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Programme

SCRREEN2

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SCRREEN
Solutions for CRitical Raw materials - a European Expert Network

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FACTSHEETS UPDATES

NATURAL GRAPHITE

AUTHOR(S):

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NATURAL GRAPHITE

OVERVIEW

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. 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.

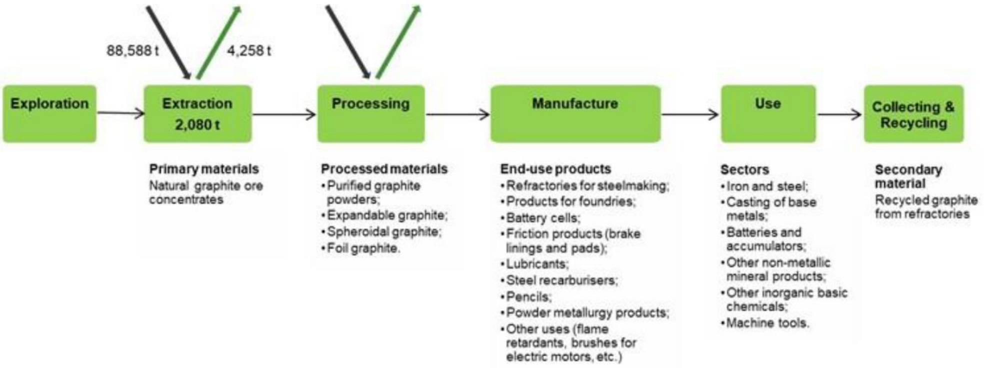

Figure 1: Simplified value chain for natural graphite[1] (average 2012-2016)

Table 1. Natural Graphite supply and demand (extraction) in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
1,019,167	China 67% Brazil 8% Mozambique 5% India 5% North Korea 4%	77,340	8%	China 42% Mozambique 15% Brazil 13% Madagascar 6%	97%

Price: Natural graphite prices have been driven by the steel industry and the increasing demand for lithium-ion batteries sector (Brown et al., 2020; MineralInfo, 2021; NG, 2021). In general, graphite prices showed relatively low volatility as result of persistent oversupply and the type of price establishment, which is not traded on commodity exchanges but directly negotiated by suppliers and consumers on quarterly/monthly contracts (MineralInfo, 2021).

Primary supply: China remains the main natural graphite producer. According to recent data, graphite production in 2018 in China reached 1.25 million tonnes. About the 1/3 of total production was amorphous graphite and 2/3 of the total production was flake graphite (ICMNR 2019, German Mineral Resources Agency 2020). World natural graphite production excluding China and EU did not exceed 0.5 million tons in 2018

