Typical applications of these types of graphite include lubricants, fire retardant additive in plastics and fire retardant foams for insulation and manufacturing, sealing material for high temperature applications, liners in industrial furnaces, as well as in electronic devices to control and spread heat flow, EMI (electromagnetic interference) shielding (Asbury, 2016; Graphex Mining Ltd, 2016).

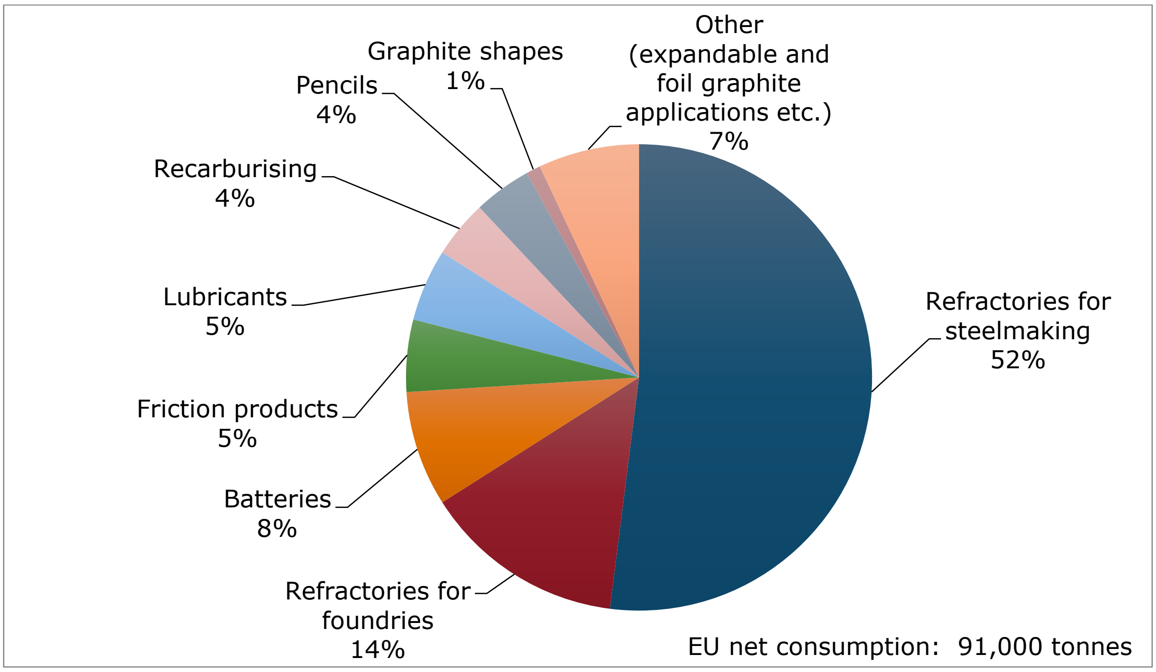

Figure 109: Global uses of natural graphite in 2014. Data are from Roskill (2015), CRM_InnoNet (2015) and BRGM (2012)

Relevant industry sectors are described using NACE sector codes in Table 60.

Table 60: Natural graphite applications, 2-digit NACE sectors and associated 4-digit NACE sector, and value added per sector (Eurostat, 2016b)

Applications	2-digit NACE sector	Value added of sector (millions €)	4-digit NACE sector
Refractories for steelmaking	C24 - Manufacture of basic metals	57,000	C24.1.0 - Manufacture of basic iron and steel and of ferro-alloys
Refractories for foundries	C23 - Manufacture of other non-metallic mineral products	59,166	C23.1.1 - Manufacture of flat glass
Batteries	C27 - Manufacture of electrical equipment	84,609	C27.2.0 - Manufacture of batteries and accumulators
Friction products	C23 - Manufacture of other non-metallic mineral products	59,166	C23.9.9 - Manufacture of other non-metallic mineral products n.e.c.
Lubricants	C20 - Manufacture of chemicals and chemical products	110,000	C20.1.3 - Manufacture of other inorganic basic chemicals
Recarburising	C24 - Manufacture of basic metals	57,000	C24.1.0 - Manufacture of basic iron and steel and of ferro-alloys
Pencils	C23 - Manufacture of other non-metallic mineral products	59,166	C23.9.9 - Manufacture of other non-metallic mineral products n.e.c.
Graphite shapes	C28 - Manufacture of machinery and equipment n.e.c.	191,000	C28.4.9 - Manufacture of other machine tools

The iron and steel industry being the main driver for natural graphite demand, Asia is the largest regional market. In Europe, the refractory sector accounted for about 40% of the demand in 2014 followed by the foundry sector (20%), lubricants, friction products, and others products including flame retardants, sealing applications (Roskill, 2015). The graphite market is complex, as natural and synthetic graphite can both be used in several applications and therefore a large portion of global demand is supplied by synthetic graphite.

With an apparent consumption of natural graphite of about 91,000 tonnes per year on average over the period 2010-2014 and a very limited mining production, the EU is heavily dependent on external sources of supply (import reliance of 99%).

14.3.3 Prices

The two most important parameters of natural graphite pricing are carbon content and mesh size (the size of the grains) which both depend on the natural forms of graphite (amorphous, flake and vein). Larger and purer flakes attract higher prices. Transport, specifically sea freight, can account for up to 30% of the total price. Outside of China, the price is set by the negotiations between the larger mining companies and the major refractory manufacturers. In China, the flake graphite price is set by producers in Shandong and Heilongjiang while amorphous graphite price is controlled by the government-run company that produces about 90% of the world’s supply, in Hunan province (Moores, 2013).

Flake graphite prices remained relatively stable for many years until 2005, after which they climbed gradually to 2008, before declining in 2009 following the global financial crisis. Due to China's huge steel needs, flake graphite prices soared in 2011-2012 but have since returned to 2008 levels due to excess production and reduced demand from the steel industry (Figure 110). Amorphous prices are much lower (less than $US500/tonne). Uncoated spherical graphite for use in lithium-ion batteries is currently around $US 3,000/tonne, having decreased slightly during 2015. Coated spherical graphite commands significantly higher prices ($US 7,000/tonne or more) (Moores, 2013).

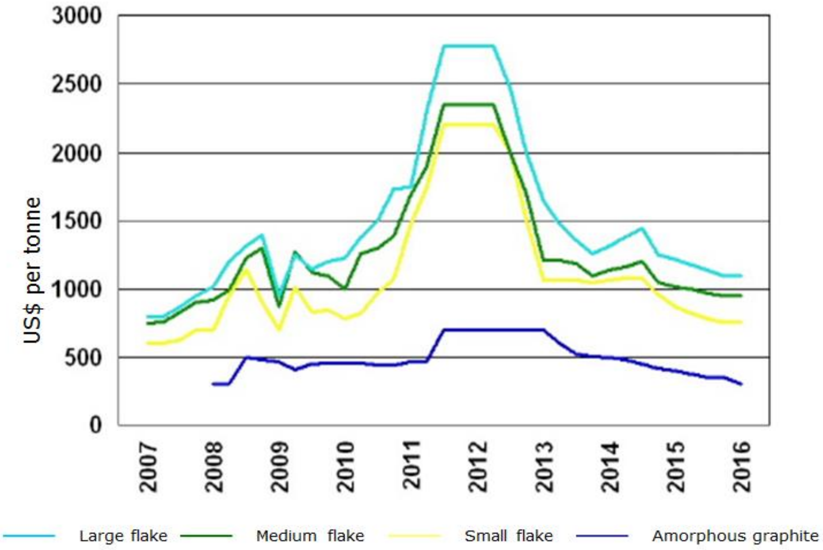

Figure 110: Amorphous and flake graphite prices. (Mason Graphite, 2017)

14.4 Substitution

Refractories is the only application where there is no existing substitute for natural graphite. Synthetic graphite and other materials can replace natural graphite in most other applications. The choice of the substitute is mostly driven by the price of the substitutes.

- Refractories: there is no existing substitute for natural graphite for two main reasons. Firstly flakes morphology helps strengthening the structure of the refractory and this is not achievable with synthetic graphite and secondly, synthetic graphite is currently not cost effective (too expensive) and is not readily available (European carbon and graphite Association, 2016; Engel, 2016).
- Foundry applications: synthetic graphite and calcined petroleum coke can be used in some applications.
- Recarburizing: synthetic graphite powder and other carbon products such as high carbon scraps and calcined petroleum coke are also commonly used, depending of their prices on the market.
- Lubricants: synthetic graphite and molybdenum disulphide are also currently used.
- Li-ion batteries anode: spheroidal graphite used in material is either produced from synthetic or natural graphite.
- Friction products: synthetic graphite can be used instead of natural graphite.

14.5 Discussion of the criticality assessment

14.5.1 5.1. Data sources

Production data for natural graphite ore are from the World Mining Data (2016). Trade data were extracted from the Eurostat Easy Comext database (Eurostat, 2016a). Data on trade agreements are taken from the DG Trade webpages, which include information on trade agreements between the EU and other countries (European Commission, 2016).

Information on export restrictions are derived from the OECD Export restrictions on the Industrial Raw Materials database (OECD, 2016). Application shares are taken from Roskill (2015), CRM_InnoNet (2015) and BRGM (2012).

For trade data, the Combined Nomenclature NC8 codes: 25041000 'Natural graphite in powder or in flakes' & 25049000 'Natural graphite (excl. in powder or in flakes)' have been used.

14.5.2 5.2. Economic importance and Supply Risk Calculation

The calculation of economic importance (EI) was based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 60). The value added data correspond to 2013 figures. The calculation of the Supply Risk (SR) was carried out at the extraction stage (i.e. natural graphite concentrates) of the life cycle, using both the global HHI and the EU-28 HHI.

14.5.3 5.3. Comparison with previous EU assessments

A revised methodology was introduced in the 2017 assessment of critical raw materials in Europe and both the calculations of economic importance and supply risk are now different; therefore the results with the previous assessments are not directly comparable. The results of the 2011, 2014 and 2017 assessments are shown in Table 61.

Table 61: Economic importance and supply risk results for Natural graphite in 2011, 2014 and 2017 assessments (European Commission, 2011; European Commission, 2014)

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Natural graphite	8.7	1.3		7.4	2.2		2.9	2.9

Economic importance and supply risk results in 2017 differ from previous assessment results for the following reasons:

The significant decrease in EI is due to the revised EI calculation used in the 2017 assessment. The 2017 assessment considers natural graphite applications only, whereas in the 2014 assessment, the calculation of the economic importance was based on natural graphite and synthetic graphite applications e.g. electrodes for the steel industry accounted for 34% of the global demand in the 2010 assessment; however these are not made out of natural graphite but of synthetic graphite. The economic importance indicator is therefore lower and the supply risk indicator is higher in the 2017 assessment.

14.6 Other considerations

14.6.1 Forward look for supply and demand

Refractories for the steel industry remain the dominant market for natural graphite consumption and graphite production has tended to follow global steel production. Worldwide steel output peaked in 2014 and decreased 3% in 2015 due to China's slower economic growth, reducing China's demand for refractories. Chinese steel demand picked up slightly in 2016 due to a number of government stimulus measures. According to the Worldsteel Association (2016) global steel demand will grow by 0.5% in 2017. The battery sector (Li-ion) is expected to increase the demand for natural and synthetic graphite on the back of maturing electric vehicle demand and the inception of the utility storage market (Moores, 2016; Scogings, 2016). Another fast growing market is predicted to be expandable graphite for foil, insulation and fire retardant product, as demand for flame retardant building materials is expected to grow in China.

Table 62: Qualitative forecast of supply and demand of Natural graphite

Material	**Criticality of the material in 2017**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Natural graphite	x		+	+	+	+	+	+

14.6.2 Environmental and regulatory issues

Natural Graphite is not subject to EU REACH regulations (ECHA, 2017).

14.7 Data sources

14.7.1 Data sources used in the factsheet

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14.8 Acknowledgments

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15. NATURAL RUBBER

Key facts and figures

Material name	Natural Rubber	World/EU production (tonnes)[1]	11,965,000/0
Parent group (where applicable)	N/A	EU import reliance (%)[1]	100%
Life cycle stage assessed	Extraction	Substitution index for supply risk [SI (SR)][1]	0.92
Economic importance (EI) (2017)	5.4	Substitution Index for economic importance [SI(EI)][1]	0.92
Supply risk (SR) (2017)	1.0	End of life recycling input rate (EOL-RIR)	1%
Abiotic or biotic	Biotic	Major end uses in the EU[1]	Automotive (75%), furniture (12%), sportswear/shoes (5%), Machinery (4%)
Main product, co-product or by-product	Main product	Major world producers[1]	Thailand (32%), Indonesia (26%), Vietnam (8%), India (8%)
Criticality results	2011	2014	2017
	Not assessed	Not critical	Critical

[1] 2010-2014 average, unless otherwise stated.

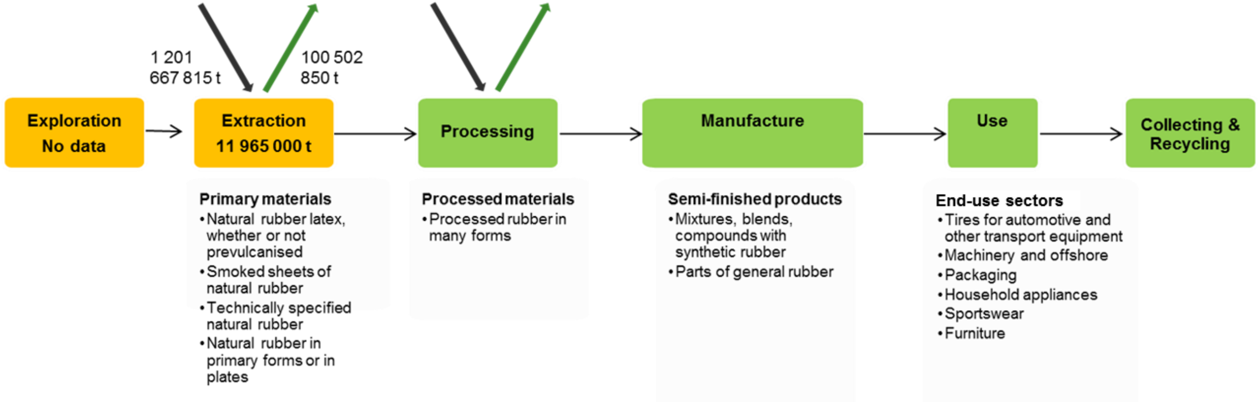

Figure 111: Simplified value chain for natural rubber

The green boxes of the production and processing stages in the figure above suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. EU reserves are displayed in the exploration box.

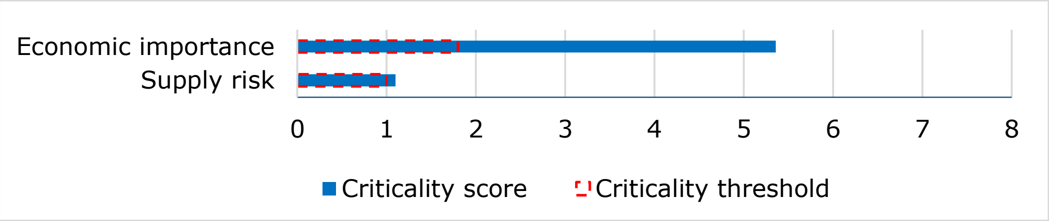

Figure 112: Economic importance and supply risk scores for natural rubber

15.1 Introduction

Natural rubber is primarily harvested from the rubber tree Hevea brasiliensis, although native to the Amazon region over 90% of natural rubber is now produced in Southeast Asia. The tire industry is the largest consumer of natural rubber, accounting for around 75% of annual demand. Use of Natural Rubber in European value chains is dominated by the tire industry, whereas in Asia the General Rubber Goods (GRG) applications in high-tech industries play an important role. There are many uncertainties in natural rubber production for both end-user and producer given the biotic nature of the raw material.

15.2 Supply

15.2.1 Supply from primary materials

Natural rubber (NR) is a biotic material which is harvested from rubber trees, mainly growing in tropical forests close to the equator. The rubber tree is a perennial crop that is harvested throughout the year and its tapping intensity to some extent can be altered in both directions. These trees are harvested by making a slight cut in through the bark into the lactiferous vessels of the trees which produce a milky white latex fluid. Care must be taken not to cut too deeply into the cambium layer as this will injure the tree. The product is collected on the same day in the form of liquid latex or can be collected at the time of the next tapping as a dried cuplump. For optimum yields, trees should be tapped twice weekly (Luckett, 2012).

15.2.1.1 Resources and reserves

The overall acreage of national rubber plantations is estimated around 12 million hectares (IRSG, 2016), see Table 63 for the most dominant countries in terms of acreage. The exact amount of hectares is uncertain and fluctuating and therefore no direct relation can be made between the amount of hectares, yield and global production.

The yield in kg/ha was around 1,100 in the year 2000, 1,200 in the year 2015 and expected to be around 1,500 in the year 2030 (IRSG, 2016). The global summated annual planting and replanting activity was around 200,000ha in the year 2015. Rubber plantations are facing competition of other crops (palm oil, grains etc.) that limit the flexibility to expand the total acreage of natural rubber plantations.

Table 63: Global reserves of natural rubber in year 2015 (Data from LMC 2016)

Country	Natural rubber Area (ha)
Thailand	2,300,000
Indonesia	2,080,000
Vietnam	950,000

15.2.1.2 Refining

Refining i.e. processing of tapped rubber is chiefly done in the production country, also in the vicinity of the plantation. Solid processed natural rubber is roughly delivered in three distinct types: ribbed smoked sheets (RSS), technically specified rubber (TSR) and other base rubber products. The tire industry, the dominant user, has increasingly demanded TSR given the technological advances. Around 10% of the supply of rubber is delivered in the shape of latex, an even more processed form of rubber.

15.2.1.3 World production

The global production of natural rubber between 2010 and 2014 was 11, 965,000 tonnes on average. The NR production is dominated by Thailand, Indonesia, Vietnam, India, China and Malaysia which account for close to 75% of global production. In 2015 the total production of Natural Rubber reached 12.3 million tonnes. Global production has increased rapidly over the past 50 years. This increase has been mostly due to increased production in the abovementioned countries. Figure 113 shows the global production.

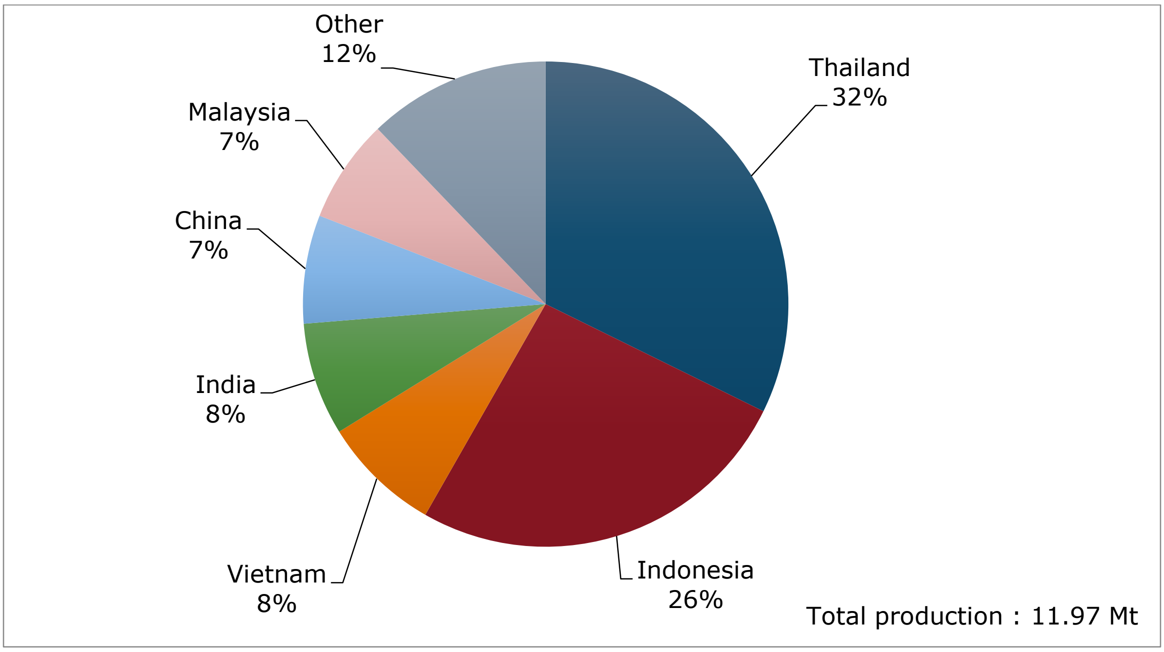

Figure 113: Global production of natural rubber, average 2010–2014 (FAO)

15.2.2 Supply from secondary materials

The use of primary natural rubber is currently only for an estimated 0.9% being replaced by secondary natural rubber.

The EU uses around 9% of the world supply of natural rubber. Given the natural rubber use in other parts of the world (39% China, 8% USA, 14% India and Japan, 30% rest of the world), the stock of used products containing Natural Rubber for production of secondary materials is therefore not particularly high in the EU.

The management of Used Tires is well organized in Europe and quite successful. In 2015, 92% of those tires (vs. 51% in 1996) were either reused as second-hand tires or reconditioned through retreading, or - when unsuitable for further use on a vehicle - recycled or sent to energy recovery as End-of-Life Tire (ELT). However, for the criticality assessment of NR, it is important to highlight that tire recycling features an open-loop recycling, meaning that ELT-derived rubber granulates are mainly recycled in other applications than tires as current tire devulcanization technologies are not selective enough to get high quality devulcanization, which is requested to meet stringent technical performances imposed by EU regulation (tire wet grip, Rolling Resistance, noise) as well as safety performances. Therefore, the current recycling of ELTs & End of-Life GRG products does not lead to a reduction of the NR supply risk.

With regard to recycling, more than 1 million tonnes of ELTs are annually processed for granulation and are used in a multitude of applications - such as synthetic turf, children playgrounds, sport surfaces, moulded objects, asphalt rubber, acoustic & insulation applications - substituting other raw materials than NR (for example, virgin EPDM in synthetic turf, polyurethane in moulded objects, ...).

In the 2nd sector where NR is used (GRG), the recycling of GRG products mainly occurs for production scrap but in a limited way mainly due to the heterogeneity of elastomers used and the multitude of SMEs in the GRG sector making economies of scale difficult to get.

End-of-life recycling of GRG products is limited either due to contamination issues (at dismantling of End-of-life vehicles) or due to the mere impossibility to recycle the application (condoms, clinical gloves, etc.).

15.2.3 EU trade

NR is a commodity traded at three main trading platforms: SICOM/SGX (The Singapore Commodity Exchange/Singapore Exchange), The Tokyo Commodity Exchange ("TOCOM") and SHFE (The Shanghai Futures Exchange).

Figure 114 shows the import and export flow related to the EU-28, bearing in mind that the exports only concern re-exports. The origin of EU imports shows a similar pattern as compared to the global production, with main suppliers from Asian countries (Indonesia, Malaysia and Thailand). See Figure 115.

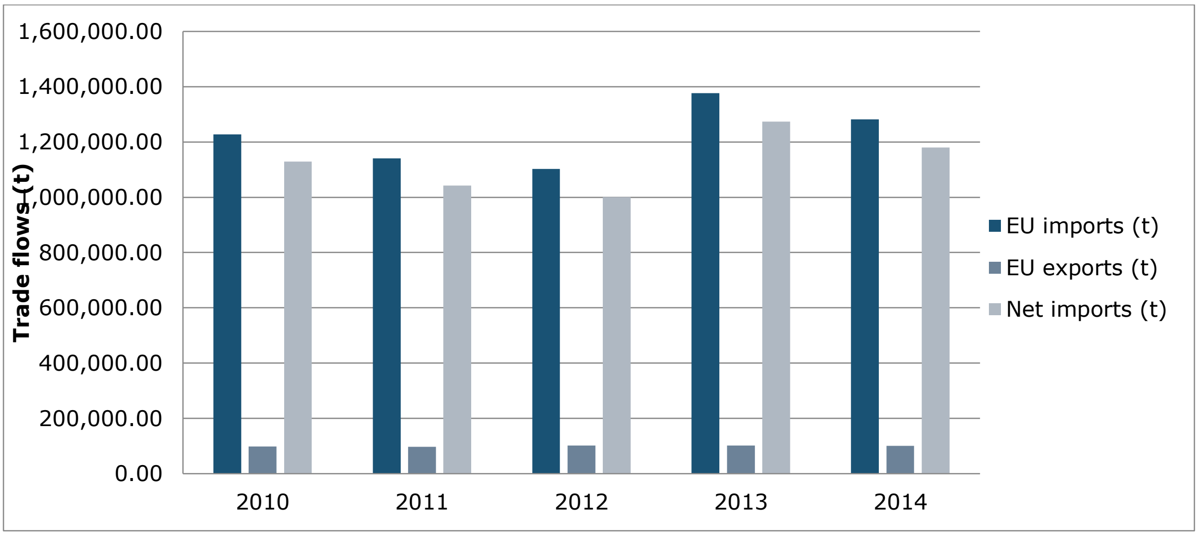

Figure 114: EU trade flows for natural rubber. (Data from Eurostat Comext, 2016)

EU trade is analysed using product group codes. It is possible that materials are part of product groups also containing other materials and/or being subject to re-export, the "Rotterdam-effect". This effect means that materials can originate from a country that is merely trading instead of producing the particular material.

Export restrictions between 2010 and 2014 from supplying countries relate almost exclusively to export quota. For example Indonesia and Thailand have an export quota of more than 2 million tonnes, whereas the one for Malaysia, Vietnam and India is lower (between 550,000 and 650,000 tonnes). Major south-east Asian producers (Thailand, Indonesia, Malaysia and most other major producers of natural rubber) have only exported up to 70% of natural rubber in primary forms in that period. In 2015 and 2016, the IRSG has considered various additional tax measures, which have yet to be recorded officially by the OECD database.

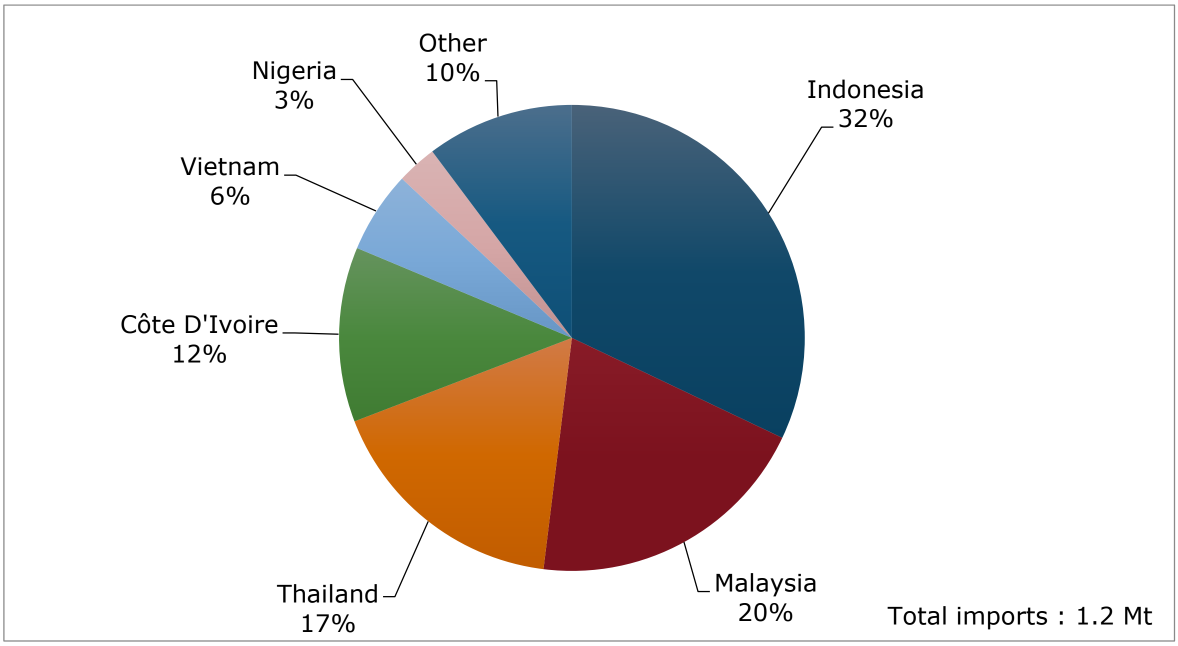

Figure 115: EU imports of natural rubber, average 2010-2014. (Data from Eurostat Comext, 2016)

15.2.4 EU supply chain

It is reported that the tire industry uses up to 75% of natural rubber consumed in the EU (LMC, 2016). An average car tire will contain 15% natural rubber by weight and a truck tire will contain 30%. The remaining content of tires consists of synthetic rubber, carbon black and silica as tire fillers, steel cord and wires to provide strength and other chemicals such as oils and zinc oxide.

Other General Rubber Goods uses can be divided into three categories: industrial products, such as moulded and extruded products, belting, hose and tube; consumer products, such as footwear, toys, sports and leisure goods; and latex products, such as dipped goods, thread, adhesives, carpet underlay, gloves and condoms.

In 2014, the production of natural rubber containing goods within the EU amounted to 2.6 Mt of General Rubber Goods and around 4.8Mt of Tires. The rubber processing sector in the EU employed around 350,000 people directly in 2014.

The EU is fully relying on imports (import reliance of 100%), where 8% of its imports are exported outside the EU as re-exports. There is no EU domestic production of NR.

15.3 Demand[14]

15.3.1 EU consumption

The annual average consumption of natural rubber in the EU was 1,101,164 tonnes over the 2010-2014 period.

15.3.2 Use of rubber in manufacturing

The Figure 116 presents the main uses of natural rubber. Relevant industry sectors are described using the NACE sector codes (Eurostat, 2016c) in Table 64.

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[14] For selected Natural Rubber product groups.

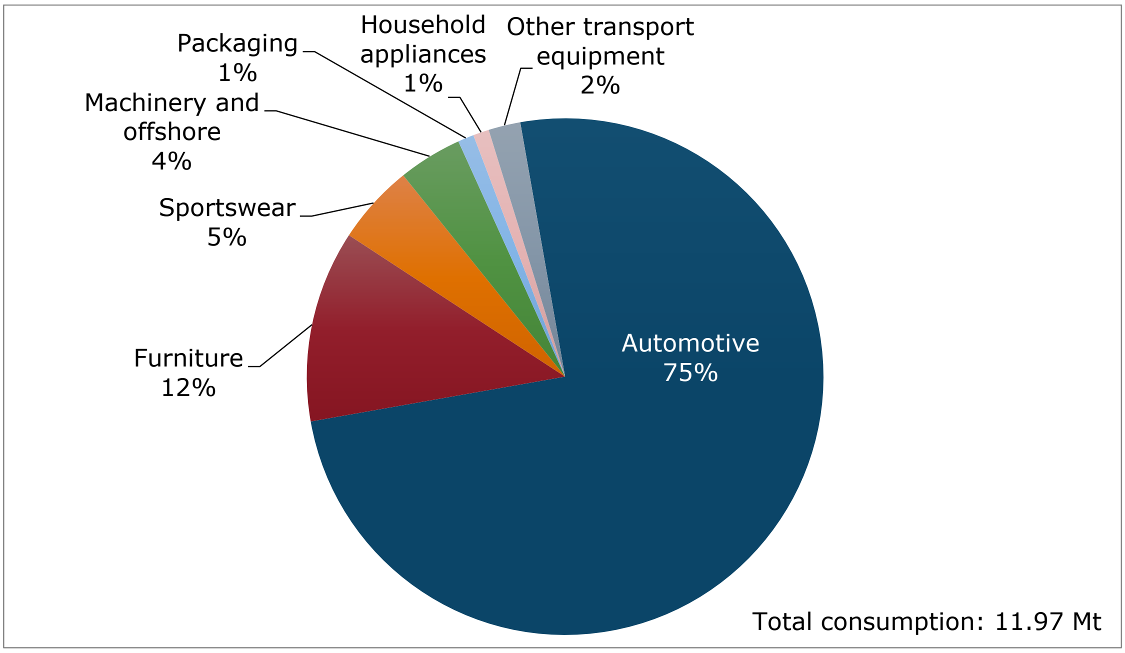

Figure 116: Global/EU end uses of natural rubber. Average figures for 2010-2014. (Data from LMC, 2016)

Table 64: Natural rubber applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Data from the Eurostat database, Eurostat, 2016c)

Applications	2-digit NACE sector	4-digit NACE sector	Value added of sector (millions €)
Packaging	C22 - Manufacture of rubber and plastic products	22.11 Manufacture of rubber tyres and tubes; retreading and rebuilding of rubber tyres	82,000
Household appliances	C27 - Manufacture of electrical equipment	27.51 Manufacture of electric domestic appliances	84,608
Belts	C28 - Manufacture of machinery and equipment n.e.c.	28.13 Manufacture of other pumps and compressors	191,000
Tyres	C29 - Manufacture of motor vehicles, trailers and semi-trailers	29.10 Manufacture of motor vehicles	158,081
Tyres	C30 - Manufacture of other transport equipment	30.12 Building of pleasure and sporting boats	53,644
Furniture	C31 - Manufacture of furniture	31.02 Manufacture of kitchen furniture	28,281
Sportswear and specific clothing	C32 - Other manufacturing	32.30 Manufacture of sports goods	41,612

It is reported that the tire industry uses up to 75% of natural rubber consumed in the EU (LMC 2016). An average car tire will contain 15% natural rubber by weight and a truck tire will contain an average 30%. The remaining content of tires consists among others of synthetic rubber, carbon black and silica as tire fillers, steel cord and wires to provide strength and other chemicals such as oils and zinc oxide.

Other General Rubber Goods uses can be divided into three categories: industrial products, such as moulded and extruded products, belting, hose and tube. These products are generally used in machinery and household goods. Another class of applications is in final consumer products, such as footwear, toys, sports and leisure goods; and latex products, such as dipped goods, thread, adhesives, carpet underlay, gloves and condoms.

15.3.3 Prices

The price of natural rubber has hovered between 40 cents and 190 cents per pound over the last years. See Figure 117. The price volatility is mainly influenced by shifting demand from industry and shifting supply as a result of influences from the environment. See also chapter 6 for a discussion about the natural rubber market and price mechanism.

Figure 117: Prices for natural rubber 2006-2016. (Data from indexmundi, 2016)

15.4 Substitution

Research for rubber substitutes is concentrated on finding alternative plant sources of latex. More specifically scientists are looking at using *Parthenium argentatum* (guayule) and *Taraxacum koksaghyz* (Russian dandelion) as alternative rubber and latex sources; these are the only other species known to produce large amounts of rubber with high molecular weight. In this respect the EU has launched the EU- PEARLS (Production and Exploitation of Alternative Rubber and Latex Sources) project (Polymers & Tire Asia 2010). This project is formed of consortium which links stakeholders from the EU and other countries working on developing these two alternatives to natural rubber from *Hevea brasiliensis*. The TRL level of this research suggests that any significant market effect will be absent (at least) in the very short term (ETRMA, 2016).

The choice of the elastomer is at the heart of any substitution option. The elastomer presents certain mechanical property such as wear and tear resistance, stiffness, heat resistance and hysteresis.

In heavy trucks and airplanes especially, the choice for the elastomer is limited given the need for the material to perform and relatively high stresses and changing temperatures. The share of natural rubber for these products ranges around 35%, opposed to other tire products where the content is normally between 10% and 20%, based on the specifications of the tire part.

The most important synthetic rubbers are Polybutadiene, Butyl and Halo-Butyl, Polyisoprene and Stirene Butadiene. Given the requirements of the substitution of natural rubber with synthetic rubber is limited to 2 percentage points in tires. The substitution rate is higher for General Rubber Goods, depending on the specific application. In packaging, household appliances, sportswear and furniture, plastics in general can be a substitute. (LMC 2016)

Synthetic rubber has been long used as an alternative or supplement to natural rubber. An example is styrene butadiene; however these synthetic rubbers cannot match price and performance of natural rubber. (Van Beilen and Poirer 2007), Furthermore, synthetic rubber at present has not achieved the same performance as natural rubber in tire applications. For example, synthetic rubber does not have an equally high molecular mass which defines the quality of the rubber and does not contain the non-rubber components which are found in the latex produced by rubber plants. (Gronover et.al., 2010) Natural rubber also exhibits greater resistance to tearing at high temperatures and builds up less heat from flexing. For this reason, truck tires require a higher percentage of natural rubber that those for passenger cars. A last important point to be made about synthetic tires is that these are produced from oil. Given the current oil prices and the fact that this is not a renewable source this should not be considered as a sustainable alternative to natural rubber.

15.5 Discussion of the criticality assessment

15.5.1 Data sources and representativeness

The trade assessment is based on four products groups, with CN codes 40011000 (Natural Rubber or Latex, whether or not pre-vulcanized). The product groups 40012100 (smoked sheets of natural rubber), 40012200 (technically specified natural rubber (TSNR), 40012900 (natural rubber in primary forms or in plates) are considered a processed form. Moreover, they were out of scope in the previous CRM assessment. They are therefore not part of the trade assessment.

Data sources for natural rubber are generally good. Data is available in time series for the period of 2010-2014. Adequate sources are publicly available. To supplement official data sources, knowledge about natural rubber is present within European organizations such as ETRMA.

The International Rubber Supply Group has a database of its own. ETRMA might be able to arrange access to this database in case of specific requests. For the 2017 criticality assessment, the use of public data from FAO was preferred. Moreover, differences between the FAO data and the IRSG data where mostly smaller than a two percentage points.

15.5.2 Calculation of EI and SR parameters

The application of Natural Rubber is allocated to end-use sectors such as the automotive industry rather than the rubber manufacturing itself. This is done given the quality of the data linking the use of natural rubber to the more downstream sectors, including specific quantities of the raw material and the fact that tires are not used in any other sector. This has an influence on the economic importance, which has a larger numerical value given this allocation.

Natural Rubber is assessed at the extraction stage, not the processing stage as these processes normally take place in the same country.

The sensitivity of the results lies almost solely in the share of natural rubber used in tires and the fact that this application is mapped to the automotive sector. The share of other sectors is small and therefore not of great influence on the end result. End-Of-life replacement rate is generally considered small, as is the opportunity to substitute natural rubber currently in the production of tires.

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 64). The value added data correspond to 2013 figures.

The supply risk was assessed on natural rubber using both the global HHI and the EU-28 HHI as prescribed in the revised methodology.

15.5.3 Comparison with previous EU assessments

Natural rubber was first assessed in 2014. It was not assessed in 2011. The result of the 2014 assessment was an Economic Importance that was clearly above the criticality threshold (around 7.7); however the supply risk score was below the criticality score with a numerical value of around 0.8. See Table 65. The allocation of applications and the supply data are similar in the 2017 assessment compared to the 2014 assessment. The main reason for the difference in results is explained by the changes in the revised methodology regarding the calculation of the supply risk, recycling and substitution options. For example, the calculation of the SR for natural rubber in the 2017 assessment notably takes into account actual EU sourcing from Indonesia (35%), Malaysia (22%), Thailand (19%) and the Ivory Coast (13%), with no known production in Europe. Therefore, natural rubber is characterised by an import dependency of 100%. The 2017 assessment reports a final SR score of 1.0 (SR=0.8 in 2014), which is influenced by the lack of readily available substitutes for all identified end-use applications and the low EOL-RIR (1%).

Table 65: Economic importance and supply risk results for natural rubber in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011		2014		2017	
Indicator	EI	SR	EI	SR	EI	SR
Natural rubber	N/A	N/A	7.7	0.9	5.4	1.0

15.6 Other considerations

15.6.1 Forward look for supply and demand

The forecast of the worldwide supply of natural rubber is chiefly determined by the following factors: demand for automotive and other transport equipment, oil prices, balance between markets for tires and general rubber goods, and the development of synthetic rubber manufacturing technology. The (LMC International 2016) report estimates a supply/demand deficit from 2023, increasing to an annual deficit of 900Kt in 2030. Alternative scenarios could see a surplus of 250 kt and an even larger deficit of around 2,250 kt in that same year. The International Rubber Study Group (IRSG, 2016) report sees a surplus in all scenarios in the year 2025, ranging between 48 and 115 kt.

Table 66: Qualitative forecast of supply and demand for natural rubber

Material	Criticality of the material in 2017		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Natural Rubber	x		+	+	?	+	+	?

15.6.2 Environmental and regulatory issues

The environmental issues as they are perceived by the stakeholders in the chain seem to relate mostly to the end-use applications. More efficient cars, lighter cars and alternative propulsion are discussed. Land use, toxicity, water use or emissions related to Natural Rubber are hardly discussed in branch reports.

As a biotic material, Natural Rubber supply is influenced by biotic influences. Production in South American plantations is hampered by a fungal disease known as South American leaf blight, creating uncertainty about the supply from that region in the coming years. The endemic fungus *Microcyclus ulei*, an ascomycete that together with its host plant originates from the Amazon area. Since the beginning of rubber exploitation in the region, all attempts to plant rubber trees at a plantation scale in South and Central America have failed completely as a result (NCBI 2007). The disease is still restricted to its continent of origin, but its potential to be distributed around the world rises with every transcontinental airline connection that directly links tropical regions.

Major increase in supply of the raw material cannot be adjusted within a few years. The long maturity period of rubber trees (5-7 years) means that new natural rubber supply potential for the entire forecast period has largely been decided. As such, the Natural Rubber supply potential (normal production) will continue to increase in 2016-2025, based on trees largely planted. The maximum yield is reached around the fifth to the tenth year of tapping. A rubber tree is productive for 20 to 40 years, where the length of the productive period is largely determined by the tapping intensity. Afterwards replanting is required. This means the plant cycle itself brings to constant periods of scarcity in NR on the market. Moreover, the Natural Rubber cultivation is currently characterized by a lack of qualified and available manpower (IRSG, 2016).

15.6.3 Supply market organisation

The Natural Rubber market supply is characterized by sourcing inflexibility (see also chapter 2 of this factsheet), i.e. mainly from South-East Asia (>90%), where the four major producing countries (representing >75% of NR supply) operate in an oligopolistic structure. The International Rubber Consortium Ltd. (“IRCo”) is a company created in 2002 pursuant to a Memorandum of Understanding signed among the governments of Indonesia, Malaysia and Thailand, i.e. the three most important natural rubber producers. Other countries that have been invited to become members include India, Papua New Guinea, Singapore and Sri Lanka. (Steptoe Johnson 2011) Another risk is evolving from the fact that some companies have integrated themselves both upstream and downstream in the natural rubber supply chain. For example, the Chinese group Sincochem acquired 51% of the rubber plantation company GMG Global Ltd. Integrating production and processing thus ensures on going supply of the raw material.

15.7 Data sources

15.7.1 Data sources used in the factsheet

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15.7.2 Data sources used in the criticality assessment

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15.8 Acknowledgments

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16. NIOBIUM

Key facts and figures

Material name and element symbol	Niobium, Nb	World / EU production (tonnes)[1]	Extraction : 113,000/ 0 Refining: 50,451 / 0
Parent group	n.a.	EU import reliance [1]	100%
Life cycle stage / material assessed	Refining / Ferroniobium	Substitution index for supply risk [SI(SR)]1	0.94
Economic importance (EI) (2017)	4.8	Substitution Index for economic importance [SI(EI)][1]	0.91
Supply risk (SR) (2017)	3.1	End of life recycling input rate (EOL-RIR)	0.3%
Abiotic or biotic	Abiotic	Major global end uses (2014)	Steel (all forms) (86%), Superalloys (8%), Chemicals (6%)
Main product, co-product or by-product	Main product	Major world producers[1]	*Extraction*: Brazil (95%), Canada (4%) *Refining*: Brazil (90%), Canada (10%)
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] average for 2010-2014, unless otherwise stated.

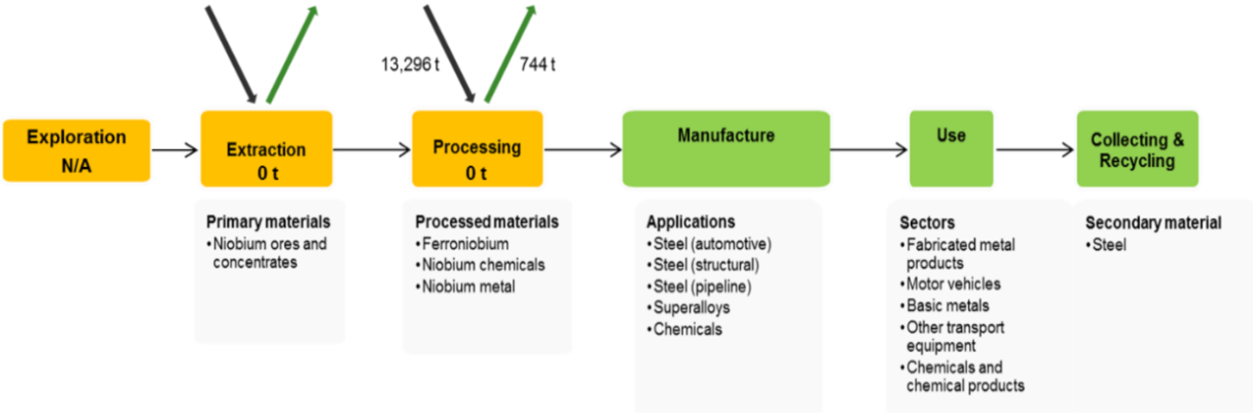

Figure 118: Simplified value chain for niobium

The orange boxes of the production and processing stages in the figure above suggest that activities are not undertaken within the EU. The black arrows pointing towards the extraction and processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

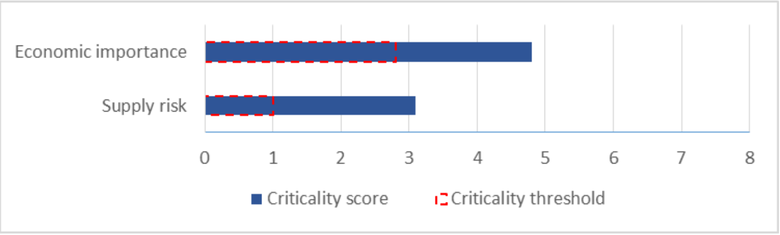

Figure 119: Economic importance and supply risk scores for niobium

16.1 Introduction

Niobium (chemical symbol Nb) is grey in colour. It is a relatively hard, paramagnetic, refractory transition metal. It has a density of 8.57 g/cm^3 and a very high melting temperature (2,468°C). Niobium is also highly resistant to chemical attack and behaves as a superconductor at very low temperature. Niobium has an upper-crustal abundance of 12 ppm (Rudnick, 2003), which is higher than some of the other refractory metals, but lower than many of the base metals. Niobium is not found as a free metal in nature, but chiefly occurs in minerals such as columbite and pyrochlore, the latter being the primary ore mineral of niobium. Niobium is mostly consumed in the production of ferroniobium (containing around 65% niobium), which is an important component in high strength low alloy (HSLA) steels used to make car bodies, gas pipelines and ship hulls. It is also used in the manufacture of superconducting magnets, carbide-based cutting tools, high-performance glass coatings and superalloys. Niobium has no known biological role. In its native form niobium is fairly inert and poses few, if any, environmental or human health issues.

Trade data for niobium ores and concentrates are not available, for this reason the criticality assessment for niobium is based on the production and trade of ferroniobium, which is the chief product that enters international trade. Primary extraction of niobium ores and concentrates does not take place in Europe, nor does the production of ferroniobium. Therefore the EU is entirely reliant on imports of ferroniobium to meet its current demand. Apparent consumption of ferroniobium in Europe (2010–2014) was on average about 12,500 tonnes per annum, the majority of which (ca. 86 %) was used in the manufacture of steel.

16.2 Supply

16.2.1 Supply from primary materials

16.2.1.1 Geological occurrence

Primary niobium deposits are most commonly associated with peralkaline granites or syenites, and/or carbonatites (i.e. an igneous rock that consists of more than 50% primary carbonate minerals). Secondary deposits of niobium, such as laterites, and residual placers, typically form by the weathering of primary igneous deposits (Dill, 2010). An overview of these deposits is given in Table 67.

Niobium deposits associated with peralkaline granites and syenites are typically less than 100 million tonnes in size and have ore grades of between 0.1 and 1 wt. % Nb_2O_5, contained in ore minerals such as columbite, eudialyte and loparite. Alkaline magmas responsible for the formation of these deposits are derived by melting of enriched sub-continental lithospheric mantle and are typically enriched in the high field strength elements (HFSE) (i.e. niobium, zirconium and rare earth elements). These incompatible (i.e. elements that become concentrated in molten magma rather than early crystallising solid minerals) HFSE are further upgraded by magmatic (e.g. fractional crystallisation) and/or hydrothermal processes (BGS, 2011).

Carbonatite-hosted niobium deposits can be divided into primary and secondary deposit types. Primary deposits are generally in the tens of millions of tonnes size range and typically have ore grades of less than 1 wt. % Nb_2O_5. Carbonatites are found in areas of crustal extension or rifting and are thought to be derived from direct melting of the mantle. They are enriched in HFSE (e.g. niobium, zirconium and rare earth elements), but also barium, strontium, thorium and uranium. Important ore minerals in these rocks include perovskite and pyrochlore, and niobium-rich silicates such as titanite (BGS, 2011). Secondary niobium deposits are associated with deep, tropical weathering of carbonatites and are typically very large (up to 1,000 million tonnes) and have very high ore grades (up to 3 wt. % Nb_2O_5 in lateritic deposits, but as high as 12 wt. % Nb_2O_5 in some residual placers). Pyrochlore is the most common ore mineral in these secondary ore deposits (BGS, 2011).

Table 67: Summary of important niobium deposit types (BGS, 2011)

Deposit type	**Brief description**	**Typical grades and tonnage**	**Major examples**
Carbonatite-hosted primary deposits	Niobium deposits found within carbonatitic igneous rocks in alkaline igneous provinces	Niobec, proven & probable reserves: 23.5 million tonnes at 0.59% Nb_2O_5	Niobec, Canada; Oka, Canada
Carbonatite-sourced secondary deposits	Zones of intense weathering or sedimentary successions above carbonatite intrusions in which niobium ore minerals are concentrated	< 1000 million tonnes at up to 3% Nb_2O_5 in lateritic deposits. Up to 12% Nb_2O_5 in placer deposit at Tomtor, tonnage not known	Araxá and Catalăo, Brazil; Tomtor, Russia; Lueshe, DRC
Alkaline granite and syenite	Niobium and lesser tantalum deposits associated with silicic alkaline igneous rocks. Ore minerals may be concentrated by magmatic or hydrothermal processes	Generally < 100 million tonnes, at grades of 0.1 to 1% Nb_2O_5 and < 0.1% Ta_2O_5	Motzfeldt and Ilímaussaq, Greenland; Lovozero, Russia; Thor Lake and Strange Lake, Canada; Pitinga, Brazil; Ghurayyah, Saudi Arabia; Kanyika, Malawi

16.2.1.2 Exploration

The Minerals4EU project identified that niobium exploration in Europe, in 2013, was primarily taking place in Portugal, Ireland and Greenland. However, exploration may have taken place in other EU countries where no information was provided during the survey (Minerals4EU, 2014). Global exploration for niobium in recent years has taken place in various countries such as Tanzania, the United States, Malawi, Greenland and Saudi Arabia. Selected advanced niobium exploration projects are shown in Table 68.

Table 68: Selected advanced niobium exploration projects (Data from various company reports and websites)

Project	**Country**	**Company**	**Resource (Mt)***	**Nb_2O_5 content (%)**
Panda Hill	Tanzania	Cradle Resources	36	0.54
James Bay	Canada	NioBay	62	0.52
Elk Creek	United States	NioCorp	80	0.71
Kanyika	Malawi	Globe Metals and Mining	21	0.44
Motzfeldt	Greenland	Regency Mines	340	0.19
Ghurayyah	Saudi Arabia	Tertiary Minerals	400	0.28

** Includes all categories of resource.*

16.2.1.3 Mining, processing and extractive metallurgy

Niobium is chiefly mined as a primary product. Near-surface niobium deposits are typically exploited by open-pit mining methods, which commonly involve removing overburden, digging or blasting the ore, followed by removal of the ore by truck or conveyor belt for stockpiling prior to processing. Deeply buried niobium deposits are mined underground using conventional mining methods, such as room and pillar, where mining progresses in a horizontal direction by developing numerous stopes, or rooms, leaving pillars of material for roof support. Ore is blasted and then transported by rail, conveyor or dump truck to the processing plant.

Regardless of the mining method employed primary niobium ores are first crushed in jaw, cone or impact crushers and milled in rod or ball mills operating in closed circuits with vibrating screens and screw classifiers to liberate niobium mineral particles. The slurry containing niobium and waste rock is further concentrated to around 54% niobium oxide using a number of methods in multiple stages: gravity separation, froth flotation, magnetic and electrostatic separation, and acid leaching may be used, depending on the physical and chemical characteristics of the ore (BGS, 2011).

Typically niobium ores from carbonatite-associated deposits are screened, classified, and deslimed (i.e. removal of very fine particles). Carbonate material is removed by froth flotation, followed by an additional desliming stage. Magnetite is removed by low-intensity magnetic separation, and sent to waste. The sought-after pyrochlore is collected by froth flotation. A final stage of froth flotation is used to remove sulphides, such as pyrite. Residual impurities may be leached by hydrochloric acid, leaving a final concentrate that contains about 54% niobium pentoxide (IAMGOLD, 2009; BGS, 2011).

Niobium concentrates are further refined by hydrometallurgical processes to produce niobium fluorides, oxides or chlorides. These compounds can then be converted to niobium metal by electrometallurgical (e.g. electrolysis) or pyrometallurgical (e.g. aluminothermic reaction) processes. Ferroniobium, containing 65–66% niobium, is also produced by aluminothermic reaction, but with the addition of iron oxide powder. Niobium carbide is produced by high temperature sintering of niobium oxide powder with carbon (Albrecht, 1989; BGS, 2011).

16.2.1.4 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of niobium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[15], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for niobium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for niobium and tantalum (together), but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and

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[15] www.crirsco.com

different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for niobium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015). Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

Global resources of niobium are very large (about 84 million tonnes), but occur almost exclusively in Brazil (see Table 69), which currently accounts for about 96 % of all global resources (Linnen, Trueman and Burt, 2014). Four European countries are known to have niobium resources, namely Portugal, France, Finland and Sweden. Norway and Greenland also have resources in Europe. However, these resources are all based on historical estimates that are not reported in accordance with the UNFC system of reporting. There are no data about niobium resources in Europe in the Minerals4EU website (Minerals4EU, 2014).

Known global reserves of niobium (as Nb_2O_5) are estimated to be about 2 million tonnes, about 90 % (1.8 million tonnes) of which are found in Canada (Table 69). There are no data about niobium reserves in Europe in the Minerals4EU website (Minerals4EU, 2014).

Table 69: Global resources (measured and indicated*) and reserves (proven and probable) of niobium in 2014 (Linnen, Trueman and Burt, 2014)

Country	**Niobium(Nb_2O_5 content) Resources (tonnes)**	**Niobium(Nb_2O_5 content) Reserves (tonnes)**
Brazil	78,133,000	44,000
Canada	3,005,000	1,810,000
Australia	165,000	164,000
China	2,200,000	-
Egypt	4,000	-
Malawi	174,000	-
Mozambique	52,000	-
United States	129,000	-
*World total ***	*83,861,000*	*2,019,000*

* Inferred resources are also reported in Brazil, Gabon, Kenya, Canada, Tanzania, Ethiopia, Saudi Arabia, Spain, Angola, Mozambique and the USA.

** Some deposits are omitted because no reliable reserve or resource data are available.

16.2.1.5 World production

Global extraction of niobium ores and concentrates currently takes place in nine countries and averages 113,000 tonnes per annum over the 2010–2014 period. However, production is heavily concentrated, with about 95 % of world production taking place in Brazil (see Figure 120). The only other significant producer of niobium ores and concentrates is Canada, which accounts for about 4 % of the global total. Seven countries, Russia, Burundi, Democratic Republic of Congo, Madagascar, Nigeria, Rwanda, and China account for the remaining 1 % (BGS, 2016).

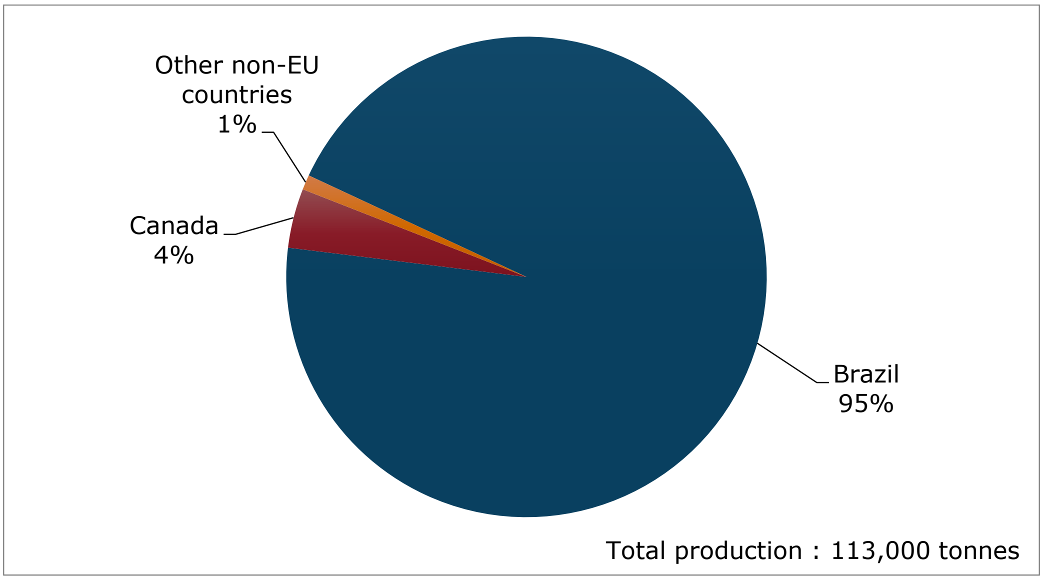

Figure 120: Global production of niobium ores and concentrates, average 2010–2014 (Data from UN Comtrade database)

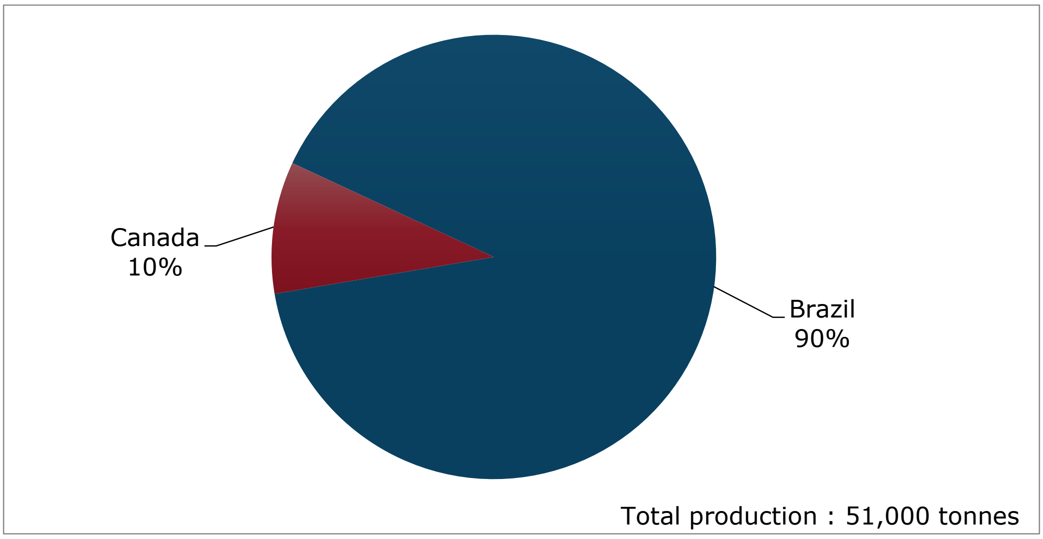

Figure 121: Global production of ferroniobium, average 2010–2014 (Data from UN Comtrade database)

With the exception of the African countries listed above, companies extracting niobium ores are typically integrated, meaning they also produce processed niobium products, such as niobium oxide, ferroniobium and niobium metal. Average global production of ferroniobium during the 2010-2014 period was almost 51,000 tonnes per annum. Figure 121 shows global ferroniobium production only took place in only two countries, Brazil and Canada.

16.2.2 Supply from secondary materials

According to the United Nations Environment Programme (UNEP) the End of Life (EoL) recycling rate for niobium, chiefly as a constituent of ferrous (e.g. steel) scrap, is greater than 50 % (UNEP, 2013). However, the amount of niobium physically recovered from scrap (i.e. functional recycling) is negligible, with estimates by BIO by Deloitte given at less than 1 %, i.e. 0.3% (BIO Intelligence Service, 2015).

16.2.3 EU trade

Niobium is not traded in the form of ores and concentrates, but rather processed materials such as ferroniobium or niobium metal. According to BIO Intelligence Service, ferroniobium is not produced in the EU (BIO Intelligence Service, 2015), meaning the EU is entirely reliant on imports for its supply, with an average net import figure of about 13,300 tonnes per annum during the period 2010–2014.

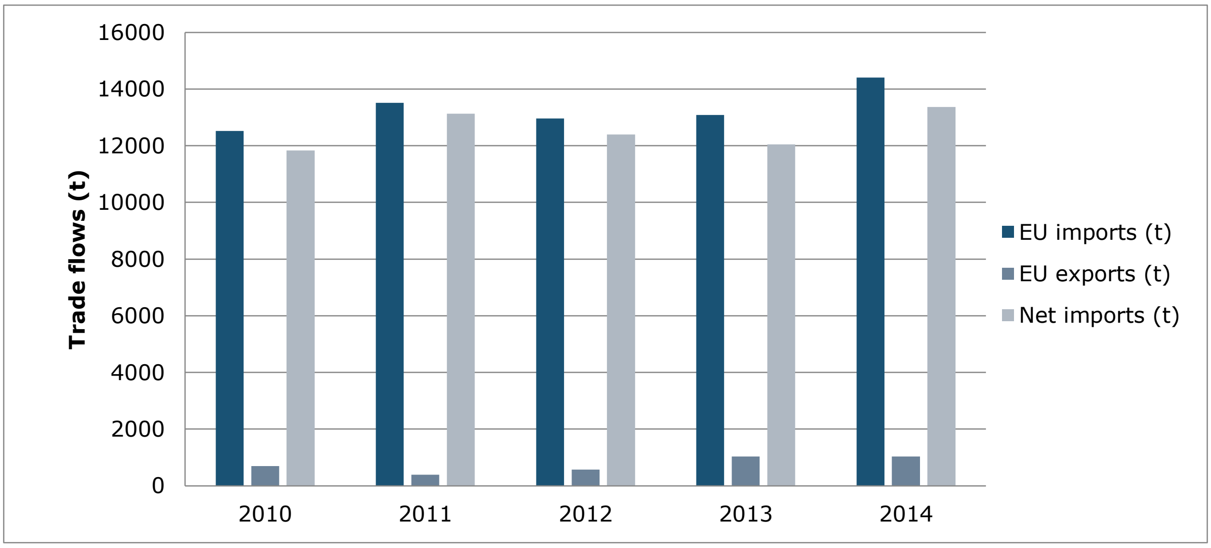

Figure 122: EU trade flows for ferroniobium (Data from COMEXT database Eurostat, 2016a)

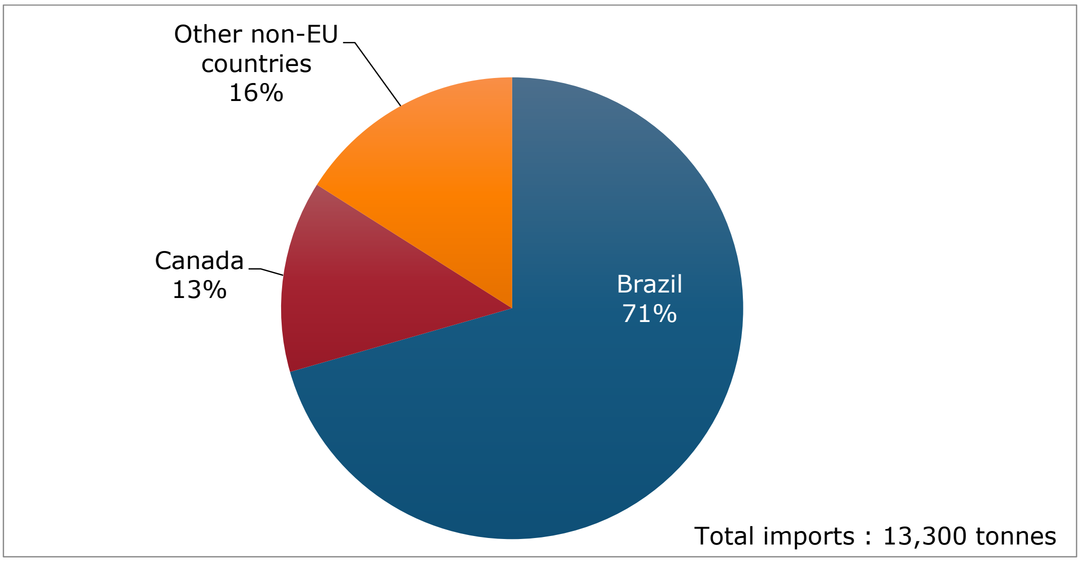

Figure 123: EU imports of ferroniobium, average 2010-2014 (Data from COMEXT database - Eurostat, 2016a)

Figure 122 shows that imports to the EU have fluctuated slightly during the 2010–2014 period, with a gently increasing trend observed since 2012. These increases are in line with increased exports of ferroniobium from Canada to the EU. Exports of ferroniobium from the EU to the rest of the world have been gradually increasing since 2011 (Figure 122). Almost 84 % of all EU imports of ferroniobium come from only two countries, namely Brazil (71 %) and Canada (13 %) (Figure 123).

16.2.4 EU supply chain

Primary niobium ores and concentrates are not mined in the EU, nor are they traded with the EU. Ferroniobium is not produced in the EU, meaning the EU is entirely reliant on ferroniobium imports to meet demand. However, specialist niobium-based alloys (e.g. superalloys) and chemicals (e.g. lithium niobate) are manufactured in Europe, although it is difficult to quantify how much (BIO by Deloitte, 2015; Beta Technology *pers. comm.,* 2016). NPM Silmet (Estonia) is a significant European niobium producer. Ferroniobium is primarily used in the production of HSLA steels, with the majority (about 11,000 tonnes) of EU imports going to only nine countries, namely Austria, Belgium, Germany, France, Finland, Italy, Spain, Sweden and the United Kingdom. The relatively large proportion of imports to these countries is in generally line with their steel output e.g. Germany is the largest steel producer in Europe (IISI, 2016) and therefore accounts for the greatest share of ferroniobium imports.

There are currently no export quotas placed on ferroniobium exported to the EU from other countries; however, ferroniobium exports from China entering the EU are subject to an export tax of between 25 and 75 %. The amount of material entering the EU from China is very small (OECD, 2016).

16.3 Demand

16.3.1 EU consumption

Consumption of ferroniobium in the EU was about 12,500 tonnes per year during the period 2010–2014. None of this came from within the EU. Therefore it is hardly surprising that the estimated import reliance is as high as 100 %.

16.3.2 Applications/end-uses

Global end-uses of niobium are shown in Figure 124 and relevant industry sectors are described using the NACE sector codes in Table 70.

About 86 % of niobium (in the form of ferroniobium) is used in the production of HSLA steels. Niobium is an important additive in steel for two reasons: (1) it increases strength by refining the microstructure and by forming nano-particle; and (2) the strength increases it gives allow weight savings in the final product. For example, adding 300 grams of niobium to the steel of a medium-sized car reduces the weight of the vehicle by 200 kilograms (CBMM, 2016). Other applications in which the increased strength of HSLA steel is desirable, include pipelines, ship hulls and railway tracks. For example, gas pipelines made from steel containing about 0.11% niobium, have thinner walls, wider diameters and can operate at higher pressures (CBMM, 2016).

Niobium-bearing alloys account for about 8 % of global niobium consumption. These alloys may contain significant quantities of niobium and are typically used in high-performance, or specialised applications where traits such as corrosion resistance and high-strength at high operating temperatures are sought. For example, alloys such as C-129Y (79% niobium; 10% tungsten; 10% hafnium and 0.1% yttrium) and C-3009 (61% niobium; 30% hafnium and 9% tungsten) can operate at temperatures of up to 1,650°C. These alloys are used in the nuclear industry (e.g. reactor parts) and space industry (e.g. rocket thruster nozzles) (Wikipedia, 2016a). Other alloys of niobium include niobium-titanium and niobium-tin alloys, which are used to manufacture the superconducting magnets fund in MRI (Magnetic Resonance Imaging) scanners (BGS, 2011).

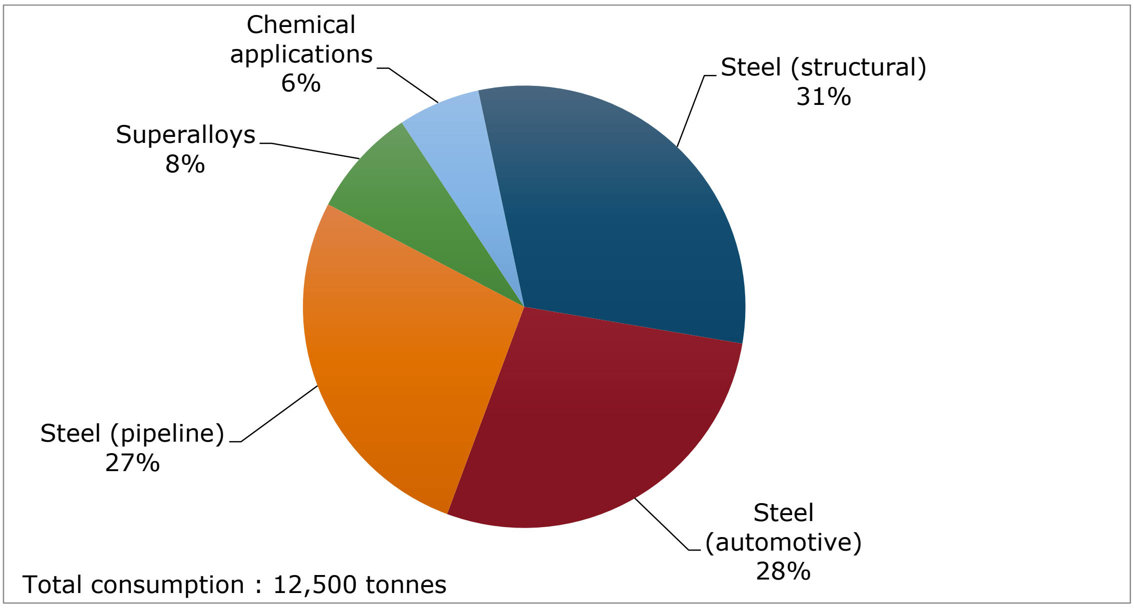

Figure 124: Global end uses of niobium. Figures for 2014 (Data from EC, 2014)

Table 70: Niobium applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016c)

Application	2-digit NACE sector	Value added of NACE 2 sector (millions €)	4-digit NACE sector
Steel (structural)	C25 - Manufacture of fabricated metal products, except machinery and equipment	159,513	C2511 Manufacture of metal structures and parts of structures
Steel (automotive)	C29 - Manufacture of motor vehicles, trailers and semi-trailers	158,081	C2910 Manufacture of motor vehicles
Steel (pipeline)	C24 - Manufacture of basic metals	57,000	C2420 Manufacture of tubes, pipes, hollow profiles and related fittings, of steel
Superalloys	C30 - Manufacture of other transport equipment	53,644	C3030 Manufacture of air and spacecraft and related machinery
Chemicals	C20 - Manufacture of chemicals and chemical products	110,000	C2059 Manufacture of other chemical products n.e.c.

The production of niobium-based compounds accounts for about 6 % of global niobium consumption. Many of these compounds have unique optical, piezoelectric (i.e. the ability to generate an electric charge in response to mechanical stress) and pyroelectric (i.e. the ability to generate an electric charge in response to heating or cooling) properties that are sought after in several high-technology applications. For example, high-purity niobium oxide is used in the production of high-refractive index glass used in the manufacture of camera lenses. Compounds such as lithium niobate are used in the production of capacitors and surface acoustic wave filters, which are used in the manufacture of mobile phones and other touch screen devices. Niobium nitride is also used in the production of superconducting magnets found inside MRI scanners (TANB, 2016).

Another important use of niobium is in the production of niobium carbides. These are extremely-hard, ceramic substances which are produced by sintering niobium powder with carbon at high-temperature. They are resistant to wear and high-temperature and are therefore used to produce hard cutting tools (e.g. industrial high-speed cutting tools) and refractory coatings that are used in nuclear reactors and industrial furnaces (BGS, 2011).

16.3.3 Prices

Ferroniobium is not openly traded on any metal exchange; contract prices are negotiated between buyer and seller and generally remain confidential (BGS, 2011). According to figures published in the CRM_InnoNet niobium profile prices were in the order of US$40 per kilogram in 2015 (CRM_InnoNet, 2015). Prices of chromium depends greatly on its forms: chromite, ferrochromium, or metal. According to the DERA raw materials price monitor and the LMB Bulletin, all niobium prices have decreased of more than 40% since 2015 compared to the period 2011-2015:

- Niobium concentrates (min 50% Nb_2O_5) costs 35.6 US$/kg in average on the period 2011-2015 but only 20.8 US$/kg in average on the period December 2015 - November 2016, i.e. a price drop of 41.7%.
- Niobium pentaoxide (min 99.5%) costs 249.3 US$/kg in average on the period 2011-2015 but only 26.7 US$/kg in average on the period December 2015 - November 2016, i.e. a price drop of 45.9%.

16.4 Substitution

Published information (e.g. CRM_InnoNet) suggests that metals such as vanadium, molybdenum, tantalum and titanium may substitute for niobium in the production of HSLA steel and superalloys. However, assuming 1:1 substitution in alloys is overly simplistic, for the simple reason that the properties of a given alloy are not controlled by a single metal, but rather by several metals. In addition each metal may produce a range of effects in the alloy. For example, niobium is used in combination with small amounts of several other metals, including, but not limited to chromium, nickel, copper, vanadium, molybdenum, titanium, calcium, rare earth elements and zirconium, in the production of HSLA steel. The interaction between these additions is complex, but they can be used to modify properties such as strength, toughness, corrosion resistance and formability (Beta Technology *pers. comm.* 2016; Wikipedia, 2016b). Therefore it cannot be reasonably assumed that the increased addition of one of these metals in the absence of niobium would produce a steel with the same properties.

Any substitution would be associated with a price and/or performance penalty. In general there appears to be little economic or technical incentive to substitute niobium in its principal applications.

16.5 Discussion of the criticality assessment

16.5.1 Data sources

Production data for ferroniobium was based on trade data from the UN Comtrade database, assuming that Brazilian and Canadian exports account for about 95 % of global production (Beta Technology *pers. comm.,* 2016). EU trade data were taken from the Eurostat COMEXT online database (Eurostat, 2016a) using the Combined Nomenclature (CN) code 7209 9300 (ferroniobium). Data were averaged over the five-year period 2010–2014 inclusive. Other data sources used in the assessment are listed in section 16.7.

16.5.2 Calculation of economic importance and supply risk indicators

The calculation of Economic Importance (EI) was based on the 2-digit NACE sectors shown in Table 71. For information about the application share of each sector see section on applications and end-uses. Figures for value added were the most recently available at the time of the assessment (i.e. 2013) and are expressed in thousands of Euros.

The Supply Risk (SR) was calculated at the refined stage of the life cycle using both the global HHI and EU-28 HHI calculation as outlined in the methodology.

16.5.3 Comparison with previous EU criticality assessments

A revised methodology was introduced in the 2017 assessment of critical raw materials in Europe and both the calculations of economic importance and supply risk are now different; therefore the results with the previous assessments are not directly comparable. The results of this review and earlier assessments are shown in Table 71.

Table 71: Economic importance and supply risk results for niobium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017.

Assessment	2011		2014		2017	
Indicator	EI	SR	EI	SR	EI	SR
Niobium	8.95	2.80	5.87	2.46	4.8	3.1

Although it appears that the economic importance of antimony has reduced between 2014 and 2017 this is a false impression created by the change in methodology. The value added in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a 'megasector', which was used in the previous assessments. The economic importance figure is therefore reduced. The supply risk score is higher compared to the previous assessments, which is due to the revised methodology and the way the supply risk is calculated. Therefore, differences between the assessments are largely due to changes in methodology (as outlined above) and the form of the commodity that has been assessed, that is the most recent assessment was based on the production and trade of ferroniobium rather than the extraction and trade of niobium ores and concentrates as was done on previous EC criticality assessments.

16.6 Other considerations

The use of ferroniobium in the production of HSLA steel means that future demand is likely to be driven by the construction and automotive sectors, particularly in rapidly developing countries such as China and India. Ferroniobium production is likely to remain concentrated in Brazil; however, the Araxá niobium deposit, owned by CBMM, has a history of increasing production to meet long-term market demand (Linnen, Trueman and Burt, 2014). Global resources of niobium are large, therefore significant potential exists for supply to become diversified if advanced projects (Table 68) in other parts of the world come to fruition.

Table 72: Qualitative forecast of supply and demand of niobium

Material	Criticality of the material in 2017		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Niobium	x		+	+	+	+	+	+

16.7 Data sources

16.7.1 Data sources used in the factsheet

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17. PLATINUM-GROUP METALS (PGM)

Key facts and figures

Material names and element symbols	platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir), osmium (Os)	World/EU production (tonnes)[1]	World production: 452 EU production: 2
Parent group (where applicable)	Platinum-Group Metals (PGM)	EU import reliance (%)	See individual PGM factsheets
Life cycle stage/ materials assessed	Processing/ refined metals	Substitution index for supply risk [SI(SR)]	See individual PGM factsheets
Economic importance EI (2017)	5.0	Substitution Index for economic importance [SI(EI)]	See individual PGM factsheets
Supply risk SR (2017)	2.5	End of life recycling input rate (EOL-RIR)	See individual PGM factsheets
Abiotic or biotic	Abiotic	Major end uses in the EU	Autocatalysts, jewellery, chemical manufacture, electrical *(see individual PGM factsheets for quantitative information)*
Main product, co-product or by-product	Main products or by-product of nickel mining	Major world producers	South Africa, Russia, Zimbabwe, Canada *(see individual PGM factsheets for quantitative information)*

[1] Average for 2010–2014, unless otherwise stated.

17.1 Introduction

The platinum-group metals (PGM), sometimes referred to as the platinum-group elements (PGE), are (in order of increasing atomic number): ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). These metals are very rare in the Earth's continental crust with abundances in the range 1-5 parts per billion (ppb). They tend to be found together, commonly associated with ores of nickel and copper. The PGM occur in numerous alloys, in base metal sulfide minerals and in a wide variety of PGM-bearing minerals with, among others, sulphur, arsenic, antimony and tellurium. They rarely occur in native form. The PGM are highly resistant to wear, tarnish, chemical attack and high temperature. The PGM are regarded as precious metals, like gold and silver. All PGM, commonly in combination with one another or with other metals, can act as catalysts which are exploited in a wide range of applications. Platinum and palladium are of major commercial significance, with rhodium the next most important. The main use of PGM is in autocatalysts, but other major applications include jewellery, chemical manufacture, petroleum refining and electrical products.

The 6 PGM are generally derived from the same types of ore deposit in which they occur together, commonly in the same mineral phases. For this reason they are classed as co-products, because they have to be mined together. In practice, one or other of the individual PGM, normally platinum or palladium, is the main economic driver supporting the extractive operations while the other PGM are by-products that make a minor revenue contribution.

Almost all PGM derived from primary source materials (i.e. mine production) is traded in the form of refined metal produced from integrated mining/metallurgical operations. There is only very limited international trade in PGM ores and concentrates.

This factsheet deals mostly with the PGM as a group of metals that occur together in nature. However, given the greater commercial importance of platinum and palladium, there is generally much more information available on platinum and palladium than there is for rhodium, ruthenium and iridium. Osmium is a little used, toxic metal for which there is virtually no quantitative data on any part of its value chain. For this reason it is not possible to carry out a quantitative criticality assessment using the methodology employed in the 2017 criticality assessment. For further information on individual PGM and their criticality assessment please refer to the factsheets for platinum, palladium, rhodium, ruthenium and iridium.

17.2 Supply

17.2.1 Supply from primary materials

17.2.1.1 Geological occurrence

The majority of global PGM resources and reserves are found in two deposit classes: the PGM-dominant class and the nickel-copper sulfide class. The PGM-dominant class has platinum as the main economic product, generally with lesser amounts of palladium and rhodium production. Associated nickel and copper are present in minor quantities that contribute less to the deposit value. Two types of PGM-dominant ores account for the majority of platinum production, the Merensky Reef type and the chromitite reef type, both of which are best developed in the Bushveld Igneous Complex in South Africa (Gunn, 2014). The Merensky Reef type comprises extensive, laterally continuous, thin layers (termed ‘reefs’) in large layered mafic-ultramafic intrusions. Ore grades in the Merensky Reef in the Bushveld Igneous Complex are typically 5-7 g/t Pt+Pd, with Pt/Pd ratio of about 3. Similar deposits are mined in the Great Dyke in Zimbabwe and in the

Stillwater Complex in USA. The chromitite reef type has a similar morphology to the Merensky Reef comprising thin continuous layers of massive chromite with sparse base metal sulfides. Grades are typically in the range 4-8 g/t Pt+Pd, with Pt/Pd ratio value of about 2.5. The most important development of this type of mineralisation is in the UG2 chromitite in the Bushveld Igneous Complex, which is the largest repository of known platinum resources in the world. A third type of Pt-Pd-bearing mineralisation, which is gaining in economic importance, is known as contact type. This is best developed on the northern limb, known as the Platreef, of the Bushveld Igneous Complex, although other deposits assigned to this class are also found in Canada, USA and Finland (Viljoen, 2016; Gunn, 2014).

The nickel-copper sulfide deposits are found in various geological settings related to a range of igneous processes. The Norilsk-Talnakh district of the Taimyr Peninsula in Russia is the most important: it is the world's largest producer of nickel and, as some of the ores are very rich in PGM, it is the world's largest palladium producer and second largest platinum producer. PGM grades fall in the range 1-10 g/t Pt+Pd, with a Pt/Pd ratio value less than one. The resource in the region has been estimated at more than 1.3 billion tonnes of ore averaging 1.77% Ni, 3.57% Cu, 0.06% Co, 1.84 g/t Pt and 7.31 g/t Pd (Naldrett, 2004). Economically important resources of PGM in magmatic nickel-copper sulfide deposits are found in the Sudbury district of Canada, the Kambalda area of Western Australia, the Pechenga district of Russia and at the Jinchuan deposit in China (Gunn, 2014).

The other PGM (rhodium, ruthenium, iridium and osmium) are generally present in platinum-palladium ores in very small amounts, rarely exceeding a few per cent of the total PGM content. However, the proportion of iridium, rhodium and ruthenium in the UG2 chromitite is significantly greater than in the Merensky Reef. Consequently, as mining of the UG2 has increased markedly in recent decades, so the potential availability of these PGM has increased.

17.2.1.2 Mining

The method used to mine PGM-bearing deposits depends on their size, grade, depth and morphology and the value of any co-products. Underground extraction uses a variety of standard mining methods depending on the characteristics of the orebody. The deepest currently operating platinum mines are located in South Africa, where mining takes place at a maximum depth of 2.2 km in the Zondereinde mine on the western limb of the Bushveld Igneous Complex. Typically these operations use labour-intensive drilling and blasting techniques, though attempts are being made to introduce more mechanisation into the workplace. Underground mining is also employed in the Norilsk-Talnakh mines in Russia and at several sites in Zimbabwe, Canada and USA. Opencast and underground mining are sometimes combined at a single mine, and may take place simultaneously in order to access shallow and deeper parts of an ore body e.g. Kroondal and Marikana mines, western Bushveld Complex (Buchholz and Foya, 2015).

Surface mines are generally cheaper and safer to operate than underground mines. Open-pit mining is most appropriate for near-surface (<100 m), lower-grade, steeply dipping or massive ore bodies where large-scale surface excavations would not cause significant environmental impact. This method typically involves removing the overburden, digging the ore or blasting with explosives, then removing the ore by truck or conveyor belt for stockpiling prior to further processing. Examples of surface mining operations for PGM include the Mogalakwena operation in South Africa and the Lac des Iles mine in Canada.

17.2.1.3 Beneficiation

The grades of the mined ores from the Bushveld Igneous Complex, the world's chief source of platinum, are generally in the range 4-8 g/t of combined Pt+Pd. After mining the ores are processed to increase their PGM content. Concentration is normally carried out at, or close to, the mine site and involves crushing the ore and separating PGM-bearing and gangue minerals, using a range of physical and chemical processes. Subsequent smelting and refining may be carried out at or near the mine, or concentrate may be transported to a centralised facility for processing to metal.

Crushing, followed by fine grinding, also known as milling, is used to maximise separation of the ore minerals from the gangue. The crushed ore is mixed with water to create a slurry which is fed into a series of grinders until a powder of the required grain size is produced. Following milling, additional water is added to the powdered ore to produce a suspension and air is blown upwards through the tanks. Chemicals are added to the mix, making some minerals water-repellent and causing air bubbles to stick to their surfaces. Consequently, these minerals collect in froth at the surface and are removed as a metal concentrate. This process is known as froth flotation.

17.2.1.4 Smelting and refining

Following flotation, the final concentrate, which has Pt+Pd content between 100 and 1000 g/t, is dried. The dried concentrate is smelted in an electric furnace at temperatures exceeding 1300°C. The PGM and base-metal sulphides accumulate in a matte, while the unwanted minerals form a slag that is discarded (Jones, 2005). Once the matte has been tapped from the smelter, the liquid metal undergoes a process known as converting. This involves blowing air, or oxygen, into the matte to oxidise contained iron and sulphur. Silica is added to the matte to react with the oxidised iron to form a slag that can be easily removed, while the sulphur is collected from the offgas to produce sulphuric acid. The converter matte consists of copper and nickel sulphide with smaller quantities of iron sulphides, cobalt and PGM. This is usually cast into ingots and is then sent to the base metal treatment plant.

Refining to produce high-purity PGM products is a very lengthy and complicated process (Crundwell et al., 2011). The methods involved differ from company to company and for commercial reasons the techniques used are closely guarded secrets. Initially, the matte is transferred to the base metal refinery for base metal removal. The PGM-bearing residue from the base metal refinery, containing over 60 % PGM, is transferred to the precious metal refinery for separation and purification of the PGM. All commonly used refining processes separate and produce individual PGM by utilising differences in their chemistry. Refining is achieved either through a series of dissolution and precipitation stages involving PGM salts, or by using a technique known as total leaching, which is followed by sequential metal separation with the aid of solvent extraction

PGM-bearing nickel-copper-sulfide-dominant ores, such as those from Russia and Canada, are treated somewhat differently to PGM-dominant ores from South Africa due to their higher sulphide content and different mineralogy (Gunn, 2014). In many operations the PGM are extracted as a by-product of nickel, copper and cobalt production. The metallurgical process is therefore designed around the main product, normally nickel, whilst maximising PGM recoveries.

The PGM mining sector is integrated from mining to refining. The top four PGM producers (Anglo Platinum, Norilsk, Impala and Lonmin) account for approximately 80 % of the market and maintain considerable processing assets that supply the market with refined PGM and by-products (Ndlovu, 2015).

17.2.1.5 Exploration

During the Minerals4EU project it was identified that in 2013 PGM exploration in Europe took place in Greenland, Sweden, Portugal and UK. However, exploration may have taken place in other EU countries where no information was provided during the survey (Minerals4EU, 2015).

17.2.1.6 Resources and reserves of PGM

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of PGM in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[16], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for PGM. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for PGM, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for PGM at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

It is difficult to obtain reliable global resource and reserve estimates for the PGM as a group or for individual members of the group such as platinum. This is because of the variability between reporting standards used, the fact that the PGM may be aggregated (Pt+Pd+Rh or Pt+Pd+Rh+Au) and because of the dynamic nature of resources and reserves which are subject to continual revision as exploration and mining proceed and market conditions change. Furthermore the terms reserves and resources are often confused and used incorrectly, thus making compilations on national or regional scales very difficult.

The USGS (2016) estimates global PGM resources to be in excess of 100,000 tonnes contained metal. Mudd (2012) summarised global PGM mineral resources in a detailed study of publicly available data for 2010. He derived a total figure of 90,732 tonnes of PGM (4E i.e. Pt+Pd+Rh+Au). Approximately 70 % of the total PGM resource was located in South Africa. Mudd (2016) revised his global estimate of PGM resources to 100,464 tonnes of PGM. BRGM (2014) compiled company data for 2012 and estimated global resources of PGM as 93,530 tonnes of which 71 % was located in South Africa.

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[16] www.crirsco.com

Resource data for some countries in Europe are available in the Minerals4EU website (see Table 73) (Minerals4EU, 2014) but cannot be summed as they are partial and they do not use the same reporting code.

Table 73: Resource data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2014)

Country	Reporting code	PGM	Quantity	Unit	Grade	Code Resource Type
Greenland	JORC	Pt	5.08	Mt	0.06 g/t	Indicated
Sweden	Historic	Pd	0.2	Mt	0.4 g/t	Historic Resource Estimates
Finland	NI 43-101	Pd	145	Mt	0.47 g/t	Measured
	JORC	Pd	15	Mt	1.3 g/t	Indicated
	NI 43-101	Pt	145	Mt	0.22 g/t	Measured
	JORC	Pt	15	Mt	0.39 g/t	Indicated
	None	Rh	8.5	Mt	0.092 g/t	Historic Resource Estimates

Reserves of PGM are estimated at 66,000 tonnes by the USGS (2016), with over 95 % located in South Africa (Table 74). However, figures from Norilsk Nickel (2015) estimate that proven and probable reserves of PGM in the Norilsk-Talnakh district and the Kola Peninsula in Russia are 12,100 tonnes, which is considerably greater than the USGS estimate of 1,100 tonnes for Russia. BRGM (2014) estimated a global PGM reserve of 14,582 tonnes based on company data for 2012. About 70 % of the reserve was located in South Africa. The Minerals4EU website reports only reserve data in EU for Finland (NI43-101), with proven reserves of Pt and Pd of respectively 75 Mt at 0.22 g/t and 75 Mt at 0.16 g/t (Minerals4EU, 2014).

Table 74: World reserves of PGM (data from USGS, 2016)

Country	PGM Reserves (tonnes)
South Africa	63,000
Russia	1,100#
Zimbabwe	*
Canada	310
USA	900
Other countries	800
Total	*66,110*

*Zimbabwe PGM reserves included in ‘Other countries’

Norilsk (2015) reports much larger resources for PGM in Russia

17.2.1.7 World mine production

PGM mine production for 2014 is summarised in Table 75. Global supply of platinum is dominated by South Africa with about 64 % of total mine production from several mines, most underground, on the Bushveld Igneous Complex. South Africa is also the dominant supplier of the ‘minor’ PGM, rhodium, ruthenium, iridium and osmium.

Three companies dominate PGM mining in South Africa: Anglo American Platinum, Impala Platinum and Lonmin. Each of these runs integrated operations in South Africa, from mining through concentration and smelting to refining. South African production of platinum has fallen considerably in recent years due to the combined effects of the global economic recession and local issues related to labour unrest and escalating costs in South Africa.

Global supply of palladium is dominated by Russia, with about 44 % of total production in 2014. The majority of this is derived from underground mines working nickel sulfide ores in the Norilsk-Talnakh district. Other significant palladium producers are South Africa, Canada, Zimbabwe and USA.

Table 75: World mine production and supply of PGM from recycling in 2014 (mine production data from BGS World Mineral Statistics database; recycling data from Johnson Matthey, 2015)

Country	**Platinum**		**Palladium**		**Other PGM (Rh, Ru, Ir, Os)**	
	Tonnes	Proportion (%)	Tonnes	Proportion (%)	Tonnes	Proportion (%)
South Africa	93.99	64.13	58.41	31.95	36.04	81.96
Russia	22.00	15.01	81.30	44.46	2.80	6.37
Zimbabwe	12.48	8.52	10.14	5.54	2.80	6.37
Canada	10.70	7.30	18.70	10.23	1.20	2.73
USA	3.65	2.49	12.20	6.67	0.00	0.00
China	1.40	0.96	0.70	0.38	0.00	0.00
Colombia	1.13	0.77	0.00	0.00	1.13	2.58
Finland	1.06	0.72	0.81	0.44	0.00	0.00
Botswana	0.09	0.06	0.56	0.31	0.00	0.00
Poland	0.06	0.04	0.03	0.02	0.00	0.00
World total (mine production)	**146.57**		**182.8**		**43.98**	
Recycling (supply from secondary materials)*	**64.4**		**85.6**		**9.6**	
Total Supply	**210.97**		**268.4**		**53.58**	

*Excluding closed loop recycling

17.2.2 Supply from secondary materials

The supply of PGM from secondary materials is well established and has been growing strongly in recent years (Figure 125). Globally in 2014 29.9 % of the total supply of Pt+Pd+Rh was from recycling compared with 7.5 % in 2004. On account of the high value of PGM and the availability of the infrastructure to support recycling, including collection, separation, disaggregation and metallurgical capacity, secondary PGM are a major source of supply in Europe. Recycling of automotive catalysts is the most important contributor to secondary supply, especially as, using state-of-the art recycling technologies, 95 per cent of the PGM content of spent autocatalysts can now be recovered during the refining process (IPA, 2015). Automotive catalysts represent the main source of secondary material in the EU. Besides autocatalysts other materials from end-of-life products, notably jewellery and electronic scrap, are used as feedstock to PGM recycling processes. Production of post-consumer PGM from functional recycling in EU has been estimated at around 25.6 tonnes of PGM (Pt+Pd+Rh) (BIO Intelligence Service, 2015).

Recycling of process catalysts from the chemicals industry and of PGM equipment used in the glass industry are also important sources of secondary PGM. This recycling follows a closed-loop system whereby the industry owns the PGM used in its processes. New metal supply is only required to cover small life cycle losses and increased demand from market growth and new applications. End-of-life recycling rates in these applications are well over 80 % (Hagelüken, 2014).

