16 NATURAL GRAPHITE

16.1 Overview

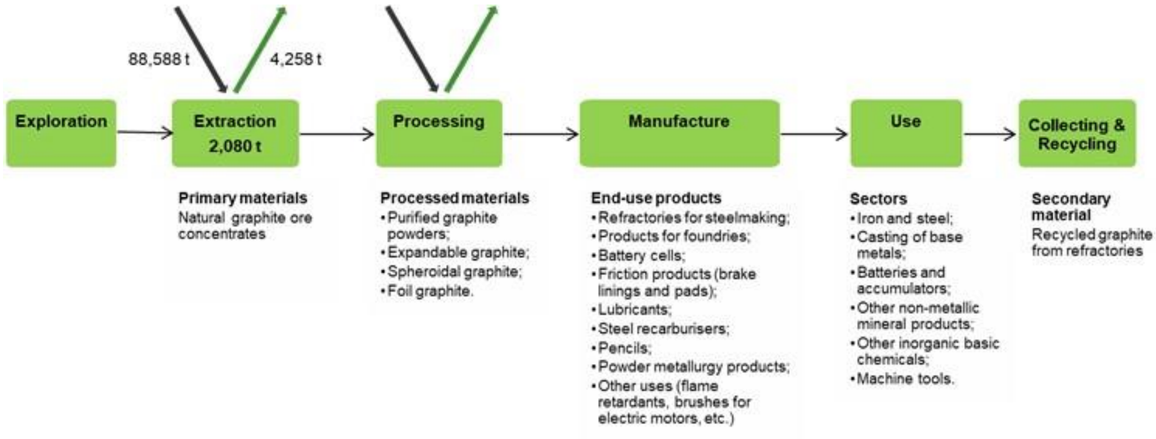

Figure 193: Simplified value chain for natural graphite[164] (average 2012-2016)

Natural graphite (C, atomic number 6) 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 perfect basal cleavage. It consists of planar sheets formed from three-coordinated carbon atoms. Intra-planar bonding is powerful, 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 (3,650 ºC). Graphite has a high thermal resistance and lubricity, is resistant to corrosion, chemically inert and non-toxic. These properties make it a raw material with a wide range of uses. There are three types of natural graphite for commercial use, classified by purity and particle size: flake graphite (with a distinct flake structure that is categorised by the industry in terms of size as fine, medium or large), amorphous graphite (with no flake structure and typically lower carbon grade) and vein graphite (a speciality product only produced in Sri Lanka).

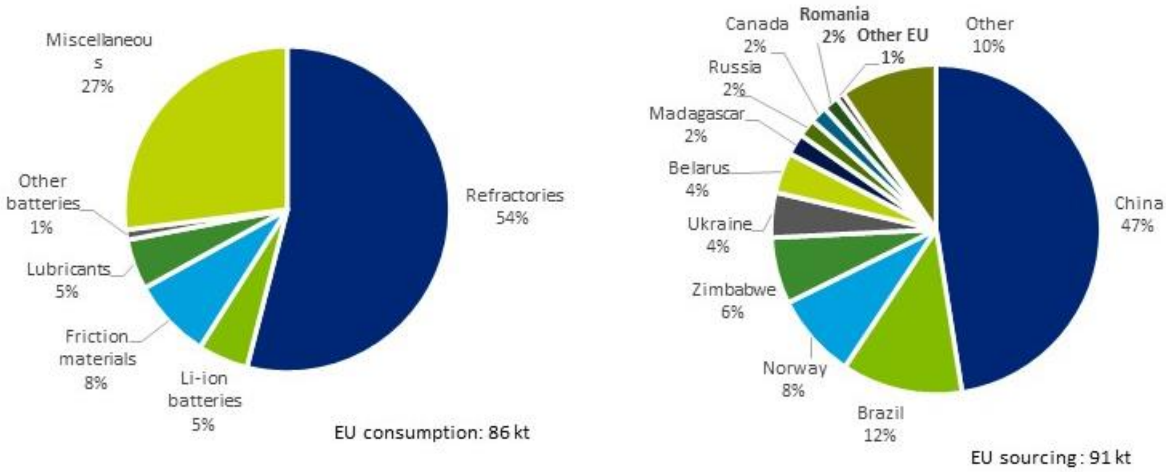

Figure 194: End uses of natural graphite in the EU, and EU sourcing of natural graphite (average 2012-2016)

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

In the criticality assessment natural graphite is analysed at the extraction stage. The trade codes used in this assessment are: CN 25041000 "Natural graphite in powder or in flakes"; CN 25049000 "Natural graphite (excl. in powder or in flakes)". A carbon content of 95% is assumed for trade flows. Quantities are expressed in C content, and all figures are averaged over the five years 2012–2016 unless otherwise mentioned.

China is the largest world producer and exporter of natural graphite with 71% and 59% market shares, respectively, in 2017. China is the dominant consumer of natural graphite used in batteries, and the only commercial-scale producer for battery-grade spherical graphite. Natural graphite's consumption is directly related to the production of steel, due to its widespread use in refractories. The deployment of electric vehicles and the development of energy storage systems is projected to drive most of the growth of future natural graphite demand. The outlook for future supply is positive as supply is increasing from Africa led by the ramp up of production in Mozambique, and as a number of large-scale natural flake graphite projects are anticipated to reach production by 2025.

Following the 2011 market boom when flake graphite prices soared due to China's huge steel needs, prices returned to low levels due to excess production and weak demand from the steel industry. A short-term recovery occurred in 2018 driven by reduced supply and strong demand for Li-ion batteries, but prices have been suppressed again as supply from new projects in Africa began to ramp up. Flake graphite of higher purity and size attracts premium prices, whereas amorphous prices are much lower. Heavily processed graphite products such as spherical graphite command significantly higher prices.

The EU consumption of natural graphite is about 86 kt, of which only 2% is sourced through domestic production. China is the principal supplier of natural graphite, providing almost half of the EU demand (47%). Other important suppliers are Brazil (12%), Norway (8%) and Zimbabwe (7%). The EU import reliance for natural graphite is 98%.

Due to its diverse properties, natural graphite is a material applied in a broad spectrum of industrial sectors. Although only a small proportion of refractories contain graphite, refractories for steelmaking are the leading consumer of natural graphite. Other uses include foundry applications, lubricants, friction materials, batteries, brushes for electrical motors, sealing applications, fire retardants, and pencils. Synthetic graphite can be used instead of natural graphite in several applications such as batteries, brake linings, lubricants and carbon brushes. Synthetic graphite cannot substitute natural graphite in refractory applications.

Natural graphite is used to manufacture the anode in batteries and fuel cells for electric vehicles and energy storage systems. The uptake of electromobility is expected to decarbonise the transport sector, especially in combination with the decarbonisation of power generation. Energy storage systems are essential for development of renewable, intermittent energy sources in order to decarbonise the power production sector.

China hosts half of the world's graphite reserves, estimated at 110,000 kt. Significant reserves are also located in Mozambique and Tanzania, each with a 15% share of world's total. Concerning the EU, the largest natural graphite deposits are situated in Sweden, Czech Republic and Finland.

China is the largest glogal supplier of natural graphite with 69% of production, followed by India (12%) and Brazil (8%). Small quantities of natural graphite are currently produced in Germany and Austria. The EOL-RIR of natural graphite in the EU is only 3%.

16.2 Market analysis, trade and prices

16.2.1 Global market

The graphite market is complex and fragmented because natural graphite is not a homogeneous commodity. Both natural and synthetic graphite can be used in several applications. A large portion of the total the demand for graphite is met by synthetic graphite, which are estimated at 1,500-1,600kt., whereas the current size of the natural graphite market is estimated for around 1 million tonnes (Leguérinel and Le Gleuher 2017).

The end uses, and the associated commercial value of natural graphite is determined by the characteristics of the mined natural graphite and the subsequent processing of natural graphite concentrates. In many cases, specific applications require one type of processed graphite in particular. Three types of natural graphite are mined for commercial use, classified by purity and particle size: flake graphite, amorphous or microcrystalline graphite, and vein or lump graphite. The production of flake graphite accounts for 50% to 60% of the total production of natural graphite, the production of amorphous graphite for 40% to 50%, and vein graphite for less than 1% (Roskill 2015) (Leguérinel and Le Gleuher 2017). The market value of the world mine production of natural graphite is estimated at EUR 0.75 billion[165] in 2017.

Natural graphite is mined in several countries, but production is concentrated in China, which dominates the world natural graphite production with a share of 71% in 2017 (WMD 2019). According to USGS (USGS 2018b) approximately 70% of China's output is amorphous graphite, and 30% is flake graphite with a low proportion of large flakes in size distribution. According to Roskill (Roskill 2015), in 2014 the shares of amorphous and flake graphite production in China were almost 50%, and since 2010 the production of amorphous graphite has undergone major consolidations in the Hunan region.

The iron and steel industry have been the largest market for natural graphite, through their use of graphite in refractories, foundries and as a recarburiser. The steady growth of the Chinese steel industry has been the driving force for natural graphite demand for the last two decades. The world production of natural graphite fell by a compound annual rate of 0.2% between 2007 and 2016. This can be attributed to a slow-down of Chinese steel production between 2011 and 2014 and a decrease in 2015, reducing China's demand for refractories (Roskill 2015), (European Commission 2014).