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

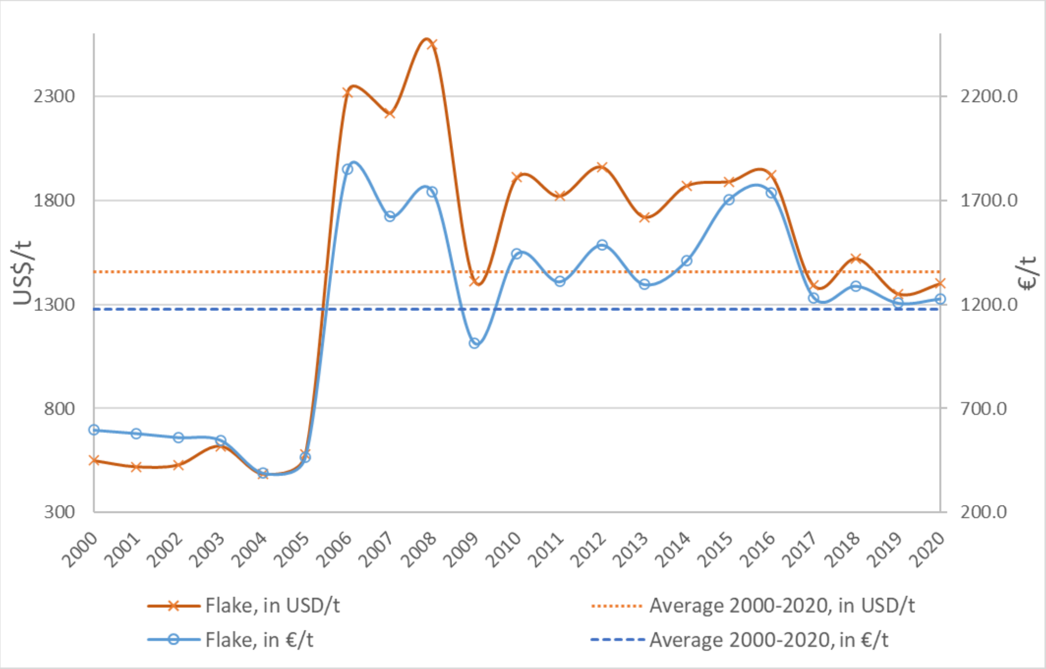

Figure 2. Annual average price of natural graphite (flake) between 2000 and 2020, in US$/t and €/t (based on USGS, 2021).

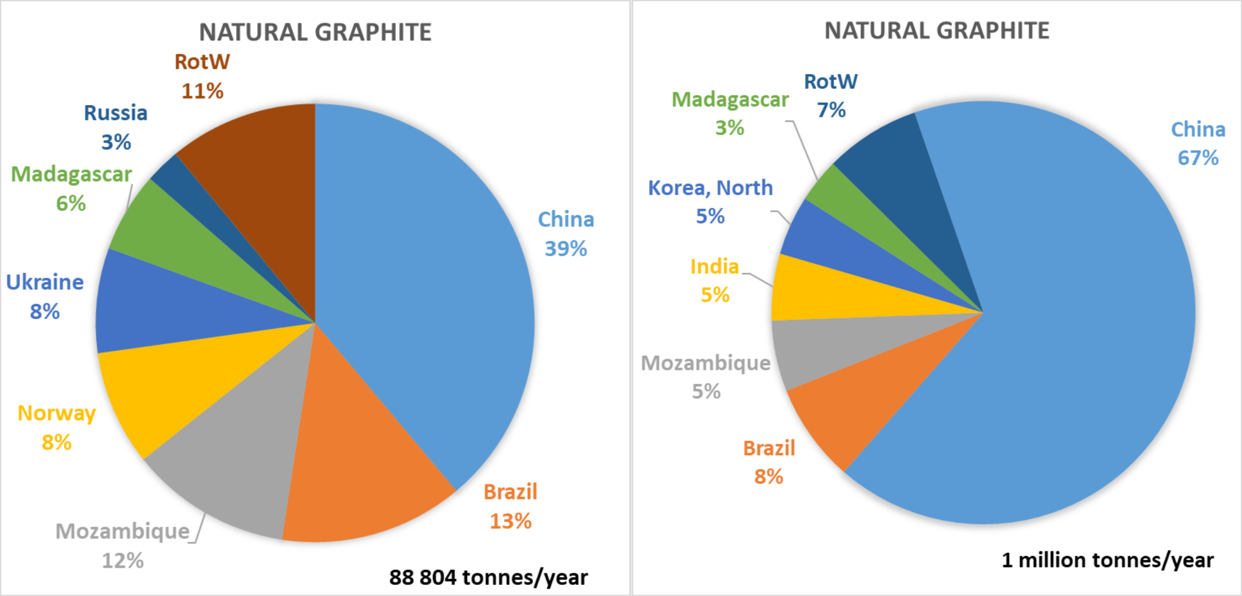

Figure 3. EU sourcing of natural graphite global mine production (average 2016-2020)

Secondary 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).

Use: Due to its combination of metallic and non-metallic properties, natural graphite is used for a wide variety of applications. At the EU level, the main ones are steel making (32%), batteries (25%) and lubricants (13%).

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Substitution: 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.