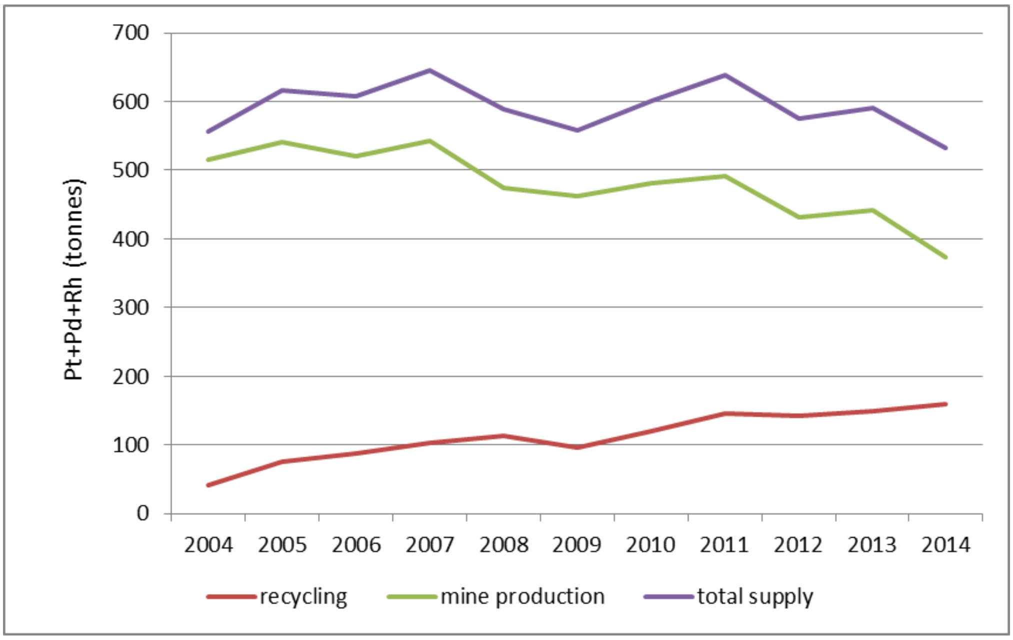

Figure 125: Global supply of PGM (Pt+Pd+Rh) from recycling and mine production, 2004–2014 (source of data: Johnson Matthey, 2016a and Johnson Matthey Market Data tables)

End-of-life products, such as automotive catalysts, jewellery scrap and electronic equipment, all rich in PGM, are consumer items and, as such, they may or may not enter the recycling stage. This forms an 'open loop' system and its efficiency is governed by many parameters including consumer behaviour, implementation of relevant policy, and collection and pre-treatment practices. In an open loop system, losses of PGM tend to be higher than in a closed loop and recycling rates are correspondingly lower, estimated to be 50–60 % for autocatalysts and 5–10 %.

Another source of PGM, and other precious metals, are industrial by-products of the non-ferrous metals mining, processing and manufacturing industries. These include various intermediate products and residues such as complex mining concentrates, slags, mattes, flue dust, ash, slimes and production waste from the electronics, glass, jewellery and chemical industries. At its Hoboken plant in Belgium, where these materials are processed for their content of valuable metals, Umicore has a production capacity for platinum, palladium and rhodium of 25, 25 and 5 tonnes per annum, respectively, in the form of high purity powder (minimum 99.95%), known as sponge. Ruthenium is also available as a powder with a minimum purity of 99.9% (Umicore, 2016). Umicore's precious metal recovery now focusses chiefly on recyclable materials and industrial by products rather than on metal concentrates.

17.2.3 The supply chain in EU

A small amount of primary production of PGM takes place in Europe (Finland and Poland in Table 75). The Kevitsa nickel-copper mine in northern Finland is producing PGM (platinum and palladium) as a by-product of Ni and Cu production. In 2015 approximately 1 tonne of platinum and 0.8 tonnes of palladium were produced at Kevitsa

(Boliden, 2016). KGHM in Poland produces PGM (about 0.1 tonnes of platinum and palladium per annum) from residual slimes derived from its electrolytic copper refining (KGHM, 2015).

PGM are supplied to the European markets in many different forms. Ores and concentrates of PGM are not a widely traded commodity. The PGM are generally traded as unwrought metal, in fine powders, in semi-manufactured forms such as ingots, wire and mesh, and as base metals containing PGM (Figure 126). They are also supplied in various intermediate products, components and final products (e.g. catalysts, jewellery).

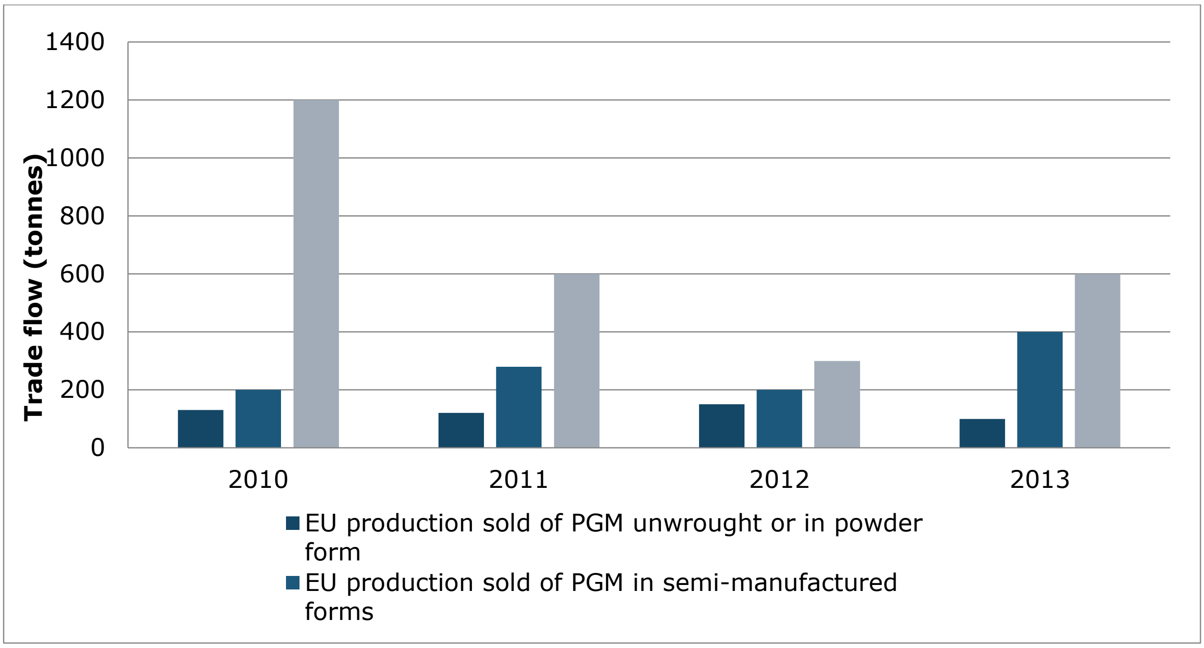

Figure 126: Production sold of PGM in various forms in EU28 (excluding waste and scrap) (Data from Eurostat Prodcom database, using Prodcom codes 24413030, 24413050 and 24413070)

The global PGM fabrication sector is dominated by five companies (Johnson Matthey, BASF, Umicore, Heraeus and Tanaka) that account for approximately 85 % of the market (Ndlovu, 2015). Four of these have a strong presence in Europe with PGM finding use mainly in the production of autocatalysts. These companies run large integrated operations with most deriving their supplies from a combination of primary (mine) and secondary (refinery) sources. They deliver a diverse range of PGM-bearing materials and products to the market from specialised plants located in different parts of the world, including Europe.

17.2.4 EU trade

Since 2010 some substantial changes in the physical trade flows of PGM are apparent (Figure 127). In 2010 and 2011 imports of PGM from extra-EU28 countries outweighed exports and EU was a net importer. A significant drop in the EU PGM imports in 2012 changed this balance and EU was a net exporter in 2012 and 2014 with a small net import value in 2013. Overall exports of PGM have remained relatively stable over the 5 year period with a slight increase in 2014. In contrast, imports of PGM dropped by approximately 59 % between 2010 and 2014. The reason for this drop is not known for this review. The PGM imports from 2012 onwards have returned to pre-2010 levels.

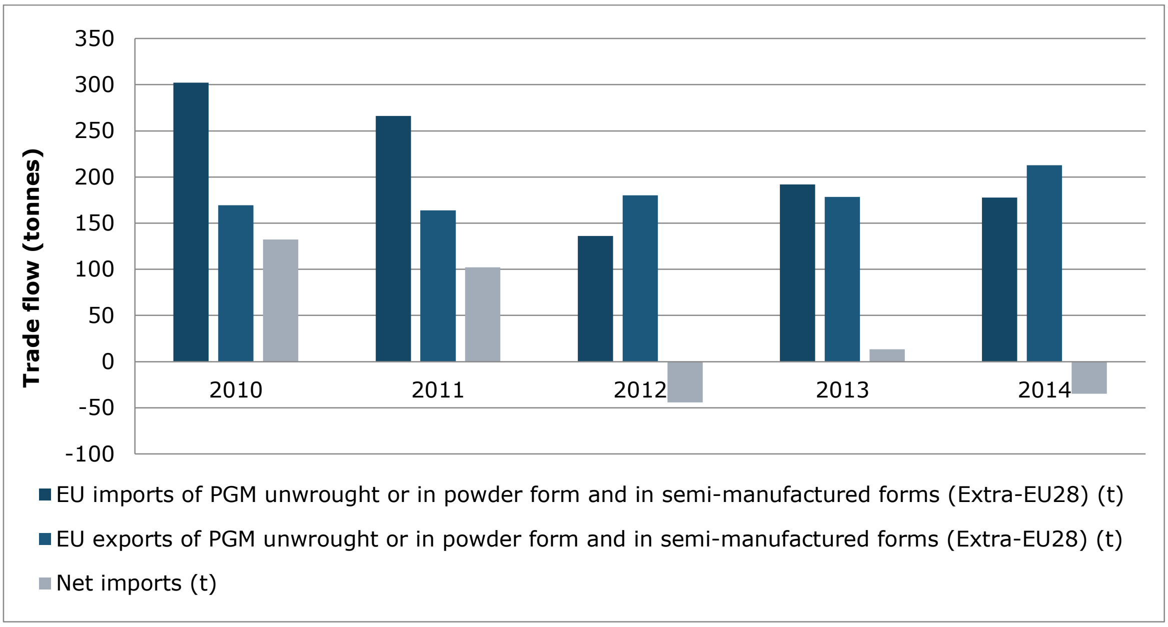

Figure 127: Trade flows between the EU member States and non-EU countries 2010–2014 for PGM in unwrought, powder and semi-manufactured form (Data from Eurostat Comext database on International trade)

Switzerland, South Africa, the United States and Russia are the chief suppliers of PGM to Europe (Figure 128). The import shares from these countries have remained relatively stable over the years with only 2012 figures showing lower imports to the EU from Switzerland and South Africa and 2011 figures showing higher imports from the United States. EU imports twice as much PGM in unwrought or powder form as in semi-manufactured forms. Switzerland has traditionally been a central point of PGM storage and distribution by producers, traders and bankers and has significant precious metal refining capacity. Major platinum and palladium exchange-traded funds, which are based on physical holdings of these metals, are also located in Switzerland. The import share shown in Figure 128 is, therefore, not unexpected.

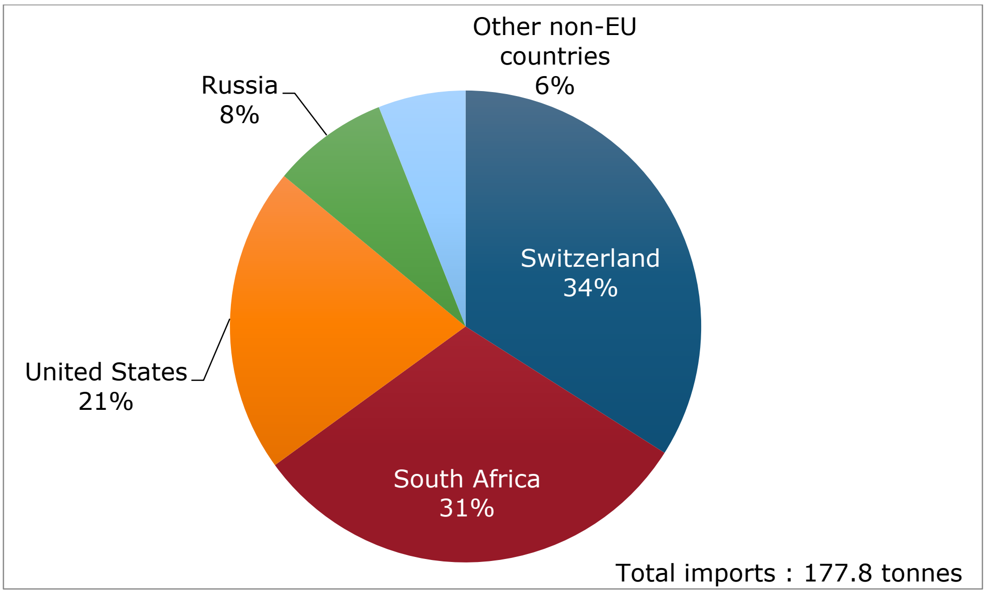

Figure 128: Sources of EU imports in 2014 for PGM in unwrought, powder and semi-manufactured form (data from Comext database - Eurostat, 2016a)

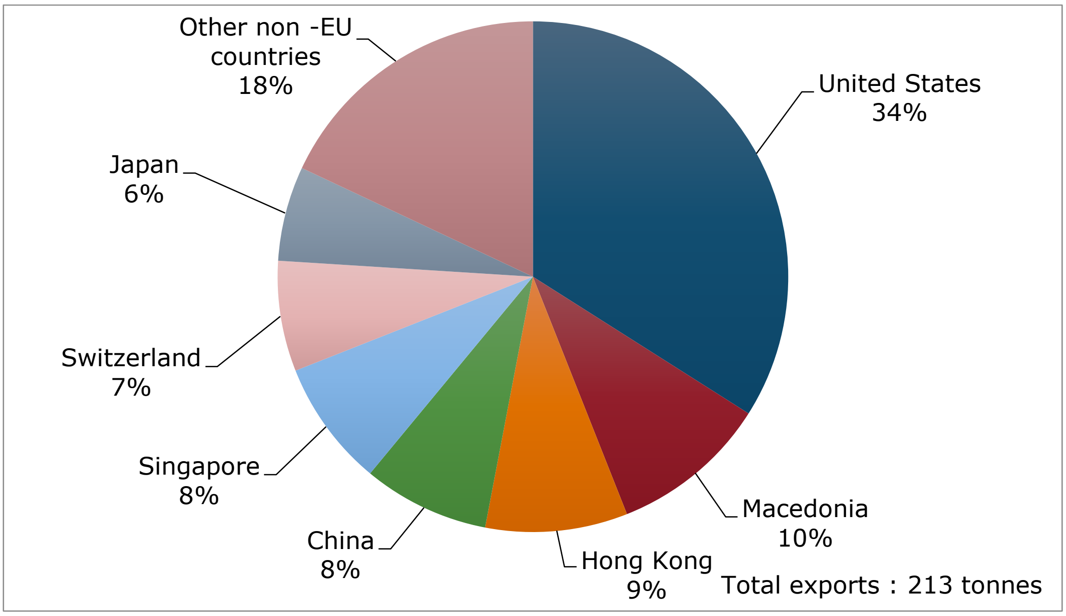

Figure 129: Destinations of EU exports in 2014 of PGM in unwrought, powder and semi-manufactured form (data from Comext database (Eurostat, 2016a))

The United States is the most important destination for PGM exports from the EU (Figure 129) in 2014, as it was in previous years. Other countries with substantial shares of PGM exports from the EU include the Former Yugoslav Republic of Macedonia, Hong Kong and China.

Another important form of PGM traded between EU and extra-EU28 countries is waste and scrap. Data on traded physical flows of waste and scrap is available for platinum only and is presented in the Platinum Factsheet.

17.3 Demand

17.3.1 Applications

The main uses of PGM are in catalysts for the automotive and chemical industries and in electronic/electrical applications. Other important uses include jewellery and investment. However, given the different properties of each PGM many applications are specific to individual members of the group. The main application sectors for platinum and palladium in the world and in Europe are summarised in Table 75. Further quantitative information on PGM demand is given in the separate factsheets for the individual PGM.

Table 3. Platinum and palladium demand, world and Europe, in 2015 (data from Johnson Matthey, 2016a)

	Platinum (tonnes)			
	World	Share (%)	Europe	Share (%)
Autocatalyst	106.7	40.6	51.5	79.6
Chemical	16.5	6.3	3.3	5.1
Electrical	7.2	2.7	0.4	0.6
Glass	6.9	2.6	0.3	0.5
Investment	14.1	5.4	-2.7	-4.2
Jewellery	87.9	33.4	6.3	9.7
Medical and Biomedical	6.5	2.5	2.1	3.2
Petroleum	4	1.5	-0.1	-0.2
Other	13.3	5.1	3.6	5.6
TOTAL Gross Demand	**263.1**		**64.7**	

	Palladium (tonnes)			
	World	Share (%)	Europe	Share (%)
Autocatalyst	237.3	81.7	50.5	91.8
Chemical	18.6	6.4	2.7	4.9
Dental	14.8	5.1	2.2	4.0
Electrical	29.6	10.2	3.2	5.8
Investment	-20.5	-7.1	-6.2	-11.3
Jewellery	7.1	2.4	1.8	3.3
Other	3.5	1.2	0.8	1.5
TOTAL Gross Demand	**290.4**		**55**	

- **Autocatalysts:** Autocatalysts are the major application for PGM, where they are essential for the function of catalytic converters to reduce emissions from petrol and diesel engines. Platinum in light duty diesel engines accounted for 60 % of autocatalyst use in 2014, with around 20 % for both light duty petrol and heavy duty diesel engines. Close to 90 % of palladium in autocatalysts is used for light duty petrol engines, with the remainder used in light duty diesel. Platinum and palladium can be interchanged to certain extent, depending on the prices and demand for each, however they cannot be considered fully substitutable. Autocatalysts are the principal application for rhodium accounting for almost 80 % of demand. Rhodium is essential for the function of three-way catalytic converters which reduce emissions of nitrogen oxides from petrol engines and which account for more than 95 % of total autocatalyst usage of rhodium (Johnson Matthey, 2015).

- **Jewellery:** The value and physical properties of PGM means they are suitable and desirable for high value jewellery, which accounts for over a fifth of their consumption.
- **Catalysts in chemical, electrochemical and petrochemical applications:** PGM are widely used as catalysts in the industrial sector, primarily in chemical manufacture and petroleum refining. Their properties and high value mean they are particularly suitable for catalytic processes, where only a small quantity of the metal can have a large impact on production and they can generally be recovered at the end of the process. Almost all PGM are used as catalysts on an industrial scale. Platinum is used as a catalyst in a variety of processes, with the most important being petroleum refining (where it is in some applications combined with rhenium) and nitric acid production. Palladium and rhodium are both used in the production of several plastics and polymer precursors. Ruthenium is used in ammonia production, as well as with iridium in electrochemical processes.
- **Electronics:** PGM find various uses in the electronics industry. Both platinum and palladium are used in the construction of some printed circuit boards. The use of palladium in electronics has grown with the miniaturisation of electronics for applications such as mobile phones where palladium is used in multi-layered ceramic capacitors. Specific uses for platinum and ruthenium are in computer hard disk drives, and iridium is linked to the manufacturing process for LEDs and is used in organic LEDs.
- **Glass:** PGM are used in the manufacture of some glass types when high processing temperatures are used. Their high melting point, strength and resistance to corrosion mean they are suitable for this purpose. Both platinum and rhodium are used during the production of glass fibre, LCD manufacture and some other types of glass (but not for bottle glass).
- **Medical industry:** PGM, mainly palladium, find uses in dental applications, specifically alloys for fillings and bridges. The PGM are also used in components in medical scanners, sensors and drugs.
- **Investments:** The high value of the PGM means that they are used as investments, which can influence the market for these materials. This particularly influences platinum and palladium trading, as these are the largest volume. Investment in the other PGM is relatively small.

Current demand in Europe for platinum and palladium is estimated at 24 % and 17 % of the world's supply (respectively 263 and 290 t, see Table 75) respectively (Johnson Matthey, 2015). The majority of this is used in autocatalysts.

17.3.2 Prices and markets

PGM are bought and sold in various ways. Platinum and palladium are typically exchange traded with a number of daily market prices quoted for the pure (minimum 99.9%) metals in US dollars per troy ounce. For example, the London Metal Exchange delivers daily prices for platinum and palladium on behalf of the London Bullion Market Association. Johnson Matthey also publishes daily prices based on the company's quoted prices for its customers of wholesale quantities of platinum group metals set by its trading desks in the USA, Hong Kong and the UK. The price reflects Johnson Matthey's current view of prevailing market prices and may take into account Johnson Matthey's view on current market bids and offers. The price is for metal in sponge form with minimum purities of 99.95% for platinum and palladium, and 99.9% for rhodium, iridium and ruthenium. The platinum group metals are also traded through long-term supply contracts and individual trades between large consumers and suppliers and trading houses.

The price of platinum has experienced considerable volatility in the past 15 years having hovered around US$400 per ounce throughout much of the 1990s. Following the introduction of emission-control legislation the price followed a generally upward trend, peaking at all-time record high of US$ 2276 per troy ounce in March 2008 (Figure 130). However, the price fell back sharply with the onset of the global financial crisis in the second half of 2008. Although the price recovered in 2009 and 2010, it has followed a general downward path since mid-2011 as a consequence of the continuing global economic recession. In 2015 the platinum price declined by 24 % to an average of US$1,053, the lowest annual average in ten years (Thomson Reuters, 2016).

The price of palladium has also shown a high degree of volatility in recent years in response to changing global economic conditions (Figure 131). In 2014 the price averaged US$692, a fall of 14 % from the previous year (Thomson Reuters, 2016).

Figure 130: The price of platinum, December 2001 – December 2016 (data from Johnson Matthey, 2016b)

Figure 131: The price of palladium, December 2001 – December 2016 (data from Johnson Matthey, 2016b

17.4 Substitution

Substitution of PGM has long been an objective due to their high price. However, in general, the best and commonly the only available substitution is of one PGM for another. For example, at present there are virtually no effective and economic alternatives to PGM in autocatalysts although some substitution is possible for diesel engines where some platinum may be substituted by palladium. This may occur when the price differential between the metals is large enough. For example, the high palladium price in 2001 stimulated some substitution by platinum at that time. Gold is another possible substitute for PGM but its price has deterred its widespread use for this purpose. For the same reason nickel and copper were substituted for palladium in certain electronics applications, albeit with some reduction in performance. Consequently for many high-tech electronics applications palladium remains the material of choice.

The PGM perform important roles as catalysts in the manufacture of various chemicals, both organic and inorganic, and in petroleum refining. In many cases the catalyst is a mixture of more than one PGM and other metals, which has been optimised over a long period. Consequently there is little practical incentive to substitute the PGM, unless the prevailing economic conditions make it important to do so. Furthermore, substituting PGM in closed loop applications offers little economic benefit as life cycle losses in these applications are very small.

Nassar (2015) presented a detailed review of the potential for PGM substitution in the major commercial applications of the PGM. He concluded that in most applications substitution is either not possible or impractical for various technical or economic reasons. Where substitutes are available they are most commonly other PGM or nickel, cobalt and gold. The fact that the PGM are co-products, produced together from the same ores, means that their ability to substitute for one another in the event of supply disruption is limited. Overall it was concluded that the potential for PGM substitution in most high volume applications is limited.

Possible substitutes for specific PGM in particular applications are reviewed in the factsheets for the individual PGM.

17.5 Discussion of the criticality assessment

In the previous EU criticality assessment (EC, 2014) the PGM were treated as a single group, although the major influences on the measured criticality of the group were platinum, palladium, and, to a lesser extent, rhodium because these metals have much greater economic importance than the other PGM and more data are available to assess their supply risk. In the 2017 assessment, the criticality of five PGM was assessed individually using the revised methodology. These assessments are discussed in the factsheets that cover the individual PGM. Osmium was not assessed because of the very small size of its market and the lack of any quantitative data on its supply and demand. The SR and EI score for the PGM were calculated through an arithmetic average of the individual SR and EI scores of platinum, palladium, iridium, rhodium and ruthenium.

The results of this review and earlier assessments are shown in Table 76.

Table 76: Economic importance and supply risk results for palladium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
PGM	6.68	3.63		6.58	1.18		5.0	2.5

In the 2014 criticality assessment of the PGM group the EI value was 6.6 and the SR was 1.2. In the 2017 criticality assessment, based on the arithmetic average of the values for the five individual PGM, the EI and SR values are 5.0 and 2.5, respectively. These differences cannot be readily explained because of the recent methodological changes that have been introduced. Another notable difference between the two assessments relates to the life cycle stage assessed. In the 2014 assessment, the supply risk was calculated on the basis of the global supply of ores and concentrates. However, given that there is actually very little trade in PGM ores and concentrates, the current assessment was based on the processing stage (i.e. refined metal). Furthermore, in the 2017 assessment, considerable attention was paid to elucidating the detailed supply chain of the individual PGM and their end uses. Accordingly the EI and SR values derived for the group as a whole in the 2017 criticality assessment are considered to be more reliable than those calculated in the 2014 assessment.

17.6 Other considerations

17.6.1 Forward look: supply

Given the important industrial applications of the PGM and the fact that they are mined in only a few countries and are not readily substituted, there has long been concern over their security of supply. Various measures have been taken over more than 30 years to ensure supply and mitigate the potential impacts of shortages. These have included the establishment of government stockpiles in some countries, research to understand deposit formation, to find new resources, to extract PGM from different ore types, to identify possible substitutes and to promote recycling. Given the substantial PGM resources known in the major producing countries (South Africa, Russia, Zimbabwe and Canada) it is expected that they will continue to be the main sources for many years to come. A study by the USGS of the PGM mineral inventory in southern Africa pointed to the existence of huge resources in the Bushveld Complex in South Africa and the Great Dyke in Zimbabwe and also suggested the likely occurrence of substantial additional resources in adjacent under-explored areas (Zientek et al., 2014). Further, the global PGM production capacity increased significantly between 1995 and 2010 and was expected to increase further by 2015 (Wilburn, 2012). For example, Ivanhoe Mines is constructing a major new PGM mine on the Platreef, the northern limb of the Bushveld Complex in South Africa (Ivanhoe Mines, 2016). Production is scheduled to start in 2018 and, when fully operational, this mine will be one of the largest and lowest cost PGM mines in the world. Although it is clear that known and potential PGM resources are more than adequate for many decades, what may become problematic is the ability to access these resources as a result of social, environmental, political and economic factors.

In South Africa various factors have combined in recent years to increase concerns about the security of PGM supplies. Prominent among these are labour disputes over wages and working conditions, mining accidents which have led to shaft closures and lost production and calls for nationalisation of the industry. In addition to rising wages, other costs have also increased significantly including the price of power, water, fuel and materials. The effects of these have been exacerbated by the prolonged global recession continued economic uncertainties, low metal prices and fluctuating exchange rates. This resulted in a contraction of the South African platinum industry from about 5 million ounces in the mid-2000s to about 4.3 million ounces in 2016. There has been a massive drop in capital expenditure in the South African platinum industry from over 30 billion rand in 2008 to less than 10 billion rand in 2015 (WPIC, 2015). The output of the major producing companies, Anglo American Platinum, Impala Platinum and Lonmin, fell by about one third between 2007 and 2015 as a result of ore reserve depletion, rationalisation and shaft closures at large underground mines on the western limb of the Bushveld Complex.There has been a recent period of cost cutting and industry restructuring but major capital investment is required to increase mechanisation in the mines and to develop new capacity and open new mines. Various mines have closed or are being considered for closure, while others have changed ownership. It is very likely that South Africa will remain the major global supplier of PGM, because of its huge resource base, the established mining and processing infrastructure and expertise and its great importance to the economy of South Africa. However, it is also probable that there will be fewer but more modern operations producing significantly less than in the past and employing fewer workers. Although job losses will be resisted by the government and the unions, they are inevitable if companies are to maintain their incomes and remain economically viable.

In the Norilsk-Talnakh area the PGM, chiefly palladium, are essentially a by-product of nickel mining so it is difficult to assess the long-term availability of PGM from these mines, especially while nickel prices remain at low levels. In the short term supply from Norilsk Nickel is expected to be stable (Johnson Matthey, 2016a). For many years PGM supplies from Russia were supported by sales from government stocks. Although these sales have now ceased the stocks are now owned by the Russian central bank and, depending on prices and other factors, may provide an additional source of future supply. The other source of Russian PGM supply are alluvial mining operations in the Far East. These provide only a small proportion of Russia’s output, but grades are reported to be falling so their share is likely to continue to decrease as it has since 2014 (Johnson Matthey, 2016a).

The supply of PGM from recycling makes an important contribution to meeting global PGM demand. About 26 % of global palladium demand was met from recycling in 2015, and 21 % of global platinum demand (Johnson Matthey, 2016a). However, the prevailing low PGM prices and weakness in global steel markets have led to a reduction in the volume of autocatalysts being collected, processed and refined. End of life vehicles are being used for longer or are exported to developing countries where they fetch higher prices. Consequently recoveries of platinum from autocatalyst recycling fell by over 12 % in 2015 and staged only a modest (3 %) rise in 2016 (Johnson Matthey, 2016a). Similarly, scrappage rates for jewellery have been low due to the low PGM prices. If low PGM prices prevail for a significant period then they are likely to pose an additional constraint on supply. However, in the longer term an increasing proportion of PGM supply is expected to be derived from secondary sources, stimulated by increased environmental regulation and fiscal incentives to promote recycling and to encourage greater efficiencies in the recycling of end of life products. Hagelüken and Grehl (2012) have suggested that globally up to 2010 there was as much as 3000 tonnes of PGM in the autocatalysts of vehicles in use on the road, equivalent to more than six years of the combined global mine production of platinum, palladium and rhodium in 2010. Over time vehicles being scrapped will have higher contents of PGM in their autocatalysts reflecting the introduction of new or more stringent emissions regulations in various countries. In India and China the introduction of emissions legislation and the increased production of diesel trucks will lead to increased demand for platinum. However, improvements in recovery rates will not be easy to achieve without government interventions to reduce losses and to introduce more effective schemes for collection and processing of end of life vehicles.

17.6.2 Forward look: demand

Catalytic converters for motor vehicles will likely remain the largest demand sector for PGM for the foreseeable future and is considered likely to grow further as a result of increasing vehicle sales, both light duty and heavy duty, and stricter emission controls. Total demand for platinum from the European vehicle sector will reach its highest level in 2016 since 2008. Diesel catalysts used in light and heavy duty vehicles and off-road applications account for 95 % of platinum usage in Europe (Johnson Matthey, 2016a). Europe accounts for about 60 % of diesel cars manufactured globally and since the early 1990s the use of platinum-rich catalysts has become universal and PGM loadings have increased. At the same time the requirements to greatly reduce NOx and particulate matter emissions have greatly increased the complexity and variety of diesel catalyst systems. For example, between 2013 and 2015 there was a 13 % increase in the average platinum content of a diesel autocatalyst system in Europe (Johnson Matthey, 2015). In the EU Real Driving Emissions (RDE) standards will be phased in between 2017 and 2022 for both petrol and diesel vehicles. These changes, which will restrict the permitted difference for NOx emissions under real driving and laboratory conditions, will have significant impacts on the diesel catalysts developed by European carmakers. It is unclear which particular technology will be adopted and the likely impact on PGM demand. Also, in the longer term it likely that internal combustion engines will be increasingly replaced by electric vehicles of various types. In particular, some commentators have suggested that the market share in Europe of the diesel engine will decline rapidly as governments and consumers demand cleaner air and lower pollution levels, especially in cities.

While there is a very high level of interest worldwide in replacing the internal combustion engine with cleaner alternatives, it is not clear which replacement technology will become dominant. While the development of hybrid and battery-powered electric vehicles seems to most prominent at present, major car companies, such as Hyundai, Honda, Toyota and Mercedes Benz, continue to develop and refine fuel cell electric vehicles (FCEV). However, the number of FCEV sold worldwide is currently very small, expected to be less than 3000 units in 2016 (Johnson Matthey, 2016a). However, if FCEV achieve significant market penetration in the future this will inevitably lead to increased platinum demand if the current fuel cell technologies prevail.

On account of their general designation as ‘critical’ in many parts of the world there is considerable research in progress which aims to either reduce or replace the use of PGM in various applications. For example, the EC-funded Partial PGM project, which started in 2016, is aiming to develop more efficient exhaust after-treatment systems for petrol vehicles, facilitating compliance with future emission control regulations, while at the same time reducing the amount of PGM and rare earth elements used in them. Another EC-funded project, CritCat, which also began in 2016, aims to develop substitutes for PGM-based catalysts used in chemical manufacture and in emerging energy-conversion technologies, such as the production of hydrogen and synthetic gas (syngas) fuels.

It is difficult to predict future PGM demand for jewellery and investment as it varies considerably by country in response to cultural attitudes and changing metal prices. However, in recent years there has been generally strong growth in demand for platinum jewellery in China, Japan and India. Industrial consumption of platinum in chemicals, glass and petroleum refining is expected to reach a five-year high in 2016, due to a large extent to significant investment in new plants and expansions by China and Chinese-owned plants in North America and elsewhere (Johnson Matthey, 2016a).

In the longer term it has been suggested that global demand from emerging technologies will require major increases in the production of both platinum and palladium (Marscheider-Weidemann et al., 2016). For example, platinum demand for new technologies is expected to increase from a base level close to zero in 2013 to about 110 tonnes in 2035 as a result of increased use in catalysts and fuel cells. This compares with total global production of platinum in 2013 of about 190 tonnes. Similarly, demand for palladium from emerging technologies is estimated to increase fivefold in the same period, from 20 tonnes in 2013 to 100 tonnes in 2035. Total global production of palladium in 2013 was about 200 tonnes.

17.7 Data sources

17.7.1 Data sources used in the factsheet

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17.7.2 Data sources used in the criticality assessment

This factsheet deals with five PGM, excluding osmium, as a group. The criticality assessments were carried out on individual members of the group. Please see the material-specific factsheets for details of the criticality assessments and the data sources used.

17.8 Acknowledgements

This Factsheet was prepared by the British Geological Survey (BGS). The authors would like to thank the following for their contributions to the preparation of this Factsheet: C. Hagelüken (Umicore), M. Schmidt (BGR/DERA), P. Duncan (Johnson Matthey), V. Zepf (University of Augsburg), G. Mudd (Monash University) and members of the EC Ad Hoc Working Group on Critical Raw Materials.

18. IRIDIUM

Key facts and figures

Material name and Element symbol	Iridium Ir	World/EU production in 2016 (tonnes)	7.1 / 0
Parent group (where applicable)	Platinum-Group Metals (PGM)	EU import reliance[1]	100%
Life cycle stage / material assessed	Processing / refined metal	Substitution index for supply risk [SI (SR)][1]	0.96
Economic importance (EI) (2017)	4.3	Substitution index for supply risk [SI (EI)][1]	0.93
Supply risk (SR) (2017)	2.8	End of life recycling input rate	14%
Abiotic or biotic	Abiotic	Major non-monetary end uses in EU[1]	Electrical (43%), electrochemical (27%), chemicals (7%)
Main product, co-product or by-product	Co-product (with other PGM): by-product (with Ni and Cu)	Major world producers in 2016	South Africa (85%), Zimbabwe (9%)

[1] average for 2010-2014, unless otherwise stated;

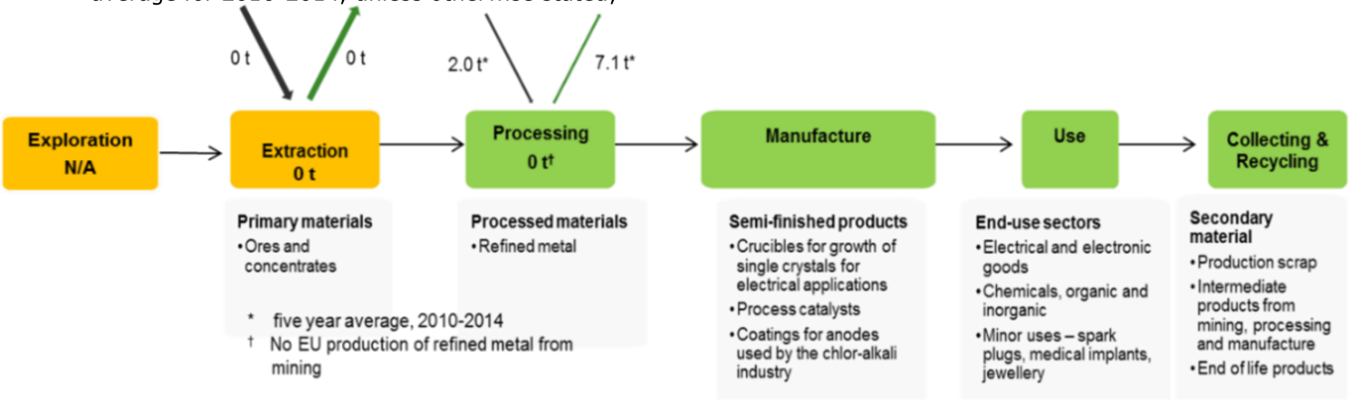

Figure 132: Simplified value chain for iridium

The green boxes in the figure above identify activities undertaken within the EU. The black arrows represent imports to the EU and the green arrows represent exports from the EU. Iridium-bearing ores and concentrates are not generally traded in the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

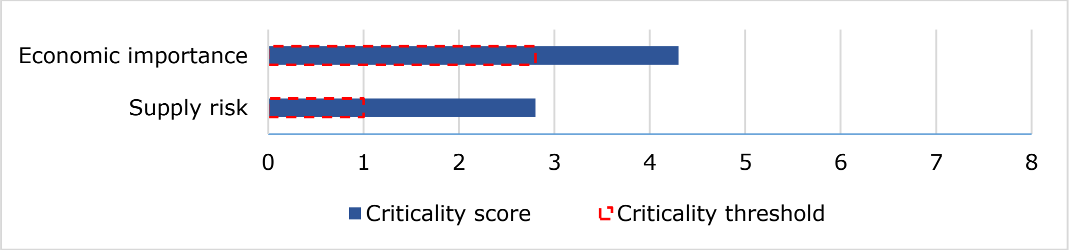

Figure 133: Economic importance and supply risk scores for iridium

18.1 Introduction

Iridium (Ir) is one the six chemical elements referred to as the platinum-group metals (PGM) or the platinum-group elements (PGE), which are, in order of increasing atomic number: ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). These metals are very rare in the Earth's crust with abundances in the range 1-5 parts per billion (ppb). The iridium abundance in the upper crust is 0.022 ppb (Rudnick, 2003). They tend to be found together, commonly associated with ores of nickel and copper. The PGM occur in numerous alloys, in base metal sulfide minerals and in a wide variety of PGM-bearing minerals with, among others, sulfur, arsenic, antimony and tellurium. They rarely occur in native form. The PGM are highly resistant to wear, tarnish, chemical attack and high temperature. After osmium, iridium is the second most dense of the known elements with a density of 22,550 kgm^{-3}. It is also the most corrosion-resistant metal known. All PGM, commonly in combination with one another or with other metals, can act as catalysts which are exploited in a wide range of applications. The market for iridium is relatively small and it is the fifth most commercially important of the PGM, behind platinum, palladium, rhodium and ruthenium. The main use of iridium is in the manufacture of electrical products, with chemical and electrochemical applications the next most important.

Almost all iridium derived from primary source materials (i.e. mine production) is traded in the form of refined metal produced from integrated mining/metallurgical operations. There is only very limited international trade in iridium ores and concentrates.

Most topics related to iridium have been covered in the general PGM Factsheet that deals with the five PGM (excluding osmium) together. This is because the PGM occur together in nature and are generally co-products from the same deposits. Also, much of the available public data deals with them as a group. They are, therefore, commonly discussed together, with comparisons drawn between individual PGM where data allow. In this factsheet additional information and data specific to iridium are presented where available.

18.2 Supply

18.2.1 Supply from primary materials

The geological occurrence, mining, processing, extractive metallurgy and resources and reserves have been discussed in the general PGM Factsheet.

The majority of iridium is derived from mafic-ultramafic igneous complexes like the Bushveld Igneous Complex in South Africa and the Great Dyke in Zimbabwe. Minor production is from nickel sulfide deposits in Russia, Canada, USA and elsewhere (Gunn, 2014). Most PGM extracted from the Bushveld Igneous Complex are derived from two horizons: the Merensky Reef and the UG2 Chromitite. The proportion of iridium, rhodium and ruthenium in the UG2 is significantly greater than in the Merensky Reef. Consequently, as mining of the UG2 has increased markedly in recent decades, so the potential availability of these PGM has increased.

While it is considered likely that iridium resources may also be found elsewhere there is very little available geochemical data for iridium in other deposit types and geological settings. Consequently it is difficult to assess the abundance of iridium in these potential new sources.

18.2.1.1 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of iridium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[17], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for iridium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for iridium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for iridium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

18.2.1.2 World mine production

Data are not published for annual world mine production of iridium for the period 2010-14.

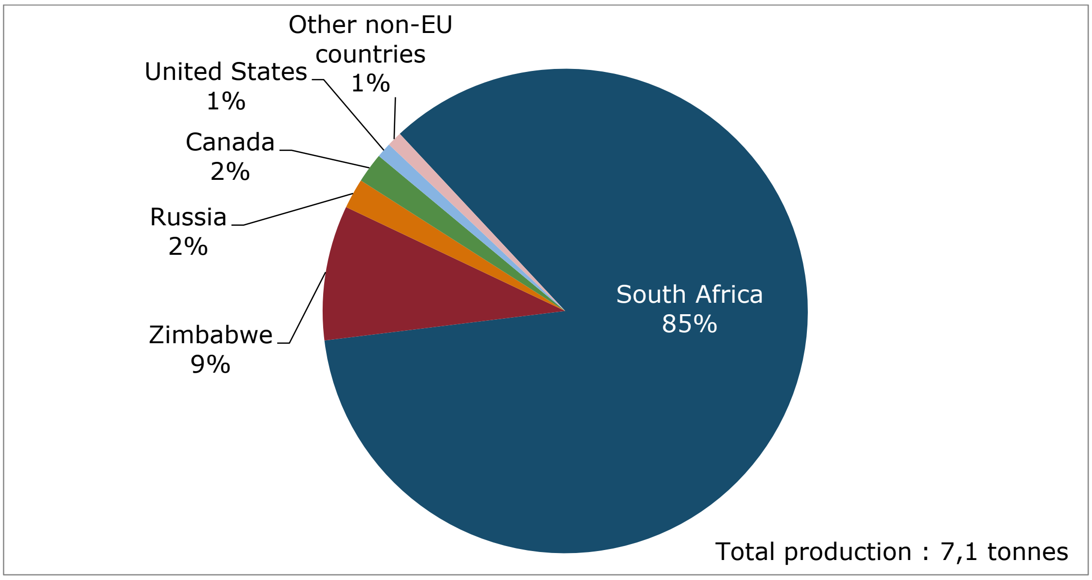

Figure 134: The distribution of global mine production of iridium in 2016. (Data from Johnson Matthey, 2016a)

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[17] www.crirsco.com

However, data were obtained for 2016 from Johnson Matthey (Johnson Matthey, 2016a). Total global mine production of iridium in 2016 was approximately 7.1 tonnes, much less than the annual production of the other PGM. Iridium supply is strongly dominated by South Africa which accounted for about 85 % of the total in 2016 (Figure 134). Zimbabwe was the second most important producer (8.8 % of total), followed by Russia (2.6 %) and Canada (1.7 %).

18.2.2 Supply from secondary materials

As discussed in the PGM Factsheet, recycling makes an important and growing contribution to global PGM supply. However, the end of life recycling rate varies considerably by country and by application. For iridium overall recycling accounts for a small proportion of the metal produced globally each year. Hagelüken (2014) indicates *that* end of life recycling rates of iridium in open loop consumer applications are very low, while in industrial applications a rate of 40–50 % is typical. The EoL-RIR used in the assessment is 14% (JRC, 2016).

18.2.3 EU trade

As discussed in the PGM Factsheet, the PGM are traded in the EU in a variety of forms – as metal in unwrought or powder form, in semi-manufactured forms and various intermediate products and wastes. For iridium, trade data are available only under a single Combined Nomenclature (CN) code (7110 4100), which includes iridium, osmium and ruthenium metal in unwrought or powder form.

Figure 135 shows EU trade in ruthenium and iridium metal combined (Ru+Ir) with non-EU countries. In each of the years 2010–2014 the EU was a significant net exporter of Ru+Ir metal. While it is clear that there is considerable trade in Ru+Ir metal, it is not possible to determine if that metal was derived from primary or secondary material. Net exports of Ru+Ir metal from the EU to non-EU countries averaged 20.6 tonnes per annum in the period 2010–2014.

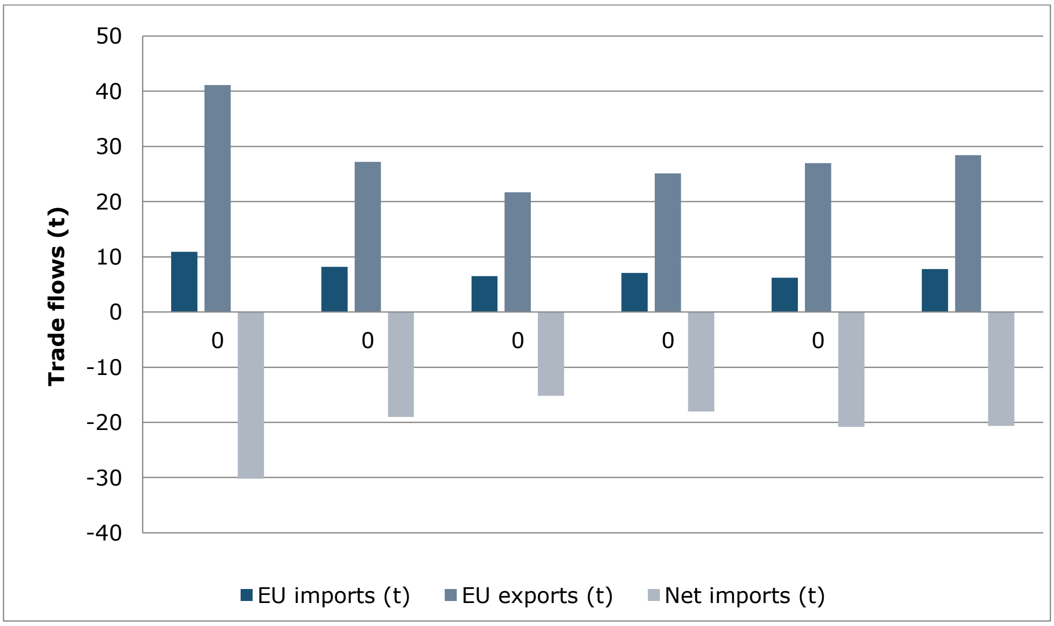

Figure 135: EU trade in ruthenium and iridium metal, in unwrought or powder form, with non-EU countries, 2010–2014 (Data from Comext database (Eurostat, 2016a))

The EU import reliance for iridium is 100%. EU imports of Ru+Ir metal averaged about 7.8 tonnes per annum between 2010–2014. The main sources of these imports were

South Africa (58.3 % of total), Japan (12.6 %), United States (10.1 %) and Taiwan (7.5 %) (Figure 136).

During the same period the EU exported about 28.4 tonnes of Ru+Ir metal per annum. Nearly 90 % of the exports were sent to four countries: Singapore (50 % of the total), United States (23 %), Japan (11 %) and Taiwan (5 %).

No trade restrictions have been reported over the 2010-2014 period (OECD, 2016). The EU and South Africa have a free trade agreement in place (European Commission, 2016).

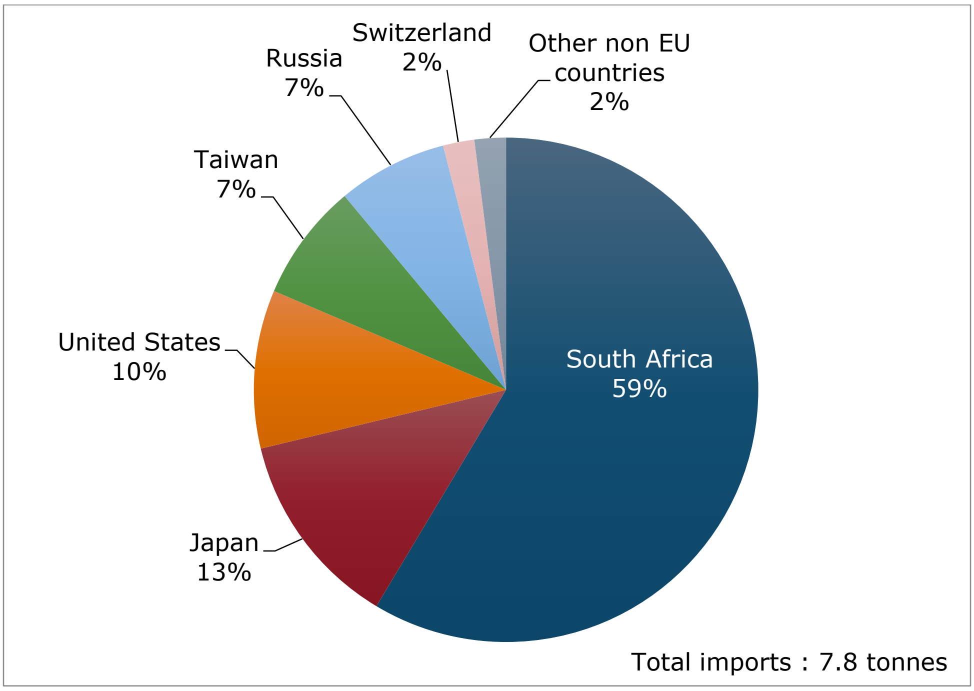

Figure 136: The sources of EU imports of ruthenium and iridium metal, in unwrought or powder form, from non-EU countries, 2010–2014 (Data from Comext database (Eurostat, 2016a))

18.2.4 EU supply chain

The supply chain for iridium in the EU is complex and difficult to quantify. Iridium supplies are derived from both primary sources (mines) and secondary sources (refineries). The EU is 100% reliant on imports for iridium. Refineries in the EU process a wide range of iridium-bearing materials emanating from European and overseas sources. These include end-of-life products and manufacturing waste (new scrap). The end of life recycling rate is 14% (JRC, 2016). By-products from the non-ferrous mining, processing and manufacturing industries also contribute to the EU supply of iridium. There is no reported production of iridium from mines in the EU.

18.3 Demand

18.3.1 Consumption

Given the diversity of forms in which iridium is traded, the limited scope of trade data specific to iridium and the absence of any distinction between iridium metal derived from primary and secondary source materials, it is not possible to determine a single reliable figure for EU consumption of iridium.

Gross global demand for iridium in 2015 was 7.8 tonnes (Johnson Matthey, 2016c). In 2016 iridium demand in Europe amounted to approximately 0.9 tonnes, which was about 14 % of global demand (Johnson Matthey, 2016a).

18.3.2 Applications

The main uses of the PGM are discussed in the PGM factsheet.

The predominant application of iridium is in the electrical industry, where, on account of its high melting point and resistance to chemical attack, it is mostly used in crucibles for growing single crystal sapphire (Figure 137). The sapphire provides a substrate for the production of gallium nitride which is used in blue and green light emitting diodes (LEDs) increasingly utilised in flat screen displays in portable electronic equipment. Another major use of iridium is with ruthenium in dimensionally stable anodes for the electrochemical production of chlorine and sodium hydroxide. The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 77.

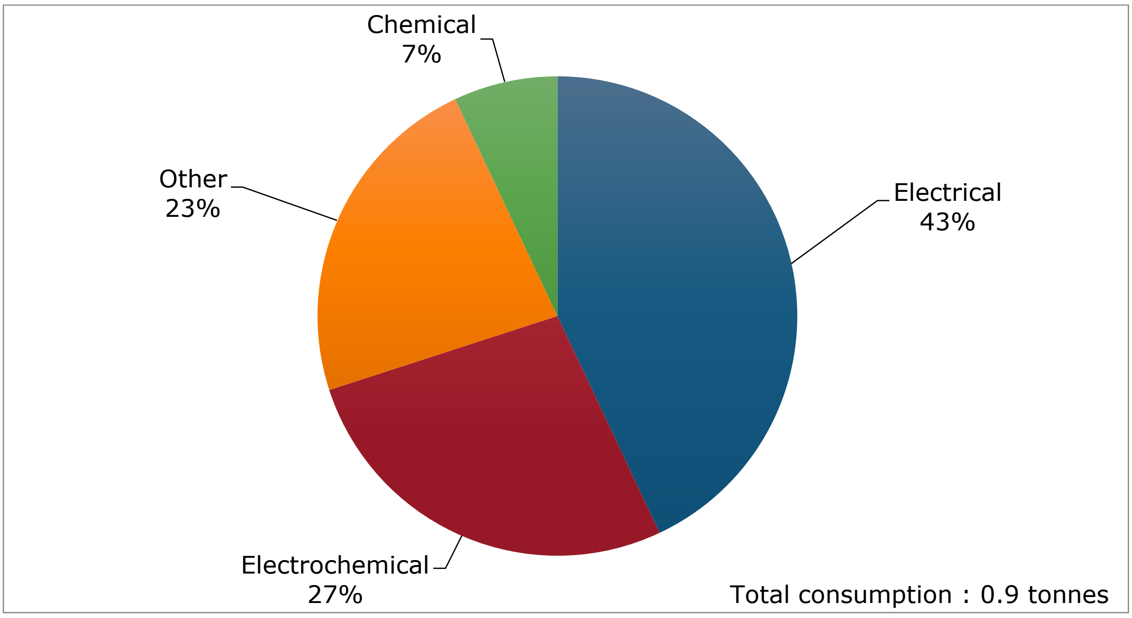

Figure 137: Global end uses of iridium in 2015 (Data from Johnson Matthey, 2016c)

Table 77: Iridium applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016c)

Applications	2-digit NACE sectors	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
Electrical	C26 - Manufacture of computer, electronic and optical products	75,260	C2611 - Manufacture of electronic components
Chemical	C20 - Manufacture of chemicals and chemical products	110,000	C2014 - Manufacture of other organic basic chemicals
Electrochemical	C20 - Manufacture of chemicals and chemical products	110,000	C2013 - Manufacture of other inorganic basic chemicals
Other	C29 - Manufacture of motor vehicles, trailers and semi-trailers	158,081	C2931 - Manufacture of electrical and electronic equipment for motor vehicles

Iridium is also employed in a range of other applications such as in electrodes for high-performance spark plugs and for controlling the emissions from the exhaust systems of gasoline direct injection (GDI) engines. It is also used for medical implants, generally alloyed with platinum, and in linings and parts used in the production of glass. Iridium catalysts are used in the manufacture of chemicals, promoting hydrogenation, hydroformylation and acetic acid synthesis. For example, the Cativa process, which produces acetic acid by the carbonylation of methanol, is promoted by an iridium-ruthenium catalyst.

18.3.3 Prices and markets

Unlike platinum and palladium, iridium is not traded on the major metal exchanges. Iridium is generally sold through long-term supply contracts between fabricators and mines. Johnson Matthey is the main fixer of the iridium price, publishing daily prices from its trading desks in the USA, Hong Kong and the UK. The price is for metal in sponge form with a minimum purity of 99.9% iridium.

The price of iridium has experienced major fluctuations in recent years in response to changing industrial demand (Figure 138). Over the first decade of the 2000s the price varied between about US$100 and US$400 per troy ounce. However in early 2010 it began to rise rapidly, peaking in late 2011 at about US$1085. This sharp increase can be attributed chiefly to a rapid and significant expansion of demand for iridium crucibles by the electrical sector where they are used for growing single crystal sapphire which is used a substrate for LEDs used in backlit LED televisions (Johnson Matthey, 2011). However the high level of demand from the electrical sector was not sustained and the price fell back sharply to about US$400 in late 2013. Reduced demand from the chlor-alkali industry in China also contributed to the falling price in this period (Johnson Matthey, 2013). Since 2013 the price has experienced considerable volatility. It currently stands at US$700 per troy ounce (January 2017).

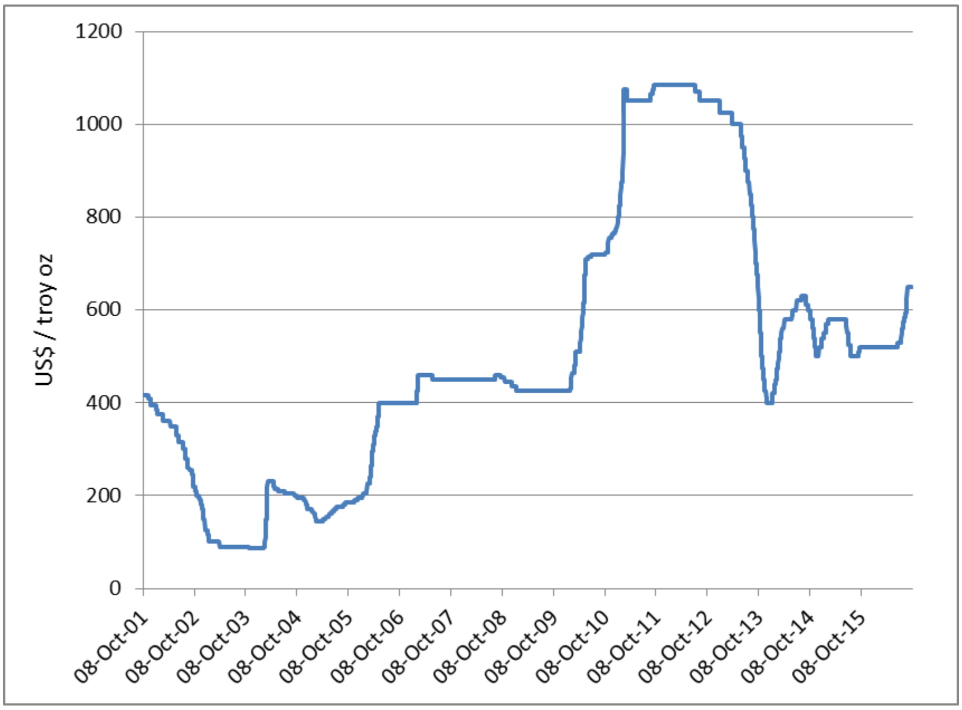

Figure 138: The price of iridium, October 2006 – October 2016 (data from Johnson Matthey, 2016b)

18.4 Substitution

Nassar (2015) reviewed the possibilities for elemental substitution of the PGM in their main applications. Given that the PGM are co-products, in the event of a supply disruption of iridium, the ability to substitute it with other PGM is likely to be limited. Similarly, given that iridium production is highly concentrated in southern Africa, it would not be easy to bring new supply on stream quickly because the level of production is dependent on that of the 'paying' metals, platinum and palladium.

In the electrical industry where iridium is used in crucibles for the growth of large single crystals of sapphire, possible substitutes include molybdenum and tungsten (Nassar, 2015). However, we have no data on market share of these alternative materials.

In the chlor-alkali industry the membrane technology, which is gradually replacing alternative methods of chlorine manufacture, uses anodes based on a mixture of iridium and ruthenium. We have no information on the relative proportions of each PGM used for this purpose nor the degree to which one can be substituted by the other. Many other anode compositions have been patented but few are in commercial use (Nassar, 2015).

18.5 Discussion of the criticality assessment

18.5.1 Data sources

Production data for iridium are not generally available in the public domain. The data used for the criticality assessment of iridium were for 2016 only and were provided by Johnson Matthey (Johnson Matthey, 2016a). There is no CN8 code specific to iridium ores and concentrates. The most relevant CN8 code would be 26169000: *Precious metal ores and concentrates excluding silver*. However this code reports data for several precious metals and it is therefore inappropriate to use in the iridium assessment.

Trade data for unwrought iridium metal are not available separately. Iridium metal in unwrought or powder form is combined with osmium and ruthenium under CN code 7110 4100. These data were extracted from the COMEXT online database (Eurostat, 2016) and were averaged over the five-year period 2010–2014. For the purposes of the criticality assessment trade in osmium is assumed to be very small and has been ignored. The relative proportions of ruthenium and iridium are not known but for the purposes of this assessment have been estimated at 75 per cent ruthenium and 25 per cent iridium, in accordance with the relative size of their markets. The trade data include metal from all sources, both primary and secondary. It is not therefore possible to identify the source of the metal and the relative contributions of primary and secondary materials. In reality, Europe is a significant producer of refined iridium, which originates both from primary and secondary materials. Therefore, the actual net import reliance may be lower than calculated using the global HHI. The significance of the EU's reliance on iridium derived from imports of secondary materials is not known and has not been investigated in the 2017 criticality assessment.

Other data sources are listed in section 18.7.

18.5.2 Calculation of economic importance and supply risk indicators

For the calculation of Economic Importance (EI), the 2-digit NACE sectors shown in Table 77 were used. For information relating to the application share of each category, see section on applications and end-uses. The share of the applications of iridium denoted as 'other' is relatively large (23%). Therefore, rather than allocating this among the three major identified applications (electrical, electrochemical and chemical), this share was attributed to the 2-digit NACE sector C29, reflecting the use of iridium in spark plugs and vehicle exhaust systems. The figures for value added were the most recently available at the time of the assessment, i.e. 2013.

The calculation of the Supply Risk (SR) was carried out at the refined material stage of the life cycle using only the global HHI calculation. Actual supply to the EU cannot be determined from Eurostat because the trade data do not discriminate between iridium metal derived from primary and secondary sources. The Eurostat trade data include metal from different life cycle stages and from numerous sources/countries. It cannot therefore be used to calculate the risk to primary iridium supply to the EU.

While there is a possibility to substitute iridium in some of its applications, it has not generally been possible to quantify the shares of the substitute materials currently in use.

The end of life recycling input rate for iridium was based on UNEP data (UNEP, 2011) and presented by JRC (2016).

18.5.3 Comparison with previous EU criticality assessments

In this revision of the EU critical raw materials list a revised methodology for assessing economic importance and supply risk has been used and consequently the results are not directly comparable to the previous EU critical raw materials studies.

The results of this review and earlier assessments are shown in Table 78Table 76.

Table 78: Economic importance and supply risk results for iridium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Iridium	6.68*	3.63*		6.58*	1.18*		4.3	2.8

*in the 2011 and 2014 assessments the PGM were considered as a single group which included iridium. In the current assessment iridium was considered as a single metal

18.6 Other considerations

The factors affecting the future supply and demand for PGM have been discussed in the PGM Factsheet. It is considered that South Africa will continue to be the main global supplier of iridium. The size of the global geological resource of iridium is not well known but there is considerable potential in the longer term to find additional resources in countries which do not currently produce PGM and in other geological settings.

Given that iridium is effectively a by-product of platinum and/or palladium extraction, its supply is closely tied to the production of those PGM which are the ‘paying’ metals. However, given that most PGM are now mined from the UG2 Chromitite, that the PGM resources in the UG2 Chromitite are much larger than in the Merensky Reef, and that the UG2 ore contains a higher proportion of iridium than the Merensky Reef, the future availability of iridium from South Africa is considered unlikely to be problematic (Zientek et al., 2014). However, in order to ensure the long-term availability of iridium more geological research is needed to improve our knowledge of its distribution and abundance elsewhere in the earth’s crust and in ores that might be potential sources of supply.

Most iridium is used in closed loop industrial applications where losses are low and recycling rates high. In most ‘consumer goods’ the recycling rate of iridium is low because it is used either in dissipative applications, such as spark plug tips, or in medical implants which are not recovered at the end of life.

While it is difficult to predict how technological change will impact on demand for a particular metal, there is considerable global interest in clean energy generation and storage. Iridium has proven to be an effective catalyst in the production of hydrogen from the electrolysis of water (Angerer et al., 2016). This technology involves polymer electrolyte membrane (PEM) electrolysers, which are essentially the reverse of a fuel cell. Water and power are the inputs and hydrogen and oxygen the outputs. Hydrogen produced in this way might be used to refuel fuel cell electric vehicles (FCEV). However, these electrolyers use only small amounts of iridium and platinum as coatings on their electrodes. If PEM electrolysis were used on a larger scale, for example to feed hydrogen into the natural gas grid, then this might lead to significantly increased demand for iridium in the longer term. Iridium is also used in conjunction with platinum on one of the electrodes in FCEV. This is an area of increasing iridium demand but the possible impact on iridium availability and price will depend on the market share of FCEV. At present the share is very small (about 3000 units per year globally) and it would have to grow very significantly, to tens of thousands of units per year, to make a significant impact on iridium supply.

Table 79: Qualitative forecast of supply and demand of iridium

Material	**Demand forecast**			**Supply forecast**		
	5 years	10 years	20 years	5 years	10 years	20 years
Iridium	+	+	?	+	+	?

18.7 Data sources

18.7.1 Data sources used in the factsheet

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18.7.2 Data sources used in the criticality assessment

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European Commission. (2016) EU trade agreements webpage [online]. Directorate General for Trade. http://ec.europa.eu/trade/policy/countries-and-regions/agreements/index_en.htm

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Zientek, M., Causey, J., Parks, H. and Miller, R. (2014). Platinum-group elements in southern Africa – Mineral inventory and an assessment of undiscovered mineral resources. US Geological Survey Scientific Investigations Report 2010–5090–Q.

18.8 Acknowledgements

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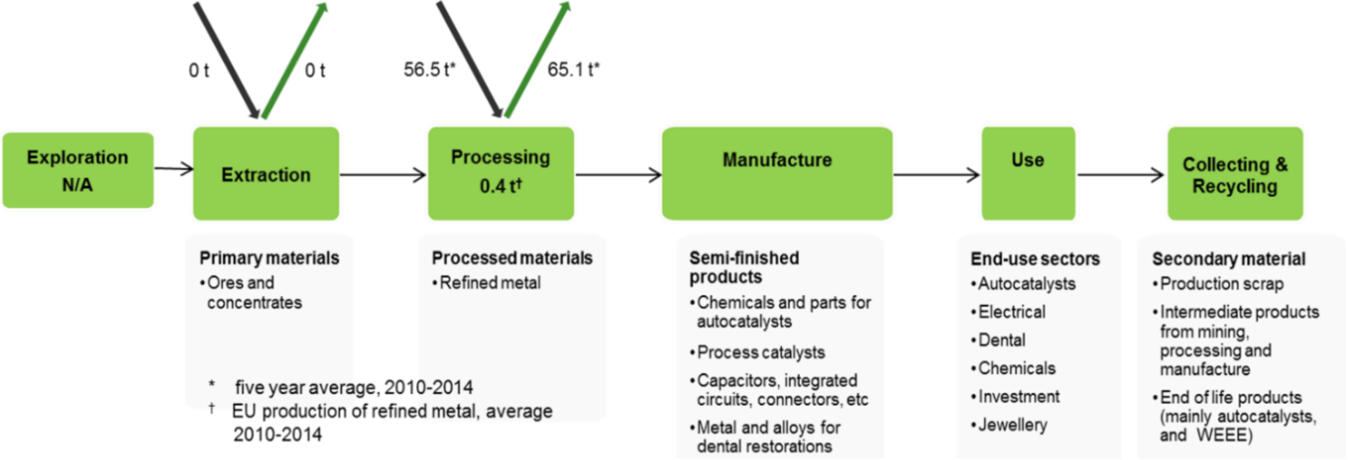
19. PALLADIUM

Key facts and figures

Material name and Element symbol	Palladium Pd	World/EU production (tonnes)[1]	209 / 0.4
Parent group (where applicable)	Platinum-Group Metals (PGM)	EU import reliance[1]	100%
Life cycle stage / material assessed	Processing / refined metal	Substitution index for supply risk [SI (SR)][1]	0.99
Economic importance (EI) (2017)	5.6	Substitution Index for economic importance [SI(EI)][1]	0.94
Supply risk (SR) (2017)	1.7	End of life recycling input rate	10%
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Autocatalysts (75%), electrical (10%), chemical (5%)
Main product, co-product or by-product	Co-product (with other PGM): by-product (Ni, Cu)	Major world producers[1]	Russia (46%), South Africa (36%), Canada (7%),

[1] average for 2010-2014, unless otherwise stated;



* five year average, 2010-2014

† EU production of refined metal, average 2010-2014

Figure 139: Simplified value chain for palladium

The green boxes in the figure above identify activities undertaken within the EU. The black arrows represent imports to the EU and the green arrows represent exports from the EU. Palladium-bearing ores and concentrates are not generally traded in the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

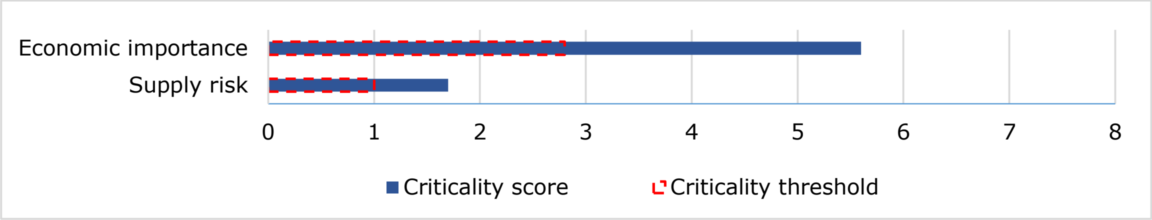


Figure 140: Economic importance and supply risk scores for palladium

19.1 Introduction

Palladium (Pd) is one the six chemical elements referred to as the platinum-group metals (PGM) or the platinum-group elements (PGE), which are, in order of increasing atomic number: ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). These metals are very rare in the Earth's crust with abundances in the range 1-5 parts per billion (ppb). The abundance of palladium in the upper crust is 0.52 ppb (Rudnick, 2003). They tend to be found together, commonly associated with ores of nickel and copper. The PGM occur in numerous alloys, in base metal sulfide minerals and in a wide variety of PGM-bearing minerals with, among others, sulfur, arsenic, antimony and tellurium. They rarely occur in native form. The PGM are highly resistant to wear, tarnish, chemical attack and high temperature. The PGM are regarded as precious metals, like gold and silver. All PGM, commonly combined with one another or with other metals, can act as catalysts which are exploited in a wide range of applications. Platinum and palladium are of major commercial significance, with rhodium the next most important. The main use of palladium is in autocatalysts, with electrical and chemical manufacture the second and third most important applications respectively.

Almost all palladium derived from primary source materials (i.e. mine production) is traded in the form of refined metal produced from integrated mining/metallurgical operations. There is only very limited international trade in palladium ores and concentrates.

Most topics related to palladium have been covered in the general PGM Factsheet that deals with the five PGM (excluding osmium) together. This is because the PGM occur together in nature and are generally co-products from the same deposits. Also, much of the available public data deals with them as a group. They are, therefore, commonly discussed together, with comparisons drawn between individual PGM where data allow. In this factsheet additional information and data specific to palladium are presented where available.

19.2 Supply

19.2.1 Supply from primary materials

The geological occurrence, mining, processing, extractive metallurgy and resources and reserves have been discussed in the general PGM Factsheet.

In addition to the major resources derived from mafic-ultramafic igneous complexes like the Bushveld Igneous Complex in South Africa and the nickel sulfide deposits in Russia, Canada, USA and elsewhere, palladium is also known to be enriched to potentially economic concentrations in several other geological settings (Gunn, 2014). These settings have not been the source of palladium production to date, but palladium might in the future become available as a by-product of other metals in deposits of these types.

19.2.1.1 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of palladium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[18], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for palladium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for palladium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for palladium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

Palladium data are normally reported in combination with other PGM, most commonly with platinum and sometimes with rhodium and/or gold. See the PGM factsheet for more details. Some mining companies publish separate resource and reserve data for palladium in individual deposits. An estimate from BRGM, made by compiling mining companies' data, announces about 6,100 t of global reserves of palladium in 2013 (BRGM, 2015), with most of them located in South Africa (52.2%), followed by Russia (29%), USA (7.5%), Zimbabwe (6.2%) and Canada (4.7%) (BRGM, 2015).

19.2.1.2 World mine production

Average annual world mine production of palladium for the period 2010-14 was 209 tonnes having fallen from a high of about 229 tonnes in 2011 as a result of weak global demand. Global supply is dominated by Russia which accounted for about 45% of the total (Figure 141).

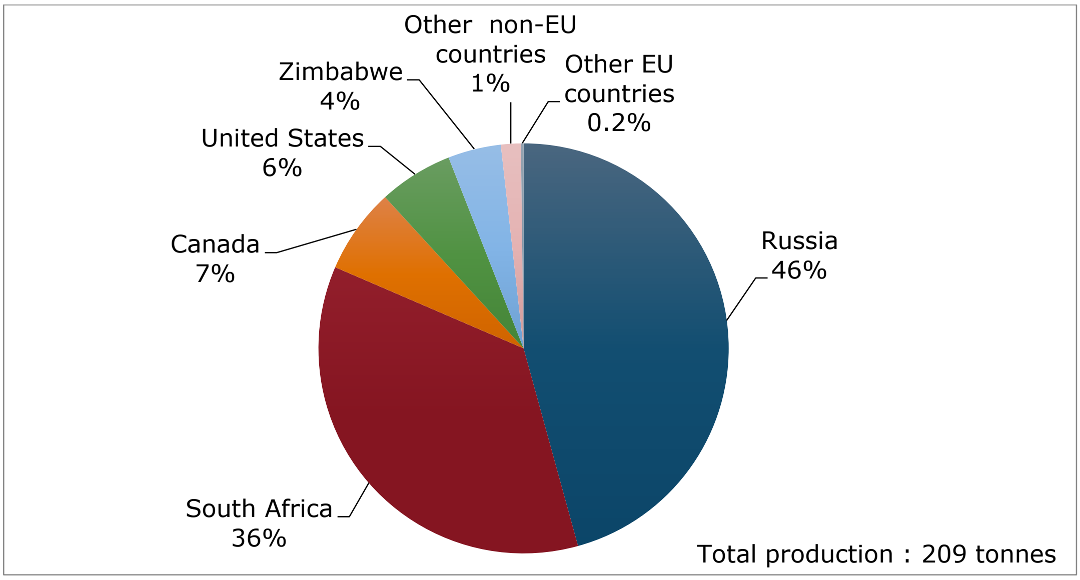


Figure 141: The distribution of global mine production of palladium, average 2010–2014. (Data from BGS World Mineral Statistics database BGS, 2016)

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[18] www.crirsco.com

South Africa was the second most important producer (36 % of total), followed by Canada (7 %) and USA (6 %). Little extraction is performed in the EU (0.2% of the global production), mainly in Finland (less than 400 kg), Poland and Serbia (about 20 kg).

19.2.2 Supply from secondary materials

As discussed in the PGM Factsheet, recycling makes an important and growing contribution to global PGM supply. The high value of palladium makes it generally attractive for recycling and sophisticated technology has been developed that permits highly effective recovery of palladium from a variety of waste streams, notably autocatalysts and waste electrical and electronic equipment (WEEE). However, the end of life recycling rate varies considerably by country and by application. Closed loop recycling can achieve very high levels of palladium recovery, whereas in open loop recycling the rate achieved is critically dependent on numerous factors, particularly the prevailing palladium price and a host of others that influence the collection efficiency of end of life products. The EoL-RIR used is this assessment is 10% (JRC, 2016).

In addition to recovery from end of life products palladium is also recycled from a range of intermediate products and wastes from mineral beneficiation, smelting, refining and manufacturing processes. There is believed to be significant international trade in palladium-bearing waste and scrap, but Eurostat data are not available to ascertain the volumes involved.

According to BGRM, the supply of palladium from secondary materials was 38% of total supply i.e. 64.5 tonnes in 2013, of which 75% came from autocatalysts and 17% from WEEE (BRGM, 2015).

19.2.3 EU trade

As discussed in the PGM Factsheet the PGM are traded in the EU in a variety of forms – as metal in unwrought or powder form, in semi-manufactured forms and various intermediate products and wastes. For palladium, trade data are available only for palladium metal in unwrought or powder form (Combined Nomenclature (CN) code 7110 2100). Figure 142 shows EU trade in palladium metal with non-EU countries. While it is clear that there is considerable trade in palladium metal, it is not possible to determine if that metal was derived from primary or secondary material.

The EU import reliance for palladium is 100%. The EU imports about 56.5 tonnes of Pd in average over the 2010-2014 period (Eurostat, 2016a). The main sources of EU imports of palladium metal are Russia, Switzerland, South Africa and the USA (Figure 143). While Russia, South Africa and USA are integrated primary producers, Switzerland has traditionally been a central point of PGM storage and distribution by producers, traders and bankers. Major platinum and palladium exchange-traded funds, which are based on physical holdings of these metals, are also located in Switzerland.

The EU exported about 65 tonnes of palladium metal per annum between the years 2010–2014. The main destinations for these exports were USA (39 %), China (17 %), Switzerland (9 %) and Brazil (8 %). Japan, South Korea and Macedonia each received about 5 % of the total exports.

No trade restrictions have been reported over the 2010-2014 period (OECD, 2016). The EU and South Africa have a free trade agreement in place (European Commission, 2016).

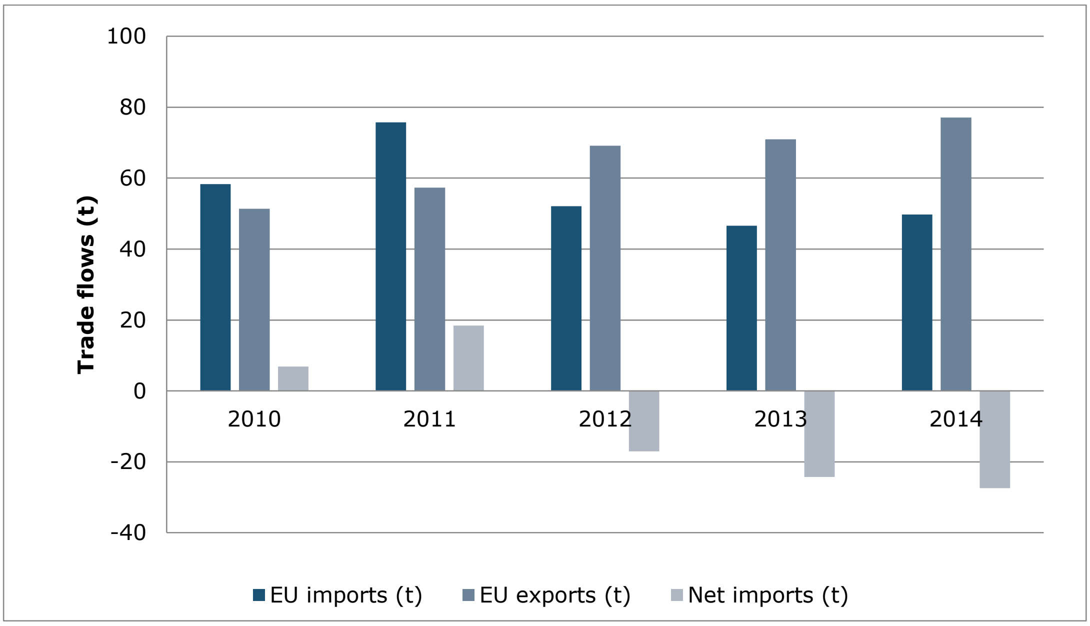

Figure 142: EU trade in palladium metal, in unwrought or powder form, with non-EU countries, 2010–2014 (Data from Comext database - Eurostat, 2016a)

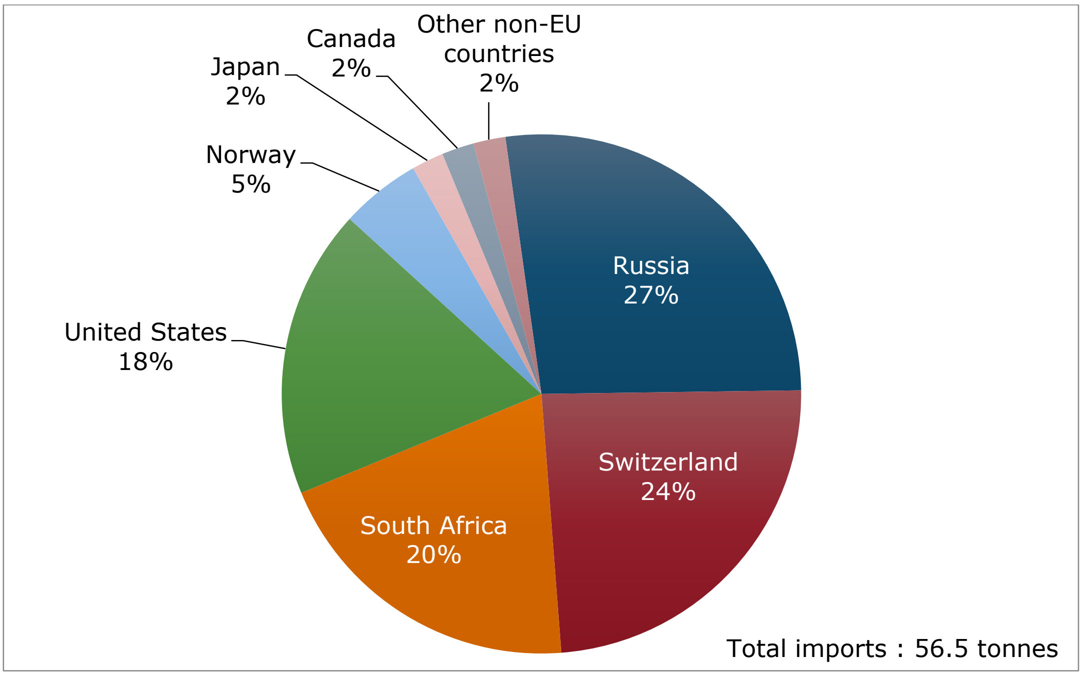

Figure 143: The distribution of EU imports of palladium metal, in unwrought or powder form, from non-EU countries, 2010–2014 (Data from Comext database - Eurostat, 2016a)

19.2.4 EU supply chain

The supply chain for palladium in the EU is complex and difficult to quantify. It is discussed in the PGM Factsheet. Palladium supplies are derived from both primary sources (mines) and secondary sources (refineries). The EU is 100% reliant on palladium imports. Refineries in the EU process a wide range of palladium-bearing materials emanating from European and overseas sources. These include end-of-life products, such as autocatalysts and WEEE, and manufacturing waste (new scrap). By-products from the non-ferrous mining, processing and manufacturing industries also contribute to the EU supply of palladium. These include concentrates, slags, mattes, flue dust, ash, slimes and other residues. EU mine production makes a small contribution (c. 0.4 tonnes, average 2010–2014) to European palladium supply. About 94 % of this is from Finland and the remainder from Poland.

19.3 Demand

19.3.1 EU consumption

Given the diversity of forms in which palladium is traded, the lack of data on trade in palladium-bearing waste and scrap and the absence of any distinction between palladium derived from primary and secondary source materials, it is not possible to determine a single reliable figure for EU consumption of palladium.

In 2015 palladium demand in Europe amounted to approximately 55 tonnes, which was about 19 % of global demand. The majority of that was used in autocatalysts (see following section). According to BRGM, in 2013 the European consumption of palladium was 60.5 tonnes (BRGM, 2015).

19.3.2 Applications

The main uses of palladium are discussed in the PGM Factsheet. Gross global demand for palladium in 2015 was about 290 tonnes (Johnson Matthey, 2016). The predominant global use was in autocatalysts, which accounted for 72 % of demand (Figure 144). The remainder was used chiefly in chemical, dental and electrical applications. In Europe, the pattern of use was similar, although autocatalysts dominated even more strongly, accounting for nearly 92 % of demand (Johnson Matthey, 2016).

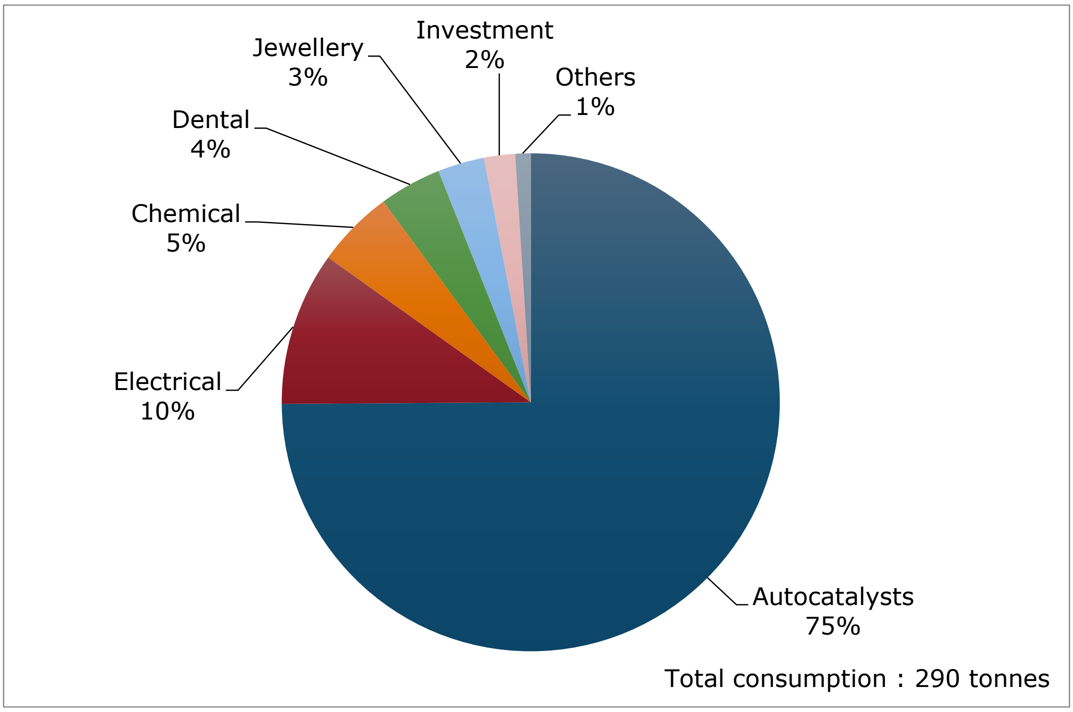

Figure 144: Global end uses of palladium in 2015 (Data from Johnson Matthey, 2016)

The level of global investment demand for palladium has fluctuated considerably since 2011. Unlike platinum, almost all palladium investment is accounted for by exchange-traded funds (ETFs). As shown in Figure 142, there was considerable selling of palladium ETFs during 2015 as a result of continuing uncertainty over world economic growth

(Johnson Matthey, 2016). The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 80.

Table 80: Palladium applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016c)

Applications	2-digit NACE sectors	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
Autocatalysts	C29 - Manufacture of motor vehicles, trailers and semi-trailers	158,081	C2932 - Manufacture of other parts and accessories for motor vehicles
Electrical	C26 - Manufacture of computer, electronic and optical products	75,260	C2611 - Manufacture of electronic components
Chemical	C20 - Manufacture of chemicals and chemical products	110,000	C2015 - Manufacture of fertilisers and nitrogen compounds
Dental	C32 - Other manufacturing	41,612	C3250 - Manufacture of medical and dental instruments and supplies
Jewellery	C32 - Other manufacturing	41,612	C3212 - Manufacture of jewellery and related articles

Investment* - there is no NACE code associated with investment and therefore no related value-added.

19.3.3 Prices and markets

Like platinum, palladium is typically exchange traded with a number of daily market prices quoted for the pure (minimum 99.99%) metal in US dollars per troy ounce. Palladium is also sold through long-term supply contracts between fabricators and mines. The price of palladium, shown in the PGM Factsheet, has shown a high degree of volatility in recent years in response to changing global economic conditions. In 2015 the price averaged US$692, a fall of 14% from the previous year (Thomson Reuters, 2016). In 2014 a major market deficit had supported the palladium price, whereas in 2015 supply from South Africa increased considerably while demand remained little changed.

19.4 Substitution

The high price of palladium and the perceived possibility of future supply disruptions have led to considerable interest in finding alternatives to palladium in many applications. Nassar (2015) reviewed the possibilities for elemental substitution of the PGM in their main applications. For palladium the potential substitutes are other PGM, gold or base metals, although these may have associated price or performance penalties. Given that the PGM are co-products, in the event of a supply disruption of palladium, the ability to substitute it with platinum is likely to be limited. In the investment sector palladium may be substituted by gold or other PGM (platinum and rhodium), but the level of this is dependent on many factors, chiefly related to price because, unlike other applications, palladium investment is strongly price elastic.

19.5 Discussion of the criticality assessment

19.5.1 Data sources

Production data for palladium was taken from the British Geological Survey's World Mineral Statistics dataset (BGS, 2016) and represents global production from primary producing countries. The BGS data are reported as mine production in kilograms of contained metal, although, in fact, the material sold by the mines is generally neither ore nor concentrate but rather refined metal. There is no CN8 code specific to palladium ores and concentrates. The most relevant CN8 code would be 26169000: *Precious metal ores and concentrates excluding silver*. However this code reports data for several precious metals and it is therefore inappropriate to use in the palladium assessment.

Trade data for unwrought palladium metal was extracted from the Eurostat COMEXT online database (Eurostat, 2016a) using the Combined Nomenclature (CN) code 7110 2100. These data were averaged over the five-year period 2010–2014. The trade data include metal from all sources, both primary and secondary. It is not therefore possible to identify the source of the metal and the relative contributions of primary and secondary materials. In reality, Europe is a major producer of refined palladium, which originates both from primary and secondary materials, and therefore the actual net import reliance is much lower than calculated using the global HHI. The EU reliance on imports from secondary sources is a significant factor for the security of palladium supply, but is not within the scope of this project.

Other data sources are listed in section 19.7.

19.5.2 Calculation of economic importance and supply risk indicators

For the calculation of Economic Importance (EI), the 2-digit NACE sectors shown in Table 80 were used. For information relating to the application share of each category, see section on applications and end-uses. As required by the methodology, the application shown as 'others' was distributed among the remaining applications. The figures for value added were the most recently available at the time of the assessment, i.e. 2013.

The calculation of the Supply Risk (SR) was carried out at the refined material stage of the life cycle using only the global HHI calculation. Actual supply to the EU cannot be determined from Eurostat because the trade data do not discriminate between palladium metal derived from primary and secondary sources. The Eurostat trade data include metal from different life cycle stages and from numerous sources/countries. It cannot therefore be used to calculate the risk to primary palladium supply to the EU.

While there is a possibility to substitute palladium in some of its applications, it has not generally been possible to quantify the shares of the substitute materials currently in use. In autocatalysts the shares of the market held by platinum and palladium are well known from data published regularly by Johnson Matthey and other organisations, but in practice the amount of substitution that might be achieved is difficult to quantify as it depends on numerous economic and technical factors. In electrical and electronic applications gold, nickel and copper are possible substitutes for palladium. However, the high price of gold is generally a deterrent to its use, while the use of nickel or copper are generally associated with some reduction in performance. Consequently for many high-tech electronics applications palladium remains the material of choice. In the manufacture of various organic and inorganic chemicals palladium is normally used in conjunction with other metals in long established formulations to catalyse specific chemical processes. Although palladium substitution might be possible in some of these, there is generally little economic or technical incentive to do so, especially as the catalysts are recycled very efficiently.

The end of life recycling input rate for palladium was calculated from data collected in the MSA study carried out for the European Commission (Bio by Deloitte, 2015).

19.5.3 Comparison with previous EU criticality assessments

The results of this review and earlier assessments are shown in Table 81.

Table 81: Economic importance and supply risk results for palladium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011		2014		2017	
Indicator	EI	SR	EI	SR	EI	SR
Palladium	6.68*	3.63*	6.58*	1.18*	5.6	1.7

*in the 2011 and 2014 assessments the PGM were considered as a single group which included palladium. In the current assessment palladium was considered as a single metal

19.6 Other considerations

The factors affecting the future supply and demand for palladium have been discussed in the PGM Factsheet. It is considered that Russia and South Africa will continue to be the main global suppliers of palladium. Although palladium may be considered as a by-product of nickel mining in Russia, it is unlikely that this will become a constraint on palladium supply, at least in the short term. Global geological resources of PGM are very large relative to current levels of consumption and there is considerable potential in the longer term to find additional resources in other countries and in other geological settings.

Recycling currently makes an important contribution to palladium supply and, given favourable economic conditions and supportive legislation, the share of palladium from secondary materials is likely to increase as end of life products are collected more efficiently and processed using the optimum technology.

In the short term the imposition of increasingly strict emission control legislation across the world is likely to continue to increase demand for palladium in autocatalysts. In the longer term the move away from carbon-based fuels for powering road vehicles may lead to reduced demand for palladium.

Table 82: Qualitative forecast of supply and demand of palladium

Material	Demand forecast			Supply forecast		
	5 years	10 years	20 years	5 years	10 years	20 years
Palladium	+	+	?	+	+	?

19.7 Data sources

19.7.1 Data sources used in the factsheet

BGS. (2016). World Mineral Statistics database. [online] Available at: https://www.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS

Bio Intelligence Service (2015). Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials – Final Report. Prepared for the European Commission, DG GROW. p 41-43

BRGM. (2015). Fiche de synthèse sur la criticité des métaux - Le palladium. [online] Available at: http://www.mineralinfo.fr/sites/default/files/upload/documents/Fiches_criticite/fichecriticitepalladium-publique150409.pdf

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European Commission (2016). DG Trade. Agreements [online] Available at: http://ec.europa.eu/trade/policy/countries-and-regions/agreements/

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Johnson Matthey. (2016). PGM Market Report May 2016. [online] Available at: http://www.platinum.matthey.com/services/market-research/pgm-market-reports

Nassar, N. (2015). Limits to elemental substitution as exemplified by platinum-group metals. Green Chemistry, 17, 2226–2235.

Rudnick, R.L. and Gao. S. (2003). Composition of the Continental Crust. In: Treatise on Geochemistry, Volume 3. Editor: Roberta L. Rudnick. Executive Editors: Heinrich D. Holland and Karl K. Turekian. pp. 659. ISBN 0-08-043751-6. Elsevier, p.1-64

Thomson Reuters. (2016). GFMS Platinum Group Metals Survey 2016.