China is the dominant supplier of natural graphite worldwide, accounting for 59% of the value of world exports in 2017. Brazil and Germany are following the rank of top world exporters of natural graphite, accounting for 6% of the total value of exports each. Japan is the primary destination country for world exports of natural graphite with a 20% share of the value of global imports in 2017, followed by the US (14%), South Korea (10%) and Germany (10%) (see Figure 195). Despite being a major exporter, since 2018 China has begun to import large quantities of flake graphite suitable for processing in battery-grade from Mozambique and Madagascar in order to meet the surging demand in the world's largest lithium-ion battery industry. China's own graphite resources are becoming harder to reach and production costs continue to rise (Roskill 2019a) (Roskill 2019d).

[165] Estimation based on the reported production by World Mining Data of 943 kt for 2017, times the average unit value of EU imports of natural graphite (HS 2504) in 2016 (EUR 777 per tonne)

Figure 195 presents the top world importers and exporters of natural graphite based on trade data for trade code HS 250410 "Natural graphite in powder or in flakes" and HS 250490 "Natural graphite (excl. in powder or in flakes)".

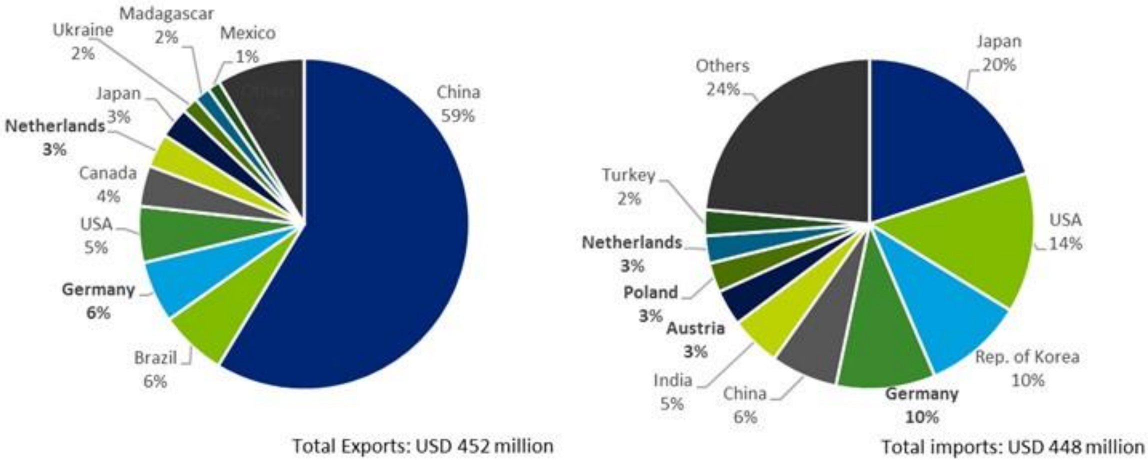

Figure 195: Top-10 natural graphite exporting (left) and importing (right) countries in 2017 by value. Background data from (UN Comtrade 2019)

Concerning downstream high-value products of natural graphite, China is the largest producer of natural graphite suitable for processing into spherical graphite. Furthermore, almost all of the world's output of spherical graphite for lithium-ion battery anode material is carried out in China, which is either consumed domestically or exported to Japan and South Korea for use in lithium-ion batteries (Roskill 2015). A small number of companies outside China have also developed spherical graphite, but they only account for a tiny part of global production (Roskill 2015). China dominates the anode materials market and hosts the largest overall capacity (370 kt or 78% of the worldwide capacity) for anode materials used in Li-ion batteries (Roskill 2019f). Since 2018, a number of flake graphite mining companies outside China have ongoing development projects to produce spherical graphite. Most of them operate in Africa and North America, to become the first commercial-scale producers outside of China (Roskill 2019d).

16.2.2Outlook for supply and demand

The battery sector is expected to drive the growth of future graphite demand due to the transition to electric mobility and the development of the energy storage market. Steel-associated applications such as refractories, which underpin demand as the most important consumers, are projected to increase as well, but to a lesser extent; in case the steelmaking industry activity remains constant in the short-term consumption for refractories is expected to decline (Roskill 2015) (USGS 2018b). The market of expandable graphite for foil, insulation and fire retardant products is expected to grow fast. High-tech emerging applications, such as fuel cells and pebble-bed nuclear reactors, will also note a rise in demand (USGS 2018b). However, a significant impact on the market from fuel cells, which integrate large quantities (around 90 kg in a vehicle) of synthetic or natural graphite of very high purity, is not anticipated by 2030 A notable increase in future demand for new types of nuclear reactors is more uncertain in the same timeframe (Leguérinel and Le Gleuher 2017).

The prospects of the demand growth for lithium-ion batteries are discussed in many studies and the projected surge is beyond doubt. According to the forecasts made in the context of the H2020 SCRREEN project, the demand for graphite for domestic energy storage and electric vehicles is forecasted to grow exponentially in the EU. In 2035, it is projected to reach 41 kt for energy storage and 98 kt for electric vehicles, as compared to 0,1 kt and 0,07 kt of demand respectively in 2015 (Ait Abderrahim and Monnet 2018).

The outlook for natural graphite supply is positive as several companies continue to develop new mining projects in Africa, Australia, Canada, US, Sweden etc. (S&P Global Market Intelligence 2018) (Scogings, Chesters, and Shaw 2015). In 2017, Syrah Resources began production at its large-scale Balama flake graphite project in Mozambique with a capacity of 350 kt of graphite concentrate per year. The mine's production ramped up to more than 100 kt in its first year of operation in 2018, becoming the largest producer globally. The vast majority of its shipments have been addressed to the Chinese battery industry. At the end of 2018, the Balama project hosted the world's largest reserve of graphite. It contained about 113,000 kt of reserves at an average grade of 16.4% TGC, equivalent to 18.500 kt of graphite (Syrah Resources 2019). Most large-scale projects at advanced development stage moving closer to first production are situated in Africa, i.e. Mozambique, Madagascar, and Tanzania (S&P Global Market Intelligence 2018), (Roskill 2019e).

The market outlook for natural graphite global supply and demand is presented in Table 85.

Table 85: Qualitative forecast of supply and demand of natural graphite

Material	Criticality of the material in 2020		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Natural graphite	x		+	+	+	+	+	+

16.2.3EU trade

The EU is greatly reliant on imports for its natural graphite supply and imports about 89 kt per year on average during the period 2012-2016 (see Figure 196). Significant intra-EU trade also takes place (ESTAT Comext 2019). Almost half of the EU imports came from China (49%), 12% from Brazil and 8% from Norway. In the same period, the EU exported small amounts of natural graphite of about 4.5 kt. Figure 196 illustrates the import and export flows of natural graphite to and from the EU. Figure 197 shows the origin countries for the EU imports of natural graphite.

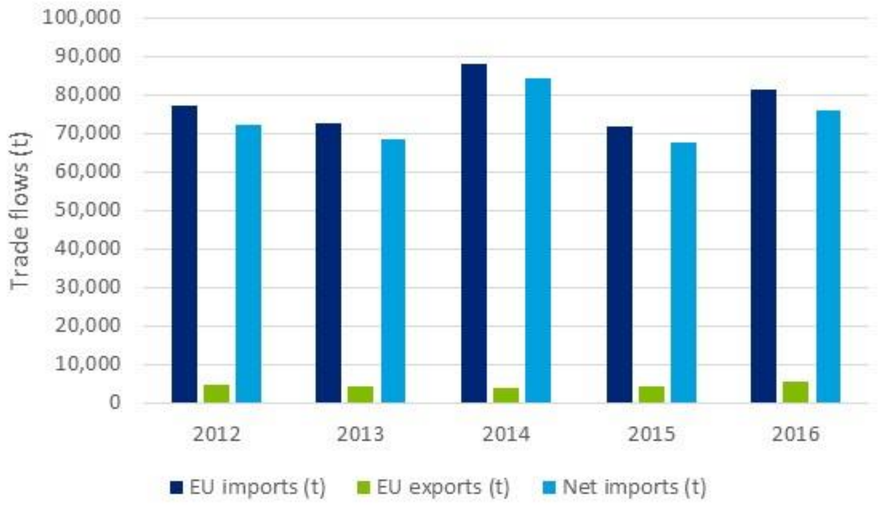

Figure 196: EU trade flows for natural graphite (ESTAT Comext 2019)

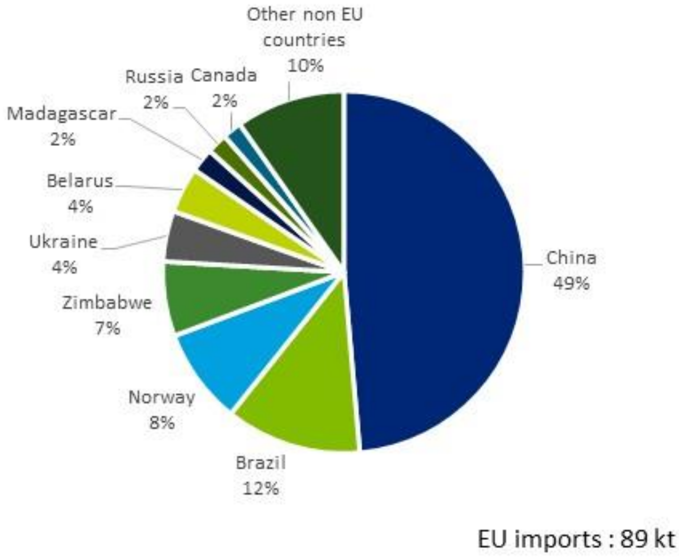

Figure 197: EU imports of natural graphite. Average 2012-2016[166] (ESTAT Comext 2019)

China, the main EU supplier and the dominant world producer, applied a 20% tax in 2017 to exports of both HS 250410 and HS 250490 natural graphite grades (OECD 2019). However, according to BRGM, China abolished the tax on exports of natural graphite on 1/1/2017 (Leguérinel and Le Gleuher 2017). Trade relations with Norway, the third supplier of natural graphite to the EU, are governed by the agreement on the European Economic Area (EEA), which stipulates free movement of goods (European Commission 2019). Finally, the EU signed an Economic Partnership Agreement (EPA) on 10 June 2016 with the Southern African Development Community (SADC). Among other countries, the agreement comprises Mozambique, an emerging significant producer of natural graphite. Mozambique started applying the EPA in February 2018 (European Commission 2019).