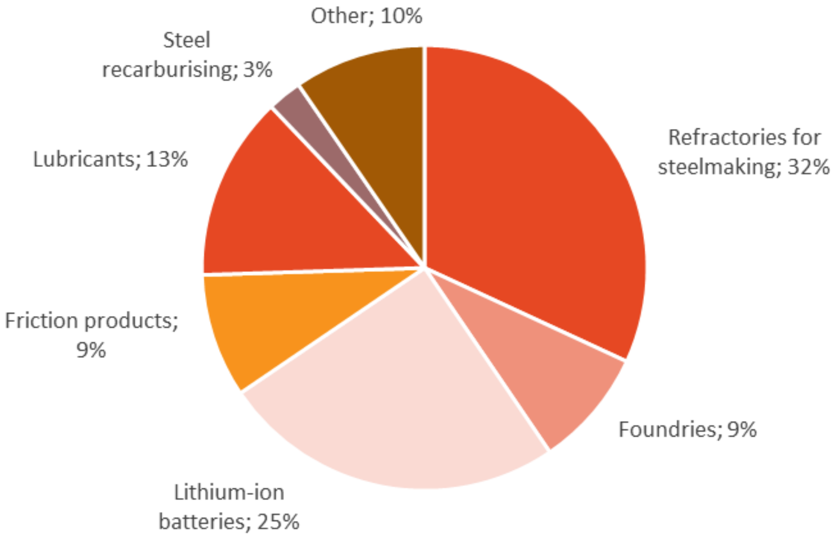

Figure 4: End uses of natural graphite in the EU (average 2012-2016)

Other considerations: Natural graphite is an inert and non-toxic material (Leguérinel and Le Gleuher 2017), it is not subject to restrictions by the REACH regulation (ECHA 2019). China is the leading supplier of natural graphite, both to the 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).

Table 2. Substitution of natural graphite in main uses

Application	Share	Substitutes	SubShare	Cost	Performance
Refractories	54%	Graph free refractory materials	0%	Similar or lower costs	Similar
Refractories	54%	No substitutes	100%		No substitute
Friction materials	8%	No substitutes	100%		No substitute
Lubricants	6%	Molybdenum disulfide	25%	Similar or lower costs	Similar
Lubricants	6%	No substitutes	75%		No substitute
Batteries	8%	Synthetic graphite	80%	Similar or lower costs	Similar
Batteries	8%	No substitutes	20%		No substitute
Iron casting	13%	Synthetic graphite	30%	Very high costs (more than 2 times)	Similar
Iron casting	13%	Calcined petroleum coke	10%	Similar or lower costs	Similar
Iron casting	13%	Secondary synthetic graphite from machining shapes	10%	Similar or lower costs	Similar
Iron casting	13%	No substitutes	50%		No substitute

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3. Natural Graphite supply and demand (extraction) in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
1,019,167	China 67% Brazil 8% Mozambique 5% India 5% North Korea 4%	77,340	8%	China 42% Mozambique 15% Brazil 13% Madagascar 6%	97%

The global graphite market was valued around € 12.8 billion in 2019 (Allied-Market-Research, 2020). 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 1,500-1,600 ktonnes, whereas the size of the natural graphite market was estimated at around 1 million tonnes in 2017 (Leguérinel & 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% (Leguérinel & Le Gleuher, 2017; Roskill, 2015).

Natural graphite is mined in several countries, but production is concentrated in China, which dominates the world natural graphite production with a share of 67% (Table 3). According to USGS, approximately 60% of China's output is amorphous graphite, and 40% is flake graphite with a low proportion of large flakes in size distribution. According to 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 (EC, 2014; Roskill, 2015).

After China, the dominant global producer, 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 6. 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, 2019b, 2019a). Large graphite deposits are being developed in Madagascar, northern Mozambique, Namibia and south-central Tanzania, with the largest natural graphite in Mozambique (USGS, 2021).