19.7.2 Data sources used in the criticality assessment

BGS. (2016). British Geological Survey World Mineral Statistics database. online] Available at: https://www.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS

Bio by Deloitte. (2015). Study on Data for a Raw Material System Analysis. Background data (unpublished)

European Commission. (2016) EU trade agreements webpage [online]. Directorate General for Trade. http://ec.europa.eu/trade/policy/countries-and-regions/agreements/index_en.htm

Eurostat. (2016) International trade in goods database (COMEXT) [online]. http://ec.europa.eu/eurostat/data/database

Johnson Matthey. (2016). PGM Market Report May 2016. [online] Available at: http://www.platinum.matthey.com/services/market-research/pgm-market-reports

OECD. (2016) Export restrictions on Industrial Raw Materials database [online]. http://qdd.oecd.org/table.aspx?Subject=ExportRestrictions_IndustrialRawMaterials

19.8 Acknowledgments

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20. PLATINUM

Key facts and figures

Material name and Element symbol	Platinum Pt	World/EU production (tonnes)[1]	187 / 0.5
Parent group (where applicable)	Platinum-Group Metals (PGM)	EU import reliance[1]	98%
Life cycle stage / material assessed	Processing / refined metal	Substitution index for supply risk [SI (SR)][1]	0.98
Economic importance (EI) (2017)	4.9	Substitution Index for economic importance [SI(EI)][1]	0.86
Supply risk (SR) (2017)	2.2	End of life recycling input rate	11%
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Autocatalysts (69%), jewellery (9%), chemical (6%)
Main product, co-product or by-product	Main-product (with other PGM); by-product (with Ni and Cu)	Major world producers[1]	South Africa (71%), Russia (16%), Zimbabwe (6%)

[1] average for 2010-2014, unless otherwise stated;

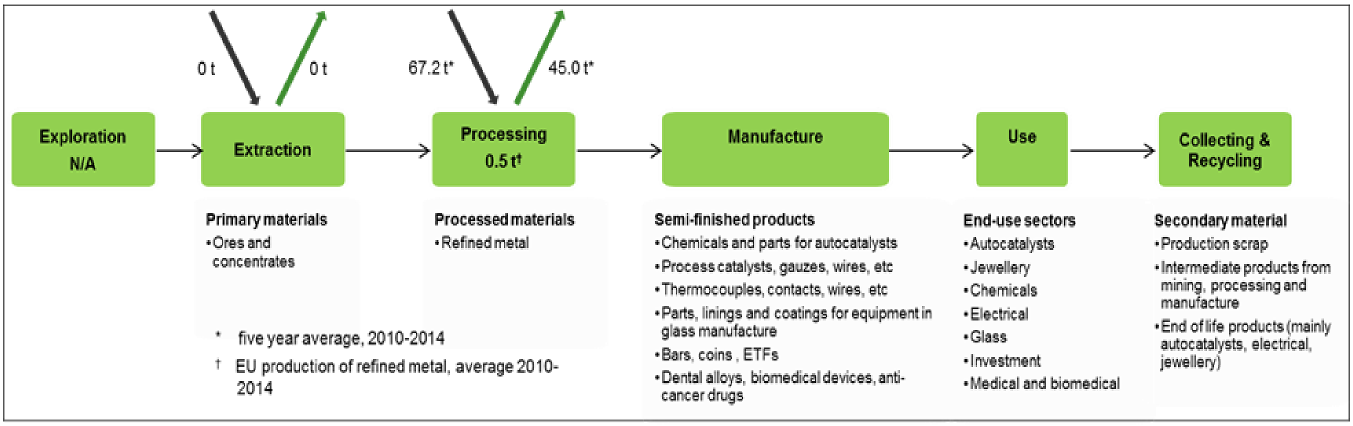

Figure 145: Simplified value chain for platinum

The green boxes in the figure above identify activities undertaken within the EU. The thick black arrows represent imports to the EU and the green arrows represent exports from the EU. Platinum-bearing ores and concentrates are not generally traded in the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

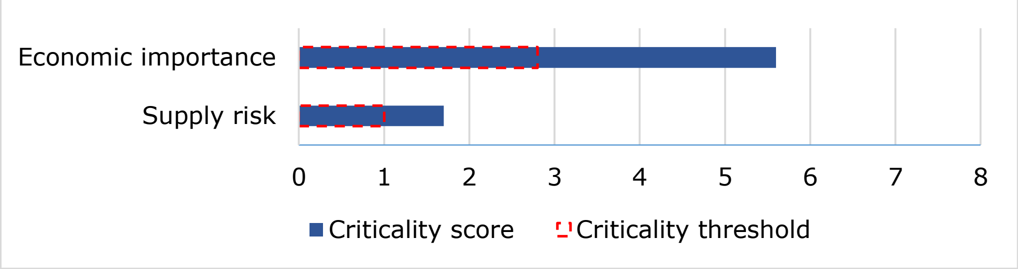

Figure 146: Economic importance and supply risk scores for platinum

20.1 Introduction

Platinum (Pt) is one the six chemical elements referred to as the platinum-group metals (PGM) or the platinum-group elements (PGE), which are, in order of increasing atomic number: ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). These metals are very rare in the Earth's crust with abundances in the range 1-5 parts per billion (ppb). The abundance of platinum in the upper crust is 0.5 ppb (Rudnick, 2003).They tend to be found together, commonly associated with ores of nickel and copper. The PGM occur in numerous alloys, in base metal sulfide minerals and in a wide variety of PGM-bearing minerals with, among others, sulfur, arsenic, antimony and tellurium. They rarely occur in native form. The PGM are highly resistant to wear, tarnish, chemical attack and high temperature. The PGM are regarded as precious metals, like gold and silver. All PGM, commonly combined with one another or with other metals, can act as catalysts which are exploited in a wide range of applications. Platinum and palladium are of major commercial significance, with rhodium the next most important. The main use of platinum is in autocatalysts, with jewellery and chemical manufacture the second and third most important applications respectively.

Almost all platinum derived from primary source materials (i.e. mine production) is traded in the form of refined metal produced from integrated mining/metallurgical operations. There is only very limited international trade in platinum ores and concentrates.

Most topics related to platinum have been covered in the general PGM Factsheet that deals with the five PGM (excluding osmium) together. This is because the PGM occur together in nature and are generally co-products from the same deposits. Also, much of the available public data deals with them as a group. They are, therefore, commonly discussed together, with comparisons drawn between individual PGM where data allow. In this factsheet additional information and data specific to platinum are presented where available.

20.2 Supply

20.2.1 Supply from primary materials

The geological occurrence, mining, processing, extractive metallurgy and resources and reserves have been discussed in the general PGM Factsheet.

In addition to the major resources derived from mafic-ultramafic igneous complexes like the Bushveld Igneous Complex in South Africa and the nickel sulfide deposits in Russia and elsewhere, platinum is also known to be enriched to potentially economic concentrations in several other geological settings (Gunn, 2014). Small-scale production from placer deposits has taken place for many decades in the Urals and the Russian Far East, in Colombia, Alaska and New Zealand. High tenor platinum values are also known in Alaskan-Ural type complexes, in ophiolites and hydrothermal veins, but these are not currently worked for platinum. Low grade platinum enrichments are also well known in laterites, unconformity-related gold-uranium deposits, porphyry deposits, black shales and carbonatites and other alkaline complexes. These settings have not been the source of platinum production to date, but platinum might in the future become available as a by-product of other metals in deposits of these types.

20.2.1.1 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of platinum in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[19], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for platinum. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for platinum, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for platinum at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

Platinum data are normally reported in combination with other PGM, most commonly with palladium and sometimes with rhodium and/or gold. See the PGM factsheet for more details. Some mining companies publish separate resource and reserve data for platinum in individual deposits. An estimate from BRGM, made by compiling mining companies' data, announces about 7,905 t of global reserves of platinum in 2013 (BRGM, 2015), with most of them located in South Africa (81.7%), followed by Zimbabwe (7.3%), Russia (5.9%), USA (1.6%), and Canada (1.6%) (BRGM, 2015).

20.2.1.2 World mine production

Average annual world mine production of platinum for the period 2010-14 was 187 tonnes having fallen from a high of 226 tonnes in 2011 as a result of weak global demand. Global supply is dominated by South Africa which accounted for about 70 % of the total (Figure 147). Russia was the second most important producer (16 % of total), followed by Zimbabwe (6 %) and Canada (4 %). Little extraction is performed in the EU (0.3% of the global production), mainly in Finland (less than 500 kg), Poland (40 kg) and Serbia (3 kg).

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[19] www.crirsco.com

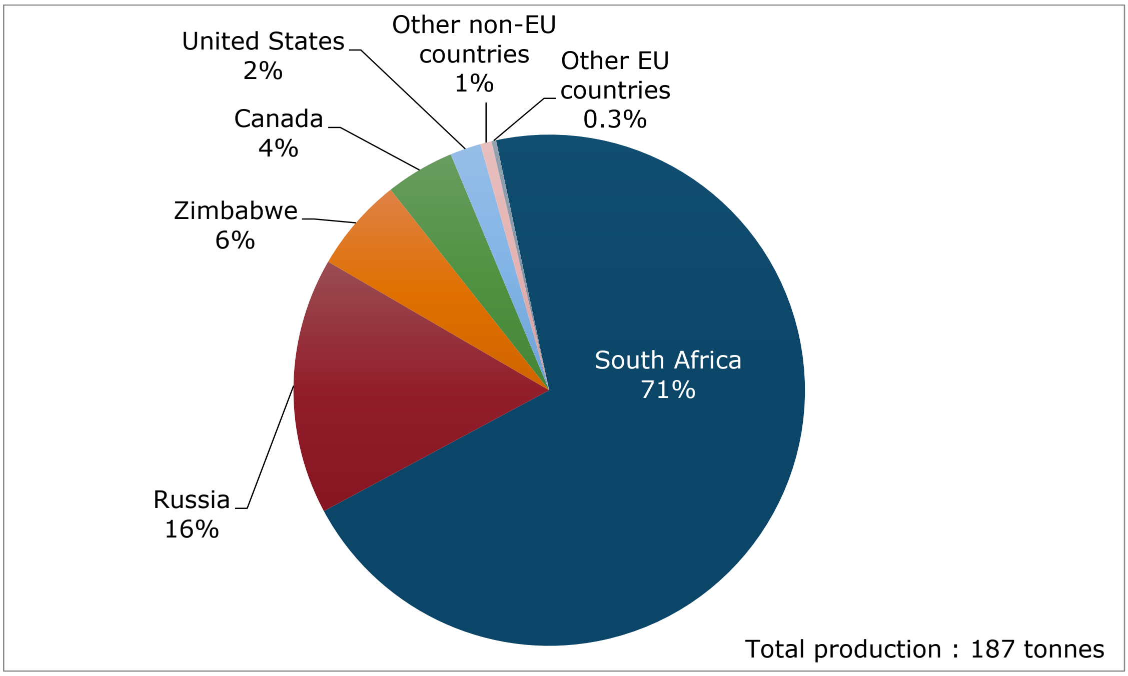

Figure 147: The distribution of global mine production of platinum, average 2010–2014. (Data from BGS World Mineral Statistics database (BGS, 2016))

20.2.2 Supply from secondary materials

As discussed in the PGM Factsheet, recycling makes an important and growing contribution to global PGM supply. The high value of platinum makes it generally attractive for recycling and sophisticated technology has been developed that permits highly effective recovery of platinum from a variety of waste streams. However, the end of life recycling rate varies considerably by country and by application. Closed loop recycling can achieve very high levels of platinum recovery, whereas in open loop recycling the rate achieved is critically dependent on numerous factors, particularly the prevailing platinum price and a host of others that influence the collection efficiency of end of life products. The EoL-RIR used is this assessment is 11% (JRC, 2016).

In addition to recovery from end of life products platinum is also recycled from a range of intermediate products and wastes from mineral beneficiation, smelting, refining and manufacturing processes. There is significant international trade in platinum-bearing waste and scrap (see following section).

According to BGRM, the supply of platinum from secondary materials was 26% of total supply i.e. 64.5 tonnes in 2013 (BRGM, 2015), of which 61% came from autocatalysts and 37% from jewellery (BRGM, 2015).

20.2.3 EU trade

As discussed in the PGM Factsheet the PGM are traded in the EU in a variety of forms – as metal in unwrought or powder form, in semi-manufactured forms and various intermediate products and wastes. For platinum, trade data are available for platinum waste and scrap (Combined Nomenclature (CN) code 7112 9200), for platinum metal in unwrought or powder form (CN code 7110 1100) and for platinum catalysts in the form of wire cloth or grill (CN code 7115 1000).

EU trade in platinum catalysts is relatively small compared with unwrought metal or powder and compared with platinum waste and scrap (Figure 148). For waste and scrap the tonnages shown are gross weight and, because the platinum concentration of the waste and scrap is not specified, the actual platinum content is not known. Nevertheless it is clear that the EU imports and exports considerable quantities of platinum in waste and scrap thus making an important contribution to the supply chain.

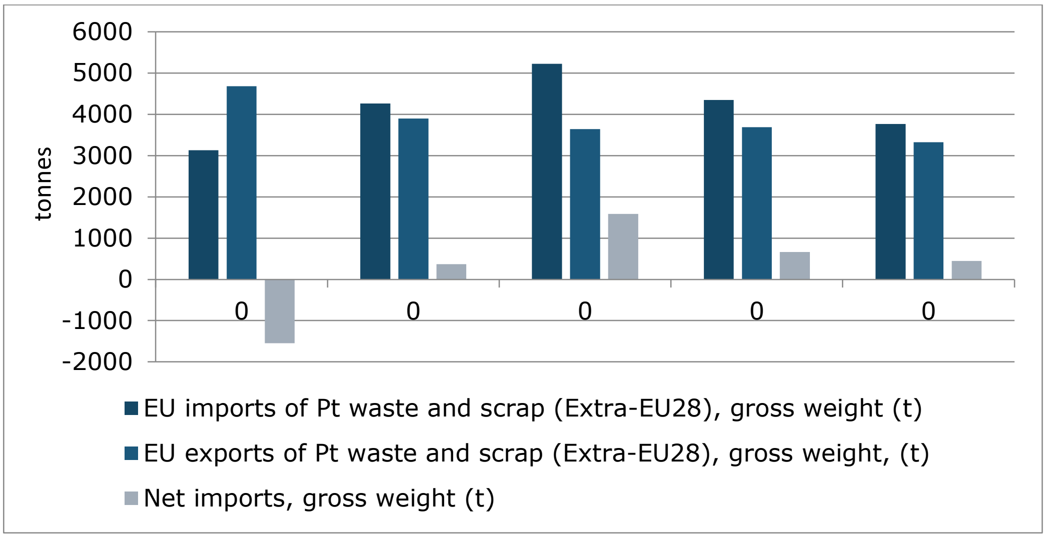

Figure 148: EU trade in platinum-bearing waste and scrap with non-EU countries, 2010–2014 (Data from Comext database (Eurostat, 2016a))

The EU import reliance for platinum is 98%. The EU imports about 67.2 tonnes of Pt in average over the 2010-2014 period (Eurostat, 2016a). The EU imports platinum waste and scrap from many countries (Figure 149). In contrast, 95 % of the exports of platinum waste and scrap from the EU go to the United States, with the majority of the remainder going to South Africa and South Korea. These trade patterns are considered to relate to the global distribution of the appropriate technologies for handling different types of waste and scrap materials, with some being processed in European facilities and others in the United States.

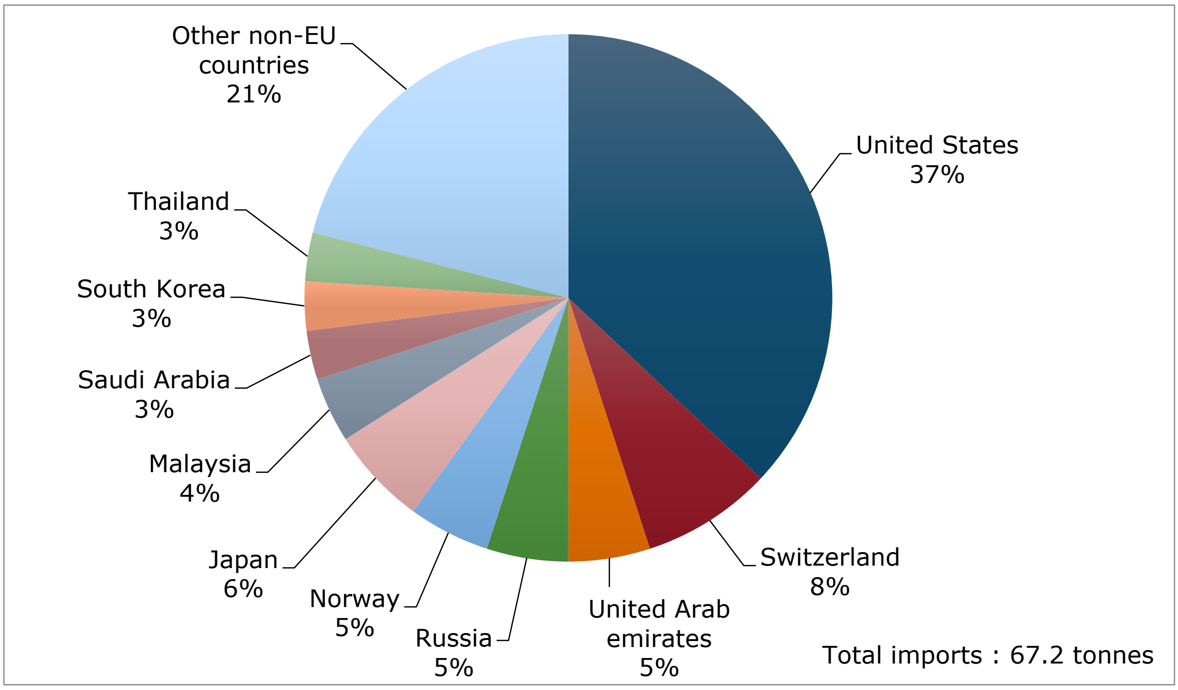

Figure 149: EU imports of platinum-bearing waste and scrap in 2014 (Data from Comext database: Eurostat, 2016a)

EU trade in platinum metal, in unwrought or powder form, with non-EU countries is shown in Figure 150. It is clear that there is considerable trade in platinum metal, although it is not possible to determine if that metal was derived from primary or secondary material.

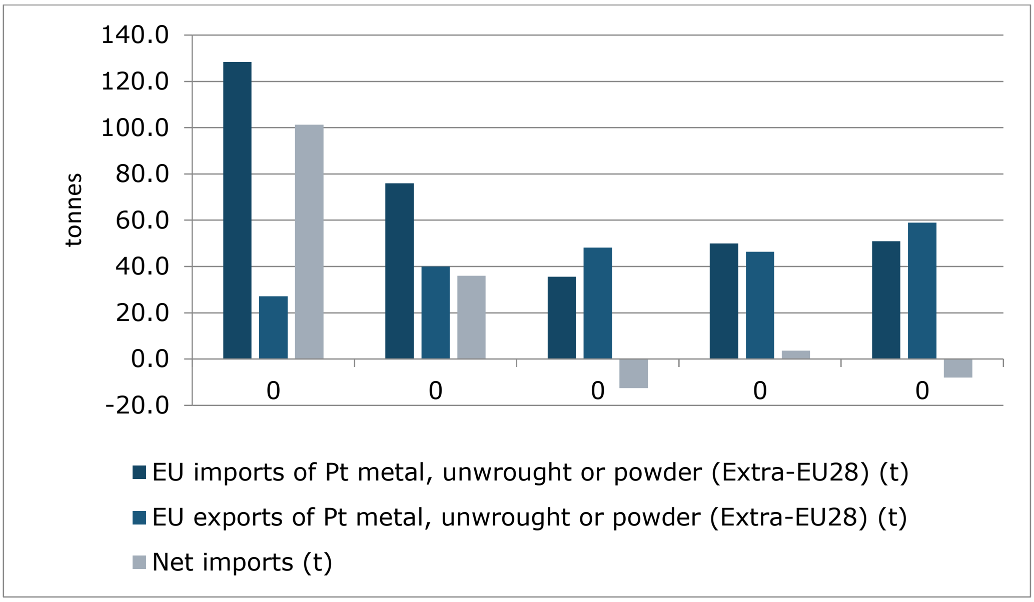

Figure 150: EU trade in platinum metal, in unwrought or powder form, with non-EU countries, 2010–2014 (Data from Comext database (Eurostat, 2016a))

Russia has put an export tax up to 25% over the 2010-2014 period (OECD, 2016). The EU have free trade agreements in place with South Africa and Serbia (European Commission, 2016).

20.2.4 EU supply chain

The supply chain for platinum in the EU is complex and difficult to quantify. It is discussed in the PGM Factsheet. Platinum supplies are derived from both primary sources (mines) and secondary sources (refineries). The EU is 98% reliant on platinum imports. Refineries in the EU process a wide range of platinum-bearing materials emanating from European and overseas sources. These include end-of-life products, such as autocatalysts and jewellery, and manufacturing waste (new scrap). By-products from the non-ferrous mining, processing and manufacturing industries also contribute to the EU supply of platinum. These include concentrates, slags, mattes, flue dust, ash, slimes and other residues. EU mine production makes a small contribution to European platinum supply, with annual production of about one tonne, about 90 % of which is from Finland and the remainder from Poland.

20.3 Demand

20.3.1 EU consumption

Given the diversity of forms in which platinum is traded, uncertainty about the platinum content of platinum-bearing waste and scrap and the absence of any distinction between platinum derived from primary and secondary source materials, it is not possible to determine a single reliable figure for EU consumption of platinum.

In 2015, platinum demand in Europe amounted to approximately 65 tonnes, which was about 25 % of global demand. The majority of that, about 69 %, was used in autocatalysts (see following section).

20.3.2 Applications

The main uses of platinum are discussed in the PGM Factsheet. There are, however, some notable differences between patterns of platinum use in Europe and the rest of the world (Figure 151 and Figure 152 respectively).

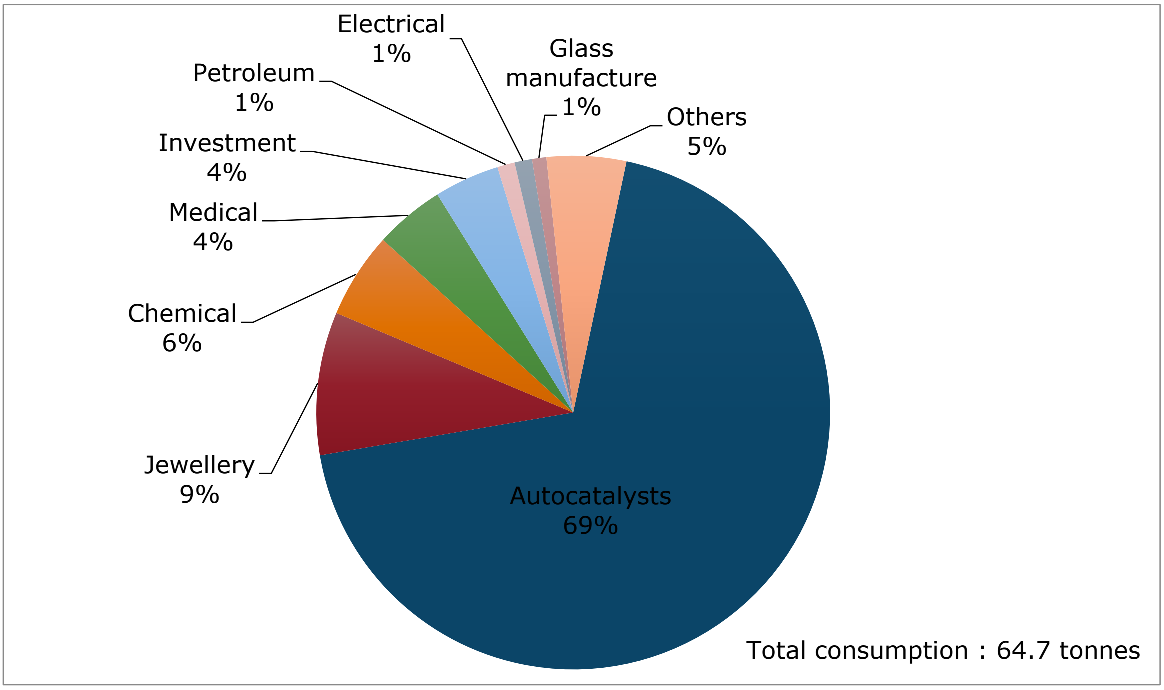

Figure 151: End uses of platinum in the EU in 2015. (Data from Johnson Matthey, 2016)

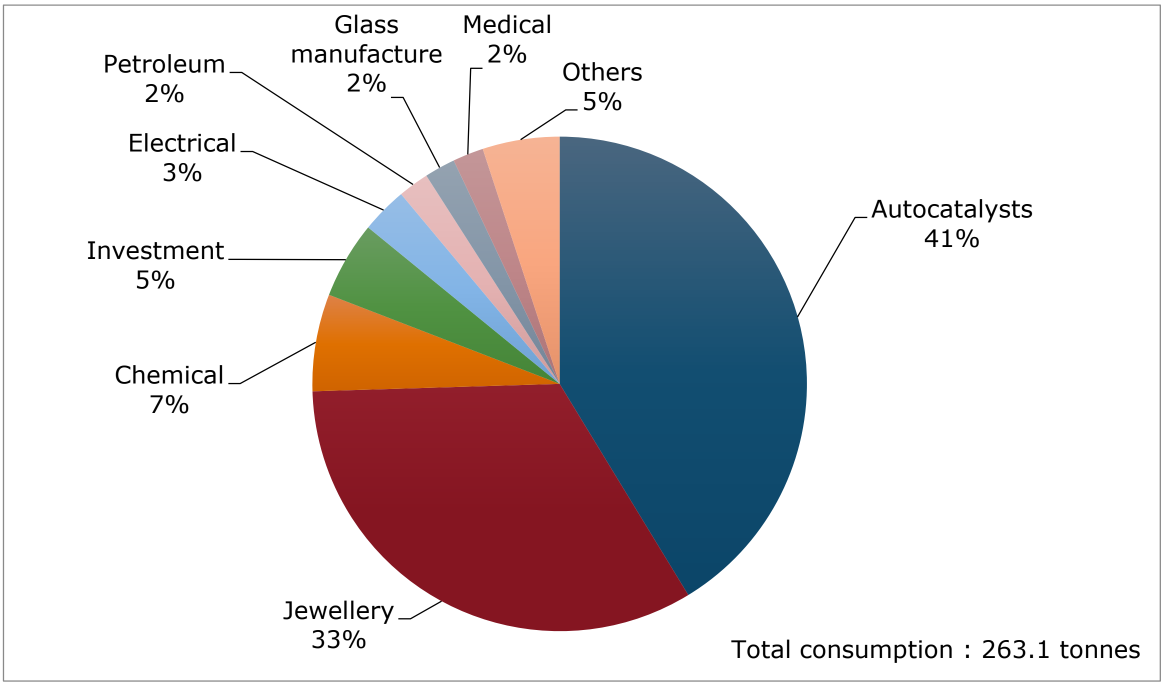

Figure 152: Global end uses of platinum in 2015. (Data from Johnson Matthey, 2016)

In Europe, the use of platinum is very much dominated by autocatalysts (69%), reflecting the dominance of diesel-powered vehicles in the European vehicle fleet compared with the rest of the world (Figure 151). The second most important use of platinum is in jewellery, which also shows a marked difference between Europe and the rest of the world. Jewellery accounted for about 33 % of world platinum use in 2015, compared with close to 10 % in Europe. This difference can be accounted for by the growing market for platinum jewellery in China, Japan and India. The proportions of platinum used in chemical manufacture and oil refining are similar in the EU (5.4 %) and the rest of the world (6.3 %). In electrical/electronic applications and glass making demand in Europe is considerably less than elsewhere (Figure 152).

The level of global investment demand for platinum fluctuated considerably between 2011 and 2015 but remained positive. In contrast investment demand in Europe has been negative in 2013, 2014 and 2015 as investors returned their platinum holdings to the market (Johnson Matthey, 2016).

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 83.

Table 83: Platinum applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016c)

Applications	2-digit NACE sectors	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
Autocatalysts	C29 - Manufacture of motor vehicles, trailers and semi-trailers	158,081.4	C2932 - manufacture of other parts and accessories for motor vehicles
Jewellery	C32 - Other manufacturing	41,612.6	C3212 - manufacture of jewellery and related articles
Chemical	C20 - Manufacture of chemicals and chemical products	110,000.0	C2013 - manufacture of other inorganic basic chemicals; C2014 - manufacture of other organic basic chemicals; C2015 - manufacture of fertilisers and nitrogen compounds
Medical	C32 - Other manufacturing	41,612.6	C3250 - manufacture of medical and dental instruments and supplies
Petroleum	C19 - Manufacture of coke and refined petroleum products	13,547.3	C1920 - manufacture of refined petroleum products
Electrical	C26 - Manufacture of computer, electronic and optical products	75,260.3	C2620 - manufacture of computers and peripheral equipment; C2640 - manufacture of consumer electronics; C2680 - manufacture of magnetic and optical media
Glass manufacture	C23 - Manufacture of other non-metallic mineral products	59,166.0	C2311 – manufacture of flat glass

Investment* - there is no NACE code associated with investment and therefore no related value-added.

20.3.3 Prices and markets

Platinum is typically exchange traded with a number of daily market prices quoted for the pure (minimum 99.99%) metal in US dollars per troy ounce. Platinum is also sold through long-term supply contracts between fabricators and mines. After a long period of relative stability during the 1990s it followed a generally upward trend following the wide introduction of emission control legislation. However, since the global economic recession the price has generally declined: in 2015 the average price was US$1053 per ounce, see Figure 153, the one the lowest levels in 10 years (Thomson Reuters, 2016).

Figure 153: The price of platinum, December 2001 – December 2016 (data from Johnson Matthey, 2016b)

20.4 Substitution

The high price of platinum and the perceived possibility of future supply disruptions have led to considerable interest in finding alternatives to platinum in many applications. Nasser (2015) reviewed the possibilities for elemental substitution of the PGM in their main applications. For platinum the potential substitutes are other PGM or base metals, although these may have associated price or performance penalties. Given that the PGM are co-products, in the event of a supply disruption of platinum, the ability to substitute it with palladium is likely to be limited. Although the substitution of platinum in jewellery is possible, in practice cultural attitudes and historical factors greatly restrict this from happening. In the investment sector platinum may be substituted by gold or other PGM (palladium and rhodium), but the level of this is dependent on many factors, chiefly related to price because, unlike other applications, platinum investment is strongly price elastic.

20.5 Discussion of the criticality assessment

20.5.1 Data sources

Production data for platinum was taken from the British Geological Survey's World Mineral Statistics dataset BGS, 2016) and represents global production from primary producing countries. The BGS data are reported as mine production in kilograms of contained metal, although, in fact, the material sold by the mines is generally neither ore nor concentrate but rather refined metal. There is no CN8 code specific to platinum ores and concentrates. The most relevant CN8 code would be 26169000: *Precious metal ores and concentrates excluding silver*. However this code reports data for several precious metals and it is therefore inappropriate to use in the platinum assessment.

Trade data for unwrought platinum metal was extracted from the Eurostat COMEXT online database (Eurostat, 2016a) and used the Combined Nomenclature (CN) code 7110 1100. These data were averaged over the five-year period 2010–2014. The trade data include metal from all sources, both primary and secondary. It is not therefore possible to identify the source of the metal and the relative contributions of primary and secondary materials. In reality, Europe is a major producer of refined platinum, which originates both from primary and secondary materials, and therefore the actual net import reliance is much lower than calculated using the global HHI. The EU reliance on imports from secondary sources is a significant factor for the security of platinum supply, but is not within the scope of this project.

Other data sources are listed in section 20.7.

20.5.2 Calculation of economic importance and supply risk indicators

For the calculation of Economic Importance (EI), the 2-digit NACE sectors shown in Table 83 were used. For information relating to the application share of each category, see section on applications and end-uses. As required by the methodology, the application shown as 'others' was distributed among the remaining applications. The figures for value added were the most recently available at the time of the assessment, i.e. 2013.

The calculation of the Supply Risk (SR) was carried out at the refined material stage of the life cycle using only the global HHI calculation. Actual supply to the EU cannot be determined from Eurostat because the trade data do not discriminate between platinum metal derived from primary and secondary sources. The Eurostat trade data include metal from different life cycle stages and from numerous sources/countries. It cannot therefore be used to calculate the risk to primary platinum supply to the EU.

While there is a possibility to substitute platinum in some of its applications, it has not generally been possible to quantify the shares of the substitute materials currently in use. In autocatalysts the shares of the market held by platinum and palladium are well known from data published regularly by Johnson Matthey and other organisations, but in practice the amount of substitution that might be achieved is difficult to quantify as it depends on numerous economic and technical factors. In jewellery platinum is not considered to be substitutable for cultural and historic reasons. In the chemicals industry platinum is normally used in conjunction with other metals in long established formulations to catalyse specific chemical processes. Although platinum substitution might be possible in some of these, there is generally little economic or technical incentive to do so, especially as the catalysts are recycled very efficiently.

The end of life recycling input rate for platinum was calculated from data collected in the MSA study carried out for the European Commission (Bio by Deloitte, 2015).

20.5.3 Comparison with previous EU criticality assessments

The results of this review and earlier assessments are shown in Table 84.

Table 84: Economic importance and supply risk results for platinum in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Platinum	6.68*	3.63*		6.58*	1.18*		4.9	2.2

*in the 2011 and 2014 assessments the PGM were considered as a single group which included platinum. In the current assessment platinum was considered as a single metal

20.6 Other considerations

The factors affecting the future supply and demand for platinum have been discussed in the PGM Factsheet. As mentioned, it is considered that South Africa will continue to be the main global supplier of platinum. Geological resources in South Africa and Zimbabwe are very large relative to current levels of consumption and there is considerable potential in the longer term to find additional resources in other countries and in other geological settings. Recycling currently makes an important contribution to platinum supply and, given favourable economic conditions and supportive legislation, the share of platinum from secondary materials is likely to increase as end of life products are collected more efficiently and processed using the optimum technology.

In the short term the imposition of increasingly strict emission control legislation across the world is likely to continue to increase demand for platinum in autocatalysts. In the longer term the move away from carbon-based fuels for powering road vehicles may lead to reduced demand for platinum in catalytic converters. However, if fuel cell vehicles achieve significant market penetration in the future this is very likely to lead to increased demand for platinum.

Table 85: Qualitative forecast of supply and demand of platinum

Material	**Demand forecast**			**Supply forecast**		
	5 years	10 years	20 years	5 years	10 years	20 years
Platinum	+	+	?	+	+	?

20.7 Data sources

20.7.1 Data sources used in the factsheet

BGS. (2016). British Geological Survey World Mineral Statistics database. [online] Available at: https://www.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS

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European Commission (2014) Report on critical raw materials for the EU - Critical raw materials profiles.

Eurostat (2016)a. International Trade Easy Comext Database [online] Available at: http://epp.eurostat.ec.europa.eu/newxtweb/

Eurostat (2016)c. Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E). [online] Available at: http://ec.europa.eu/eurostat/en/web/products-datasets/-/SBS_NA_IND_R2

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Rudnick, R.L. and Gao. S. (2003). Composition of the Continental Crust. In: Treatise on Geochemistry, Volume 3. Editor: Roberta L. Rudnick. Executive Editors: Heinrich D. Holland and Karl K. Turekian. pp. 659. ISBN 0-08-043751-6. Elsevier, p.1-64

Thomson Reuters. (2016). GFMS Platinum Group Metals Survey 2016.

20.7.2 Data sources used in the criticality assessment

BGS. (2016). British Geological Survey World Mineral Statistics database. [online] Available at: https://www.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS

Bio by Deloitte. (2015). Study on Data for a Raw Material System Analysis. Background data (unpublished)

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Eurostat (2016)a. International Trade Easy Comext Database [online] Available at: http://epp.eurostat.ec.europa.eu/newxtweb/

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Johnson Matthey. (2016). PGM Market Report May 2016. [online] Available at: http://www.platinum.matthey.com/services/market-research/pgm-market-reports

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20.8 Acknowledgements

This Factsheet was prepared by the British Geological Survey (BGS). The authors would like to thank the following for their contributions to the preparation of this Factsheet: C. Hagelüken (Umicore), M. Schmidt (BGR/DERA), P. Duncan (Johnson Matthey), V. Zepf (University of Augsburg), G. Mudd (Monash University) and members of the EC Ad Hoc Working Group on Critical Raw Materials.

21. RHODIUM

Key facts and figures

Material name and Element symbol	Rhodium Rh	World/EU production (tonnes)[1]	21.5 / 0
Parent group (where applicable)	Platinum-Group Metals (PGM)	EU import reliance[1]	100%
ife cycle stage / material assessed	Processing / refined material	Substitution index for supply risk [SI (SR)][1]	1.00
Economic importance (EI) (2017)	6.6	Substitution Index for economic importance [SI(EI)][1]	1.00
Supply risk (SR) (2017)	2.5	End of life recycling input rate	24%
Abiotic or biotic	Abiotic	Major non-monetary end uses in EU[1]	Autocatalysts (82%), chemicals (8%), glass (4%)
Main product, co-product or by-product	Co-product (with other PGM): by-product (with Ni and Cu)	Major world producers[1]	South Africa (83%), Russia (10%), Zimbabwe (4%)

[1] average for 2010-2014, unless otherwise stated

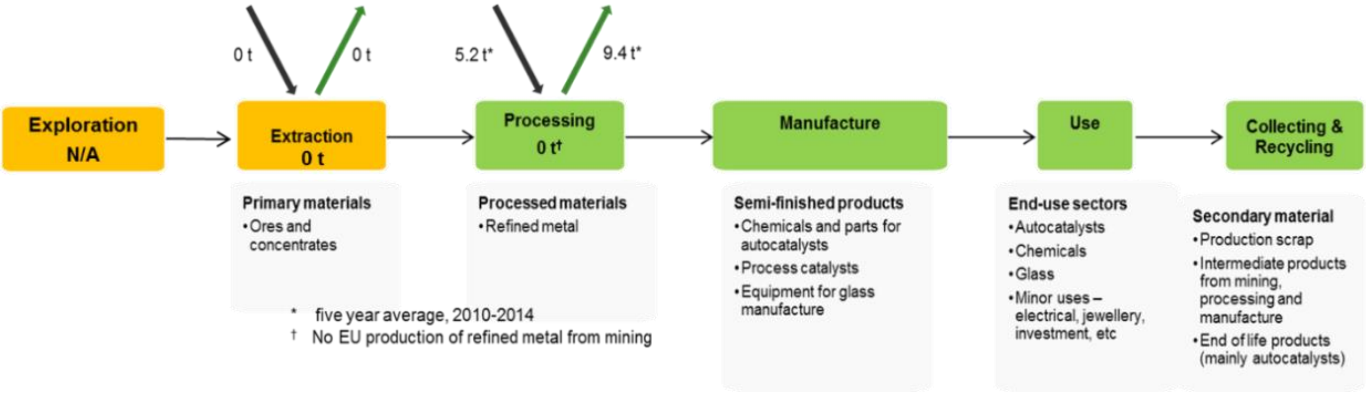

Figure 154: Simplified value chain for rhodium

The green boxes in the figure above identify activities undertaken within the EU. The thick black arrows represent imports to the EU and the green arrows represent exports from the EU. Rhodium-bearing ores and concentrates are not generally traded in the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

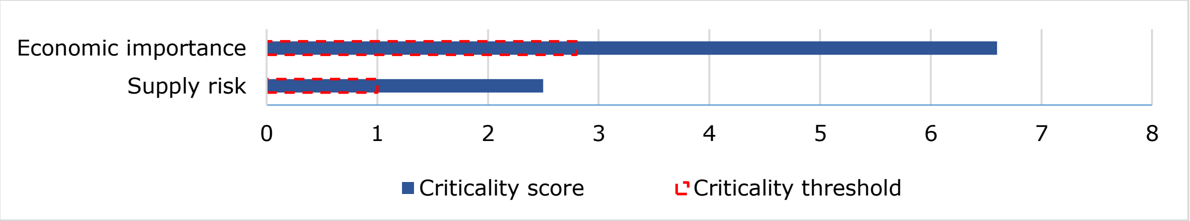

Figure 155: Economic importance and supply risk scores for rhodium

21.1 Introduction

Rhodium (Rh) is one the six chemical elements referred to as the platinum-group metals (PGM) or the platinum-group elements (PGE), which are, in order of increasing atomic number: ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). These metals are very rare in the Earth's crust with abundances in the range 1-5 parts per billion (ppb). They tend to be found together, commonly associated with ores of nickel and copper. The PGM occur in numerous alloys, in base metal sulfide minerals and in a wide variety of PGM-bearing minerals with, among others, sulfur, arsenic, antimony and tellurium. They rarely occur in native form. The PGM are highly resistant to wear, tarnish, chemical attack and high temperature. The PGM are regarded as precious metals, like gold and silver. All PGM, commonly combined with one another or with other metals, can act as catalysts which are exploited in a wide range of applications. Rhodium is the third most commercially important of the PGM, behind platinum and palladium. The main use of rhodium is in autocatalysts, with the manufacture of chemicals and glass the second and third most important applications respectively.

Almost all rhodium derived from primary source materials (i.e. mine production) is traded in the form of refined metal produced from integrated mining/metallurgical operations. There is only very limited international trade in rhodium ores and concentrates.

Most topics related to rhodium have been covered in the general PGM Factsheet that deals with the five PGM (excluding osmium) together. This is because the PGM occur together in nature and are generally co-products from the same deposits. Also, much of the available public data deals with them as a group. They are, therefore, commonly discussed together, with comparisons drawn between individual PGM where data allow. In this factsheet additional information and data specific to rhodium are presented where available.

21.2 Supply

21.2.1 Supply from primary materials

The geological occurrence, mining, processing, extractive metallurgy and resources and reserves have been discussed in the general PGM Factsheet.

The majority of rhodium is derived from mafic-ultramafic igneous complexes like the Bushveld Igneous Complex in South Africa and the Great Dyke in Zimbabwe. Minor production is from nickel sulfide deposits in Russia, Canada, USA and elsewhere (Gunn, 2014). Most PGM extracted from the Bushveld Igneous Complex are derived from two horizons: the Merensky Reef and the UG2 Chromitite. The proportion of rhodium, ruthenium and iridium in the UG2 is significantly greater than in the Merensky Reef. Consequently, as mining of the UG2 has increased markedly in recent decades, so the potential availability of these PGM has increased.

While it is considered likely that rhodium resources may also be found elsewhere there is very little available geochemical data for rhodium in other deposit types and geological settings. Consequently it is difficult to assess the abundance of rhodium in these potential new sources.

21.2.1.1 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of rhodium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[20], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for rhodium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for rhodium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for rhodium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

There are no global or national resource or reserve data for rhodium in the public domain. If they are reported at all, rhodium data are normally presented in combination with other PGM, most commonly platinum and palladium, and sometimes with gold. See PGM factsheet for more details.

21.2.1.2 World mine production

Average annual world mine production of rhodium for the period 2010-14 was approximately 21.5 tonnes having fallen from about 24 tonnes in 2010 as a result of weak industrial demand. Global supply is dominated by South Africa which accounted for about 83 % of the total (Figure 155). Russia was the second most important producer (10 % of total), followed by Zimbabwe (4 %) and Canada (3 %).

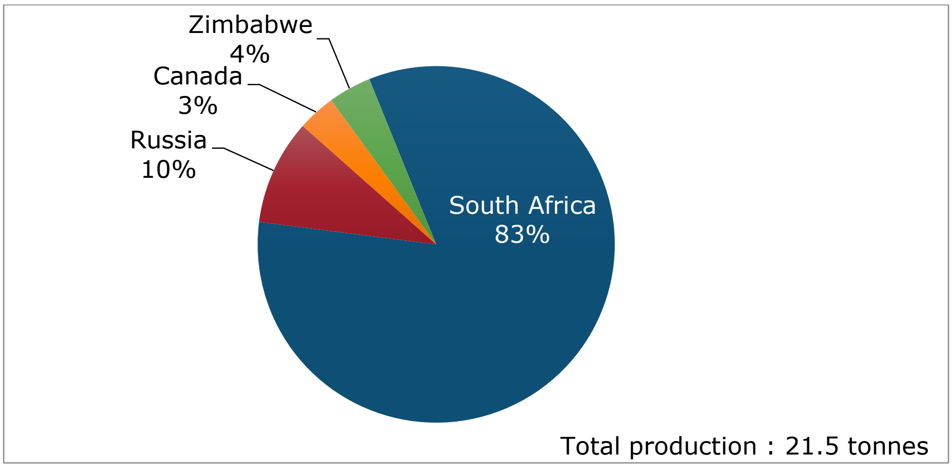

Figure 156: The distribution of global mine production of rhodium, average 2010–2014. (Data from BGS, 2016)

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[20] www.crirsco.com

21.2.2 Supply from secondary materials

As discussed in the PGM Factsheet, recycling makes an important and growing contribution to global PGM supply. The high value of rhodium makes it generally attractive for recycling and sophisticated technology has been developed that permits highly effective recovery of rhodium from a variety of waste streams, notably autocatalysts, industrial catalysts and equipment for glass manufacture. However, the end of life recycling rate varies considerably by country and by application. Closed loop recycling can achieve very high levels of rhodium recovery, whereas in open loop recycling the rate achieved is critically dependent on numerous factors, particularly the prevailing rhodium price and a host of others that influence the collection efficiency of end of life products. The end of life recycling rate of rhodium is considered at 24% for the EU (Bio Intelligence Service, 2015).

In addition to recovery from end of life products rhodium is also recycled from a range of intermediate products and wastes from mineral processing, smelting, refining and manufacturing processes.

21.2.3 EU trade

As discussed in the PGM Factsheet the PGM are traded in the EU in a variety of forms – as metal in unwrought or powder form, in semi-manufactured forms and various intermediate products and wastes. For rhodium, trade data are available only for rhodium metal in unwrought or powder form (Combined Nomenclature (CN) code 7110 3100). Figure 157 shows EU trade in rhodium metal with non-EU countries. In each of the years 2010–2014 the EU was a net exporter of rhodium metal. While it is clear that there is considerable trade in rhodium metal, it is not possible to determine if that metal was derived from primary or secondary material. The import reliance is 100%.

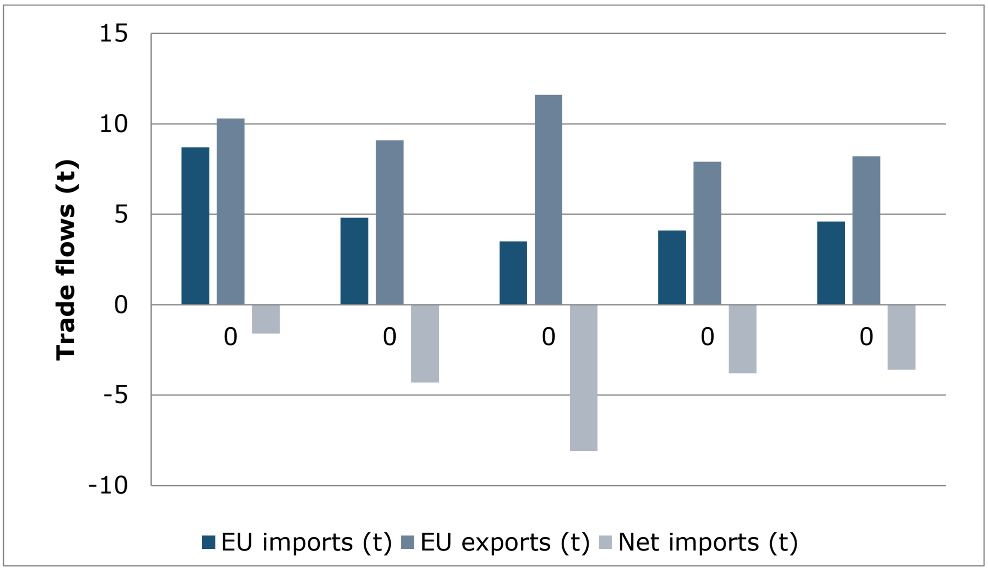

Figure 157: EU trade in rhodium metal, in unwrought or powder form, with non-EU countries, 2010–2014 (Data from Comext database (Eurostat, 2016a))

EU imports of rhodium metal averaged about 5.2 tonnes per annum between 2010–2014. The main sources of these imports were South Africa, USA, Russia and Japan (Figure 158).

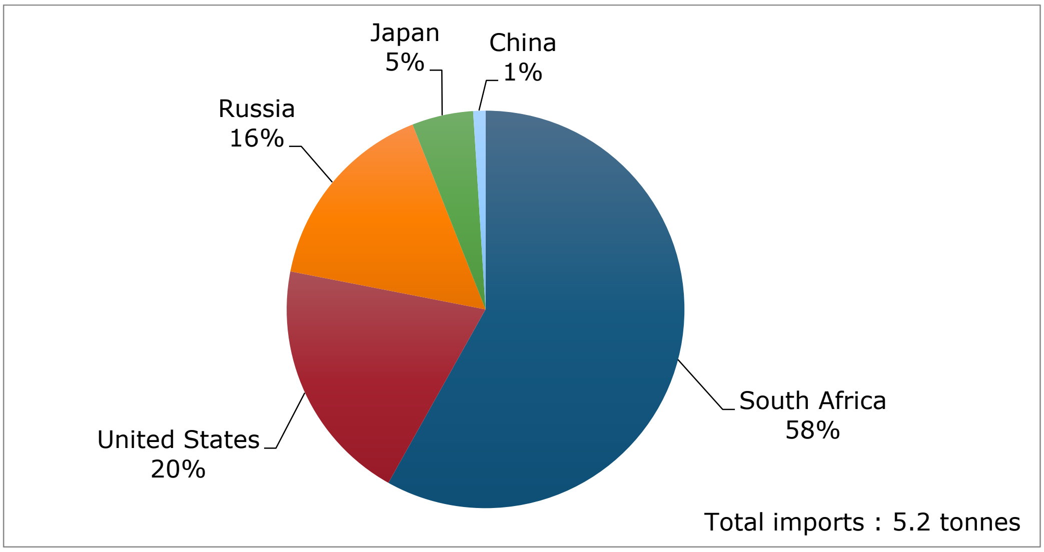

Figure 158: The sources of EU imports of rhodium metal, in unwrought or powder form, from non-EU countries, 2010–2014 (Data from Comext database (Eurostat, 2016a))

During the same period the EU exported about 9.4 tonnes of rhodium metal per annum. Nearly 95 % of the exports were sent to four countries: USA (34 % of the total), Hong Kong (28 %), China (20 %) and Japan (12 %).

No trade restrictions have been reported over the 2010-2014 period (OECD, 2016). The EU and South Africa have a free trade agreement in place (European Commission, 2016).

21.2.4 EU supply chain

The supply chain for rhodium in the EU is complex and difficult to quantify. Rhodium supplies are derived from both primary sources (mines) and secondary sources (refineries). Refineries in the EU process a wide range of rhodium-bearing materials emanating from European and overseas sources. These include end-of-life products, chiefly autocatalysts, and manufacturing waste (new scrap). By-products from the non-ferrous mining, processing and manufacturing industries also contribute to the EU supply of rhodium. These include concentrates, slags, mattes, flue dust, ash, slimes and other residues. There is no reported production of rhodium from mines in the EU. The import reliance is 100%

21.3 Demand

21.3.1 Consumption

Given the diversity of forms in which rhodium is traded, the limited scope of trade data specific to rhodium and the absence of any distinction between rhodium metal derived from primary and secondary source materials, it is not possible to determine a single reliable figure for EU consumption of rhodium.

Gross global demand for rhodium in 2015 was 30.8 tonnes (Johnson Matthey, 2016b). In 2015 rhodium demand in Europe amounted to approximately 5 tonnes, which was about 16 % of global demand (Johnson Matthey, 2016c). The majority of that was used in autocatalysts (see following section).

21.3.2 Applications

The main uses of the PGM are discussed in the PGM Factsheet.

The predominant use was in autocatalysts, which accounted for 83.4 % of global demand in 2015 (Figure 159). The remainder was used chiefly for the manufacture of chemicals and glass.

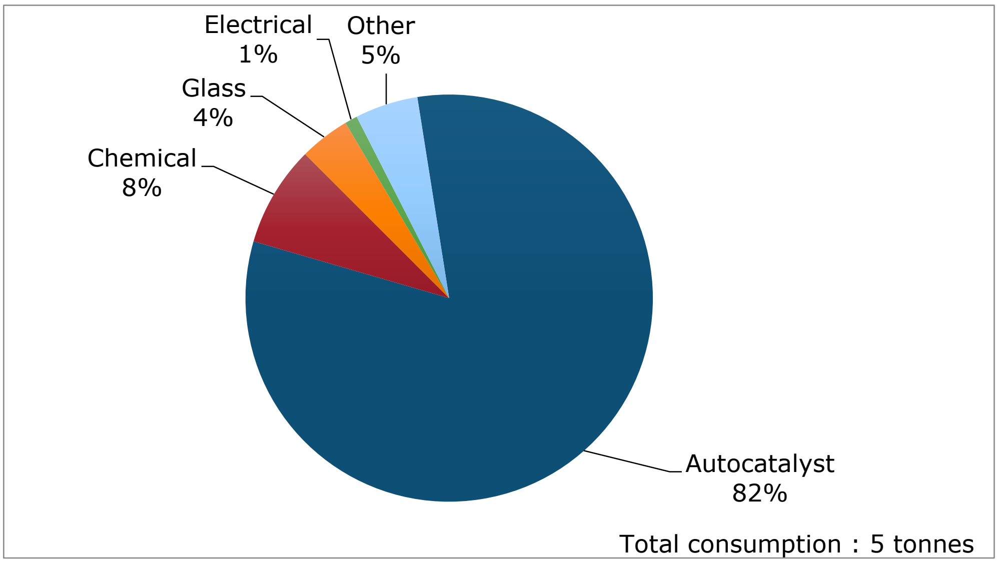

Figure 159: Global end uses of rhodium in 2015.(Data from Johnson Matthey, 2016b)

A range of other minor uses, which accounted for about 1.9 % of the total, includes investment, thermocouples, contacts, spark plug tips, white gold alloys and electroplating. In Europe, gross demand for rhodium in 2016 was approximately 5 tonnes, which was used in autocatalysts, industrial applications and jewellery (Johnson Matthey, 2016c). The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 86.

Table 86: Rhodium applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016c)

Applications	2-digit NACE sectors	Value added of NACE 2 sector (M€)	4-digit NACE sectors
Autocatalysts	C29 - Manufacture of motor vehicles, trailers and semi-trailers	158,081	C2932 - Manufacture of other parts and accessories for motor vehicles
Chemical	C20 - Manufacture of chemicals and chemical products	110,000	C2015 - Manufacture of fertilisers and nitrogen compounds
Glass	C23 - Manufacture of other non-metallic mineral products	59,166	C2311 - Manufacture of flat glass
Electrical	C26 - Manufacture of computer, electronic and optical products	75,260	C2712 - Manufacture of electricity distribution and control apparatus

21.3.3 Prices and markets

Unlike platinum and palladium, rhodium is not traded on the major metal exchanges. Rhodium is generally sold through long-term supply contracts between fabricators and mines. Johnson Matthey is the main fixer of the rhodium price, publishing daily prices from its trading desks in the USA, Hong Kong and the UK. The price is for metal in sponge form with a minimum purity of 99.9% rhodium.

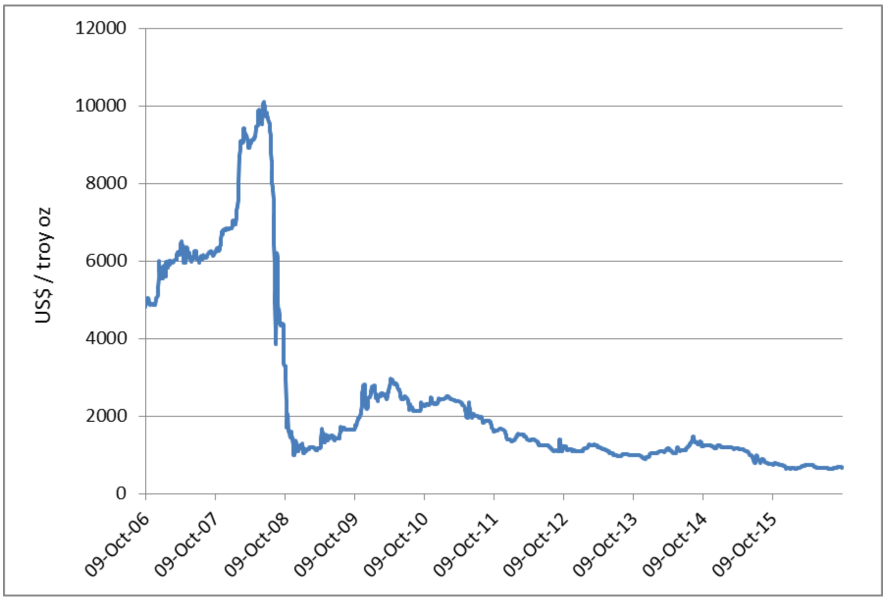

Figure 160: The price of rhodium, October 2006 – October 2016 (data from Johnson Matthey, 2016a)

The price of rhodium has experienced major fluctuations in recent years in response to changing global economic conditions (Figure 160). In 2003, the average price for rhodium was about US$530 per troy ounce. In response to rapidly growing demand for autocatalysts the price rose steadily from 2004 onwards, peaking in excess of US$10,000 in July 2008. However, with the onset of global economic recession and dwindling demand, it fell back to about US$1000 by January 2009. Following a shortlived recovery in 2010 and 2011, the price has followed a general downward trend. As a result of weak industrial demand and an improved supply situation, prices continued to fall in 2015, ending the year at US$660. In 2015 the average rhodium price was US$955, a fall of 19% from the previous year (Thomson Reuters, 2016).

21.4 Substitution

The high price of rhodium, its price volatility and the perceived possibility of future supply disruptions have led to considerable interest in finding alternatives to rhodium in many applications. Nassar (2015) reviewed the possibilities for elemental substitution of the PGM in their main applications. For rhodium the potential substitutes are other PGM, gold or base metals, although these may have associated price or performance penalties. Given that the PGM are co-products, in the event of a supply disruption of rhodium, the ability to substitute it with other PGM is likely to be limited.

21.5 Discussion of the criticality assessment

21.5.1 Data sources

Production data for rhodium was taken from the British Geological Survey's World Mineral Statistics database and represents global production from primary producing countries. However, the BGS data for rhodium production are not complete for all countries for the 2010–2014 reference period: while data for South Africa, the leading producer, are complete, for Zimbabwe data are available only for 2010 and 2011. For Russia estimates of rhodium production were made on the basis of the rhodium content of the PGM-bearing nickel sulfide ores worked in the Norilsk-Talnakh district (Naldrett, 2004). The BGS data are reported as mine production in kilograms of contained metal, although, in fact, the material sold by the mines is generally neither ore nor concentrate but rather refined metal. There is no CN8 code specific to rhodium ores and concentrates. The most relevant CN8 code would be 26169000: *Precious metal ores and concentrates excluding silver*. However this code reports data for several precious metals and it is therefore inappropriate to use in the rhodium assessment.

Trade data for unwrought rhodium metal was extracted from the Eurostat COMEXT online database (Eurostat, 2016) using the Combined Nomenclature (CN) code 7110 3100. These data were averaged over the five-year period 2010–2014. The trade data include metal from all sources, both primary and secondary. It is not therefore possible to identify the source of the metal and the relative contributions of primary and secondary materials. In reality, Europe is an important producer of refined rhodium, which originates both from primary and secondary materials, and therefore the actual net import reliance is lower than calculated using the global HHI. The EU reliance on imports from secondary sources is a significant factor for the security of rhodium supply, but is not within the scope of this project.

Other data sources are listed in section 21.7.

21.5.2 Calculation of economic importance and supply risk indicators

For the calculation of Economic Importance (EI), the 2-digit NACE sectors shown in Table 86 were used. For information relating to the application share of each category, see section on applications and end-uses. As required by the methodology, the application shown as 'others' was distributed among the remaining applications. The figures for value added were the most recently available at the time of the assessment, i.e. 2013.

The calculation of the Supply Risk (SR) was carried out at the refined material stage of the life cycle using only the global HHI calculation. Actual supply to the EU cannot be determined from Eurostat because the trade data do not discriminate between rhodium metal derived from primary and secondary sources. The Eurostat trade data include metal from different life cycle stages and from numerous sources/countries. It cannot therefore be used to calculate the risk to primary rhodium supply to the EU.

While there is a possibility to substitute rhodium in some of its applications, it has not generally been possible to quantify the shares of the substitute materials currently in use. In autocatalysts the shares of the market held by platinum, palladium and rhodium are well known from data published regularly by Johnson Matthey and other organisations, but in practice the amount of substitution that might be achieved is difficult to quantify as it depends on numerous economic and technical factors. In the manufacture of various organic and inorganic chemicals rhodium is normally used in conjunction with other metals in long established formulations to catalyse specific chemical processes. Although rhodium substitution might be possible in some of these, there is generally little economic or technical incentive to do so, especially as the catalysts are recycled very efficiently.

The end of life recycling input rate for rhodium was calculated from data collected in the MSA study carried out for the European Commission (Bio Intelligence Service, 2015).

21.5.3 Comparison with previous EU criticality assessments

In this revision of the EU critical raw materials list a revised methodology for assessing economic importance and supply risk has been used and consequently the results are not directly comparable to the previous EU critical raw materials studies.

The results of this review and earlier assessments are shown in Table 87.

Table 87: Economic importance and supply risk results for rhodium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011		2014		2017	
Indicator	EI	SR	EI	SR	EI	SR
Rhodium	6.68*	3.63*	6.58*	1.18*	6.6	2.5

*in the 2011 and 2014 assessments the PGM were considered as a single group which included rhodium. In the current assessment rhodium was considered as a single metal

21.6 Other considerations

The factors affecting the future supply and demand for PGM have been discussed in the PGM Factsheet. It is considered that South Africa and Russia will continue to be the main global suppliers of rhodium. The size of the global geological resource of rhodium is not well known but there is considerable potential in the longer term to find additional resources in countries which do not currently produce PGM and in other geological settings.

Table 88: Qualitative forecast of supply and demand of rhodium

Material	**Demand forecast**			**Supply forecast**		
	5 years	10 years	20 years	5 years	10 years	20 years
Rhodium	+	+	?	+	+	?

Given that rhodium is effectively a by-product of platinum and/or palladium extraction, its supply is closely tied to the production of those PGM which are the ‘paying’ metals. However, given that most PGM are now mined from the UG2 Chromitite, that the PGM resources in the UG2 Chromitite are much larger than in the Merensky Reef, and that the UG2 ore contains a higher proportion of rhodium than the Merensky Reef, the future availability of rhodium from South Africa is considered unlikely to be problematic (Zientek et al., 2014). However, in order to ensure the long-term availability of rhodium more geological research is needed to improve our knowledge of its distribution and abundance elsewhere in the earth’s crust and in ores that might be potential sources of supply.

Recycling currently makes an important contribution to rhodium supply and, given favourable economic conditions and supportive legislation, the share of rhodium from secondary materials is likely to increase as end of life products are collected more efficiently and processed using the optimum technology.

In the short term growth in global vehicle usage and the imposition of increasingly strict emission control legislation across the world is likely to continue to increase demand for rhodium in autocatalysts. In the longer term the move away from carbon-based fuels for powering road vehicles may lead to reduced demand for rhodium.

21.7 Data sources

21.7.1 Data sources used in the factsheet

Bio Intelligence Service. (2015). Study on Data for a Raw Material System Analysis. Background data (unpublished)

European Commission (2011). Critical raw materials for the EU. [online] Available at: https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

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21.7.2 Data sources used in the criticality assessment

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21.8 Acknowledgements

This Factsheet was prepared by the British Geological Survey (BGS). The authors would like to thank the following for their contributions to the preparation of this Factsheet: C. Hagelüken (Umicore), M. Schmidt (BGR/DERA), P. Duncan (Johnson Matthey), V. Zepf (University of Augsburg), G. Mudd (Monash University) and members of the EC Ad Hoc Working Group on Critical Raw Materials.

22. RUTHENIUM

Key facts and figures

Material name and Element symbol	Ruthenium Ru	World/EU production in 2016 (tonnes)	27.7 / 0
Parent group (where applicable)	Platinum-Group Metals (PGM)	EU import reliance[1]	100%
Life cycle stage / material assessed	Processing / refined metal	Substitution index for supply risk [SI(SR)][1]	0.96
Economic importance (EI) (2017)	3.5	Substitution Index for economic importance [SI(EI)][1]	0.91
Supply risk (SR) (2017)	3.4	End of life recycling input rate	11%
Abiotic or biotic	Abiotic	Major non-monetary end uses in EU[1]	Electrical (61%), chemicals (17%), electrochemical (15%)
Main product, co-product or by-product	Co-product (with other PGM): by-product (with Ni and Cu)	Major world producers in 2016	South Africa (93%), Zimbabwe (3%), Russia (2%)

[1] average for 2010-2014, unless otherwise stated;

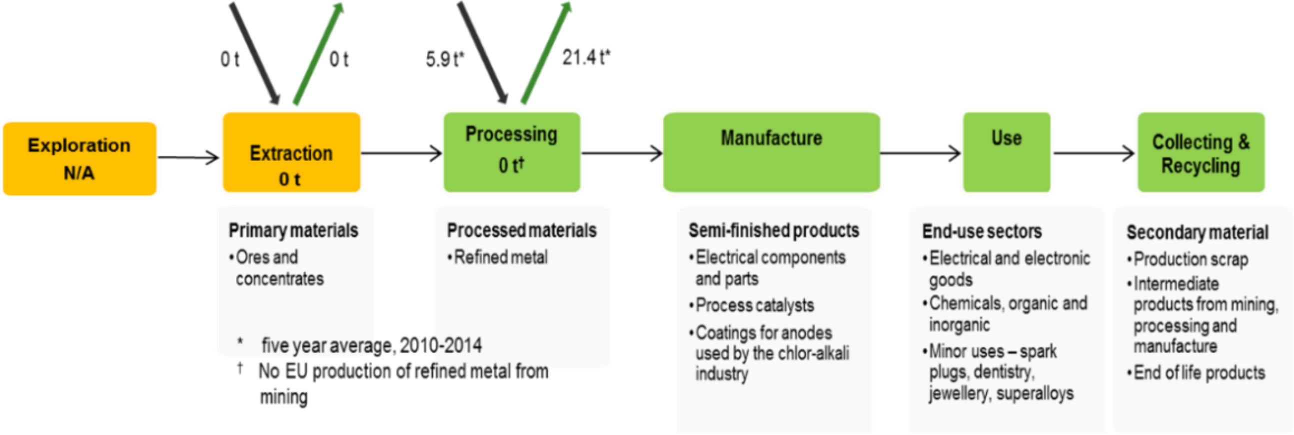

Figure 161: Simplified value chain for ruthenium

The green boxes in the figure above identify activities undertaken within the EU. The thick black arrows represent imports to the EU and the green arrows represent exports from the EU. Ruthenium-bearing ores and concentrates are not generally traded in the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

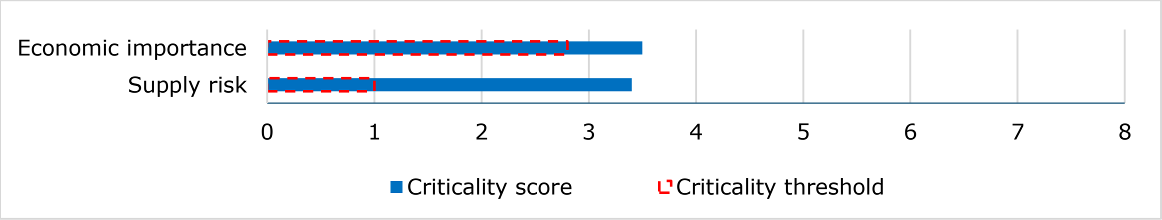

Figure 162: Economic importance and supply risk scores for ruthenium

22.1 Introduction

Ruthenium (Ru) is one the six chemical elements referred to as the platinum-group metals (PGM) or the platinum-group elements (PGE), which are, in order of increasing atomic number: ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). These metals are very rare in the Earth's crust with abundances in the range 1-5 parts per billion (ppb). The abundance of ruthenium in the upper crust is 0.34 ppb (Rudnick, 2003). They tend to be found together, commonly associated with ores of nickel and copper. The PGM occur in numerous alloys, in base metal sulfide minerals and in a wide variety of PGM-bearing minerals with, among others, sulfur, arsenic, antimony and tellurium. They rarely occur in native form. The PGM are highly resistant to wear, tarnish, chemical attack and high temperature. The PGM are regarded as precious metals, like gold and silver. All PGM, commonly combined with one another or with other metals, can act as catalysts which are exploited in a wide range of applications. Ruthenium is the fourth most commercially important of the PGM, behind platinum, palladium and rhodium. The main use of ruthenium is in electronic and electrical applications, with chemical and electrochemical processes for the manufacture of organic and inorganic chemicals the next most important.

Almost all ruthenium derived from primary source materials (i.e. mine production) is traded in the form of refined metal produced from integrated mining/metallurgical operations. There is only very limited international trade in ruthenium ores and concentrates.

Most topics related to ruthenium have been covered in the general PGM Factsheet that deals with the five PGM (excluding osmium) together. This is because the PGM occur together in nature and are generally co-products from the same deposits. Also, much of the available public data deals with them as a group. They are, therefore, commonly discussed together, with comparisons drawn between individual PGM where data allow. In this factsheet additional information and data specific to rhodium are presented where available.

22.2 Supply

22.2.1 Supply from primary materials

The geological occurrence, mining, processing, extractive metallurgy and resources and reserves have been discussed in the general PGM Factsheet.

The majority of ruthenium is derived from mafic-ultramafic igneous complexes like the Bushveld Igneous Complex in South Africa and the Great Dyke in Zimbabwe. Minor production is from nickel sulfide deposits in Russia, Canada, USA and elsewhere (Gunn, 2014). Most PGM extracted from the Bushveld Igneous Complex are derived from two horizons: the Merensky Reef and the UG2 Chromitite. The proportion of iridium, rhodium and ruthenium in the UG2 is significantly greater than in the Merensky Reef. Consequently, as mining of the UG2 has increased markedly in recent decades, so the potential availability of these PGM has increased.

While it is considered likely that ruthenium resources may also be found elsewhere there is very little available geochemical data for ruthenium in other deposit types and geological settings. Consequently it is difficult to assess the abundance of ruthenium in these potential new sources.

22.2.1.1 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of ruthenium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[21], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for ruthenium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for ruthenium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for ruthenium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

There are no global or national resource or reserve data for ruthenium in the public domain. If they are reported at all, ruthenium data are normally presented in combination with other PGM, most commonly platinum and palladium, and sometimes with gold. See PGM factsheet for more details

22.2.1.2 World mine production

Data are not published for annual world mine production of ruthenium for the period 2010-14. However, data were obtained for 2016 from Johnson Matthey (Johnson Matthey, 2016a). Total global production of ruthenium in 2016 was 27.7 tonnes. Global supply is strongly dominated by South Africa which accounted for about 93 % of the total in 2016 (Figure 163). Zimbabwe was the second most important producer (3.3 % of total), followed by Russia (2.2 %) and Canada (0.5 %).

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[21] www.crirsco.com

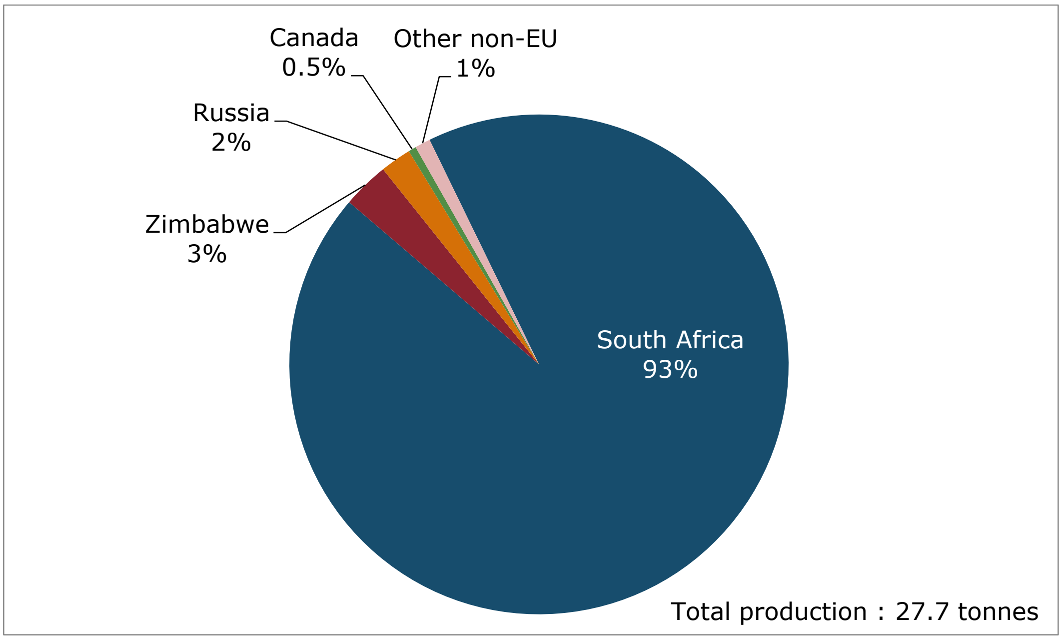

Figure 163: The distribution of global mine production of ruthenium in 2016. (Data from Johnson Matthey, 2016a)

22.2.2 Supply from secondary materials

As discussed in the PGM Factsheet, recycling makes an important and growing contribution to global PGM supply. However, the end of life recycling rate varies considerably by country and by application. Closed loop recycling can achieve very high levels of ruthenium recovery, chiefly from catalysts, but also from manufacturing waste and by-products such as chemicals, solutions and other chemical scrap. In open loop recycling the rate achieved is generally much lower. Hagelüken (2014) indicates that end of life recycling rates of ruthenium in electrical applications are less than 5 %, while in industrial applications a rate of 40–50 % is more typical. The end of life recycling rate used in the assessment is 11% (JRC, 2016).

22.2.3 EU trade

As discussed in the PGM Factsheet, the PGM are traded in the EU in a variety of forms – as metal in unwrought or powder form, in semi-manufactured forms and various intermediate products and wastes. For ruthenium, trade data are available only under a single Combined Nomenclature (CN) code (7110 4100), which includes iridium, osmium and ruthenium metal in unwrought or powder form. The import reliance is 100%.

Figure 164 shows EU trade in ruthenium and iridium metal combined (Ru+Ir) with non-EU countries. In each of the years 2010–2014 the EU was a significant net exporter of Ru+Ir metal. While it is clear that there is considerable trade in Ru+Ir metal, it is not possible to determine if that metal was derived from primary or secondary material. Net exports of Ru+Ir metal from the EU to non-EU countries averaged 20.6 tonnes per annum in the period 2010–2014.

EU imports of Ru+Ir metal averaged about 7.8 tonnes per annum between 2010–2014. The main sources of these imports were South Africa (58.3 % of total), Japan (12.6 %), United States (10.1 %) and Taiwan (7.5 %) (Figure 165).

During the same period the EU exported about 28.4 tonnes of Ru+Ir metal per annum. Nearly 90 % of the exports were sent to four countries: Singapore (50 % of the total), United States (23 %), Japan (11 %) and Taiwan (5 %).

No trade restrictions have been reported over the 2010-2014 period (OECD, 2016). The EU and South Africa have a free trade agreement in place (European Commission, 2016).

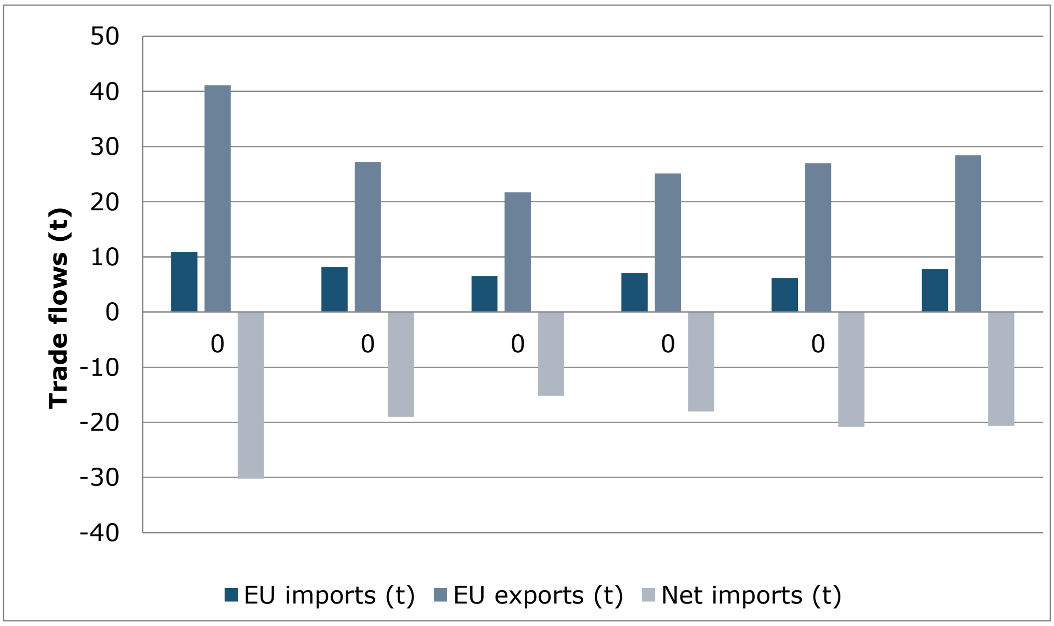

Figure 164: EU trade in ruthenium and iridium metal, in unwrought or powder form, with non-EU countries, 2010–2014 (Data from Comext database (Eurostat, 2016a))

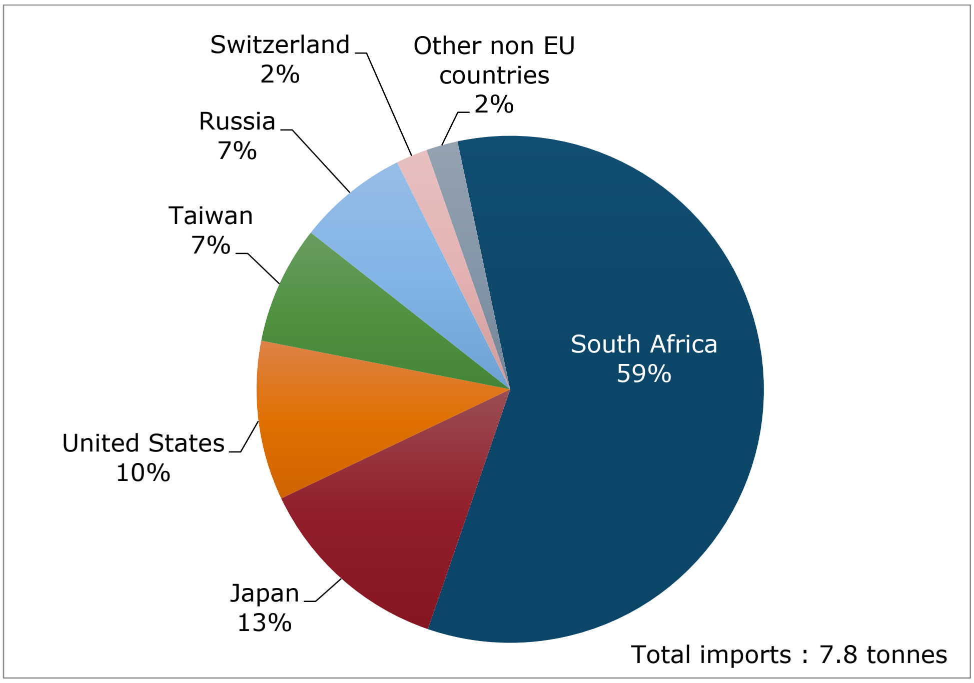

Figure 165: The sources of EU imports of ruthenium and iridium metal, in unwrought or powder form, from non-EU countries, 2010–2014 (Data from Comext database - Eurostat, 2016a)

22.2.4 EU supply chain

The supply chain for ruthenium in the EU is complex and difficult to quantify. Ruthenium supplies are derived from both primary sources (mines) and secondary sources (refineries). Refineries in the EU process a wide range of ruthenium-bearing materials emanating from European and overseas sources. These include end-of-life products and manufacturing waste (new scrap). By-products from the non-ferrous mining, processing and manufacturing industries also contribute to the EU supply of ruthenium. There is no reported production of ruthenium from mines in the EU. The import reliance is 100%.

22.3 Demand

22.3.1 Consumption

Given the diversity of forms in which ruthenium is traded, the limited scope of trade data specific to ruthenium and the absence of any distinction between ruthenium metal derived from primary and secondary source materials, it is not possible to determine a single reliable figure for EU consumption of ruthenium.

Gross global demand for ruthenium in 2015 was 29.4 tonnes (Johnson Matthey, 2016c). In 2016 ruthenium demand in Europe amounted to approximately 2.5 tonnes, which was about 8 % of global demand (Johnson Matthey, 2016a).

22.3.2 Applications

The main uses of the PGM are discussed in the PGM Factsheet.

The predominant use was in electrical components and products, such as thick film pastes, hard disk drives and contacts for thermostats and relays, which accounted for 48.3 % of global demand in 2015 (Figure 166). The remainder was used in chemical and electrochemical applications. A range of other minor uses, which accounted for about 12 per cent of the total, includes spark plugs, jewellery, dentistry and superalloys. In Europe, gross demand for ruthenium in 2016 was approximately 2.5 tonnes, which was used mainly in industrial applications (Johnson Matthey, 2016a).

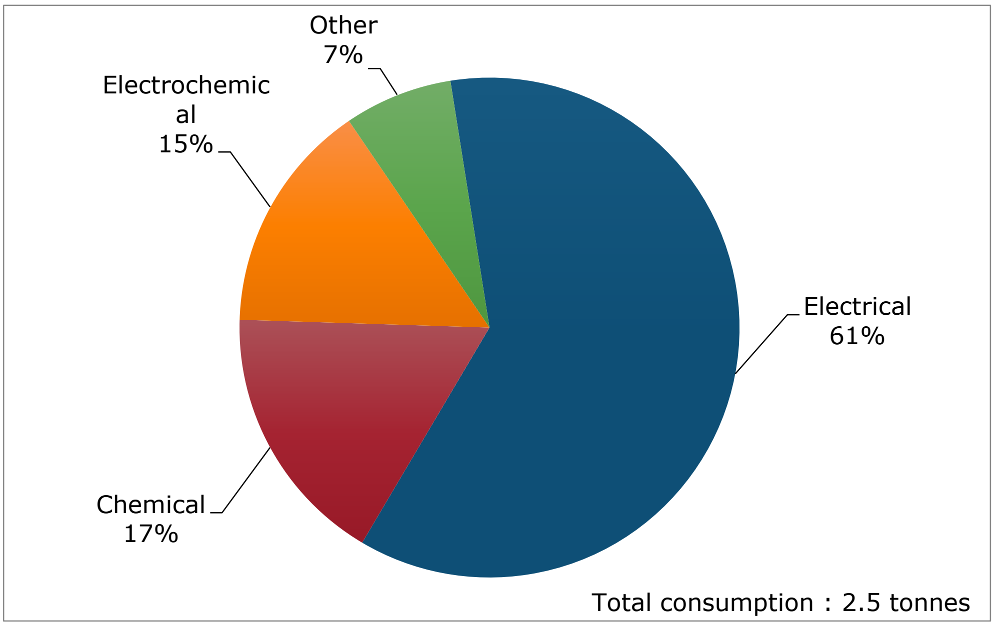

Figure 166: Global end uses of ruthenium in 2015 (Data from Johnson Matthey, 2016c)

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 89.

Table 89: Ruthenium applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016c)

Applications	2-digit NACE sectors	Value added of NACE 2 sector (millions€)	4-digit NACE sectors
Electrical	C26 - Manufacture of computer, electronic and optical products	75,260	C2620 - Manufacture of computers and peripheral equipment
Chemical	C20 - Manufacture of chemicals and chemical products	110,000	C2014 - Manufacture of other organic basic chemicals C2013 - Manufacture of other inorganic basic chemicals
Electrochemical	C20 - Manufacture of chemicals and chemical products	110,000	C2013 - Manufacture of other inorganic basic chemicals

22.3.3 Prices and markets

Unlike platinum and palladium, ruthenium is not traded on the major metal exchanges. Ruthenium is generally sold through long-term supply contracts between fabricators and mines. Johnson Matthey is the main fixer of the ruthenium price, publishing daily prices from its trading desks in the USA, Hong Kong and the UK. The price is for metal in sponge form with a minimum purity of 99.9% ruthenium.

The price of ruthenium has experienced major fluctuations in recent years in response to changing global economic conditions (Figure 167). From levels between US$30–50 per troy ounce in 2004, the price followed an upward trend peaking at about US$870 in February 2007. However, with the onset of global economic recession it fell back to US$75 in early 2009. Following a brief recovery in 2010 the price has generally declined, standing at US$40 in early 2017.

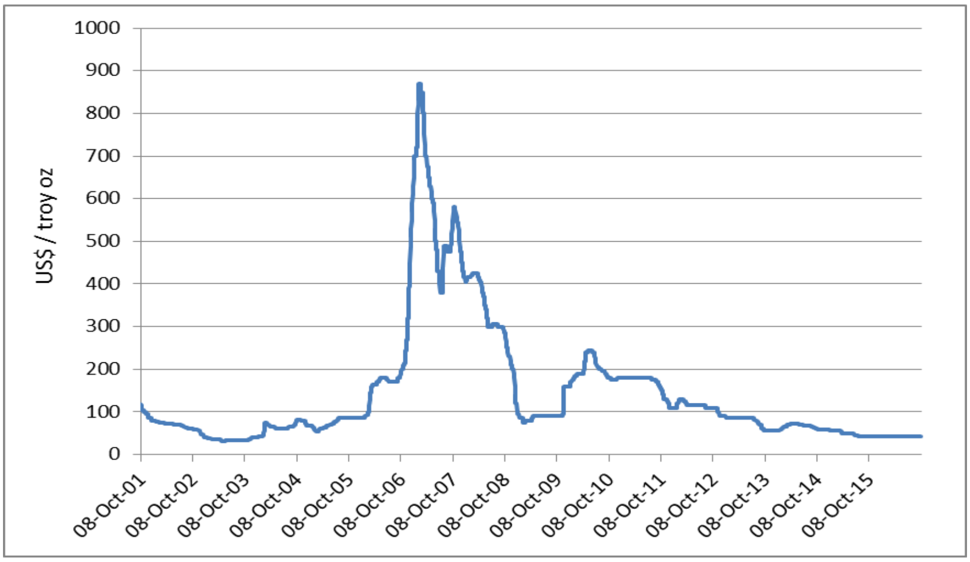

Figure 167: The price of ruthenium, October 2006 – October 2016 (data from Johnson Matthey, 2016b)

22.4 Substitution

Nassar (2015) reviewed the possibilities for elemental substitution of the PGM in their main applications. Given that the PGM are co-products, in the event of a supply disruption of ruthenium, the ability to substitute it with other PGM is likely to be limited. Similarly, given that ruthenium production is highly concentrated in South Africa, it would not be easy to bring new supply on stream quickly because the level of production is dependent on that of the 'paying' metals, platinum and palladium.

Ruthenium has many uses in electrical components and products. In some of these substitution by other PGM (iridium, rhodium and palladium) and by silver are possible, but we have no data on market share. Similarly, where ruthenium is used as a process catalyst in chemical manufacture, some substitutes exist but we have no information on their market shares. For example, in the majority of ammonia synthesis plants a magnetite-based catalyst is used. However, the KBR Advanced Ammonia Process uses a ruthenium catalyst which is thought to be 20 times more effective than the process that uses the magnetite catalyst (Nassar, 2015). In the chlor-alkali industry dimensionally stable anodes used in the production of chlorine and sodium hydroxide are coated with ruthenium and iridium oxides. We have no information on the relative proportions of each or the degree to which one can be substituted by the other.

22.5 Discussion of the criticality assessment

22.5.1 Data sources

Production data for ruthenium are not generally available in the public domain. The data used for the criticality assessment of ruthenium were for 2016 only and were provided by Johnson Matthey (Johnson Matthey, 2016a). There is no CN8 code specific to ruthenium ores and concentrates. The most relevant CN8 code would be 26169000: *Precious metal ores and concentrates excluding silver*. However this code reports data for several precious metals and it is therefore inappropriate to use in the ruthenium assessment.

Trade data for unwrought ruthenium metal are not available separately. Ruthenium metal in unwrought or powder form is combined with osmium and iridium under CN code 7110 4100. These data were extracted from the COMEXT online database (Eurostat, 2016) and were averaged over the five-year period 2010–2014. For the purposes of the criticality assessment trade in osmium is assumed to be very small and has been ignored. The relative proportions of ruthenium and iridium are not known but for the purposes of this assessment have been estimated at 75 per cent ruthenium and 25 per cent iridium, in accordance with the relative size of their markets. The trade data include metal from all sources, both primary and secondary. It is not therefore possible to identify the source of the metal and the relative contributions of primary and secondary materials. In reality, Europe is an important producer of refined ruthenium, which originates both from primary and secondary materials, and therefore the actual net import reliance is lower than calculated using the global HHI. The EU reliance on imports from secondary sources may be a significant factor for the security of ruthenium supply, but is not within the scope of this project.

Other data sources are listed in section 22.7.

22.5.2 Calculation of economic importance and supply risk indicators

For the calculation of Economic Importance (EI), the 2-digit NACE sectors shown in Table 89 were used. For information relating to the application share of each category, see section on applications and end-uses. As required by the methodology, the application shown as ‘others’ was distributed among the remaining applications. The figures for value added were the most recently available at the time of the assessment, i.e. 2013.

The calculation of the Supply Risk (SR) was carried out at the refined material stage of the life cycle using only the global HHI calculation. Actual supply to the EU cannot be determined from Eurostat because the trade data do not discriminate between ruthenium metal derived from primary and secondary sources. The Eurostat trade data include metal from different life cycle stages and from numerous sources/countries. It cannot therefore be used to calculate the risk to primary ruthenium supply to the EU.

While there is a possibility to substitute ruthenium in some of its applications, it has not generally been possible to quantify the shares of the substitute materials currently in use.

The end of life recycling input rate for ruthenium was based on UNEP data (UNEP, 2011) and presented by JRC (2016).

22.5.3 Comparison with previous EU criticality assessments

In this revision of the EU critical raw materials list a revised methodology for assessing economic importance and supply risk has been used and consequently the results are not directly comparable to the previous EU critical raw materials studies.

The results of this review and earlier assessments are shown in Table 90.

Table 90: Economic importance and supply risk results for ruthenium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011		2014		2017	
Indicator	EI	SR	EI	SR	EI	SR
Ruthenium	6.68*	3.63*	6.58*	1.18*	3.5	3.4

*in the 2011 and 2014 assessments the PGM were considered as a single group which included ruthenium. In the current assessment ruthenium was considered as a single metal

22.6 Other considerations

The factors affecting the future supply and demand for PGM have been discussed in the PGM Factsheet. It is considered that South Africa will continue to be the main global supplier of ruthenium. The size of the global geological resource of ruthenium is not well known but there is considerable potential in the longer term to find additional resources in countries which do not currently produce PGM and in other geological settings. Given that ruthenium is effectively a by-product of platinum and/or palladium extraction, its supply is closely tied to the production of those PGM which are the ‘paying’ metals. However, given that most PGM are now mined from the UG2 Chromitite, that the PGM resources in the UG2 Chromitite are much larger than in the Merensky Reef, and that the UG2 ore contains a higher proportion of ruthenium than the Merensky Reef, the future availability of ruthenium from South Africa is considered unlikely to be problematic (Zientek et al., 2014). However, in order to ensure the long-term availability of ruthenium more geological research is needed to improve our knowledge of its distribution and abundance elsewhere in the earth’s crust and in ores that might be potential sources of supply.

The recycling rate of ruthenium from consumer products is currently very low. Given favourable economic, technical and regulatory conditions improved ruthenium recovery from sources such as WEEE might be envisaged.

While it is difficult to predict how technological change will impact on demand for a particular metal, it is possible that demand for ruthenium in hard disk drives will decline as solid state drives replace the older type of drives based on perpendicular magnetic recording in which ruthenium plays an important role.

Table 91: Qualitative forecast of supply and demand of ruthenium

Material	Demand forecast			Supply forecast		
	5 years	10 years	20 years	5 years	10 years	20 years
Ruthenium	+	+	?	+	+	?

22.7 Data sources

22.7.1 Data sources used in the factsheet

European Commission (2011). Critical raw materials for the EU. [online] Available at: https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

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European Commission (2016). DG Trade. Agreements [online] Available at: http://ec.europa.eu/trade/policy/countries-and-regions/agreements/

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UNEP (United Nations Environment Programme). (2011) Recycling Rates of Metals A Status Report. p.44. http://www.unep.org/resourcepanel/Portals/50244/publications/UNEP_report2_Recycling_130920.pdf

22.8 Acknowledgements

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23. PHOSPHATE ROCK AND WHITE PHOSPHORUS

Key facts and figures

Material name and Formula	Phosphate rock, $Ca_5(PO_4)_3(F,Cl,OH)$			White Phosphorus, P_4		
Parent group (where applicable)	N/A			N/A		
Life cycle stage/ material assessed	Extraction			Refinery		
Economic importance EI (2017)	5.1			4.4		
Supply risk SR (2017)	1.0			4.1		
Abiotic or biotic	Abiotic			Abiotic		
Main product, co-product or by-product	Main product			Main product		
World/EU production (million tonnes)[1]	217,627,419 /873,682			915,000/0		
EU import reliance[1]	88%			100%		
Substitution index for supply risk [SI (SR)]	1.00			0.91		
Substitution Index for economic importance [SI(EI)]	1.00			0.91		
End of life recycling input rate (EOL-RIR)	17%			0%		
Major end uses in EU[1]	Mineral Fertilizer (86%), Food additives (10%), Fireworks and detergents (4%)			Chemical industry applications (90%), electronics (5%), Metal products (5%)		
Major world producers[1]	China (44%), Morocco (13%), United States (13%)			China (58%), Vietnam (19%), Kazakhstan (13%)		
Criticality results	2011	2014	2017	2011	2014	2017
	Not assessed	Critical	Critical	Not assessed	Not assessed	Critical

[1]Average for 2010-2014, unless otherwise stated.