16.2.4 Prices and price volatility

Natural graphite is not traded on commodity exchanges, and there are no spot or futures markets. Prices are established by direct negotiations between buyers and producers on the basis of quarterly or monthly contracts (Leguérinel and Le Gleuher 2017). The steel industry demand historically drives graphite price. Another key demand driver is currently the expanding Li-ion battery sector.

Natural graphite's price is a function of the type of graphite (amorphous or flake). The carbon content and particle size (mesh size) are the main parameters controlling the quality and price of each type. The nature and amount of impurities (ash) are also affecting prices. Larger (+80 mesh and above) and purer (94% plus carbon) flakes are priced at higher rates as they are desirable for a lot of end uses, whereas amorphous graphite prices are much lower.

After a long period of stable and low prices until 2005, flake graphite prices started to climb gradually. From 2009 to 2011 natural graphite prices rose sharply for flake graphite, with large flake reaching up to USD 3,000 per tonne in early 2012, on account of strong

[166] Since there was no information in Eurostat (Comext) for the entire averaging period for some countries, only the available data were used in the average for the period 2012-2016. For example, imports from Zimbabwe are only reported for the year 2016, therefore, the average for the period 2012-2016 contains only year 2016.

demand from the steel industry in China and other applications (e.g. friction materials, lubricants, graphite foils, alkaline batteries), and fears of supply deficit due to forecasts for increased demand in emerging applications. Prices subsequently experienced a long decline again due to excess production and reduced demand from the steel industry (Leguérinel and Le Gleuher 2017), (Robinson, Hammarstrom, and Olson 2017), (Roskill 2015), (Northern Graphite 2019). The price of large, high-grade flake graphite, which attracts the highest rates in the market, fell by 70% from December 2011 to December 2016 (from USD 2500-3000 per tonne in 2011 to USD 700-750 per tonne in December 2016) on the European market (Figure 198). The fall in prices is more noticeable for flakes that are more dependent on the steel sector than amorphous graphite, the price of which has remained relatively stable since 2014 between USD 350-800 per tonne (USGS 2019a).

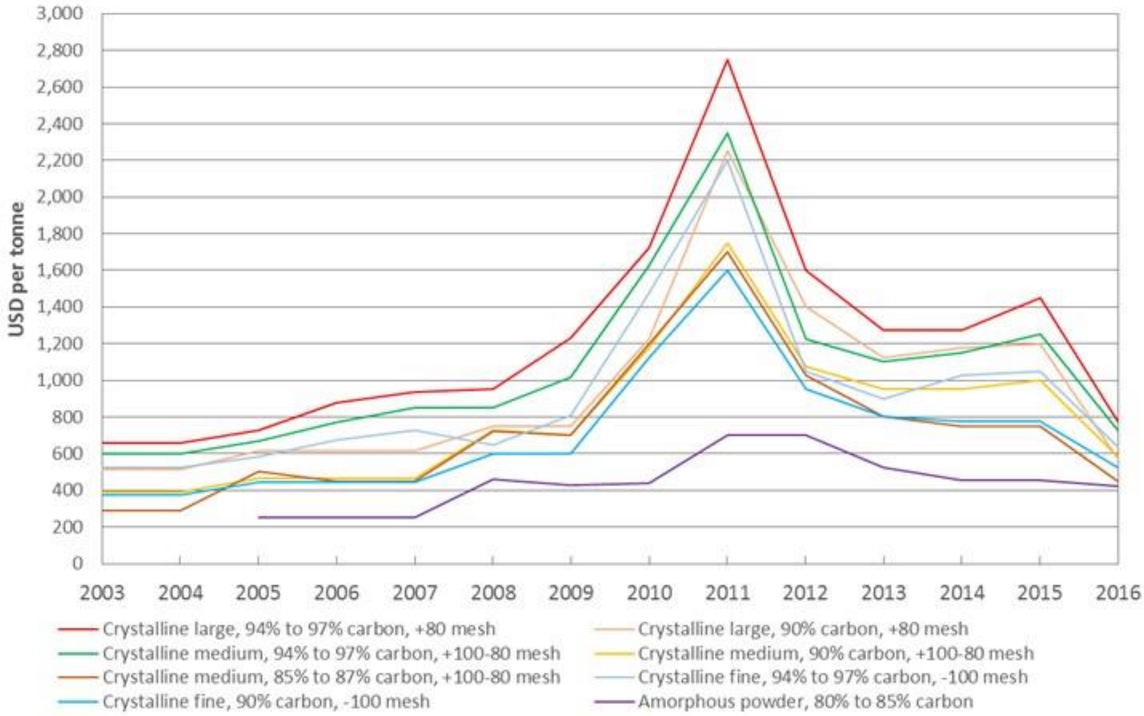

Figure 198: Natural graphite median price of published weekly prices by type, at end-of-year. CIF Europe (USD/tonne). Background data from Industrial Minerals in (USGS 2019a)

In the second half of 2017 natural graphite prices recovered. The average annual price for large, high-grade flake graphite rose by 33% in 2018 compared to 2017 (Figure 199), whereas the yearly average unit value of all EU natural graphite imports (for trade code HS 2504) has also increased by 10% in 2018 to EUR 856 per tonne (background data from (ESTAT Comext 2019)). The recovery can be attributed to improving demand from steel industry, environmental-related plant closures in China and sustained rising demand from the lithium-ion battery industry (Northern Graphite 2019). In 2019, prices have seen a downwards readjustment due to supply-side pressures as a large amount of supply is entering the market from the ramp-up of newly commissioned mines in Mozambique and Madagascar (Northern Graphite 2019) (Roskill 2019b).

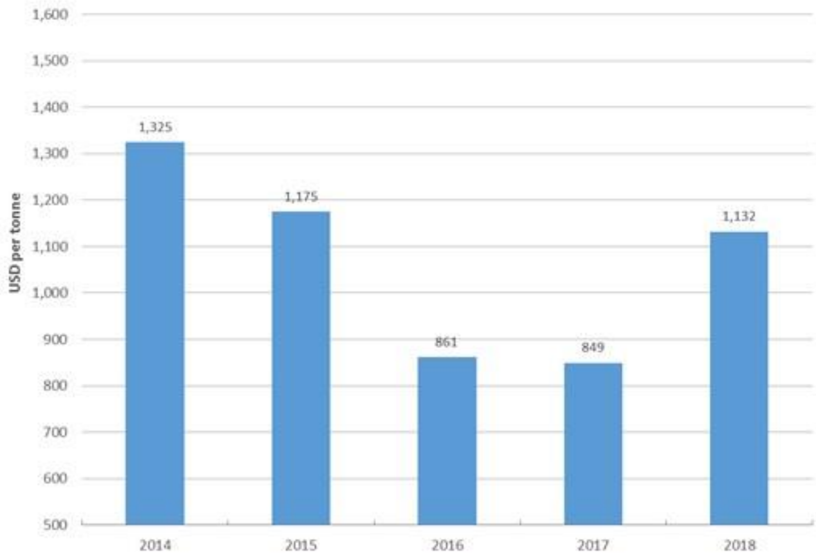

Figure 199: Price trend of large flake graphite, 94-97 % C, +80 mesh, CIF Europe, yearly average (USD/tonne). Background data from (BGR 2019)

Heavily processed graphite products such as spherical graphite, expandable graphite and high-purity graphite attract higher prices. The price of spherical graphite depends on the price of the raw material as well as the purity, size and shape of the particles (Leguérinel and Le Gleuher 2017). In the first nine months of 2015, the average value of uncoated spherical graphite exported from China was USD 4,400 per tonne, around six times higher than the value of conventional flake exports (Roskill 2015). Prices for coated spherical graphite, the end product used in the manufacture of Li-ion battery anodes, are even higher, between USD 8,000 and 12,000 per tonne, a price comparable to synthetic graphite (Leguérinel and Le Gleuher 2017). The average value of spherical graphite imports to China, which consist mainly of coated products, was USD 9,400 per tonne in the first nine months of 2015 (Roskill 2015).

16.3 EU demand

16.3.1 EU consumption

With an apparent consumption of natural graphite of about 85,000 tonnes per year on average over the period 2012-2016 and a limited mine production, the EU is heavily dependent on external sources of supply. The EU import reliance as a percentage of apparent consumption is 98%.