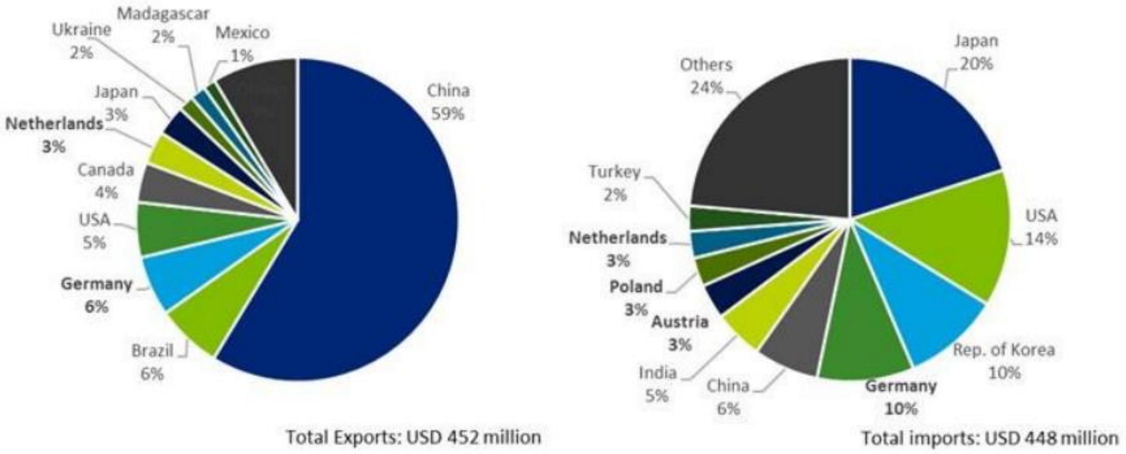

Figure 5. Top-10 natural graphite exporting (left) and importing (right) countries in 2017 by value (Source: UN, 2021)

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, 2019b).

Regarding its substitution potential, synthetic graphite powder, scrap from discarded machined shapes, and calcined petroleum coke compete for use in iron and steel production. Synthetic graphite powder and secondary synthetic graphite from machining graphite shapes compete for use in battery applications. Finely ground coke with olivine constitutes a potential competitor in foundry-facing applications. Molybdenum disulfide competes as a dry lubricant but is more sensitive to oxidising conditions (USGS, 2021).

The market for recycled refractory graphite material is expanding, with material being recycled into products such as brake linings and thermal insulation. Recovering high-quality flake graphite from steelmaking kish is technically feasible, but currently not practiced. However, the abundance of graphite in the world market inhibits increased recycling efforts (USGS, 2021).

OUTLOOK FOR SUPPLY AND DEMAND

The global graphite market is expected to reach USD 21.6 billion by 2027, at a CAGR of 5.3% from 2020 to 2027, driven primarily from demand in the Asia Pacific region (Allied-Market-Research, 2020). The battery sector, in particular the high demand for lithium ion battery industry, 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. Pre-pandemic, steel associated applications such as refractories, which underpin demand as the most important consumers, were 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, 2021). The market of expandable graphite for foil, insulation and fire retardant products was expected to grow fast. High-tech emerging applications, such as fuel cells and pebble-bed nuclear reactors, should also note a rise in demand (USGS, 2021). 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, was not anticipated by 2030.

A notable increase in future demand for new types of nuclear reactors is more uncertain in the same timeframe (Leguérinel & 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, A. Monnet, 2018).

However, it is worth noting that the COVID-19 outbreak has presented a challenge for the graphite market industry, as the demand from the key end-user industries, like the electronics, metallurgy, and automotive industries (including electric vehicles), slowed down due to the lockdown measures. Furthermore, the production facilities of the electronics parts were halted, owing to the logistics slowdown and unavailability of the workforce across the world (Mordo-Intelligence, 2020). Globally, the COVID-19 pandemic had some effect on graphite supplies at the start of the pandemic but mostly to operations outside of China. The impact was limited in China and the recovery was quick, which was demonstrated by China's pattern of exports. Chinese producers quickly increased production after a few months of closures in 2020. This allowed China to gain a more dominant position in the market and slow down the diversification of the supply chain (USGS, 2021).

Globally, the development of substitute anode materials for lithium-ion batteries in high-end applications, stringent environmental regulations, and the impact of the COVID-19 outbreak are expected to hinder the market growth (Mordo-Intelligence, 2020).