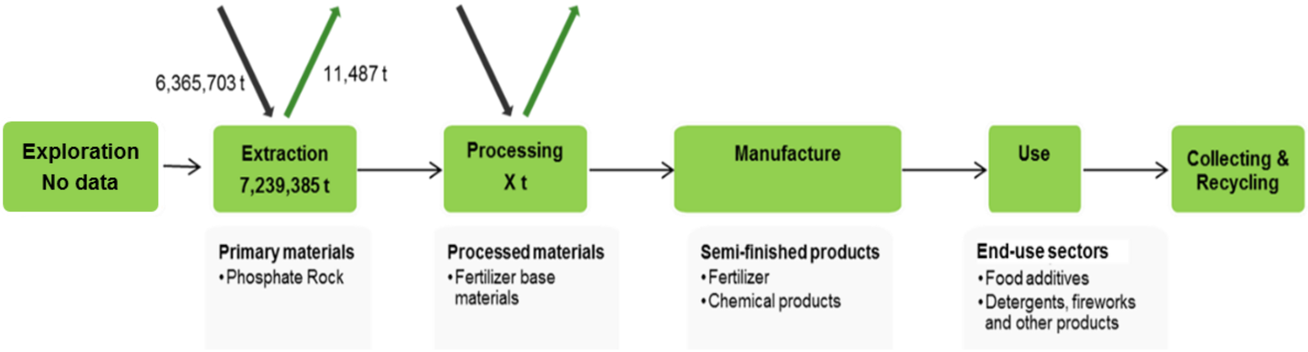

Figure 168: Simplified value chain for phosphate rock

The green boxes of the production and processing stages in the figure above suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

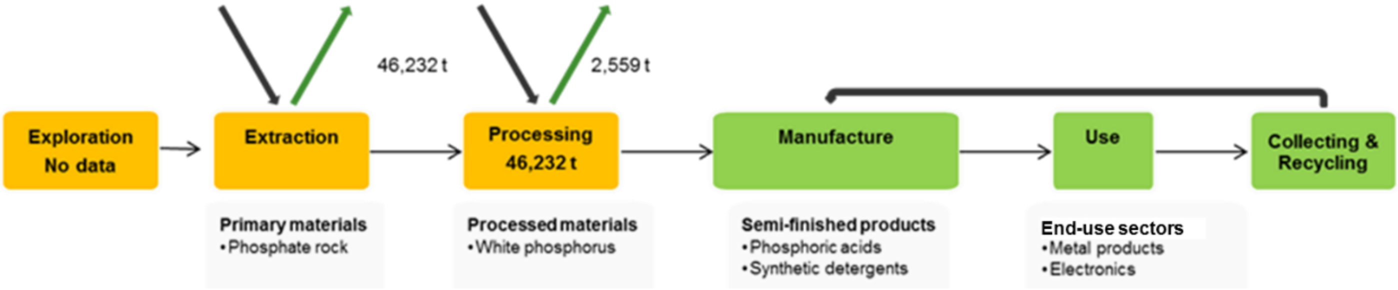

Figure 169: Simplified value chain for white phosphorus

The orange boxes of the production and processing stages in the above figure suggest that activities are not undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

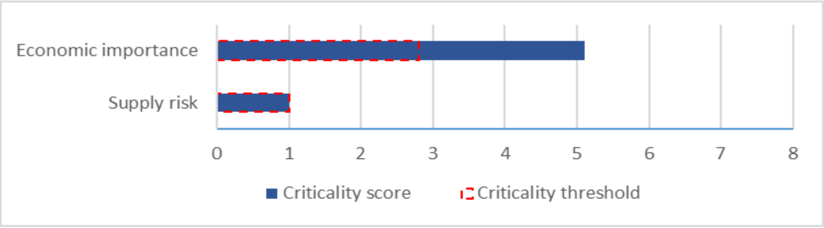

Figure 170: Economic importance and supply risk scores for phosphate rock

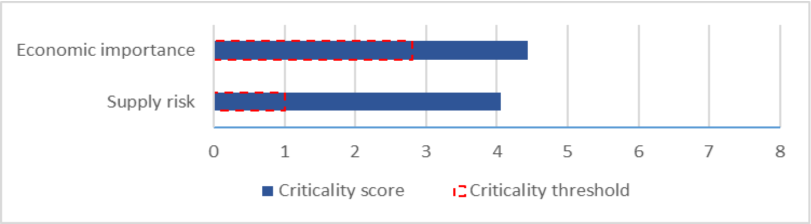

Figure 171: Economic importance and supply risk scores for white phosphorus

23.1 Introduction

This factsheet addresses two forms of phosphorus: phosphate rock (the original source of phosphorus used in fertilisers, animal feed, food and industrial applications) and white phosphorus P_4, a high-value form of phosphorus produced by specific furnace installations.

Phosphate rock is the main source of phosphorous from the earth’s crust. As phosphorous is one of the six main building blocks of life (together with oxygen, hydrogen, potassium, nitrogen and carbon), it plays a significant part in the bio based economic processes that take place in the global economy. Phosphorus is vital for all life on planet earth, including plants, animals and humans. 95% of global phosphate production goes to fertilisers and animal production (animal feed). The growing world population and increasing meat and dairy consumption in much of the world lead to an increased demand for phosphate for agriculture (Enghag, 2004). The remaining 5% is used in a wide range of industrial applications including cleaning and water treatment, fire safety, electronics and batteries, lubricants, agro-chemicals, medical applications, human food additives including a number of applications where phosphorus compounds are today non substitutable.

Phosphate rock refers to rocks containing about three-hundred phosphate minerals, usually calcium phosphate as apatite with the formula $Ca_5 (PO_4)_3(F, Cl, OH)$ (Enghag, 2004), which can be commercially exploited, either directly or after processing. It thus also denotes the product obtained from the mining and subsequent metallurgical processing of phosphorus-bearing ores. At present, phosphate rock is the only primary input material for phosphorus production worldwide (USGS, 2016a). It is estimated that the world consumption of phosphates will increase from just under forty-seven million tonnes in 2015 to over fifty-one million tonnes in 2020 (P_2O_5 equivalent) .

The supply chain for phosphate rock used in fertilizers is depicted in Figure 168. It can be estimated that European firms are involved in all of these stages, but so far no reliable data has been available on that issue.

To complement the analysis of phosphate rock, this factsheet also describes white phosphorus, or P_4. This is an elemental form of phosphorus, produced from phosphate rock in specific phosphorus furnace installations, which are highly energy intensive. P_4 is used in the production of a range of phosphorus containing chemicals. P_4 can also be used to produce very pure phosphoric acid, but this is mostly obtained by purification of phosphoric acid produced from phosphate rock, because this is cheaper (lower energy cost). The extremely pure phosphoric acid needed in microelectronics (chip etching) is however currently generally produced from P_4.

There are various allotropic forms of elemental phosphorus but only two forms have commercial significance - white and red phosphorus - and white phosphorus P_4 is the most commercially important, accounting for 99% of demand worldwide. However most phosphoric acid needed to make fertilizers does not need to be very pure and is more cheaply made directly from rock phosphate ores and not via the element (ECI, 2016).

White phosphorus is a colourless to yellow translucent wax-like substance with a pungent, garlic-like smell. It is highly reactive with air or water.

A wide range of the phosphorus-based products used in chemical industry can today only be produced via white phosphorus P_4. These products cannot be produced from phosphoric acid. The elemental P_4 is produced from phosphate rock by thermal reducing furnaces. Further processing results in red phosphorus. The EU has no production of P_4 today.

23.2 Supply

23.2.1 Supply from primary materials

23.2.1.1 Geological occurrence/exploration of phosphate rock

The abundance in the earth's crust of phosphorus pentoxide (P_2O_5) is about 0.13% of the total crust, which indicates a relatively high presence of P (Rudnick & Gao, 2003). Sedimentary marine phosphorites are the principal deposits for phosphate rock. Depending on the mineralogical, textural and chemical characteristics (e.g. ore grade, impurities), as well as the local availability of water around the mining site, different refining processes are applied to obtain phosphate rock concentrates. Although these resources are found worldwide, known reserves are highly concentrated (over 70% in Morocco). It is estimated that world resources of phosphate rock total 300 billion tonnes; known world reserves are shown in Table 92. The biggest deposits are located in northern Africa, China, the Middle East, and the USA. Large deposits of phosphates are also located on the continental shelf and on seamounts in the Atlantic and Pacific Oceans, but exploiting these deep-sea sources is still not considered an economically viable option. Besides the sedimentary phosphate deposits, some igneous rocks are rich in phosphate minerals too. However, sedimentary deposits are more abundant and usually higher in grade (P content, but also higher in contaminants). About 80% of the global production of phosphate rock is exploited from sedimentary phosphate deposits (USGS, 2016a; Kauwenbergh, 2010).

Exploration activities and mine expansions took place in Australia and Africa in 2011. There are two major projects in Africa: the expansion of a phosphate mine in Morocco and a new project off the Namibian coast. Smaller projects are under various stages of development in several African countries, such as Angola, Congo (Brazzaville), Guinea-Bissau, Ethiopia, Mali, Mauritania, Mozambique, Uganda, and Zambia. Expansion of production capacity was planned in Egypt, Senegal, South Africa, Tunisia, and Togo. Other development projects for new mines or expansions are on-going in Brazil, China, and Kazakhstan (USGS, 2016a). In Europe hardly any phosphate rock is available, except for a small mining operation based in Finland for several decades (De Ridder et al., 2012).

Apart from known geological reserves, organic sources of phosphorites are possible. Guano, bone meal or other organic sources are of less economic importance as phosphate sources, because of supply issues, processing costs, or simply because quantities available are much smaller.

23.2.1.2 Processing of phosphate rock

Currently, most phosphate rock production worldwide is extracted using opencast dragline or open-pit shovel/excavator mining methods, e.g. in the United States, Morocco, Russia and China. During surface mining, overburden is drilled, blasted, and removed by dragline to the side of the mining area for subsequent reclamation. Very large draglines, electric shovels, and bulldozers recover the upper ore body. The intercalating limestone layer is then blasted and removed to expose the phosphate bed, which is loaded onto special large volume trucks (MEC, 2016).

Further processing of phosphate rock is needed to produce elemental phosphorus. White phosphorus may be made by several methods. By one process, tri-calcium phosphate, the essential ingredient of phosphate rock, is heated in the presence of carbon and silica in an electric furnace or fuel fired furnace. Elementary phosphorus is liberated as vapour and may be collected under phosphoric acid, an important compound in making super-phosphate fertilizers. (ECI, 2016). Worldwide, a gradual shift to manufacturing high-purity phosphoric acid from wet process acid has taken place because it has lower production costs and none of the hazardous waste disposal issues that are associated with elemental phosphorus (USGS, 2016a). Further processing of white phosphorus will result in compounds such as phosphorus trichloride, acids, sulphides, sodium hypophosphite, phosphine, phosphides.

23.2.1.3 Resources and reserves of phosphate rock

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of phosphate rock in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[22], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for phosphate rock. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for phosphate rock, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for phosphate rock at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

The resources are relatively abundant globally and known reserves are documented and sedimentary phosphate deposits occur on every continent (McKelvey, 1967) but known reserves are highly concentrated in a few countries, mainly Morocco, see Table 92.

Resource data for some countries in Europe are available in the Minerals4EU website (Minerals4EU, 2014), see Table 93, but cannot be summed as they are partial and they do not use the same reporting code. For reserves, the Minerals4EU website only reports phosphate rock reserves in Ukraine, with 115.8 Mt of apatite ore, and 4.55 Mt of P_2O_5 contained in the apatite ores according to Russian Classification (RUS)A.

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[22] www.crirsco.com

Table 92: Global known reserves of phosphate rock in year 2015 (Data from USGS, 2016a)

Country	Estimated phosphate rock known reserves (tonnes)	Percentage of total (%)
Morocco	50,000,000,000	73
China	3,700,000,000	5
Algeria	2,200,000,000	3
Syria	1,800,000,000	3
South Africa	1,500,000,000	2
Jordan	1,300,000,000	2
Russia	1,300,000,000	2
Egypt	1,200,000,000	2
United States	1,100,000,000	2
Australia	1,000,000,000	1
Saudi Arabia	960,000,000	1
Peru	820,000,000	1
Iraq	430,000,000	1
Brazil	320,000,000	0
Others (including Finland)	1,075,000,000	2
World total (rounded)	*68,705,000,000*	*100*

Table 93: Resource data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2014)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
Spain	Adapted version of the USGS Circular 831 of 1980	30.8	Mt	11.78%	Proven reserves
UK	None	100.7	Mt	2.19%	Historic Resource Estimates
Finland	JORC	540	Mt	4%	Total
Norway	JORC	14.6	Mt	5.18%	Indicated
Ukraine	Russian Classification	131,930	kt	-	(RUS)P1
Estonia	Nat. rep. code	2,935.74	kt	-	Measured+Indicated
Greece	USGS	500	kt	10-25%	Measured
Serbia	JORC	72	Mt	9%	Total

23.2.1.4 World production

The global production of phosphate rock between 2010 and 2014 was 217,627,419 tonnes on average. Current production of phosphate rock is concentrated in a limited number of countries. In the period between 2010 and 2014, the global market for phosphate rock was on average 217 million tonnes. Although most phosphate rock resources are located in Morocco, China is the dominant producer. The largest phosphate rock mining countries are shown in Figure 172, with China, the USA, and Morocco leading the producing countries, manufacturing respectively 44%, 13%, and 13% of global production between 2010 and 2014. Finland produced just under 900Kt on average between 2010 and 2014. This can be expected to change in the future because of the concentration of known reserves in Morocco and the progressive depletion of exploitable reserves in the USA

Global production of phosphate rock was estimated to have increased between 2004 and 2012, due to an increased production in China especially, almost doubling its phosphate rock output in this period (BGS, 2016).

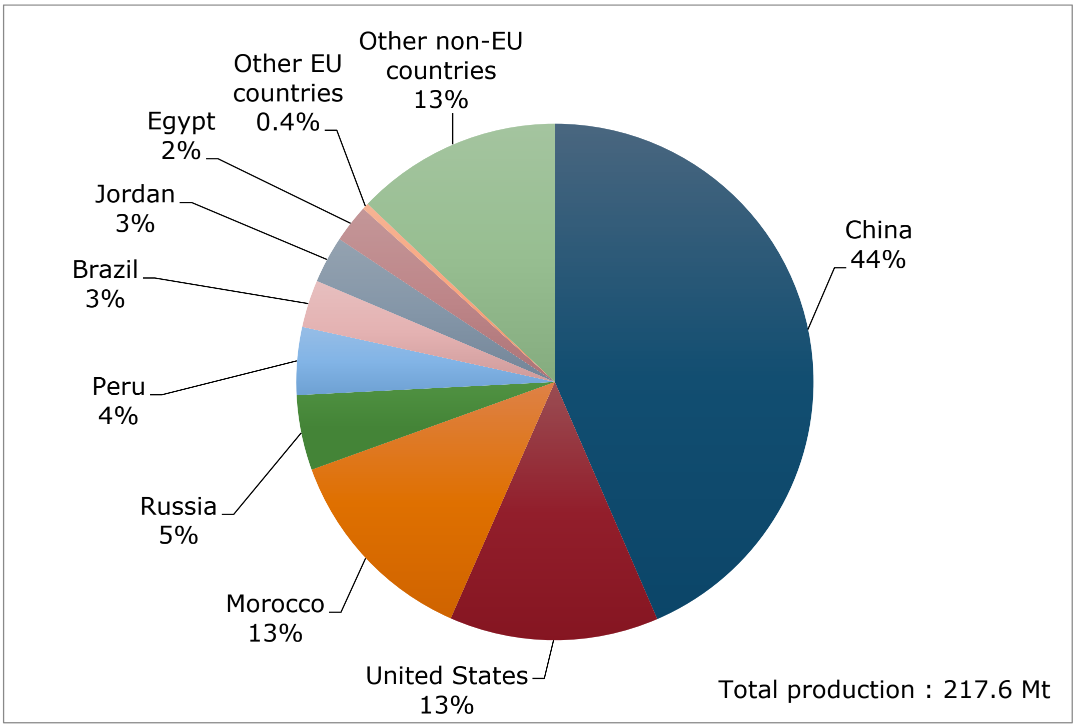

Figure 172: Global mine production of phosphate rock, average 2010–2014 (Data from BGS World Mineral Statistics database)

The global production of P_4 between 2010 and 2014 was 915,000 tonnes on average. The distribution of global production of white phosphorus is shown in Figure 173. Production by thermal acid still accounts for more than 50% of annual world production capacity of high-purity phosphoric acid, primarily in China. Production in the United States is limited to one plant. The only other operating elemental phosphorus facilities in the world were in Kazakhstan and Vietnam (USGS, 2016a).

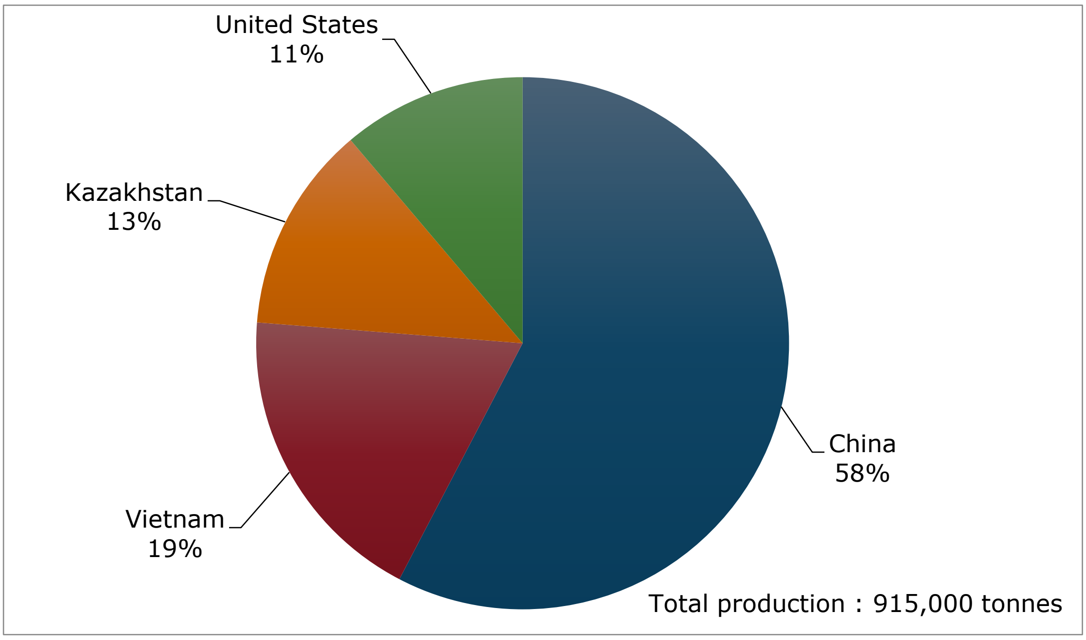

Figure 173: Global production of white phosphorus, base year 2012. Data from (USGS, 2016a)

23.2.2 Supply from secondary materials

Although phosphorus is recyclable, the input material phosphate rock is not recyclable, and as a result the recycling input rate can be regarded as zero.

For its applications in agriculture, phosphate rock can be replaced by secondary sources of phosphorous. To illustrate opportunities, given the current state of technology and market conditions, to replace the input of phosphate rock with other sources of P, a recycling value of 17% is assumed based on the Raw Material System Analysis method (BIO by Deloitte (2015). Here, various other inputs of phosphorous are mentioned that replace the input from primary phosphate rock. The total size of this flow is estimated to be around 180 tonnes of P (listed as "G.1.2, the production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU"). This figure for the phosphorus recycling value is an estimate of the % by which recycling of biogenic waste flows such as food and vegetal waste, manure and sewage sludge substitutes the use of mineral phosphate fertilisers (i.e. primary input material).

Other EOL recycling input rates are reported as well. Van Dijk et al. (2016) found that recycling rates were 70% in crop production, 24% in animal production, 52% in food production and around 76% in non-food applications of phosphorous.

The secondary supply of the element phosphorous is an important and recurring topic in discussing the criticality of phosphate rock. There is evidence that increased flows of secondary phosphorous could potentially be extracted and recycled from current production and consumption flows (RISE foundation, 2016; Van Dijk et al. 2016; Leip et al., 2015).

Examples of potential sources of secondary phosphorous are provided the DONUTSS project (DONUTSS, 2016). Fresh pig manure contains 0.4% of P_2O_5, whereas dry pig manure has 5% and after incineration the ash contains 18.8%. For chicken litter, these numbers are 1.9%, 3.9% and 15.3% respectively. Kitchen waste generally contains 18.8% of P_2O_5. Garden waste, another source from households, is much lower given a high cellulose and water content.

Processes exist to potentially produce white phosphorus P_4 from phosphorus-rich waste streams (e.g. ICL Recophos process to produce P_4 from sewage sludge incineration ash or meat and bone meal ash) but these are today only at the pilot scale and no industrial installation is yet under construction, nor operational, neither in the EU nor elsewhere (Thornton, 2016).

23.2.3 EU trade

Overall, the EU is a net importer of phosphate rock, importing over 6 million tonnes net per year of Natural Calcium Phosphates and Natural Aluminium Calcium Phosphates, Natural and Phosphatic Chalk, Unground and Ground (Figure 174). This number has grown strongly in recent years, specifically compared to 2009 when imports were still only around 2 million tonnes of phosphates.

The EU has become dependent after 2012 on foreign trade for its supply of phosphorus, as can be seen in Figure 175, while the traded volumes clearly have increased.

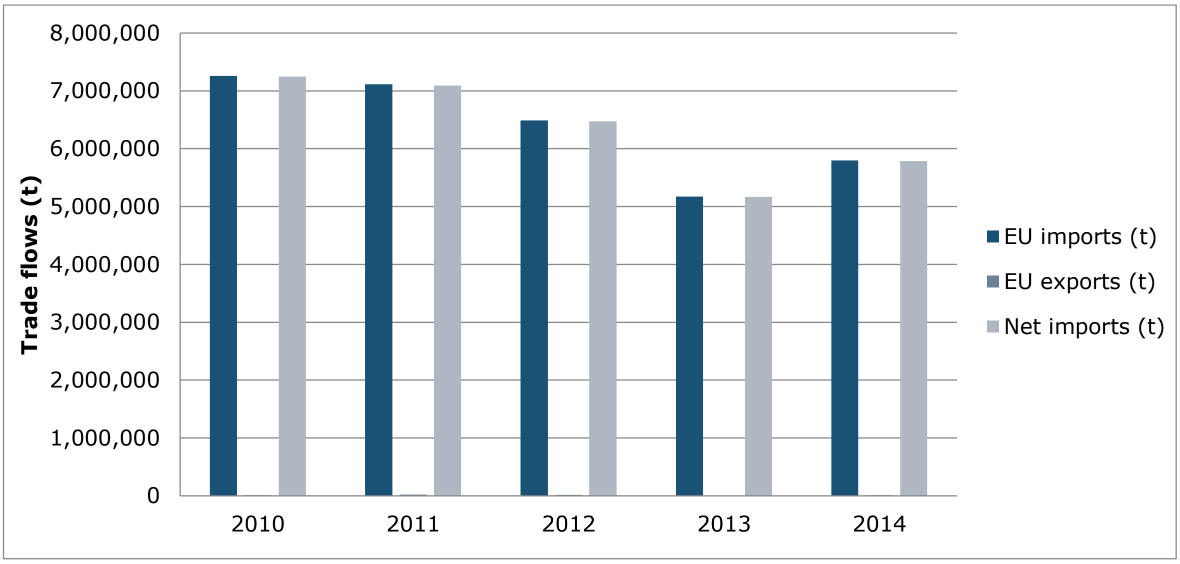

Figure 174: EU trade flows for phosphate rock. (Eurostat COMEXT database, 2016)

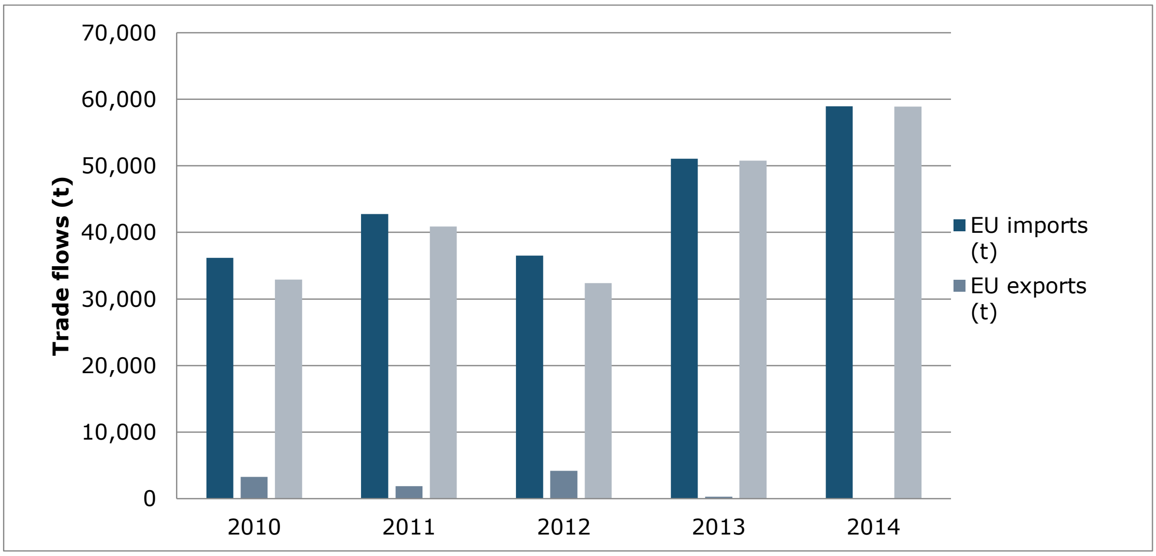

Figure 175: EU trade flows for P_4. (Eurostat COMEXT database, 2016)

Morocco is the largest importer of phosphate rock into the EU, covering around 31% of all imports. Other major importers include Algeria, Russia, Israel and Jordan (Figure 176), with shares between 10% and 20%. EU exports are mainly towards Norway; however, these amounts are negligible compared to imports.

Kazakhstan is the biggest importer of white phosphorus into the EU, covering around 77% of all imports. Other major importers are China and Vietnam (Figure 177).

EU trade is analysed using product group codes. It is possible that materials are part of product groups also containing other materials and/or being subject to re-export, the "Rotterdam-effect". This effect means that materials can originate from a country that is merely trading instead of producing the particular material.

For the 2010-2014 period, small export taxes (5% and 7.5%) are put in place by Jordan and Morocco for the relevant product groups containing natural calcium phosphates. China has imputed a tax rate of 35%. Vietnam has had an export tax that shifted between 10% and 40% in the period between 2010 and 2014. Lastly, the Russian federation has an instituted a licensing requirement and a small export tax (6.5%) around 2010 and 2011.

The export restrictions for phosphorus are slightly similar to phosphate rock for the 2010-2014 period.

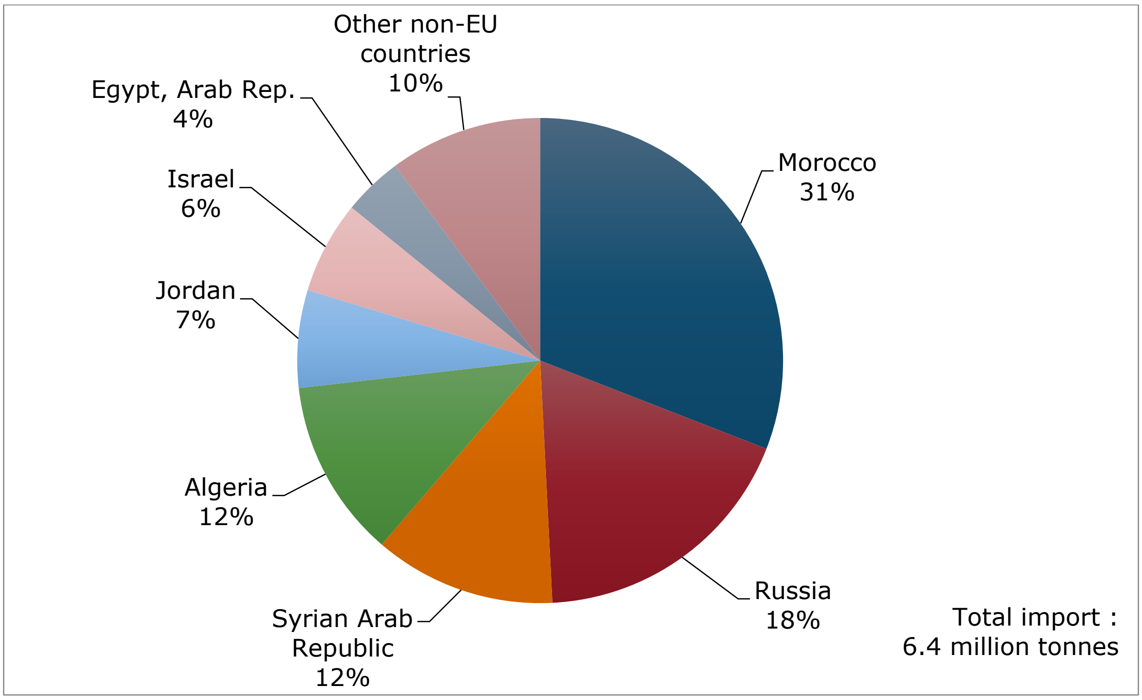

Figure 176: EU imports of phosphate rock, average 2010-2014 (Data from Eurostat COMEXT database)

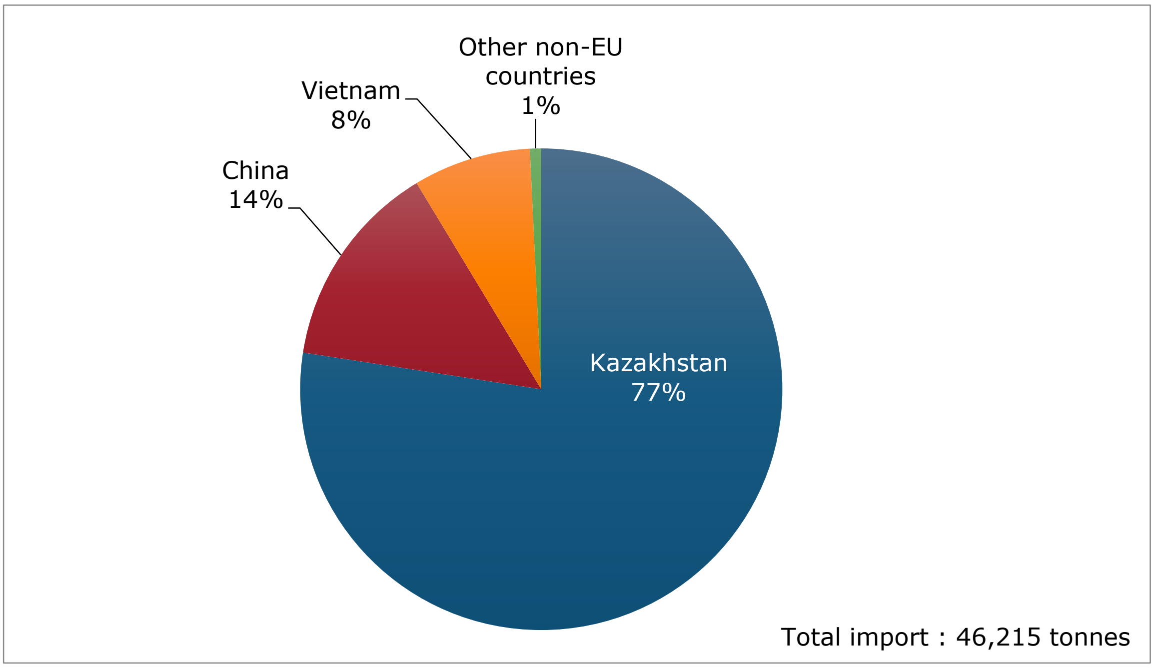

Figure 177: EU imports of phosphorus, average 2010-2014 (Eurostat COMEXT database, 2016)

China dropped a surtax of 75% on phosphorus in 2009, but kept an export tax of 15% on average in the time period. Morocco requires an export tax of 7.5% on phosphorus. Vietnam had an export tax of 5% in the period of 2010-2014. Egypt issued an export tax of no less than 1000% around the time of the Arab spring political events in 2011, as part of the global price spike of phosphate rock, phosphorus and fertilizers around that time. Brazil and Russia require a license to trade phosphorus, which is relevant to exports from Kazakhstan travelling by land to the EU.

23.2.4 EU supply chain

The import reliance for phosphorus is 100% as there is no domestic production in the EU.

The phosphorus in phosphate rock as a primary input material is presently a cornerstone in food production. Given spatial economic reasons, such as transport cost, urbanization and geopolitical issues, agriculture and food production are highly relevant for any (group of) state(s) in the current global economic system (FAO, 2014). The EU is no exception to this statement, and has a prioritized domestic self-reliance on essential food groups. Moreover, the EU is an exporter of high value produce and food products, between 6% and 7% of the value of total external EU exports (Eurostat, 2016). All agro-food related activities cannot take place without a supply of phosphorous into the agricultural system.

Europe’s import reliance of phosphate rock or phosphoric acid or phosphate fertiliser is currently around 88%, given the input from Finland. The recurring comment is that these figures do not capture use, stock accumulation and extraction potential of phosphorous in the downstream parts of chains of these materials. Therefore, care is needed when interpreting the dependency of the EU on external supply of phosphorous of sufficient quality. The EU sourcing (domestic production + imports) for phosphate rock is presented in Figure 178.

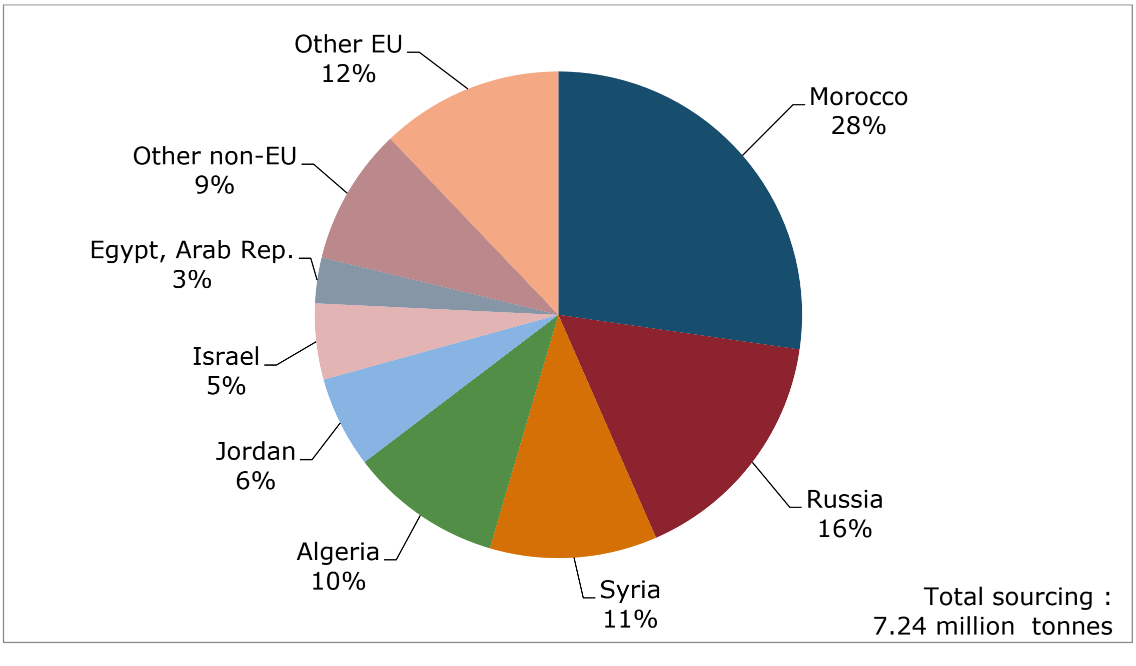

Figure 178: EU sourcing (domestic production + imports) of phosphate rock, average 2010-2014 (Eurostat COMEXT database, 2016)

23.3 Demand

23.3.1 EU consumption

The EU annual consumption of phosphate rock is just under 7.3 million tonnes over the 2010-2014 period, following from (Eurostat COMEXT database, 2016) and (BGS, 2016). The EU consumption of white phosphorus is 46.2 thousand tonnes, using the same sources and (USGS, 2016a).

23.3.2 Applications / End uses

Phosphorus is a vital part of plant and animal nourishment. Phosphate rock is globally utilized for the fertilization of food crops, generally with the other two main nutrients (N, K) and often with other nutrients (S, Mg, Ca, Cu etc.), see Figure 179. There is no substitute for use of phosphorous in food chains, apart from efficiency gains along the food production-processing-consumption chain, for example by diet changes related to food phosphorus intake. For individuals, intake volumes are advised (FAO, 2016) to be around: 250 gram per person per year is minimal requirement. 1,100 gram of phosphorous in food is the prescribed gross intake, halve of that is actual intake/consumption (depending on age and other attributes) given waste, digestion etc. The Council for Responsible Nutrition (2013) recommended daily requirement for health (DV) for phosphorus is 1,000 mg. In Europe, EFSA , the European Food Safety Agency (EFSA, 2015) concluded that no upper safety limit for phosphorus in diet is necessary and recommended not to modify the DRVs (Dietary Reference Values) for phosphorus recommended by SCF (Scientific Committee for Food) in 1993, that is 700 mgP/day for adults and equimolar with calcium intakes.

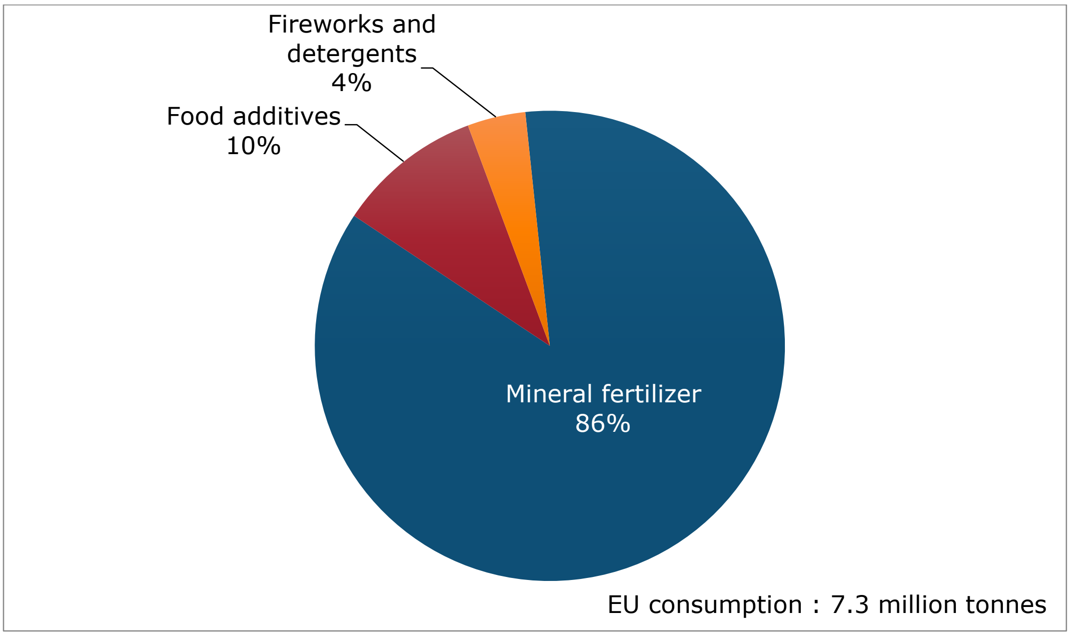

Figure 179: Global end uses of phosphate rock. Average figures for 2010-2014. (Schipper, 2001)

Pure phosphorus, partially obtained from phosphate rock, is used for the production of chemicals (e.g. flame retardants, oil additives, industrial water treatment, emulsifying agents), see Figure 180. Around 5% of world phosphate rock production is used in applications other than agriculture (other than fertilisers and animal feed additives). The "industrial" applications include: lubricant additives, pharmaceuticals (both in the pharmaceutical molecule, and as intermediates in drug synthesis), agrochemicals, anti-scaling agents, detergents, flame retardants, oil additives, industrial water treatment, emulsifying agents, matches and pyrotechnics, nickel plating, asphalt and plastic additives, catalysts, luminescent materials, metal extraction (most of the world's cobalt is produced using a phosphorus intermediate).

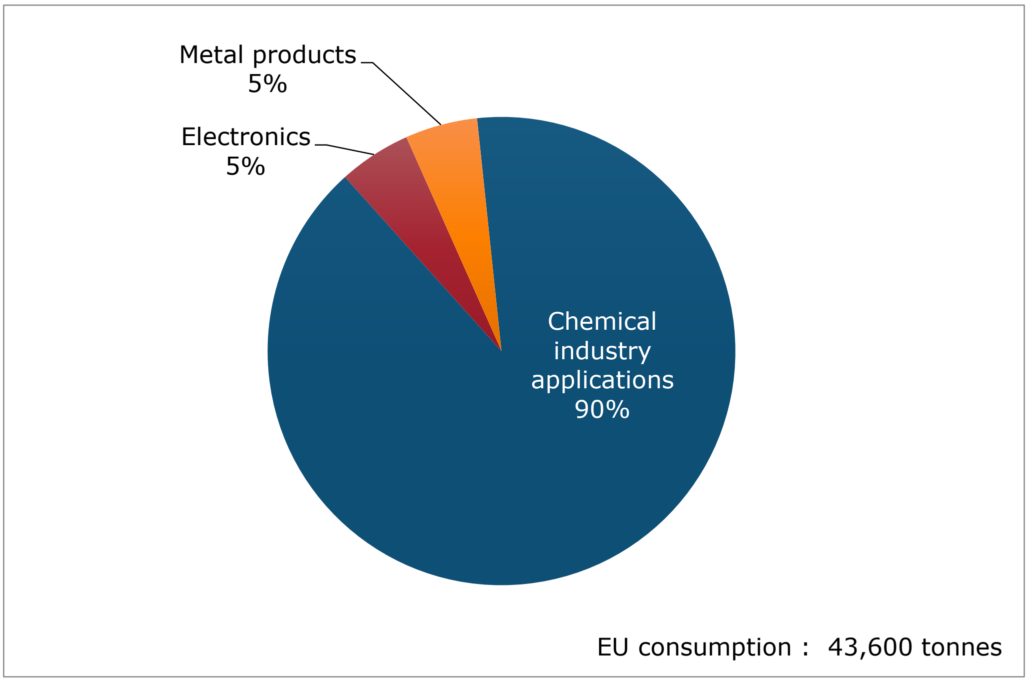

Figure 180: Global end uses of white phosphorus. Average figures for 2010-2014. (ECI, 2016)

Relevant industry sectors are described using the NACE sector codes (Eurostat, 2016c) in Table 94.

Table 94: Phosphate rock or white phosphorus applications, 2-digit NACE sectors, associated 4-digit NACE sectors and value added per sector (Data from the Eurostat database, Eurostat, 2016)

Applications	**2-digit NACE sector**	**4-digit NACE sector**	**Value added of sector (millions €)**
Food additives	C10 - Manufacture of food products	All subsectors (meat, starch, dairy etc.)	174,000
Fertilizers, detergents	C20 - Manufacture of chemicals and chemical products	20.15 Manufacture of fertilisers and nitrogen compounds	110,000
Metal products, unspecified	C25 - Manufacture of fabricated metal products, except machinery and equipment	25.61 Treatment and coating of metals	159,513
Electronic parts	C26 - Manufacture of computer, electronic and optical products	26.11 Manufacture of electronic components	75,260

23.3.3 Prices

The development of prices for phosphate rock is shown in Figure 181. The price spike around 2008 originated from an imbalance between supply and constantly expanding demand over decades, especially in Asia, a lack of investment in mining and the very long delay time between planning new mining capacity and its coming on stream, and from implementation of export tariffs by some countries and political unrest fuelling concerns about supply security (Arab Spring). Demand was particularly strong in China and India, countries with large and growing populations. Another factor was increased demand for fertilizers to produce biofuels in the United States, Brazil, and Europe. Increased livestock production created still more demand for grain and thus for fertilizers. (IFDC, 2010) the price spike also affected commodities such as potassium. Overall, phosphate rock and fertiliser prices are both tied to global food prices. The global economic crises caused the prices to fall relatively quickly, but prices remain more volatile ever since.

The average price of Phosphate rock ore (70%) from Morocco between 2011 and 2015 was 149.33 US$ (DERA, 2016). The prices of White Phosphorous are opaque but stable, ranging between 200US$/kg and 500US$/kg in 2016.

Agricultural use of P is also relatively resilient as it is accumulated is soils such that farmers can easily skip high-cost years (Wellmer & Scholz, 2016).

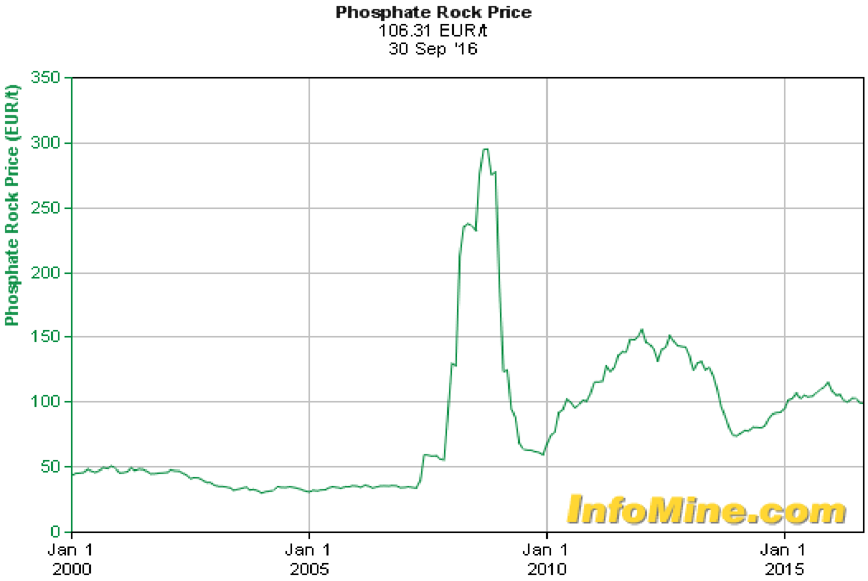

Figure 181: Global developments in price of phosphate rock (Data from InvestmentMine, 2016)

The value of exports of elemental phosphorous in 2014 and 2015 from the United States lay around 3$/kg.

23.4 Substitution

There is a particular thin line in case of phosphate rock when it comes to discerning substitution from recycling input rate. This relates to the recurring question if the element phosphorous in whatever form needs to be assessed rather than the primary input material phosphate rock that contains phosphorus in mineral appetite form.

For this assessment, we have chosen to consider no substitution option for use of phosphate rock in fertilizer. The many opportunities from other sources of phosphorous are represented by the applied end-of-life recycling rate of 17% (see above) rather than a reduction of supply risk from substitution.

Substitution of white phosphorous P_4 and thus also of phosphate rock in other chemical applications is also set to 0% because many of these are specific phosphorus chemicals where no substitute is available to date (example: fire safety, where phosphorus based flame retardants are developing to replace halogenated substances).

23.5 Discussion of the criticality assessment

23.5.1 Data sources

The CN codes used for the trade analysis are 25101000 and 25102000. These product groups describe ground and unground natural calcium phosphates, natural aluminium calcium phosphates and natural and phosphatic chalk. The CN code used for the trade analysis of phosphorus is 28047000, and is labelled Phosphorous. It contains also small shares of red phosphorus, a measuring error that is ignored for transparency sake.

The data has a very strong coverage, on EU level, is available for time series and updated at regular intervals and is publicly available.

Phosphate rock was chosen as the initial bottleneck, and evaluated as such in the previous criticality assessment. For consistency, the choice has been made to assess once more the extraction stage rather than the refining stage that would take P as the actual raw material. This might ignore the relevant insights in the criticality of phosphorous. The element itself is a major part of other stages in both the production chain as well as the life cycle of P bearing biomass. Moreover, the choice for phosphate rock has repercussions on the discussion of the supply chain and substitution options. To enable comparison, the assessment of white phosphorus was made after all to describe the refinery stage of P.

23.5.2 Calculation of Economic Importance and Supply Risk indicators

If a system would be modelled to describe all flows of P on this planet (as was attempted in the RMSA study), experts (SCOPE Newsletter, 2016) would appreciate dominant better assessment of the roles of different types of recycling, contemplations about entropy ("where is the P"), the quality difference of the ores affecting the application range etc.

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 94). The value added data correspond to 2013 figures.

23.5.3 Comparison with previous EU assessments

Phosphate rock was first assessed in the previous CRM assessment (European Commission, 2014). The results of the 2017 assessment show the consistency that was expected with the decision to assess phosphate rock as the commodity of interest, rather than the element phosphorus. The slight reduction in economic importance is due to the slight reduction of the share in total value added of chemical products manufacturing and food products manufacturing in the European economy. The allocation of phosphate rock to these sectors has not significantly changed between the two studies.

The supply risk was assessed on phosphate rock and P_4 using both the global HHI and the EU-28 HHI as prescribed in the revised methodology.

P_4 or white phosphorus is being assessed for the first time in 2017 with the EI and SR results presented in the following table. P_4 was not assessed in 2011 or in 2014, therefore, it is not possible to make any comparisons with the previous assessments.

There are some differences on criticality scores if the element phosphorous, rather than the commodity phosphate rock, would be assessed (see Table 95). The supply risk is increased given the high country concentration and the economic importance is lower given the fact that the food industry is not depending on white phosphorus.

Table 95: Economic importance and supply risk results for a phosphate rock and white phosphorus in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011		2014		2017	
Indicator	EI	SR	EI	SR	EI	SR
Phosphate rock	Not assessed		5.8	1.1	5.1	1.0
White phosphorus	Not assessed		Not assessed		4.4	4.1

23.6 Other considerations

23.6.1 Forward look for supply and demand

The estimations in the Table 96 regarding future demand and supply trends are based on Heffer & Prud'homme (2016), Thornton (2016) and FAO (2015).

It should be noted that the "20 years" scale is approximately the delay time between planning new phosphate rock mining capacity, and its production coming onto the market, given delays in authorization, funding, machinery investment, transport and processing infrastructure (Thornton, 2016).

Sources describing differences between the supply and demand outlooks of phosphorus compared to phosphate rock are not identified.

Table 96: Qualitative forecast of supply and demand of phosphate rock (Heffer & Prud'homme, 2016; Thornton, 2016; FAO, 2015)

Materials	**Criticality of the material in 2017**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Phosphate rock	x		+	+	++	+	+	0
White phosphorus	x		0	0	-	+	+	0

23.6.2 Environmental and regulatory issues

The volumes of phosphorous that end up in soil and ground water do considerably affect the biochemical processes in a negative way. Especially aquatic ecosystems do receive a negative impact, due to the process of eutrophication, resulting in oxygen depletion. This has in turn an effect on biodiversity, since aquatic animal populations are affected by invasive new species that benefit from the new resource balance (Sutton et al., 2013).

For example in several EU member states, phosphorus discharge into the environment is the principal factor (other than morphological modification) causing freshwater bodies to fail to achieve EU Water Framework Directive quality objectives (Leaf, 2015)

White phosphorus is the probably most dangerous form of phosphorus that is known to us. White phosphorus is highly reactive (it was used in phosphorus bombs of the Second World War) and poisonous and significant exposure can be fatal (Lenntech, 2016). For this reason, white phosphorus P_4 is usually reacted immediately on production to other "holding derivatives" (usually PCl_4), these derivatives can then be transported and used to produce the different phosphorus chemicals for which P_4 is a necessary raw material. The problems of handling P_4 produced in P_4 furnaces and converting it safety to derivatives which can be traded is one of the obstacles to setting up of new P_4 furnace installations.

The energy requirement of existing phosphorus production techniques is high. Each tonne of phosphorus produced requires about 14 MWh (ECI, 2016), which is comparable with the average electricity requirement of a tonne of aluminium.

23.6.3 Supply market organisation

A potentially important development on the supply side could be regulation about the cadmium content in phosphate rock. If the EU adopts tight standards for phosphate fertilisers relating to a maximum amount of cadmium, the potential supply from many sedimentary sources (in particular Morocco) would pose problems, requiring either a process removing cadmium process or a switch to igneous sources. Phosphate rock ores from Finland would not be affected by this ruling given their geological properties. If only Europe were to adopt tight standards, this would probably not significantly impact world supply (high cadmium rock and so fertiliser would be used elsewhere in the world) but could increase costs and could make Europe dependent on certain supplier countries (in particular Russia). Investments in plants that extract secondary phosphorous are being made in the coming years (Northfranceinvest, 2016).

White phosphorous could be subject of disruptive market developments. The two main suppliers of the EU are currently Kazakhstan and Vietnam. The former poses transport logistics security issues. Vietnam production is largely dependent on energy supply from China, which may at some time be interrupted, stopped or re-priced.

23.7 Data sources

23.7.1 Data sources used in the factsheet

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23.8 Acknowledgments

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24. RARE EARTH ELEMENTS (REES)

Key facts and figures

Material name and Element symbol	See individual factsheets	World/EU production (tonnes)[1]	135,650 / 0
Parent group	Rare Earth Elements (REEs)	EU import reliance[1]	100%
Life cycle stage / material assessed	Extraction / mixed REOs	Substitution index for supply risk [SI (SR)][1]	See individual factsheets
Economic importance score (EI) (2017)	Light REEs: 3.6 Heavy REEs: 3.7	Substitution Index for economic importance [SI(EI)][1]	See individual factsheets
Supply risk (SR) (2017)	Light REEs: 4.9 Heavy REEs: 4.8	End of life recycling input rate (EOL-RIR)	See individual factsheets
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Catalysts (23%), Permanent magnets (22%), Metallurgical alloys (16%)
Main product, co-product or by-product	Main product or co-product of iron ore extraction and others	Major world producers[1]	China (95%), USA (1.7%), Russia (1.3%), Australia (1.2%)

		2011	2014	2017
Criticality results	LREEs	Critical	Critical	Critical
	HREEs	Critical	Critical	Critical

[1] Average for 2010-2014, unless otherwise stated.

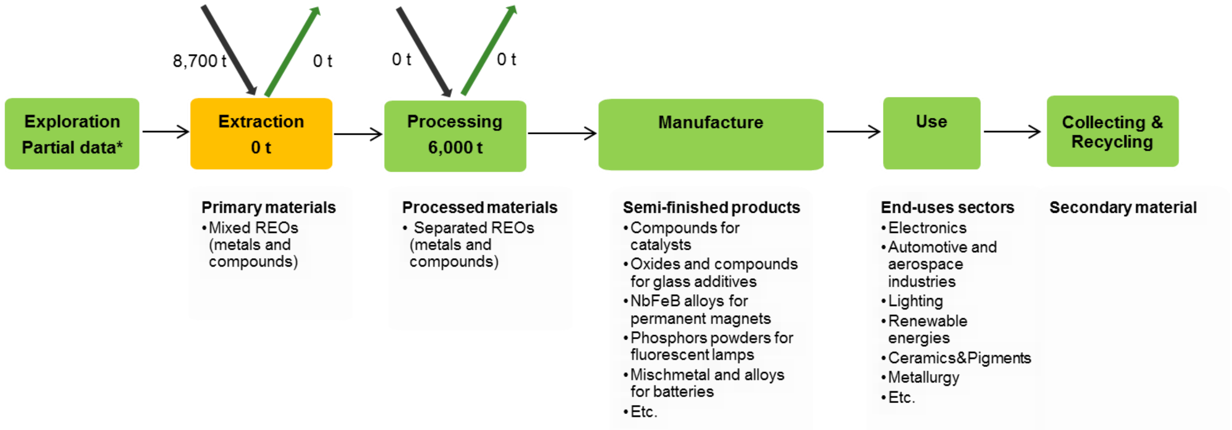

Figure 182: Simplified value chain for REEs

The green boxes of the production and processing stages in the above figure suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. *EU reserves are displayed in the exploration box but need to be interpreted with caution (cf. 2.1.2)

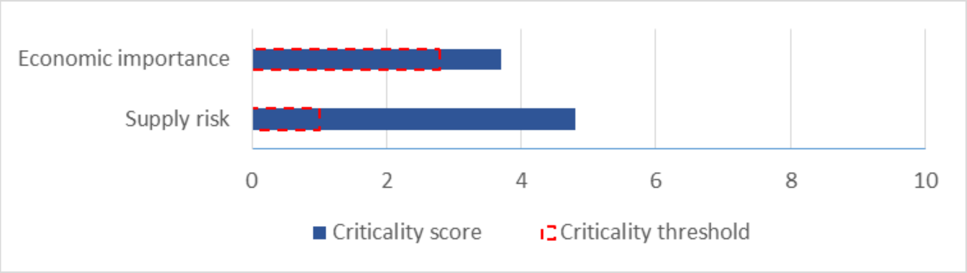

Figure 183: Economic importance and supply risk scores for heavy rare-earth elements (arithmetic average)

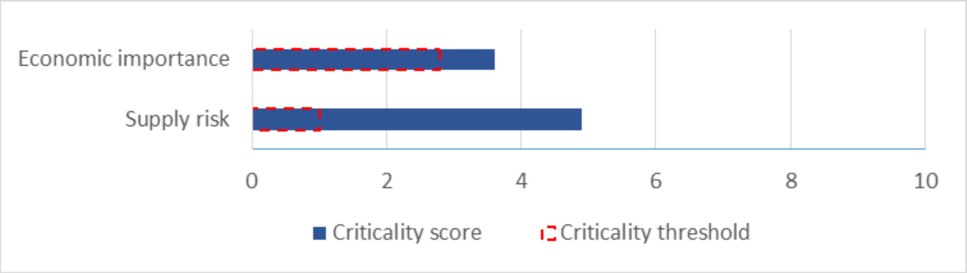

Figure 184: Economic importance and supply risk scores for light rare-earth elements (arithmetic average)

24.1 Introduction

The Rare Earth Elements (REEs) are a group of 15 to 17 elements, depending on the inclusion of yttrium and scandium in the definition. The lanthanide group forms the major part of REEs. It comprises the 15 elements of the periodic table with atomic numbers 57 to 71: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu). Yttrium (Y, atomic number 39) and scandium (Sc, atomic number 21) share physical and chemical properties with the lanthanides. However, only yttrium is to be treated together with REEs, as it is found in the same ore deposits and share a great part of REEs value chain. Scandium has quite geological and industrial specific properties and will be treated separately. Promethium which has no stable isotope in nature is considered in the 2017 criticality assessment.

The REEs are typically split into two groups, the Light Rare Earth Elements (LREE) and Heavy Rare Earth Elements (HREE), both for physico-chemical and commercial reasons. Even if various definitions exist, the LREEs are most commonly defined as the lanthanide elements lanthanum through to samarium (La, Ce, Pr, Nd, Sm) and the HREEs defined as the lanthanide elements europium through to lutetium and yttrium (Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu & Y).

Rare Earth Elements are all silvery-white to grey metals, highly reactive with water and oxygen. Most of them form stable compounds in the 3+ and 4+ oxidation states, tarnish easily in air (mostly light REEs) and usually have a high electrical conductivity. The combined crustal abundance of REEs is of the order of 200 ppm (Roskill, 2015). Four of them (cerium, lanthanum, neodymium and yttrium) are even more common than lead or cobalt in the upper continental crust (Rudnick, 2003). They are not found as pure metals in nature but form part of a great variety of minerals (more than 200 identified). The most common ones at a commercial level are bastnaesite, monazite, loparite, xenotime and lateritic ion-adsorption clays.

REEs find uses in a great variety of applications linked with their magnetic, catalytic and optical properties. None of the first stages of REEs production currently take place in the EU. Their main uses are in automotive, telecom and electronics sectors, as well as aerospace, defence and renewable energies.

In any discussion of REEs it is important to distinguish between heavy and light REEs, because geological deposits of heavy REEs (HREEs) are far scarcer than deposits of light REEs (LREEs). It is reminded that in nature, rare earth deposits do not occur as individual rare earth oxides (e.g. Tb_4O_7 or Nd_2O_3) but as complex mixtures in minerals (such as bastnaesite). HREE-rich deposits currently in operation are nearly exclusively limited to ion-exchange clay deposits in the south of China (Chi and Tian, 2008). For this reason, HREEs are often considered more “critical” than LREEs. This is not always true, however, because market demand may be such that an LREE (e.g., Nd in permanent magnets) may be considered far more critical than an HREE (e.g. Gd). Note that in LREE ores, the proportion of Nd compared to other light elements is relatively low (a typical distribution in ores is: 50% Ce, 20-25% La, 12-20% Nd and 4-5% Pr), which contributes to creating an imbalance between supply and demand (Binnemans et al., 2013): in order to obtain Nd, approximately twice as much Ce and at least as much La must be produced.

24.2 Supply

24.2.1 Supply from primary materials

24.2.1.1 Geological occurrence

REEs ore deposits occur in a wide variety of rocks and genetic types (Wall, 2014; BRGM, 2015). In summary, the most important ones for commercial exploitation are carbonatite-associated deposits (including weathered carbonatites), ion adsorption deposits, alkaline igneous rocks (including alkaline granites), placer deposits, and more anecdotic hydrothermal deposits and seafloor deposits.

Deposits vary in terms of size and grade. Carbonatite-associated deposits tend to be medium to large tonnage and high grade. The main examples are the Bayan Obo mine in China (accounting for about 60% of LREEs global production in 2014) and Mountain Pass in the USA, with bastnaesite as the main ore mineral. They are typically enriched in LREE.

Alkaline rock deposits are generally larger tonnage but lower grade. An example is the nepheline syenite deposit of Lovozero in Russia, where loparite is the main ore mineral.

Beach sand placer deposits are variable in size and generally low grade; the main REE-bearing mineral in those deposits is monazite (with potential thorium content) which is exploited as a by-product of rutile, ilmenite and others.

Ion adsorption deposits are rather small and low grade but relatively rich in HREEs contained in ion-adsorption clays and xenotime mineralization. The majority is located in Southern China. They are mostly artisanal small-scale mines, however accounting for 98% of HREEs global production.

The concentration of rare earth elements varies with each type of mineralisation, and also between each individual ore body.

24.2.1.2 Mining

Most REE mines, such as Bayan Obo, Mountain Pass and Mount Weld, are open-cast operations, involving conventional blast, and load and haul techniques. No underground mines have ever been designed for the exclusive production of REEs but there are, or has been, production of REE from a few underground mines. For example, the former thorium mine at Steenkampskraal, South Africa, and the former uranium mines at Elliot Lake, Ontario, Canada.

Different mining techniques are used for the beach sand placer deposits because they are generally much less consolidated than carbonatites, alkaline rocks or hydrothermal deposits. They are also often under water. Mining techniques include dredging and excavation by bucket wheel or by excavator. Some crushing may be required.

There are few details available of mining techniques for ion adsorption deposits in China but many are small-scale operations, with much of the mining done by manual labor. The clay deposits are excavated and leached to extract REEs, mostly using in-situ leaching techniques, sometimes on large areas.

24.2.1.3 Processing and extractive metallurgy

REEs have a complex supply chain, and products are sold at several stages along the processing and separation sequence. The first step is the processing of the ore to produce mineral concentrates containing mixed rare earth oxides (REOs). Those concentrates can be sold at this stage to downstream processors. However, an increasing proportion of ore is now processed in vertically integrated companies (both in China and the rest of the world) partly due to the difficulty (and cost) to have the specific technology and knowledge to process each individual type of ore (Roskill, 2015).

Further processing lead to REEs compounds such as rare earth carbonates, nitrates and chlorides. Those products can be sold to end users such as catalyst manufacturers or are supplied to downstream processors for separation.

The goal of separation is to obtain individual rare earths compounds to a degree of purity of 99.9% (3N) to 99.9999% (6N). The majority of production is in the oxide form but individual rare earth carbonates, chlorides or fluorides can also be produced. This step is technically difficult and costly in comparison to others. It involves various phases; initial separation results in the isolation of lighter elements such as lanthanum and cerium, as well as intermediate products such as mischmetal (La-Ce, La-Ce-Pr or La-Ce-Pr-Nd) and didymium (Pr-Nd). These products are combinations of individual rare earths and can be supplied directly either to magnet alloy producers or in the iron and steel industry. The heavier fractions (Sm-Eu-Gd) are separated in the end. The main method used for separation is solvent extraction (SX), suitable at the industrial scale to produce large tonnages of individual compounds. Ion adsorption is more adequate to extract small quantities of HREEs of 6N purity (BRGM, 2015).

Further refining is needed for the production of REEs metals and alloys. It is also a very costly and complicated step. Most of the time, metallothermic reduction is used for preparation, followed by further reduction where boron, iron or cobalt can be added to form the desired magnets alloys. Pure REEs metals (99,999% or more) are the most expensive products and usually purchased for very specific applications.

24.2.1.4 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of REEs in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[23], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for REEs. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for REEs, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for REEs at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015). Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

Resource data for some countries in Europe are available in the Minerals4EU website (see Table 97) (Minerals4EU, 2014) but cannot be summed as they are partial and they do not use the same reporting code.

Table 97: Resource data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2014)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
Greece	USGS	485	Mt	1.17% REE	Inferred
Turkey	NI 43-101	49	Mt	725 ppm REE	Inferred
Portugal	None	2.4	Mt	0.44% REE	Historic Resource Estimates
Ukraine	Russian Classification	0.21	kt	Yttrium	P1
Finland	None	0.5	Mt	2.4% Ln2O3	Historic Resource Estimates
Sweden	NI 43-101	46.1 46.1	Mt Mt	0.28% Heavy REE 0.29% Light REE	Indicated
Norway	None	8	Mt	0.434 % REE	Historic Resource Estimates
Greenland	JORC	4.3	Gt	0.65% REO	Inferred
	NI 43-101	5.884	Mt	1.77% REO	Indicated

Reserves of REEs estimated by the USGS were around 130 million tonnes REO (Gambogi, 2016). BRGM estimates are more conservative and amount to 80 million tonnes (BRGM, 2015), as presented in Table 98.

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[23] www.crirsco.com

Table 98: Global reserves of REOs (BRGM, 2015)

Country	Reserves (tonnes of REOs)
China	65,840,000
Brazil	7,460,000
Australia	2,563,000
USA	1,694,000
Greenland	1,528,000
Tanzania	940,000
Canada	805,000
Russia	153,000
Sweden	140,000
South Africa	64,000
Malaysia	43,000
Total	*81,230,000*

Figures for countries where no reporting obligation apply are the most difficult to evaluate and can vary from one source to another (e.g. Brazil, China, India) which explain some differences.

Sweden and Greenland present interesting potential for REEs exploitation, although currently penalized by low market conditions or environmental issues. The Minerals4EU website only provides some data about Yttrium lanthanide and yttrium ore reserves in Ukraine, at about 417 kt (RUS A) (Minerals4EU, 2014). However, only Greenland and Sweden assessments of rare earths reserves (respectively 1,528,000 tonnes and 140,000 tonnes of REO – see Table 98) have been performed using international reporting code and ca be qualified as reliable at the present date.

24.2.1.5 World mine production

On average, global production of REOs amounts from 130,000 to 140,000 tonnes. China remains responsible for around 95% of total production (average of 2010-2014) as shown in Figure 185. However, in 2014, increased productions from the companies Molycorp in the USA (around 4,000 t) and Lynas in Australia/Malaysia (7,000 t) have slightly reduced China’s share. But it was only temporary as both companies have experienced financial difficulties in the following years. Molycorp’s mining and separation operations were idled indefinitely in October 2015. Price declines were cited as a key factor in the suspension of operations (Mining Journal, 2015). Lynas’ activities are also penalized by a huge debt (Hoyle, 2016).

Productions in other countries tend to be modest and dependent on market conditions. In Russia, production by the company Solikamsk remains stable (around 2,000 t REOs annually) although REEs extraction is not their main activity In Brazil and India, a major part of supply comes from stockpiles on which data is sometimes lacking. In Malaysia and Vietnam, extraction is mostly artisanal and sometimes illegal.

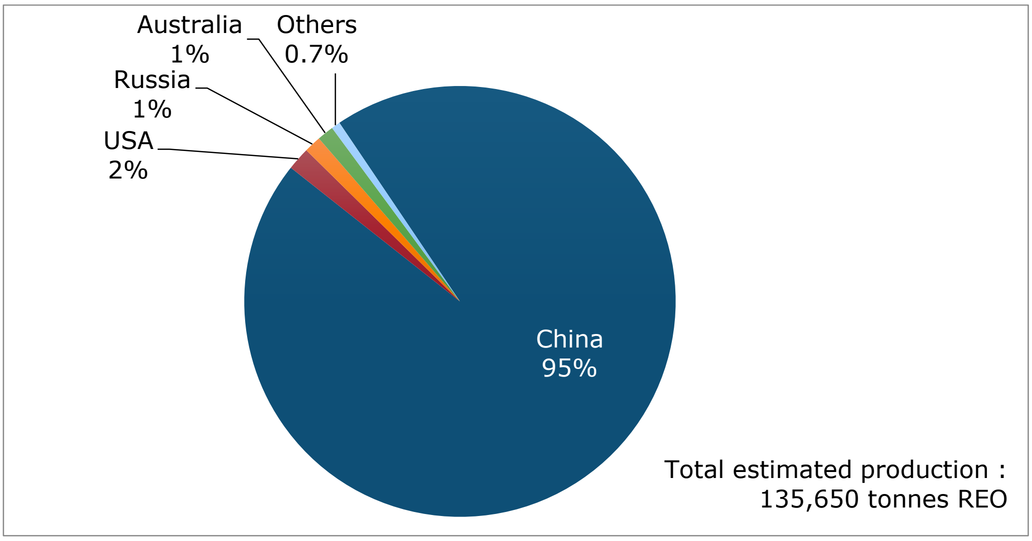


Figure 185: Global mine production of REOs, average 2010–2014. Compilation of data (BGS, 2016; BRGM, 2015; Roskill, 2015; World Mining Data 2016)

REEs are also known to be extracted illegally in China, which at some periods could have accounted for 30-40% of Chinese production (Kingsnorth, 2013). The evolution of illegal production levels remains unclear as of 2016 (Higgins, 2016).

24.2.2 Supply from secondary material

Less than 1% of REEs were thought to have been recycled from end-of-life products in 2010 (Kara et al., 2010). Today, this rate is still very low, especially in Europe because of the lack of efficient collecting systems and prohibitive costs of building REEs recycling capacities (ERECON, 2014). Solvay, one of the main REE-based phosphors producers in the EU developed a recycling unit together with Umicore in France in 2012 but had to stop operations by January 2016 because it had become uneconomic (Delamarche, 2016). However, a lot of research projects are on-going to identify the best targets and processes (ERECON, 2014)

Recycling is often difficult because of the way that REE are incorporated as small components in complex items or are part of complex materials. The processes required are energy intensive and complex (Schüler et al., 2011).

Nevertheless, as for many metals, new scraps generated during the manufacture of alloys are an important secondary source, mainly in a closed loop (30% of magnet alloys end up in scraps during manufacture) (Higgins, 2016).

Research and development in this area should evolve quickly, especially in Japan and China (NiMH batteries recycling, plants in Vietnam) (Higgins, 2016).

24.2.3 EU trade

Import reliance on REOs contained in mixed rare-earth compounds is 100%. According to Eurostat figures (customs codes 28053010, 28053090, 28469000, 28461000), the amounts of imported REEs was quite stable during the 2010–2014 period, at around 8,000 t/yr.

According to EUROSTAT data and conversion factors (see Table 102), the three main suppliers of the EU are China (40%), the United States (34%) and Russia (25%).

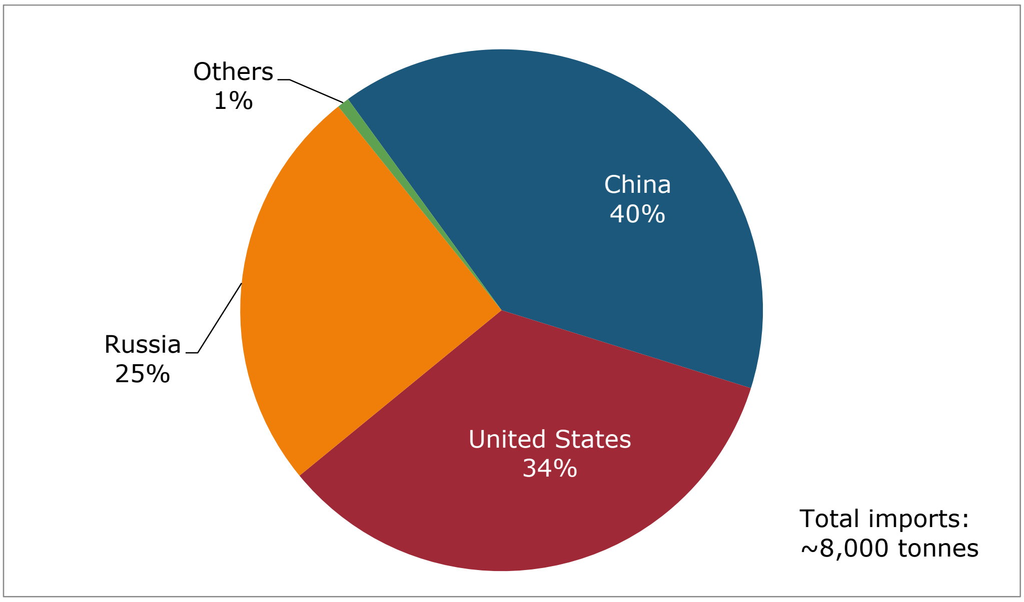


Figure 186: Extra-EU imports of mixed REOs compounds. Average 2010-2014. Data from Eurostat Comext, with conversion factors (Eurostat, 2016)

Over the 2010-2014 period, China has imposed export quotas and export taxes for all REEs. In May 2015, China ended its rare-earth export quotas, removed export tariffs, and began to impose resource taxes on rare earths based on sales value instead of production quantity (Metal Pages, 2015).

24.2.4 EU supply chain

Import reliance has been estimated at 100% for REEs at the stage of mixed REOs. In the EU, a few players are found at different stages of the REE value chain. Some have the ability to separate individual REOs (in Estonia and France) and manufacture REE-based products for various industries (phosphors, catalysts, polishing powders, etc.). There are also alloys makers and magnets manufacturers (in Germany, the UK, Slovenia) operating from imported processed materials. The ASTER project specifies 6kt REO metals and compounds produced in EU (separation products), by Estonia and France (Guyonnet, 2015).

Generally speaking, there is no critical mass of REE transformation and manufacturing in the EU; although critical in many industries a large proportion of REE consumption comes from finished products imports to the EU (magnets, alloys, hard drives, laptops, electric or hybrid vehicles, etc.).

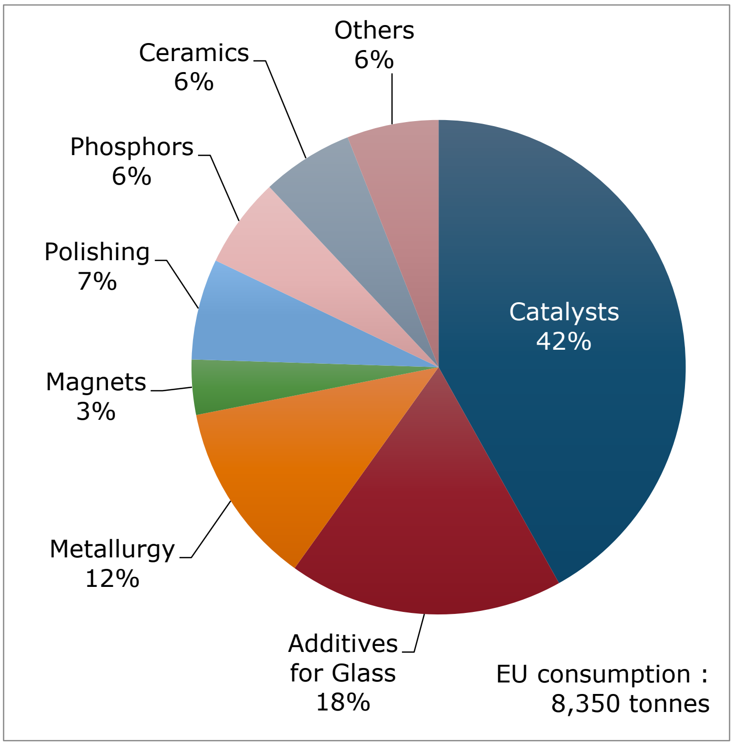
24.3 Demand

24.3.1 EU consumption

The EU consumption of REE is entirely based on imports, about 8,350 tonnes.

24.3.2 Applications

The major applications vary according to individual Rare Earth Elements, but also regionally. Overall, the EU global consumption of REEs by end-use is the presented in Figure 187 (expressed in tonnes REOs). The repartition of end-uses is different in the EU compared to the global situation (see Figure 187), with a higher use of REEs in catalysts in the EU, whereas REEs are by far less used in magnets.



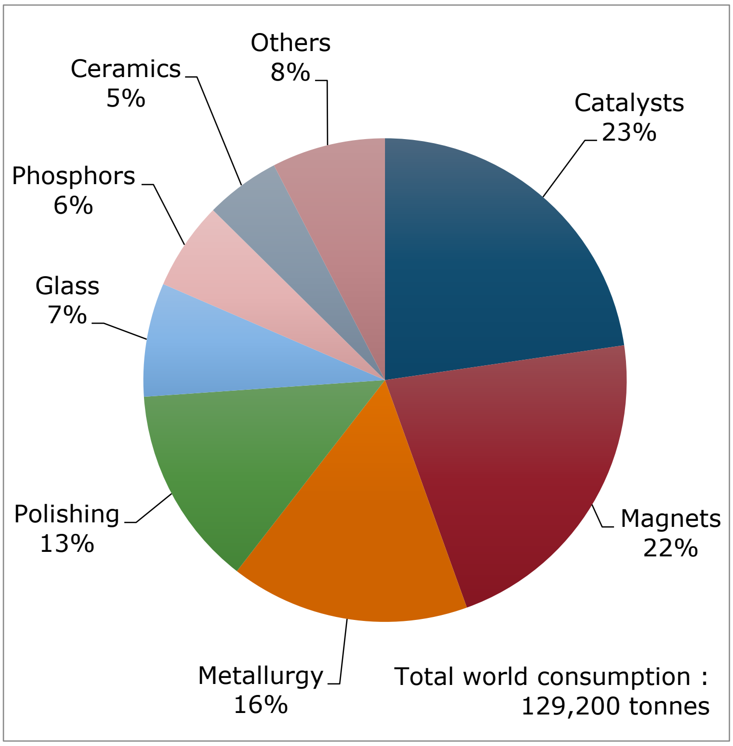


Figure 187: EU end uses of REEs **Global end uses of REEs**

(Data from the ASTER project – Guyonnet et al., 2015)

Globally, the main markets for LREEs, such as lanthanum and cerium are in catalysts, metallurgy and glass/polishing. The main markets for praseodymium, neodymium dysprosium and samarium are in magnets, while the main markets for the HREEs are in phosphors and ceramics. These particular aspects will be developed in individual factsheets, with associated NACE sectors, but the Table 99 provides an overview of the application shares of the individual REE.

Table 99: Applications of the individual REEs (Data from the ASTER project – Guyonnet et al., 2015)

Applications	Heavy REEs							Light REEs				
	Eu	Tb	Gd	Er	Dy	Y	Ho, Tm, Lu, Yb	Ce	Nd	La	Pr	Sm
Magnets	-	32%	**97%**	-	**100%**	-	-	-	**37%**	-	**24%**	**97%**
Metal	-	-	-	-	-	-	-	6%	12%	3%	11%	-
Batteries	-	-	-	-	-	7%	-	6%	13%	10%	12%	-
FCC	-	-	-	-	-	-	-	8%	-	**67%**	-	-
Cat Auto	-	-	-	-	-	-	-	**35%**	6%	-	10%	-
Polishing	-	-	-	-	-	-	-	11%	-	5%	10%	-
Glass	-	-	-	**74%**	-	4%	**100%**	**31%**	8%	10 %	8%	-
Phosphors	**96%**	**68%**	-	26%	-	**46 %**	-	1%	-	2%	-	-
Ceramics	-	-	-	-	-	**35%**	-	2%	11%	2%	15%	-
Others	4%	-	3%	-	-	8%	-	-	10%	-	10%	3%

24.3.3 Prices

Prices of REEs experienced great variations in recent years, as shown in Figure 188. In 2010-2011 a 12-fold increase was observed, mainly triggered by a strong reduction of Chinese export quotas and geopolitical tension in a period of high demand. From early

2012, prices were already down from half and went down almost continuously until 2016 (DERA, 2016).

Only the main commercially-important REEs have an updated quotation of price on a weekly basis (Metal Pages). For REEs with minor uses such as ytterbium, holmium, thulium, or lutetium, products are sold between private parties at undisclosed prices. The only way to estimate the metal or oxide prices is to simulate a purchase to specialized suppliers (websites such as Alibaba www.alibaba.com).

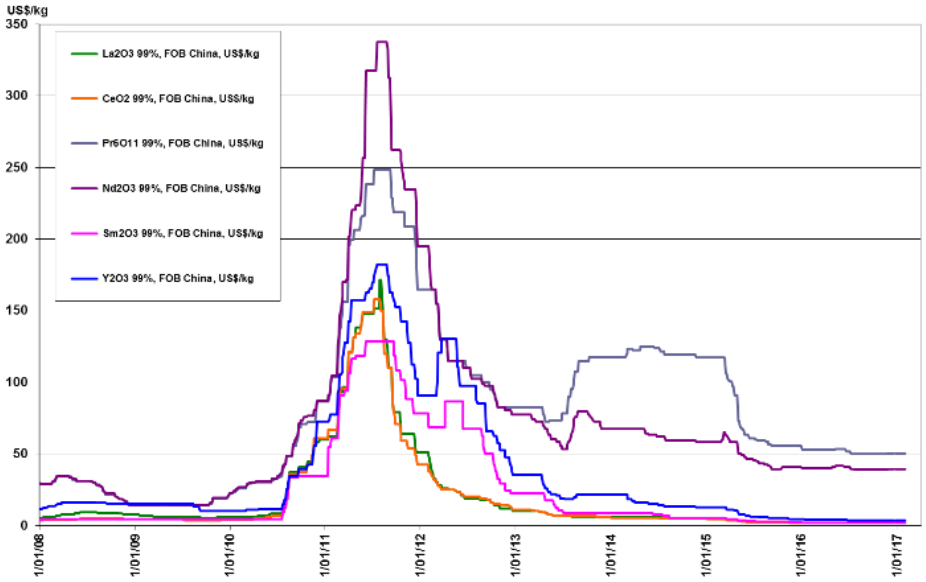
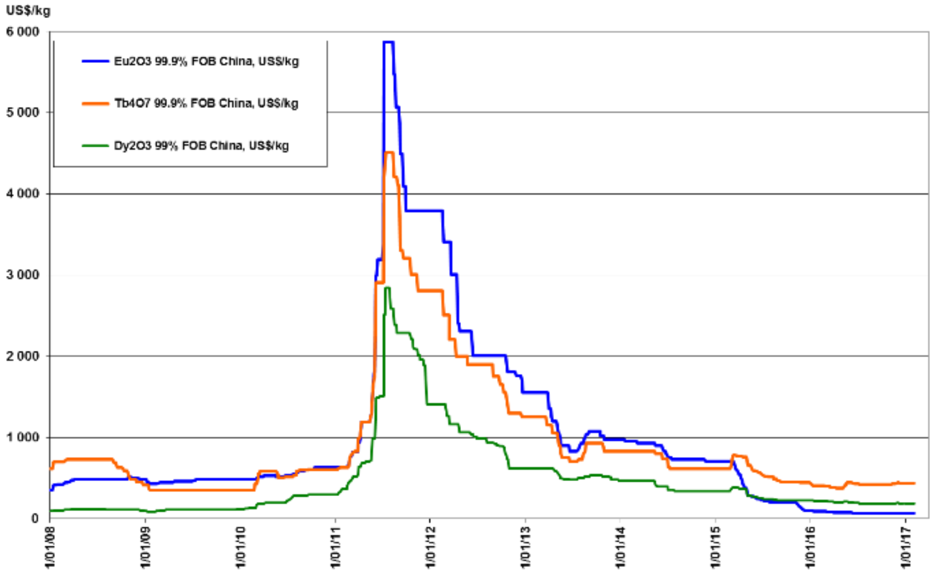


Figure 188: Main commercial Rare-earths oxide prices. Data from DERA, 2016. 99% FOB China US$/kg



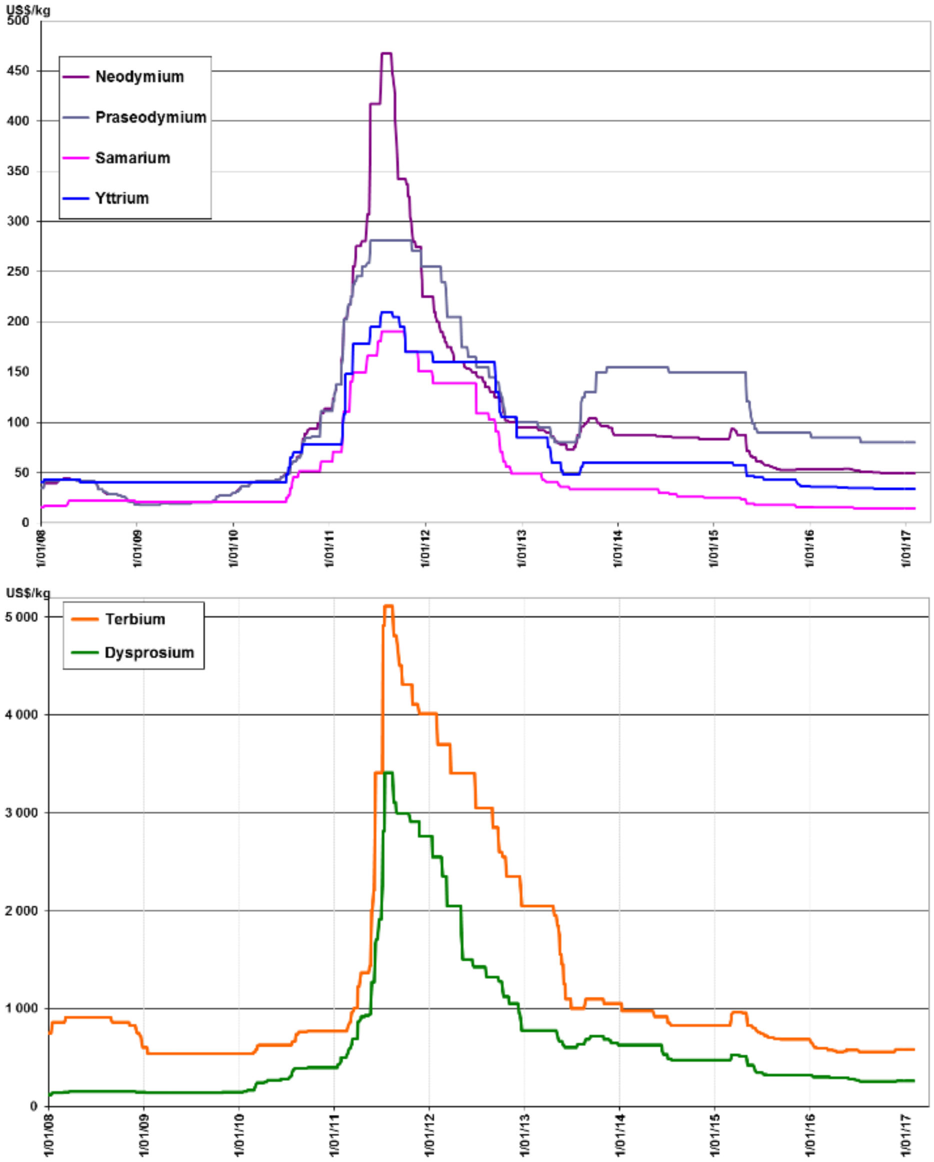


Figure 189: Main commercial Rare-earths oxide prices. Data from DERA, 2016. 99% FOB China US$/kg

24.4 Substitution

In most of their applications, REEs are not substitutable without losses of performance. However, for economic reasons, many R&D strategies have focused on reducing the amount of REEs used in their different applications. These particular aspects will be developed in individual factsheets and are summarised in Table 100.

Table 100: Summary of REEs substitutes

Use	Substitutes			
	General comment	**REE**	**Substitution elements**	**Alternative technologies**
Fluid cracking catalysts	Not easily substitutable	La	Ce	-
		Ce	La	
Autocatalysts	Some dematerialisation is possible	Ce	La, Nd, Pr	-
Other catalysts	Not easily substitutable	-	-	-
Glass	Not easily substitutable	Er	-	-
Batteries	There is a growing shift to Li-ion batteries in the major markets for NiMH batteries	Ce	-	Li-ion batteries. NiCd or lead-acid batteries are also an alternative
		Pr	-	
		La	Co	
		Nd	Co	
Metallurgy	Some dematerialisation is possible	Ce	Ca, La, Nd, Gd	-
		Gd	Pr	
		Pr	Gd	-
		La	Ce, Nd, Gd, Ca	-
Polishing	Some dematerialisation is possible	Ce	Ce, Pr, FeO, Al_2O_3	-
		La	Ce, FeO, Al_2O_3	-
Phosphors (lighting and displays)	The falling cost of LEDs means that there is now a viable competitor for fluorescent lamps for low-energy lighting	Er	Y, Gd	LED, that contain 1000 times less phosphor than fluorescent lamps
		Gd	Eu, Y, Tb	
		Tb	Eu, Y	
Ceramics	Not easily substitutable in either construction or electronics	-	-	-
Magnets	Several options exist to reduce or replace the rare earth content of magnets, either by material substitution or by using alternative magnet technology	Dy	Tb, Gd	wind turbine exempt of Dy using a cooling system to reduce the temperature of the use
		Gd	Dy, Tb	-
		Nd	Pr	ferrite or SmCo magnets
		Pr	Nd	ferrite or SmCo magnets
		Sm	-	NdFeB, ferrite or AlNiCo magnets
		Tb	Dy, Ga	-
Others	Some of the minor markets have substitutes.			
	YAG-lasers (as dopants, but with a different wavelength)	Er	Nd, Y	

24.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of REE oxide in mixed rare-earth compounds and metals. This choice was motivated by the lack of data on refined dysprosium production and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

24.5.1 Data sources

Data sources for the estimation of REE supply are summed up in Table 101.

Table 101: Sources of data for the estimation of REE supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, USGS, Roskill, BRGM, ASTER project	Relative concentration of the individual REE in the total world production of REEs	EC (2014) Report on critical raw materials
	EU	Imports to the EU	EUROSTAT	Share of the individual REE in the total EU use of REEs	ASTER project

The codes used for the EUROSTAT extraction (COMEXT database) and the REO content are reported below (sources: Guyonnet et al., 2015; updated in Bio Intelligence Service, 2015 for the conversion factors).

Table 102: EUROSTAT codes for REE and REO conversion factors

NC8 Code	**Description**	**Estimated REO conversion factor**
28053010	Intermixtures or interalloys of rare-earth metals, scandium and yttrium	1.2
28053090	Rare-earth metals, scandium and yttrium (excl. Intermixtures or interalloys)	1.2
28461000	Cerium compounds	0.72
28469000	Compounds, inorganic or organic, of rare-earth metals, of yttrium or of scandium or of mixtures of these metals (excl. cerium)	0.63

The disaggregation factors for individual REEs are reported in Table 103 and in each individual factsheet. They were estimated during the ASTER project (Guyonnet et al., 2015).

Table 103: Disaggregation factors for individual REEs

REE	**Relative concentration of the individual REE in the total world production of REEs**	**Share of the individual REE in the total EU use of REEs**
La	27.4%	41.0%
Ce	30.2%	39.4%
Pr	6.3%	2.6%
Nd	21.6%	6.4%
Eu	0.4%	0.4%
Gd	0.1%	0.2%
Tb	1.1%	0.4%
Dy	4.3%	0.2%
Y	8.1%	8.8%
Sm	0.1%	0.4%
Er	0.1%	0.2%
Ho, Tm, Yb, Lu	0.1%	0.2%

24.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (See individual factsheets for the applications, 2-digit NACE sectors and value added per sector).

24.5.3 Comparison with previous EU criticality assessments

A revised methodology was introduced in the 2017 assessment of critical raw materials in Europe and both the calculations of economic importance and supply risk are different compared to the results of the previous assessments. Therefore, the changes observed are largely due to the revised methodology and not due to significant market changes.

It should also be noted that the REEs were not assessed separately in either of the previous assessments. The individual assessment results of each of the 15 REEs (see individual REE factsheets) indicate that each one should be considered critical, with the exception of erbium (EI=2.7) and lanthanum (EI=1.4) since their EI results are below the EI criticality threshold of 2.8.

The main driver for the Supply Risk result for the overall REEs group is explained by important EU reliance on Chinese production, which are characterised by the quotas / export taxes from China enacted during the 2010 – 2014 period. The three main suppliers of REEs to the EU are China (40%), the United States (34%) and the Russian Federation (25%). These 3 countries represent approximately 99% of EU imports of REEs (about 8k tonnes). Generally speaking, there is no significant REE transformation and manufacturing activity in the EU; a large proportion of EU consumption / imports of REEs comes from finished products to the EU (e.g. magnets, alloys, hard drives, laptops, electric or hybrid vehicles, etc.). Further, in most of their applications, REEs are not substitutable without losses of performance. However, for economic reasons, many R&D strategies have focused on reducing the amount of REEs used in their different applications.

The results of the 2017 assessment and the previous assessments are shown in Table 104.

Table 104: Economic importance and supply risk results for REE in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment year	2011		2014		2017	
Indicator	EI	SR	EI	SR	EI	SR
LREEs	5.78	4.86	5.37	4.67	3.6	4.9
HREEs			5.21	3.13	3.7	4.8

24.6 Other considerations

24.6.1 Forward look for supply and demand

A boom in exploration activities was observed in the 2010-2013 period, after the 2011 price spike. Many projects flourished all over the world. However, even though many deposits were identified, almost none of those projects were able to go forward to the production stage.

China is currently struggling with over capacities and still willing to reduce illegal activities on its territory. The biggest challenge is the consolidation of the southern Chinese REEs activities where it is more difficult to form a conglomerate than in the

North (China Northern Rare Earth Group created in 2014 around Bayan Obo) because of the great number of medium-size players, and because the central State has less control on production due to remoteness and different local authorities powers (3 different provinces). These sites are highly strategic because they are almost the only source of HREEs in the world today (mostly Dy and Tb) for which demand is still critical in high performance permanent magnets. The question of individual rare earths separation is still very important as well (higher value for HREEs separation capacities).

On the supply side, a new separation plant is operational in India since early 2016, supported by Shin Etsu and Toyota (4 000 t annual capacities). Lynas although struggling with a huge debt and current low prices of REEs is not likely to fail into bankruptcy thanks to strong support from the Japanese government (via JOGMEC) and Japanese companies (it is an indispensable alternative source of supply for the Japanese industry against Chinese monopoly).