16.3.2 Uses and end-uses of natural graphite in the EU

Refractories for the steel industry are the largest market for natural graphite consuming about half of the world's production of natural graphite, even though that only a small proportion of refractories contain graphite. On a global scale, in 2014 about 70% of the world's natural graphite consumption was destined for metallurgical applications, in particular for the manufacture of refractories for steelmaking (54%), applications in foundries (15%), and recarburising in the steel industry (4%). The battery market accounted for 8% of global graphite consumption in 2014 (see Figure 200).

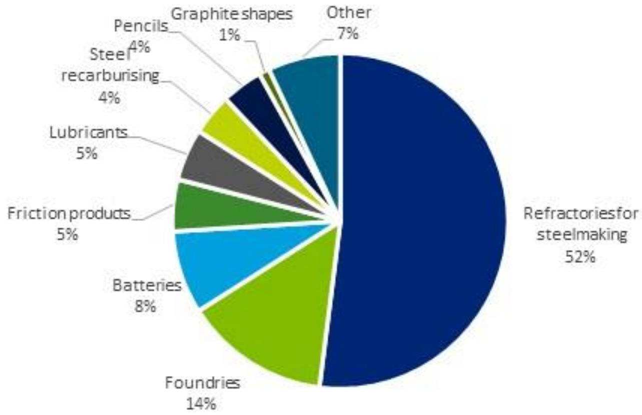

Figure 200: Global end uses of natural graphite in 2014. (BRGM 2016)

Figure 201 presents the breakdown of natural graphite consumption in the EU in 2016. The distribution shows that the main application is also in refractories with a similar share in the total material use (54%). Other applications include batteries (6%), friction products (8%), lubricants (5%), and other miscellaneous.

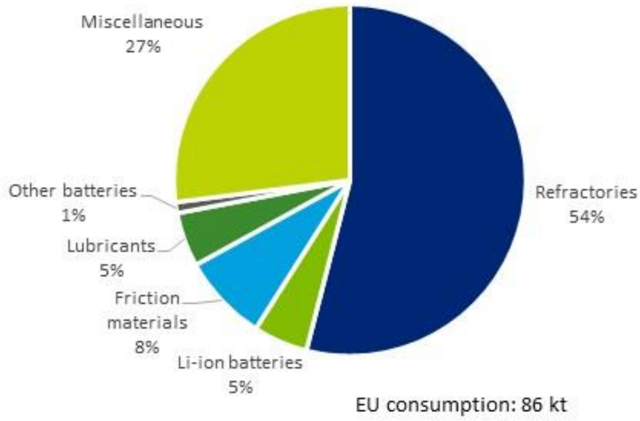

Figure 201: EU end uses of natural graphite[167] in 2016. Background data from (Draft MSA 2019)

Relevant industry sectors are described using the NACE sector codes in Table 86. Since it was not possible to assign sectors for the 27% of the EU applications (see Figure 201), the global distribution was used in the assessment as presented in Figure 200.

Table 86: Natural graphite applications, 2-digit NACE sectors and examples of associated 4-digit NACE sector, and value-added per sector (Eurostat 2019)

Applications	2-digit NACE sector	Value-added of sector (millions €)	Examples of 4-digit NACE sector
Refractories for steelmaking	C24 - Manufacture of basic metals	55,426	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Refractories for foundries	C23 - Manufacture of other non-metallic mineral products	57,255	C2311 - Manufacture of flat glass
Batteries	C27 - Manufacture of electrical equipment	80,745	C2720 - Manufacture of batteries and accumulators

[167] Natural graphite demand for finished products manufactured in the EU

Applications	2-digit NACE sector	Value-added of sector (millions €)	Examples of 4-digit NACE sector
Friction products	C23 - Manufacture of other non-metallic mineral products	57,255	C2399 - Manufacture of other non-metallic mineral products n.e.c.
Lubricants	C20 - Manufacture of chemicals and chemical products	105,514	C2013 - Manufacture of other inorganic basic chemicals
Recarburising	C24 - Manufacture of basic metals	55,426	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Pencils	C23 - Manufacture of other non-metallic mineral products	57,255	C23.9.9 - Manufacture of other non-metallic mineral products n.e.c.
Graphite shapes	C28 - Manufacture of machinery and equipment n.e.c.	182,589	C2849 - Manufacture of other machine tools

Due to its combination of metallic and non-metallic properties, natural graphite is used for a wide variety of applications which are described below (Yang, Hu, Sundqvist, Eriksson, Bacher, John, et al. 2018), (BRGM 2012),(Roskill 2015)(European Commission 2017),(Robinson, Hammarstrom, and Olson 2017):

•*Refractories for steelmaking:* The major market for natural graphite is in magnesia-carbon and alumina-carbon refractories for the steel industry. According to Roskill, consumption of refractories is around 15 kg per tonne of crude steel worldwide (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 impurity level. Natural flake graphite with large crystals increases the brick mechanical strength. Amorphous graphite powder can also be used, mostly for monolithic refractories. 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 (EAF), and in high-wear areas such as slag lines in ladles. 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 refractory shapes, which contain between 5% and 15% graphite, are used as functional components (e.g. stopper rods and ladle shrouds) in continuous steel casting operations. Magnesia-carbon and alumina-carbon refractories require natural graphite with a particle size larger than 150 µm (100 mesh) and purity between 87% to 90%, and 95% to 99% respectively;
•*Foundries:* In foundries, natural graphite-based coatings and washings are employed as facings to protect from erosion refractory linings, troughs and other equipment that convey molten metal, as well as to ease the release of cast products from moulds. Furthermore, graphite is the main component in the manufacture of clay-bonded crucibles to handle molten metal. The mix contains up to 60% graphite. Finally, natural graphite powders are used as a cover of molten metal (e.g. copper and copper alloys) to prevent oxidation of the melt. Amorphous graphite is preferred due to a lower cost for foundry applications, but also fine-grained, low-grade flake graphite can be used. Large-sized flake graphite provides a longer service life of graphite crucibles;
•*Batteries:* Due to its high electrical conductivity, inertness and reversible Li-ion intercalation between the basal planes of the crystal structure, flake graphite is a critical component of primary and rechargeable batteries, i.e. in cathodes of alkaline batteries as an additive, in anodes and cathodes of lead-acid batteries as an additive, in anodes of Li-ion batteries (LIB) as the main material. In 2015, Li-ion batteries accounted for about 75-85% and alkaline batteries for around 10-15% of the total graphite demand for batteries, and the remainder was covered by lead-acid and other battery types (Roskill 2015). Li-ion batteries contain significant amounts of graphite in comparison to lithium, e.g. it takes 10 to 20 times more graphite than lithium, depending on the cathode used, to make a Li-ion battery (Leguérinel and Le Gleuher 2017). Flake natural graphite is the precursor to the

battery-grade quality for Li-ion anodes known as spherical graphite. Spherical graphite consists of high purity (>99.95% C and absence of metallic impurities) rounded particles with typical sizes in the range of 10-25 µm. The spheroidal shape of the particles improves compaction and density within the battery compartment, which increases the energy and recharge capacity of the Li-ion batteries. In comparison to available carbon-based active materials (synthetic graphite, amorphous carbon, Si-C composites etc.), natural graphite had a global market share of 46% in 2016 (Pillot 2017) and 39% in 2017 (Pillot 2018);

- *Friction products:* Due to its high natural lubricity, natural graphite powders are added in the manufacture of high-temperature dry lubricants and oil and water dispersions for use under conditions of extreme friction and heat, such as in heavy machinery, seamless tube rolling mills etc. Amorphous and flake graphite are commonly used with a carbon content of more than 98 %. The graphite content of the lubricants varies between 5 and 10 % depending on the application;
- *Lubricants:* Because of its high thermal conductivity, thermal stability and lubrication properties, natural graphite is a critical component of friction linings as it provides heat dissipation and effective lubrication at the friction interface. Friction applications include brake and clutch linings used by the automotive, aviation and rail industries. The natural graphite used has to be of high purity (close to 99.9 %);
- *Recarburising:* Amorphous graphite is used as a source of carbon to raise the carbon content of molten steel (recarburising), as well as in grey and ductile iron in ferrous foundries;
- *Pencils:* Natural graphite mixed with clay has been used in pencil leads since a long time ago, due to its softness, non-toxicity and black streak. Flake graphite is favoured for higher quality in pencils;
- *Graphite shapes:* Purified and micronised graphite is an essential additive in metal powder mixtures for the fabrication of sintered parts, mainly for automotive applications. Graphite provides internal lubrication making maximum compression possible, as well as increased mechanical strength after sintering.
- *Electrical applications*: Electrical conductivity and lubricity allow natural graphite's use in electrical applications, i.e. in the manufacture of brushes for electric motors and other current-carrying carbon products, to effectively transfer electric current and minimise frictional wear. Vein graphite is chosen for high-quality applications because of its purity and crystallinity;
- *Flame-retardants:* Expandable graphite has an efficient flame-retardant effect as it swells up when exposed to heat, thus isolating the fire from the material underneath or sealing a gap. Applications include the use of expandable graphite in plastics, coatings, insulation foams (e.g. PU plates), textiles, firestops for buildings and constructions etc.;
- *Pebble-bed nuclear reactors*: Due to its low absorption of X-rays and neutrons, high thermal conductivity and ability to maintain these properties at high temperature, graphite is used as a neutron moderator in emerging pebble-bed nuclear reactors (PBNRs);
- *Fuel cells*: Purified flake graphite and purified expanded flake graphite can be used as the main filler material in bipolar plates for fuel cells. In particular, natural graphite makes up the anode and cathode material of Proton Exchange Membrane (PEM) fuel cells used in transport and stationary energy storage (Roskill, 2015);
- *Other:* Finally, natural graphite is employed in a high number of other applications such as seals and gaskets made of graphite foil for high-temperature applications, additive in insulation foams (e.g. EPS) for enhanced heat reflection, drilling mud additives, equipment to handle molten glass, heat insulation panels, additives for improving tribological and conductive characteristics of plastics, etc.

16.3.3Substitution

Synthetic graphite and natural graphite are competing in various applications. They are commonly substituted for each other, or blends containing both types are prepared by manufacturers (Robinson, Hammarstrom, and Olson 2017). The choice of the substitute is mostly driven by the relative price, carbon grade and particle size and shape.

Substitution is also a function of raw material availability and product performance that can be specific to each end use (Roskill 2015).

Synthetic graphite can be made from calcined petroleum needle coke, a by-product of the petroleum industry, coal tar pitch or other carbon-containing precursors (Asbury Carbons, 2019). The higher costs associated with the production of synthetic graphite in comparison to natural graphite mining are somewhat offset by the costs of purification to raise natural graphite's grade (Roskill 2015). In general, synthetic graphite has an advantage over natural graphite in applications which require the highest carbon grades and the lowest level of impurities, such as batteries and graphite shapes. Natural amorphous graphite is the preferred material in a lower grade or lower value applications, or where the use of graphite as a powder is beneficial (Roskill 2015). Alternative substitutes for graphite in some applications are typically other forms of carbon such as the secondary synthetic graphite recovered from discarded foundry and other carbon-containing materials (Robinson, Hammarstrom, and Olson 2017).

The substitution in the criticality assessment was considered in detail for refractories for steelmaking and foundry applications. The other end uses were not included in the evaluation due to a lower than 10% share. In particular:

•*Refractories*. Refractories for steelmaking is one application in which there is no competition by synthetic graphite (Leguérinel and Le Gleuher 2017), (Tercero et al. 2015). The flaky shape of natural graphite is beneficial to the structure of the final refractory product, whereas the higher porosity of synthetic graphite (10-15% compared to 2-3% for natural graphite) makes it unsuitable for most refractory applications. When synthetic graphite is used in some refractory applications, firing at temperatures approaching 2,000 C^0 are required to form a dense graphite structure, but the refractories have low oxidation resistance and cannot be readily exposed to air, water vapour and carbon dioxide at high temperatures. Besides, the cost of processing natural graphite is not high because the carbon grades (85-99% C) required by refractories can be achieved by basic processing methods (Roskill 2015). In crucible production, graphite can be substituted by silicon carbide, but with lower performance (Tercero et al 2015);
•Foundry applications. Synthetic graphite powder, finely ground coke with olivine, talc, mica or zircon may be used as the substitutes in foundry-facing applications (Tercero et al. 2018), (USGS 2019b).

Concerning the rest of the applications, the following potential substitutes are listed:

•*Batteries*. Spheroidal graphite used in anodes of Li-ion batteries is either manufactured from synthetic or natural graphite. Secondary synthetic graphite from machining graphite components is also an available substitute (Tercero et al. 2015), (USGS 2019b). The main area of competition between natural and synthetic graphite is currently in anode materials for Li-ion batteries, and some manufacturers even use mixtures of natural and synthetic graphite in the anode. If the price of battery-grade natural graphite increases to parity with the price of synthetic graphite, then increased uptake of synthetic graphite as a substitute in Li-ion batteries can be anticipated (Roskill 2015). In terms of anode technology, silicon-graphite chemistries, which enable higher power densities, are expected to become available soon (Bunsen et al. 2019);
•*Lubricants*. Natural graphite can be substituted by synthetic graphite. Also, molybdenum disulphide competes with natural graphite as a dry lubricant but is prone to oxidation (Tercero et al. 2015), (USGS 2019b), (Roskill 2015);
•*Friction materials and carbon brushes*. Synthetic graphite can be used instead of natural graphite (Roskill 2015);
•*Recarburising*. High-carbon scrap from discarded graphite shapes and calcined petroleum coke can substitute the use of natural graphite to increase the carbon content in molten iron and steel (Tercero et al. 2015), (USGS 2019b). Substitution with synthetic graphite is also possible, but not applied in practice because of the higher costs (Roskill 2015);

•*Fire-proofing materials, seals and gaskets* etc. Synthetic graphite does not compete with natural graphite in applications using expandable natural graphite (Roskill 2015).

16.4 Supply

16.4.1 EU supply chain

Figure 202 shows the simplified Sankey diagram for natural graphite flows for the year 2012.

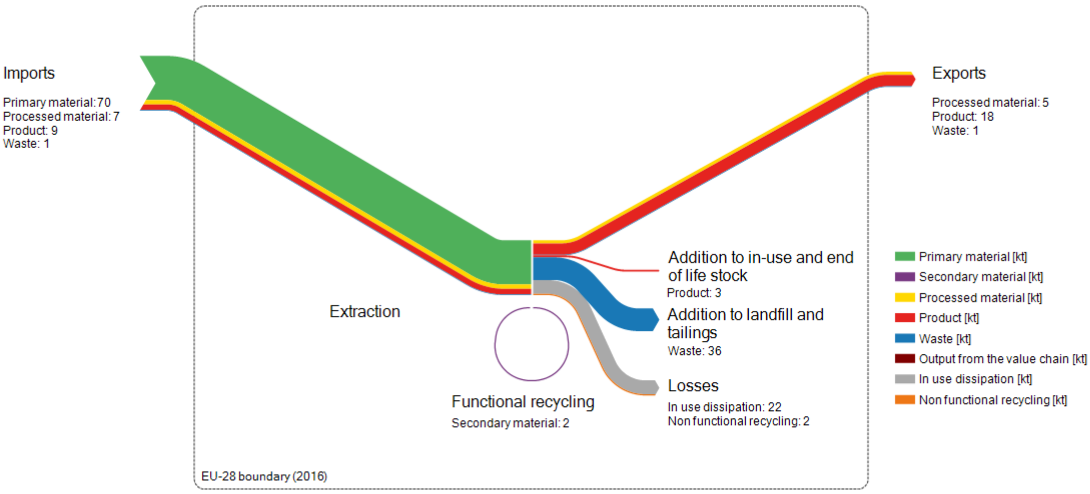

Figure 202: Simplified MSA of natural graphite flows in the EU in 2016 (Draft natural graphite MSA 2019)

16.4.1.1 EU sourcing of natural graphite

The EU production was about 2,080 tonnes as an average over 2012-2016 accounting for only 0.2% of the global output. Currently, there are two active underground mines in the EU: the Kaisersberg mine in Austria (Grafitbergbau Kaisersberg GmbH) which produces amorphous graphite, and the Kropfmühl mine (Graphit Kropfmühl, a subsidiary of AMG Advanced Metallurgical Group) in Germany which recommenced operation in 2012 and produces flake graphite. The Woxna flake graphite open-pit mine in Sweden, operated by Leading Edge Materials Corp, began production in early 2015 but suspended a few months later due to low prices; since then the installation is maintained on a production-ready basis. In Romania, graphite deposits were exploited in the past, e.g. the Catalinul and Ungurelaşu mine (Lauri et al. 2018). According to reported statistics by (WMD 2019), natural graphite's production in Romania concluded in 2012, whereas according to statistics published by the British Geological Survey mining of natural graphite in Romania ceased in 2010 (BGS 2019).

Figure 203 presents the EU sourcing (domestic production + imports) for natural graphite averaged over the period 2012–2016. The EU is dependent on imports for its consumption of natural graphite, with an import reliance of 98%.

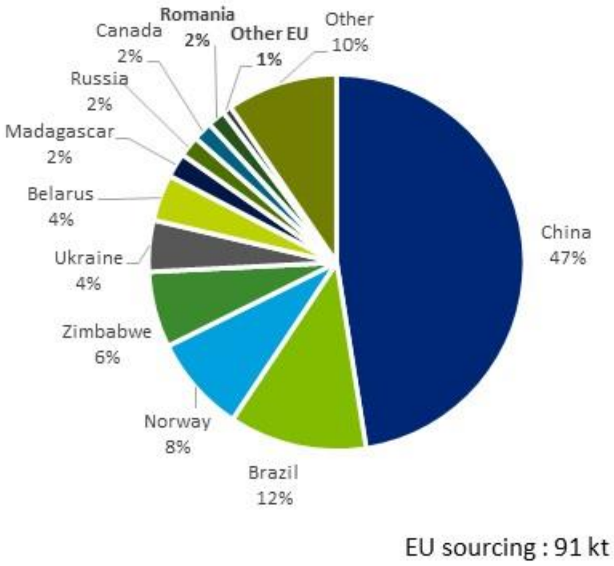

Figure 203: EU sourcing of natural graphite. Average 2012-2016, (Eurostat, 2019), (WMD, 2019)

16.4.1.2 EU sourcing of processed/refined natural graphite

Processing capacity for the refining of natural graphite exists in the EU, for example:

- The *Graphite Týn* plant in Czechia (AMG group) produces purified, micronised, and expandable natural graphite (AMG GK 2019);
- The *Sundsvall* plant in Sweden, through a proprietary electro-thermal treatment and purification process, produces purified graphite for recarburisers, melt covers in foundries, friction materials, and polymer additives (Superior Graphite 2019);
- The *Kaisersberg* plant in Austria produces micronised graphite, and other refined graphite products such as expandable graphite (Grafitbergbau Kaisersberg 2019);
- Graphit *Kropfmühl* (AMG group) operates two plants in Germany to process crude natural graphite and fabricate graphite products such as graphite dispersions, lubricants and graphite parts. Refined natural graphite products include expandable and expanded graphite (Kropfmühl 2019), (Roskill 2015);
- SGL *Carbon* produces speciality and downstream graphite products based on processed natural graphite such as components made of high-purity fine grain graphite for silicon crystals production, expanded and flexible graphite. Producing sites for graphite materials are located in Germany (Bonn, Limburg, Meitingen), France (Grenoble, Chedde), Spain (Madrid), Italy (Verdello), Poland (Nowy Sacz, Racibórz), (SGL Carbon 2019), (Roskill 2015).
- In the Netherlands (Maastricht), *Asbury Carbons* processes graphite for end-use products since 2014, e.g. flake graphite with purity up to 99.9% (Asbury Carbons 2019) (Roskill 2015);
- Sinograf in Poland supplies natural flake and amorphous graphite for refractories and foundries along with a range of intermediate and downstream products including graphite micro powders, expanded graphite and flexible graphite products etc. (Sinograf 2019).

However, at present, there is no production capacity for spherical graphite in the EU. The company (Leading Edge Corp) holding the Woxna mine, Sweden, is currently (2019) working for a graphite processing plant which would produce spherical, battery-grade graphite and other forms of processed graphite at the mine site (Leading Edge 2019a), (Leading Edge 2019b). Moreover, according to announcements made by the owning company (Talga Resources Ltd) of the Vittangi mine development project in Sweden, the concentrate of the mining operation will be refined to a coated lithium-ion battery graphite anode material (Talga Resources 2019).

16.4.1.3 Recycled natural graphite supply

Recycling and processing of spent graphite-based refractories started more than thirty years ago in the EU. Recycled materials are used in some applications as a full or partial replacement to virgin materials such as in monolithic and shaped refractories (European Commission 2017). The end-of-life recycling input rate was estimated at 3% in 2012 (BIO Intelligence Service 2015), as well as in 2016 (Draft MSA 2019).

Currently there is no scale for specific Li-ion battery recycling that would embark on dismantling the battery, instead of using graphite as a heat source in the pyrometallurgical process (Euromines 2019). Recovery of graphite from spent lithium batteries is foreseen at the Accurec Recycling GmbH facility in Krefeld, Germany, after a planned investment in thermal deactivation and treatment (Recharge 2018).

16.4.2 Supply from primary materials

16.4.2.1 Geology, resources and reserves of natural graphite

Geological occurrence: No specific information is available for the crustal abundance of natural graphite. The average carbon abundance of the earth's crust is estimated at 200 ppm distributed between organic compounds, hydrocarbons, coal and mineral forms (diamonds, graphite, carbonate rocks). Natural graphite deposits are generally a result of metamorphism of sedimentary rocks (e.g. marble, schist, and gneiss) rich in carbonaceous material. The ore type is classified as amorphous, flake or vein graphite according to the degree of crystallisation, grain-size, and morphology which are determined by the geologic setting (Robinson, Hammarstrom, and Olson 2017) (BRGM 2012).

Deposits of amorphous graphite are formed from the metamorphism of highly carbonaceous sediments, usually coal beds. The orebody consists of layers, seams, and lenses, each a few meters thick and hundreds of meters to several kilometres in length. The average commercial ore grade varies from 50 to 90 % carbon, higher than flake graphite; the raw ore and the commodity may contain non-graphitic carbonaceous material in addition to graphite. China and Russia/Ukraine hold the most abundant resources globally. Other deposits are located in the People's Republic of Korea and Mexico. According to the USGS estimates, approximately half of the total identified resources worldwide are amorphous graphite (Robinson, Hammarstrom, and Olson 2017). Amorphous graphite production accounted for 35% to 40% of the world mine production in 2014 (BRGM 2016).

Flake graphite is found as disseminated, plate-like particles that crystallised in the carbonaceous metamorphic rock. The body of the ore occurs in tabular form or lenses, as much as 33 m thick and thousands of meters long; the ore grade is low, on average between 5 and 30 % graphitic carbon. The most significant flake graphite deposits are located in China, Russia/Ukraine (e.g. the Zavalyevskiy deposit in Ukraine), and Mozambique (e.g. the Balama deposit) where major mine development projects are underway; total resources and reserves in Mozambique amount to 342 million tonnes in graphite content (S&P Global, 2018). Important flake graphite deposits also exist in Madagascar, Brazil, India and Canada. In 2014, flake graphite accounted for 60-65 % of world production (BRGM 2016).

The vein or lump graphite occurs in thin veins in igneous and high-grade metamorphic rocks formed by deposition from high-temperature fluids. Vein graphite deposits are significant for the low level of impurities and the high degree of crystallinity. It is commercially extracted only in underground mines in Sri Lanka with average graphitic carbon in the range 60-95%. Vein graphite global reserves represent only 0.1% of the total, and in 2014 vein graphite accounted for 0.3% of the global natural graphite production.

Graphite is a common mineral in metamorphic rocks throughout Europe, however it is rare to find economically interesting deposits. The bulk of the graphite occurrences occur in Northern Europe and Ukraine, and a number of amorphous graphite occurrences are also found in Austria. The Trælen deposit in Norway is the world's richest graphite deposit in production with an average ore grade of 31%, and 1,800 kt proven reserves (Gautneb et al. 2019).

Global resources and reserves[168]: According to the United States Geological Survey (USGS), the world's inferred resources exceed 800,000 kt of recoverable graphite. Besides, USGS estimates world reserves at 270,000 kt at the end of 2017 (USGS 2018a). However, this figure is not used in this factsheet, as reported reserves by some countries are expressed in volume of graphite ore (and not in graphite content)[169]. Compared to other industrial minerals, individual deposits of natural graphite are not well documented in terms of tonnage or grade, and country totals are often largely estimated (Roskill 2015).

World reserves of natural graphite are estimated at around 110,000 kt of graphite content (Table 87).

Table 87: Global reserves of natural graphite in 2017. Background data in (Robinson, Hammarstrom, and Olson 2017) (USGS 2018a)

Country	Estimated natural graphite reserves (kt of recoverable graphite content)	Percentage of the total (%)
China	55,000	50%
Mozambique	17,000	15%
Tanzania	17,000	15%
Russia[170]	4,500	4%
Mexico	3,100	3%
Ukraine[6]	2,900	3%
Sri Lanka	1,850	2%
North Korea	1,700	2%

[168] There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of 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, 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.

[169] The USGS (USGS, 2018a) reports 70,000 kt for natural graphite reserves in Brazil and 90,000 kt in Turkey. However, according to the 2014 Brazilian Minerals Yearbook (http://www.anm.gov.br/dnpm/paginas/sumario-mineral), graphite reserves are 72,000 kt of ore, and according to the Turkish Statistical Survey (http://www.mapeg.gov.tr/Istatistik.aspx), graphite reserves are 90,000 kt of ore at 6-17% C.

[170] Total reserves of 7,400 t are reported jointly for Russian Federation and Ukraine by USGS (2017). The split is based on the assumption that reserves are proportional to the mine production of 2016

Country	Estimated natural graphite reserves (kt of recoverable graphite content)	Percentage of the total (%)
Madagascar	1,600	1%
Canada	1,500	1%
Other countries	3,850	4%
World total (rounded)	110,000	

EU resources and reserves[171]*:* The most important natural graphite deposits in the EU and their associated resources and reserves are summarised below:

• In Sweden, the Woxna deposit contains NI 43-101 compliant estimated total resources of 9,700 kt of ore at 9.1% graphitic C (Flinders Resources 2015). The Vittangi (Nunasvaara), Raitajärvi and Jalkunen deposits currently have JORC-compliant mineral resource estimates, with Nunasvaara containing 12,300 kt of ore with a very high ore grade of 25.5% graphitic C, Raitajärvi containing 4,300 kt of ore at 7.1% graphitic C, and Jalkunen containing 31,500 kt of ore at 14.9% graphitic C (Talga Resources 2018). Reserves are announced at 1,900 kt of ore at 23.5% of graphitic C (Talga Resources 2018);
• In Finland, the Aittolampi flake graphite deposit is under exploration comprising a JORC-compliant total resource estimate of 19,300 kt of ore at 4.5% graphitic C (Beowulf Mining 2018);
•In Austria, proved ore reserves of 160 kt and mineral resources of 1,500 kt are reported for the Kaisersberg deposit (Lauri et al. 2018);
•In Czechia, eight graphite deposits are registered by the national authorities of amorphous (Velké Vrbno-Konstantin, Bližná-Černá v Pošumaví, Český Krumlov-Rybářská ulice, Velké Vrbno-Luční hora 2), flake graphite (Český Krumlov-Městský vrch, Lazec-Krenov, Koloděje nad Lužnicí-Hosty) and mixed (amorhous and flake) (Spolí) (Czech Geological Survey 2017).