Therefore, it appears that the risk of another crisis is not high. From a technical point of view, REEs will still be critical in 10 years for they will continue to be superior to most materials in their main uses. The only question is the reliability of supply and nervousness to price volatility.

24.7 Data sources

24.7.1 Data sources used in the factsheet

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24.7.2 Data sources used in the criticality assessment

See individual factsheets

24.8 Acknowledgments

This Factsheet was prepared by Deloitte and BRGM. The authors would like to thank the EC Ad Hoc Working Group on Critical Raw Materials for their contributions to the preparation of this Factsheet, as well as the industrial experts from Tasman Metals and Less Common Metals.

25. CERIUM

Key facts and figures

Material name and Element symbol	Cerium, Ce	World/EU production[1]	World: 51,382 t EU: 0 t
Parent group (where applicable)	Rare-Earth Elements (REEs)	EU import reliance[1]	100%
Life cycle stage assessed	Extraction/ mixed REOs	Substitution index for supply risk [SI (SR)]	0.98
Economic importance score EI(2017)	Light REEs: 3.6	Substitution Index for economic importance [SI(EI)]	0.95
Supply risk SR (2017)	Light REEs: 4.9	End of life recycling input rate (EOL-RIR)	1%
Abiotic or biotic	Abiotic	Major end uses [1]	Autocatalyst: 35% Glass & Ceramics: 33% Polishing Powders: 11%
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated;

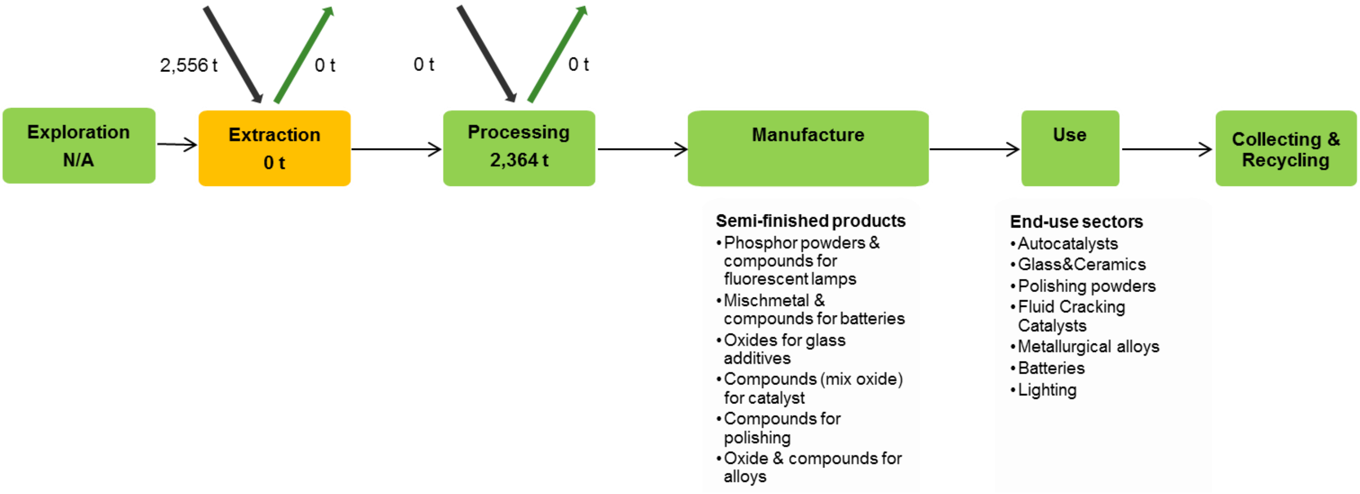

Figure 190: Simplified value chain for cerium

Figures indicated in the above figure are only indicative. The green boxes suggest that activities are undertaken within the EU. The black arrows represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

25.1 Introduction

Cerium (chemical symbol Ce) is considered as a light REE. Its upper crust abundance is 63 ppm (Rudnick, 2003). It is a silvery metal which tarnishes in air in a few days. It does not occur naturally as a metallic element and is found (for commercial exploitation) mainly in the minerals bastnäsite, loparite and monazite. Because of its chemical and optical properties and relative abundance it is found in many applications such as autocatalysts, glass and ceramics, polishing powders, fluid cracking catalysts (FCC), metallurgical alloys (mischmetal) and NiMH batteries (mischmetal).

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

25.2 Supply

Please refer to the general REEs Factsheet for geological occurrence, mining, processing, extractive metallurgy and resources and reserves data.

25.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of cerium in the EU. Supply solely depends on imports in the form of cerium oxide and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several sources and hypotheses (BGS, 2016; BRGM, 2015; Bio Intelligence Service, 2015). With cerium representing 37.9% of the total production of REEs in terms of relative concentration, the world annual production of cerium in the form of mixed rare-earth compounds is estimated to be 51,382 t.

China remains responsible of around 95% of total production (average of 2010-2014) as shown in Figure 191.

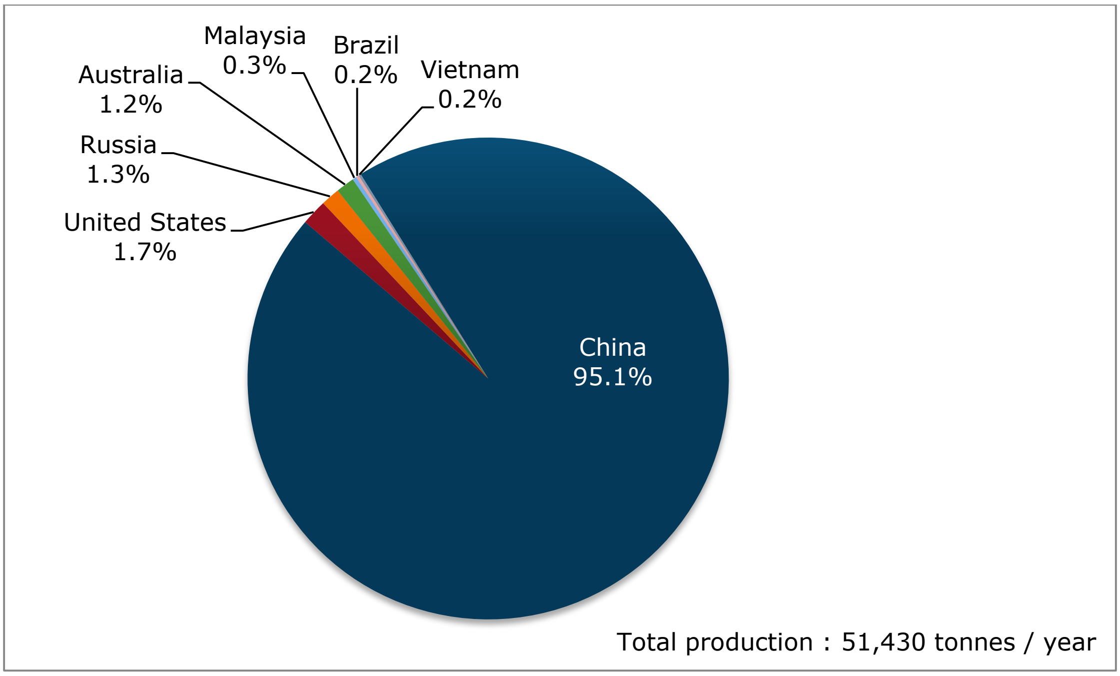

Figure 191: Global mine production of cerium. Average 2010–(Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015)

25.2.2 Supply from secondary materials

As for many REEs, the end-of-life recycling rate for cerium is < 1% (UNEP, 2011). However, recycling has developed for polishing powders since 2011, mostly in Japan, where cerium can be re-used in the form of mishmetal (BRGM, 2015).

25.2.3 EU trade

EU import reliance on cerium contained in mixed rare-earth oxides and compounds is 100%. Cerium is the only REE with a specific custom code in Eurostat Comext database, CN8 28461000 (Eurostat, 2016). Around 3,116 t of cerium are imported each year in the EU (average 2010-2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015 – see also 3.1).

The two main suppliers of cerium to the EU are China (62%) and the United States (19 %) (Figure 192).

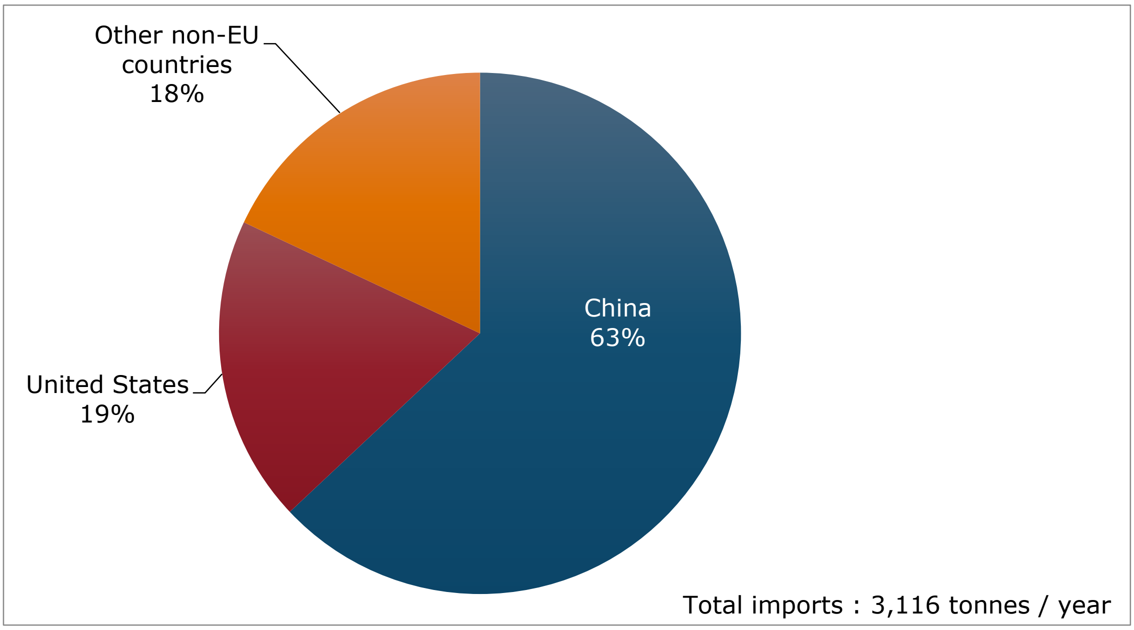

Figure 192: EU imports of cerium, average 2010-2014 (Eurostat, 2016; Guyonnet et al., 2015). Other countries are Russia, Australia, Brazil, Maylasia, Vietname and other non-EU countries

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 11,606 t/yr quota for cerium for the period 2010-2014. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

25.2.4 EU supply chain

Generally speaking, there is no critical mass of REE transformation and manufacturing in the EU; although critical in many industries a large proportion of REE consumption comes from finished products imports (flat screens, laptops, electric or hybrid vehicles, etc.).

However, a few players are found at different stages of the REE value chain. Some have the ability to separate individual REOs (in Estonia and France) and manufacture REE-based products for various industries. In particular, the EU is likely to use more cerium for catalysts uses in the petroleum industry than in the rest of the world (BRGM, 2015).

25.3 Demand

25.3.1 EU consumption

The use of cerium in the EU represents 39.4% of the total EU use of REEs, which gives an estimated 3,116 t of cerium consumed in the EU per year (average 2010 – 2014) (Guyonnet et al., 2015; Bio Intelligence Service, 2015; Eurostat, 2016).

25.3.2 Applications

Cerium is used for a variety of applications, but the four main uses are polishing, metallurgy other than batteries, autocatalysts and glass (European Commission, 2014). Other uses for cerium include batteries, fluid cracking catalysts, other catalysts, phosphors, ceramics, fertiliser, water treatment, paints and coatings (European Commission, 2014).

In recent years, demand for cerium used in the glass polishing sector has declined. It is likely to increase in the automotive catalyst sector due to low prices, good availability and stricter regulation on transportation emissions (ARAFURA, 2016).

The end-use of cerium products in the EU are presented in Figure 193 (BRGM, 2015- and relevant industry sectors are described using the NACE sector codes in Table 105.

Table 105: Cerium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016)

Applications	2-digit NACE sectors	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
Autocatalysts	C20 - Manufacture of chemicals and chemical products	110,000	C2029 - Manufacture of other chemical products n.e.c.
Glass&Ceramics	C23 - Manufacture of other non-metallic mineral products	59,166	C2310 - Manufacture of glass and glass products
Polishing powders	C26 - Manufacture of computer, electronic and optical products	75,260	C2670 - Manufacture of optical instruments and photographic equipment
Fluid Cracking Catalysts	C19 - Manufacture of coke and refined petroleum products	13,547	C1920 - Manufacture of refined petroleum products
Metal (excl. Batteries)	C24 - Manufacture of basic metals	57,000	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Batteries	C27 - Manufacture of electrical equipment	84,609	C2720 - Manufacture of batteries and accumulators
Lighting	C27 - Manufacture of electrical equipment	84,609	C2740 - Manufacture of electric lighting equipment

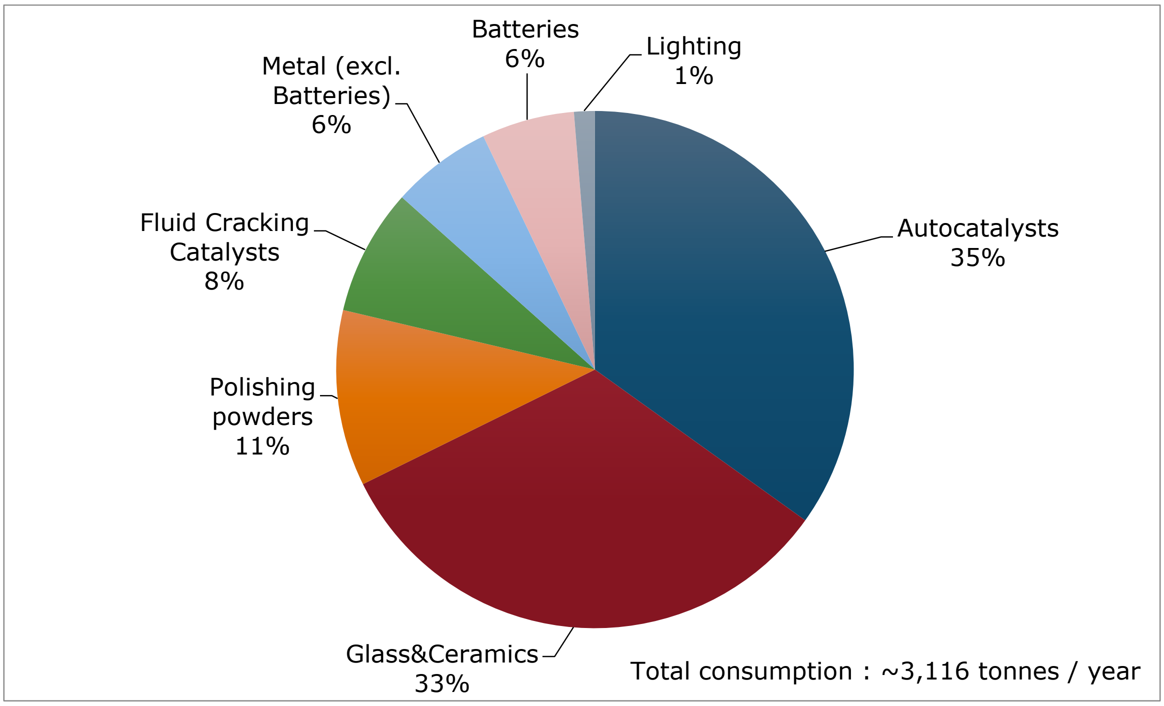

Figure 193: EU end-uses of cerium. Average figures for 2010-2014 (Guyonnet et al., 2015)

25.3.3 Prices

Prices of cerium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from 3 $/kg in 2002-2003 to an all-time high of 170 $/kg in July 2011, prices of Ce metal went down to reach a relatively stable value of around 6 $/kg in 2015 and 2016 (See Group Factsheet, data from DERA, 2016). The skyrocketing of prices in 2010 – 2011 was triggered by the strong reduction of Chinese quotas.

25.4 Substitution

Cerium is the most abundant REE in geological ores. It is always extracted and produced together with more valuable REEs. Therefore, it is one of the cheapest and most available Rare Earth Element. Unless another spike in prices, there is generally no advantage of substituting cerium in its main applications. Moreover, in most of these applications, main substitutes are other REEs (usually rarer and more expensive).

In the auto-catalyst sector cerium could be substituted by:
- Lanthanum
- Neodymium
- Praseodymium

Cerium used for the purpose of polishing can be substituted by:
- Iron oxide
- Alumina powder

As for its use in metallurgical applications, cerium can be substituted by:
- Calcium
- Lanthanum
- Neodymium
- Gadolinium

25.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of mix Rare Earths Oxides (including cerium). This choice was motivated by the lack of data on production at further stages and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

25.5.1 Data sources

Data sources for the estimation of cerium oxide supply are summed up in Table 106 below. The share of applications in the EU was estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 106: Sources of data for the estimation of cerium supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGm, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

25.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 105). The value added data correspond to 2013 figures.

25.6 Other considerations

25.6.1 Forward look for supply and demand

Supply of rare-earths in general and cerium in particular is constantly subject to changes. The market of rare-earths is opaque and it is thus very difficult to predict the future evolution of supply (Rare Earth Investment News, 2016). Although China's campaign against illegal mining should take hold and remove some of the volatility in pricing, investments in mining activities are still uncertain – notably following the bankrupcy of Molycorp and the failure of the Mountain Pass project in the USA (The AusIMM Bulletin, 2016). The overall demand for cerium is expected to increase by around 6% per year (Rare Earth Investment News, 2016). However, as for lanthanum, supply is expected to more than keep up, moving the market into an increasing surplus.

Table 107: Qualitative forecast of supply and demand of cerium

Material	**Demand forecast**			**Supply forecast**		
	5 years	10 years	20 years	5 years	10 years	20 years
Cerium	+	+	?	+	+	?

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25.8 Acknowledgments

This Factsheet was prepared by Deloitte and BRGM. The authors would like to thank the EC Ad Hoc Working Group on Critical Raw Materials for their contributions to the preparation of this Factsheet, as well as the industrial experts from Tasman Metals and Less Common Metals.

26. DYSPROSIUM

Key facts and figures

Material name and Element symbol	Dysprosium, Dy	World/EU production[1]	World: 1,357 t EU : 0 t
Parent group (where applicable)	Rare-Earth Elements (REEs)	EU import reliance[1]	100%
Life cycle stage assessed	Extraction/mixed REOs	Substitution index for supply risk [SI(SR)]	0.95
Economic importance score EI (2017)	Heavy REEs: 3.7	Substitution Index for economic importance [SI(EI)]	0.90
Supply risk SR (2017)	Heavy REEs: 4.8	End of life recycling input rate (EOL-RIR)	0%
Abiotic or biotic	Abiotic	Major end uses [1]	Magnets : 100%
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated;

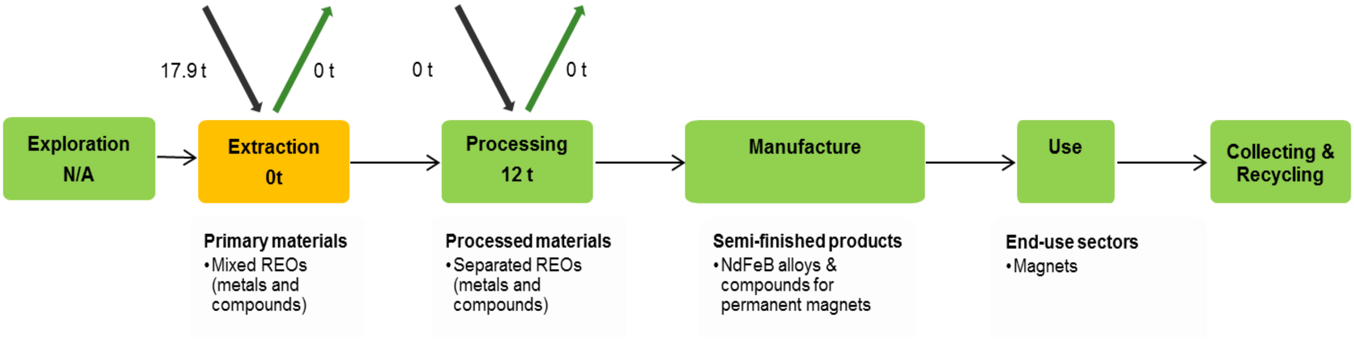

Figure 194: Simplified value chain for dysprosium

Figures are only indicative. The green boxes in the above figure suggest that activities are undertaken within the EU. The black arrows represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. *See group profile for EU resources and reserves data.

26.1 Introduction

Dysprosium (chemical symbol Dy) is considered as a heavy REE. Dysprosium's upper crust abundance is 3.9 ppm (Rudnick, 2003). It does not occur naturally as a metallic element and is found (for commercial exploitation) almost exclusively in the minerals xenotime and ion-adsorption clays (in Southern China). Dysprosium is a silvery very hard metal which slowly oxidizes in air (a few years). Its main and almost exclusive use is in permanent magnets NdFeB, where it allows resistance up to 200°C

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

26.2 Supply

Please refer to the general REEs Factsheet for geological occurrence, mining, processing, extractive metallurgy and resources and reserves data.

26.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of dysprosium in the EU. Supply solely depends on imports in the form of dysprosium oxide and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several sources and hypotheses (BGS, 2016; BRGM, 2015; Bio Intelligence Service, 2015). With dysprosium representing 1.0% of the total production of REEs in terms of relative concentration, the world annual production of dysprosium in the form of mixed rare-earth compounds is estimated to be 1,357 t.

China remains responsible of around 95% of total production (average of 2010-2014) as shown in Figure 195. Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 306 t/yr quota for dysprosium. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

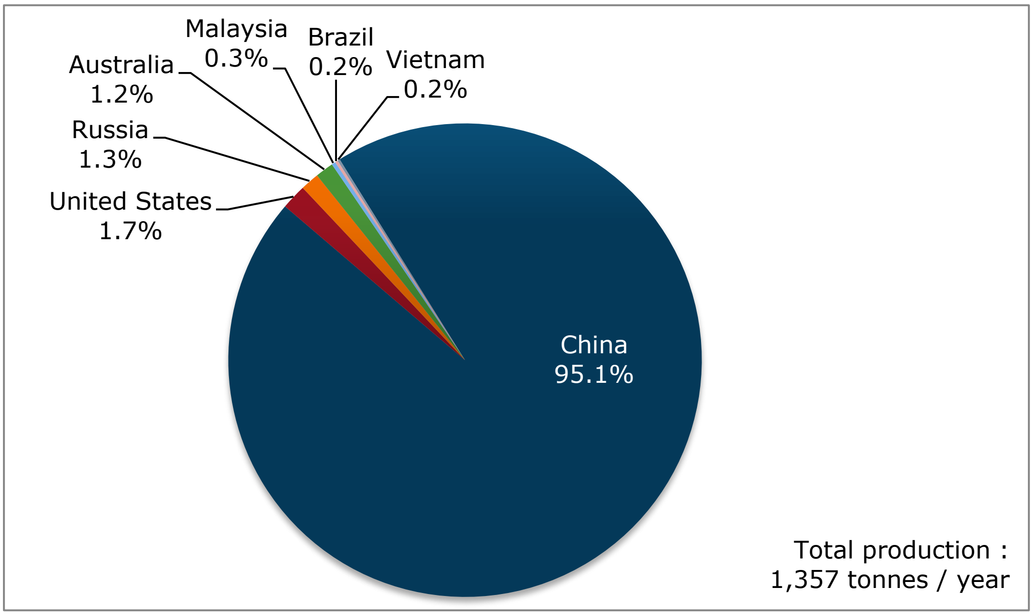

Figure 195: Global mine production of dysprosium, average 2010–2014 (Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015)

26.2.2 Supply from secondary materials

As of 2015, no circuit for dysprosium recycling in end-of-life permanent magnets existed (0% recycling rate). This result was obtained during the RMSA study (Bio Intelligence Service, 2015).

26.2.3 EU trade

EU import reliance on dysprosium contained in mixed rare-earth oxides and compounds is 100%. Around 18 t of dysprosium are imported each year in the EU (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015 – see also 3.1). The quantities of imported dysprosium experienced a slight increase during the 2010 – 2014 period.

The three main dysprosium suppliers of the EU were China (40%), the United States (34 %) and Russia (25%) (Figure 196).

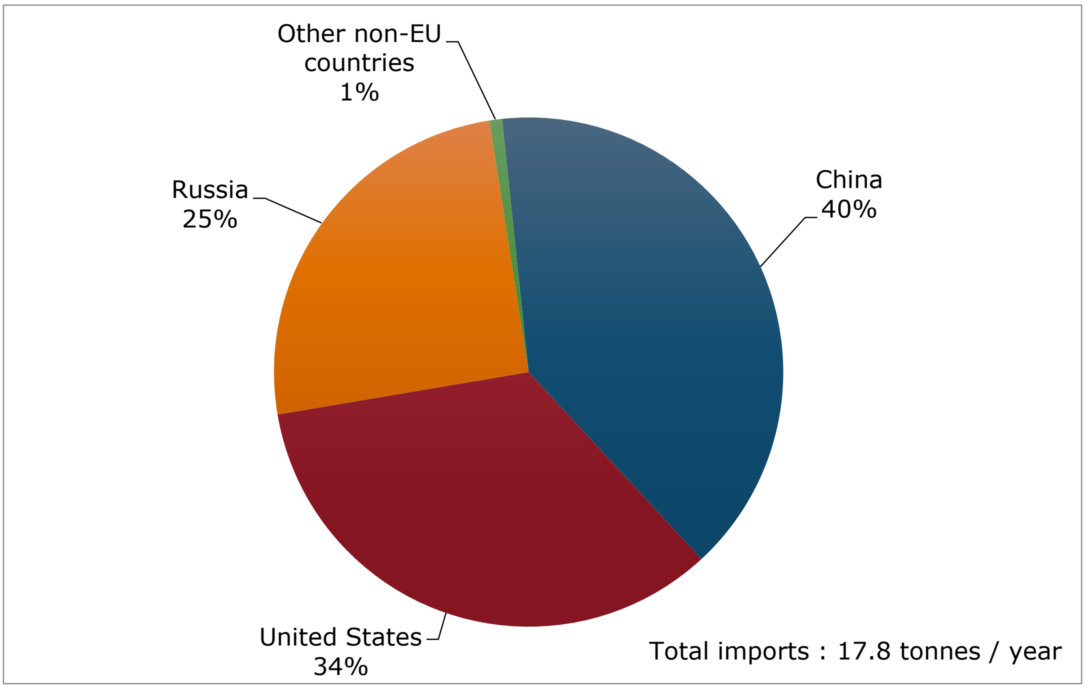

Figure 196: EU imports of dysprosium compounds. Average 2010-2014. (Eurostat, 2016; Guyonnet et al., 2015)

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 306 t/yr quota for dysprosium. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015)

26.2.4 EU supply chain

Generally speaking, there is no critical mass of REE transformation and manufacturing in the EU; although critical in many industries a large proportion of REE consumption comes from finished products imports (electronic material, vehicles, hard drives, laptops, etc.).

However, a few players are found at different stages of the REE value chain. In particular, there are several alloys makers and magnets manufacturers (in Germany, the UK, and Slovenia) likely to use imported quantities of dysprosium alloys and compounds (BRGM, 2015).

26.3 Demand

26.3.1 EU consumption

The use of dysprosium in the EU represents 0.2% of the total EU use of REEs, which gives an estimated 18 t of dysprosium consumed in the EU per year (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015).

26.3.2 Applications

The main and almost exclusive use of dysprosium is in permanent magnets NdFeB. Dysprosium is added to NdFeB magnets (2-11% w/w) to increase the Curie temperature, which means that it allows the use of those magnets at up to 200°C. The main finished products driving dysprosium consumption for magnets include new generations of wind turbines, industrial motors, etc. Relevant industry sectors are described using the NACE sector codes in Table 108.

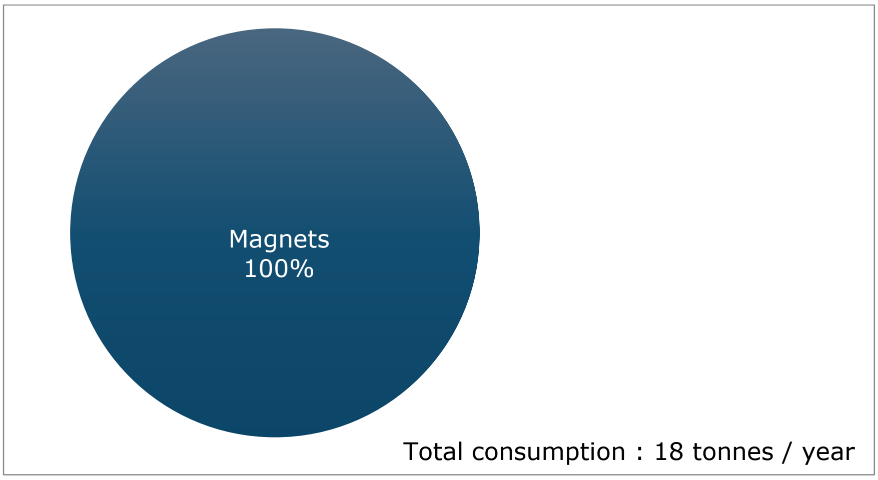

Figure 197: EU end-uses of dysprosium. Average figures for 2010-2014 (Bio Intelligence Service, 2015)

Table 108: Dysprosium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016)

Applications	2-digit NACE sectors	Value added of sector (millions €)	4-digit NACE sectors
Magnets	C25 - Manufacture of fabricated metal products, except machinery and equipment	159,513	C2599 - Manufacture of other fabricated metal products n.e.c.

26.3.3 Prices

Prices of dysprosium metal and oxide experienced great variations from 2010 to 2016. Dy oxide prices (99% FOB China) went from 30 $/kg in 2002-2003 to an all-time high of 3,400 $/kg in July 2011. Since then, they have continuously decreased. From around 600 $/kg in 2014, they were around 320 $/kg in 2015, 200$/kg in 2016 and 190 $/kg in 2017 (See Group Factsheet, data from DERA, 2016). The skyrocketing of prices in 2010 – 2011 was triggered by the conjunction of two main factors:

- A strong reduction of Chinese quotas; and
- An increase of demand for permanent magnets, driven by the expected growth of the renewable energy and electric vehicles markets.

26.4 Substitution

Due to the high prices and supply constraints around dysprosium, magnet manufacturers have been seeking for some years to engineer-out the use of the metal. An alternative is to reduce the content of dysprosium by positioning Dy atoms at the grain boundaries of the NdFeB alloys: this technique allows to use less dysprosium for a similar coercive force enhancement (Shin-Etsu, 2012). Others industrials (e.g. Siemens) have also begun to design wind turbines exempt of dysprosium thanks to a cooling system to reduce the temperature of use (BRGM, 2015).

26.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of mix Rare Earths Oxides (including dysprosium). This choice was motivated by the lack of data on production at further stages and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

26.5.1 Data sources

Data sources for the estimation of dysprosium oxide supply are summed up in Table 109 below. The share of applications in the EU was estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 109: Sources of data for the estimation of Dy supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGM, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

26.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 108). The value added data correspond to 2013 figures.

26.6 Other considerations

26.6.1 Forward look for supply and demand

Supply of rare-earths in general and dysprosium in particular is constantly subject to changes. The market of rare-earths is opaque and it is thus very difficult to predict the future evolution of supply (Rare Earth Investing News, 2016). Although China’s campaign against illegal mining should take hold and remove some of the volatility in pricing, investments in mining activities are still uncertain – notably following the bankrupcy of Molycorp and the failure of the Mountain Pass project in the USA (The AusIMM Bulletin, 2016).

The future evolution of dysprosium demand is driven by two forces:

- The anticipated growth of the permanent magnet market for the manufacture of wind turbines and electric vehicles. Those applications are supported by green energy and green transportation initiatives which are likely to incentivise a growth of their production (Rare Earth Investing News, 2016). Globally, the rapid increase of the demand for air conditioning by Indian and other South-East Asian customers could also play in the expected growth of the permanent magnets market (Powder Metallurgy Review, 2016). As a result of those factors, the demand of Dy-containing magnets is expected to increase;
- Efforts to reduce the content of dysprosium in NdFeB magnets: Adamas expects the content of dysprosium in magnets to drop from 2.3% in 2014 to 1.9% in 2020 (Guyonnet et al., 2015).

Table 110: Qualitative forecast of supply and demand of dysprosium

Material	Demand forecast			Supply forecast		
	5 years	10 years	20 years	5 years	10 years	20 years
Dysprosium	+	+	?	+	+	?

26.7 Data sources

26.7.1 Data sources used in the factsheet

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26.8 Acknowledgments

This Factsheet was prepared by Deloitte and BRGM. The authors would like to thank the EC Ad Hoc Working Group on Critical Raw Materials for their contributions to the preparation of this Factsheet, as well as the industrial experts from Tasman Metals and Less Common Metals.

27. ERBIUM

Key facts and figures

Material name and Element symbol	Erbium, Er	World/EU production[1]	World: 950 t EU: 0 t
Parent group (where applicable)	Rare-Earth Elements (REEs)	EU import reliance[1]	100%
Life cycle stage assessed	Extraction/mixed REOs	Substitution index for supply risk [SI (SR)]	0.96
Economic importance score EI (2017)	Heavy REEs: 3.7	Substitution Index for economic importance [SI(EI)]	0.92
Supply risk SR (2017)	Heavy REEs: 4.8	End of life recycling input rate (EOL-RIR)	1%
Abiotic or biotic	Abiotic	Major end uses [1]	Optical (74%) Lighting (26%)
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated;

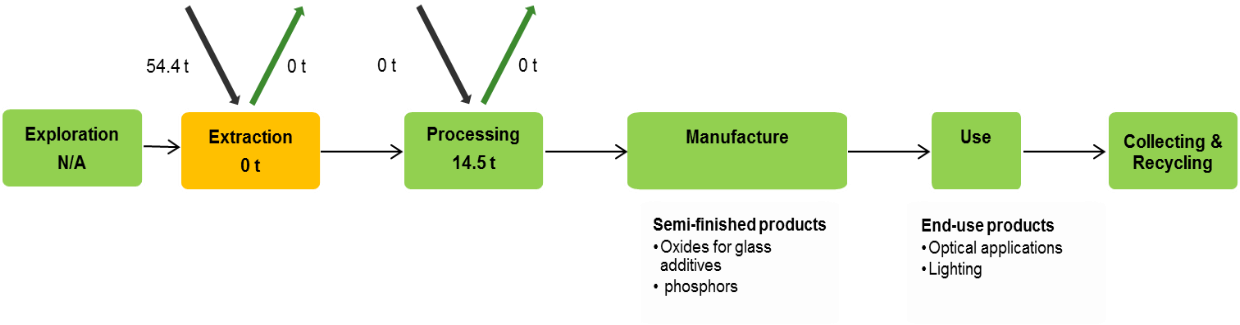

Figure 198: Simplified value chain for erbium

The green boxes of the production and processing stages in the above figure suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

27.1 Introduction

Erbium (chemical symbol Er) is considered as a heavy REE. Erbium's upper crust abundance is 2.3 ppm (Rudnick, 2003). It is a silvery hard metal, which slowly oxidizes in air (a few years). It is used mainly used in optical fibers, for glass colorizing and as dopant in lasers and phosphors.

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

27.2 Supply

Please refer to the general REEs Factsheet for geological occurrence, mining, processing, extractive metallurgy and resources and reserves data.

27.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of erbium in the EU. Supply solely depends on imports in the form of erbium oxide and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several sources and hypotheses (BGS, 2016; BRGM, 2015; Bio Intelligence Service, 2015). With erbium representing 0.7% of the total production of REEs in terms of relative concentration, the world annual production of erbium in the form of mixed rare-earth compounds is estimated to be 950 t.

China remains responsible of around 95% of total production (average of 2010-2014) as shown in Figure 2. Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 214 t/yr quota for erbium. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

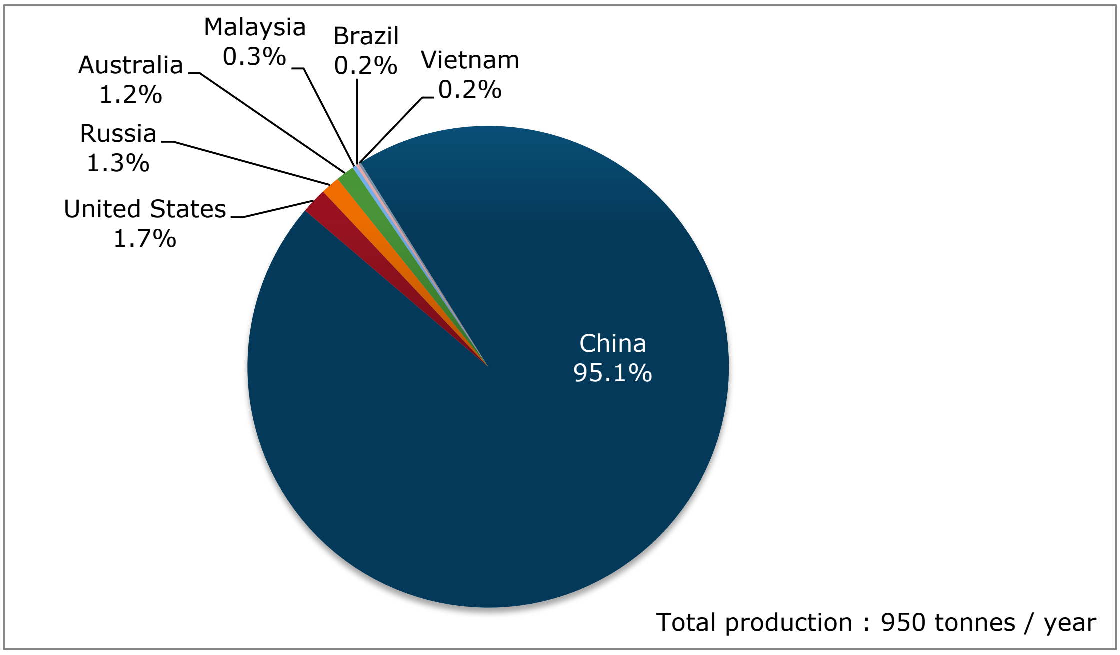

Figure 199: Global mine production of erbium average 2010–2014 (Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015)

27.2.2 Supply from secondary materials

The recycling rate was assessed with the UNEP study (UNEP, 2013). Only 1% of erbium worldwide is recycled.

27.2.3 EU trade

EU import reliance on erbium contained in mixed rare-earth oxides and compounds is 100%. Around 10.8 t of erbium are imported each year in the EU (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015 – see also 3.1). The quantities of imported erbium experienced a slight increase during the 2010 – 2014 period.

The three main suppliers of erbium to the EU are China (40%), the United States (34 %) and Russia (25%) (Figure 200).

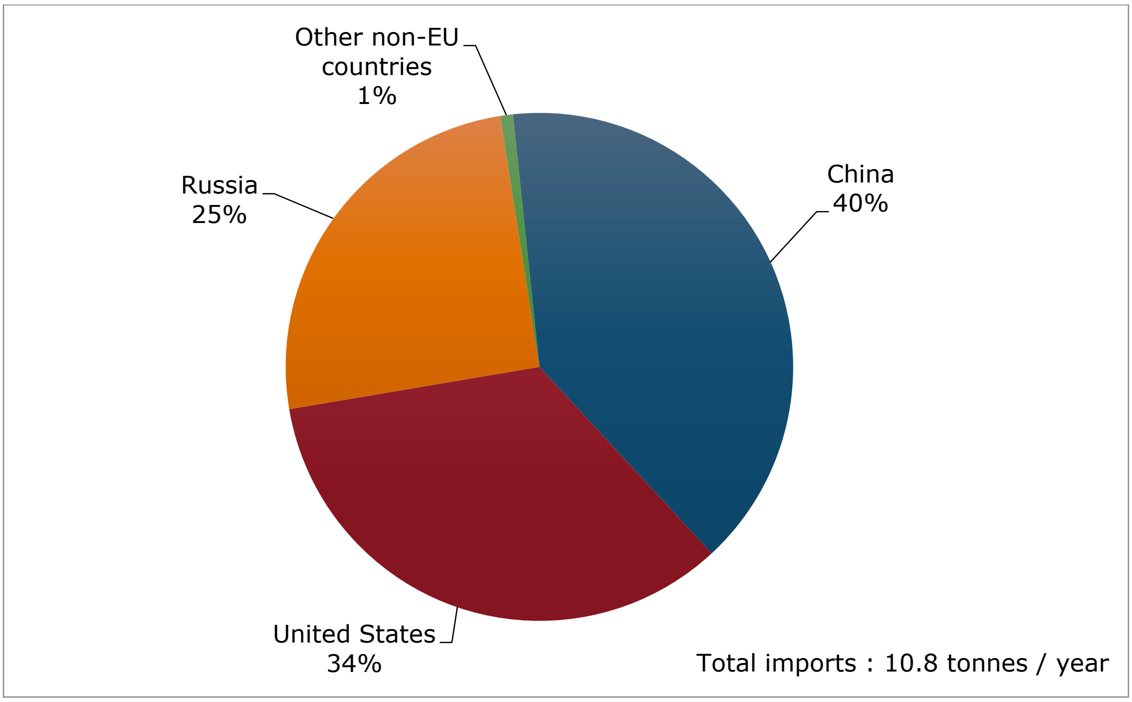

Figure 200: EU imports of erbium, average 2010-2014 (Eurostat, 2016; Guyonnet et al., 2015)

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 214 t/yr quota for erbium. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

27.2.4 EU supply chain

Generally speaking, there is no critical mass of REE transformation and manufacturing in the EU; although critical in many industries a large proportion of REE consumption comes from finished products imports (electronic material, vehicles, hard drives, laptops, etc.).

27.3 Demand

27.3.1 EU consumption

The use of erbium in the EU represents 0.2% of the total EU use of REEs, which gives an estimated 10.8 t of erbium consumed in the EU per year (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015).

27.3.2 Applications

The majority of erbium is used in glass for optical application (72%), although phosphors for lighting applications are also an important use (EC, 2014). Other uses for erbium include the nuclear industry (neutron-absorbing control rods), and metallurgy (metallurgical additive, erbium-nickel alloy) (BRGM, 2015).

The principal optical uses involve its pink-colored Er^{3+} ions, which have optical fluorescent properties particularly useful in certain laser applications (BRGM, 2015):

- Colorant for glass: erbium oxide has a pink color, and is sometimes used as a colorant for glass, cubic zirconia and porcelain.
- Erbium-doped optical silica-glass fibers are the active element in erbium-doped fiber amplifiers (EDFAs), which are widely used in optical communications.
- Co-doping of optical fiber with Er and Yb is used in high-power Er/Yb fiber lasers or
- Medical applications (i.e. dermatology, dentistry) with erbium-doped lasers Er:YAG

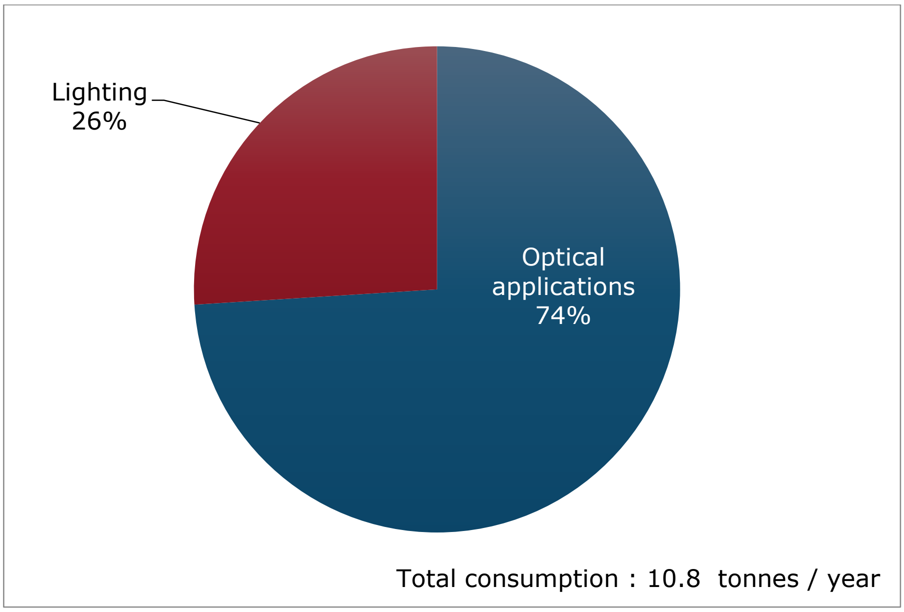

Figure 201: EU end-uses of erbium. Average figure for 2010-2014 (EC, 2014)

Information about the breakdown of the European market by application was not available at the time of writing.

Relevant industry sectors are described using the NACE sector codes in Table 111.

Table 111: Erbium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016)

Applications	2-digit NACE sector	Value added of sector (millions €)	4-digit NACE sectors
Optical applications	C23 - Manufacture of other non-metallic mineral products	59,166	C2310 - Manufacture and processing of other glass, including technical glassware
Lighting	C27 - Manufacture of electrical equipment	84,609	C2740 - Manufacture of electric lighting equipment

27.3.3 Prices

No data specific for erbium prices are available.

27.4 Substitution

Most erbium applications have possible substitutes, although with significant loss of performance (EC, 2014).

In glass colorization, it cannot be substituted without the loss of pink colour stability (BRGM, 2015). In phosphors, Erbium can be substituted with Y and Gd [2]. Neodymium and Ytterbium can also be used as dopants instead of Erbium in YAG-lasers but with a different wavelength.

27.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of mix Rare Earths Oxides (including erbium). This choice was motivated by the lack of data on production at further stages and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

27.5.1 Data sources

Data sources for the estimation of erbium oxide supply are summed up in Table 112 below. The share of applications in the EU were estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 112: Sources of data for the estimation of Er supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGM, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

27.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 105). The value added data correspond to 2013 figures.

27.6 Other considerations

27.6.1 Forward look for supply and demand

Supply of rare-earths in general and erbium in paticular is constantly subject to changes. The market of rare-earths is opaque and it is thus very difficult to predict the future evolution of supply (Rare Earth Investing News, 2016). Although China's campaign against illegal mining should take hold and remove some of the volatility in pricing, investments in mining activities are still uncertain – notably following the bankrupcy of Molycorp and the failure of the Mountain Pass project in the USA (The AusIMM Bulletin, 2016).

The overall demand for erbium is expected to increase by around 6% per year until 2020 (EC, 2014).

Table 113: Qualitative forecast of supply and demand of Erbium

Material	**Demand forecast**			**Supply forecast**		
	5 years	10 years	20 years	5 years	10 years	20 years
Erbium	+	?	?	+	?	?

27.7 Data sources

27.7.1 Data sources used in the factsheet

BGS (2016). European mineral production 2010-2014 [online]. Keyworth, Nottingham British Geological Survey, Available at: http://www.bgs.ac.uk/mineralsuk/statistics/home.html

Bio Intelligence Service (2015). Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials – Final Report. Prepared for the European Commission, DG GROW.

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European Commission (EC). (2014). Report on Critical Raw Materials for the EU. Critical Raw Materials Profiles [online] Brussels European Commission. Available at: http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/

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27.7.2 Data sources used in the criticality assessment

BGS (2016). European mineral production 2010-2014 [online]. Keyworth, Nottingham British Geological Survey, Available at: http://www.bgs.ac.uk/mineralsuk/statistics/home.html

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BRGM (2015) Panorama 2014 du marché des Terres Rares. Rapport public BRGM/RP-64330-FR. 194 p., 58 fig., 32 tab.

Dominique Guyonnet, Mariane Planchon, Alain Rollat, Victoire Escalon, Johann Tuduri, Nicolas Charles, Stéphane Vaxelaire, Didier Dubois, Hélène Fargier (2015). Material flow analysis applied to rare earth elements in Europe, Journal of Cleaner Production, Volume 107, 16 November 2015, Pages 215-228

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27.8 Acknowledgments

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28. EUROPIUM

Key facts and figures

Material name and Element symbol	Europium, Eu	World/EU production[1]	World : 407 t EU : 0 t
Parent group (where applicable)	Rare-Earth Elements	EU import reliance[1]	100%
Life cycle stage /material assessed	Extraction/mixed REOs	Substitution index for supply risk [SI (SR)]	1.00
Economic importance score (2017)	Light REEs: 3.6	Substitution Index for economic importance [SI(EI)]	1.00
Supply risk SR (2017)	Light REEs: 4.9	End of life recycling input rate (EOL-RIR)	38%
Abiotic or biotic	Abiotic	Major end uses[1]	Lighting (96%)
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated;

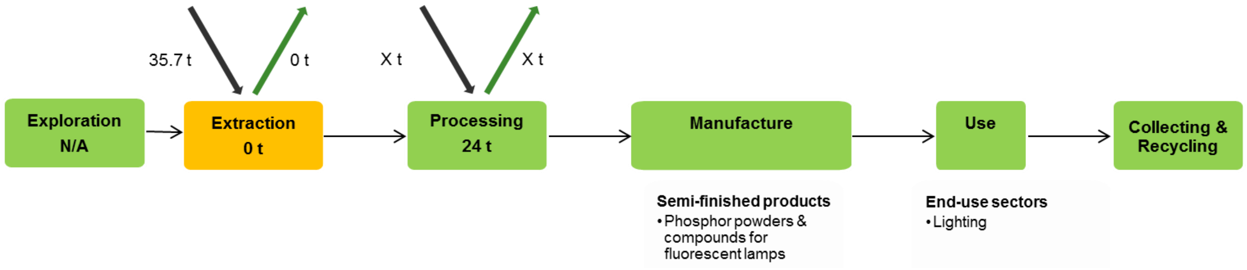

Figure 202: Simplified value chain for europium

Figures are only indicative. The green boxes in the above figure suggest that activities are undertaken within the EU. The black arrows represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. *See group profile for EU resources and reserves data.

28.1 Introduction

Europium (chemical symbol Eu) is considered as a light REE. Its upper crust abundance is 1 ppm (Rudnick, 2003). It does not occur naturally as a metallic element and is found in minerals such as bastnäsite and monazite. It is a moderately hard, silvery metal which readily oxidizes in air and water. The main use of europium is in lighting and exploits the phosphorescence of europium compounds.

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

28.2 Supply

Please refer to the general REEs Factsheet for geological occurrence, mining, processing, extractive metallurgy and resources and reserves data.

28.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of europium in the EU. Supply solely depends on imports in the form of europium oxide and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several sources and hypotheses (BGS, 2016; BRGM, 2015; Bio Intelligence Service, 2015). With europium representing 0.3% of the total production of REEs in terms of relative concentration, the world annual production of europium in the form of mixed rare-earth compounds is estimated to be 407 t.

China remains responsible of around 95% of total production (average of 2010-2014) as shown in Figure 203. Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 92 t/yr quota for europium. China also taxed the export of europium by 25% (OECD, 2016). In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

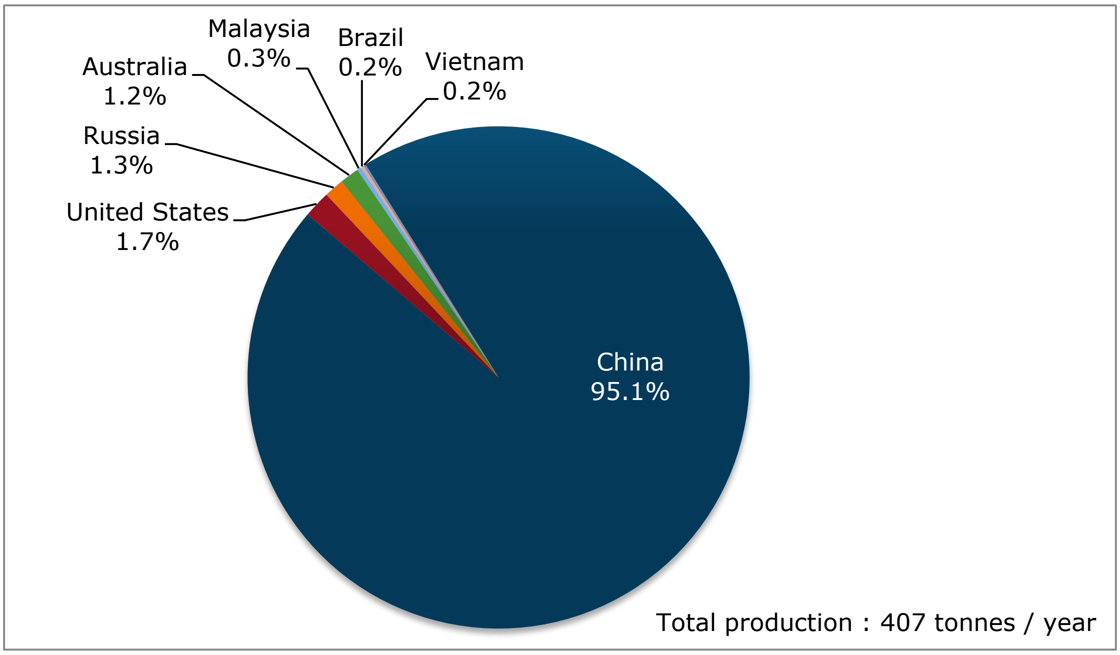

Figure 203: Global mine production of europium, average 2010–2014 (Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015)

28.2.2 Supply from secondary materials

The end of life recycling input rate was assessed with the RMSA study (Bio Intelligence Service, 2015) and amounts to 38%.

Recycling activities were undertaken from end-of-life lamps at the Solvay plant in La Rochelle from 2011 until its closure in 2016 (Usine Nouvelle, 2016). Recycling processes were initiated in 2011 in a context of uncertainty of supply, when China announced a reduction of export quotas (see also following section). At the time, primary europium oxide was expensive (around 5,900 $/kg) (BRGM, 2015) and there was a demand for cheaper, recycled europium oxide. However, by 2015 prices of primary europium dropped significantly to 210 $/kg (BRGM 2015), thus rendering the recycling process far less competitive than during the crisis (2011-2014). This lead to Solvay announcing in early 2016 the closure of the plant by the end of 2016.

28.2.3 EU trade

EU import reliance on europium contained in mixed rare-earth oxides and compounds is 100%. Around 36 t of Eu are imported each year in the EU (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015 – see also 3.1). The quantities of imported europium experienced a slight increase during the 2010 – 2014 period.

The three main suppliers of europium to the EU are China (40%), the United States (34 %) and the Russian Federation (25%) (Figure 204).

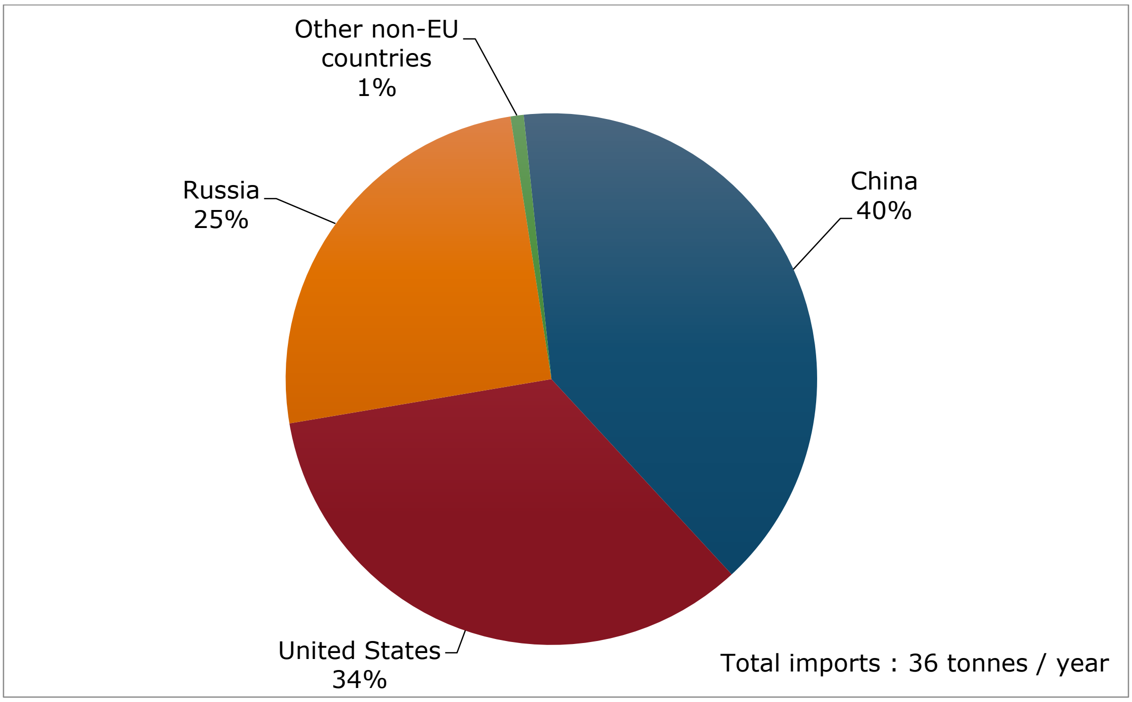

Figure 204: EU imports of europium, average 2010-2014 (Eurostat, 2016; Guyonnet et al., 2015). Other countries are Malaysia and Vietnam

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 92 t/yr quota for europium. China also taxed the export of europium by 25% (OECD, 2016). In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

28.2.4 EU supply chain

The EU relies solely on imports for the supply of europium oxide. The separation of europium was performed in the Solvay plant in La Rochelle and was estimated at around 14 t/yr in the EU (Guyonnet et al., 2015) for the 2010-2014 period.

28.3 Demand

28.3.1 EU consumption

The use of europium in the EU represents 0.4% of the total EU use of REEs, which gives an estimated 36 t of europium consumed in the EU per year (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015).

28.3.2 Applications

Europium is used in the in the world and in EU almost exclusively in lighting applications (BRGM, 2015). It represents 5% of the composition of phosphors used for lighting. Some other uses in nuclear and optic industries can be mentioned, as well as protection for fraud of Euro banknotes (BRGM, 2015).

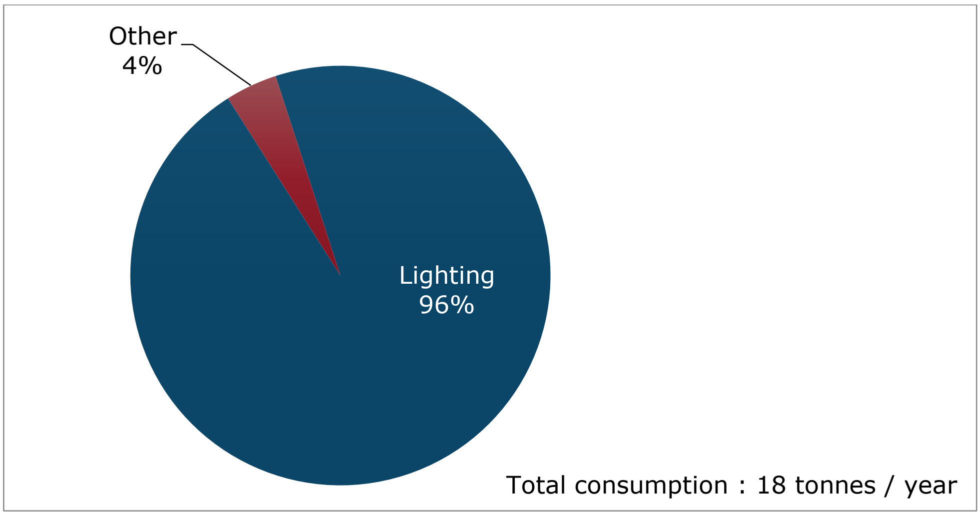

Figure 205: EU end-uses of europium. Average figure for 2010-2014 (Guyonnet et al., 2015)

Relevant industry sectors are described using the NACE sector codes in Table 114.

Table 114: Europium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016).

Applications	2-digit NACE sector	Value added of sector (millions €)	4-digit NACE sectors
Lighting	C27 - Manufacture of electrical equipment	84,609	C2740 - Manufacture of electric lighting equipment

28.3.3 Prices

Prices of europium metal and oxide experienced great variations from 2010 to 2016. Eu oxide prices (99% FOB China) went from 785 $/kg in 2002-2003 to an all-time high of 6,800 $/kg in July 2011(one of the highest growth ever for metal prices). Since then, they have continuously decreased, to 445 $/kg in 2015 and 70 $/kg in 2017 (See Group

Factsheet, data from DERA, 2016). Despite europium was for more than 15 years the most expensive of all the REE, its uses and value have decreased and terbium took the lead in 2014-2015 (See Group Factsheet, data from DERA, 2016).

28.4 Substitution

There is no substitute to Eu in fluorescent lamps. The alternative lighting technology LED, which penetration in the market is fast and important and is taking over the fluorocompact market share (McKinsey, 2012), also uses phosphors based on rare earths, including Eu, but the amount of phosphor needed per LED in 1,000 times lower than for fluorescent lamps (2 mg of phosphor powder/LED instead of 2g/LFL or CFL) (Guyonnet et al., 2015).

28.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of mix Rare Earths Oxides (including europium). This choice was motivated by the lack of data on production at further stages and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

28.5.1 Data sources

Data sources for the estimation of europium oxide supply are summed up in Table 115 below. The share of applications in the EU was estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 115: Sources of data for the estimation of Eu supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGM, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

28.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 114).

28.6 0ther considerations

28.6.1 Forward look for supply and demand

Supply of rare-earths in general and europium in particular is constantly subject to changes. The market of rare-earths is opaque and it is thus very difficult to predict the future evolution of supply (Rare Earth Investment News, 2016). Although China’s campaign against illegal mining should take hold and remove some of the volatility in pricing, investments in mining activities are still uncertain – notably following the bankrupcy of Molycorp and the failure of the Mountain Pass project in the USA The AusIMM Bulletin, 2016).

The demand of europium is likely to drop considerabely in the future (Guyonnet et al., 2015). The future decrease of europium demand is directly linked to the very significative reduction (at least 65%) of rare earth needs for the lighting industry between 2015 and 2030 (Guyonnet et al., 2015).

This evolution is due to the changes in the lighting market structure and is driven by two forces:

- The anticipated decrease of the fluorescent lamps market face to the growing new technology LEDs (Mc Kinsey, 2012): in the lighting market as a whole, LED lighting penetration is projected to be around 40% in 2016 and over 60% in 2020 (Mc Kinsey, 2012).
- The content of rare earths (including Eu) in LEDs is much lower than in fluorescent lamps (1,000 times lower) (Guyonnet et al., 2015).
- As the lifetime of LED is 40,000-50,000 hours, compared to 10,000-25,000 hours for fluorescent lamps, the decrease in rare earth need for the lighting sector will amplify in the coming years (Guyonnet et al., 2015).

Table 116: Qualitative forecast of supply and demand of europium

Material	Demand forecast			Supply forecast		
	5 years	10 years	20 years	5 years	10 years	20 years
Europium	-	?	?	-	?	?

28.7 Data sources

28.7.1 Data sources used in the factsheet

BGS (2016) World Mineral Production 2010-2014 [online]. Keyworth, Nottingham British Geological Survey, Available at: http://www.bgs.ac.uk/mineralsuk/statistics/home.html

Bio Intelligence Service (2015). Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials – Final Report. Prepared for the European Commission, DG GROW.

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28.7.2 Data sources used in the criticality assessment

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28.8 Acknowledgments

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29. GADOLINIUM

Key facts and figures

Material name and Element symbol	Gadolinium, Gd	World/EU production[1]	World: 2,307 t EU: 0 t
Parent group (where applicable)	Rare-Earth Elements (REEs)	EU import reliance[1]	100%
Life cycle stage assessed	Extraction/mixed REOs	Substitution index for supply risk [SI (SR)]	0.94
Economic importance score EI (2017)	Heavy REEs: 3.7	Substitution Index for economic importance [SI(EI)]	0.90
Supply risk SR (2017)	Heavy REEs: 4.8	End of life recycling input rate (EOL-RIR)	1%
Abiotic or biotic	Abiotic	Major end uses [1]	Magnets (35%) Lighting (23%) Metallurgy (28%)
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated;

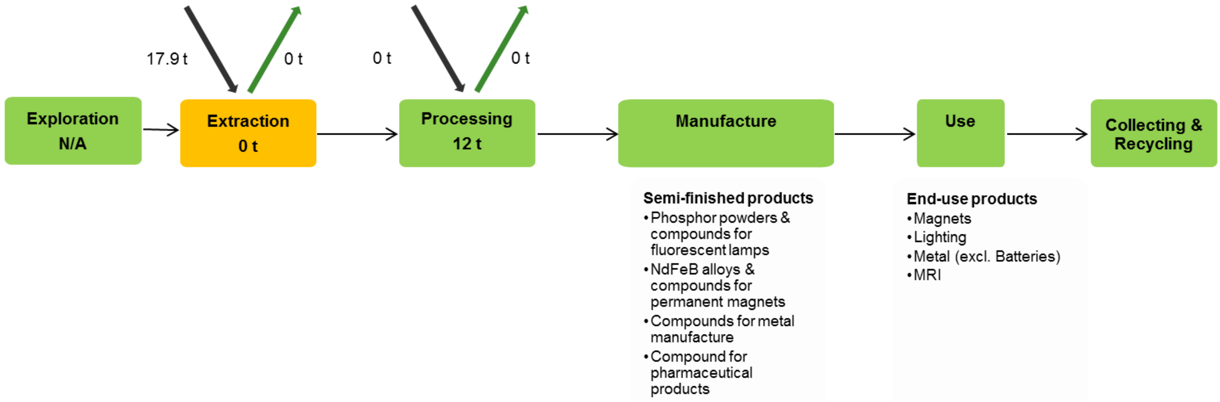

Figure 206: Simplified value chain for gadolinium

The green boxes of the production and processing stages in the above figure suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

29.1 Introduction

Gadolinium (chemical symbol Gd) is considered as a heavy REE. Gadolinium's upper crust abundance is 4.0 ppm (Rudnick, 2003). It does not occur naturally as a metallic element and is found in minerals such as bastnäsite and monazite. Gadolinium is a silvery-white, malleable and ductile rare earth metal. Gadolinium metal possesses unusual metallurgic properties, to the extent that as little as 1% gadolinium can significantly improve the workability and resistance to high temperature oxidation of iron, chromium, and related alloys. Its main applications are permanent magnets, lighting and metallurgy. Gadolinium as a metal or salt has exceptionally high absorption of neutrons and therefore is used for shielding in neutron radiography and in nuclear reactors.

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

29.2 Supply

Please refer to the general REEs Factsheet for geological occurrence, mining, processing, extractive metallurgy and resources and reserves data.

29.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of gadolinium in the EU. Supply solely depends on imports in the form of gadolinium oxide and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several sources and hypotheses (BGS, 2016; BRGM, 2015; Bio Intelligence Service, 2015). With gadolinium representing 1.7% of the total production of REEs in terms of relative concentration, the world annual production of gadolinium oxide in mixed rare-earth compounds and metals is estimated to be 2,307 t.

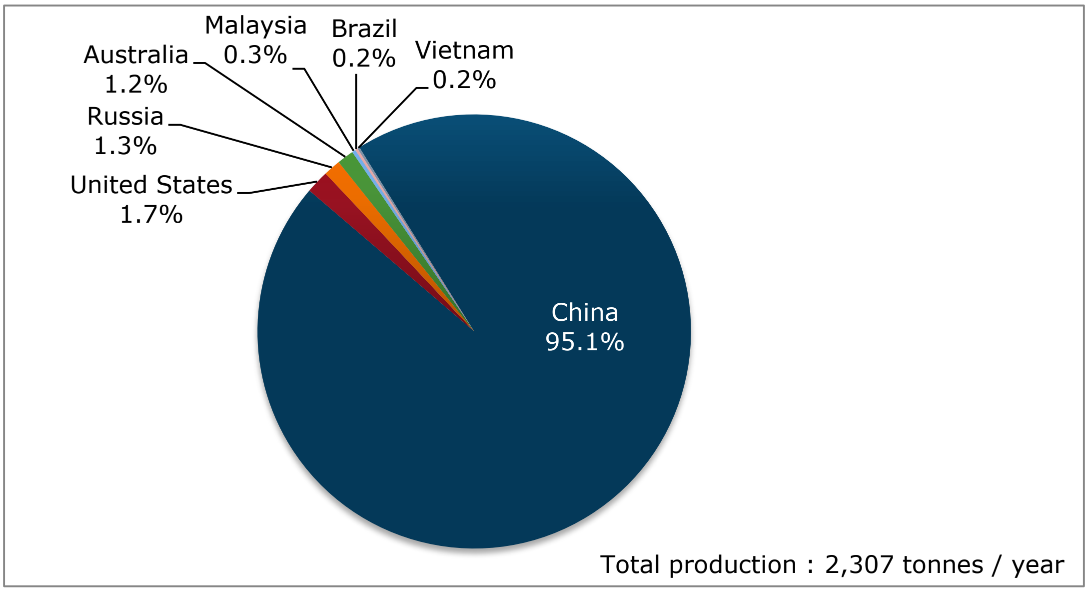

Figure 207: Global mine production of gadolinium, average 2010–2014 (Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015)

China remains responsible of around 95% of total production (average of 2010-2014) as shown in Figure 207. Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015) which gives an estimated 520 t/yr quota for gadolinium for the period 2010-2014. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

29.2.2 Supply from secondary materials

The recycling rate was assessed with the UNEP study (UNEP, 2013). Only 1% of gadolinium worldwide is recycled.

29.2.3 EU trade

EU import reliance on gadolinium contained in mixed rare-earth oxides and compounds is 100%. Around 18 t of gadolinium are imported each year in the EU (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015 – see also 3.1). The quantities of imported gadolinium experienced a slight increase during the 2010 – 2014 period.

The three main suppliers of gadolinium to the EU are China (40%), the United States (34 %) and Russia (25%) (Figure 208).

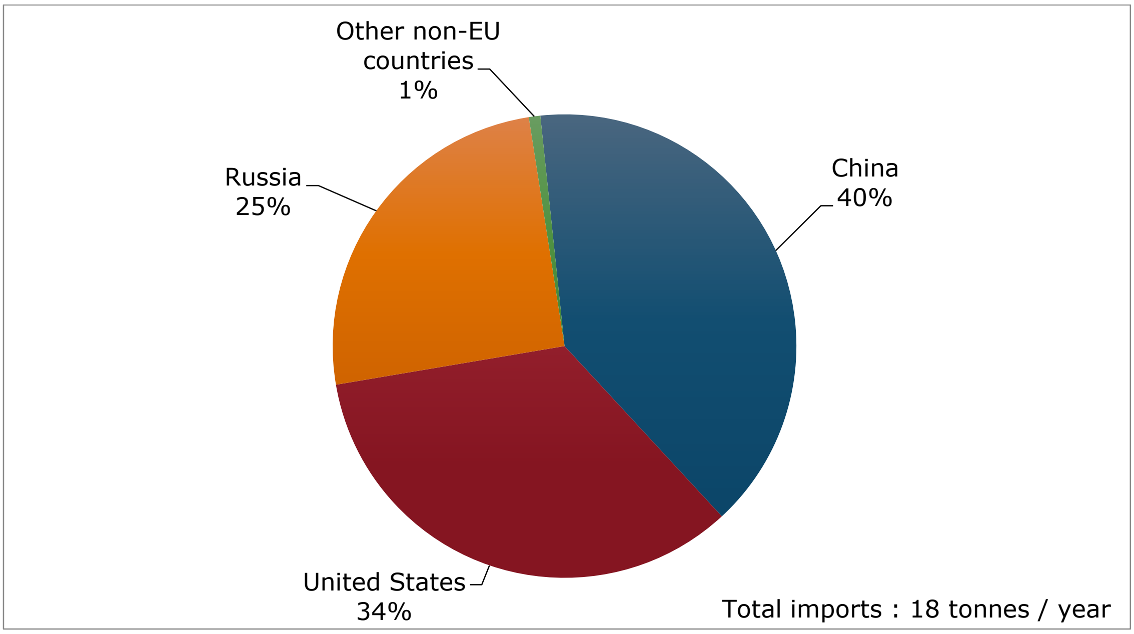

Figure 208: EU imports of gadolinium, average 2010-2014 (Eurostat, 2016; Guyonnet et al., 2015)

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015) which gives an estimated 520 t/yr quota for gadolinium for the period 2010-2014. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

29.2.4 EU supply chain

The EU relies solely on imports for the supply of gadolinium oxide.

29.3 Demand

29.3.1 EU consumption

The use of gadolinium in the EU represents 0.2% of the total EU use of REEs (Guyonnet, 2015), which gives an estimated 18 t of gadolinium consumed in the EU per year (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015).

29.3.2 Applications

Gadolinium is mainly used for NdFeB permanent magnets, for lighting applications and for metallurgy (BRGM, 2015) (see Figure 209), relevant industry sectors are described using the NACE sector codes in Table 114.

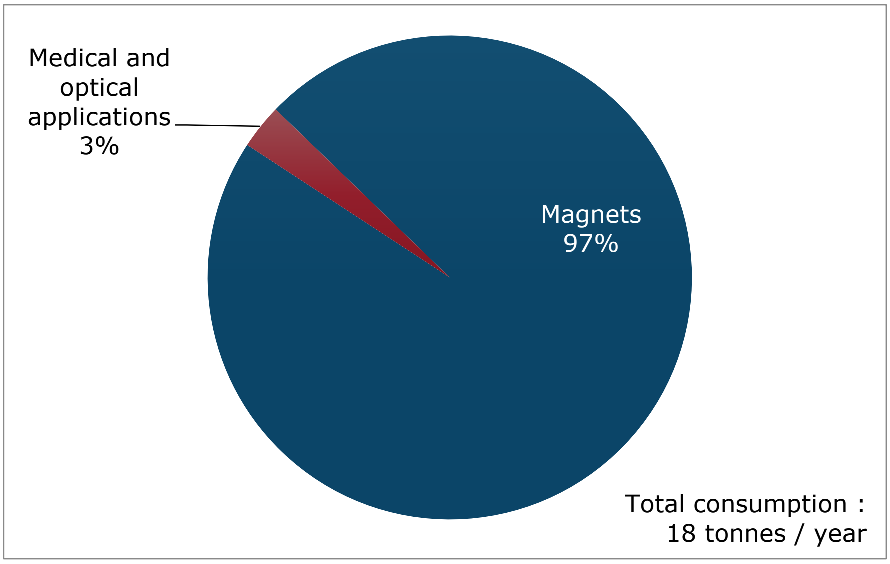

Figure 209: World end-uses of gadolinium. Average figure for 2010-2014 (EC, 2014)

The major applications for gadolinium can be described in more detail as follows:

- Gd is primarly used in NdFeB alloys (Kiggins, 2015) but also in SmCo alloys (Humphries, 2013) for temperature compensation and resistance to corrosion (BRGM, 2015).
- Gadolinium oxide is used as a luminophore and gives the green color in television tubes (BRGM, 2015).
- Gadolinium metal possesses unusual metallurgic properties, to the extent that as little as 1% gadolinium can significantly improve the workability and resistance to high temperature oxidation of iron, chromium, and related alloys. Gadolinium is used in metallurgical applications for improving the mechanical characteristics of alloyed steel, for desulphurisation, or for binding trace elements in stainless steel.
- Gd is used as a medical contrasting agent for MRIs (EC, 2014).
- Other uses of gadolinium include optics and nuclear industry. Indeed, gadolinium as a metal or salt has exceptionally high absorption of neutrons and therefore is used for shielding in neutron radiography and in nuclear reactors (EC, 2014).

Information about the breakdown of the European market by application was not available at the time of writing.

Table 117: Gadolinium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016)

Applications	**2-digit NACE sector**	**Value added of sector (millions €)**	**4-digit NACE sectors**
Magnets	C25 - Manufacture of fabricated metal products, except machinery and equipment	159,513	C2599 - Manufacture of other fabricated metal products n.e.c.
Lighting	C27 - Manufacture of electrical equipment	84,609	C2740 - Manufacture of electric lighting equipment
Metal (excl. Batteries)	C24 - Manufacture of basic metals	57,000	C2410 - Manufacture of basic iron and steel and of ferro-alloys
MRI	C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations	79,545	C2100 - Manufacture of pharmaceutical preparations

29.3.3 Prices

Prices of gadolinium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from 30 $/kg in 2008 to an all-time high of 226 $/kg in July 2011, prices of Tb metal went down to reach a relatively stable value of around 61 $/kg in 2015 (BRGM, 2015). The skyrocketing of prices in 2010 – 2011 was triggered by the conjunction of two main factors:

- A strong reduction of Chinese quotas; and
- An increase of demand for permanent magnets, driven by the expected growth of the renewable energy and electric vehicles markets.

Following a classic “bubble” pattern, this price increase was followed by a drop of demand (due to savings and substitution) and lead to a bubble burst – therefore the decrease of prices between 2011 and 2013.

29.4 Substitution

Gadolinium’s use in magnets is considered to be relatively readily substitutable (EC, 2014). Gadolinium can be substituted by dysprosium or terbium for its temperature compensation properties in NdFeB magnets. Dysprosium remains the preferred material for this application (BRGM, 2015).

There is no substitute to Gd in television tubes. The alternative technology is LCD screens, which is dominant in the market and uses other rare earths as luminophore such as Eu, Tb or Y (BRGM, 2015).

Gd is used for improving the mechanical characteristics of alloyed steel, for desulphurization. Praseodymium can be used instead for this application, for a similar performance (EC, 2014).

Gadolinium is currently irreplaceable in medical imagery uses (EC, 2014).

29.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of mix Rare Earths Oxides (including gadolinium). This choice was motivated by the lack of data on production at further stages and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

29.5.1 Data sources

Data sources for the estimation of gadolinium oxide supply are summed up in Table 118 below. The share of applications in the EU were estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 118: Sources of data for the estimation of Gd supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGM, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

29.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 114). The value added data correspond to 2013 figures.

29.6 Other considerations

29.6.1 Forward look for supply and demand

Supply of rare-earths in general and gadolinium in paticular is constantly subject to changes. The market of rare-earths is opaque and it is thus very difficult to predict the future evolution of supply (Rare Earth Investing News, 2016). Although China’s campaign against illegal mining should take hold and remove some of the volatility in pricing, investments in mining activities are still uncertain – notably following the bankrupcy of Molycorp and the failure of the Mountain Pass project in the USA (The AusIMM Bulletin, 2016).

The overall demand for gadolinium is expected to increase by around 9% per year until 2020 relating to uses in magnets (linked to a possible growth in magnetic refrigeration) and in medical imagery (EC, 2014).

Table 119: Qualitative forecast of supply and demand of gadolinium

Material	Demand forecast			Supply forecast		
	5 years	10 years	20 years	5 years	10 years	20 years
Gadolinium	+	?	?	+	?	?

29.7 Data sources

29.7.1 Data sources used in the factsheet

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29.7.2 Data sources used in the criticality assessment

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29.8 Acknowledgments

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30. HOLMIUM, LUTETIUM, YTTERBIUM, THULIUM

Key facts and figures

Material name and Element symbol	Ho, Lu, Yb, Tm	World/EU production[1]	World: 1,764 t EU: 0 t
Parent group (where applicable)	Rare-Earth Elements (REEs)	EU import reliance[1]	100%
Life cycle stage assessed	Extraction/mixed REOs	Substitution index for supply risk [SI(SR)]	1.00
Economic importance score EI (2017)	Heavy REEs: 3.7	Substitution Index for economic importance [SI(EI)]	1.00
Supply risk SR (2017)	Heavy REEs: 4.8	End of life recycling input rate (EOL-RIR)	1%
Abiotic or biotic	Abiotic	Major end uses [1]	Optical (100%)
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated

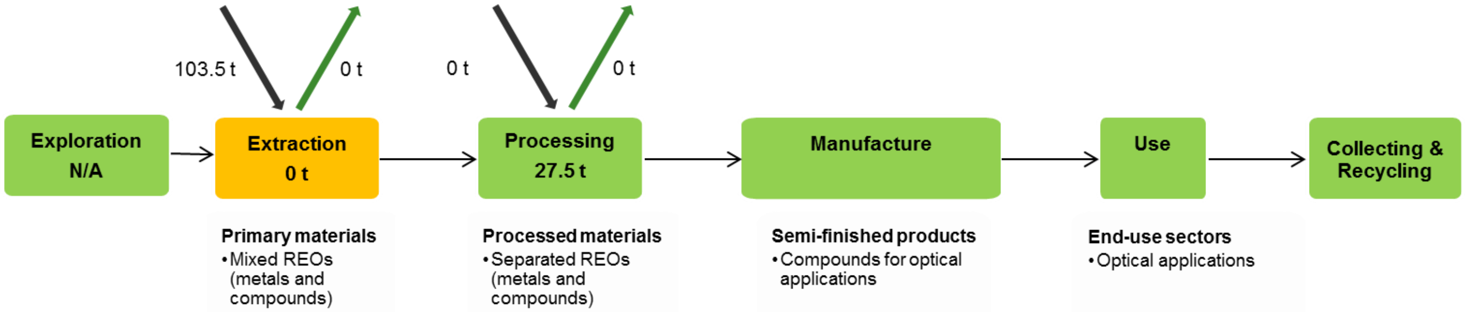

Figure 210: Simplified value chain for Ho, Lu, Tm, Yb

The green boxes of the production and processing stages in the above figure suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

30.1 Introduction

Holmium (chemical symbol Ho), thulium (chemical symbol Tm), ytterbium (chemical symbol Yb) and lutetium (chemical symbol Lu) are all heavy rare earth elements. They are at the end of the lanthanide series, with a very low natural abundance and only few niche applications mostly related to their optical properties (Laser dopants, radiography, etc.).

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

30.2 Supply

Please refer to the general REEs Factsheet for geological occurrence, mining, processing, extractive metallurgy and resources and reserves data.

30.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of Holmium, Lutetium, Ytterbium and Thulium in the EU. Supply solely depends on imports in the form of oxides and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several sources and hypotheses (BGS, 2016; BRGM, 2015; Bio Intelligence Service, 2015). With Ho, Lu, Tm, Yb representing 1.3% of the total production of REEs in terms of relative concentration, the world annual production of Holmium, Lutetium, Ytterbium and Thulium oxide in mixed rare-earth compounds and metals is estimated to be 1,764 t.

About 95% of Ho, Lu, Tm, Yb originates from China (average of 2010-2014) as shown in Figure 2. Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 367 t/yr quota for Ho, Lu, Tm, Yb. There was an additional export tax of 15%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

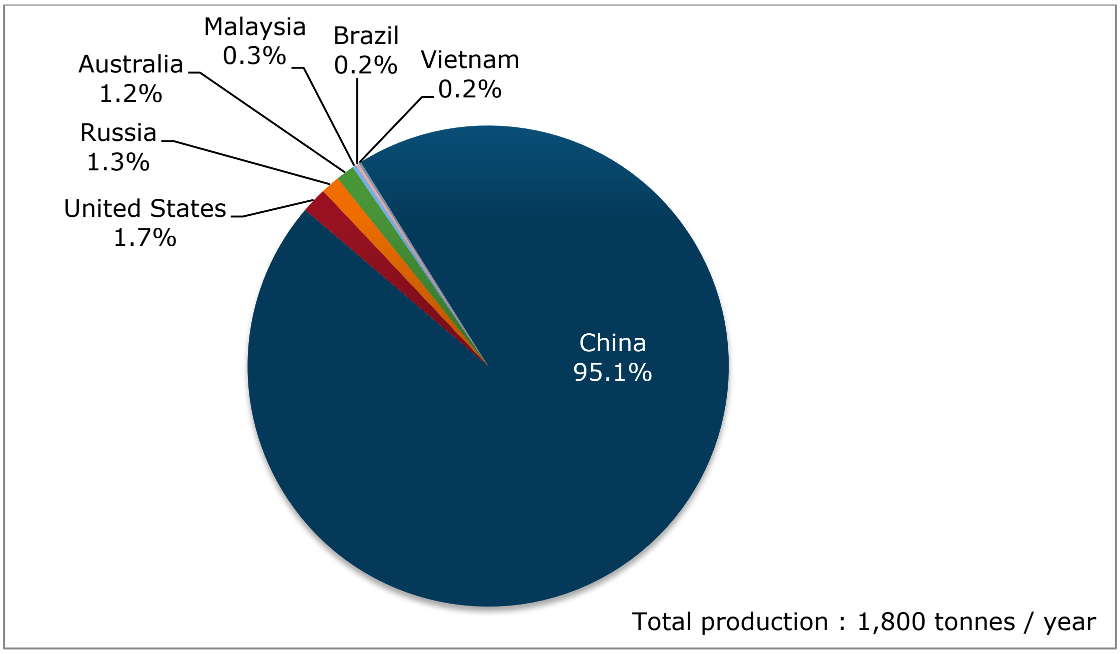

Figure 211: Global mine production of Ho, Lu, Tm, Yb, average 2010–2014 (Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015)

30.2.2 Supply from secondary materials

The recycling rate was assessed with the UNEP study (UNEP, 2013). Only 1% of Ho, Lu, Yb and Tm worldwide is recycled.

30.2.3 EU trade

EU import reliance on Ho, Lu, Tm, and Yb contained in mixed rare-earth oxides and compounds is 100%. Around 11 t of Ho, Lu, Tm and Yb are imported each year in the EU (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015 – see also 3.1).

The three main suppliers of Ho, Lu, Tm and Yb to the EU are China (40%), the United States (34 %) and Russia (25%).

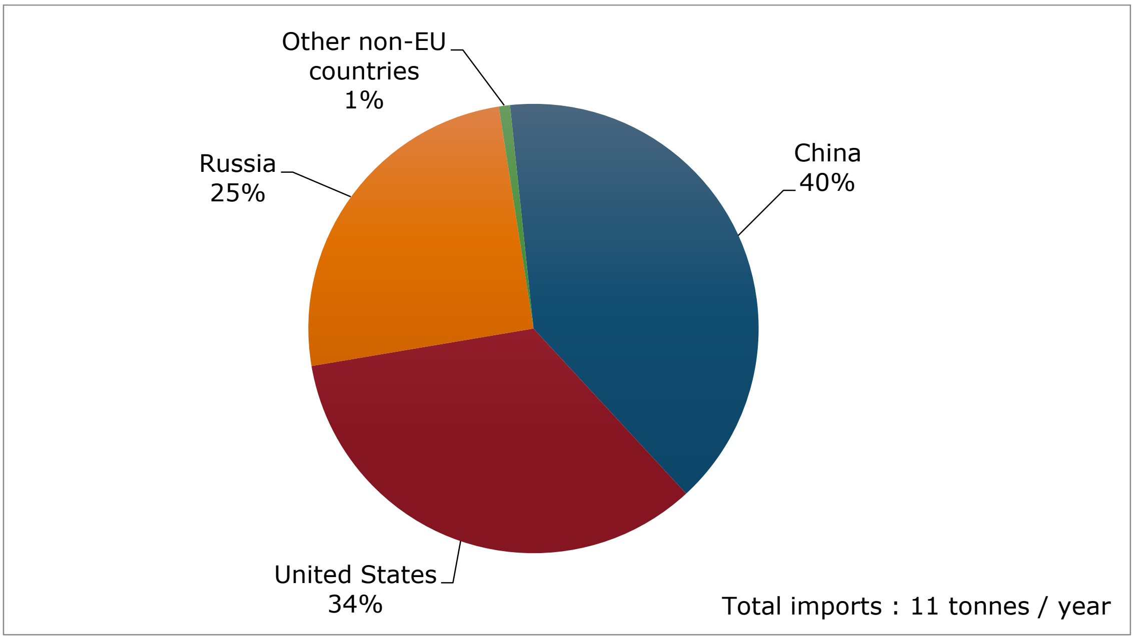

Figure 212: EU imports of Ho, Lu, Tm, Yb, average 2010-2014 (Eurostat, 2016; Guyonnet et al., 2015)

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 367 t/yr quota for Ho, Lu, Tm, Yb. There was an additional export tax of 15%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

30.2.4 EU supply chain

Generally speaking, there is no critical mass of REE transformation and manufacturing in the EU; although critical in many industries a large proportion of REE consumption comes from finished products imports (electronic material, vehicles, hard drives, laptops, etc.).

30.3 Demand

30.3.1 EU consumption

The use of Ho, Lu, Tm, Yb represents 0.1% of the total EU use of REEs, which gives an estimated 11 t of Ho, Lu, Tm, Yb consumed in the EU per year (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015).

30.3.2 Applications

The use of holmium, thulium, ytterbium and lutetium in individual applications is too small to be estimated with accuracy. Their major uses are as follows:

- Holmium: pigments, magnets, lasers and nuclear.
- Thulium has no real commercial use; but glass, phosphors and fibre optics have potential.
- Ytterbium: fibre optics, lasers, photovoltaics, stress gauges.
- Lutetium: phosphors, PET detectors, glass.

Each one of these elements are used in niche applications mostly related to their optical properties (Laser dopants, fiber optics, radiography, etc.).

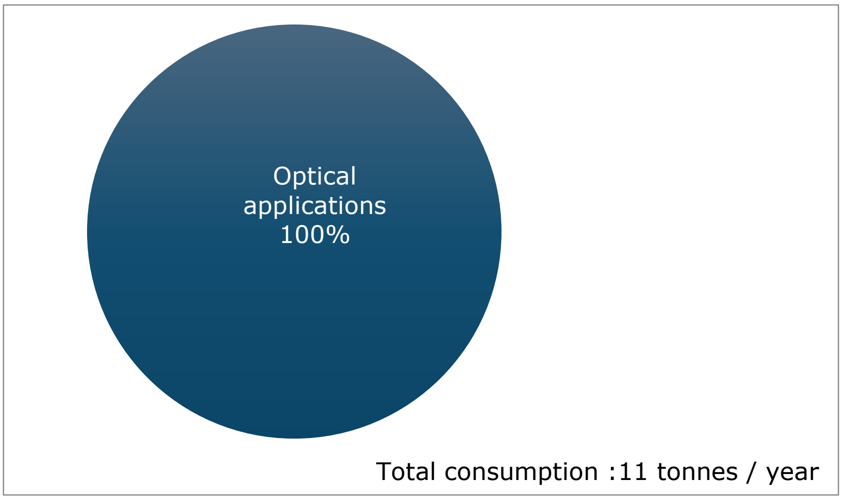

Figure 213: Global end-uses of Ho, Lu, Tm, Yb. Average figure for 2010-2014 (EC, 2014)

Information about the breakdown of the European market by application was not available at the time of writing.

Relevant industry sectors are described using the NACE sector codes in Table 120.

Table 120: Ho, Lu, Tm, Yb applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016)

Applications	2-digit NACE sector	Value added of sector (millions €)	4-digit NACE sectors
Optical applications	C23 - Manufacture of other non-metallic mineral products	59,166	C2310 - Manufacture and processing of other glass, including technical glassware

30.3.3 Prices

No data specific for Ho, Lu, Tm, Yb prices are available.

30.4 Substitution

Most applications have possible substitutes, given the large market surplus and the relative lack of commercial applications for these metals (EC, 2014).

30.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of mix Rare Earths Oxides (including Ho, Lu, Tm, Yb). This choice was motivated by the lack of data on production at further stages and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

The criticality assessment was performed at the extraction stage, which was defined as the step of production of Ho, Lu, Tm, Yb oxide in mixed rare-earth compounds and metals. This choice was motivated by the lack of data on refined Ho, Lu, Tm, Yb production and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

30.5.1 Data sources

Data sources for the estimation of Ho, Lu, Tm, Yb oxide supply are summed up in Table 121 below. The share of applications in the EU were estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 121: Sources of data for the estimation of Ho, Lu, Tm and Yb supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGM, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

30.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 120). The value added data correspond to 2013 figures.

30.6 Other considerations

30.6.1 Forward look for supply and demand

The overall supply and demand for Ho-Tm-Yb-Lu supply is expected to increase by around 8% per year until 2020 (EC, 2014).

Table 122: Qualitative forecast of supply and demand of Ho-Tm-Yb-Lu

Materials	Demand forecast			Supply forecast		
	5 years	10 years	20 years	5 years	10 years	20 years
Ho-Tm-Yb-Lu	+	?	?	+	?	?

30.7 Data sources

30.7.1 Data sources used in the factsheet

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30.7.2 Data sources used in the criticality assessment

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Dominique Guyonnet, Mariane Planchon, Alain Rollat, Victoire Escalon, Johann Tuduri, Nicolas Charles, Stéphane Vaxelaire, Didier Dubois, Hélène Fargier (2015). Material flow analysis applied to rare earth elements in Europe, Journal of Cleaner Production, Volume 107, 16 November 2015, Pages 215-228

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30.8 Acknowledgments

This Factsheet was prepared by Deloitte and BRGM. The authors would like to thank the EC Ad Hoc Working Group on Critical Raw Materials for their contributions to the preparation of this Factsheet, as well as the industrial experts from Tasman Metals and Less Common Metals.

31. LANTHANUM

Key facts and figures

Material name and Element symbol	Lanthanum, La	World/EU production[1]	World: 35,146 t EU : 0 t
Parent group (where applicable)	Rare-Earth Elements (REEs)	EU import reliance[1]	100%
Life cycle stage assessed	Extraction/mixed REOs	Substitution index for supply risk [SI (SR)]	0.99
Economic importance score EI (2017)	Light REEs: 3.6	Substitution Index for economic importance [SI(EI)]	0.98
Supply risk SR (2017)	Light REEs: 4.9	End of life recycling input rate (EOL-RIR)	1%
Abiotic or biotic	Abiotic	Major end uses [1]	Fluid Cracking Catalysts: 67% Glass & Ceramics: 13% Batteries : 10%
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated;

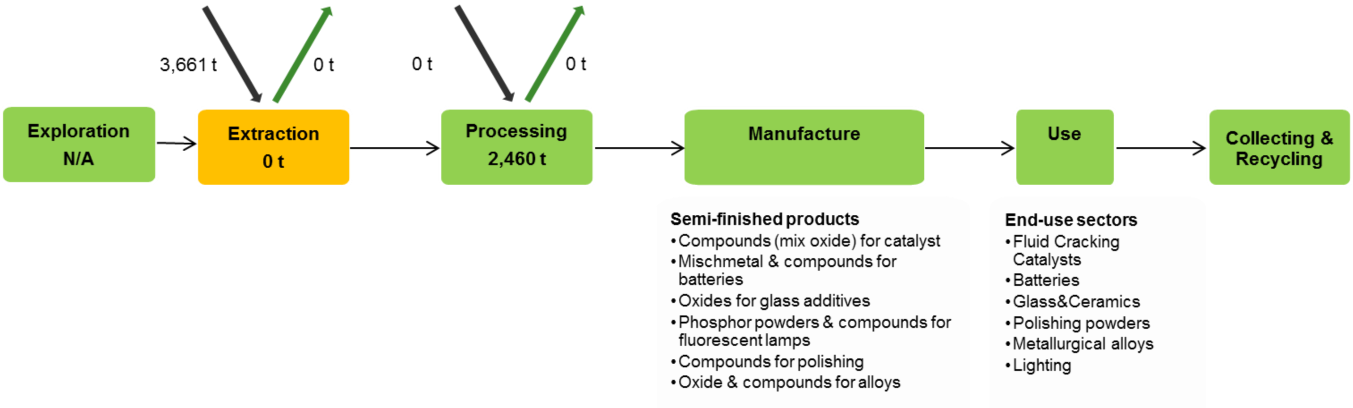

Figure 214: Simplified value chain for lanthanum

The green boxes of the production and processing stages in the above figure suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

31.1 Introduction

Lanthanum (chemical symbol La) is considered as a light REE. Its upper crust abundance is 31 ppm (Rudnick, 2003). Although it is classified as a rare earth element, lanthanum is the 28th most abundant element in the Earth's crust, almost three times as abundant as lead. It is the second most common of the lanthanides after cerium. In minerals such as monazite and bastnäsite, lanthanum composes about a quarter of the lanthanide content. It is a silvery white metallic element. It tarnishes rapidly when exposed to air and is soft enough to be cut with a knife. Lanthanum compounds have numerous applications as fluid cracking catalysts, additives in glass and ceramics, as well as in mischmetal for batteries.

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

31.2 Supply

Please refer to the general REEs Factsheet for geological occurrence, mining, processing, extractive metallurgy and resources and reserves data.

Lanthanum is always being found in combination with cerium and the other rare earth elements in minerals such as monazite and bastnäsite, and is extracted from those minerals by a process of such complexity that pure lanthanum metal was not isolated until 1923.

31.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of cerium in the EU. Supply solely depends on imports in the form of cerium oxide and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several sources and hypotheses (BGS, 2016; BRGM, 2015; Bio Intelligence Service, 2015). With lanthanum representing 26% of the total production of REEs in terms of relative concentration, the world annual production of lanthanum in mixed rare-earth compounds and metals is estimated to be 35,146 t.

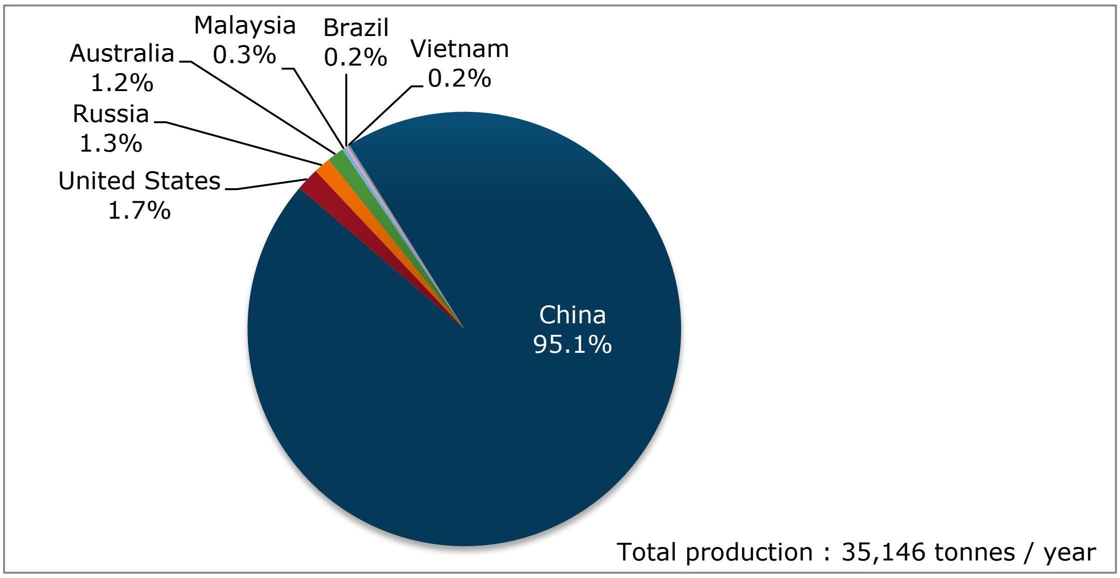

Figure 215: Global mine production of lanthanum average 2010–2014 (Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015)

About 95% of lanthanum originates from China (Figure 215). Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 7,931 t/yr quota for lanthanum for the period 2010-2014. There was an additional export tax of 15%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

31.2.2 Supply from secondary materials

The recycling rate was assessed with the UNEP study (UNEP, 2013). Only 1% of lanthanum worldwide is recycled.

31.2.3 EU trade

EU import reliance on lanthanum contained in mixed rare-earth oxides and compounds is 1 00%. Around 3,660 t of lanthanum are imported each year in the EU (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015 – see also 3.1). The amounts of imported lanthanum have increased steadily from 2010 to 2014.

The three main suppliers of lanthanum to the EU are China (40%), the United States (34 %) and Russia (25%).

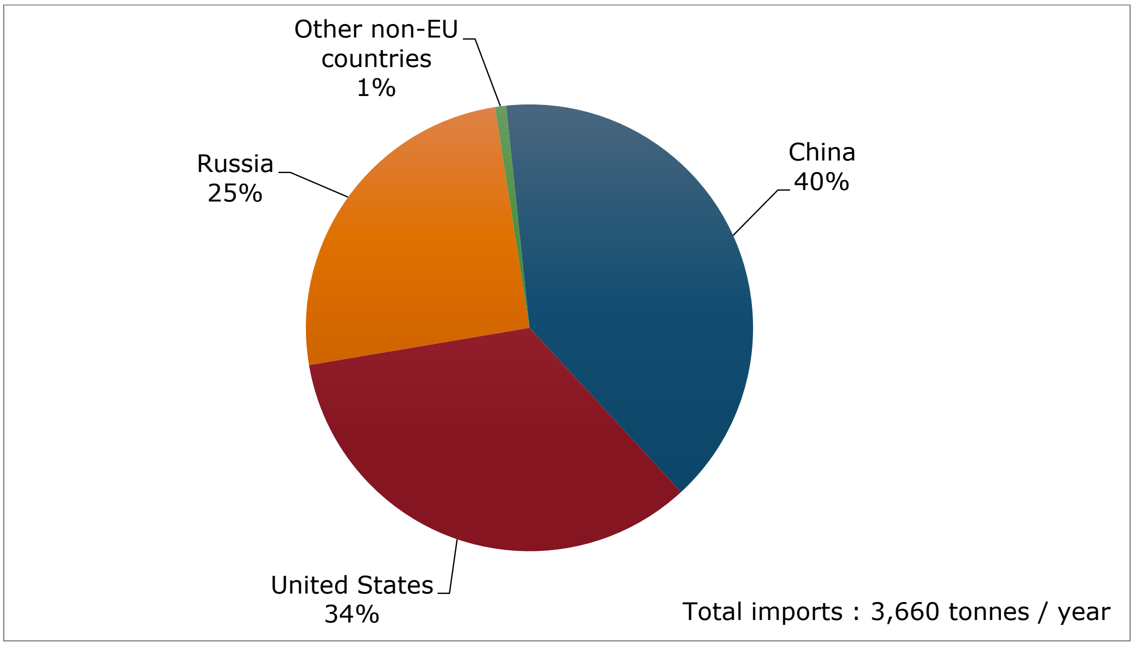

Figure 216: EU imports of lanthanum, average 2010-2014 (Eurostat, 2016; Guyonnet et al., 2015). Other countries are Malaysia, Vietnam, Brazil and Australia

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 7,931 t/yr quota for lanthanum for the period 2010-2014. There was an additional export tax of 15%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

31.2.4 EU supply chain

The EU relies solely on imports for the supply of lanthanum. The import reliance is thus 100%.

31.3 Demand

31.3.1 EU consumption

The use of lanthanum in the EU represents 41% of the total EU use of REEs, which gives an estimated 3,660 t of lanthanum consumed in the EU per year (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015).

31.3.2 Applications

Lanthanum is used for a variety of applications; its three main uses are in FCCs, nickel-metal hydride batteries and glass & ceramics (EC, 2014), see Figure 217. Other uses for lanthanum include autocatalysts, polishing powders, lighting applications, metallurgical uses, fertiliser, algal control and cement (EC, 2014).

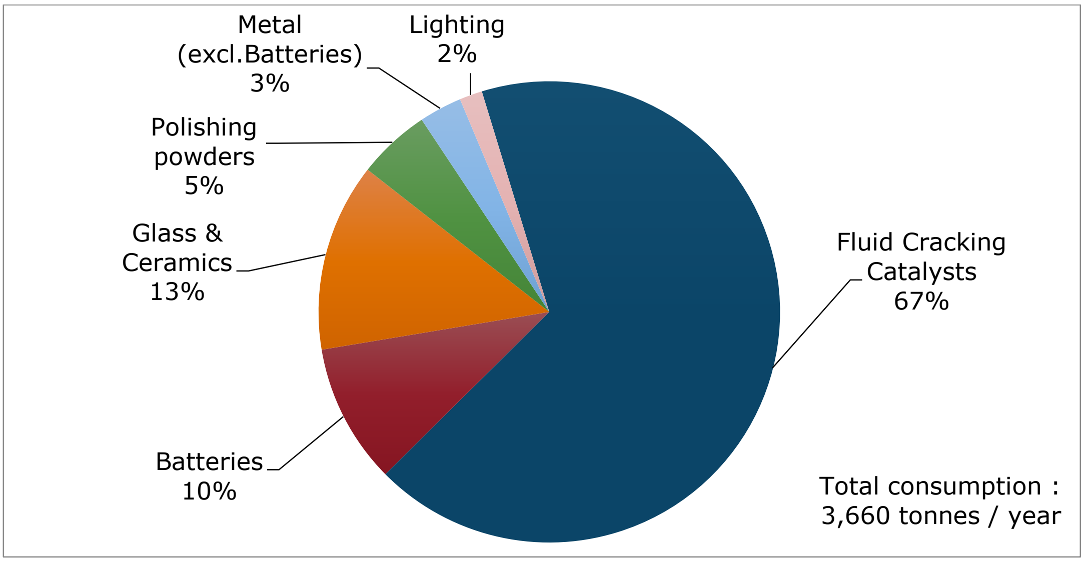

Figure 217: EU end uses of lanthanum. Average figures for 2010-2014. (Bio Intelligence Service, 2015)

Relevant industry sectors are described using the NACE sector codes in Table 123.

Table 123: La applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016)

Applications	2-digit NACE sector	Value added of sector (M€)	4-digit NACE sectors
Fluid Cracking Catalysts	C19 - Manufacture of coke and refined petroleum products	13,547	C2029 - Manufacture of other chemical products n.e.c.
Batteries	C27 - Manufacture of electrical equipment	84,609	C2720 - Manufacture of batteries and accumulators
Glass& Ceramics	C23 - Manufacture of other non-metallic mineral products	59,166	C2331 - Manufacture of ceramic tiles and flags
Polishing powders	C26 - Manufacture of computer, electronic and optical products	75,260	C2670 - Manufacture of optical instruments and photographic equipment
Metal (excl. Batteries)	C24 - Manufacture of basic metals	57,000	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Lighting	C27 - Manufacture of electrical equipment	84,609	C2740 - Manufacture of electric lighting equipment

31.3.3 Prices

Prices of lanthanum metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from 3 $/kg in 2002-2003 to an all-time high of 166 $/kg in July 2011, prices of La metal went down to reach a relatively stable value of around 6 $/kg in 2015 (BRGM, 2015). The skyrocketing of prices in 2010 – 2011 was triggered by the strong reduction of Chinese quotas.

Following a classic "bubble" pattern, this price increase was followed by a drop of demand (due to savings and substitution) and lead to a bubble burst – therefore the decrease of prices between 2011 and 2013.

31.4 Substitution

Several applications have possible substitutes for lanthanum, although with significant loss of performance or a greater cost (EC, 2014). In term of FCC use, lanthanum can be replaced by cerium (BRGM, 2015). However, nickel-metal hydride batteries are being superseded by Li-ion batteries in many applications due to better performance. In some of its minor uses, lanthanum is thought to be relatively readily substitutable (EC, 2014).

Lanthanum used for the purpose of polishing can be substituted by cerium, iron oxide and alumina powders (BRGM, 2015).

There is no substitute to La in fluorescent lamps. The alternative lighting technology LED, which penetration in the market is fast and important and is taking over the fluorocompact market share (McKinsey, 2012), also uses phosphors based on rare earths, including La, but the amount of phosphor needed per LED in 1000 times lower than in fluorescent lamps (2 mg of phosphor powder/LED instead of 2g/LFL or CFL) (Guyonnet et al., 2015).

In metallurgical applications, lanthanum can be substituted by cerium, neodymium, gadolinium and calcium.

31.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of mix Rare Earths Oxides (including lanthanum). This choice was motivated by the lack of data on production at further stages and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

31.5.1 Data sources

Data sources for the estimation of lanthanum oxide supply are summed up in Table 124 below. The share of applications in the EU were estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 124: Sources of data for the estimation of lanthanum supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGM, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

31.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 123). The value added data correspond to 2013 figures.

31.6 Other considerations

31.6.1 Forward look for supply and demand

Supply of rare-earths in general and lanthanum in paticular is constantly subject to changes. The market of rare-earths is opaque and it is thus very difficult to predict the future evolution of supply (Rare Earth Investing News, 2016). Although China’s campaign against illegal mining should take hold and remove some of the volatility in pricing, investments in mining activities are still uncertain – notably following the bankrupcy of Molycorp and the failure of the Mountain Pass project in the USA (The AusIMM Bulletin, 2016).

Table 125: Qualitative forecast of supply and demand of lanthanum

Material	**Demand forecast**			**Supply forecast**		
	5 years	10 years	20 years	5 years	10 years	20 years
Lanthanum	+	?	?	+	?	?

31.7 Data sources

31.7.1 Data sources used in the factsheet

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31.7.2 Data sources used in the criticality assessment

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31.8 Acknowledgments

This Factsheet was prepared by Deloitte and BRGM. The authors would like to thank the EC Ad Hoc Working Group on Critical Raw Materials for their contributions to the preparation of this Factsheet, as well as the industrial experts from Tasman Metals and Less Common Metals.

32. NEODYMIUM

Key facts and figures

Material name and Element symbol	Neodymium, Nd	World/EU production[1]	World : 22,391 EU : 0 t
Parent group (where applicable)	Rare-Earth Elements (REEs)	EU import reliance[1]	100%
Life cycle stage assessed	Extraction/mixed REOs	Substitution index for supply risk [SI (SR)]	0.92
Economic importance score EI(2017)	Light REEs: 3.6	Substitution Index for economic importance [SI(EI)]	0.89
Supply risk SR (2017)	Light REEs: 4.9	End of life recycling input rate (EOL-RIR)	1%
Abiotic or biotic	Abiotic	Major end uses [1]	Magnets (41%), metallurgical alloys (13%), ceramics (12%)
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated;

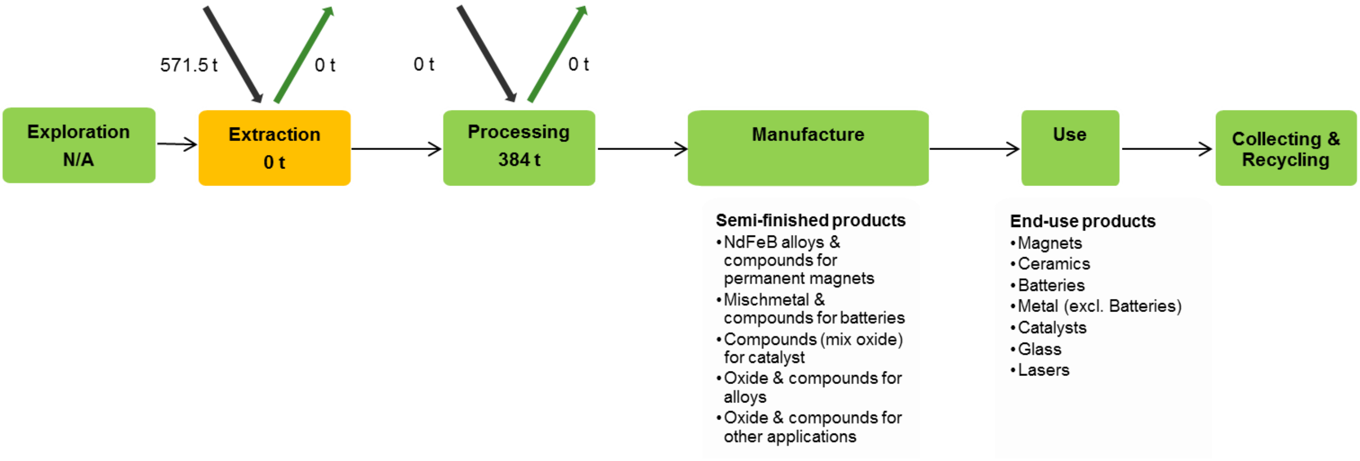

Figure 218: Simplified value chain for neodymium

The green boxes of the production and processing stages in the figure above suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%.

32.1 Introduction

Neodymium (chemical symbol Nd) is considered as a light REE. Neodymium's upper crust abundance is 27 ppm which is more than cobalt (17.3 ppm) (Rudnick, 2003). It is one of the most abundant REE, together with lanthanum and cerium. It does not occur naturally as a metallic element and is mainly found (for commercial exploitation) in the minerals bastnäsite, monazite, and ion-adsorption clays. It is a soft silvery metal that tarnishes in air in a few days. Its main use is in permanent magnets NdFeB. It is also valued for its chemical and optical properties in other applications such as metallurgical alloys, ceramics, or as a laser dopant (BRGM, 2015).

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

32.2 Supply

Please refer to the general REEs Factsheet for geological occurrence, mining, processing, extractive metallurgy and resources and reserves data.

32.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of neodymium in the EU. Supply solely depends on imports in the form of neodymium oxide and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several hypotheses (BGS, 2016; BRGM, 2015; Guyonnet et al., 2015). With neodymium representing 16.5% of the total production of REEs in terms of relative concentration, the world annual production of neodymium in the form of mixed rare-earth compounds is estimated to be 22,391 t.

China remains responsible of around 95% of total production (average of 2010-2014) as shown in Figure 219.

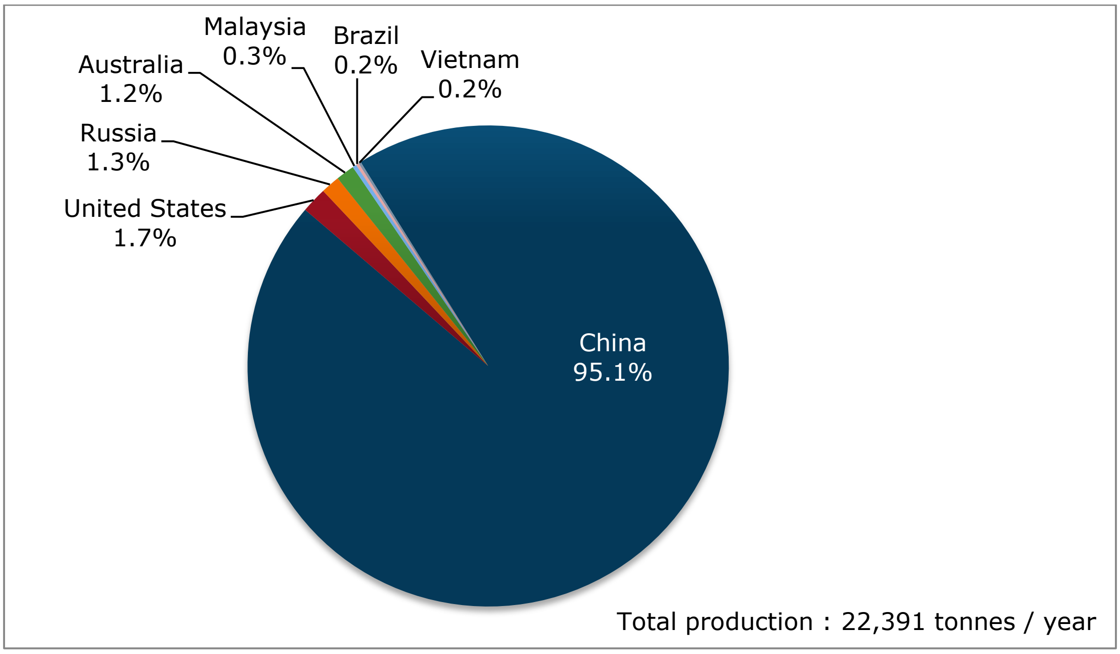

Figure 219: Global mine production of neodymium, average 2010–2014 (Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015)

In recent years, more neodymium is sold in the form of didymium, a Pr-Nd alloy obtained after the first stages of REE separation. It has a purity of 3N (99.9%) and can be supplied directly to magnet alloy producers or others.

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015) which gives an estimated 6,614 t/yr quota for neodymium for the period 2010-2014. There was an additional export tax of 15%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

32.2.2 Supply from secondary materials

The recycling rate was assessed with the RMSA study (Bio Intelligence Service, 2015). It appears that very little neodymium is currently recycled (1% recycling rate) in End-of-Life products.

32.2.3 EU trade

EU import reliance on neodymium contained in mixed rare-earth oxides and compounds is 100%. Around 571 t of neodymium are imported each year in the EU (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015 – see also 32.3.1). The quantities of imported neodymium experienced a slight increase during the 2010 – 2014 period.

The three main suppliers of the EU were China (40%), the United States (34 %) and the Russia (25%) (Figure 220).

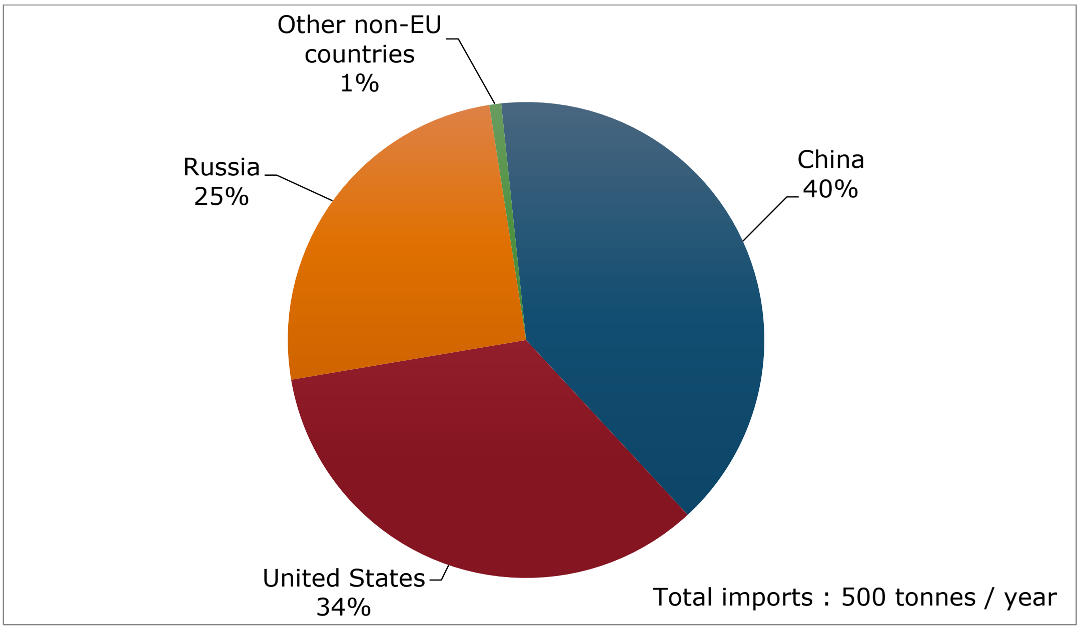

Figure 220: EU imports of neodymium, average 2010-2014 (Eurostat, 2016; Guyonnet et al., 2015). Other non-EU countries are Australia, Brazil, Malaysia and Brazil

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015) which gives an estimated 6,614 t/yr quota for neodymium for the period 2010-2014. There was an additional export tax of 15%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

32.2.4 EU supply chain

Some companies have the ability to separate individual REOs (in Estonia and France[24]) or to produce neodymium metal (in Estonia the company Silmet is separating rare-earth mixtures to produce neodymium metal (300-400 t/yr) (Guyonnet et al., 2015).

Downstream, there are also alloy makers and magnet manufacturers (in Germany, the UK, Slovenia) operating from imported processed materials.

Other manufacturers of REE-based products are present in various industries (phosphors, catalysts, polishing powders, etc.) and are potential users of neodymium.

32.3 Demand

32.3.1 EU consumption

The use of neodymium in the EU represents 6.4% of the total EU use of REEs, which gives an estimated 571 t of neodymium consumed in the EU per year (average 2010 – 2014)(Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015).

32.3.2 Applications

The main application of neodymium in the EU is for NdFeB permanent magnets (37% of total use) – see Figure 221. The main finished products driving neodymium consumption for magnets include industrial motors, hard drives, automobiles and wind turbines.

Neodymium is also used in NiMH batteries (Umicore, 2016), as a part of the batteries' cathode (13% of total use) although this use is declining (Higgins, 2016). In ceramics applications (11% of total use), neodymium is mainly used as a blue pigment in ceramic tiles (Yoldjian, 1985). In electronic ceramics, it is used as an insulator. Other applications include the manufacture of metals, catalysts, glass and lasers (BRGM, 2015).

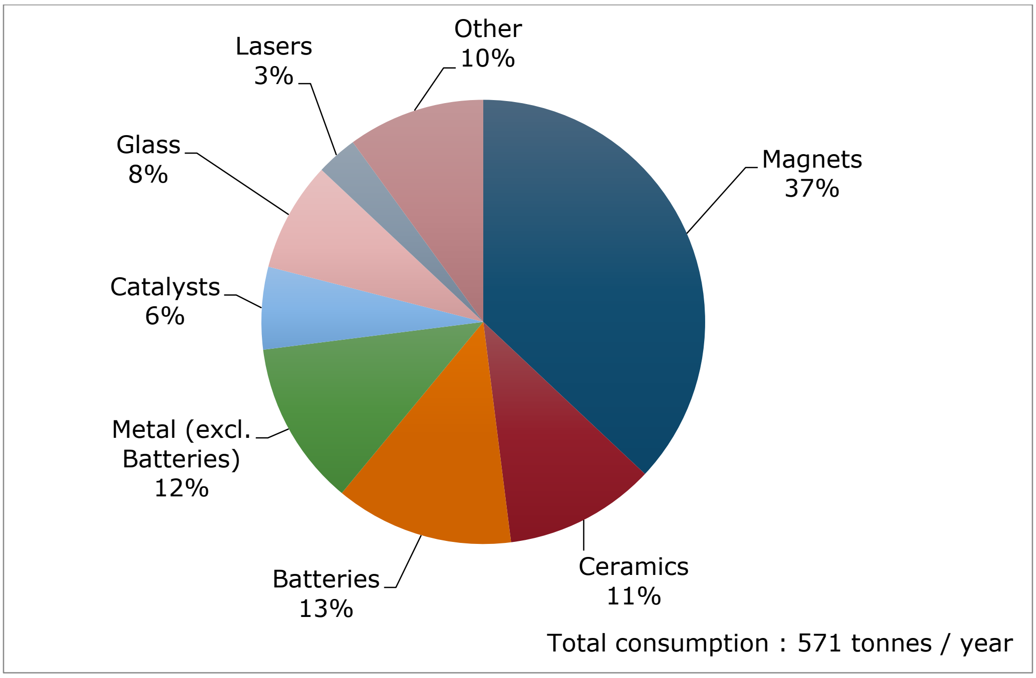

Figure 221: EU end-uses of neodymium. Average figures for 2010-2014 (Guyonnet et al., 2015)

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[24] Until 2016. Not the case anymore.

Relevant industry sectors are described using the NACE sector codes in Table 126.

Table 126: Neodymium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016)

Applications	2-digit NACE sector	Value added of sector (M€)	4-digit NACE sectors
Magnets	C25 - Manufacture of fabricated metal products, except machinery and equipment	159,513	C2599 - Manufacture of other fabricated metal products n.e.c.
Ceramics	C23 - Manufacture of other non-metallic mineral products	59,166	C2331 - Manufacture of ceramic tiles and flags
Batteries	C27 - Manufacture of electrical equipment	84,609	C2720 - Manufacture of batteries and accumulators
Metal (excl. batteries)	C24 - Manufacture of basic metals	57,000	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Catalysts	C20 - Manufacture of chemicals and chemical products	110,000	C2029 - Manufacture of other chemical products n.e.c.
Glass	C23 - Manufacture of other non-metallic mineral products	59,166	C2310 - Manufacture of glass and glass products
Lasers	C26 - Manufacture of computer, electronic and optical products	75,260	C2670 - Manufacture of optical instruments and photographic equipment

32.3.3 Prices

Prices of neodymium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from 7 $/kg in 2002-2003 to an all-time high of 467 $/kg in July 2011, prices of Nd metal went down to reach a relatively stable value of around 80 $/kg in 2014 and 53 $/kg in 2015 (BRGM, 2015).

32.4 Substitution

Neodymium can be substituted in magnet and batteries applications (BRGM, 2015; Bio Intelligence Service, 2015).

- Magnets: options exist to substitute neodymium in permanent magnets, either by material substitution or by using alternative magnet technology.
    - Material substitution: Replacing neodymium by praseodymium in NdFeB magnets: Experts confirm that the industry uses one or the other indifferently depending on price and availability (Higgins, 2016)
    - Technology substitution: Using alternative technology: the main solution is to use ferrite magnets; this technology is widely used for some electric motors and captors. However, this solution comes with a loss of performance compared to NdFeB magnets and is thus not adapted to high technology applications.

- Batteries: neodymium is used in NiMH batteries, which have been progressively replaced by Li-ion batteries.

Neodymium in other applications is not easily substituted.

32.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of neodymium oxide in mixed rare-earth compounds and metals. This choice was motivated by the lack of data on refined neodymium production and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

32.5.1 Data sources

Data sources for the estimation of neodymium oxide supply are summed up in Table 127 below. The share of applications in the EU was estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 127: Sources of data for the estimation of Nd supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGM, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

32.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 126). The value added data correspond to 2013 figures.

32.6 Other considerations

32.6.1 Forward look for supply and demand

Supply of rare-earths in general and neodymium in particular is constantly subject to changes. The market of rare-earths is opaque and it is thus very difficult to predict the future evolution of supply (Rare Earth Investment News, 2016). Although China's campaign against illegal mining should take hold and remove some of the volatility in pricing, investments in mining activities are still uncertain – notably following the bankrupcy of Molycorp and the failure of the Mountain Pass project in the USA (The AusIMM Bulletin, 2016). The future evolution of neodymium demand is driven by two forces:

- Efforts engaged by many companies to eliminate REEs in general and neodymium in particular from their supply chain following the Chinese export restriction era. It included avoiding REE permanents magnets technologies where possible, and proved successful in some specific functions, notably in the automotive, aerospace, and renewable energies sectors (c.f. companies Enercon, Siemens). However, REE performances remain superior in many applications and are likely to be used if prices and availability are favorable;

- The present context of anticipated growth for green energy and green transportation initiatives. These sectors, as well as increasing demand for air conditioning by Indian and other South-East Asian customers remain potential important markets for REE-based permanent magnets (Rare Earth Investment News, 2016; Powder Metallurgy review, 2016)

Table 128: Qualitative forecast of supply and demand of neodymium

Material	Demand forecast			Supply forecast		
	5 years	10 years	20 years	5 years	10 years	20 years
Neodymium	+	+	?	+	+	?

32.7 Data sources

32.7.1 Data sources used in the factsheet

BGS (2016). European mineral production 2010-2014

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Yoldjian (1985). The use of rare earths in ceramics, Journal of the Less-Common Metals, 111; 17 - 22

32.7.2 Data sources used in the criticality assessment

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32.8 Acknowledgments

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33.PRASEODYMIUM

Key facts and figures

Material name and Element symbol	Praseodymium, Pr	World/EU production (tonnes)[1]	World : 6,514 t EU : 0 t
Parent group (where applicable)	Rare-Earth Elements	EU import reliance[1]	100%
Life cycle stage assessed	Extraction/mixed REOs	Substitution index for supply risk [SI (SR)]	0.94
Economic importance score EI(2017)	Light REEs: 3.6	Substitution Index for economic importance [SI(EI)]	0.90
Supply risk SR (2017)	Light REEs: 4.9	End of life recycling input rate (EOL-RIR)	10%
Abiotic or biotic	Abiotic	Major end uses [1]	Magnets (24%) Ceramics (15%) Batteries (12%)
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated;

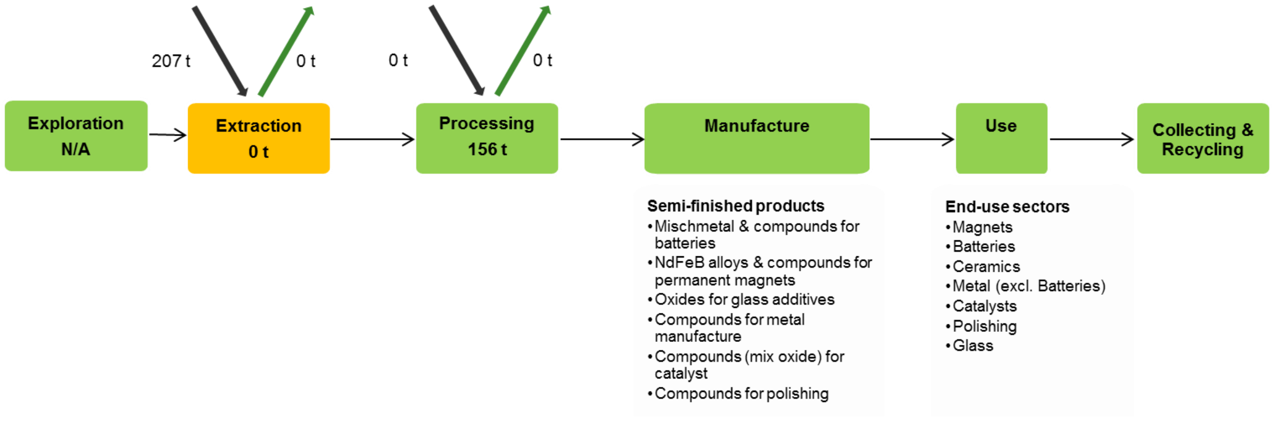

Figure 222: Simplified value chain for praseodymium

The green boxes of the production and processing stages in the figure above suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%.

33.1 Introduction

Praseodymium (chemical symbol Pr) is considered as a light REE. Praseodymium's crust abundance is 8.6 ppm and its upper crust abundance is 7.1 ppm (Rudnick, 2003). It does not occur naturally as a metallic element and is found in minerals such as bastnäsite and monazite. It is a soft, silvery, malleable and ductile metal. It is valued for its magnetic, electrical, chemical, and optical properties. Its main uses are in permanent magnets NdFeB, batteries, ceramics, metallurgy, catalysts, polishing powders and glass.

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

33.2 Supply

Please refer to the general REEs Factsheet for geological occurrence, mining, beneficiation, extractive metallurgy and resources and reserves data.

33.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of praseodymium in the EU. Supply solely depends on imports in the form of praseodymium oxide and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several hypotheses (BGS, 2016; BRGM, 2015; Guyonnet et al., 2015). With praseodymium representing 4.8% of the total production of REEs in terms of relative concentration the world annual production of praseodymium in the form of mixed rare-earth compounds would be around 6,514 t.

China remains responsible of around 95% of total production (average of 2010-2014) as shown in Figure 223. Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 1,470 t/yr quota for praseodymium for the period 2010-2014. There was an additional export tax of 15%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

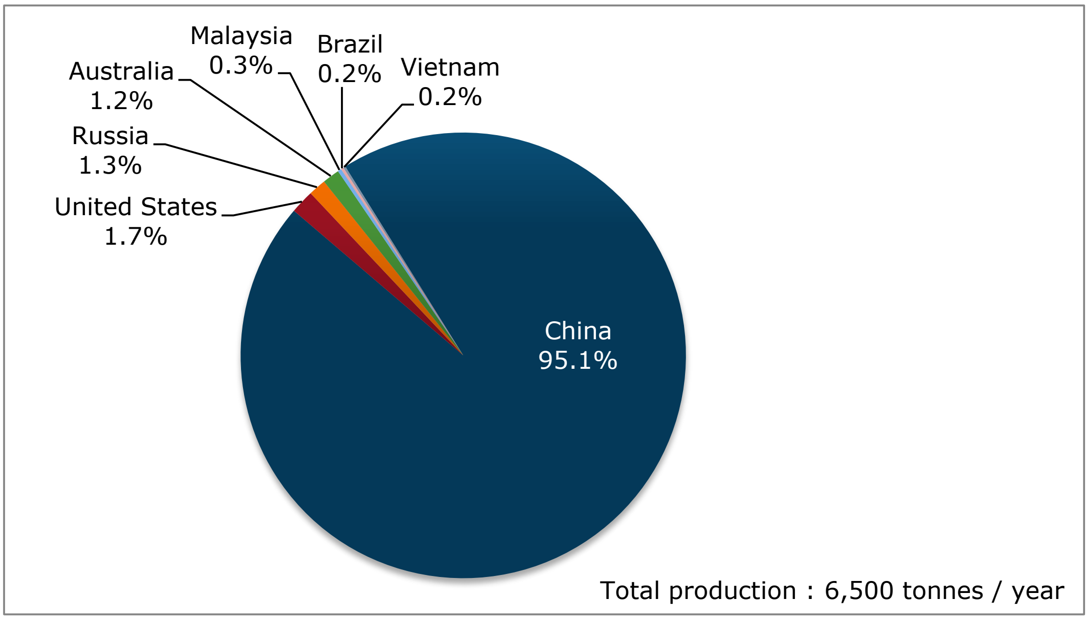

Figure 223: Global mine production of praseodymium, average 2010–2014 (Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015)

33.2.2 Supply from secondary materials

The recycling rate of praseodymium was estimated at 10% (BRGM, 2015).

33.2.3 EU trade

EU import reliance on praseodymium contained in mixed rare-earth oxides and compounds is 100%. Around 232 t of praseodymium are imported each year in the EU (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015 – see also 33.3.1). The quantities of imported praseodymium experienced a slight increase during the 2010 – 2014 period.

The three main suppliers of the EU were China (40%), the United States (34 %) and Russia (25%) (Figure 224).

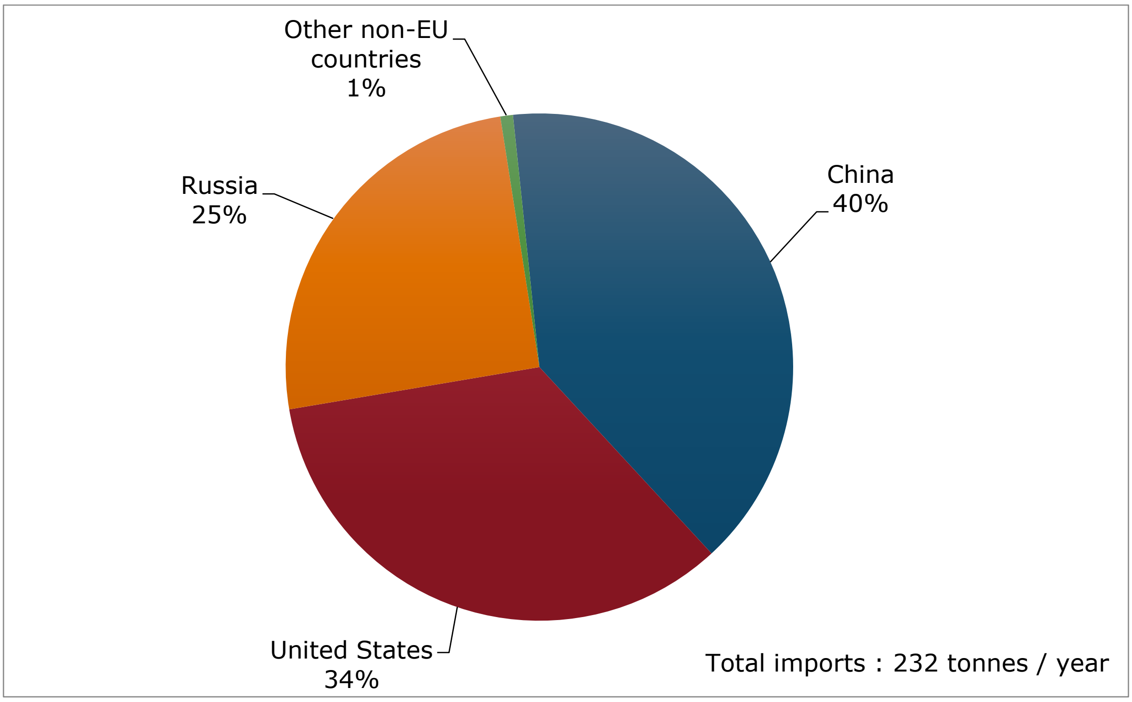

Figure 224: EU imports of praseodymium, average 2010-2014 (Eurostat, 2016; Guyonnet et al., 2015)

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 1,470 t/yr quota for praseodymium for the period 2010-2014. There was an additional export tax of 15%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

33.2.4 EU supply chain

Generally speaking, there is no critical mass of REE transformation and manufacturing in the EU; although critical in many industries a large proportion of REE consumption comes from finished products imports (electronic material, vehicles, hard drives, laptops, etc.).

33.3 Demand

33.3.1 EU consumption

The use of praseodymium in the EU represents 2.6% of the total EU use of REEs, which gives an estimated 232 t of praseodymium consumed in the EU per year (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015).

33.3.2 Applications

Praseodymium is used in the EU in many applications. Most praseodymium is used in magnet applications in NdFeB magnets (24%), although ceramics, batteries and metallurgical uses other than batteries are also important applications. Other uses for praseodymium include catalysts, polishing and fiber amplifiers. In ceramics applications, praseodymium is mainly used as a yellow pigment in ceramic tiles (Yoldjian, 1985).

The main categories of end uses for praseodymium are shown in Figure 225 and relevant industry sectors are described using the NACE sector codes in Table 129.

Table 129: Praseodymium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016)

Applications	2-digit NACE sector	Value added of sector (M €)	4-digit NACE sectors
Magnets	C25 - Manufacture of fabricated metal products, except machinery and equipment	159,513	C2599 - Manufacture of other fabricated metal products n.e.c.
Ceramics	C23 - Manufacture of other non-metallic mineral products	59,166	C2331 - Manufacture of ceramic tiles and flags
Batteries	C27 - Manufacture of electrical equipment	84,609	C2720 - Manufacture of batteries and accumulators
Metal (excl. batteries)	C24 - Manufacture of basic metals	57,000	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Catalysts	C20 - Manufacture of chemicals and chemical products	110,000	C2029 - Manufacture of other chemical products n.e.c.
Glass	C23 - Manufacture of other non-metallic mineral products	59,166	C2310 - Manufacture of glass and glass products
Polishing powders	C26 - Manufacture of computer, electronic and optical products	75,260	C2670 - Manufacture of optical instruments and photographic equipment

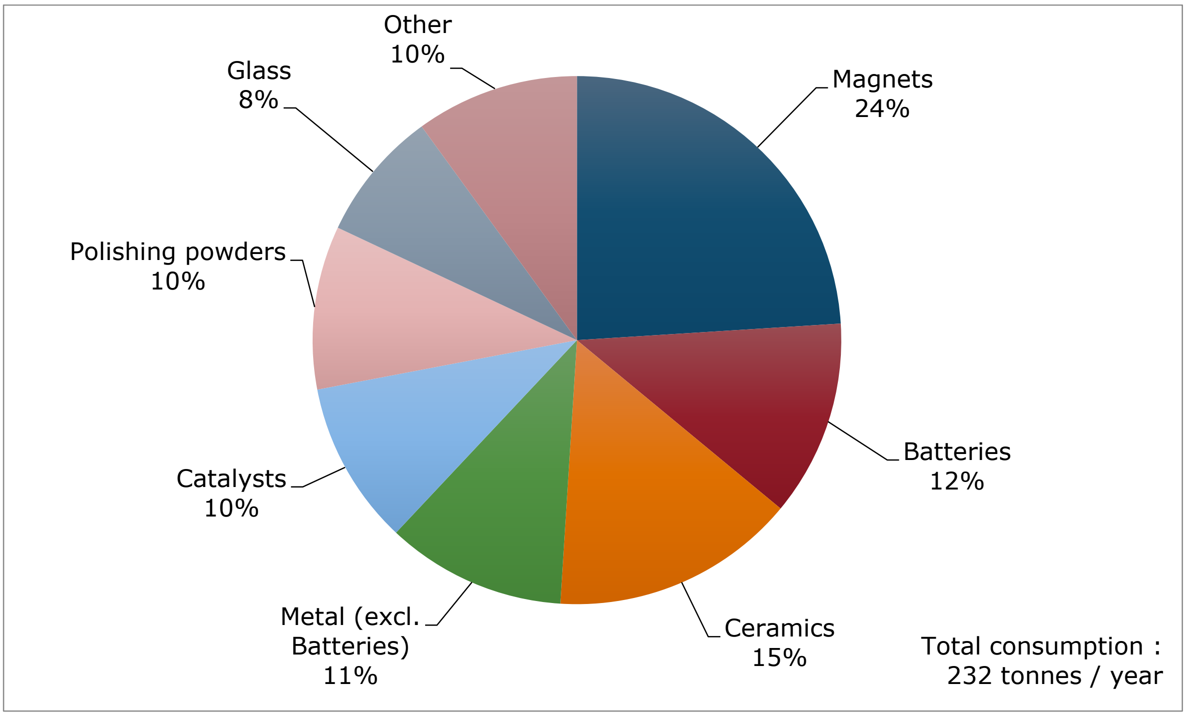

Figure 225: EU end-uses of praseodymium. Average figures for 2010-2014 (Guyonnet et al., 2015)

33.3.3 Prices

Prices of praseodymium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from 6 $/kg in 2002-2003 to an all-time high of 281 $/kg in July 2011, prices of Pr metal went down to reach a relatively stable value of around 90 $/kg in 2015 (BRGM, 2015).

33.4 Substitution

Praseodymium can be substituted in magnet and batteries applications, as well as in metallurgical applications (BRGM, 2015; Bio Intelligence Service, 2015):

- Magnets: options exist to substitute praseodymium in permanent magnets, either by replacing praseodymium by neodymium in NdFeB magnets (experts confirm that the industry uses one or the other indifferently, with in fact Pr already used as an inferior substitute for Nd (European Commission, 2014)) or by using alternative magnet technology (mainly ferrite magnets or SmCo magnets in some electric motors and captors, but with a loss of performance so not adapted to high technology applications).
- Batteries: praseodymium is used in NiMH batteries, which have been progressively replaced by Li-ion batteries. NiCd or lead-acid batteries are also alternatives in rechargeable batteries.
- Metallurgy: Pr is used for improving the mechanical characteristics of alloyed steel, for desulphurization. GadolinIum can be used instead for this application, for a similar performance (European Commission, 2014)
- Praseodymium is other applications is not easily substituted, for example there is no alternative for the yellow color in ceramics.

33.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of praseodymium oxide in mixed rare-earth compounds and metals. This choice was motivated by the lack of data on refined praseodymium production and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

33.5.1 Data sources

Data sources for the estimation of praseodymium oxide supply are summed up in Table 130 below. The share of applications in the EU was estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 130: Sources of data for the estimation of Pr supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGM, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

33.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 129). The value added data correspond to 2013 figures.

33.6 Other considerations

33.6.1 Forward look for supply and demand

Supply of rare-earths in general and praseodymium in paticular is constantly subject to changes. The market of rare-earths is opaque and it is thus very difficult to predict the future evolution of supply (Rare Earth Investment News, 2016). Although China's campaign against illegal mining should take hold and remove some of the volatility in pricing, investments in mining activities are still uncertain – notably following the bankrupcy of Molycorp and the failure of the Mountain Pass project in the USA (The AusIMM Bulletin, 2016).

The overall demand for praseodymium is expected to increase by around 6% per year (European Commission, 2014). However, supply is expected to more than keep up, keeping the market in significant surplus. The future evolution of praseoeodymium demand is driven by the anticipated growth of the permanent magnet market for the manufacture of wind turbines and electric vehicles. Those applications are supported by green energy and green transportation initiatives which are likely to incentivise a growth of their production (Rare Earth Investment News, 2016). Globally, the rapid increase of the demand for air conditioning by Indian and other South-East Asian customers is also factoring in the expected growth of the permanent magnet market (Rare Earth

Investment News, 2016; Powder Metallurgy review, 2016). As a result of those factors, the demand of Pr-containing magnets is expected to increase by at least 80% from 2010 to 2020 (Guyonnet et al., 2015).

Table 131: Qualitative forecast of supply and demand of Praseodymium

Material	**Demand forecast**			**Supply forecast**		
	5 years	10 years	20 years	5 years	10 years	20 years
Praseodymium	+	+	?	+	+	?

33.7 Data sources

33.7.1 Data sources used in the factsheet

BGS (2016) European mineral production 2010-2014

BGS (2016). World Mineral Production 2010-2014 [online]. Keyworth, Nottingham British Geological Survey, Available at: http://www.bgs.ac.uk/mineralsuk/statistics/home.html

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33.7.2 Data sources used in the criticality assessment

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33.8 Acknowledgments

This Factsheet was prepared by Deloitte and BRGM. The authors would like to thank the EC Ad Hoc Working Group on Critical Raw Materials for their contributions to the preparation of this Factsheet, as well as the industrial experts from Tasman Metals and Less Common Metals.

34. SAMARIUM

Key facts and figures

Material name and Element symbol	Samarium, Sm	World/EU production[1]	World: 2,714 t EU: 0 t
Parent group (where applicable)	Rare-Earth Elements (REEs)	EU import reliance[1]	100%
Life cycle stage assessed	Extraction/mixed REOs	Substitution index for supply risk [SI (SR)]	0.82
Economic importance score EI (2017)	Heavy REEs: 3.7	Substitution Index for economic importance [SI(EI)]	0.79
Supply risk SR (2017)	Heavy REEs: 4.8	End of life recycling input rate (EOL-RIR)	1%
Abiotic or biotic	Abiotic	Major end uses [1]	Magnets (97%)
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated;

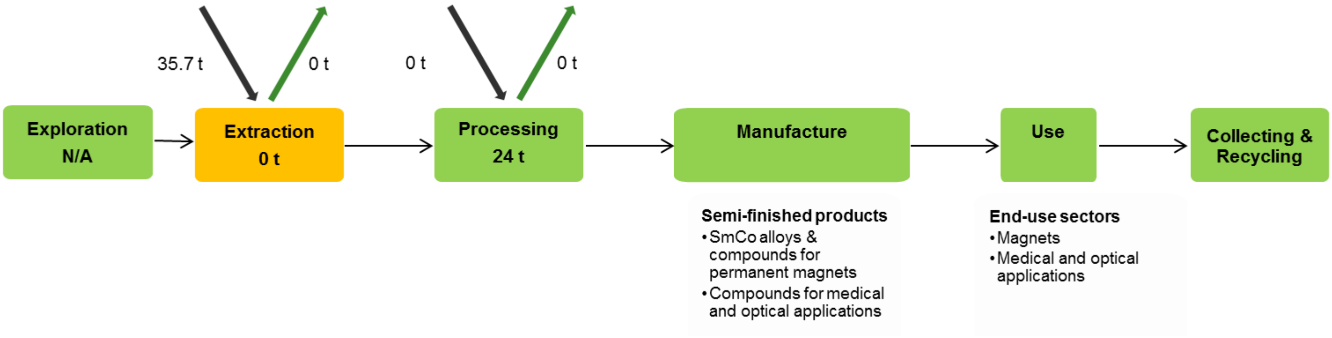

Figure 226: Simplified value chain for samarium

The green boxes of the production and processing stages in the figure above suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

34.1 Introduction

Samarium (chemical symbol Sm) is considered as a heavy REE. Its upper crust abundance is 4.7 ppm. Although classified as a rare earth element, samarium is the 40th most abundant element in the Earth's crust and is more common than such metals as tin. Samarium is not found free in nature, but, like other rare earth elements, is contained in several minerals including cerite, gadolinite, samarskite, monazite and bastnäsite, the last two being the most common commercial sources of the element. Samarium is a moderately hard silvery metal that readily oxidizes in air. Its main and almost exclusive use is in permanent magnets SmCo, and also niche applications mostly related to its optical properties (Laser dopant, radiography, etc.).

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

34.2 Supply

34.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of samarium in the EU. Supply solely depends on imports in the form of samarium oxide and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several sources and hypotheses (BGS, 2016; BRGM, 2015; Bio Intelligence Service, 2015). With samarium representing 2.0% of the total production of REEs in terms of relative concentration, the world annual production of samarium oxide in mixed rare-earth compounds and metals is estimated to be 2,714 t.

China remains responsible of around 95% of total production (average of 2010-2014) as shown in Figure 2. Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 612 t/yr quota for samarium. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

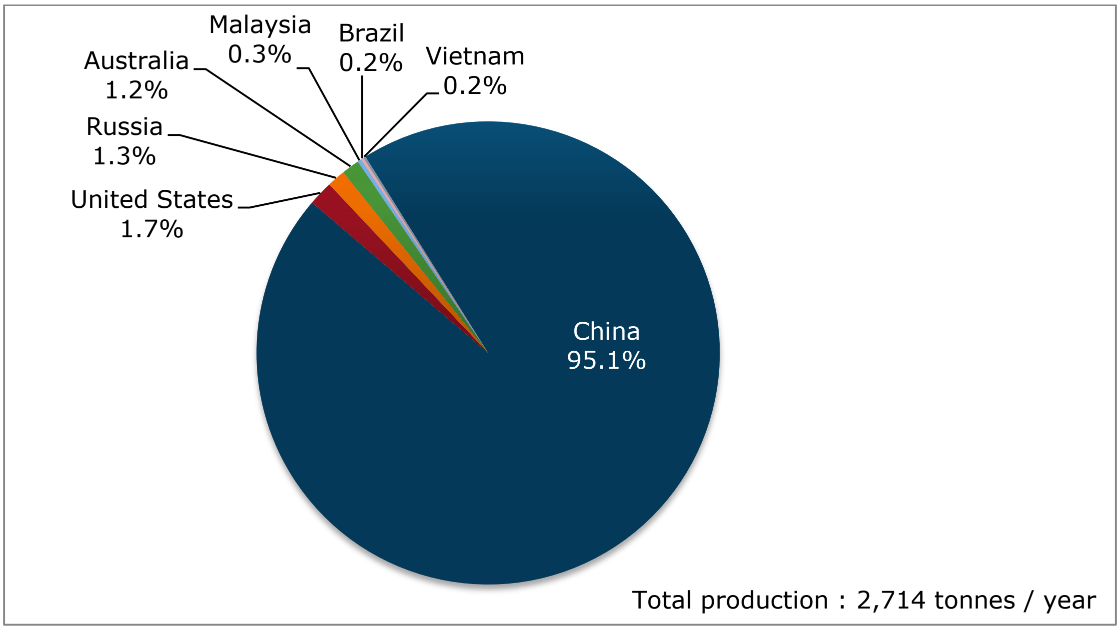

Figure 227: Global mine production of samarium, average 2010–2014 (Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015)

34.2.2 Supply from secondary materials

The recycling rate was assessed with the UNEP study (UNEP, 2013). Only 1% of samarium worldwide is recycled.

34.2.3 EU trade

EU import reliance on lanthanum contained in mixed rare-earth oxides and compounds is 100%. Around 35.7 t of samarium are imported each year in the EU (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015 – see also 3.1). The quantities of imported lanthanum experienced a slight increase during the 2010 – 2014 period.

The three main suppliers of the EU were China (40%), the United States (34 %) and Russia (25%) (Figure 228).

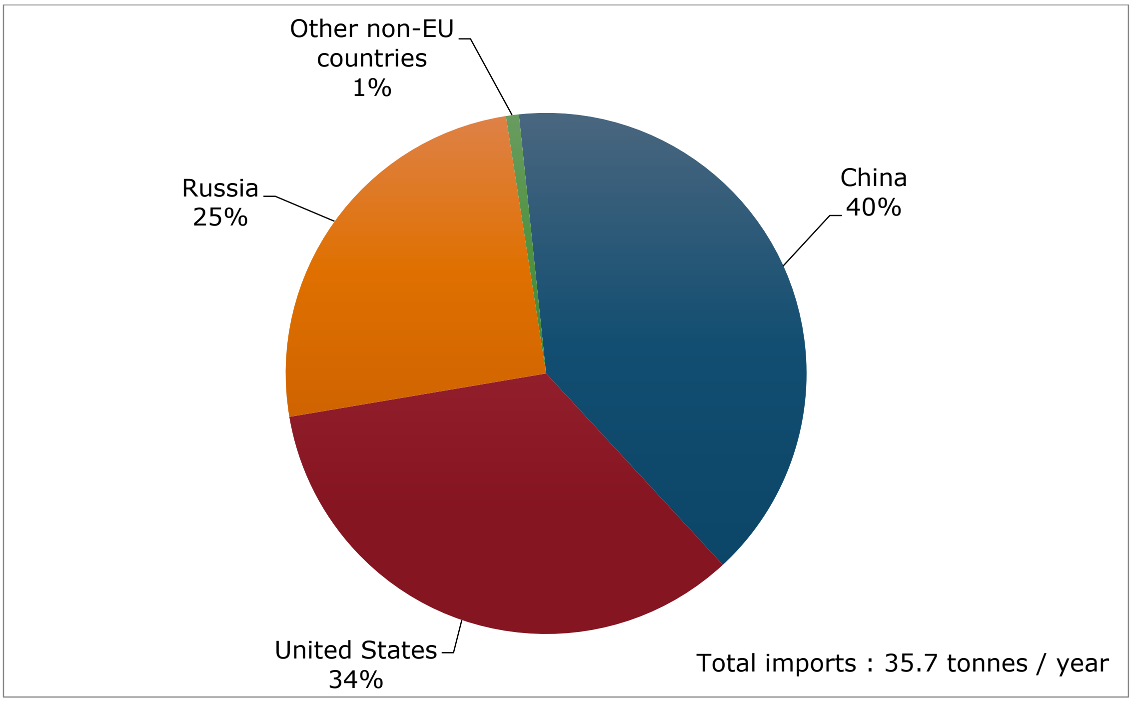

Figure 228: EU imports of samarium, average 2010-2014 (Eurostat, 2016; Guyonnet et al., 2015)

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 612 t/yr quota for samarium. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

34.2.4 EU supply chain

The EU relies solely on imports for the supply of samarium oxide. The import reliance is thus 100%.

34.3 Demand

34.3.1 EU consumption

The use of samarium in the EU represents 0.4% of the total EU use of REEs, which gives an estimated 35.7 t of samarium consumed in the EU per year (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015).

34.3.2 Applications

The main application for samarium is Sm-Co permanent magnets. Sm-Co magnets have high permanent magnetization, which is about 10,000 times that of iron and is second only to that of neodymium magnets. However, samarium-based magnets have higher resistance to demagnetization, as they are stable to temperatures above 700 °C (cf. 300–400 °C for neodymium magnets) (BRGM, 2015). These magnets are found in small motors, headphones, and high-end magnetic pickups for guitars and related musical instruments.

Other uses of Sm are niche applications mostly related to its optical properties (laser dopant, radiography, etc.) and nuclear industry (EC, 2014).

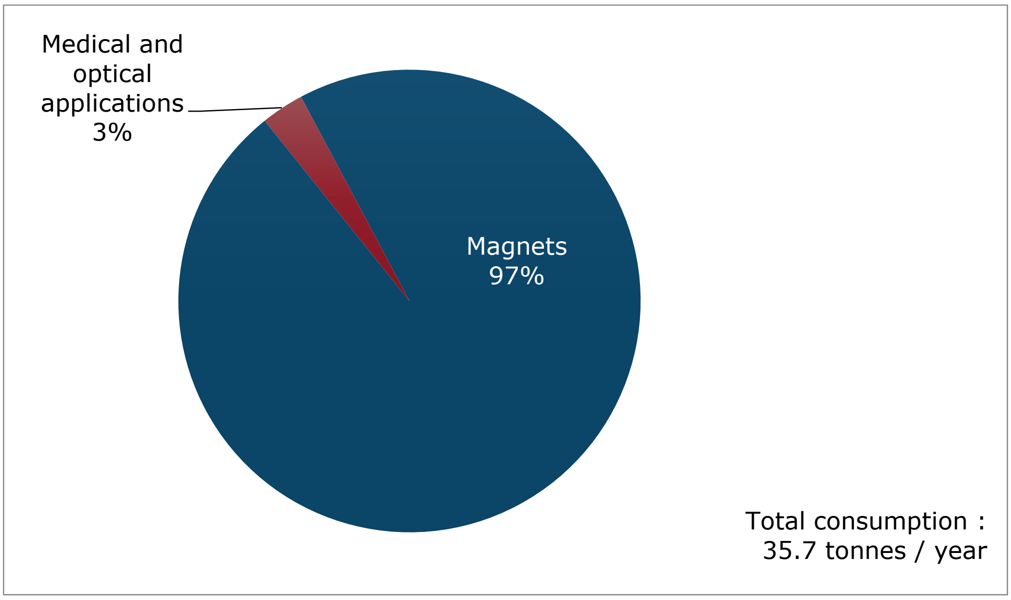

Figure 229: EU end-uses of samarium. Average figures for 2010-2014 (Bio Intelligence Service, 2015)

Relevant industry sectors are described using the NACE sector codes in Table 132.

Table 132: Samarium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016).

Applications	2-digit NACE sector	Value added of sector (M€)	4-digit NACE sectors
Lighting	C27 - Manufacture of electrical equipment	84,609	C2740 - Manufacture of electric lighting equipment
Medical and optical applications	C26 - Manufacture of computer, electronic and optical products	75,260	C2670 - Manufacture of optical instruments and photographic equipment

34.3.3 Prices

Prices of samarium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from 13 $/kg in 2002-2003 to an all-time high of 190 $/kg in July 2011, prices of Sm metal went down to reach a relatively stable value of around 17 $/kg in 2015 (BRGM., 2015). The skyrocketing of prices in 2010 – 2011 was triggered by the conjunction of two main factors:

- A strong reduction of Chinese quotas; and
- An increase of demand for permanent magnets, driven by the expected growth of the renewable energy and electric vehicles markets.

Following a classic "bubble" pattern, this price increase was followed by a drop of demand (due to savings and substitution) and lead to a bubble burst – therefore the decrease of prices between 2011 and 2013.

34.4 Substitution

Most applications have possible substitutes, although with significant loss of performance. In its main use (for magnets), samarium is considered to have already been widely substituted by other types of permanent magnest such as NdFeB magnets, ferrite or AlNiCo magnets (EC, 2014).

No substitutes are known for its niche applications.

34.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of mix Rare Earths Oxides (including samarium). This choice was motivated by the lack of data on production at further stages and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

34.5.1 Data sources

Data sources for the estimation of samarium oxide supply are summed up in Table 133 below. The share of applications in the EU were estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 133: Sources of data for the estimation of Sm supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGM, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

34.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 132). The value added data correspond to 2013 figures.

34.6 Other considerations

34.6.1 Forward look for supply and demand

Supply of rare-earths in general and samarium in paticular is constantly subject to changes. The market of rare-earths is opaque and it is thus very difficult to predict the future evolution of supply (Rare Earth Investing News, 2016). Although China’s campaign against illegal mining should take hold and remove some of the volatility in pricing, investments in mining activities are still uncertain – notably following the bankrupcy of Molycorp and the failure of the Mountain Pass project in the USA (The AusIMM Bulletin, 2016).

The overall demand for samarium is expected to increase by around 10% per year until 2020 (EC, 2014). The future evolution of samarium demand is driven by the anticipated growth of the permanent magnet market.

Table 134: Qualitative forecast of supply and demand for samarium

Material	**Demand forecast**			**Supply forecast**		
	5 years	10 years	20 years	5 years	10 years	20 years
Samarium	+	?	?	+	?	?

34.7 Data sources

34.7.1 Data sources used in the factsheet

BGS (2016). European mineral production 2010-2014

Bio Intelligence Service (2015). Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials – Final Report. Prepared for the European Commission, DG GROW.

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34.7.2 Data sources used in the criticality assessment

BGS (2016). European mineral production 2010-2014

Bio Intelligence Service (2015). Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials – Final Report. Prepared for the European Commission, DG GROW.

BMWFW (2014) Word Mining Data

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Dominique Guyonnet, Mariane Planchon, Alain Rollat, Victoire Escalon, Johann Tuduri, Nicolas Charles, Stéphane Vaxelaire, Didier Dubois, Hélène Fargier (2015). Material flow analysis applied to rare earth elements in Europe, Journal of Cleaner Production, Volume 107, 16 November 2015, Pages 215-228

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34.8 Acknowledgments

This Factsheet was prepared by Deloitte and BRGM. The authors would like to thank the EC Ad Hoc Working Group on Critical Raw Materials for their contributions to the preparation of this Factsheet, as well as the industrial experts from Tasman Metals and Less Common Metals.

35. TERBIUM

Key facts and figures

Material name and Element symbol	Terbium, Tb	World/EU production[1]	World : 407 t EU : 0 t
Parent group (where applicable)	Rare-Earth Elements (REEs)	EU import reliance[1]	100%
Life cycle stage assessed	Extraction/mixed REOs	Substitution index for supply risk [SI (SR)]	0.93
Economic importance score EI(2017)	Heavy REEs: 3.7	Substitution Index for economic importance [SI(EI)]	0.83
Supply risk SR (2017)	Heavy REEs: 4.8	End of life recycling input rate (EOL-RIR)	6%
Abiotic or biotic	Abiotic	Major end uses [1]	Lighting (68%), Magnets (32%)
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated;

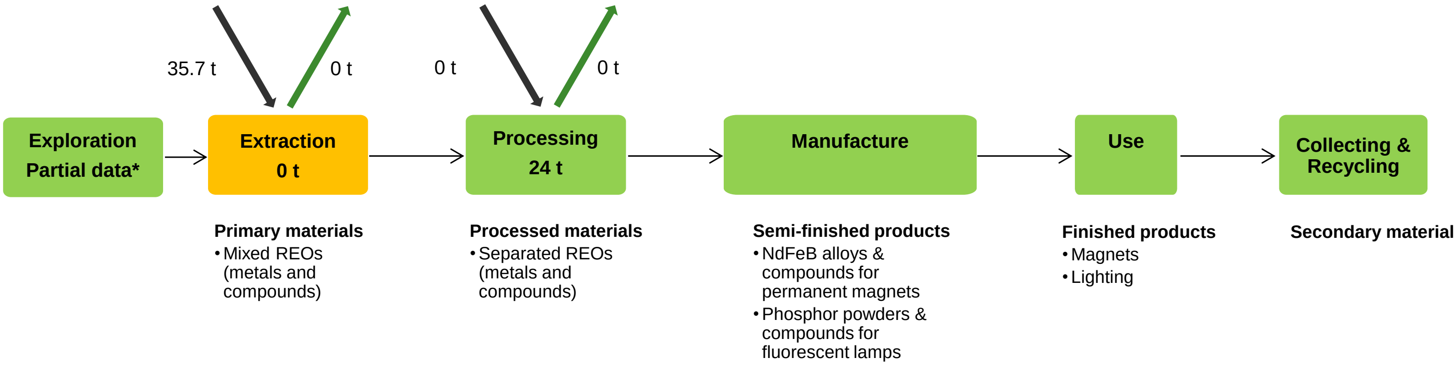

Figure 230: Simplified value chain for terbium

The green boxes of the production and processing stages in the figure above suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

35.1 Introduction

Terbium (chemical symbol Tb) is considered as a heavy REE. Its upper crust abundance is 0.7 ppm (Rudnick, 2003). It does not occur naturally as a metallic element and is found mainly in the minerals xenotime, monazite and ion-adsorption clays (for commercial exploitation). It is a silvery very hard metal which slowly oxidizes in air (a few years). Most of the world's terbium supply is used in green phosphors. It is also important in permanent magnets, as a substitute for dysprosium

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

35.2 Supply

Please refer to the general REEs Factsheet for geological occurrence, mining, processing, extractive metallurgy and resources and reserves data.

35.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of terbium in the EU. Supply solely depends on imports in the form of terbium oxide and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several hypotheses (BGS, 2016; BRGM, 2015; Guyonnet et al., 2015). With terbium representing 0.3% of the total production of REEs in terms of relative concentration, the world annual production of terbium in the form of mixed rare-earth compounds would be around 407 t.

China remains responsible of around 95% of total production (average of 2010-2014) as shown in Figure 231. Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 92 t/yr quota for terbium for the period 2010-2014. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

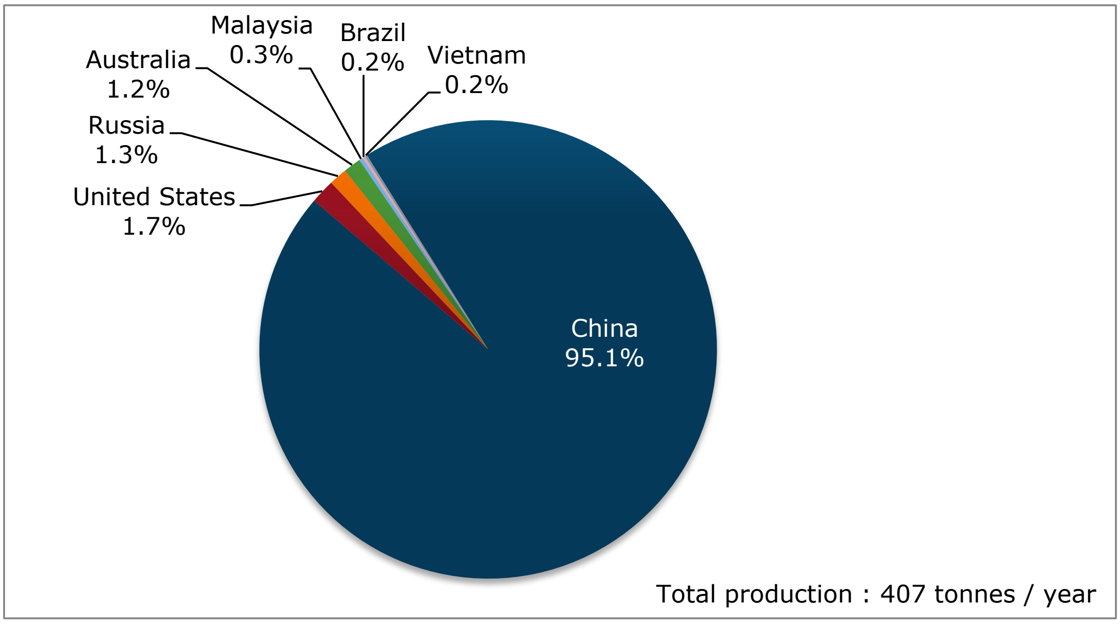

Figure 231: Global mine production of terbium, average 2010–2014 (Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015)

35.2.2 Supply from secondary materials

The recycling rate was assessed with the RMSA study (Bio Intelligence Service, 2015) and amounts to 6%.

Recycling activities were undertaken from end-of-life lamps at the Solvay plant in La Rochelle until its closure in 2016 (Usine Nouvelle, 2016). Recycling processes were initiated in 2011 in a context of uncertainty of supply, when China announced a reduction of export quotas (see also following section). At the time, primary terbium oxide was expensive (around 5,000 €/t) and there was a demand for cheaper, recycled terbium oxide. However, by 2015 prices of primary terbium dropped significantly to less than 500 €/t, thus rendering the recycling process far less competitive than during the crisis (2011-2014). This lead to Solvay announcing in early 2016 the closure of the plant by the end of 2016.

35.2.3 EU trade

EU import reliance on terbium contained in mixed rare-earth oxides and compounds is 100%. Around 36 t of terbium are imported each year in the EU (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015 – see also 35.3.1). The quantities of imported terbium experienced a slight increase during the 2010 – 2014 period.

The three main suppliers of the EU were China (40%), the United States (34 %) and the Russia (25%) (Figure 232).

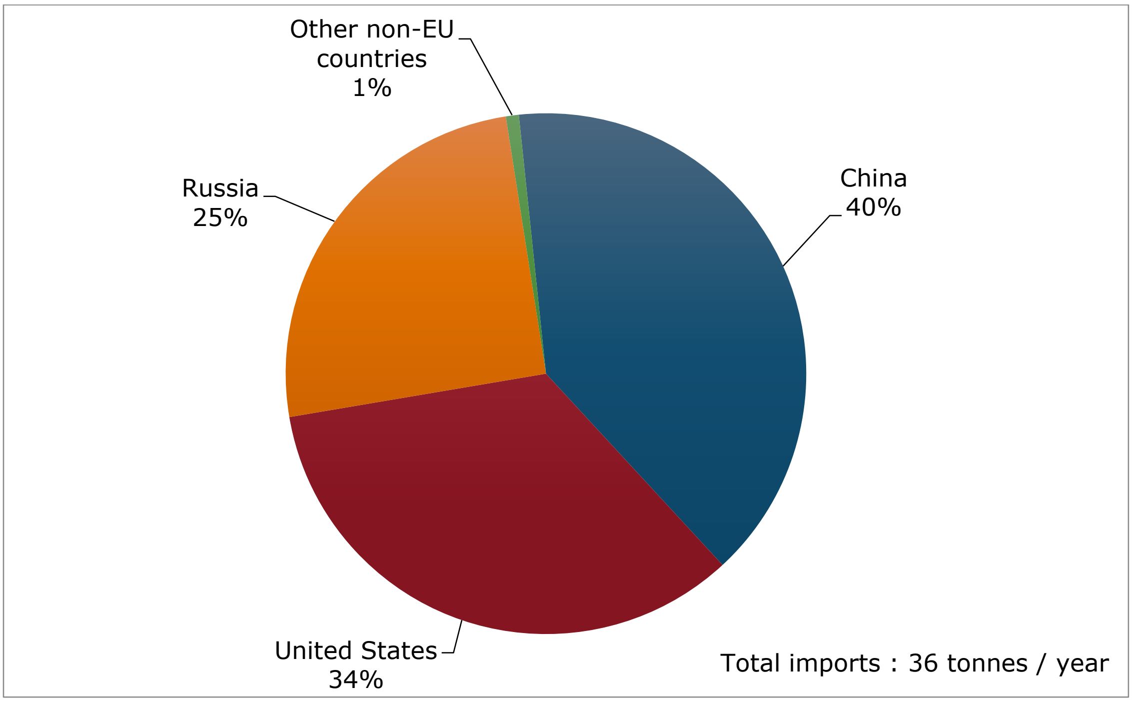

Figure 232: EU imports of terbium, average 2010-2014 (Eurostat, 2016; Guyonnet et al., 2015). Other countries are Malaysia and Vietnam

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM., 2015), which gives an estimated 92 t/yr quota for terbium for the period 2010-2014. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

35.2.4 EU supply chain

The separation of terbium metal was estimated at around 14 t/yr in the EU (Guyonnet et al., 2015) for the 2010-2014 period. Separation was performed in the Solvay plant in La Rochelle.

35.3 Demand

35.3.1 EU consumption

The use of terbium in the EU represents 0.4% of the total EU use of REEs, which gives an estimated 36 t of terbium consumed in the EU per year (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015; Guyonnet et al., 2015).

35.3.2 Applications

Terbium is used in the EU for NdFeB permanent magnets (BRGM, 2015; CRS, 2013) and for lighting applications (BRGM, 2015) (see Figure 233):

- Like dysprosium, terbium is used in NdFeB magnets to increase the Curie temperature and thus enable the use of those magnets at elevated temperatures. However, Dy is favoured over Tb because it is cheaper (BRGM, 2015).
- Terbium oxide gives the yellow or green color in neons and fluo-compact lamps. It represents 4% of the composition of luminophores used for lighting (BRGM, 2015).

Relevant industry sectors are described using the NACE sector codes in Table 135.

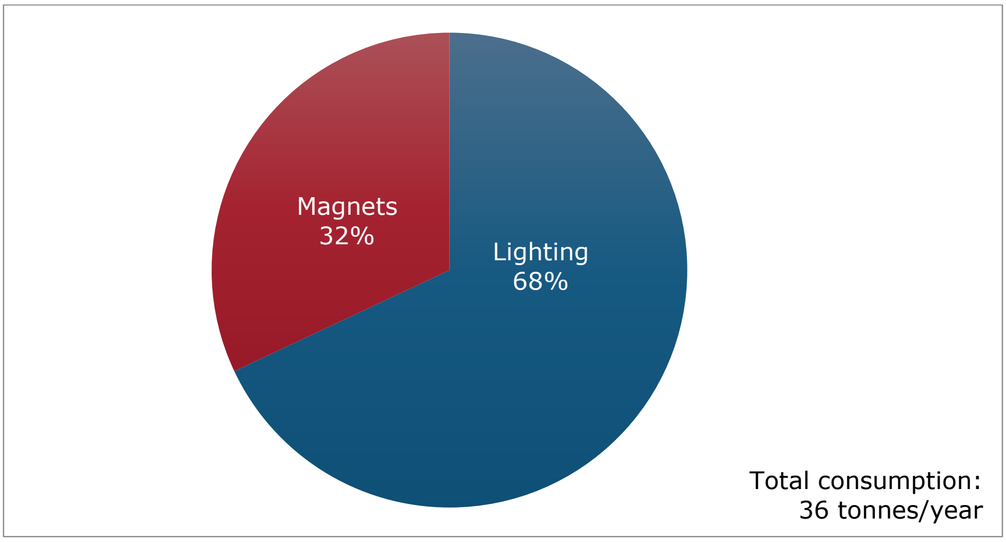

Figure 233: EU end-uses of terbium. Average figure for 2010-2014 (Guyonnet et al., 2015)

Table 135: Terbium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016)

Applications	2-digit NACE sector	Value added of sector (M€)	4-digit NACE sectors
Magnets	C25 - Manufacture of fabricated metal products, except machinery and equipment	159,513	C2599 - Manufacture of other fabricated metal products n.e.c.
Lighting	C27 - Manufacture of electrical equipment	84,609	C2740 - Manufacture of electric lighting equipment

35.3.3 Prices

Prices of terbium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from 200 $/kg in 2002-2003 to an all-time high of 5,100 $/kg in July 2011, prices of Tb metal went down to reach a relatively stable value of around 1200 $/kg in 2014 and 700 $/kg in 2015 (BRGM, 2015).

35.4 Substitution

Terbium can be substituted by dysprosium or gadolinium for its temperature compensation properties in NdFeB magnets. Dysprosium remains the preferred material for this application (BRGM, 2015).

There is no substitute to Tb in fluorescent lamps. The alternative lighting technology LED, which penetration in the market is fast and important and is taking over the fluorocompact market share (McKinsey, 2012), also uses phosphors based on rare earths, including Tb, but the amount of phosphor needed per LED in 1000 times lower than in fluorescent lamps (2 mg of phosphor powder/LED instead of 2g/LFL or CFL) (Guyonnet et al., 2015).

35.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of terbium oxide in mixed rare-earth compounds and metals. This choice was motivated by the lack of data on refined terbium production and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

35.5.1 Data sources

Data sources for the estimation of terbium oxide supply are summed up in Table 136 below. The share of applications in the EU was estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 136: Sources of data for the estimation of Tb supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGM, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

35.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 135). The value added data correspond to 2013 figures.

35.6 Other considerations

35.6.1 Forward look for supply and demand

Supply of rare-earths in general and terbium in paticular is constantly subject to changes. The market of rare-earths is opaque and it is thus very difficult to predict the future evolution of supply (Rare Earth Investment News, 2016). Although China's campaign against illegal mining should take hold and remove some of the volatility in pricing, investments in mining activities are still uncertain – notably following the bankrupcy of Molycorp and the failure of the Mountain Pass project in the USA (The AusIMM Bulletin, 2016).

The demand of terbium is likely to drop in the future because of the reduction of rare earth needs for the lighting industry (this industry is currently representing 68% of terbium applications). This reduction is expected to amount to at least 65% between 2015 and 2030 (Guyonnet et al., 2015). This evolution is due to the changes in the lighting market structure and is driven by two forces:

- The anticipated decrease of the fluorescent lamps market face to the growing new technology LEDs: in the lighting market as a whole, LED lighting penetration is projected to be around 40% in 2016 and over 60% in 2020 (Mc Kinsey, 2012).
- The content of rare earths (including Tb) in LEDs is much lower than in fluorescent lamps (1,000 times lower) (Guyonnet et al., 2015).
- As the lifetime of LED is 40,000-50,000 hours, compared to 10,000-25,000 hours for fluorescent lamps, the decrease in rare earth need for the lighting sector will amplify in the coming years (Guyonnet et al., 2015).

Table 137: Qualitative forecast of supply and demand of terbium

Material	Demand forecast			Supply forecast		
	5 years	10 years	20 years	5 years	10 years	20 years
Terbium	-	?	?	-	?	?

35.7 Data sources

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35.8 Acknowledgments

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36.YTTRIUM

Key facts and figures

Material name and Element symbol	Yttrium, Y	World/EU production[1]	World : 10,313 EU : 0 t
Parent group (where applicable)	Rare-Earth Elements (REEs)	EU import reliance[1]	100%
Life cycle stage assessed	Extraction/mixed REOs	Substitution index for supply risk [SI (SR)]	1.00
Economic importance score EI(2017)	Heavy REEs: 3.7	Substitution Index for economic importance [SI(EI)]	1.00
Supply risk SR (2017)	Heavy REEs: 4.8	End of life recycling input rate (EOL-RIR)	31%
Abiotic or biotic	Abiotic	Major end uses [1]	Lighting (46%), Ceramics (35%)
Main product, co-product or by-product	By-product	Major world producers[1]	China (95%)

[1] average for 2010-2014, unless otherwise stated;

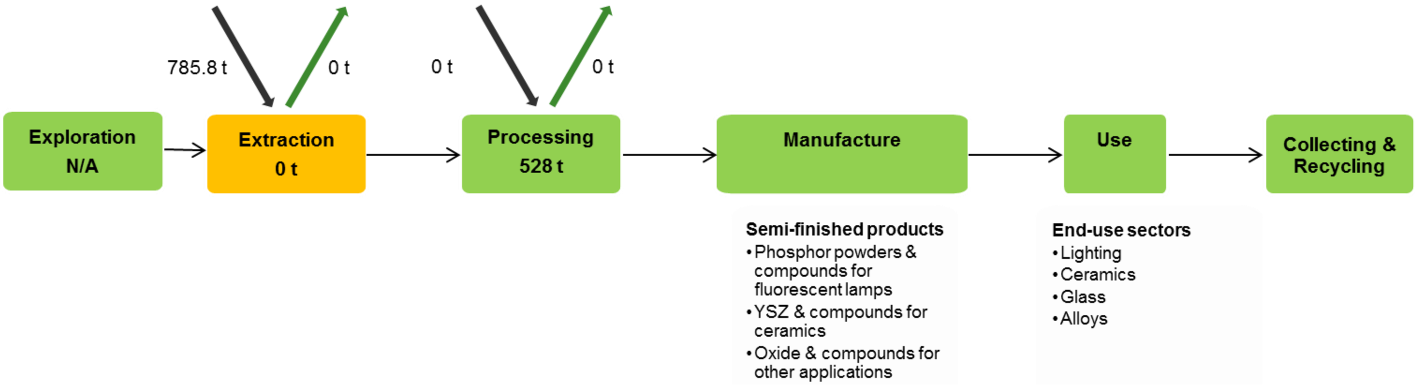

Figure 234: Simplified value chain for yttrium

The green boxes of the production and processing stages in the figure above suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

36.1 Introduction

Yttrium (chemical symbol Y) is considered a heavy REE. Its upper crust abundance is 21 ppm which is more than cobalt (17.3 ppm) (Rudnick, 2003). It does not occur naturally as a metallic element and is mainly found (for commercial exploitation) in the minerals xenotime and ion-adsorption clays (in Southern China).Yttrium is a silvery metal with high thermodynamic affinity for oxygen. It is mainly used in various phosphors, for display screens and energy efficient lighting. It also has applications in ceramics and glass, metallurgical alloys, and various medical applications and tracing.

All volumes discussed in this factsheet are expressed in tons of rare-earth oxide (t REO).

36.2 Supply

Please refer to the general REEs Factsheet for geological occurrence, mining, processing, extractive metallurgy and resources and reserves data.

36.2.1 Supply from primary materials

As for all Rare Earths Elements, there is no mining of yttrium in the EU. Supply solely depends on imports in the form of yttrium oxide and compounds. As there is no data available at the global level for individual production of REEs, following figures were obtained relying on several hypotheses (BGS, 2016; BRGM, 2015; Guyonnet et al., 2015). With yttrium representing 7.6% of the total production of REEs in terms of relative concentration, the world annual production of yttrium in the form of mixed rare-earth compounds would be around 10,313 t.

China remains responsible of around 95% of total production (average of 2010-2014) as shown in Figure 235. Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 2,327 t/yr quota for yttrium for the period 2010 - 2014. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

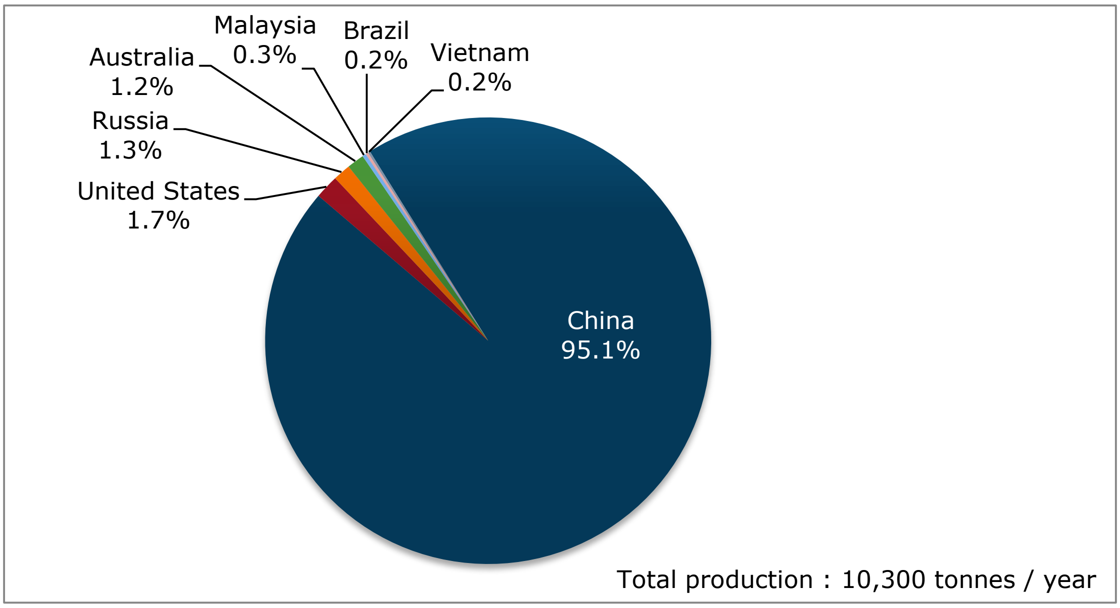

Figure 235: Global mine production of yttrium, average 2010–2014 (Compiled data from BGS, 2016; BRGM, 2015; Guyonnet et al., 2015

36.2.2 Supply from secondary materials

The recycling rate was assessed with the RMSA study (Bio Intelligence Service, 2015) and amounts to 31%.

Recycled yttrium comes mainly from the recycling of fluorescent lamps. Recycling activities were undertaken from end-of-life lamps at the Solvay plant in La Rochelle until its closure in 2016 (Usine Nouvelle, 2016). Recycling processes were initiated in 2011 in a context of uncertainty of supply, when China announced a reduction of export quotas (see also following section). At the time, primary terbium oxide was expensive (around 5,000 €/t) and there was a demand for cheaper, recycled terbium oxide. However, by 2015 prices of primary terbium dropped significantly to less than 500 $/t, thus rendering the recycling process far less competitive than during the crisis (2011-2014). This lead to Solvay announcing in early 2016 the closure of the plant by the end of 2016.

A minor part of recycled yttrium comes from oxygen sensors contained in end-of-life vehicles (Bio Intelligence Service, 2015).

36.2.3 EU trade

EU import reliance on yttrium contained in mixed rare-earth oxides and compounds is 100%. Around 786 t of yttrium are imported each year in the EU (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015). The quantities of imported yttrium experienced a slight increase during the 2010 – 2014 period.

The three main suppliers of yttrium to the EU are China (40%), the United States (34 %) and the Russian Federation (25%) (Figure 236).

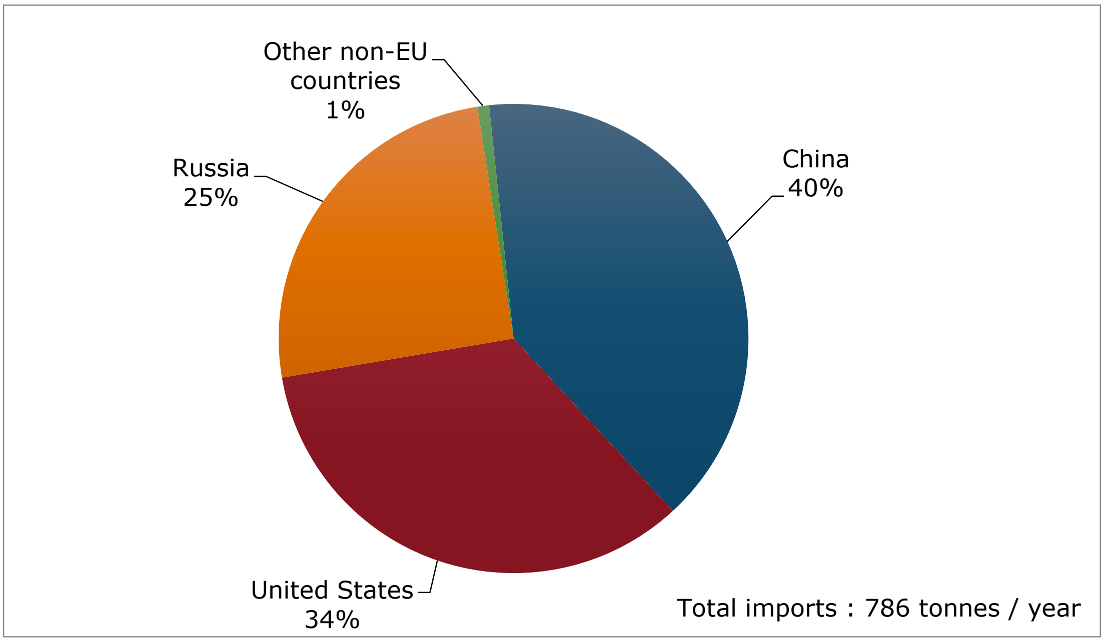

Figure 236: EU imports of yttrium, average 2010-2014 (Eurostat, 2016). Other countries are Vietnam, Malaysia, Brazil and Australia

Until 2015, Chinese REE quotas amounted to around 30,600 t REO per year (BRGM, 2015), which gives an estimated 2,327 t/yr quota for yttrium for the period 2010 - 2014. There was an additional export tax of 25%. In May 2015, China ended its REE export quotas, removed export tariffs, and began to impose resource taxes on REE based on sales value instead of production quantity (Metal Pages, 2015).

36.2.4 EU supply chain

The separation of yttrium metal was estimated at around 500 t/yr in the EU (Guyonnet et al., 2015) for the 2010-2014 period. Separation was mainly performed in the Solvay plant in La Rochelle.

36.3 Demand

36.3.1 EU consumption

The use of yttrium in the EU represents 8.8% of the total EU use of REEs (Guyonnet, 2015), which gives an estimated 786 t of yttrium consumed in the EU per year (average 2010 – 2014) (Eurostat, 2016; Bio Intelligence Service, 2015).

36.3.2 Applications

Yttrium is used in the EU for lighting and ceramics applications mainly; other uses include the manufacture of glass and alloys:

- Y is the most used REE for the production of luminophores (70%-80%). Y-compounds are doped with other REEs (Eu and Ce mainly) to produce luminophores. Y is used in both fluorescent and LED lamps.
- The major use of Y in ceramics is yttria in Ytrria-Stabilised-Zirconia (YSZ) for refractory uses. Y is also used in electronics for the manufacture of oxygen sensors in vehicles.
- Yttrium oxide is added to the glass used to make camera lenses heat and shock resistant.
- Yttrium is also used as an additive in alloys. It increases the strength of aluminum and magnesium alloys.

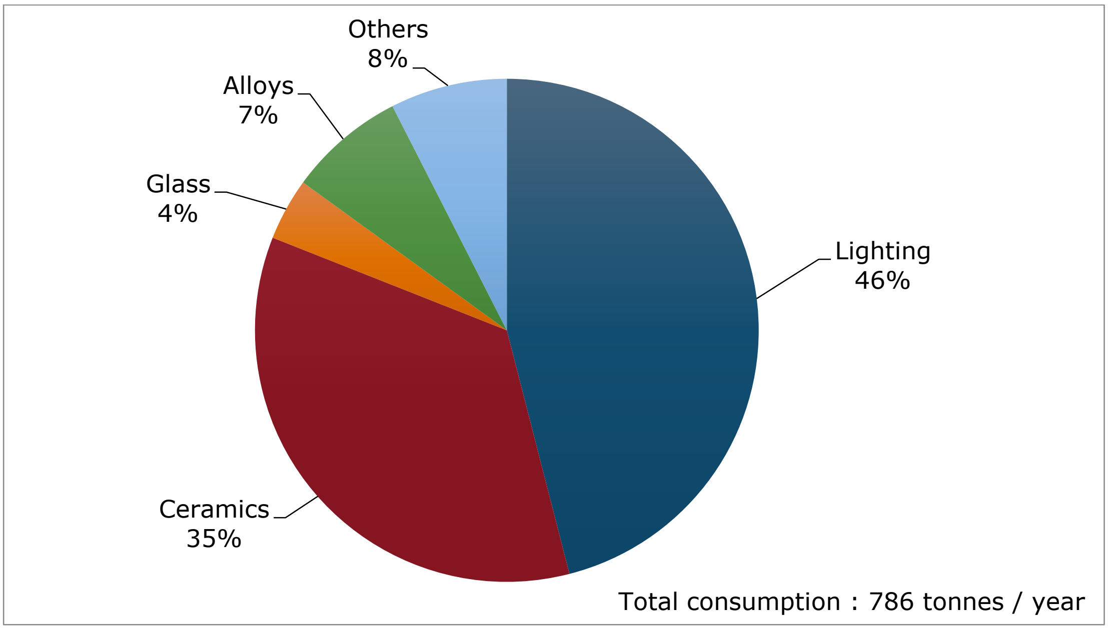

Figure 237: EU end-uses of yttrium. Average figure for 2010-2014 (Guyonnet et al., 2015)

Relevant industry sectors are described using the NACE sector codes in Table 138.