Table 88 and Table 89 present data on resources and reserves of natural graphite in the EU.

Table 88: Natural graphite resources data in the EU

Country	Classification	Quantity (Mt of ore)	Grade (%)	Reporting code	Reporting date	Source
Austria	None	1.5	NA	NA	02/2018	(Lauri et al. 2018)
Czechia	Economic explored	2.981	NA	National reporting code	12/2016	(Czech Geological Survey 2017)
	Economic prospected	4.935				

[171] 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 the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU 2019).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

	Potentially economic	5.785				
Greece	None	0.024	6	NA	02/2018	(Lauri et al. 2018)
Finland	Measured	-	-	JORC	08/2018	(Beowulf Mining 2018)
	Indicated	7.3	4.7 (TGC)			
	Inferred	12	4.4 (TGC)			
Slovakia	Historic Resource Estimates	0.29	3.4	None	11/2014	(Minerals4 EU 2019)
Sweden	Measured	-	-	JORC	06/2018	(Talga Resources 2018)
	Indicated	14.1	21.26 (TGC)			
	Inferred	34	15.1 (TGC)			
Sweden	Measured	1.0	10.7 (TGC)	NI 43-101	03/2015	(Flinders Resources 2015)
	Indicated	6.8	9.1 (TGC)			
	Inferred	1.9	8.5 (TGC)			
Sweden	Historic Resource Estimates	8.45	9.05	None	11/2014	(Minerals4 EU 2019)

Table 89: Natural Graphite reserves data in the EU

Country	Classification	Quantity (million tonnes of ore)	Grade (%)	Reporting code	Reporting date	Source
Austria	Proven	0.16	NA	NA	02/2018	(Lauri et al. 2018)
Sweden	Probable	1.94	23.53	JORC	05/2019	(Talga Resources 2019)

16.4.2.2 Exploration and new mine development projects in the EU

An increasing number of exploration companies is developing new graphite projects worldwide. In the EU the activity is concentrated in Sweden and Finland:

- The most advanced project for commercial production is the Vittangi project in Sweden owned by the Australian company Talga Resources Ltd (Talga Resources 2019). The preliminary Feasibility study has been completed, and initial production is expected in early 2021. Other exploration activities at a more advanced stage in Sweden are identified for the Jalkunen and Raitajärvi projects by the same company (Talga Resources 2018).

•The Aitolampi project in Finland has concluded the estimation of a maiden resource and a scoping study for a preliminary assessment of the technical and economic feasibility of developing a mining operation at the project is pending (Beowulf Mining 2018).

16.4.2.3 Natural graphite mining

Natural graphites ores are mined from either surface or underground mines depending on the proximity of the ore body to the surface. Most flake graphite deposits are exploited using open-pit mining methods, especially when the ore is intensively weathered; however, underground mining methods are employed in few cases of steeply dipping orebodies with high-grade minable lenses (> 15 % C). Open-pit mining involves conventional drilling and blasting methods for hard rocks or standard soft rock mining techniques. Drift mining, hard-rock mining, shaft mining and slope mining are methods used in underground mines (Robinson, Hammarstrom, and Olson 2017).

The mineral processing of natural graphite for the production of flake graphite and powder concentrates depends on the rock containing the graphite, the ore type and the grade. It varies from a simple hand sorting and screening of high-grade vein graphite and some high-grade amorphous graphite ores to a complex beneficiation process. The main steps in a standard processing route of flake graphite ore are crushing and grinding, followed by flotation and screening:

•Mechanical preparation. It is an essential stage in natural graphite's mineral processing as size and grade are the two commercially important parameters of natural graphite products. The crushing and grinding steps have to be optimised to minimise size reduction of constituent particles (flakes), but simultaneously maximise the liberation of gangue minerals;
•Flotation. Natural graphite is naturally hydrophobic; therefore, it can be upgraded by flotation. A multi-stage flotation process is generally applied. After washing to remove clay materials, the ore is subjected to a first rough flotation followed by secondary grinding and cleaning flotation. The graphitic carbon content of flake graphite concentrate ranges between 85% and 97%. A highly concentrated grade with few impurities is desirable for further refining as it lowers the purification costs;
•Screening. The concentrate is then dried, screened and classified to a variety of products of various sizes. Commercial flake graphite available for end-uses or further processing is available in distinct sizes e.g. jumpo (+50 mesh, i.e. >300 μm), large (-50+80 mesh, i.e. 180-300 μm), medium (-80+100 mesh, i.e. 150-180 μm), fine (-100 mesh, i.e. < 150 μm). Different classifications are possible.

The marketed products of natural graphite are classified by purity and particle size in three distinct categories:

•Amorphous graphite: It consists of grains with a tiny crystal size (microcrystalline graphite). Amorphous graphite is the most abundant but least pure commercial type of natural graphite. Typical commercial purity varies between 80-85 % graphitic C. Amorphous graphite is the lowest valued quality of natural graphite.
•Flake graphite: It is coarse-grained crystalline graphite that consists of platelets of graphite layers (flakes). Flake graphite is of higher quality than amorphous graphite and has the broadest range of end uses. Commercial purity ranges from 85 % up to 97 % graphitic C. Flake graphite is marketed in different sized flakes (small, medium, large, jumbo), ranging between 40 μm and 1 cm in size.
•Vein or lump graphite: It occurs in nature at the highest purity, grain size and crystallinity of the natural graphite extracted commercially. Vein graphite is the rarest form and the premier quality of natural graphite. Vein graphite is suitable for many flake

graphite's applications with a preference for high-performance speciality products. It is produced in limited tonnages at a high grade (94 % to 99.5 % graphitic C).

16.4.2.4 World and EU mine production

Natural graphite ore production data vary greatly depending on the source and should be viewed with caution, as some countries may report tonnages of concentrates and others of run-of-mine ore. The figures provided by World Mining Data (WMD 2019) and the United States Geological Survey (USGS 2018b) are close to one million tonnes per year. According to (WMD 2019), the annual production of graphite concentrates amounted to about 1,137 kt on average between 2012 and 2016. As shown in Figure 204, China is the world-leading supplier with a share of 68% (782 kt) of the total global production, while India (131 kt per year), Brazil (83 kt per year), North Korea (37 kt), and Canada (27 kt) collectively made up 25% of the worldwide output. However, according to the British Geological Survey, the output figures noted above for India refer to crude ore, and the figures for Brazil include beneficiated and directly shipped material. Moreover, according to Benchmark Minerals data in (Leguérinel and Le Gleuher 2017), in 2014 the production of natural graphite in China is around 400 kt and the production in India close to 20 kt. The analysis made by the French Geological Survey (BRGM) in (Leguérinel and Le Gleuher 2017) combining different sources of production statistics, provides a figure for the world production in 2014 of 633 kt.

In the EU, during the 2012-2016 period natural graphite was mined in Austria, Germany, Romania and Sweden accounting for about 2 kt (WMD 2019), equivalent to around 0.2% of the global output.

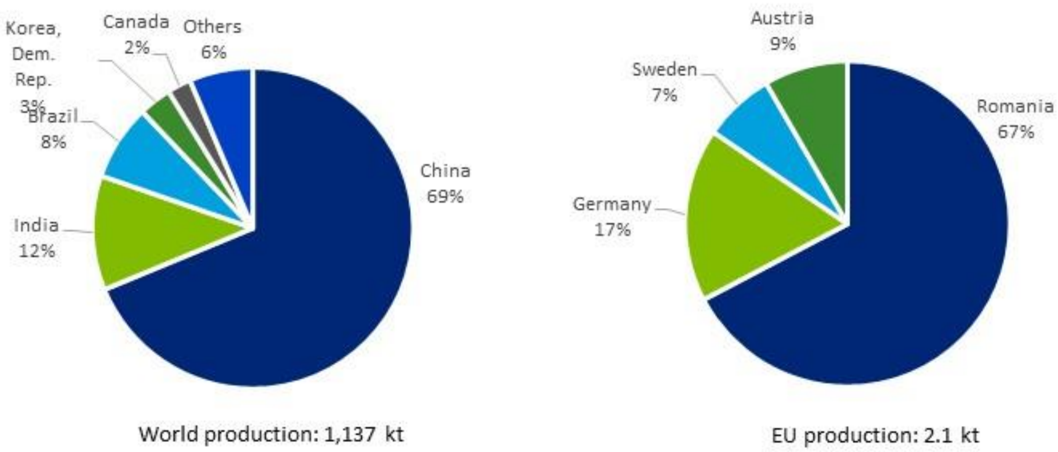

Figure 204: Global and EU mine production of natural graphite. Average for the years 2012-2016. Data from (WMD 2019)

16.4.3Processing/refining of natural graphite

The natural graphite concentrate can be subjected to chemical and thermal treatments to achieve a grade of higher purity (C content of over 99%) and optimise the combination of physical and chemical properties for particular applications. Many of these processes require the use of strong reagents, high temperatures and large energy consumption (Roskill 2015). Processed natural graphite products are intermediates for the manufacture of a wide range of value-added products for speciality technical applications. The refined forms of natural graphite can be distinguished in the following types:

- *Purified graphite*. The most common technique to refine the natural graphite after flotation is acid leaching. Various acids (e.g. HCl, HF, H_2SO_4, HNO_3) or mixtures of them are used depending on the type of the impurities in the graphite. Acid leaching is an effective technique to remove silicate impurities. When the graphite concentrate also contains sulphur, both silicates and sulphides are effectively eliminated by a combined roasting-leaching process, which can produce graphite with 99.99 % purity. Purified natural graphite can also be produced by thermal purification at high temperatures;
- *Expandable and flexible graphite*. Expandable graphite is made by chemical treatment of large-sized flake graphite with intercalating compounds (e.g. acid-based S and N compounds) at room temperature, to achieve graphite intercalation, i.e. introduction of atoms or small molecules between the planar carbon layers. The intercalated flakes are then washed and dried to remove residual elements. Under the influence of heat, the intercalating compounds vaporise which results in high inter-layer pressure causing the exfoliation (expansion) of individual graphite flakes and the increase in volume by several hundred times (150 to 300 times or even higher). The properties of expandable graphite, i.e. onset temperature of expansion and expansion volume, are determined by the quality of intercalation (proportion of intercalated layers) and by the intercalation agent. Expanded graphite is produced after thermal treatment of expandable graphite. Flexible graphite (or graphite foil) is made by rolling and compressing expanded graphite into thin sheets;
- *Spherical graphite*. It is the battery-grade graphite in anodes of Li-ion batteries. Fine and medium-flake graphite are typically used to produce spherical graphite. Spherical graphite is produced with stringent quality requirements from high-carbon flake graphite by successive stages of mechanical milling (micronising), spherodisation, purification to above 99.95% C, and coating with carbon. The process increases the surface area and conductivity making it highly suitable for use as anode material. Spherical graphite production yields generally ranges from 30% to 40% of the initial weight of the feed flake material (BRGM 2012). The fine by-products of the process can be marketed for low-value uses of amorphous graphite. The purified spherical graphite can be marketed either uncoated or coated.

16.4.3.1 World and EU refined natural graphite production

No statistical data are available for the production of value-added downstream products such as high-purity graphite, expandable/expanded graphite, and spherical graphite. Currently, China is practically the only global producer of spherical graphite worldwide producing in excess of 100 kt in 2018 for use in lithium-ion battery anode material (Roskill 2019c).

16.4.4 Supply from secondary materials/recycling

Recycling of graphite from end-of-life products is limited as a significant amount is dissipated during use, e.g. lubricants, pencils, friction pads, foundry washes, carbon brushes and, to some extent, refractories. Besides, recycling of graphite from end-of-life products is inhibited by its relative abundance in nature and lack of economic incentive due to the prevailing low prices (USGS 2019b), (European Commission 2017).

Potential secondary resources for natural graphite from end-of-life products include refractories, batteries and brake pads:

- Recycling of graphite from spent refractories is feasible through a process of crushing, pulverising, iron and slag removal, and separation by sieving (Sundqvist Ökvist et al. 2018). The market for graphite recycling from used refractories such as magnesia-carbon bricks and alumina-carbon shapes is reported to be growing, and the recovered material can be recycled into brake linings and thermal insulation (USGS 2019b) or monolithic and shaped refractories (European Commission 2017);
- Currently, there is no reported industrialised process to recycle graphite from the spent lithium-ion batteries (Sundqvist Ökvist et al. 2018). Recycling of batteries does not target graphite, which is oxidised to CO_2 during pyrometallurgical processes. However, in hydrometallurgical processes, the recovery of graphite is technically feasible (Mathieux et al. 2017).
- Friction liners for vehicle brakes are only used to approximately 50% prior to their replacement. These spent materials usually are disposed of as hazardous waste or partially smelted to low quality steel. It has been demonstrated that recycled friction liners can be used to produce new friction liners; thus, the graphite in the liners is recycled as well (Sundqvist Ökvist et al. 2018).

Recycling of end-of-life products is a minor source of natural graphite supply. It is estimated, that in 2016, only 3% (EOL-RIR) of the EU annual supply of natural graphite is sourced from end-of-life scrap (Draft MSA 2019).

Table 90: Material flows relevant to the EOL-RIR of natural graphite[172] in 2016. Data from (Draft MSA 2019)[173]

MSA Flow	Quantity (t)
B.1.1 Production of primary material as main product in EU sent to processing in EU	652
B.1.2 Production of primary material as by-product in EU sent to processing in EU	0
C.1.3 Imports to EU of primary material	0
C.1.4 Imports to EU of secondary material	0
D.1.3 Imports to EU of processed material	77,310
E.1.6 Products at end of life in EU collected for treatment	22,049
F.1.1 Exports from EU of manufactured products at end-of-life	189
F.1.2 Imports to EU of manufactured products at end-of-life	220
G.1.1 Production of secondary material from post-consumer functional recycling in EU sent to processing in EU	0
G.1.2 Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU	2,183

16.5 Other considerations

16.5.1 Environmental and health and safety issues

Natural graphite is inert and non-toxic (Leguérinel and Le Gleuher 2017), and it is not subject to restrictions by the REACH regulation (ECHA 2019).

[172] EOL-RIR=(G.1.1+G.1.2)/(B.1.1+B.1.2+C.1.3+D.1.3+C.1.4+G.1.1+G.1.2)

[173] The work carried out in 2019 increased the resolution of the MSA system. Therefore, there are changes in flows in comparison with the previous MSA methodology. B1.1 and B1.2 in the table is the result of the EU extraction after exports (MSA flows B1.1 + B1.2 – B1.3); C1.4 incorporates all secondary raw material imported to the EU both for the processing and manufacturing stages (MSA flows C1.4 and D1.9). D1.3 Incorporates imports to the EU of both semi-processed and processed material stages (MSA flows D1.3 and C1.8).

16.5.2 Contribution to low-carbon technologies

Graphite is the reference material used in the anodes of Li-ion batteries for hybrid, plug-in hybrid and battery-electric vehicles, as well as in Li-ion and lead-acid batteries for energy storage systems. Graphite in the anode can be either natural, in the form of a highly-processed spherical type, or synthetic (see section 16.3.2 and 16.3.3). The future role of electric vehicles in transport decarbonisation is widely acknowledged and documented, particularly if their deployment is coupled with a low-carbon intensity of electricity generation (European Commission 2018), (Bunsen et al. 2019). The energy storage infrastructure is considered essential to maintain a more flexible energy system and sustain the development of intermittent renewable energy sources, especially wind and solar (Tercero 2019). Finally, graphite is the primary filler material in bipolar plates for fuel cells. Purified flake graphite and purified expanded flake graphite can be used; in 2014 natural graphite accounted for 90% of the global market of graphite for fuel cells (Roskill 2015).

16.5.3 Socio-economic issues

China is the leading supplier of natural graphite, both to EU and globally. The level of governance in China is, on average, low, mainly due to the low score in the governance dimension of "voice and accountability" (World Bank 2018).

16.6 Comparison with previous EU assessments

The assessment has been conducted using the same methodology as for the 2017 list. The supply risk has been analysed at the extraction stage of the value chain (i.e. natural graphite concentrates), using both the global HHI and the EU-28 HHI, similar to the 2017 assessment. The 'refining stage' was not assessed due to the lack of published statistics for the production of the different forms of value-added processed graphite products, and the non-existence of specific trade codes for these products.

The result of the current and earlier assessments are presented in Table 91.

Table 91: Economic importance and supply risk results for natural graphite in the assessments of 2011, 2014, 2017, and 2020 (European Commission 2011);(European Commission 2014); (European Commission 2017)

Assessment	2011			2014			2017			2020	
Indicator	EI	SR		EI	SR		EI	SR		EI	SR
Natural Graphite	8.7	1.3		7.4	2.2		2.9	2.9		3.2	2.3

A revised methodology was introduced in the 2017 assessment of critical raw materials in Europe; therefore, the results with the previous assessments in 2011 and 2014 are not directly comparable, e.g. the significant decrease in EI from 2014 to 2017. The 2017 exercise considered natural graphite applications only, whereas, in the 2014 assessment, the calculation of the economic importance was based on natural graphite, and synthetic graphite applications.

In the current assessment, the supply risk indicator results differ from the 2017 assessment due to a decrease in the EU supply risk component of the indicator. In particular, the EU imports of natural graphite in years 2012-2016 have diversified and extended to more countries of origin in comparison to the 2010-2014 period. The share of

China in the EU sourcing has decreased from 66% (average 2012-2016) to 47% (average 2010-2014).

Concerning the economic importance indicator, the higher value in the current assessment is biased by the results scaling step[174]. The value-added of the largest manufacturing sector in the current assessment is lower as it corresponds to 27 Member States (i.e. excluding the UK). In contrast, in the 2017 assessment, it was related to 28 Member States.

16.7 Data sources

The source of production data for natural graphite was the 'World Mining Data' published by the Austrian Ministry for Sustainability and Tourism and the International Organising Committee for the World Mining Congress, and for trade flows the Eurostat Comext database. The EOL-RIR was calculated from datasets provided by the (Draft MSA 2019). For the end-use sectors, the global distribution was used in the assessment as published by BRGM.

Data on trade agreements are taken from the DG Trade webpages, which include information on trade agreements between the EU and other countries. Information on export restrictions is derived from the OECD database on export restrictions on Industrial Raw Materials.

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[174] The results are scaled by dividing the calculated EI score by the value of the largest manufacturing sector NACE Rev. 2 at the 2-digit level and multiplied by 10, in order to reach the value in the scale between 0-10.

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