Table 138: Yttrium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2016)

Applications	2-digit NACE sector	Value added of sector (M€)	4-digit NACE sectors
Lighting	C27 - Manufacture of electrical equipment	84,609	C2740 - Manufacture of electric lighting equipment
Ceramics	C23 - Manufacture of other non-metallic mineral products	59,166	C2331 - Manufacture of ceramic tiles and flags
Alloys	C24 - Manufacture of basic metals	57,000	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Glass	C23 - Manufacture of other non-metallic mineral products	59,166	C2310 - Manufacture of glass and glass products

36.3.3 Prices

Prices of yttrium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from 10 $/kg in 2008-2009 to an all-time high of 180 $/kg in July 2011, prices of Y metal went down to reach a relatively stable value of around 20 $/kg in 2014 (BRGM, 2015).

36.4 Substitution

There is no substitute to Y in both fluorescent and LED lamps. No substitutes exist for ceramics application either.

36.5 Discussion of the criticality assessment

The criticality assessment was performed at the extraction stage, which was defined as the step of production of yttrium oxide in mixed rare-earth compounds and metals. This choice was motivated by the lack of data on refined yttrium production and by the high import reliance of the EU economy on mixed rare-earth compounds and metals.

36.5.1 Data sources

Data sources for the estimation of yttrium oxide supply are summed up in Table 139 below. The share of applications in the EU was estimated thanks to data collected during the ASTER project (Guyonnet et al., 2015).

Table 139: Sources of data for the estimation of Y supply

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, 2016 USGS, 2016 Roskill, 2015 BRGM, 2015 Guyonnet et al., 2015	Relative concentration of the individual REE in the total world production of REEs	Bio Intelligence Service, 2015
	EU	Imports to the EU	EUROSTAT, 2016	Share of the individual REE in the total EU use of REEs	Guyonnet et al., 2015

36.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 138). The value added data correspond to 2013 figures.

36.6 Other considerations

36.6.1 Forward look for supply and demand

Supply of rare-earths in general and yttrium in particular is constantly subject to changes. The market of rare-earths is opaque and it is thus very difficult to predict the future evolution of supply (Rare Earth Investment News, 2016). Although China's campaign against illegal mining should take hold and remove some of the volatility in pricing, investments in mining activities are still uncertain – notably following the bankrupcy of Molycorp and the failure of the Mountain Pass project in the USA (The AusIMM Bulletin, 2016).

The demand of yttrium is likely to drop in the future because of the reduction of rare earth needs for the lighting industry (this industry is currently representing 46% of yttrium applications). This reduction is expected to amount to at least 65% between 2015 and 2030 (Guyonnet et al., 2015). This evolution is due to the changes in the lighting market structure and is driven by two forces:

- The content of rare earths (including Y) in LEDs is much lower than in fluorescent lamps (1,000 times lower) (Guyonnet et al., 2015).
- As the lifetime of LED is 40,000-50,000 hours, compared to 10,000-25,000 hours for fluorescent lamps, the decrease in rare earth need for the lighting sector will amplify in the coming years (Guyonnet et al., 2015).

Table 140: Qualitative forecast of supply and demand of yttrium

Material	Demand forecast			Supply forecast		
	5 years	10 years	20 years	5 years	10 years	20 years
Yttrium	-	?	?	-	?	?

36.7 Data sources

36.7.1 Data sources used in the factsheet

BGS (2016). European mineral production 2010-2014.

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36.8 Acknowledgments

This Factsheet was prepared by Deloitte and BRGM. The authors would like to thank the EC Ad Hoc Working Group on Critical Raw Materials for their contributions to the preparation of this Factsheet, as well as the industrial experts from Tasman Metals and Less Common Metals.

37. SCANDIUM

Key facts and figures

Material name and Element symbol	Scandium, Sc	World / EU production (tonnes Sc_2O_3)[1]	Refining : 15 / 0
Parent group (where applicable)	N/A	EU import reliance[1]	100%
Life cycle stage/material assessed	Processing/Sc oxide (Sc_2O_3)	Substitution index for supply risk [SI (SR)]	0.95
Economic importance (EI) (2017)	3.7	Substitution Index for economic importance [SI(EI)]	0.91
Supply risk (SR) (2017)	2.9	End of life recycling input rate (EOL-RIR)	0%
Abiotic or biotic	Abiotic	Major end uses[1]	Solid Oxide Fuel Cells (90%), Sc-Al alloys (9%)
Main product, co-product or by-product	By-product of REEs, U, Ti	Major world producers[1] (refining)	China (66%), Russia (26%), Ukraine (7%)
Criticality results	2011	2014	2017
	Critical	Non critical	Critical

[1] average for 2010-2014, unless otherwise stated;

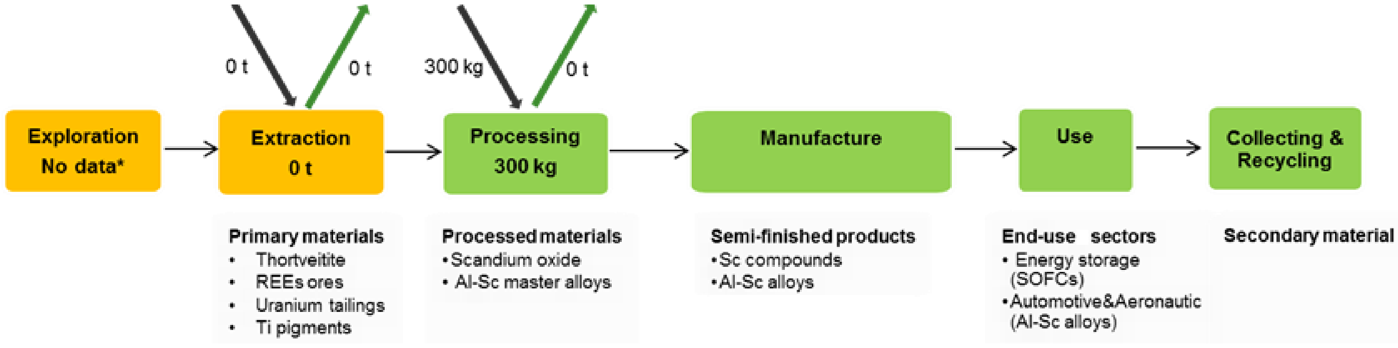

Figure 238: Simplified value chain for scandium

The orange boxes in the figure above suggest that there is no production in the EU at this step; green boxes indicate activities that are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. *There are no sufficient data to evaluate EU reserves of scandium.

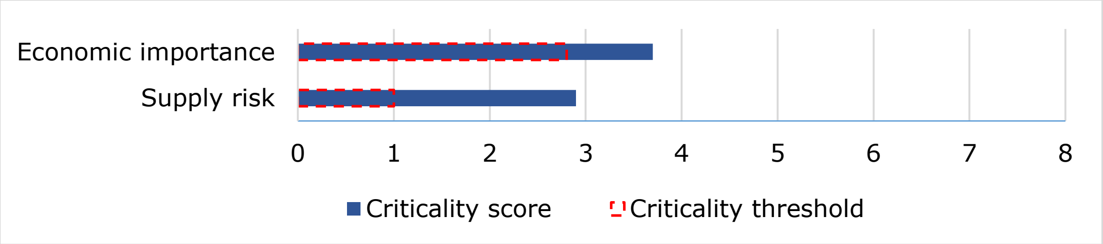

Figure 239: Economic importance and supply risk scores for scandium

37.1 Introduction

Scandium (chemical symbol Sc, from the Latin 'Scandia' for Scandinavia where it was historically discovered) is a silvery-white light transition metal. Its main properties are its light weight (density of 2.99 g/cm^3, close to the one of aluminium), high melting point (1,541°C) and small ionic radius. Scandium is not particularly rare; its abundance in the upper continental crust is 14 ppm (Rudnick, 2003). However, due to the small size of its ions, it does not selectively combine with the common ore-forming anions, and rarely forms concentrations higher than 100 ppm in nature. It shares similar characteristics with Rare Earth Elements (REEs) but has quite specific geological and industrial properties which justify a distinct classification.

Scandium exhibits characteristics of an immature and undeveloped commodity market, namely very few supply and uncertain resulting demand. In spite of this, it could show potential for two main end-uses, notably in Europe: Solid Oxide Fuel Cells for energy storage and Sc-Al alloys in aerospace and automotive sectors. There is currently no production in the EU and only few players along the value chain.

37.2 Supply

37.2.1 Supply from primary materials

37.2.1.1 Mineralogical occurrence

In the continental crust, scandium is essentially a trace constituent of igneous rocks ferromagnesian minerals. Scandium concentrations in these minerals (amphibole-hornblende, pyroxene, and biotite) are typically in the range of 5 to 100 ppm equivalent Sc_2O_3. Genetic types of scandium deposits are difficult to classify (Borisenko, 1989) because this element is widely dispersed in the lithosphere and forms solid solutions in over 100 minerals such as rare-earth minerals, wolframite-columbite, cassiterite, beryl, garnet, muscovite, and the aluminum phosphate minerals. Scandium is also often associated with the elements fluorine and titanium in magmatic and sedimentary processes and can be found in numerous types of deposits (Hocquard, 2003). In the past, some scandium production has been generated from the scandium-yttrium silicate mineral, thortveitite (Crystal Mountain, USA). Some current exploration projects notably in Australia focus on nickel and cobalt lateritic deposits with high scandium concentrations (Duyvesteyn, 2014).

Scandium is also concentrated during the processing of various ores, specifically U, Th, Al, W, Sn, Ta, Ti and REE's, which are currently the main sources of supply.

37.2.1.2 Processing and refining

Pyrometallurgical processes are suitable for recovery of scandium from primary sources (thortveitite). This route is energy intensive and rare.

Hydrometallurgical processes are more widely used for scandium recovery from secondary sources (slags, residues, tailings and waste liquors of various metals). They mainly involve leaching, solvent extraction, precipitation and calcination methods (Wang et al., 2011). Most of the time, the first step is the precipitation of insoluble scandium compounds from scandium-containing solutions. The complexities of flowsheets to recover scandium depend on the amounts and types of impurities that can co-precipitate at this stage. Scandium oxide (Sc_2O_3) is then obtained by thermal decomposition of the precipitate. After purification, Sc_2O_3 is fluorinated to obtain an intermediate compound ScF_3 (scandium fluoride). Sc metal is produced by reducing ScF_3 with calcium metal or by aluminothermic reduction. Aluminothermic reduction has the advantage of obtaining the Al-Sc alloy directly (Blazy, 2013).

In recent years, the most single important source of secondary production comes from REE and iron ore processing in Bayan Obo (China). In this case, REEs and scandium are extracted into solutions by roasting the ore in concentrated sulphuric acid at 250–300 °C and then leaching with water (Li et al., 2004).

37.2.1.3 Scandium resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of scandium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[25], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for scandium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for scandium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for scandium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

According to USGS (USGS, 2017), world resources of scandium are abundant. There are identified scandium resources in Australia, Canada, China, Kazakhstan, Madagascar, Norway, the Philippines, Russia, Ukraine, and the United States.

The global reserves of scandium are not available.

The Minerals4EU website does not display data about resources and reserves of scandium alone for Europe, but combined with REE data.

37.2.1.4 World scandium production

World mine production of scandium (average of 2010-2014) was around 15 tonnes, in the form of scandium oxide (Sc_2O_3). The repartition is presented in Figure 240.

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[25] www.crirsco.com

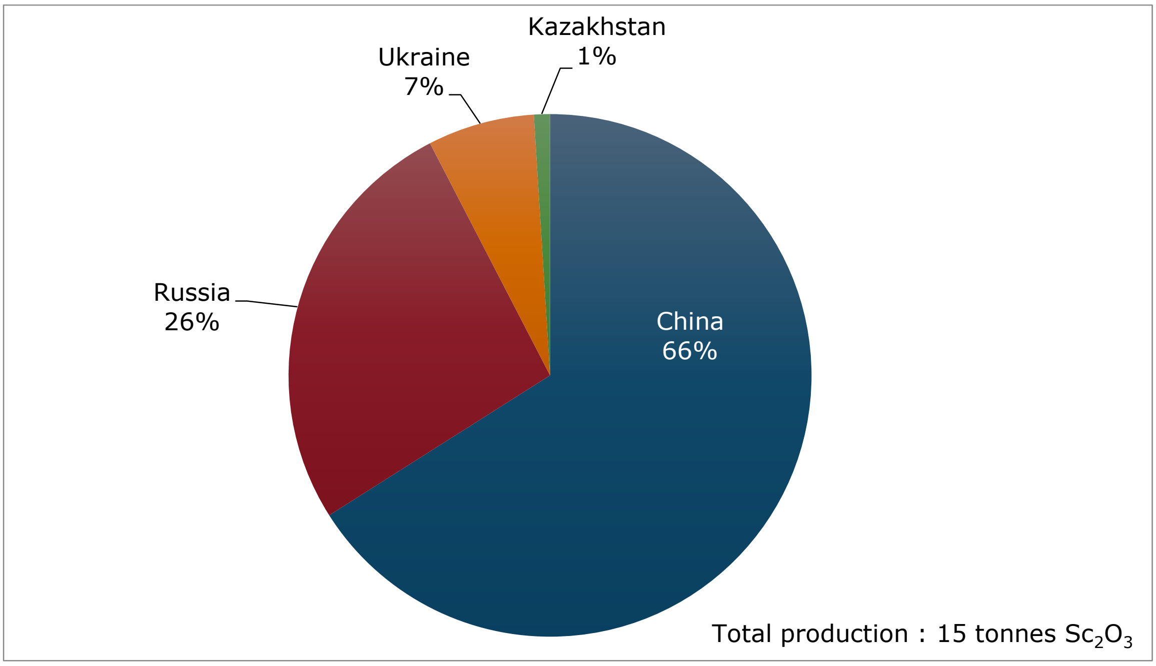

Figure 240: Global mine production of scandium oxide, average 2010–2014 (Lipmann, 2016)

Various independent authors quote global market volumes of 2-10 tonnes per year. The estimate number of 15 tonnes (Lipmann, 2016) is confirmed by EMC Metals Corporation (Duyvesteyn, 2014) based on discussions with their potential customers, the level of metals trader activity and interest, and the fact that certain scandium consumers are believed to be sourcing their own scandium through small controlled recovery operations.

Chinese production would amount to 10 tonnes per year of Sc_2O_3 (66%), mainly as a by-product of REEs extraction (Bayan Obo mine), but also from recovery of sulphate wastes from the manufacture of titanium pigments. Russia produces between 3 and 5 tonnes per year (33%), mainly from uranium mill tailings (Intermix Met, 2016). Kazakhstan is estimated to produce 100-200 kg of scandium oxide annually (1%), also from uranium mill tailings (Lipmann, 2016). Small stockpiles of this material may exist in Russia, Ukraine and Kazakhstan.

37.2.2 Supply from secondary materials

Due to its limited uses, no recycling circuit is known for scandium in end-of-life products nor at the stage of 'new scrap' (UNEP, 2013).

37.2.3 EU trade and supply chain

There is no extraction of scandium in the EU. EU import reliance for scandium is 100%. However data from EUROSTAT Comext database do not allow evaluating imports quantities, as CN8 customs codes referring to scandium (28053010, 28053090, 28469000) mix various products with scandium being the least. Therefore, scandium imports to the EU were estimated based on expert consultation (Lipmann, 2016). Over the 2010-2014 period, an average of 200 kg would have come from Russia (67%) and 100 kg from Kazakhstan (33%), mainly in the form of scandium oxide.

Not much is known about scandium transformation in the EU. At present, it is still commercialized at a very modest level, focusing more attention at the R&D level, both for uses in alloys and Solid Oxide Fuel Cells. The EU-based company Airbus developed the Scalmalloy^{TM} alloy family since 2012, with registration of the patent in 2014 (Airbus, 2016). But only one company is known to offer patented Scalmalloy™ alloys for sale; RSP Technology in Netherlands (www.rsp-technology.com).

In terms of trade restrictions, Chinese export quotas on REEs also applied to scandium and were lifted in 2015, replaced by resources taxes based on sales value (Metal Pages, 2015).

37.3 Demand

37.3.1 EU consumption

No reliable data exist on scandium consumption in the EU. It is likely that most of the imported quantities (a few hundred tonnes) are currently used either in R&D projects or in small markets (Sc-Al alloys, SOFCs) or minor other applications, such as high-quality sports equipment (cf. 3.2).

37.3.2 Applications/end uses

According to Lipmann Walton & Co (Lipmann, 2016), the lion's share (90%) of total annual production in recent years would be absorbed by use in Solid Oxide Fuel Cells (SOFCs) as shown in the Figure 241.

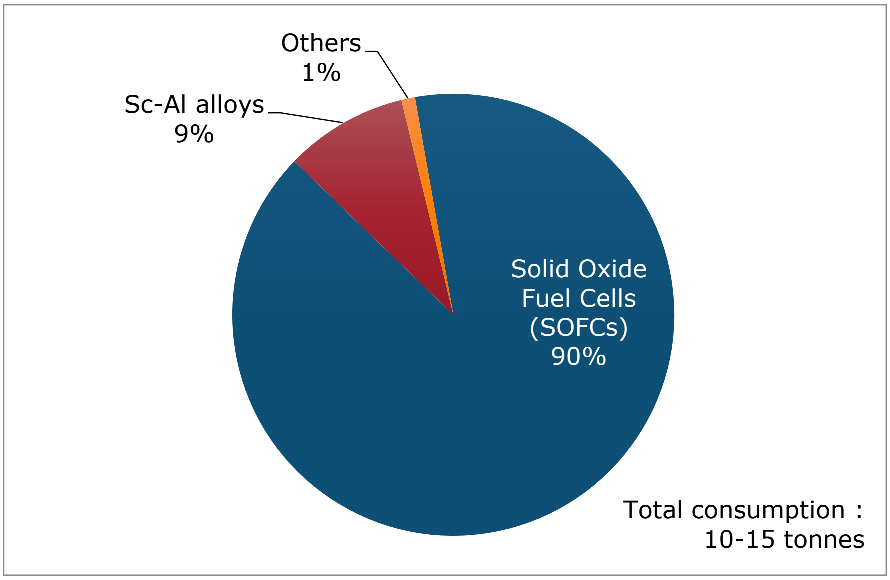

Figure 241: Global end uses of scandium. Average estimates for 2010-2014 (Data from Lipmann, 2016)

In general terms, a fuel cell is an electrochemical cell that converts a fuel source and an oxygen source into an electrical current, plus water, CO_2 and heat. It does this by promoting reactions between the fuel and oxidant (reactants), which are triggered by a very high temperature environment (1,000°C). There are a number of types of fuel cells, but SOFC design appears to be the current leader.

There are over 100 companies designing SOFC's today. However, the technical leader in commercial SOFC technology is Bloom Energy, a private company headquartered in Sunnyvale, California (Bloom Energy, 2016). It is seen as a promising alternative electrical power supply, notably for automotive transportation.

The central part of a SOFC is a solid electrolyte generally composed of zirconia. However, zirconia would never withstand high operating temperatures without being stabilized with a metal. The stabilizing and conducting metal of choice for the electrolyte has traditionally been yttrium. Its advantages are its relative abundance (global production of around 8,000-10,000 tonnes) and low price (at around 40-60$US/kg, 100 times lower than Sc oxide). But, since the price spike on REEs and yttrium in 2011, scandium was given more attention to be the stabilizing agent for zirconia. Although playing the same role; it lowers the operating temperature of the cell and increases its lifespan and efficiency by improving the power density, scandium proved to be a considerably better ionic electrical conductor than yttrium and more importantly, scandium allows the electrolyte to conduct at significantly lower temperatures (750-800°C) so that the cost, efficiency and lifespan of materials for thermal shielding can be reduced (Duyvesteyn, 2014). Barriers for expansion of scandium in this market remain price and availability of this element.

The second most important use is as an alloying element with aluminium. Aluminium-scandium (and magnesium) alloys are ones of the lightest alloys known and could help increasing fuel efficiency in aerospace and automotive transportation. Small additions of scandium have the most promising effect on aluminum alloys, for it allows obtaining materials with significantly improved set of properties. Scandium refines the crystal structure of aluminium to the point where the alloyed metal can be welded without loss in strength. It also increases plasticity in the moulding of complex shapes, improves corrosion resistance, and increases thermal conductivity. Extension to structural material for aerospace engineering could develop in the future. In 2014, Airbus patented and developed Scalmalloy^{TM}, a specific Sc-Mg-Al alloy family for use in aerospace (Airbus, 2016). However, Al-Sc alloys' are still extremely expensive, and the main market at present is mostly high-quality sports equipment (bikes, baseball bats, etc.).

Other minor uses of scandium (in the form of metal or oxide) include Ti-Sc carbides, GSGG laser, mercury vapor high-intensity light, tracing agent in oil refining or dopant in special glasses, glazes, and ceramic products (Gambogi, 2016). Scandium is also used for the manufacture of ferrites with low induction for computer memory elements (Intermix Met, 2016).

Relevant industry sectors are described using the NACE sector codes in Table 141.

Table 141: Scandium applications, 2-digit NACE sectors and associated 4-digit NACE sectors, and added value [Data from the Eurostat database, (Eurostat, 2016)]

Applications	2-digit NACE sector	Value added of sector (millions €)	4-digit NACE sectors
Solid Oxide Fuel Cells	C27 - Manufacture of electrical equipment	84,609	C2790 - Manufacture of other electrical equipment
Sc-Al alloys	C25 - Manufacture of fabricated metal products, except machinery and equipment	159,513	C2511 - Manufacture of metal structures and parts of structures

37.3.3 Prices and markets

Scandium is not traded on any metals exchange, and there are no terminal or futures markets where buyers and sellers can fix an official price. Scandium products are sold between private parties at undisclosed prices. A way to estimate Sc metal or oxide prices is to simulate a purchase to specialized suppliers. It is how USGS publishes some prices for Sc products, based on consultation of a specialist supplier (Stanford Materials Corp.). Depending on the products, prices for 2011-2015 period were of the following ranges (Gambogi, 2016):

- scandium oxide at 99.99% grade : 4,700 – 5,400 US$/kg, when in 2010 it was 1,620 US$/kg
- aluminum-scandium master alloy (2% scandium): 155-220 US$/kg,

Those prices remain much too high to enable widespread commercial adoption of scandium, in alloy applications in particular.

37.4 Substitution

In most of its applications, the use of scandium is a way to innovate and enhance performances and properties of already existing end-products. Therefore, this material could be considered as a substitute itself and alternatives exist for almost all of its uses. The choice is either driven by performance, price, or availability.

In high-performance alloys, substitutes for scandium could be titanium, lithium (especially for aluminium alloys) or carbon fibre materials. They achieve comparable results in terms of resistance and low weight for aerospace and automotive structures.

In SOFCs, yttrium and scandium can be used alternatively because they play the same role in stabilizing the zirconia-based electrolyte. The use of one or the other also depends on performance, price, or availability criteria and can evolve in time.

37.5 Discussion of the criticality assessment

37.5.1 Data sources

Criticality assessment was performed at the stage of processing based on data availability (no global information at the extraction level) and the fact that it was judged as the main bottleneck for EU. Market shares, production data and trade data were in great part based on expert consultation (Lipmann, 2016). Data on trade agreements are taken from the DG Trade webpages, which include information on trade agreements between the EU and other countries (European Commission, 2016). Information on export restrictions are derived from the OECD Export restrictions on the Industrial Raw Materials database (OECD, 2016).

37.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 141). The value added data correspond to 2013 figures. The supply risk was assessed on scandium oxide using the global HHI only as prescribed in the revised methodology.

37.5.3 Comparison with previous EU criticality assessments

Economic Importance (EI) score for scandium is slightly lower than in the previous assessments and Supply Risk (SR) score is higher. Part of the explanation comes from the change in methodology. To evaluate EI, the value added in the 2017 assessment corresponds to a 2-digit NACE sector rather than a ‘megasector’, which was used in the previous assessments. The way SR is calculated in the new methodology takes into account new parameters such as the concentration of global production, the diversity of EU supply sources, and geopolitical risks. It explains why the SR score is higher than in the previous assessments, due to the dominance of China on global production. This scores are over the criticality thresholds, therefore scandium is considered a critical raw material for the EU in 2017, which is partly justified from a strategic point of view (R&D

development in the automotive and aerospace sector), even though its uses remain anecdotic.

Table 142: Economic importance and supply risk results for scandium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Scandium	5.8	4.9		3.8	1.1		3.7	2.9

37.6 Other considerations

37.6.1 Forward look for supply and demand

As said before, scandium exhibits typical characteristics and challenges of an immature and undeveloped commodity market, meaning that lack of demand suppresses supply and non-existent supply reciprocally inhibits possible future demand.

On the demand side, the main potential driver would be a growth in the use of Sc-Al alloys in aerospace and automotive applications. A landmark was achieved by the EU-based company Airbus which developed Scalmalloy^{TM} alloy family since 2012, with registration of the patent in 2014. But some analysts judge that current prices for scandium remain much too high to enable widespread commercial adoption (yet) and others materials compete directly (Al-Li alloy family). The same reasoning applies for development of the SOFCs market.

On the supply side, much work is underway to study the potential for new multiple and reliable supply sources of Sc. Various players and countries have launched research on the recovery of scandium, notably from red mud caustic wastes (notably in Russia, with the support of the major aluminium producer UC Rusal, as well as in Quebec, Canada). Other research projects are active in Japan, the Philippines, Kazakhstan, or Ukraine on Sc recovery from uranium tailings, sulphate titanium wastes, or nickel-laterites (Gambogi, 2016). What will come up of those projects remains to be seen but should be closely followed.

In terms of exploration, various projects are worth mentioning:

Three projects in Australia:

- Clean TeQ, Syerston scandium project near Condoblin in central New South Wales;
- Nyngan project, with definitive feasibility and economic assessment near completion, also in New Souh Wales;
- Sconi project, in northern Queensland;

In the United States, developers of multimetallic deposits, including the Round Top project in Texas and the Elk Creek project in Nebraska, were examining the incorporation of scandium recovery into project plans (Gambogi, 2016).

Table 143: Qualitative forecast of supply and demand ofscandium

Material	Criticality of the material in 2017		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Scandium	x		?	?	?	?	?	?

37.6.2 Environmental and regulatory issues

None is known for scandium.

37.7 Data sources

37.7.1 Data sources used in the factsheet

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37.8 Acknowledgments

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38. SILICON METAL

Key facts and figures

Material name and Element symbol	Silicon metal, Si	World/EU production (thousand tonnes)[1]	2,288 / 195
Parent group (where applicable)	N/A	EU import reliance[1]	64%
Life cycle stage/ material assessed	Processing stage/ Refined material	Substitution index for supply risk [SI(SR)]1	0.99
Economic importance (EI) (2017)	3.8	Substitution Index for economic importance [SI(EI)][1]	0.99
Supply risk (SR) (2017)	1.0	End of life recycling input rate (EOL-RIR)	0%
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Chemical applications (54%), Aluminium alloys (38%), Solar and electronics (8%)
Main product, co-product or by-product	Main product	Major world producers[1]	China (61%), Brazil (9%), Norway (7%), US (6%)
Criticality results	2011	2014	2017
	Not assessed	critical	critical

[1] average for 2010-2014, unless otherwise stated

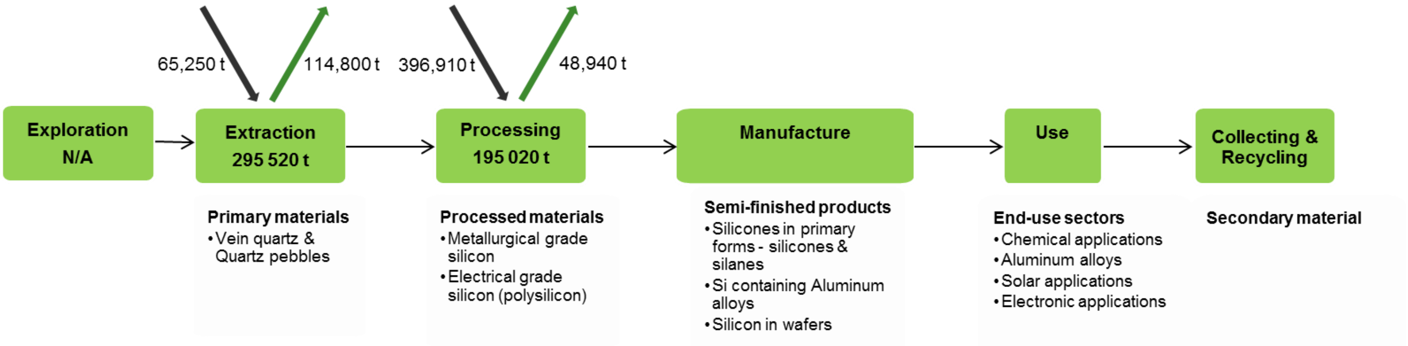

Figure 242: Simplified value chain for silicon metal

The green boxes of the production and processing stages in the figure above suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. Recycling of silicon metal is not significant in the EU. EU reserves are displayed in the exploration box.

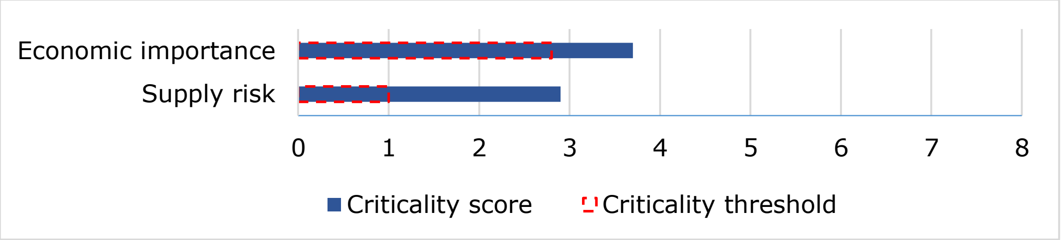

Figure 243: Economic importance and supply risk scores for silicon metal

38.1 Introduction

Silicon metal (symbol Si) is the second most abundant element in the Earth's crust in the form of silicate minerals (27.5%, after oxygen). It is an inert element extracted from vein quartz and quartz pebbles due to their high silica content. Silicon has no metallic properties but is known as silicon metal in the industry because of its lustrous appearance.

Two grades of silicon metal exist: metallurgical grade silicon (typically around 99%), representing the majority of the volumes produced, and polysilicon (with a 6N to 11N purity). The major uses of metallurgical grade silicon are in metallurgy and for the production of silicones and silanes in the chemical industry. The two sectors represent more than 90% of the total world and European silicon metal consumption. In metallurgy, silicon is used as an alloying element for aluminium alloys for casting and extrusion. The chemical compounds are incorporated in a large variety of end-user applications, such as shampoos, fixing materials or insulating material for cables. Metallurgical grade silicon is also used to produce a number of highly specialized silicon containing products for numerous applications. Polysilicon is used as a semiconductor in photovoltaic applications or in microelectronics (European Commission, 2014; Euroalliages, 2016).

Silicon metal production in the EU-28 accounts for 9% of the global production (BGS, 2016). The EU apparent consumption of silicon metal represents more around a quarter of the consumption worldwide. The silicon metal industry in the EU is concentrated in a few Member States.

38.2 Supply

38.2.1 Supply from primary materials

38.2.1.1 Geological occurrence

Quartz makes up approximately 12% by weight of the lithosphere, making it the second most common mineral in the Earth's crust. SiO_2 accounts for 66.62% of the mass of the upper crust (Rudnick, 2003). Quartz is found in magmatic, metamorphic and sedimentary rocks –– and may be distinguished between numerous quartz types, depending on its genesis and specific properties.

Quartz occurs in many different settings throughout the geological record; however, only very few deposits are suitable in volume, quality and amenability to tailored refining methods for speciality high purity applications, which require extreme qualities, with specific low-ppm or sub-ppm requirements for maximum concentrations of certain trace metals (European Commission, 2014).

Magmatic SiO_2 rocks represent more than 90% of quartz and other SiO_2 minerals of the lithosphere, however this share is not representative of the materials used to process silicon metal. The majority of quartz in SiO_2-rich igneous and volcanic rocks (granite, rhyolite) is intergrown with other rock-forming silicates. Therefore, quartz from these rocks does not play an important role as raw material. In contrast, pegmatite bodies and hydrothermal veins may provide large amounts of high-purity quartz. Such deposits can reach dimensions of several tenths or hundreds of meters and with extremely low concentrations of impurities. This material is preferentially used as raw material for the hydrothermal quartz synthesis (Haus, 2012).

Quartz from metamorphic rocks represents only about 3% of the whole quartz in the lithosphere (Rösler, 1981) and are not usable as high-quality SiO_2 raw material.

However, metamorphic quartzites of high chemical purity (98% SiO_2) can sometimes be used as raw materials for high-technology industries. Moreover, metamorphogenic quartz mobilisates often represent a high-purity SiO_2 material that can be used e.g. as raw material for single-crystal growth (Haus, 2012).

Finally, sedimentary SiO_2 rocks represent the majority of the high-purity quartz volumes supplied to the industry worldwide. However quartz in sedimentary rocks (mostly under the form of quartz sands, quartz gravel or sedimentary quartzite) is used in silica sands or ferrosilicon value chains, but its purity does not rank high enough for any use as silicon metal (Haus, 2012).

38.2.1.2 Mining of high purity quartz and processing of silicon metal

Quartz extraction occurs by drilling and blasting operations from veins deposits (vein quartz) as well as from fluvial deposits (quartz pebbles), by simple excavation methods. The major deposits of high purity quartz currently mined for silicon metal processing are located in Turkey, Egypt and Spain, among others (Euroalliages, 2016). Others include the USA, Norway and Russia. High purity quartz for the silicon metal industry is extracted as main product; most of the quartz processed in the EU into silicon originates from European countries, namely Spain and France (BGS, 2016). There is no reliable worldwide data.

Once mined, quartz is reduced to silicon metal by carbothermic reduction. This takes place in a submerged electric arc furnace containing quartz and carbon materials, such as coke and charcoal. Electric energy is supplied by electrodes submerged in the charge – with temperatures from 800 to 1,300°C at the top of the furnace, and exceeding 2,000°C at the bottom, near the electrodes (Aasly, 2008). Molten silicon metal is produced at the bottom of the furnace. The silicon produced has a purity of approximately 98.5%; the main impurities are iron, aluminium and calcium. Most silicon applications require further refining to reach 99% purity; this is done by treating the molten silica with oxidative gas and slag forming additives. Silicon of this purity is known as metallurgical grade silicon and is used in the aluminium, chemical and polysilicon industries. Semiconductor and solar grade silicon (polysilicon) must be of ultra-high purity (between 6N and 11N) to ensure semiconducting properties; this is commonly done through the Siemens process (European Commission, 2014). In this process, the metallurgical grade silicon is converted to a volatile compound that is condensed and refined by fractional distillation. Ultra-pure silicon is then extracted from this refined product.

The quartz raw material follows specific requirements from the industry to be used in silicon metal processing, among which: chemistry (specifications on impurities), lump size; as well as mechanical and thermal strength, and softening properties. These characteristics may influence the process itself or the purity of the silicon metal processed (Aasly, 2008).

The processing of silicon also generates silica fumes which have been successfully transformed by the silicon (and ferro-silicon) industry from waste to a by-product.

38.2.1.3 High purity quartz resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of silicon metal in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by

application of the CRIRSCO template[26], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for silicon metal. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for silicon metal, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for silicon metal at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

Available information on high purity quartz from the Minerals4EU platform is available in the silica sands factsheet, but is not displayed here as only a small – and unknown – share or it is part of the silicon metal value chain.

It is acknowledged that reserves of high purity quartz are large enough to meet the worldwide consumption needs for the next decades.

38.2.1.4 World production of processed silicon metal

World refined production of silicon metal is summarised in Figure 244, and totals 2,288,000 tonnes (average 2010-2014). Global supply of silicon metal is dominated by China with about 61% of the total refined production, equivalent to 1,400,000 tonnes (average 2010-2014). Brazil and Norway are the second and third largest producing countries accounting for 9% (217,000 tonnes; average over 2010-2014) and 8% (158,000 tonnes; average over 2010-2014) respectively of worldwide silicon metal production. In 2014, global capacity of silicon metal production was 5.1 million tonnes, with China representing 75% of it (Metal Bulletin, 2015).

Production has jumped from 566,000 tonnes in 1980 to 2,403,500 tonnes in 2014. This growth is attributed to the industrial expansion of China (in particular in Xinjiang province) which is clearly documented from year 2000 onwards with a steep increase in production of silicon metal. The top 10 companies in China represent more than half of the national silicon metal production in 2014 (CRU, 2016a). New silicon projects are being implemented: for instance in 2016, the silicon metal production capacity of Xinjiang province increased by 1.8 million tonnes. The overcapacity built in China in the past decades is alone equivalent to twice the current world demand.

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[26] www.crirsco.com

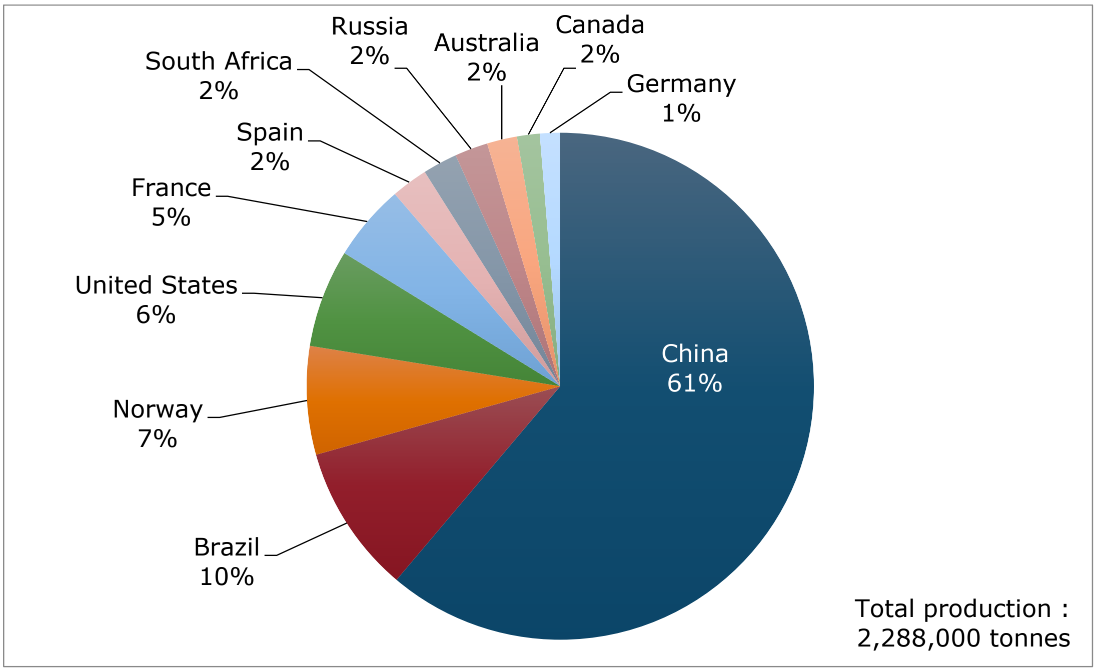

Figure 244: Global refined production of silicon metal, average 2010–2014 (Data from BGS, 2016)

38.2.2 Supply from secondary materials

Silicon metal is not currently recovered from post-consumer waste. Most chemical applications are dispersive, thus not allowing for any recovery. There is research on recycling of silicon wafers, however it has not yet materialised in marketable solutions (Euroalliages, 2016). There is no functional recycling of silicon metal in aluminium alloys.

In the industry buying metallurgical grade silicon, for economic and environmental reasons, recycling streams exist as well as separate or specialised processes for utilisation of any side streams. However, very little material is sold back into the market by metallurgical silicon users (Euroalliages, 2016).

Silicon metal used in the electronic industry is of higher quality than for other applications. Most of the silicon scrap generated during crystal ingot and wafer production for electronic applications can therefore be used in the photovoltaic industry (Woditsch and Koch, 2002).

38.2.3 EU trade

Europe is a net importer of silicon metal with an average annual net import figure in the period 2010-2014 of 344,000 tonnes (Figure 245). About 73% of the EU consumption of silicon metal is imported from non EU countries (Comext, 2016a). The main suppliers of the EU are Norway, Brazil and China, which represent respectively 35%, 18% and 18% of the total imports to the EU – although these shares are evolving along the years (Figure 246).

Imports of silicon metal to the EU increased regularly in the past two decades, with a 3% annual rise between 2000 and 2015 – mainly imported from China, where the production followed a steep increase. However in 2015 and 2016 a 2% decrease was observed. The large majority of imports are of lower purity than 4N silicon ('silicon containing < 99.99% by weight of silicon') – 98% of total imports on average over 2010-2014; the rest is polysilicon ('silicon containing >= 99.99% by weight of silicon', i.e. usually < 6N).

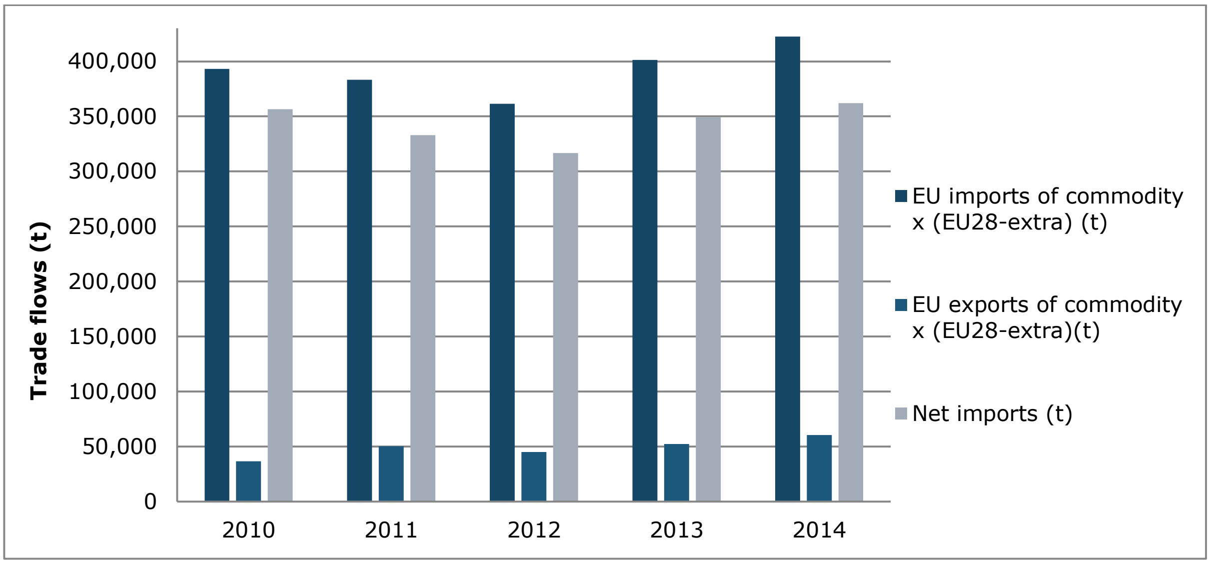

Figure 245: EU trade flows for silicon metal. (Data from Eurostat, 2016a)

Exports of silicon metal from the EU are estimated at 62,000 tonnes in 2015, which is 30 times the exports of 2000. The majority of exports (80% of total exports from EU on average over 2010-2014) are polysilicon: the silicon wafer industry is present in the EU, however part of it is exported since the relocation of industry using silicon wafer, for instance by producers of silicon solar cells in Asia (Bio Intelligence Service, 2015).

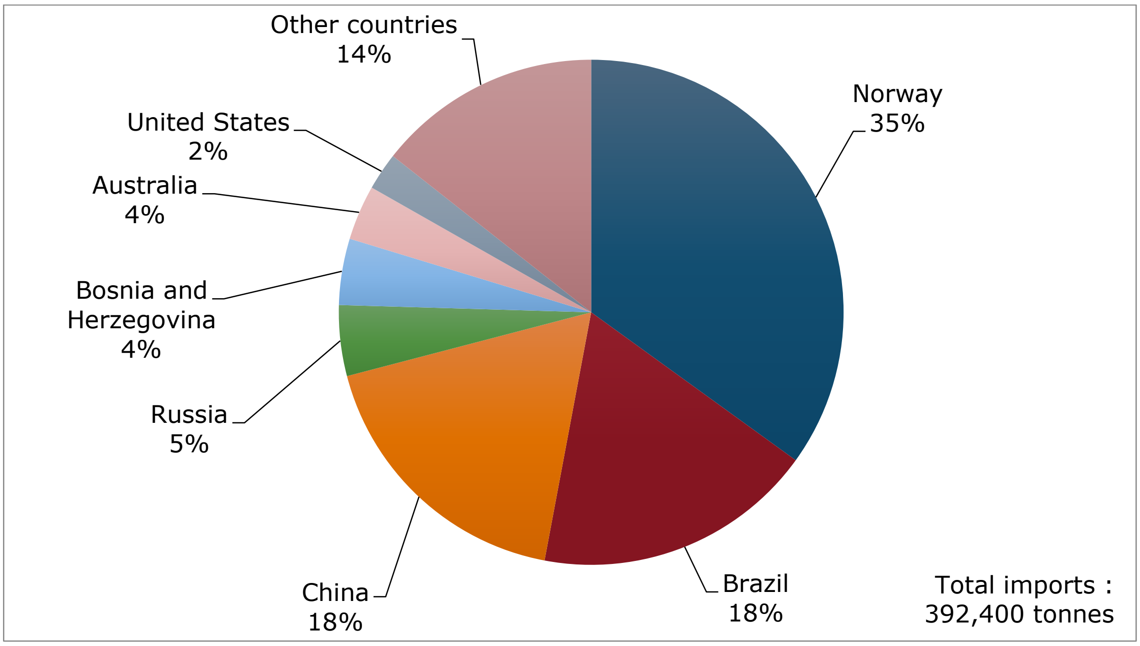

Figure 246: EU imports of silicon metal from extra-EU28 countries, average 2010-2014. (Data from Eurostat Comext, 2016a)

In addition to silicon metal, Europe is also a net importer of intermediate products containing silicon, such as silicon doped for the use in electronics, with 400 tonnes in 2015 (Comext, 2016a).

38.2.4 EU supply chain

The Figure 245 shows the EU sourcing (domestic production + imports) for silicon metal.

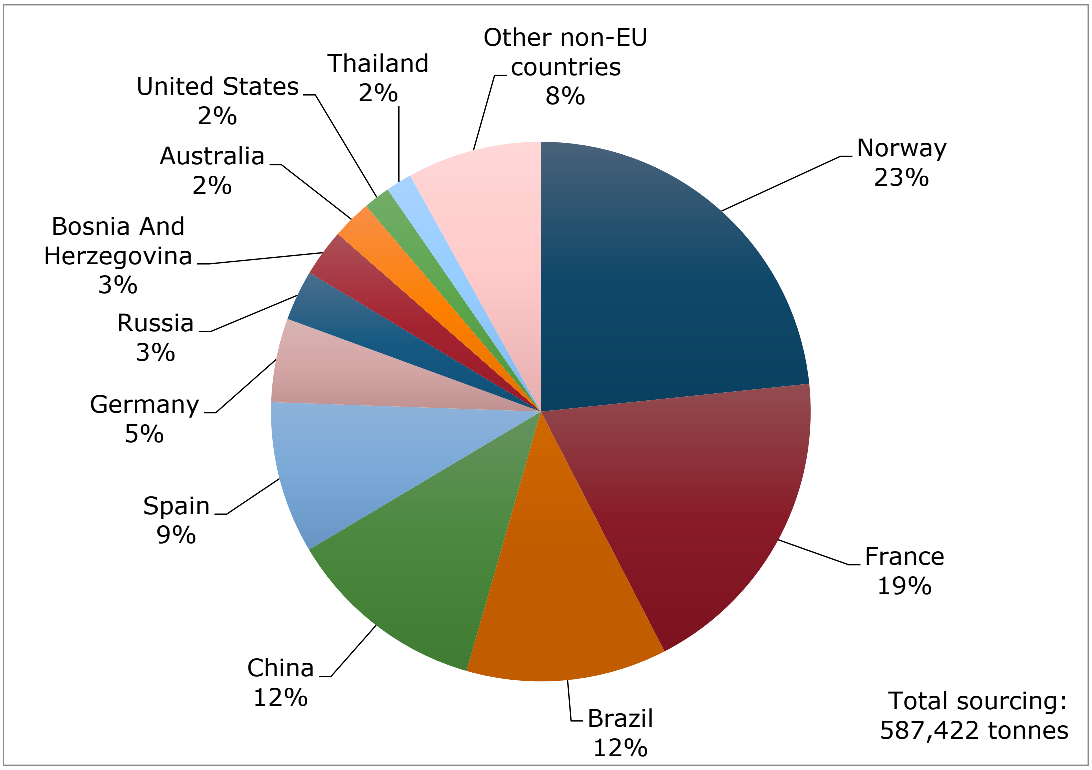

Figure 247: EU sourcing (domestic production + imports) of silicon metal, average 2010-2014. (Eurostat, 2016a; BGS, 2016)

The EU supply chain of silicon metal can be described by the following key points:

- High purity quartz is extracted in three EU Member States and processed into silicon metal – namely France, Spain and Germany. There is no precise data on high purity quartz extraction, at EU level or at global level. The majority of high purity quartz is directly turned into silicon metal onsite (Bio Intelligence Service, 2015).
- The 5 year average European production of silicon metal between 2010 and 2014 was 195,000 tonnes per year, which accounts for less than 10% of the global production. Producing EU countries are France, Spain and Germany (BGS, 2016).
- The traded quantities of silicon metal show that Europe is a net importer of silicon metal. Domestic production of silicon cannot satisfy the European demand. Norway is the main country supplying silicon metal to the EU due to its geographical proximity, and accounts for 35% of total imports (Eurostat, 2016a).
- Europe imports silicon in the forms of silicon metal as well as intermediate products such as silicon based chemicals and silicon wafers. The EU is a net importer of silicon metal and silicon wafers. The net import figure from extra-EU28 countries was 344,000 tonnes on average over 2010-2014 (Eurostat, 2016a).
- The import reliance for silicon metal in Europe is estimated at 64%, which is not an unexpected figure considering the relatively small EU production, high import and low exports figures.
- There is no restriction on commercial trade of silicon metal (i.e. no export tax, export quota or export prohibition of silicon metal from extra-EU countries) with the EU Member States. However China applied a 15% export tax on all exports of silicon metal, reestablishing de facto some level playing field with the EU according to several industrial players, which was removed in 2013 (OECD, 2016; Euroalliages, 2016).

- Some free trade agreements exist with major EU suppliers: Norway and Bosnia Herzegovina (European Commission, 2016).
- There is no current recycling of silicon metal from end of life products (Bio Intelligence Service, 2015; Euroalliages, 2016).

38.3 Demand

38.3.1 EU demand and consumption

The European consumption of silicon metal totalled around 566,000 tonnes in 2010 and approximately 540,000 tonnes in 2012 (European Commission, 2014). On average between 2010 and 2014, the consumption of silicon metal in Europe is estimated at 538,000 tonnes (BGS, 2016; Comext, 2016a; Comext, 2016b), i.e. around a quarter of the world's 2.2 million tonnes consumption (European Commission, 2014).

38.3.2 Uses and end-uses of silicon metal in the EU

The major uses by tonnage of silicon in the EU are in the aluminium and chemical industries (European Commission, 2014). In addition, silicon metal is a strategic raw material used in the renewable energy (photovoltaic industry) and in electronic devices. See Figure 102.

- Chemical industry: Silicon metal is used to produce silicones, synthetic silica and silanes. Silicone products such as surfactants, lubricant, sealants and adhesives are used in various sectors including construction (e.g. in insulating rubbers), industrial processes (e.g. as antifoam agent in the oil and gas industry), as well as personal care (e.g. cosmetics) and transport (CES, 2016). Silanes are used in the glass, ceramic, foundry and painting industries (European Commission, 2014; Euroalliages, 2016).
- Aluminium alloys: Silicon is dissolved in molten aluminium to improve the viscosity of the liquid aluminium and to improve the mechanical properties of aluminium alloys. There are two important groups of aluminium alloys which contain silicon as a main element: casting alloys and wrought alloys. In the former the silicon content is 7% to 12%; wrought alloys contain magnesium and silicon, where the silicon content is between 0.5% and 1%. The primary use is in castings in the automotive industry due to improved casting characteristics described above and the reduced weight of the components (European Commission, 2014; Euroalliages, 2016).
- Solar cells: Ultrahigh-purity grades silicon is used for the production of solar panels. Silicon solar cells are the most common cells used in commercially available solar panels. Crystalline silicon PV cells have laboratory energy conversion efficiencies as high as 25% for single-crystal cells and 20.4% for multicrystalline cells. However, industrially produced solar modules currently achieve efficiencies ranging from 18%–24%. Solar cell prices dropped significantly in 2011, partly due to polysilicon selling price decrease resulting from over production (European Commission, 2014; Euroalliages, 2016).
- Electronics: Ultra-high purity grade silicon is used extensively in electronic devices such as silicon semiconductors, transistors, printed circuit boards and integrated circuits. Semiconductor-grade silicon metal used in making computer chips is crucial to modern technology (European Commission, 2014; Euroalliages, 2016).
- Other applications of silicon metal include explosives, refractories and ceramics.

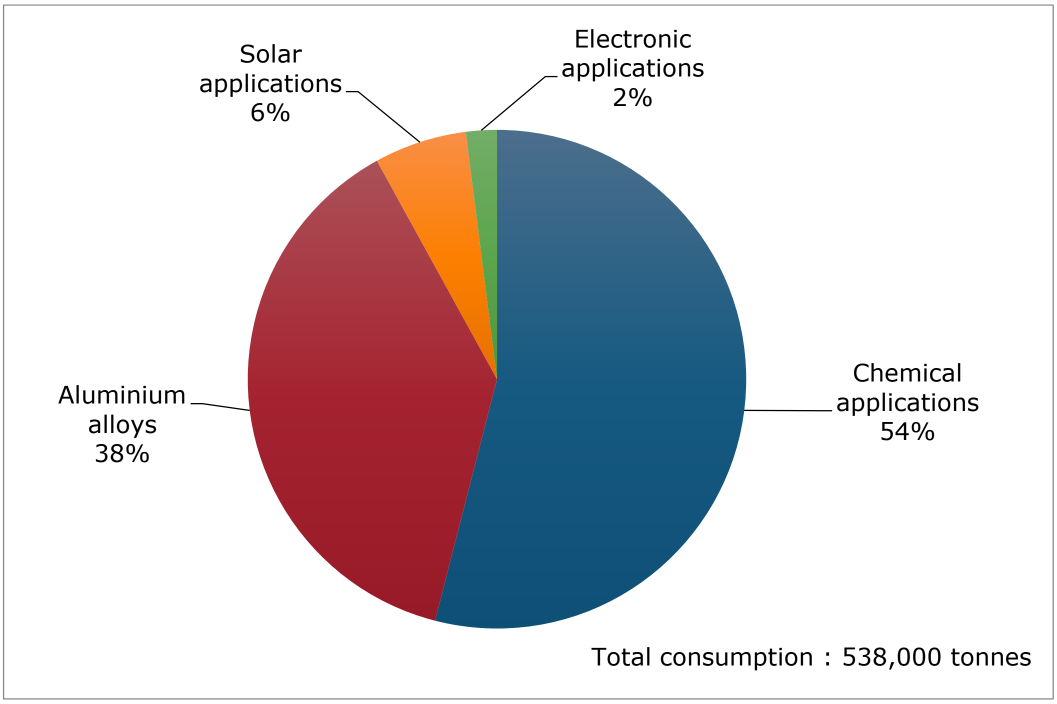

Figure 248: EU end uses of silicon metal. Average figures for 2010-2014. (Data from Bio Intelligence Service, 2015)

Relevant industry sectors are described using the NACE sector codes in Table 144.

Table 144: Silicon metal applications, 2-digit and associated 4-digit NACE sectors, and value added per sector. [Data from the Eurostat database, (Eurostat, 2016c)]

Applications	2-digit NACE sector	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
Chemical applications	C20 - Manufacture of chemicals and chemical products	110 000.0	C2016 - Manufacture of plastics in primary forms; C2017 - Manufacture of synthetic rubber in primary forms; C2030 - Manufacture of paints, varnishes and similar coatings, printing ink and mastics; C2041 - Manufacture of soap and detergents, cleaning and polishing preparations
Aluminium alloys	C24 - Manufacture of basic metals	57 000.0	C2442 - Aluminum production
Solar applications	C26 - Manufacture of computer, electronic and optical products	75 260.3	C2611 - Manufacture of electronic components
Electronic applications	C26 - Manufacture of computer, electronic and optical products	75 260.3	C2611 - Manufacture of electronic components

38.3.3 Prices and markets

Silicon metal prices are shown in Figure 249 (USGS, 2016). Silicon metal prices increased slowly between 2002 and late 2007. A sharp increase in prices was experienced following this period, with peak price around spring 2008. The economic recession in 2008 and 2009 resulted in prices decreasing sharply back to 2007 levels. Another pike in silicon prices was experienced in 2011. Prices have decreased once again since 2011; however, prices have shown an increasing trend since 2012 (European Commission, 2014). Spot prices of silicon have dropped between 2013 and 2015, due to a flat demand and a steady draw-down of silicon inventories outside China in 2014-2015 (CRU, 2015). According to the DERA raw materials price monitor and the LMB Bulletin, silicon prices on the MB free market have decreased between 2015 and 2016 compared to the period 2011-2015 as it cost 2,178 €/t in average on the period 2011-2015 but only 1,763 €/t in average on the period December 2015 - November 2016, i.e. a price drop of 19%.

The figure shown below refers to metallurgical grade silicon metal and therefore do not cover polysilicon. Import data for the US in 2010 indicate that the price of polysilicon had an average price as much as 20 times the value of silicon metal used for metallurgical and chemical applications (European Commission, 2014).

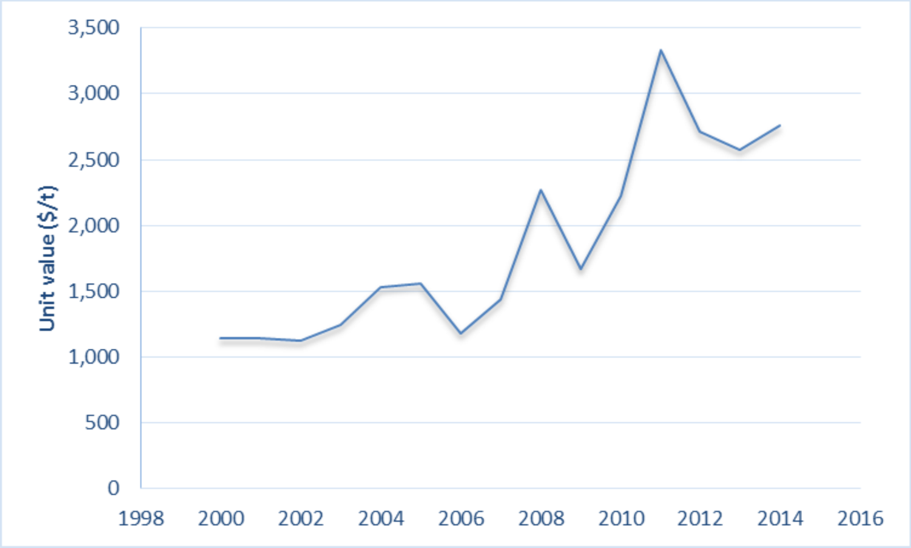

Figure 249: Metallurgical-grade silicon metal prices ($/tonne) between 2000 and 2014. (USGS, 2016)

38.4 Substitution

Substitutes are identified for the applications and end uses of the commodity of interest. In the case of silicon metal, there are no materials that can replace any of the main uses of metallurgical silicon without serious loss of end performance or increase of cost. Substitutes are assigned a 'sub-share within a specified application and considerations of the cost and performance of the substitute, as well as the level of production, whether the substitute has a 'critical' status and produced as a co-product/by-product. Exact sub-shares for the substitute materials are unknown and have been estimated. The literature used to identify substitutes for silicon metal is listed in section 38.7.

There is no material for replacement of silicon in silicones and silanes, or in end-use products based on these chemicals. Indeed, silicones are durable and heat resistant. In comparison, materials such as thermoplastics or rubber are not as performant. Therefore, the use of silicones vs. substitutes depends on the expected properties of the final product; this characteristic is already accounted for when selecting the most appropriate material. No viable current substitute is currently considered (CES, 2016).

Silicon is used to lower the melting point in aluminium manufacturing and to increase strength, machineability and corrosion resistance in aluminium products. There is currently no substitute to silicon metal for this application (Euroalliages, 2016).

Replacement technologies to silicon based technology for solar applications exist (however this is not material to material substitution but rather equivalent technology), with reduced performance. Moreover, CIGS technology is up to twice more expensive. It is estimated that Si technology represent 92% of the EU market; the rest is shared between CdTe and CIGS technologies. New hybrid technologies are currently being developed, but not on the market yet.

For silicon in the micro-electronics industry, GaAs is a substitute but with lower performance and is not used for mainstream applications. Germanium may be used as well in combination to silicon (i.e. silicon remains as physical support/monocrystalline, Ge on the top of layer). R&D on replacement technologies concerns graphic layers, carbon nanotubes (Wacker, 2016).

38.5 Discussion of the criticality assessment

38.5.1 Data sources

Market shares are based on the study on Material System Analysis (Bio Intelligence Service, 2015) and were confirmed by industry experts (Euroalliages, 2017). The distribution between solar and electronic applications was based on an assumption after discussions with stakeholders (Euroalliages, 2016; Solar Power Europe, 2016; Wacker, 2016). Production data for silicon metal are from BGS World Mineral Statistics dataset. Trade data were extracted from the Eurostat Easy Comext database (Eurostat, 2016a). Data on trade agreements are taken from the DG Trade webpages, which include information on trade agreements between the EU and other countries (European Commission, 2016). Information on export restrictions are derived from the OECD Export restrictions on the Industrial Raw Materials database (OECD, 2016).

For trade data the Combined Nomenclature (CN) codes '28046100 'Silicon containing >= 99.99% by weight of silicon' and 28046900 'Silicon containing < 99.99% by weight of silicon' have been used. These data were averaged over the five-year period 2010 to 2014. Other data sources used in the criticality assessment are listed in section 38.7.

38.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 144). The value added data correspond to 2013 figures.

The supply risk was assessed at the processing stage of silicon metal value chain using both the global HHI and the EU-28 HHI as prescribed in the revised methodology.

38.5.3 Comparison with previous EU criticality assessments

The results of this review and earlier assessments are shown in Table 145. A revised methodology was introduced in the 2017 assessment of critical raw materials in Europe and both the calculations of economic importance and supply risk are now different; therefore the results with the previous assessments are not directly comparable.

Table 145: Economic importance and supply risk results for silicon metal in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Silicon metal	-	-		7.13	1.63		3.8	1.0

Although it appears that the economic importance of silicon metal has reduced between 2014 and 2017, this should be put in perspective due to the change in methodology. The value added in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a ‘megasector’, which was used in the previous assessments. The economic importance figure is therefore reduced. The supply risk indicator is lower than in the previous assessments, which is due to the revised methodology, i.e. the inclusion of the EU supply and global supply in the calculation of the supply risk (instead of global supply only – in the latter case the 2017 supply risk would be 2.3, an increase in comparison with the 2014 assessment).

38.6 Other considerations

38.6.1 Forward look for supply and demand

The estimations for the outlook for supply and demand of silicon metal are shown in Table 146, provided by industry experts.

Growth in the silicon metal market is expected to continue in the coming years. In particular, China will continue to increase its market share among global producers in the next 5 years, following the same trend observed in the past years. This trend may be explained by production costs in China remaining at the lowest level globally speaking as well as by the Chinese production overcapacity (Euroalliages, 2016).

Overhang of idle capacity is expected to continue in 2017 as many idle furnaces can be easily restarted and as new plants are entering the market. However the global supply overhang is expected to disappear by 2018, as capacity additions will continue as slower rate than the global silicon metal demand (CRU, 2016b).

Global demand of silicon metal will continue to grow, led by increased demand from aluminium and solar industries (Euroalliages, 2016).

Table 146: Qualitative forecast of supply and demand of silicon metal

Material	**Criticality of the material in 2017**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Silicon metal	x		+	+	+	+	+	+

38.6.2 Environmental and regulatory issues

The production of silicon metal is energy intensive, therefore the energy cost is a major production cost element. The energy source used by the major silicon producing country, China, is coal. On the contrary, most silicon metal plants in Europe are historically located close to hydropower sources. According to Euroalliages, Chinese producers also benefit from lower power tariffs. In Europe, silicon production is subject to the European Directive on the Emissions Trading Scheme (2003/87/EC) which entails direct and indirect carbon costs. Today there is no global level playing field when it comes to climate requirements (Euroalliages, 2016). Silicon is not hazard classified.

38.7 Data sources

38.7.1 Data sources used in the factsheet

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38.8 Acknowledgments

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39. TANTALUM

Key facts and figures

Material name and Element symbol	Tantalum, Ta	World/EU production (tonnes of Ta_2O_5)[1]	1,800 / 0
Parent group (where applicable)	N/A	EU import reliance[1]	100%
Life cycle stage/ material assessed	Mine production/ Ore and concentrates	Substitution index for supply risk [SI (SR)][1]	0.95
Economic importance (EI)(2017)	3.9	Substitution Index for economic importance [SI(EI)][1]	0.94
Supply risk (SR) (2017)	1.0	End of life recycling input rate (EOL-RIR)	1%
Abiotic or biotic	Abiotic	Major end uses in the EU[1]	Capacitors (33%), Superalloys (22%), Sputtering targets (17%)
Main product, co-product or by-product	Mostly co-product with niobium, tin or lithium	Major world producers of Ta concentrates[1]	Rwanda (31%), Dem. Rep. of Congo (19%), Brazil (14%)
Criticality results	2011	2014	2017
	Critical	Not critical	Critical

[1] 2010-2014 average, unless otherwise stated.

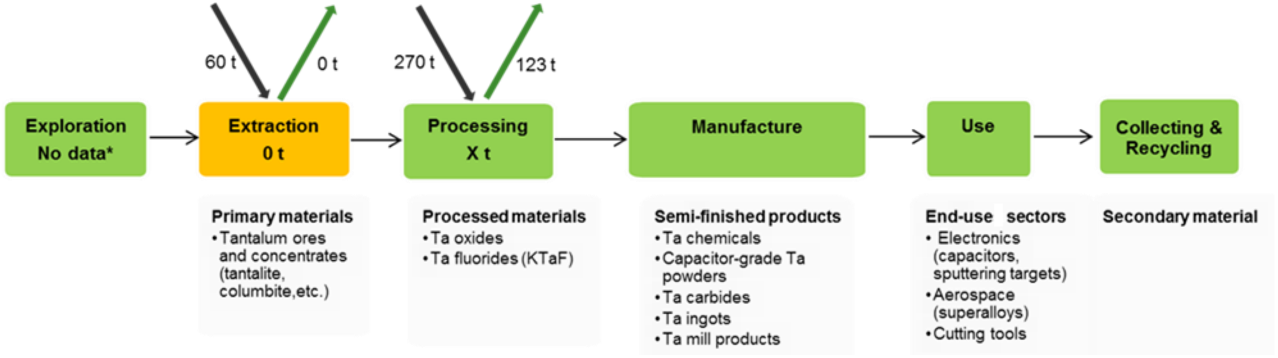

Figure 250: Simplified EU value chain for tantalum

The orange box in the figure above suggests that there is no production in the EU; green boxes indicate activities that are undertaken within the EU. The black arrows represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%.*There are no sufficient data to evaluate EU reserves of tantalum.

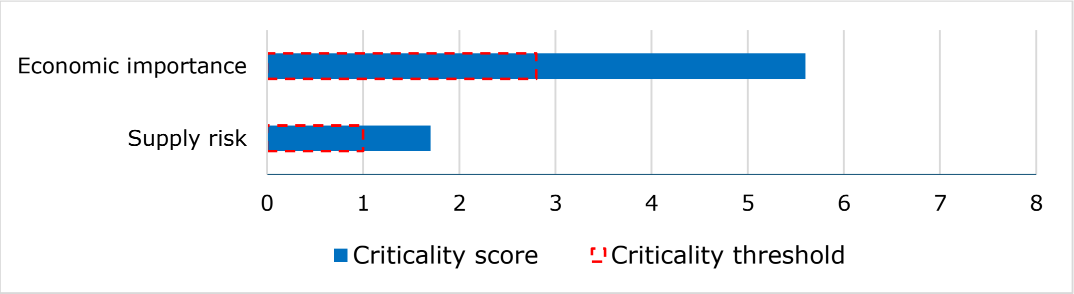

Figure 251: Economic importance and supply risk scores for tantalum

39.1 Introduction

Tantalum (chemical symbol Ta) is a silvery-grey hard, transition metal. It has a high density (16.6 g/cm^3) and the 4th highest melting point (3,020 °C). It is highly resistant to corrosion and has a great permittivity. Tantalum's estimated abundance in the upper continental crust is 0.9 ppm (Rudnick, 2003), which is quite rare. It is not found as a free metal in nature but occurs notably in the minerals microlite and tantalite-columbite. Most tantalum is produced as a co-product as it occurs in complex mineral form, often associated in ore bodies with niobium, tin or lithium. The major part of supply in recent years comes from artisanal mining. Its major uses are in capacitors (electronic devices, cell phones etc.), superalloys (aerospace), sputtering targets (storage media, inkjet printer heads etc.), but also carbides (cutting tools), mill products, medicals and chemicals.

With the exception of very small quantities of by-product from kaolin mining in France, there is currently no primary mine production of tantalum in the EU. There are a few processors notably in Estonia (from imported primary ore), Austria, Germany and the UK (mainly from secondary material).

39.2 Supply

39.2.1 Supply from primary materials

39.2.1.1 Mineral occurrence

Tantalum does not occur in a free state in nature, but in the form of complex oxides and other minerals. Whilst at least nineteen tantalum minerals had been recorded as early as 1982 (Foord, 1982), many of them are only of mineralogical interest. The main ones found in economic quantities are tantalite-columbite, microlite, wodginite and struverite. Tantalum minerals are often associated with cassiterite (the primary source of tin), and such ores are another important source of tantalum.

Tantalite-columbite is an isomorphous series, where tantalum and niobium may substitute with each other. Tantalite is the tantalum-rich end. The common ratios between the two are from 3:1 to 1:3, thus being either tantalo-columbite or columbo-tantalite (which is the most common, also shortened to ‘coltan’ especially in Central Africa). Microlite is the tantalum-rich end member of the microlite-pyrochlore series. Wodginite is less common, but was the primary tantalum mineral found in the original Wodgina deposit in Australia (from which it gained its name) and also at the Tanco mine in Canada. Struverite, a variation of rutile, is a low grade source of tantalum predominately associated with cassiterite in south-east Asia (Burt, 2016).

All primary tantalum (and niobium) deposits are associated with igneous rocks, and can be grouped into three types, on the basis of the associated igneous rocks:

- Peraluminous pegmatites and granites
- Alkaline to peralkaline granites and syenites
- Carbonatite-hosted deposits

Pegmatites have been, and continue to be, the most important source of tantalum mineralization, although only a very small fraction of pegmatites do contain tantalum. The two main periods where tantaliferous pegmatites were intruded are in the Archaean (>2.5 billion years ago) and the Proterozoic (500-1,400 million years ago) (Burt, 2016). Pegmatites are enriched in aluminium compared to the alkali based minerals (sodium and potassium-rich minerals) (Černý, 1989). Pegmatites are generally relatively small (1-100 million tonnes). They can be 'simple' or 'complex', with several discrete zones within the pegmatite, each zone containing significantly different mineral assemblages. In Central Africa many small pegmatites are found, which have been heavily weathered to the point of kaolinization and have become soft-rock deposits, particularly appropriate for artisanal exploitation.

Alkaline granites are enriched in the alkali based minerals compared to aluminium. They generally occur in rift or failed rift tectonic settings and are often relatively large deposits (100-1,000 million tonnes), with fine mineralogy (Burt, 2016). These rocks typically contain high contents of zirconium and rare earth elements (REEs) minerals. Significant concentrations of niobium and tantalum also occur, with the primary mineral being pyrochlore. A major example is the Pitinga mine in Brazil which is a Paleoproterozoic albite-rich peralkaline granite, exploited for tin, niobium and tantalum.

Syenites are another form of alkali feldspathic rock, with dominant nepheline syenite, generally highly complex. The Lovozero deposit in northern Russia is a prime example of an operating mine where tantalum and niobium are important by-products.

Carbonatites are igneous rocks that contain more than 50 percent carbonate minerals (calcite, dolomite or ankerite). Most carbonatites occur in rift settings, although several different types exist, many of which are unmineralised. Some can contain anomalous niobium-tantalum concentrations, along with various rare earth minerals. They are the main sources of niobium extraction.

39.2.1.2 Exploration

Tantalum exploration recent history is typical of 'minor' metals linked with technological shifts. Demand for tantalum increased rapidly in the late 1990s thanks to the expansion of miniaturized computers and cell phones using Ta-based capacitors. Tension on supply was increased as most existing industrial mines at that time (Australia, Brazil, Canada, China, Ethiopia, and Russia) were already running at full capacity. The two main consequences were: a dramatic increase of tantalum prices and a rush for exploration and artisanal production, particularly in Democratic Republic of Congo (DRC) and neighbouring countries of the Central African 'Great Lakes' region. It was also a period of expansion for industrial mines that could afford it, notably the two Australian mines Greenbushes and Wodgina. However, as new production came on stream in the early 2000's, the "bubble" burst and the market was unable to absorb it, leading to oversupply and low prices for much of the next decade. Such a situation led to the closure of both Australian mines (Greenbushes in 2007, Wodgina in 2008) operating at losses.

Exploration for tantalum essentially ceased and has been slowly recovering only since 2010. Particularly interesting new projects in 2016 are the ones focused on hard-rock lithium exploitation in LCT pegmatites with tantalum as an interesting by-product (e.g. Mount Marion and Mount Cattlin in Australia). In the EU, a tin-mining and smelting operation in Spain is due to come into production in Q1 2017 (Strategic Minerals Spain, 2016) which could create a new EU source of tantalum feedstock (in slags) although there is no guarantee that this production will be supplied to processors in the EU. The Minerals4EU website (Minerals4EU, 2015) indicates some exploration activities for tantalum and niobium together in Portugal, Slovakia and Ireland, but with confidential data.

39.2.1.3 Mining, processing and extractive metallurgy

Tantalum and niobium minerals are recovered through industry-standard open pit, underground and placer mining methods. In the case of primary sources deposits, ores are usually mined by standard methods, e.g. drill, blast, and muck cycles, prior to further comminution and concentration (Linnen et al., 2014).

In the case of artisanal mining of both alluvial and heavily weathered ores, initial processing may be facilitated through simple screening followed by sluices. Columbo-tantalite ores almost exclusively utilise standard wet gravity concentration equipment including jigs, spirals and tables, at least for production of a low- to medium-grade 'heavy mineral' concentrates (Linnen et al., 2014). The heavy mineral concentrates are often sold and further concentrated in dry plants consisting of such units as dry gravity concentrators, magnetic and electrostatic concentrators and occasionally removal of sulfides by flotation. Tantalite concentrates on the international market typically contain between 25–35% Ta_2O_5.

Production of tantalum metals and chemicals is a multi-stage process. The first stage is to convert tantalum concentrates to an intermediate chemical – generally potassium tantalum fluoride (K_2TaF_7) or tantalum oxide (Ta_2O_5). The 'standard' method, which is essentially unchanged for decades, is to digest the ore at high temperature in a sulfuric acid – hydrofluoric (HF) acid mix (or 'neat' HF) and, after filtering out the insoluble minerals, further processing via solvent extraction using methyl isobutyl ketone (MIBK) or liquid ion exchange using an amine extractant in kerosene. This produces highly purified solutions of tantalum and niobium, from which tantalum is crystallised, as potassium fluortantalate ('KTaF') by reaction with potassium fluoride (Linnen et al., 2014; Burt, 2016).

Metal powder, including the precursor to capacitor-grade powder, is produced by sodium reduction of the potassium tantalum fluoride in a molten-salt system at high temperature. The metal can also be produced by the carbon or aluminium reduction of the oxide or the hydrogen or alkaline earth reduction of tantalum chloride. The choice of process is based on the specific application and whether the resultant tantalum will be further consolidated by processing into ingot, sheet, rod, tubing, wire and other fabricated articles.

Tin slags, primarily from south-east Asia, are the other main feedstock to tantalum processors. Higher grade tin slags (those with a Ta_2O_5 content in excess of about 3%) reach the processors directly. When the market is favourable, lower grade slags (1-3% Ta_2O_5) are converted, usually by pyrometallurgical processing, to a 'syncon' of a tantalum content suitable for standard chemical processing. Such source can been responsible for 20% to 50% of total Ta production, depending on available supply and prices.

39.2.1.4 Resources and reserves of tantalum

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of tantalum in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[27], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

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[27] www.crirsco.com

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for tantalum. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for tantalum, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for tantalum at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

USGS (USGS, 2016) only indicates that identified resources of tantalum, most of which are in Australia, Brazil, and Canada, are considered adequate to meet projected needs.

In the context of the Minerals4EU project, potential resources of Ta (and Nb) were reported to exist in Finland, France, Portugal, Norway, Sweden, Greenland and Germany with no further evaluation (Mineras4EU,2014). Historic resources estimates are given in Table 147, with only indicative value, as these numbers do not comply with international standards of reporting and are very likely to be overestimated, as well as being uneconomic in current market conditions. New intensive exploration work would be necessary to evaluate total EU resources of Ta.

Table 147: Resource data for Europe compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2014)

Country	Reporting code	Value	Weighted Average Grade	Code Resource Type
Finland	None	251 Mt	0.0062% Ta2O5	Historic Resource Estimates
France	None	7,900 t	Ta-Nb content	Historic Resource Estimates
Portugal	None	8.04 Mt	41.79 g/t of ?	Historic Resource Estimates
Norway	None	8.03 Mt	0.995	Historic Resource Estimates
Sweden	Historic	0.6 Mt	80 g/t of ?	Historic Resource Estimates
Greenland	JORC	340	120 g/t Ta2O5	Inferred

On the global level, data from USGS (USGS, 2016) is the only global reference available, presented in Table 148. However, many current producing countries are not represented in this reporting, in particular those from Central Africa because of the type of deposits and the fact that artisanal mining operations do not rely on any preliminary resources & reserves assessment. The Mineras4EU website reports no data for tantalum reserves in Europe (Mineras4EU, 2014).

Table 148: Global reserves of tantalum in year 2011 (USGS, 2016)

Country	Reserves (tonnes of Ta)
Australia	67,000 among which 30,000 JORC compliant
Brazil	36,000
Others	N.A
TOTAL	>100,000

39.2.1.5 World production of tantalum

On the 2010-2014 period, T.I.C estimates that tantalite concentrates (25–35% Ta_2O_5) and tantalum derived from tin slags supplied to processors amounted to 1,600-1,800 tonnes by year on average (T.I.C, 2016). However, reported production figures vary according to sources. It should be noted that figures reported by the T.I.C. are from member companies only and do not claim to estimate total world consumption of tantalite concentrates and tin slags.

According to national statistics, the two main producers in recent years were Rwanda (31%) and the Democratic Republic of Congo (19%), accounting for about half of global primary supply (Figure 252). Nevertheless data reported from those two countries are always subject to uncertainties, due to the difficulties of tracing artisanal mining total output despite numerous initiatives to increase transparency (OECD, iTSCi etc.). Brazil accounted for 14% of global production, followed by an important number of smaller players. In the years 2010 and 2011, it is estimated that an important part of total production was from tin slags (Audion, 2011).

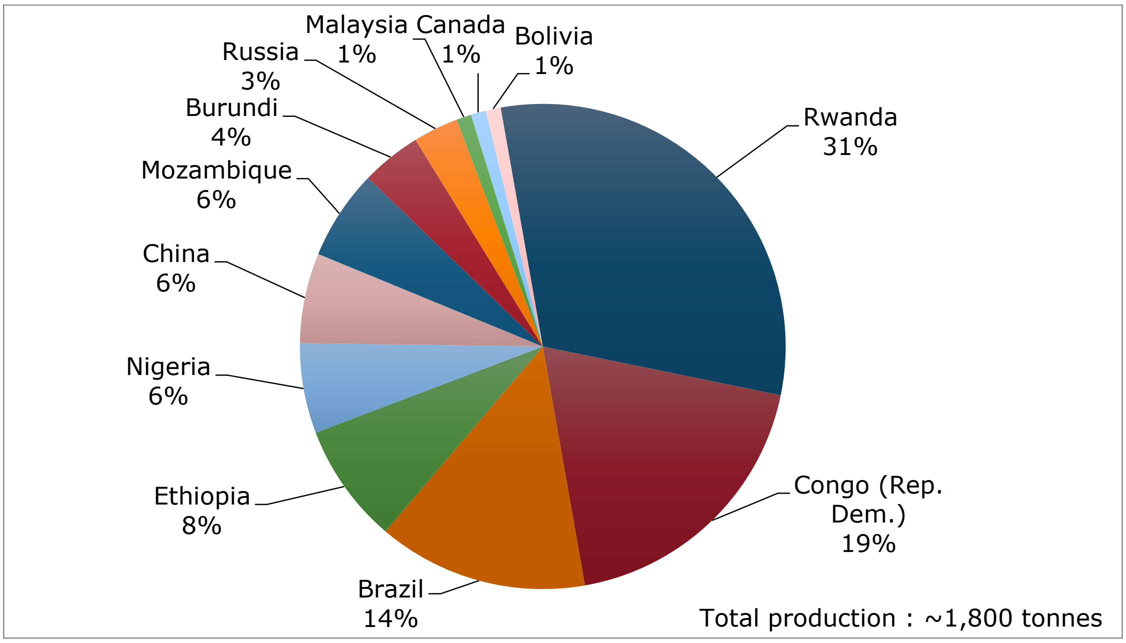

Figure 252: Global production of Ta concentrates, average 2010–2014 (Data from various sources: BGS, USGS, World Mining Data)

Even though producing countries are quite diverse at the extraction stage, the next steps of the Ta value chain are more concentrated in South-East Asia. China is the first importer of Ta concentrates globally, and operates more than half of the "official" 3Ts smelters processing tantalum (OECD, 2014), a number that could have increased since. China is also a major exporter of processed Ta-products, to the EU, USA and others.

39.2.2 Supply from secondary materials

The end-of-life recycling rate of tantalum products is under 1% (UNEP, 2011). Nevertheless, recycling of used items containing tantalum exists, but it is primarily 'pre-consumer', that is from within the upstream supply chain itself, rather than from end-users. In the aeronautic industry for instance, turbine blades are reprocessed. The composition of superalloys is known or can be tested, and the alloys are added to the melt when producing new alloys (Roskill, 2016).

Processor scrap and other secondary materials are also an important part of tantalum supply. Scrap generated during manufacturing, for example of capacitors, is returned to processors. The main source of this recycled material is from the electronics industry (capacitors, sputtering targets, etc.). Estimates from various sources give that about 30% of new demand for tantalum in any year is met from such material, a figure that hardly varied for a few decades (Burt, 2016).

In the EU, various recyclers and processors count Ta in their activities. They are located in Germany, Austria and the UK (Roskill, 2016).

39.2.3 EU trade

EU import reliance for tantalum ores and concentrates is 100%. In Eurostat Comext database (Eurostat, 2016), tantalum ores and concentrates are reported in a single category along with niobium, vanadium and zirconium (custom code CN8 261590). In depth analysis is therefore necessary to assess how much of total gross weight is likely to correspond to tantalite concentrates (30% Ta_2O_5) and how much are other materials or wrongly reported ones. Expert consultation (Stratton, 2016) led to believe that on average during 2010-2014, EU imports of tantalite concentrates were of the order of 60-100 tonnes, with the main suppliers being Nigeria (81%), Rwanda (14%) and China (5%), see Figure 253.

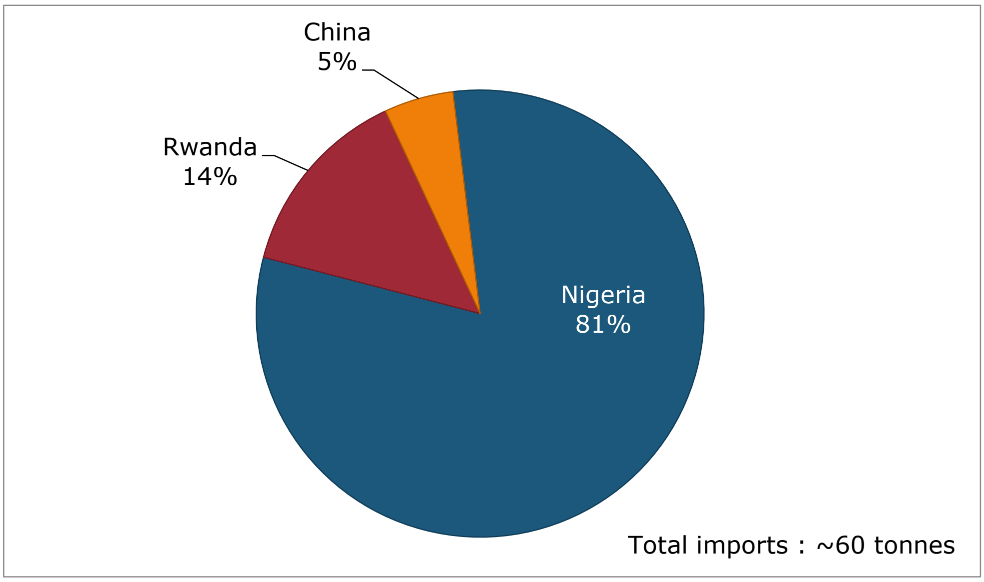

Figure 253: EU imports of tantalite concentrates, average 2010-2014 (Data from Eurostat Comext, 2016 and expert consultation)

As there is no mine production of tantalum in the EU, there are no exports of ores and concentrates. Most figures found in Eurostat Comext are likely to correspond to re-exports or to material other than tantalum wrongly classified. HC Starck in Germany is likely to be one of the main re-exporter of Ta concentrates, linked with intra-company material transfers to Thailand, USA and Japan (Roskill, 2016). France is also known to export small quantities of a Sn-Nb-Ta concentrate, by-product of kaolin mining (BRGM, 2015).

At the international level, DR Congo and China impose export taxes (respectively 10% and 25%) on Ta concentrates.

Potential negative impacts in tantalum trade could come from renewed political instability in Central Africa. Legislation on conflict minerals have begun in 2010 with the US Dodd-Frank Act. At the EU level, the Conflict Minerals Regulation (Regulation (EU) 2017/821) was published in the Official Journal of the EU in May 2017 and entered into force in June 2017. It will apply across the EU as of January 2021 (European Commission, 2016b).

39.2.4 EU supply chain

As shown in Figure 253, the EU is not a large importer of tantalum-containing minerals (compared to the USA and China for instance). Imports at the stage of processing (Ta oxides, K-salt, Ta metal-alloys) and manufactured end-products are much higher and another source of dependence for the EU, although not assessed in the 2017 criticality assessment for data availability reasons.

In the main sectors of consumption, a small number of processors/manufacturers are present in the EU;

- At the processing stage, capacities are found in Estonia (with the company NPM Silmet AS which processes columbite ore coming from Nigeria, to produce REEs, Nb and Ta products), but also in Germany and the UK (mostly for secondary processing);

- For capacitors manufacturing, 2 companies: AVX in Czech Republic and Kemet in Portugal;

- In the aerospace sector, which is one of the most important, a dozen of superalloys producers are known respectively in the UK, France, Germany, Austria, Italy and Sweden, as well as companies using Ta-containing superalloys to manufacture turbine blades for jet engines, the main one being Rolls Royce (UK). Roskill estimates that the EU could consume half of tantalum used globally in superalloys (Roskill, 2016).

- Others uses include sputtering targets, another major application for tantalum although less important in the EU. The company H.C. Starck in Germany is a major player in this market, although most of its plants are outside the EU. Others markets such as tantalum carbides, tantalum chemicals and mill products also have EU users, although it is in modest quantities and quite diverse applications.

EU supply is fed to a large extent by processed and secondary materials. It also can be noted that as in the case with most minor metals, the EU is host to many companies active in the trading in Ta minerals and products.

39.3 Demand

39.3.1 EU consumption

Apparent consumption figures derived from adding EU production and imports and subtracting exports are not reliable because of uncertainties related to the amount of tantalum produced, traded, or integrated in finished goods at every level. It is very difficult to assess these numbers precisely, which are of the order of 50-100 tonnes (contained Ta).

39.3.2 Applications / end-uses

The manufacture of capacitors is the largest single use of tantalum worldwide (Figure 254). It represents 500-600 tonnes of contained Ta used annually. All electronic devices contain capacitors, they are used to store an electrical charge for later use, and consist of two conducting surfaces (metal plates) separated by a dielectric insulating material. In the case of Ta capacitors, the dielectric is a thin film of tantalum pentoxide that forms naturally on the surface of tantalum metal to protect it from corrosion. The vast majority of capacitors in electronic devices do not contain tantalum; the use of tantalum is favoured when high capacitance, small size and high performance are required. Such capacitors are now limited to applications where they are irreplaceable. In the EU, the majority of Ta use in capacitors comes from imported finished products rather than manufacturing (in 2016, only one capacitor manufacturer seems to be active; AVX in Czech Republic).

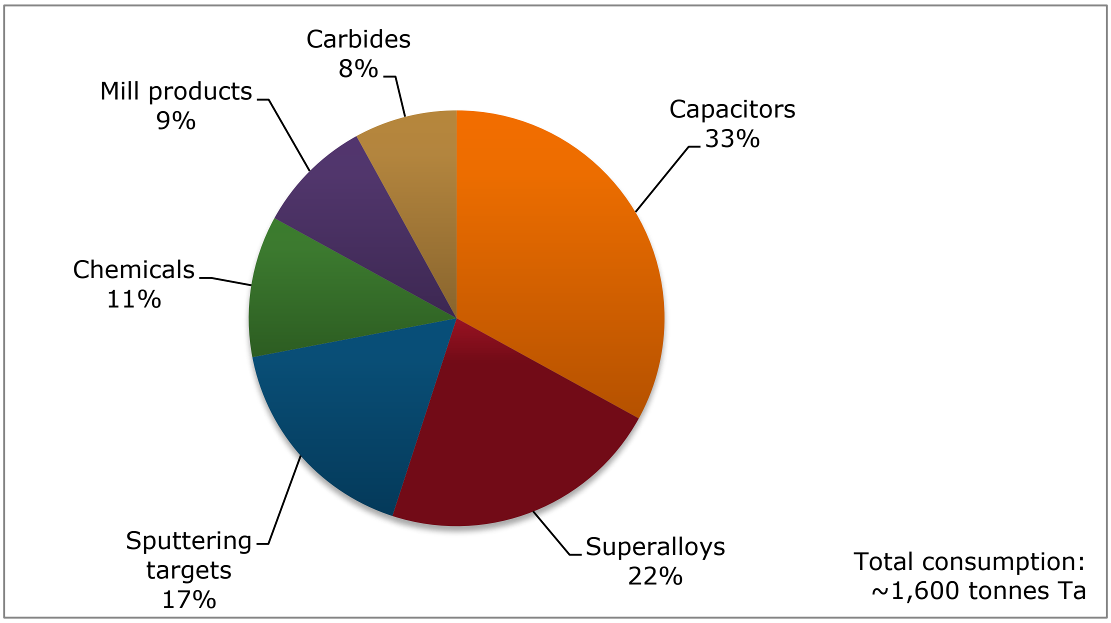

Figure 254: Global end uses of tantalum. Average figures for 2010-2014 (Data from Roskill, 2013)

Superalloys are an important use of tantalum in the EU, due to the prominence of the aerospace sector. Roskill estimates that the EU could consume half of tantalum used globally in superalloys (total use is estimated around 100-200 t of contained Ta (Roskill, 2016). As aircraft design and performance expectations improve, the alloys involved become more sophisticated and the loading of tantalum in alloys is increasing (together with other specialty metals). Superalloys find applications in the manufacture of jet engines for example, but also for land-based gas turbines.

Sputtering targets are another major application for tantalum although less important in the EU (only in imported finished products). Sputtering is a method of applying thin films of metal to a substrate and is used in the manufacture of storage media, inkjet printer heads, electronic circuitry and flat-panel displays, among others. The target is the source of the metal that is deposited. Tantalum chemicals have a very wide range of applications and are intermediates in the manufacture of other products that are often destined for the electronics industry. Tantalum mill products have a very wide range of uses, including chemical processing equipment, ballistics and surgical implants. Tantalum carbides are used in cutting tools.

Tantalum is also used in medical applications (category (medical device implants, bone and joint replacements), but with a very low share (<1%).

The calculation of economic importance of tantalum is based on the use of the NACE 2-digit codes. Relevant industry sectors are the following:

Table 149: Tantalum applications, 2-digit NACE sectors and associated 4-digit NACE sectors [Data from the Eurostat database, (Eurostat, 2016)]

Applications	2-digit NACE sector	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
Capacitors	C26 - Manufacture of computer, electronic and optical products	75,260	C2610- Manufacture of electronic components
Aerospace	C30 – Manufacture of other transport equipment	53,645	C30- Manufacture of air and spacecraft and related machinery
Sputtering targets	C26 - Manufacture of computer, electronic and optical products	75,260	C2610- Manufacture of electronic components
Mill products	C25 - Manufacture of fabricated metal products, except machinery and equipment	159,513	C2593- Manufacture of tools
Carbides	C28 – Manufacture of machinery and equipment n.e.c	191,000	C2824-Manufacture of machinery for mining, quarrying and construction
Chemicals	C20 – Manufacture of chemicals and chemical products	110,000	C2029-Manufacture of other chemical products n.e.c.

39.3.3 Prices and markets

Tantalum is not traded on any metals exchange, and there are no terminal or futures markets where buyers and sellers can fix an official price. References for prices are obtained through averages of past deals between private parties, generally available through paid subscription (e.g. Asian Metal, Metal Pages).

As indicated previously, after a spike in prices in the early 2000s, tantalite prices on the international market remained low (around 50-100 US$/kg) for most of the period 2002-2010, with another increasing episode in 2010-2012, followed by a chaotic and progressive fall until 2017 (see Figure 255).

It is also of interest to note that as we move toward the value chain, added-values escalate rapidly for selected tantalum products. For instance, either Ta metal (99.95% min.) or tantalite (99.99% min. Ta_2O_5) are generally more than twice as expensive as tantalite 30% Ta_2O_5 (Asian Metal, 2016).

Figure 255: Tantalite prices (30% Ta2O5) in $EUR/kg (InfoMine, 2017)

39.4 Substitution

Because of the relatively high price and historic supply volatility associated with tantalum, since the late 1990s manufacturers have moved to engineer it out the use of the metal (CRM Innonet, 2015) and current tantalum consumption is limited to those applications in which tantalum cannot be substituted without a significant loss of performance and quality.

In capacitors, the vast majority of them in electronic devices do not contain tantalum, mostly because of their high prices. In terms of substitution, niobium (also considered a critical raw material for the EU since 2011) can be used to produce capacitors at lower cost, but they are usually larger and have a shorter life-span. Other alternatives are ceramic capacitors (multilayer or monolithic) or standard aluminium capacitors (both also have larger size, reduced capacitance and are more sensitive to harsh and hot operating conditions). The superior performance and robustness of tantalum capacitors thus remains the only reliable choice in applications where long term reliability, size and/or security matters (e.g. automobile anti-lock brake systems, airbag activation systems, satellites, etc.).

Tantalum carbides are used in cutting tools. Other refractory metals which share similar properties of strength and resistance at high temperatures can be substitutes for carbides (tungsten, niobium, titanium, molybdenum), although prices are often comparable.

In many types of superalloys tantalum is one of several elements added to the base metal (nickel, cobalt or iron) in small but precise quantities. Substituting tantalum for another element would dramatically alter the properties of the superalloy. Once a particular superalloy has been engineered into an aero engine or industrial gas turbine and approved for commercial use any subsequent change to that superalloy would take many years to become established. Tantalum plays a critical role in superalloys and in this application it is a relatively minor cost, making substitution unlikely.

39.5 Discussion of the criticality assessment

39.5.1 Data sources

In the case of tantalum, data sources were a limiting factor to performing the criticality assessment (CA). Information on country by country production is only available for tantalum ores and concentrates at the global level. However, such information is still relatively opaque due to the fact that a great part is coming from artisanal mining, and that the global market is small (2,000 tonnes). National statistics for trade are generally the only source of public knowledge for primary supply of tantalum. However, compilation of such data by different institutions (e.g. British Geological Survey, US Geological Survey, World Mining Data) show a great diversity of results, casting doubts on their reliability.

An additional complexity is that the Tantalum-Niobium International Study Center (T.I.C.) uses another approach to build supply statistics; primary production estimates rely on declaration of shipments to processors, which allows summing all materials at the global level but do not give any indication of the origin of products. Traceability of individual producers is lost at this level. Furthermore, the same applies for processed materials which are grouped by categories (capacitor-grade Ta powders, Ta chemicals, Ta carbides, etc.) and summed at the global level in a similar way. It is even more difficult to trace origins for these intermediary products, as customs codes are even more diverse and sometimes wrongly classified.

39.5.2 Economic Importance and Supply Risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 149). The value added data correspond to 2013 figures. The supply risk was assessed using only global HHI as prescribed in the revised methodology.

39.5.3 Comparison with previous EU assessments

Tantalum was considered critical in the 2011 criticality assessment and non-critical in the 2014 criticality assessment. In the 2017 assessment, tantalum returns to the list of CRM. The Economic Importance score (EI) of tantalum is lower in the 2017 assessment than in both of the previous assessments. This is mainly due to the revised methodology, as the value added in the 2017 assessment corresponds to a 2-digit NACE sector rather than a 'megasector', which was used in the previous assessments, which tends to reduce the EI score. The Supply Risk score (SR), even though close, is higher than in 2014 (tantalum SR=1.0 in 2017; SR=0.6 in 2014), also partly due to the change of methodology, which takes into account the concentration of global production (Global HHI), the diversity of EU supply sources, and geopolitical risks. In the case of tantalum, the SR result is based on global supply data only (robust data on EU supply was not available). In the 2014 assessment, the major global suppliers in 2010 were Brazil (26%), Mozambique (18%) and Rwanda (16%). In terms of EU supply, China (29%), the US (28%) and Japan (18%) represented the largest shares. In the 2017 assessment, the major global producers of tantalum are Rwanda (31%), the Democratic Republic of Congo (19%) and Brazil (14%) (See Figure 252). Findings of the 2017 criticality assessment of tantalum indicate that EU imports of Ta ores and concentrates for the period 2010-2014 were primarily from Nigeria (81%), Rwanda (14%) and China (5%). The SR result for tantalum is therefore not surprising considering the fact that the SR calculation for tantalum takes into account the share that Nigeria (81%) represents in the EU supply. Nigeria's scaled WGI value (6.92) and the EU Supply Risk ((HHIWGI-t) EU28=4.6) are very high. Analysis of the assessment results of tantalum also indicates that imports of processed materials would be higher and more representative of Ta criticality to EU. Therefore, the level of confidence concerning Ta trade in Central Africa is a key parameter effecting the material's criticality.

Table 150: Economic Importance and Supply Risk results of tantalum in the assessments of 2011, 2014 and 2017 (European Commission, 2011; European Commission, 2014) and 2017

Assessment year	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Tantalum	7.4	1.1		7.4	0.6		3.9	1.0

39.6 Other considerations

39.6.1 Forward look for supply and demand

Since the late 1990s, the tantalum market has shown much instability and volatility. Therefore, it is important when looking forward to keep in mind that things can change quickly and dramatically, particularly on the supply side. Much uncertainty comes from the potential development of new deposits. Most of the interest lies in exploration of LCT pegmatites where Ta would be a by-product of hard rock lithium exploitation and could bring interesting new supply on the market. Still, the Ta market is currently in a slight supply surplus, and could remain so for the next few years, resulting in low prices that discourage new producers coming on stream.

As for supply risks, the level of confidence concerning tantalum trade in Central Africa is a key parameter. Since 2009, many institutional and industry led initiatives have improved transparency on artisanal mining. Once considered as a significant factor in the wars in the region, such activities are now accepted as an essential and secure source of tantalum concentrates. Nevertheless the current political instability in the region could have a negative impact in future trade, bringing the notion of conflict tantalum back to prominence again. In the case of new conflicts rising, the risk of another de-facto embargo could weigh on the region and cause a dramatic increase in prices.

On the demand side, much depends on prices. The growth of consumption of all types of electronic devices is likely to drive Ta capacitors demand. The superalloys market will be driven by the commercial aerospace prospects, with a lot depending on this industry, particularly Airbus in the EU context. Other markets could be declining, such as Ta carbides.

No further reliable forecast for demand and supply for the next 5, 10 and 20 years could been obtained from market and industry experts (see following table).

Table 151: Qualitative forecast of supply and demand of tantalum

Material	**Criticality of the material in 2017**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Tantalum	x		?	?	?	?	?	?

39.6.2 Environmental and regulatory issues

No environmental restriction is known for tantalum. Regulatory issues are linked with Conflict minerals legislation issues (European Parliament, 2016).

The Regulation (EU) 2017/821 of the European Parliament and of the Council sets up a Union system for supply chain due diligence self-certification in order to curtail opportunities for armed groups and unlawful security forces to trade in tin, tantalum and tungsten, their ores, and gold. It will take effect on 1 January 2021. It is designed to provide transparency and certainty as regards the supply practices of importers, (notably smelters and refiners) sourcing from conflict-affected and high-risk areas. The EU regulation covers tin, tantalum, tungsten, and gold because these are the four metals that are most mined in areas affected by conflict or in mines that rely on forced labour.

The regulation also draws on well-established rules drawn up by the Organisation for Economic Co-operation and Development (OECD) in a document called 'Due Diligence Guidance for Responsible Supply Chains from Conflict-Affected and High-Risk Areas.'

The regulation only applies directly to EU-based importers of tin, tantalum, tungsten and gold, whether these are in the form of mineral ores, concentrates or processed metals.

The US also has legislation on conflict minerals: Section 1502 of the Dodd-Frank Wall Street Reform and Consumer Act of 2010, which covers the same four products.

39.7 Data sources

39.7.1 Data sources used in the factsheet

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39.8 Acknowledgments

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40.TUNGSTEN

Key facts and figures

Material name and Element symbol	Tungsten, W	World/EU production (tonnes)[1]	82,000 / 2,175
Parent group	N/A	EU import reliance[1]	44%
Life cycle stage/ material assessed	Mine production/ Ore	Substitution index for supply risk [SI(SR)][1]	0.97
Economic importance (EI) (2017)	7.3	Substitution Index for economic importance [SI(EI)]1	0.94
Supply risk (SR) (2017)	1.8	End of life recycling input rate (EOL-RIR)	42%
Abiotic or biotic	Abiotic	Major end uses in EU[1]	Mill and cutting tools (31%), Mining and construction tools (21%), Other wear tools (17%),
Main product, co-product or by-product	Main product	Major world producers[1]	China (84%), Russia (4%),
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] average for 2010-2014, unless otherwise stated;

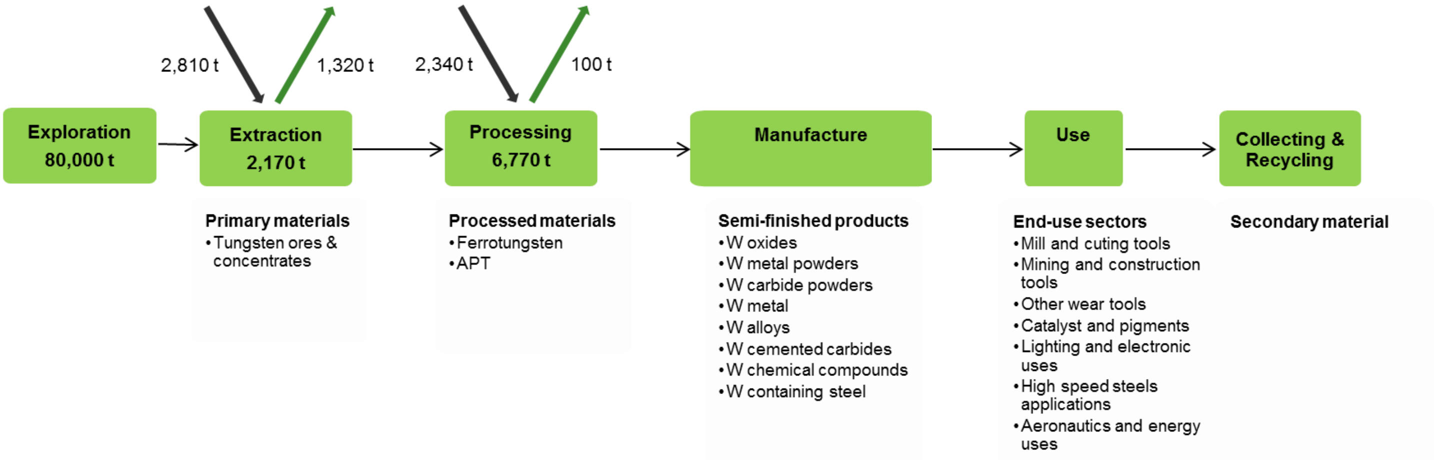

Figure 256: Simplified value chain for tungsten

The green boxes of the production and processing stages in the figure above suggest that activities are undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

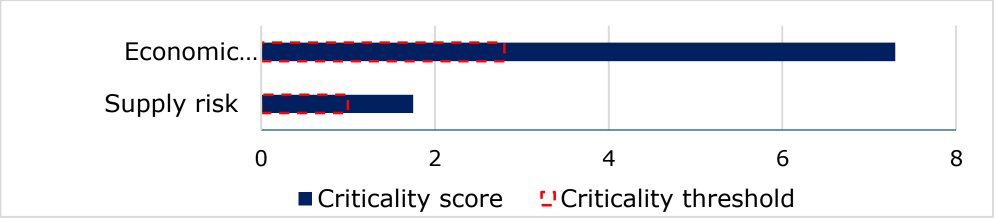

Figure 257: Economic importance and supply risk scores for tungsten

40.1 Introduction

Tungsten (W), also known as wolfram, is a hard, rare metal. Under standard conditions, tungsten is found naturally on Earth almost exclusively in mineralogic form. It is mainly contained in wolframite and scheelite. The free element is remarkable for its robustness and has the highest melting point of all the elements. Its high density is 19.3 times that of water, comparable to uranium and gold, and much higher (about 1.7 times) than that of lead. Due to this characteristic, it is used for cutting tools which represents the largest use of the element tungsten. Tungsten's many alloys have numerous applications, including incandescent lamps, X-ray tubes, superalloys, and radiation shielding. Tungsten's hardness and high density give it military applications in penetrating projectiles. Tungsten compounds are also often used as industrial catalysts.

After extraction, tungsten ore is processed in three main intermediate product lines: ammonium paratungstate (APT thereafter), tungsten oxides (further processed form of APT), and ferrotungsten. While ferrotungsten is used in tungsten containing steel; APT and tungsten oxides are manufactured into various tungsten semi-finished products: tungsten metal (highly conductive when pure), tungsten carbides (wear resistance), tungsten alloy (highly dense, for heavy parts) or chemical compounds. Finished applications are then manufactured from those tungsten components. For instance, lighting products are made from tungsten metal; mill and cutting tools or mining and construction tools are made of tungsten carbides. Aeronautics and energy applications are based on both tungsten metal and alloys.

Tungsten is an important metal with no substitutes, and a key component in steel manufacturing, construction, oil drilling, and mining industries. It is also used in the fabrication of wires and filaments used in electrical, heating, and lighting applications. The hardness and high density of this metal give it military applications in penetrating projectiles. Tungsten compounds are also often used as industrial catalysts.

All quantities are provided in W content.

40.2 Supply

40.2.1 Supply from primary materials

40.2.1.1 Geological occurrence

The average abundance of tungsten in the Earth’s crust is estimated to be 1.25-1.50 ppm (BGS, 2011), and its concentration in the upper crust is 3.3 ± 1.1 ppm (Rudnick, 2003). In nature, tungsten does not occur as free metal but in 45 different minerals, of which only two, wolframite and scheelite, have any economic importance. Tungsten minerals often occur as monotungstates, such as scheelite (calcium tungstate, $CaWO_4$), stolzite (lead tungstate, $PbWO_4$), and wolframite. Wolframite is a solid solution of ferberite (ferrous tungstate, $FeWO_4$) and hübnerite (manganous tungstate, $MnWO_4$) (BGS, 2011). Scheelite is the most abundant tungsten mineral and is present in approximately 2/3 of known tungsten deposits (BGS, 2011).

40.2.1.2 Mining, processing and extractive metallurgy

The average concentration in workable ores is usually between 0.1 and 1.0% WO_3 (BGS, 2011), which is consistent with the 0.1-2.5% WO_3 contained in economically recoverable ores (European Commission, 2014).

Mining is performed through both open-pit mining and underground mining. The ore from mine is crushed and milled, and then upgraded by means of gravity enrichment or flotation. For commercial trading 65-75% WO_3 content is required for further refining (European Commission, 2014). The ore beneficiation allows to increase the tungsten content of the concentrate up to 65-75% WO_3, which can be (BGS, 2011):

- directly used for production of ferrotungsten or steel manufacture, or
- converted by hydrometallurgy into intermediate tungsten compounds (APT or tungsten oxides), or
- further refined by pyrometallurgy into pure tungsten (metal, carbide, alloys, etc.).

For example, APT (chemical formula: $(NH_4)10(H_2W_{12}O_{42})4H_2O$), which is the main and highly pure intermediate product, is in turn used to produce the chemicals blue and yellow tungsten oxide and tungstic acid, as well as tungsten metal, tungsten powders, and other tungsten alloys (European Commission, 2014). Ferrotungsten is not produced from APT but directly from ore or scrap (Wolfram, 2016).

40.2.1.3 Tungsten ore resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of tungsten in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[28], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for tungsten. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for tungsten, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for tungsten at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015). Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

World tungsten known resources have been estimated at 7 million tonnes of contained W metal (BGS, 2011). World tungsten resources are geographically widespread. Major tungsten deposits are located in China, Canada and Russia. Canada, Kazakhstan, Russia, and the United States also have significant tungsten resources (USGS, 2016a). The biggest deposits in Europe in use between 2010 and 2014 are located in Portugal and Austria (European Commission, 2014). According to industry experts, there are more deposits known or ready to be developed in Europe, such as Hemerdon deposit (UK) that led to a mine opening in 2016, Barruecopardo which has already financing in place, and some work is done at La Parilla (both in Spain) (Wolfram, 2016). About 500,000 tonnes

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[28] www.crirsco.com

of W are contained in EU known resources according to the MSA study, estimated by contacting several geological survey in EU member states (Bio Intelligence Service, 2015). Resource data for some countries in Europe are available in the Minerals4EU website (see Table 152) (Minerals4EU, 2014) but cannot be summed as they are partial and they do not use the same reporting code.

Table 152: Resource data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2014)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
Spain	NI 43-101	615	kt	0.0032% WO_3	Measured
UK	JORC	39.9	Mt	0.18% WO_3	Measured
Portugal	NI 43-101	1495	Mt	0.55% WO_3	Indicated
Poland	Nat. rep. code	0.24	Mt	0.04% W	C2+D
Slovakia	none	2846	Mt	0.23% W	-
Czech Republic	Nat. rep. code	70.2	kt	0.8% W	Potentially economic

According to USGS, world known reserves of tungsten stand at 3.3 million tonnes of contained W metal, with more than 57% of these located in China (see Table 153) (USGS, 2016a). The MSA study has estimated that about 80,000 tonnes of W are contained in EU known reserves, by contacting several geological survey in EU member states (Bio Intelligence Service, 2015). Reserve data for some countries in Europe are available in the Minerals4EU website (see Table 154) but cannot be summed as they are partial and they do not use the same reporting code.

Table 153: Global reserves of tungsten in year 2015 (Data from (USGS, 2016a))

Country	Tungsten Reserves (tonnes)
China	1,900,000
Canada	290,000
Russia	250,000
US	140,000
Vietnam	100,000
Bolivia	53,000
UK	51,000
Spain	32,000
Austria	10,000
Portugal	4,200
Other countries	670,000

Table 154: Reserve data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2014)

Country	Reporting code	Quantity	Unit	Grade	Code Reserve Type
Spain	NI 43-101	482	kt	0.38% WO_3	Proven
UK	JORC	27.9	Mt	0.19% WO_3	Proved

40.2.1.4 World mine production

In average between 2010 and 2014, about 85% of the world's tungsten production came from China (Word Mining Congresses, 2016). To provide the domestic industry with a target and to manage the country's natural resources in a way to balance supply and demand, China imposed a tungsten mining quota in 2002. Since the introduction of the quota, the amount was more than doubled (from 43,700t concentrate of 65% WO_3 in 2002 to 89,000 t in 2013) over a period of 10 years (OECD, 2016). However, despite the quota, Chinese production has increased from 2010 to 2014.

Other producing countries are Russia, Canada, Bolivia, Vietnam, Austria, Rwanda, Spain and Portugal (see Figure 258). The global production of tungsten amounts about 82,000 tonnes of tungsten (W content) (Word Mining Congresses, 2016).

Vietnam went from a medium-scale producer to the world's number 2 by the opening of the biggest mine outside China – the Nui Phao mine - in 2013 (about 4000 tonnes in 2014 and more in 2016). In contrast, Canada will be "zero" from 2016 onwards, due to the closure of the Cantung mine in late 2015 (Wolfram, 2016).

Tungsten extraction in the EU is exclusively located in Austria, Portugal and Spain and represents around 2,000 t of tungsten content, i.e. less than 3% of the global extraction. There was no production in other EU countries until 2015, but a mine has opened in 2016 in the UK (Hemerdon) and will be a significant additional source inside of the EU (Wolfram, 2016).

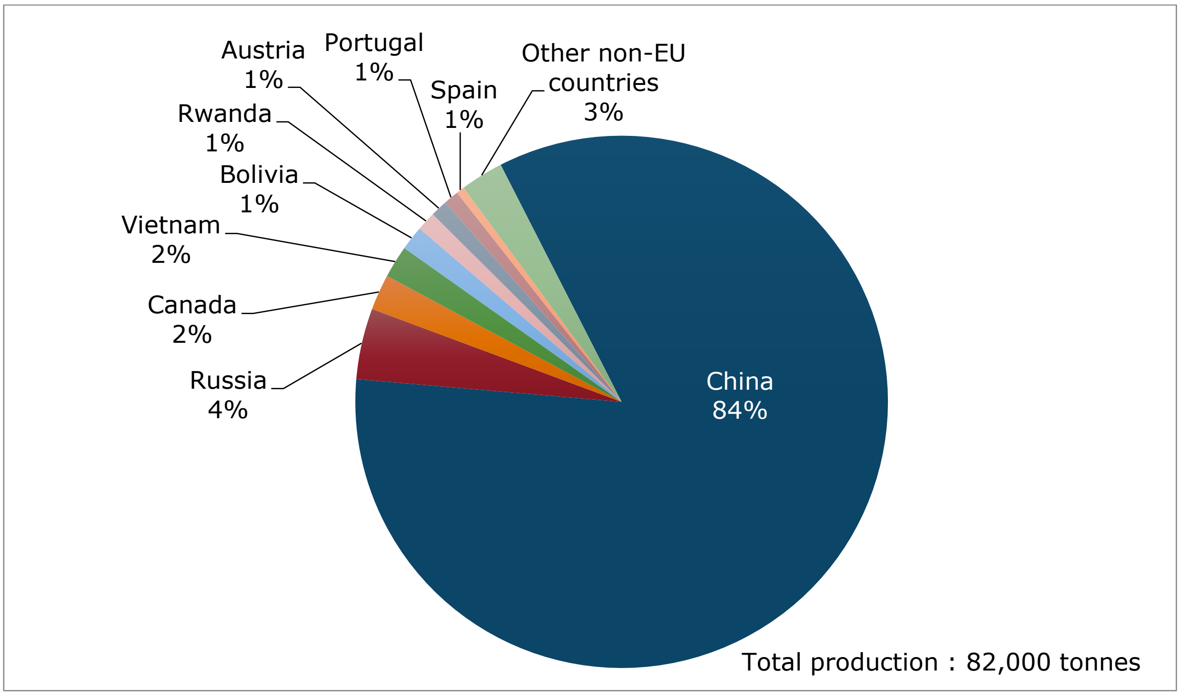

Figure 258: Global mine production of tungsten, average 2010–2014 (Data from Word Mining Congresses, 2016)

40.2.2 Supply from secondary materials

Tungsten scrap, due to its high tungsten content in comparison to ore, is a very valuable raw material. There are 4 distinct recycling processes of tungsten in the EU. The average distribution of those processes in the generation of secondary tungsten in the EU is as follow (Bio Intelligence Service, 2015):

- about 40% for a "long recycling process", where the secondary tungsten is used for APT production,
- about 20% for a "short recycling process", used directly for the metal content,
- about 30% for a "Zinc recycling process", used directly as tungsten carbide powders in the manufacturing of Tungsten cemented carbides,
- about 10% for a recycling process used directly in the manufacturing of tungsten containing steel.

Contaminated cemented carbide scrap, turnings, grindings and powder scrap are oxidized and chemically processed to APT in a way similar to that used for the processing of tungsten ores. Other tungsten containing scrap and residues might require a modified process. Clean cemented carbide inserts and compacts are converted to powder by the zinc process. This powder is added back to the manufacture of ready-to-press powder (Lasser, 1999).

Recycling of tungsten in high speed steel is high (a typical melt contains 60% to 70% scrap), including internally generated scrap. On the other hand, recycling in applications such as lamp filaments, welding electrodes and chemical uses is low because the concentration is low and so absolutely not economic to recycle (Lasser, 1999).

Based on the material flow analysis performed in the MSA study, a 42% End of Life Input-Recycling-Rate (EOL-RIR) has been estimated (Bio Intelligence Service, 2015). This is consistent with Roskill's estimate of secondary tungsten (scrap re-use) that reached 50% in 2013 in Europe (Baylis, 2014), and ITIA's estimate of 45% (ITIA, 2014). Those updated values are higher than the old estimates made by UNEP in 2011 of 10-25% of end-of-life recycling; with secondary tungsten representing 34% of supply (10% from new scrap and 24% from old scrap) (UNEP, 2011).

40.2.3 EU trade

According to Comext database, in average between 2010 and 2014, the EU strongly relies on imports of tungsten ores and concentrates (about 37,000 tonnes of W content). Indeed, according to the raw data recorded in Eurostat, Europe's import dependence for tungsten is estimated at 94% on the 2010-2014 averaged period. However, when looking at the trade characteristics each year (see Figure 259), the situation seems to vary a lot, which is not consistent with the tungsten market reality, as according to industrial experts, during the last few years, the imports for use in the EU have been always in the range of several thousand tonnes (Wolfram, 2016). Over the 2010-2014 period, the EU industry was a fairly constant offtaker of imported material, so the fluctuations in Eurostat data appear to be largely related to erroneous data (Wolfram, 2016).

Indeed, according to industry experts, apart from minor possible re-exports by traders (which are "neutral" from the point of view of supply for the EU), imports of concentrates are therefore governed by the consumption of the plants of Wolfram Bergbau & Hütten AG and HC Starck, the only companies that have the technical ability to convert concentrates to downstream products in the EU (Wolfram, 2016). Imports of concentrates by HCS have dropped (significantly) in recent years as they have developed their joint venture in Vietnam. Imports of WBH have been rather stable, but are now declining due to offtake from the newly developed Hemerdon mine that provide concentrates within the EU (Wolfram, 2016). Imports of concentrates into the EU for use in the EU are confidential but have certainly been in the range of several thousand tonnes of contained tungsten for the past few years (certainly much less than 10,000t, and certainly significantly more than 1,000t of contained tungsten) - and this rather stable, year for year (Wolfram, 2016). This picture from the industry is clearly different from the 37,000 tonnes of imports average between 2010 and 2014 in the ComExt database (Eurostat, 2016a).

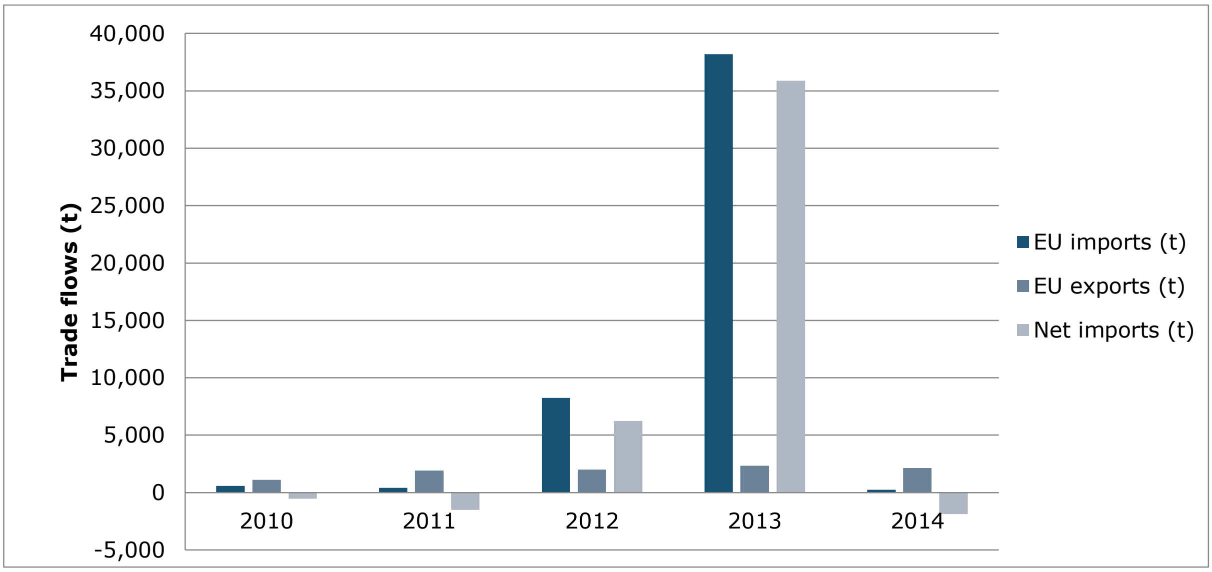

Figure 259: EU trade flows for tungsten ores and concentrates (Data from (Eurostat, 2016a), CN8 code 26110000)

In this way, the reliability of Comext data for tungsten imports have been strongly criticised by several experts of the EU tungsten market (Wolfram, 2016). Particularly, imported quantities (originating at 89% from Mexico) in the year 2013 are highly questionable, as they are in average 80% higher than the total EU imports for 2010, 2011, 2012, 2014, and as Mexico's share reaches suddenly 89% of total EU imports for that year (0% all the other years). This might be a situation of reporting error, as experts indicated that Mexico only produced 100 t (W content) maximum in 2013 and none in the previous two years. After cross-checking with Mexican exports in 2013 in the UN Comtrade database, it appears that Mexico has exported only 22 tonnes of tungsten ores and concentrates to the world, and 0 to the EU. So the Mexican exports have been excluded from Eurostat results (Figure 261). The annual EU imports corrected amounts in average 2,810 tonnes of W contained over the period 2010-2014, which is much more consistent with the estimate of 1,000 -10,000 tonnes provided by experts (Wolfram, 2016).

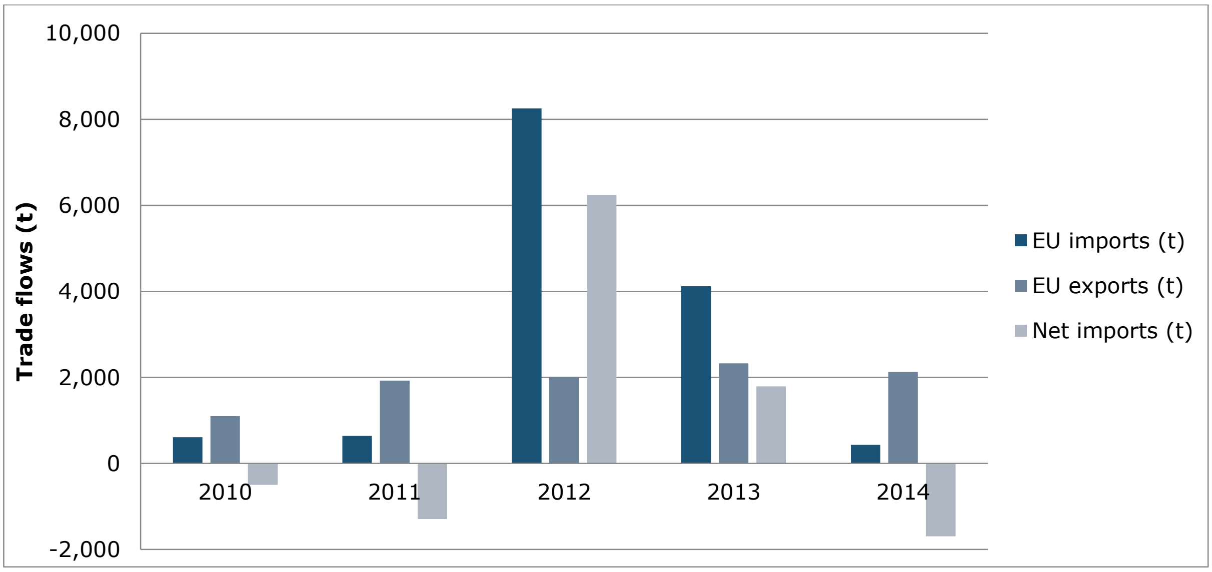

Figure 260: Corrected EU trade flows for tungsten ores and concentrates (Data from (Eurostat, 2016a), CN8 code 26110000, *corrected by removing the Mexican imports*)

The exports provided by Comext seem to be also riddled with the issue of imports re-exported: they amount about 1900 tonnes (W content, average 2010-2014) whereas the only exported production - which comes from Spain and Portugal – reaches at the maximum 1100 tonnes.

Russia appears to be the main suppliers of tungsten ores and concentrates in the EU (see Figure 261) – once Mexico removed from this list according to international trade statistics (UN Comtrade) and industrial experts (Wolfram, 2016). Experts indicated that Canada is missing from the list of EU suppliers thought it is a very important source at that time (imports from Canada into the EU in 2014 and 2015 can be estimated at 1000 tonnes each) (Wolfram, 2016). According to experts, important countries for EU supply are Russia, Canada (until 2015 / early 2016), Bolivia, Rwanda, and other confidential countries (Wolfram, 2016).

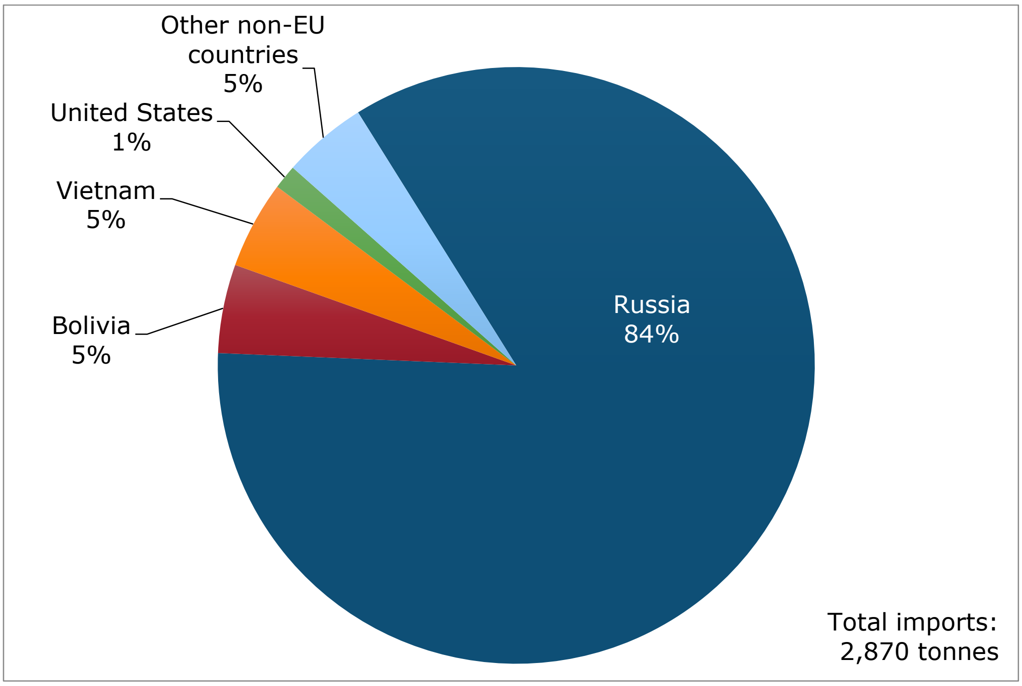

Figure 261: EU imports of tungsten ores and concentrates, average 2010-2014. (Data from Comext - Eurostat, 2016a, CN8 code 26110000, *corrected by removing the Mexican imports*)

The world major producer, China, has put a range of measures to limit exports of several kinds of tungsten, which accounts for the fact that it is not a major supplier for the EU between 2010 and 2014. China's tungsten exports were down 60% in 2013 compared to 2007 (Baylis, 2014). For example, Chinese ferrotungsten exports have all but ceased following the imposition of a 20% export tax. However, those export taxes lift back in May 2015 and quotas ended in 2015 for tungsten products but the export restriction on tungsten ores and concentrates still exist (OECD, 2016).

Russia and Vietnam have also imposed export taxes on tungsten ores and concentrates (OECD, 2016). No free trade agreements exists with EU suppliers (European Commission, 2016).

40.2.4 EU supply chain

Austria, Portugal and Spain extract tungsten ores and concentrates. The EU produced about 2,200 tonnes of W contained in ores and concentrates, only 3% of the world tungsten consumption. In average over the period 2010-2014, the EU relies on imports of tungsten ores and concentrates, with an import reliance of 44%, calculated based on corrected Eurostat data. Figure 262 presents the EU sourcing (domestic production + imports) for tungsten.

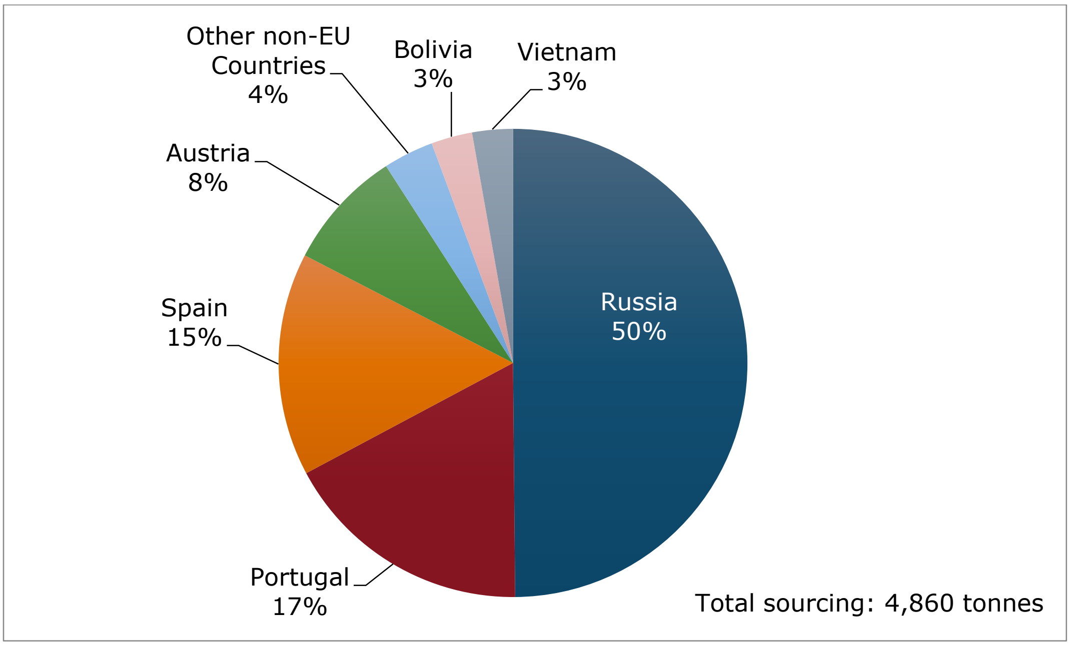

Figure 262: EU sourcing (domestic production + imports) of tungsten ores and concentrates, average 2010-2014. (Data from Eurostat, 2016a; Word Mining Congresses, 2016)

Around 45% of the European extracted tungsten is sold on the EU market. Indeed, according to experts all Austrian production – about 845 tonnes) stays in the EU (the concentrate extracted from mine is directly used by the mine owner), whereas almost the entire production (in some years the entire) from Spain and Portugal is exported (Wolfram, 2016). Forward-looking, from 2016, the Hemerdon mine in the UK will be a significant additional source inside of the EU, likely to change the entire distribution (Wolfram, 2016). Indeed, with an EU demand of several thousand tonnes of contained tungsten in concentrates per year, the EU will be self-sufficient once ramp up of the Hemerdon (Drakelands) mine in the UK is completed; even if there will be still imports, as more than half of the EU concentrate production is exported, mostly to a US subsidiary of a, EU company (Wolfram, 2016).

Wolfram Bergbau & Hütten AG (WBH) and HC Starck (HCS) are the only companies that have the technical ability to convert concentrates to downstream products in the EU. Until about 2 years ago, there was also a small ferrotungsten operation in Sweden that used a few batches of concentrates beside its usual feed from scrap (Wolfram, 2016).

40.3 Demand

40.3.1 EU demand and consumption

After an increasing tungsten demand in the EU between 2003 and 2008 (+30%), the demand for W in the EU has stabilized at about 19,500 tonnes in average on the period 2010-2013 (HC Starck, 2014). The EU represents about 20% of the world consumption, and is the second market after China (that consumes half of the W available worldwide) (Baylis, 2014). The EU demand for primary W is about 55% of the total EU consumption, completed by secondary tungsten (scrap). The total recycling rate is estimated to be around 45% in the EU, which would result in a total demand in Europe of, for example in 2013, about 18,000 tonnes of W, including the use of 8,000t of scrap (ITIA, 2014).

However, it must be noted that the EU sourcing for primary tungsten amounts about 5,000 tonnes in our estimates (i.e. a domestic annual production of 2,200 tonnes and an estimated annual imports of 2,800 tonnes), and this value seems too low to match the 10,000 tonnes of EU primary tungsten demand announced by ITIA. This difference can be explained by the fact that industrial experts have raised the issue of the absence of some important EU suppliers, such as Canada and Rwanda, in the Comext figures used in the present assessment.

40.3.2 Uses and end-uses of tungsten in the EU

Due to its exceptional physical properties, tungsten is used for a wide range of applications. The largest share is used for the production of cemented carbides. The rest is used for fabricated products, alloy steels, super alloys and tungsten alloys. The majority of tungsten is used for hard metals, whose main component is tungsten carbide (WC). They are characterized by high wear resistance even at high temperatures. Therefore hard metals are used for cutting and drilling tools. Similar properties arise from the addition of tungsten to steel. The widest range of applications is represented by tungsten alloys. They are used in lighting technology, electrical and electronic technology, high-temperature technology (e.g. furnaces, power stations), welding, spark erosion, space travel and aircraft devices, armaments and laser technology.

Relevant industry sectors are described using the NACE sector codes (Eurostat, 2016c) in Table 155.

The tungsten consumed in the EU for the manufacture of the following products (seeFigure 263) (Bio Intelligence Service, 2015):

- 67% of tungsten consumed in the EU is used for the manufacturing of tungsten carbides
- 11% of tungsten consumed in the EU is used for the manufacturing of tungsten metal
- 3% of tungsten consumed in the EU is used for the manufacturing of tungsten alloys
- 8% of tungsten consumed in the EU is used for the manufacturing of tungsten containing steels
- 11% of tungsten consumed in the EU is used for the manufacturing of chemical applications.

Tungsten cemented carbides, or hardmetals, are materials made by "cementing" very hard tungsten monocarbide grains in a binder matrix of a tough cobalt or nickel alloy by liquid phase sintering. Cemented carbides combine high hardness and strength with toughness and plasticity. Tungsten carbide is the most metallic of the carbides, and by far the most important hard phase. Due to those characteristics, tungsten carbides are used in mill and cutting tools, as well as in mining and construction tools. Other tools (wear resistance, mirrors, forming tools) are made of tungsten carbides.

Tungsten metal is used for the manufacture of fabricated products in the lighting and electronic industry. The lamp industry covers incandescent bulb filament containing W, compact fluorescent lamp, and high intensity discharge lamp HID. In the electronic & electrical industry, W metal is used as an electron emitter in integrated circuits, and also in X-ray tubes.

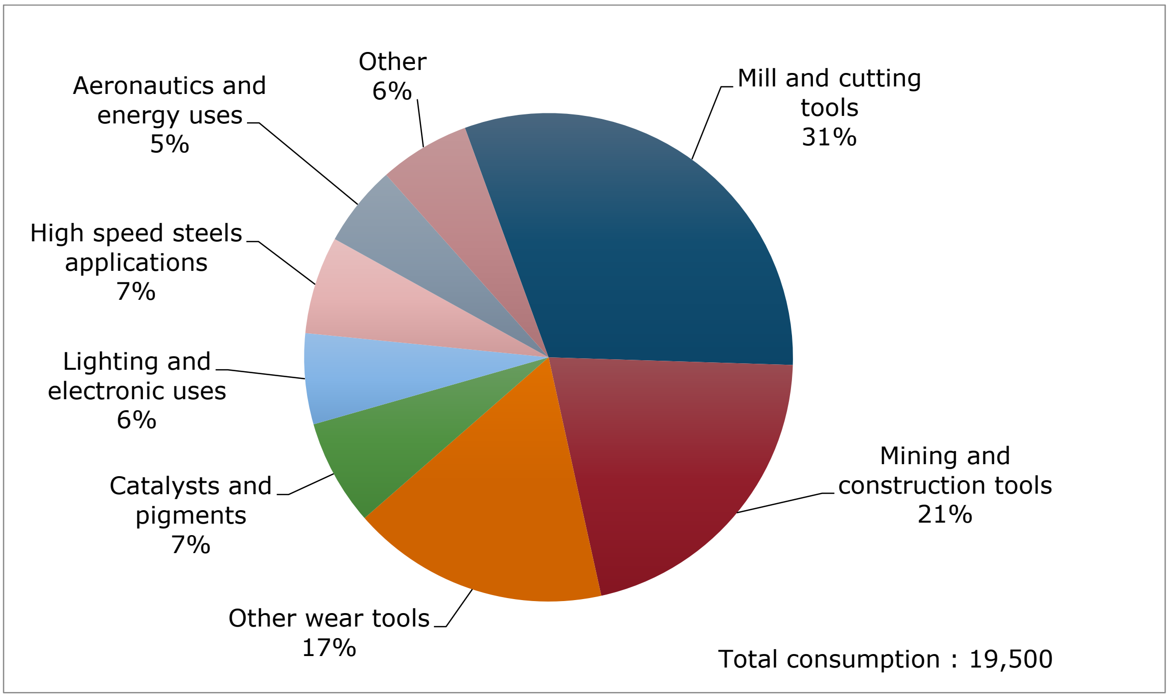

Figure 263: EU end-uses of tungsten. Average figures for 2010-2014 (Data from Bio Intelligence Service, 2015)

Table 155: Tungsten applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat, 2016c)

Applications	**2-digit NACE sector**	**Value added of NACE 2 sector (millions €)**	**4-digit NACE sectors**
Mill and cutting tools	C28 - Manufacture of machinery and equipment n.e.c.	191,000	C2841- Manufacture of metal forming machinery
Mining and construction tools	C28 - Manufacture of machinery and equipment n.e.c.	191,000	C2892- Manufacture of machinery for mining, quarrying and construction
Other wear tools	C28 - Manufacture of machinery and equipment n.e.c.	191,000	C2849- Manufacture of other machine tools
Catalysts and pigments	C20 - Manufacture of chemicals and chemical products	110,000	C2012- Manufacture of dyes and pigments; C2059- Manufacture of other chemical products n.e.c.
Lighting and electronic uses	C26 - Manufacture of computer, electronic and optical products	75,260	C2611- Manufacture of electronic components
High speed steels applications	C25 - Manufacture of fabricated metal products, except machinery and equipment	159,513	C2562- Machining
Aeronautics and energy uses	C28 - Manufacture of machinery and equipment n.e.c.	191,000	C2811- Manufacture of engines and turbines, except aircraft, vehicle and cycle engines; C2812- Manufacture of fluid power equipment; C3030- Manufacture of air and spacecraft and related machinery

Tungsten alloys and superalloys are used in the aeronautics and energy sector. W-alloys serve as counterweights in aeroplanes, helicopter-blades, rotating inertia members, x-ray and gamma ray radiation shielding, as rigid tools for machining, for darts, for weights in golf club heads, as well as for ordnance purposes (high kinetic energy penetrators, fragmentation devices, etc.

Tungsten superalloys are used in aircraft engines, marine vehicles, and stationary power units as turbine blades and vanes, exhaust gas assemblies and burner liners. They are also used as construction material for furnace parts

High speed steels (HSS) are made of tungsten steel and serve for the manufacture of various cutting tools. Tungsten steel is also used for plastic mould steels and cold/hot work steels.

Chemical applications of tungsten are mainly catalyst and pigments.

The industries that are driving the W consumption in the EU are the automotive industry, industrial engineering, mining & construction, aviation and energy (HC Starck, 2014).

40.3.3 Prices

Prices of tungsten are been multiplied by about five since 2000's, with peaks in 2006 and 2011 (the peak of 2011 was $430/mtu of WO_3 in APT) but with a recent slump which reached a 10-year low in 2016 (USGS, 2016b) (Wolfram, 2016). In 2014, one tonne of pure tungsten costs about $45,000. The figures below (Figure 264 and Figure 265) shows the evolution of tungsten metal prices ($/tonne) and prices of 10kg (= mtu) of WO_3 in APT (the most usual unit for tungsten prices). According to the DERA raw materials price monitor and the LMB Bulletin, APT prices on the European free market have decreased drastically since 2015 as it cost 353,63 US$/mtu WO_3 in average on the period 2011-2015 but only 190,04 US$/mtu WO_3 in average on the period December 2015 - November 2016, i.e. a price drop of 46.3%.

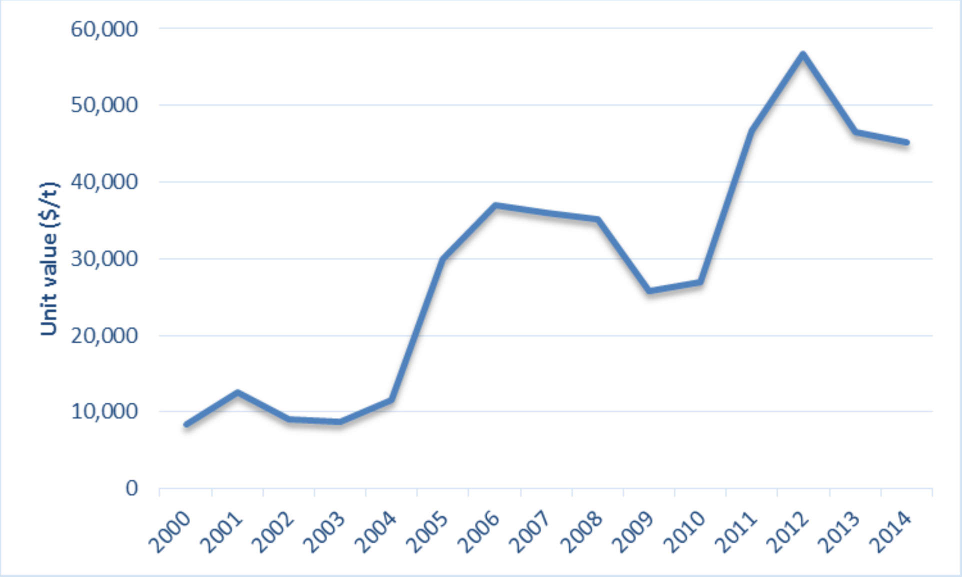

Figure 264: Tungsten prices ($/tonne) between 2000 and 2014. (USGS, 2016b)

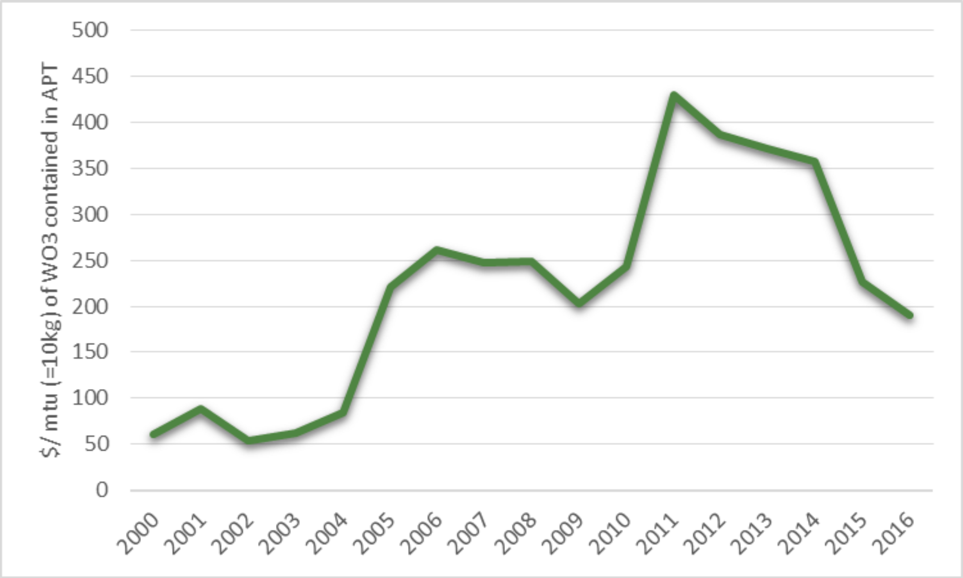

Figure 265: APT prices in \$ as mtu (=10kg) of WO_3 contained in APT. (LMB / Metal Bulletin 2017)

40.4 Substitution

Tungsten has very special performance and is most of the time the best choice of material, so very low substitution exists for this material in the industrial reality.

Molybdenum was once used to replace tungsten in the 1960-70's when tungsten was very expensive but now that the prices have fallen and stabilized in 1980’s, this substitution is not anymore needed (Eurométaux, 2016). Tungsten is even used to substitute hazardous materials such as depleted uranium and lead.

Tungsten is not really replaceable in the majority of the applications because it offers the best compromise between exceptional performance and price. For example, when tungsten prices peaked in 2011, copper was sometimes used to replace it but twice the quantity was needed to ensure the same performance (Eurométaux, 2016).

Some substitutes of tungsten can be identified for cemented carbides (hardmetals) used in mill and cutting tools, mining and construction tools, and other wear tools. Among others, molybdenum carbides and cermets (Silicon in ceramic-metallic composites) can replace tungsten carbides but the share of substitution is reduced because of reduced performance (Wolfram, 2016). Very marginal substitutes can be mentioned, such as Zirconium in ceramics, Aluminium in ceramics, super hard materials (Diamond, Cubic Boron-nitrate), Gold, Rhenium, and Tantalum; but all those materials are more expensive with most of the time a lower performance (Wolfram, 2016).

For lighting applications, tungsten filament lamps are progressively replaced by phosphorescent lamps and LEDs, which contain less or no tungsten (Wolfram, 2016).

40.5 Discussion of the criticality assessment

40.5.1 Data sources

As BGS data for world tungsten production have been criticized by experts (industrial mines in Vietnam and Australia seem to be not reported, Spain and Russia production overestimated), the data source World Mining Data (World Mining Congresses, 2016) has been preferred for the global supply assessment. Experts from ITIA and Wolfram provided feedback to complete or correct the public data.

Eurostat (ComExt) (Eurostat, 2016a) data have been used to assess the EU imports of tungsten ores and concentrates (CN8 code 26110000). Exports that are registered in the ComExt data base under the code 25051000 have not been taken into account and estimated based on expert advice. According to experts, Canada is missing from the list of EU suppliers provided by Eurostat. Supply data have been averaged on the 2010-2014 period. However, as mentioned before, Comext data for 2013 imports seem to be inconsistent, mainly due to the 62 000 tons imports from Mexico in 2013 that represent 89% of total EU imports for that year (whereas Mexico is absent from the supplier list in 2010, 2011, 2012 and 2014), and are in average 80% higher than the total EU imports for 2010, 2011, 2012 and 2014. Thus the Mexican imports have been excluded from our calculations.

40.5.2 Economic importance and supply risk calculation

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 155). The value added data correspond to 2013 figures.

The life cycle stage assessed in for the SR indicator is the extraction step. The Supply Risk (SR) is calculated using both the HHI for world production and the HHI for EU supply as prescribed in the revised methodology. China accounts for about 85% of the global supply, but Russia is the main suppliers for the EU. The EU production is exclusively performed in Austria, Portugal and Spain between 2010 and 2014. UK started in 2015, and production in 2016 was on about the same level as Austria and Spain.

40.5.3 Comparison with previous EU assessments

The results of this review and earlier assessments are shown in Table 156.

Table 156: Economic importance and supply risk results for tungsten in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Tungsten	8.75	1.81		9.05	1.99		7.3	1.8

Although it appears that the economic importance of tungsten has reduced between 2014 and 2017 this is a false impression created by the change in methodology. The value added in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a 'megasector', which was used in the previous assessments. The economic importance result is therefore reduced. The supply risk indicator is surprisingly the same as reported in the previous assessments, despite the revised methodology and the way the supply risk is calculated, in particular the Chinese quotas and the consideration of EU supply.

40.6 Other considerations

40.6.1 Forward look for supply and demand

The market outlook forecast for world tungsten demand is increasing from the current baseline, rising from about 80,000 tonnes W in 2007 to about 105,000 tonnes by 2020, with an overall industry growth forecast at 2.6% per year (Baylis, 2014), see Table 157. The split into main end-uses is as follow (Baylis, 2014):

- Cemented Carbides growth of 3.6%py,
- Steel Alloys growth of 3.0%py ,
- Tungsten Products growth of -3.2%py (Incandescent lamps in freefall),
- Chemicals/Other growth of 3.5%py.

Table 157: Qualitative forecast of supply and demand of tungsten (Data from Baylis, 2014)

Material	Criticality of the material in 2017		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Tungsten	x		+	+	?	+	+	?

According to industry experts, this growth forecast of 2.6% pa seems overly optimistic (Wolfram, 2016).

Significant changes have happened over the past few years in the tungsten market, which will impact the entire distribution: closure of Cantung mine in 2015 (Canada), opening of new mines in Vietnam (Nui Phao – the biggest mine outside China) in 2013 and in England (Hemerdon) in 2016; increase of recycling; and implantation of HC Starck joint venture in Vietnam leading to preferred import of Vietnamese tungstates instead of international concentrates (Wolfram, 2016).

With an EU demand of several thousand tonnes of contained tungsten in concentrates per year, the EU will be self-sufficient once ramp up of the Hemerdon (Drakelands) mine in the UK is completed; even if there will be still imports, as more than half of the EU concentrate production is exported, mostly to a US subsidiary of a, EU company (Wolfram, 2016).

According to industry experts, there would be no lack of resources or reserves to fully supply EU needs in concentrates would there be no economic or price concerns (Wolfram, 2016). However, experts stated that tungsten will remain a critical raw material for the EU in the coming 10 years, in particular due to its non-negligible dependency on extra-EU imports (44%) and the price tensions (WKO, 2016).

Strategic Industrial Planning Policies from PR China has encouraged an important mostly state-owned overcapacity and huge unknown levels of inventory in China. This artificial discrepancy between offer and demand of an untraded material has led to prices below profitability thresholds for most mining operations and some western operations are currently shutting down, leaving the western tungsten-consuming industries vulnarable to the quality and volumes made available by China (WKO, 2016). It is not certain if EU mines survive prolonged periods of low raw material prices as they cannot really count on state support (as it is the case in China) (Wolfram, 2016). Thus, true criticality for tungsten relates more to the dominating position of China with respect to influencing prices, support of the Chinese tungsten industry by the state, the lack of a level playing field, and the extension of anti-dumping measures (Wolfram, 2016).

40.6.2 Environmental and regulatory issues

Chronic inhalation or severe exposure to airborne tungsten dust particles and ingestion of large amounts of soluble tungsten compounds is known to be hazardous to human health (BGS, 2011).

However, tungsten and its compounds are not actually concerned by REACH, except nickel tungstate ($NiWO_4$) cited as carcinogen in the Appendix 1 of Annex XVII as nickel compound. In addition, the cemented tungsten carbide sector will be seriously impacted by upcoming reclassification of tungsten carbide-Cobalt compounds (presence of cobalt as binder) in REACH (WKO, 2016). The substitution products will be less performing, more expensive and not necessarily more health and/or environment friendly (WKO, 2016).

Tungsten is one of the conflict minerals targeted by an US regulation and soon an EU regulatory initiative.

The Regulation (EU) 2017/821 of the European Parliament and of the Council sets up a Union system for supply chain due diligence self-certification in order to curtail opportunities for armed groups and unlawful security forces to trade in tin, tantalum and tungsten, their ores, and gold. It will take effect on 1 January 2021. It is designed to provide transparency and certainty as regards the supply practices of importers, (notably smelters and refiners) sourcing from conflict-affected and high-risk areas. The EU regulation covers tin, tantalum, tungsten, and gold because these are the four metals that are most mined in areas affected by conflict or in mines that rely on forced labour.

The regulation also draws on well-established rules drawn up by the Organisation for Economic Co-operation and Development (OECD) in a document called 'Due Diligence Guidance for Responsible Supply Chains from Conflict-Affected and High-Risk Areas.' The regulation only applies directly to EU-based importers of tin, tantalum, tungsten and gold, whether these are in the form of mineral ores, concentrates or processed metals.

The US also has legislation on conflict minerals: Section 1502 of the Dodd-Frank Wall Street Reform and Consumer Act of 2010, which covers the same four products. It includes a requirement that companies using gold, tin, tungsten and tantalum make efforts to determine if those materials came from the Democratic Republic of Congo (DRC) or an adjoining country and, if so, to carry out a "due diligence" review of their supply chain to determine whether their mineral purchases are funding armed groups in eastern DRC (Federal Register, 2010).

EU industry players are concerned around the EU Conflict Mineral rule which might favours production of tungsten outside of the EU and unfair competition (Wolfram, 2016).

40.7 Data sources

40.7.1 Data sources used in the factsheet

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40.8 Acknowledgments

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41. VANADIUM

Key facts and figures

Material name and Element symbol	Vanadium, V	World/EU production (tonnes)[1]	Refined: 71,026/ 1,650
Parent group (where applicable)	N/A	EU import reliance[1]	84%
Life cycle stage/ material assessed	Processing, refined material	Substitution index for supply risk [SI(SR)][1]	0.94
Economic importance score (EI) (2017)	3.7	Substitution Index for economic importance [SI(EI)][1]	0.91
Supply risk (SR) (2017)	1.6	End of life recycling input rate	44%
Abiotic or biotic	Abiotic	Major end uses in the EU[1]	HSLA (e.g. pipes) (60%), Special steel (30%) Super alloys (3%)
Main product, co-product or by-product	Co-product and main product	Major world producers[1]	Refined: China (53%), South Africa (25%), Russia (20%)
Criticality results	2011	2014	2017
	Not critical	Not critical	Critical

[1] average for 2010-2014, unless otherwise stated;

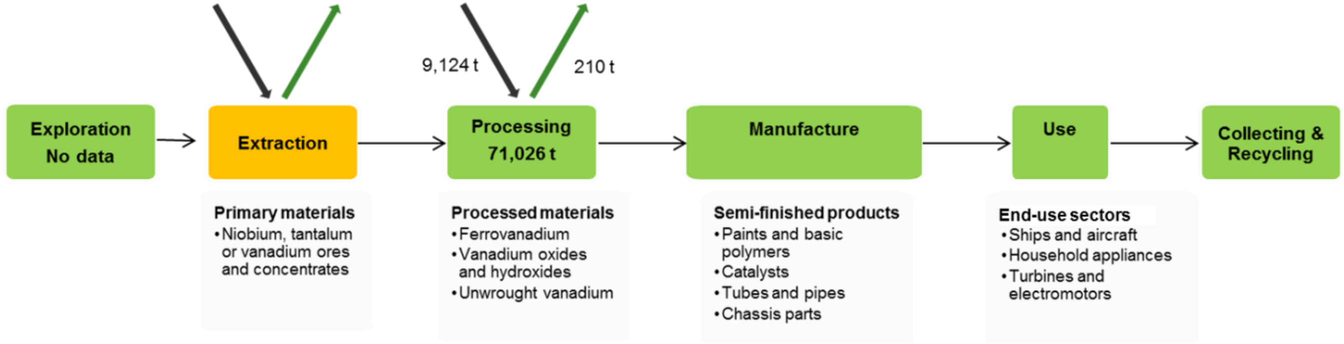

Figure 266: Simplified value chain for vanadium

The orange boxes of the extraction stage suggests that activities are not undertaken within the EU. The black arrows pointing towards the Extraction and Processing stages represent imports of material to the EU and the green arrows represent exports of materials from the EU. A quantitative figure on recycling is not included as the EOL-RIR is below 70%. EU reserves are displayed in the exploration box.

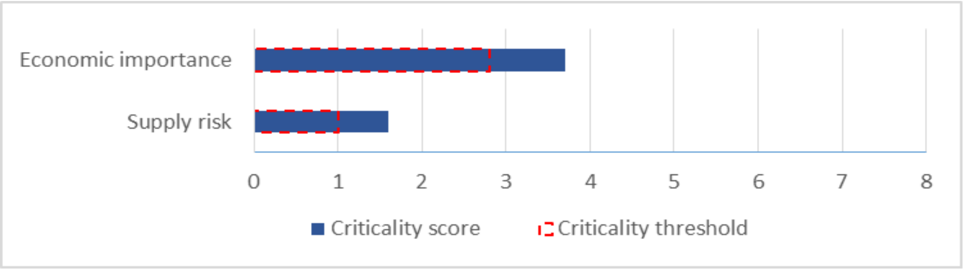

Figure 267: Economic importance and supply risk scores for vanadium

41.1 Introduction

Vanadium (V) is a steel-grey, bluish, shimmering and ductile metallic element with the atomic number 23 and a density of 6.11 g/cm^3. Its melting point is 1,910°C and its boiling point is 3,407°C. Vanadium occurs in many minerals and is basically obtained as a by-product from the production of steel. Vanadium's earliest use was in 1903, when vanadium-alloyed steel was produced. Vanadium resists corrosion due to a protective film of oxide on the surface. Its main application is as an additive in steel and titanium alloys alloy steels to improve their strength and resistance to corrosion, as well as a catalyst for chemicals (BGS, 2015).

41.2 Supply

41.2.1 Supply from primary materials

41.2.1.1 Geological occurrence/exploration

The presence of vanadium in the earth's crust is moderate, with 97 parts per million upper crustal abundance (Rudnick & Gao, 2003); in seawater it is estimated to be about 0.0014 ppm. Among 65 minerals that contain vanadium, the most common vanadium minerals include patronite (VS_4), vanadinite [$Pb_5(VO_4)_3Cl$], and carnotite [$K_2(UO_2)_2(VO_4)_2$ $_3H_2O$]. Vanadium is also present in phosphate, bauxite and iron ores. Moreover, it is present in fossil fuel deposits such as oil and coal.

41.2.1.2 Processing and refinery

Vanadium, as primary material, is mainly produced as co-product from vanadium slag before the steel convertor. It is important to appreciate the difference between steel slag and vanadium slag. The processing of vanadium slag is a hot metal pre-treatment, resulting in vanadium products. That is why vanadium is assessed at the refining stage, as vanadium oxides (V_2O_5 and V_2O_3). Figure 268 shows the sources and the most common production routes.

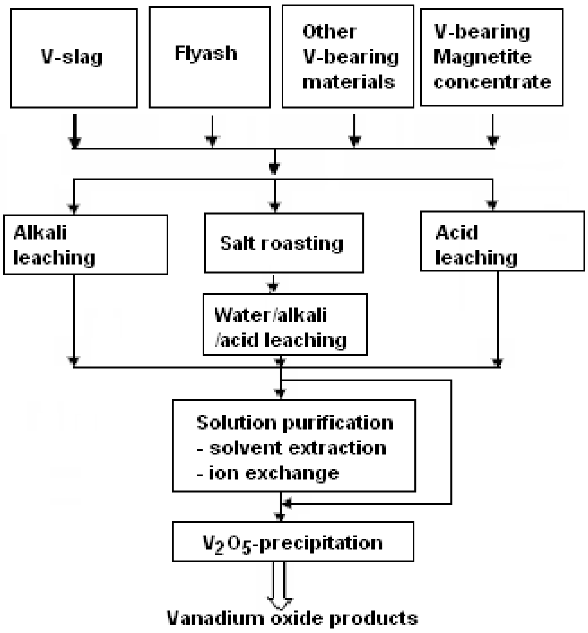

Figure 268: Production routes of vanadium

The vanadium slag process can be described as follows. Vanadium-titanomagnetite ores globally constitute the main source for production of vanadium containing commodities, most importantly vanadium pentoxide (V_2O_5) and ferrovanadium (FeV). FeV is produced from vanadium (III) oxide (V_2O_3) or (V_2O_5). Extraction of vanadium as co-product to iron is usually done by concentrating the vanadium into a vanadium-slag. Production of vanadium-slag involves two main pyro-metallurgical steps. At first, the ore concentrate or DRI (Direct Reduced Iron) is reduced to a hot metal with a vanadium content in the range of 0.4 to 1.3 mass%. In the second step, the vanadium in the hot metal is oxidized to the vanadium slag at around 1673 Kelvin. The vanadium slag is an acid FeO-SiO_2 based slag with normally 9 to 15 mass percentage of vanadium. The vanadium slag is then converted to (V_2O_5) by a salt roast and leach process. Vanadium slag is oxidized by oxygen and transformed into water soluble sodium vanadates in the presence of sodium salts (Na_2CO_3, NaCl, NaOH and/or Na_2SO_4). Thereafter, (V_2O_3) or (V_2O_5) is obtained from the leachate by precipitation and calcination (Lindvall et al., 2016).

About 30% or primary vanadium produced from direct leaching of vanadium ores. Titanomagnetite is by far the most important one a by-product, mainly from vanadium slags, although other sources are available. (SWEREA, 2016)

Other mineral oils, uranium-vanadium ores, bauxite, phosphate rock and lead vanadates can contain vanadium, although vanadium from these sources is sometimes considered secondary material.

41.2.1.3 Resources and reserves

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of vanadium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template[29], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for vanadium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for vanadium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for vanadium at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU, 2015).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts

According to USGS (USGS, 2017), world resources of vanadium exceed 63 million tons. Because vanadium is typically recovered as a byproduct or coproduct, demonstrated world resources of the element are not fully indicative of available supplies. For the EU,

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[29] www.crirsco.com

the Minerals4EU website (Minerals4EU, 2014) only provides resources data for Sweden, with 24.6 million tonnes of Historic Resource Estimates for vanadium, or 140 million tonnes at 0.2% of V of inferred resources in the JORC reporting code.

According to USGS (USGS, 2017), the world known reserves of vanadium are about 19 million tonnes. The reported reserves of vanadium are listed in Table 158. The Minerals4EU website (Minerals4EU, 2014) reports no reserves for the EU member states and only provides reserves data for Ukraine, with 15,500 tonnes of V_2O_5 contained in vanadium ores (C1 of Russian Classification).

Table 158: Estimated global reserves of vanadium (material content) in 2015 (Data from USGS, 2017 and GSF, 2012)

Country	**Estimated Vanadium Reserves (tonnes)**
China	9,000,000
Russia	5,000,000
South Africa	3,500,000
Australia	1,800,000
USA	45,000
Sweden*	15,000
Finland*	25,000
Norway*	55,000
Others	N/A
Brazil	N/A
World total (rounded)	*19,000,000*

* Data from (USGS, 2015)

41.2.1.4 World production

Global production of vanadium between 2010 and 2014 amounted to annually 71,026 tonnes. The only reported producers of vanadium in the shape of vanadium oxides are China, South Africa, Russia and Kazakhstan (Figure 269).

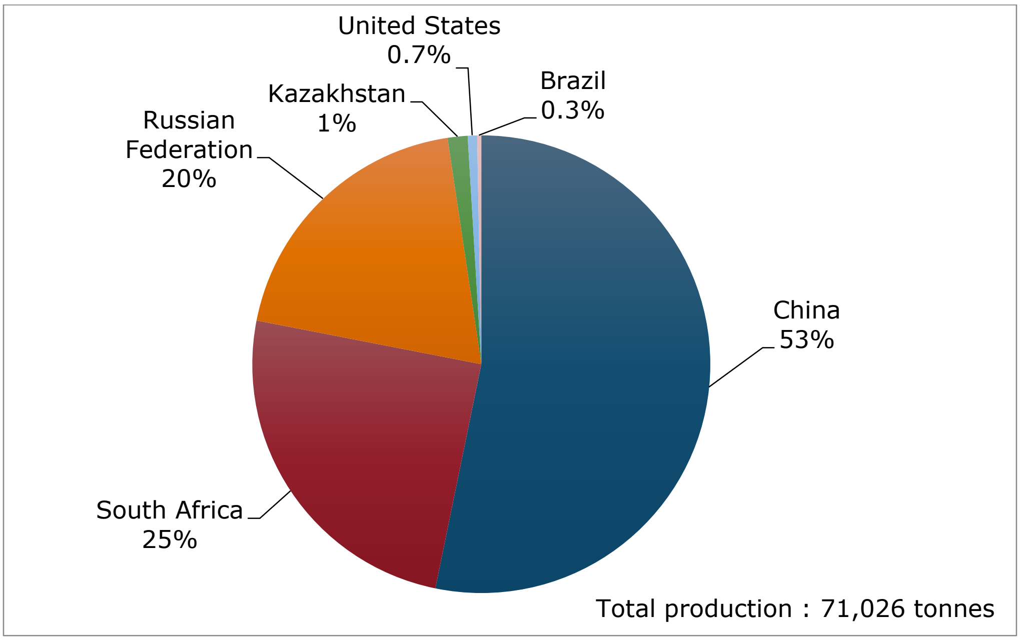

Figure 269: Global production of vanadium in tonnes, average 2010–2014 (Data from BGS World Mineral Statistics database, 2016)

In 2008, 43.86 % of the global production came from one single company and three companies roughly split 60% of the market between them (EC, 2014).

41.2.2 Supply from secondary materials

Two kinds of secondary vanadium scrap can be discerned: steel scrap, which was recycled along with the vanadium content, and spent chemical process catalysts.

The collection and handling of vanadium-containing metal scrap are fairly straightforward. Scrap is generated during semi-fabrication and manufacturing operations and consists of items such as clippings, stampings, and turnings. These are usually segregated by material specification and returned to controlled-atmosphere induction furnace operations, where the scrap is matched and melted into a product having the desired chemistry (Wernick & Themelis, 1998). Co-producers (via vanadium slag) and primary producers generally are the lowest cost producers. Those recovering vanadium from spent catalyst, fly-ask, uranium and stone coal mining incur the highest cost. This is the reason that the share of secondary sources for vanadium production has dropped in the last years (Lindvall, 2015).

Entry barriers for new producers are high, with long development time required to master technology, large capital exposure and market risks.

Secondary vanadium can also be obtained from fossil fuel processing. Vanadium is present in crude oil in the Caribbean basin, parts of the Middle East and Russia, as well as in tar sands in western Canada. Coal in parts of China and USA contains vanadium as well. During the refining or burning of these energy sources a vanadium bearing ash, slag, spent catalyst or residue is generated which can be processed for vanadium recovery (Lindvall, 2015).

Vanadium-bearing catalysts are used in hydrocarbon processing to remove nickel and vanadium from the process stream. The material recovered (residue) is processed for the metal content, and the spent catalysts are recycled (Goonan, 2011).

The total share of world production of vanadium from secondary sources has increased in the period of 2004 to 2010 and is now believed to be at around 44%. Important to note is that this includes vanadium supply from alloy recycling. Without this input, secondary sources would cover 15% of the required vanadium input (SWEREA, 2016).

41.2.3 EU trade

Russia is by far the most important supplier of vanadium oxides to the EU, taking almost 71%, or 6,452 tonnes, of the import share to the EU (see Figure 270 and Figure 271). China and South Africa follow with either 13%. The world’s main producers of vanadium oxides, China, seem to direct their extractions to other destination outside the EU or use the commodity themselves.

EU trade is analysed using product group codes. It is possible that materials are part of product groups also containing other materials and/or being subject to re-export, the "Rotterdam-effect". This effect means that materials can originate from a country that is merely trading instead of producing the particular material.

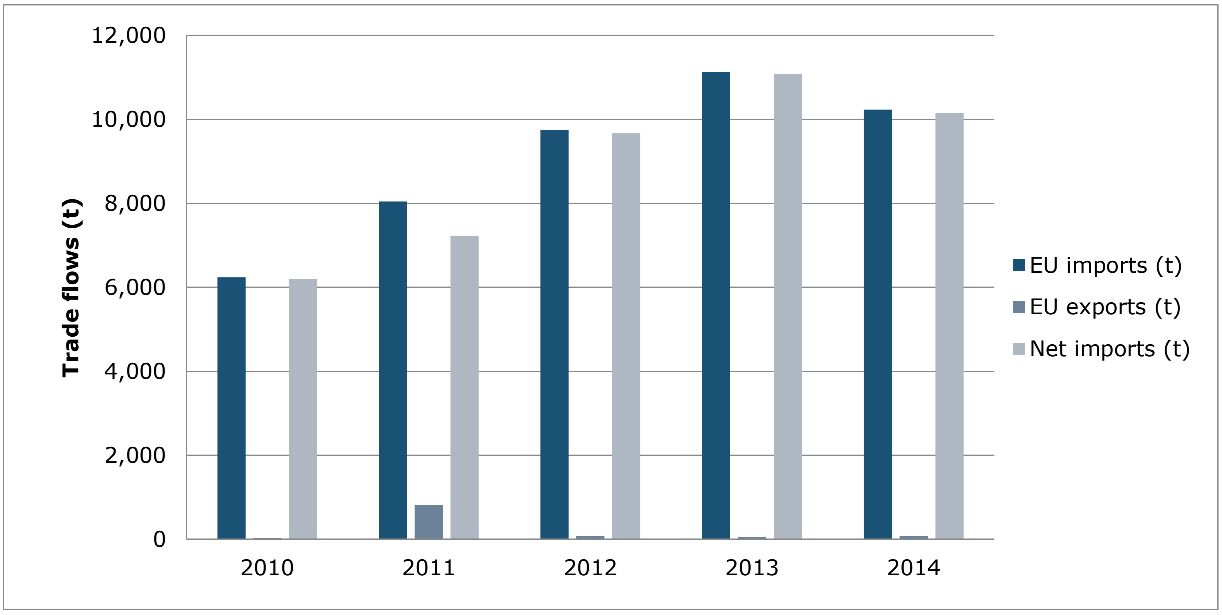

Figure 270: EU trade flows for vanadium oxides. (Data from Eurostat Comext, 2016)

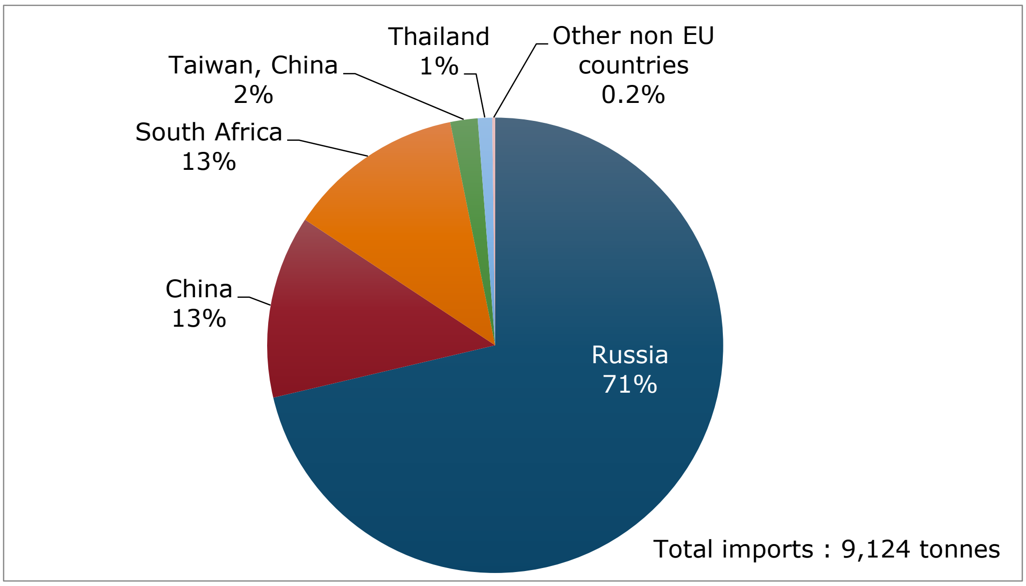

Figure 271: EU imports of vanadium oxides, average 2010-2014. (Data from Eurostat Comext, 2016)

41.2.4 EU supply chain

There is no extraction of vanadium in the EU. The EU is fully (100%) reliant on its imports of vanadium ores and concentrates and that situation is not likely to change given recent market activities of public investments.

There are around ten major mine corporations engaged in vanadium extraction and refinery, located in the US, Australia, China, Canada, South Africa but also in Austria, Germany the Czech Republic.

China is the only nation to tax vanadium oxides, at 5%. China also taxes vanadium ores and concentrates (essentially Ni, Ta & V ores) at 30%, the Democratic Republic of Congo applies 10% tax (OECD, 2016). Burundi, Russia and South Africa have a licensing requirement. There are a limited number of trade restrictions being applied to vanadium metal Morocco, Vietnam and Argentina have a tax on vanadium, whereas China applies an export quota of 231 tonnes (OECD, 2016).

The EU produces about 1,650 tonnes of vanadium oxides (mainly in Belgium, UK, the Netherlands and Germany) and imports about 9,100 tonnes. The import reliance is 84%. The EU sourcing (domestic production + imports) is presented in Figure 272.

The base metal production is Europe is relatively less specialized in the use of vanadium. Annually, about 2,000 tonnes of ferrovanadium are produced in Czech Republic (BGS, 2015). There is some economic activity in the EU specialized in vanadium recycling.

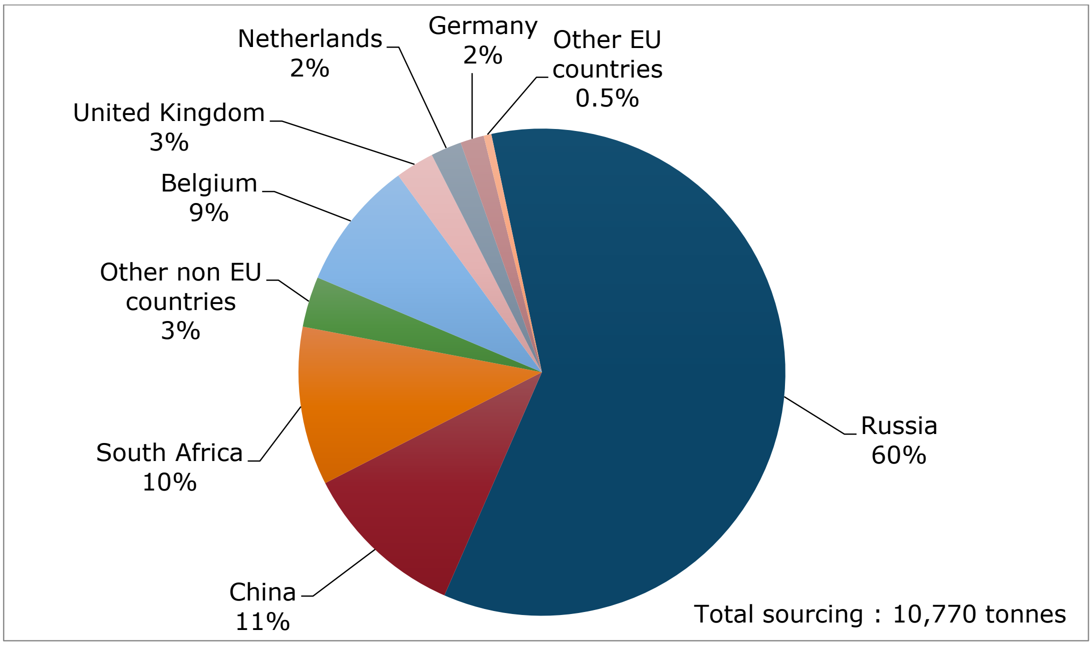

Figure 272: EU sourcing (domestic production +imports) of vanadium oxides, average 2010-2014. (Data from Eurostat Comext, 2016)

41.3 Demand

41.3.1 EU consumption

The EU consumption of vanadium is around 10,770 tonnes. The amount of vanadium being trade in the shape of oxides through the EU as re-exports is around 210t.

41.3.2 Applications / End uses

The global end-uses of vanadium are shown in Figure 273. Most of the vanadium (about 80%) produced is used as ferrovanadium or as a HSLA additive. Mixed with aluminium in titanium alloys is used in jet engines and high speed air-frames, and tool steel alloys are used in axles, crankshafts, gears and other critical components. Vanadium alloys are also used in nuclear reactors because vanadium has low neutron-adsorption abilities and it does not deform in creeping under high temperatures (Lenntech, 2016).

Vanadium oxide (V_2O_5) is used as a catalyst in manufacturing sulfuric acid and maleic anhydride and in making ceramics. It is added to glass to produce green or blue tint. Glass coated with vanadium dioxide (VO_2) can block infrared radiation at some specific temperature (Lenntech, 2016). V_2O_3 is used as feedstock for ferrovanadium production due to lower Al consumption.

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 159). The value added data correspond to 2013 figures.

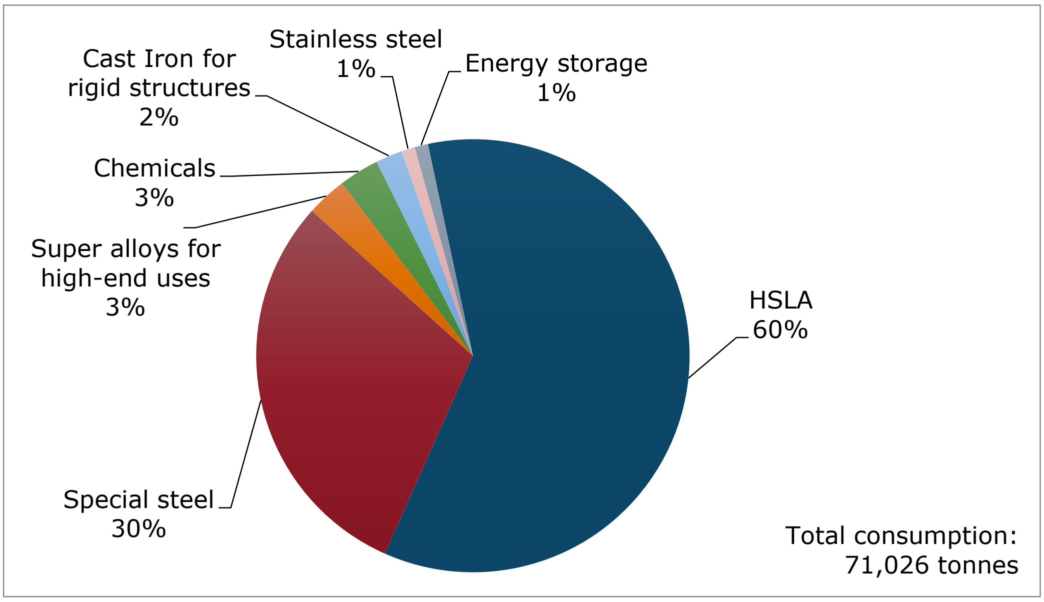

Figure 273: Global end-uses of vanadium in tonnes. Average figures for 2010-2014 (Data from Atlantic ltd, 2016)

Table 159: Vanadium applications, 2-digit NACE sectors, associated 4-digit NACE sectors, and value added per sector (Data from the Eurostat database, Eurostat, 2016)

Applications	2-digit NACE sector	4-digit NACE sector	Value added of sector (M€)
HSLA	C24 - Manufacture of basic metals	24.45 Other non-ferrous metal production	13,547.3
Special steel	C25 - Manufacture of fabricated metal products, except machinery and equipment	25.29 Manufacture of other tanks, reservoirs and containers of metal	110,000.0
Super alloys for high-end uses	C29 - Manufacture of motor vehicles, trailers and semi-trailers	29.20 Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers	57,000.0
Chemicals	C20 - Manufacture of chemicals and chemical products	20.12 Manufacture of dyes and pigments	159,513.4
Cast Iron for rigid structures	C30 - Manufacture of other transport equipment	29.20 Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers	84,608.9
Stainless steel	C28 - Manufacture of machinery and equipment n.e.c.	28.11 Manufacture of engines and turbines	191,000.0
Energy storage	C27 - Manufacture of electrical equipment		158,081.4

- **Steel (HSLA -** high-strength low-alloy**):** The key demand driver at the current time is a move to lighter weight and higher strength steels. The addition of just 0.2% vanadium to steel increases steel strength by up to 100% and reduces weight in relevant applications by up to 30% (Infomine, 2016). Vanadium itself is soft in its pure form, but when it is alloyed with other metals such as iron, it hardens and strengthens them significantly. Consequently, vanadium is used extensively to make alloys (mostly steel alloys) for tools and construction purposes. Most of the vanadium consumed is used for these applications.

- **Steel (Carbon):** Vanadium is also alloyed with iron to make carbon steel, next to the HSLA mentioned above. These hard, strong ferro-vanadium alloys are used for military vehicles and other protective vehicles. It is also used to make car engine parts that must be very strong, such as piston rods and crank shafts.
- **Chemical applications:** Some vanadium is used in other industrial applications. For example, vanadium pentoxide (V_2O_5) is used production of glass and ceramics and as a chemical catalyst.

41.3.3 Prices

The prices of vanadium are reported to be influenced by production process management costs, rather than by markets and trade developments. Over the last ten years vanadium is one of the materials that have witnessed the greatest price volatility (EC, 2014). The average price of ferrovanadium, containing 78% of V, between 2011 and 2015 was 25.11 US$/kg (DERA, 2016). Figure 274 shows the price development of ferrovanadium from 2005 to 2015.

Figure 274: Price development of ferrovanadium (Data Infomine, 2017)

41.4 Substitution

Vanadium as an alloying component in steel can be replaced by manganese, molybdenum, niobium, titanium, and tungsten to some extent. These options are available for all major uses of ferrovanadium, in tubes and pipes, turbines, automotive parts and building materials. Ferrovanadium used as noble alloy for special steel (FeV80, FeV50) can be substituted partially by FeNb. A study done on niobium for vanadium substitution in steel making (Korchynsky, 2004), concluded that 46% of vanadium used in steel could potentially be substituted by niobium. One of the main factors defining the degree of substitution is the relative price difference between the two alloys.

Vanadium compounds as catalysts are interchangeable with platinum and nickel in several chemical processes. Titanium is a substitute for vanadium use in paints and varnishes, a specific part of the chemical applications of vanadium. Batteries using vanadium are serving a growing market, that has to be assumed can also be served by batteries containing more conventional materials from the alkaline group.

41.5 Discussion of the criticality assessment

41.5.1 Data sources

The data sources of vanadium are generally good. Time series are available, global production and trade of vanadium can be taken from the data.

Given the large share of vanadium from processing, the CN code of vanadium oxides is chosen as the most appropriate product group to assess the criticality of vanadium, the CN code is 28 25 3000.

The extraction stage was not been chosen for the assessment because of the uncertainty of the data for vanadium ores, grouped in the same Comext CN product group with tantalum and niobium. Indeed, the shares of vanadium versus tantalum and niobium in the CN product group are not known (Lindvall, SWEREA).

41.5.2 Calculation of Economic Importance and Supply Risk indicators

The economic importance of vanadium has sources indicating the use of vanadium in final products. Therefore, sectors at the end of the supply chain are also part of the vanadium allocation. See also Table 159.

The supply risk was assessed on vanadium oxides (V_2O_5 and V_2O_3) using both the global HHI and the EU-28 HHI as prescribed in the revised methodology. The mining activities aimed at vanadium are, according to experts, hard to map (Chavasse, 2016).

41.5.3 Comparison with previous EU assessments

The results of this review and earlier assessments are shown in Table 160.

Table 160: Economic importance and supply risk results for vanadium in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017

Assessment	2011			2014			2017	
Indicator	EI	SR		EI	SR		EI	SR
Vanadium	9.7	0.7		9.1	0.8		3.7	1.6

The main difference from the previous two assessments is the lower score for vanadium in Economic Importance. This is, as in the case of some other alloying materials, probably due to the allocation to NACE-2 sectors rather than the “Megasectors”. This approach had the base metal products and more advanced metal products assigned to megasectors with high Value Added totals such as machinery and transport equipment. The share of these end-use sectors at the end of value chains is now smaller.

The SR result for 2017 is based on trade data for vanadium ore using both the global HHI and the EU28 HHI as prescribed in the revised criticality methodology. In the 2014 assessment, the major global producers were South Africa (37%), China (36%) and

Russia (24%). The 2017 assessment also identifies these countries as the major global producers, however with slightly different shares: China 53%, which ranks as first producer, South Africa 25% and Russia 20%. Contrary to the 2014 assessment, the 2017 assessment incorporates trade data on actual EU sourcing (shown in Figure 272), which takes into account the EU supply to estimate the Supply Risk. The dependency of Russia and China for almost 85% of the European imports explains the high SR result.

41.6 Other considerations

41.6.1 Forward look for supply and demand

Future supply from South Africa will be influenced by the recent closure of Evraz Highveld mine (Evraz Highveld, 2016). Demand for vanadium in the EU is projected to increase in all sectors (steel, titanium, chemicals and energy storage), especially driven by increased steel production, compounded by an increasing unit consumption of vanadium per ton of steel (SWEREA, 2016), see Table 161.

Future demand seems to be influenced by innovations in the manufacturing of battery products. Roskill's vanadium report includes a focused chapter dedicated to the use cases, competing technologies, advantages, disadvantages and economics of vanadium redox batteries. To 2026, it is expected the market for stationary energy storage to increase (Roskill, 2016). Application of vanadium in the Vanadium Redox battery (close to 2,000 tonnes of vanadium world demand in 2016) is rapidly growing. Some analysts predict demand for vanadium in this battery for mass storage of energy (solar, wind) could increase to over 10,000 tonnes annually in the next 5 years (SWEREA, 2016).

The Mustavaara Kaivos Clean Slag project could significantly increase vanadium supply from the EU in the future. Production is expected to amount to some 5,000 tonnes annually of FeV80 which should significantly reduce the EU's current dependence on vanadium imports (SWEREA, 2016).

Table 161: Qualitative forecast of supply and demand of vanadium

Material	**Criticality of the material in 2017**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Vanadium	x		+	+	+	+	+	+

41.6.2 Environmental and regulatory issues

It has been estimated that around 65,000 tonnes of vanadium annually enter the environment from natural sources (crustal weathering and volcanic emissions) and around 200,000 tonnes as a result of man's activities. The major anthropogenic point sources of atmospheric emission are metallurgical works (30 kg per tonne of vanadium produced), followed by the burning of crude or residual oil and coal (0.2-2 kg per 1,000 tonnes and 30-300 kg per 106 litres). Global vanadium emissions into the atmosphere from coal combustion in 1968 were estimated to range from 1,730 to 3,760 tonnes. The contribution of vanadium to the atmosphere from residual-fuel combustion was estimated at 12,400-19,000 tonnes in 1969 and 14,000-22,000 tonnes in 1970. In the production of ferrovanadium for alloy additions in steel-making, vanadium emission to the atmosphere was estimated at 144 tonnes in 1968. The burning of wood, other vegetable matter and solid wastes probably does not result in significant vanadium emission. In 1972, about 94% of all anthropogenic emissions of vanadium to the atmosphere in Canada (2,065 tonnes) resulted from the combustion of fuel oil and only 1.2% from metallurgical industries (WHO 2000).

41.7 Data sources

41.7.1 Data sources used in the factsheet

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