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&PGlobal, 2018; Scogings et al., 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

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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, 2019). Most largescale projects at advanced development stage moving closer to first production are situated in Africa, i.e. Mozambique, Madagascar, and Tanzania (Roskill, 2019b; S&PGlobal, 2018).

EU TRADE

Table 4. Relevant Eurostat CN trade codes for Natural Graphite

CN trade code	title
25041000	Natural graphite in powder or in flakes
25049000	Natural graphite (excl. in powder or in flakes)

There are two HS codes for natural graphite: Natural graphite powder or in flakes (CN 25041000), and Natural graphite (excl. in powder or in flakes) (CN 25049000). The EU is greatly reliant on imports for its natural graphite imports that account for 85,308 t per year for CN 25041000 (see Figure 1) and 6,164 t per year for CN 25049000 (see Figure 2). Over the whole period, the EU was a net importer of for both CN trade codes for natural graphite. The imports of Natural graphite (CN 25041000) varied from 75,326 t in 2000 to 94,700 t in 2021, while Natural graphite exports ranged between 4,894 t and 7,375 t per year. The imports of Natural graphite (CN 25049000) varied from 6,684 t in 2000 to 544 t in 2021;

The Natural graphite (CN 25049000) exports were slightly increased between 2018 and 2021, ranging from 294 t to 4,409 t during this period. Significant intra-EU trade also takes place (ESTAT Comext 2019).

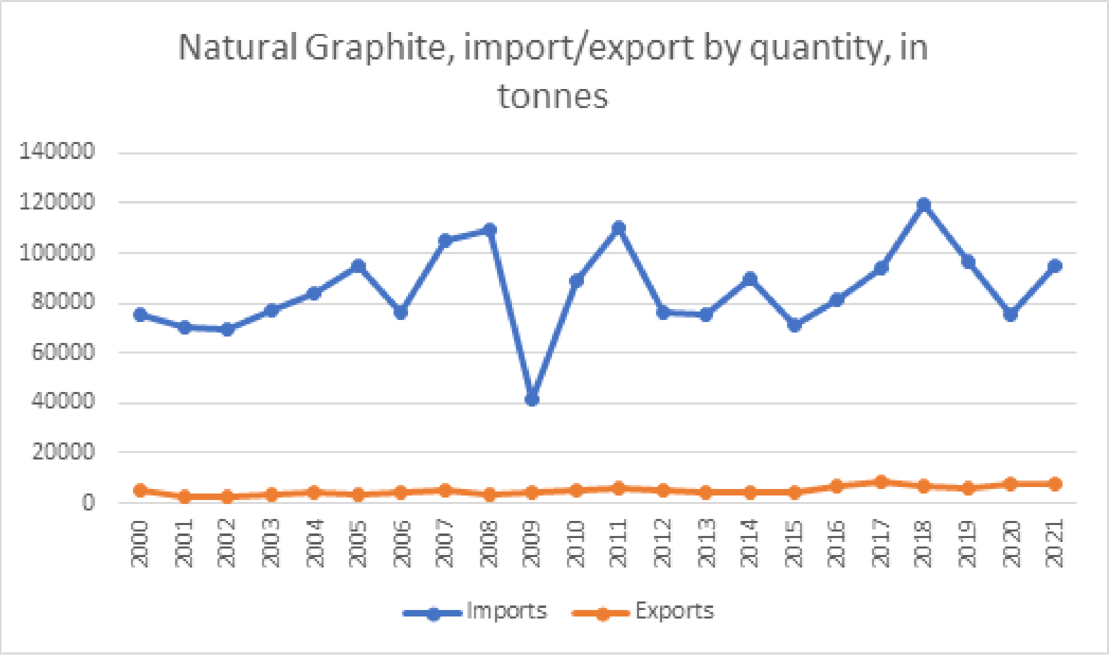

Figure 6. EU trade flows of Natural Graphite (CN 25041000) from 2000 to 2021 (based on Eurostat, 2022)

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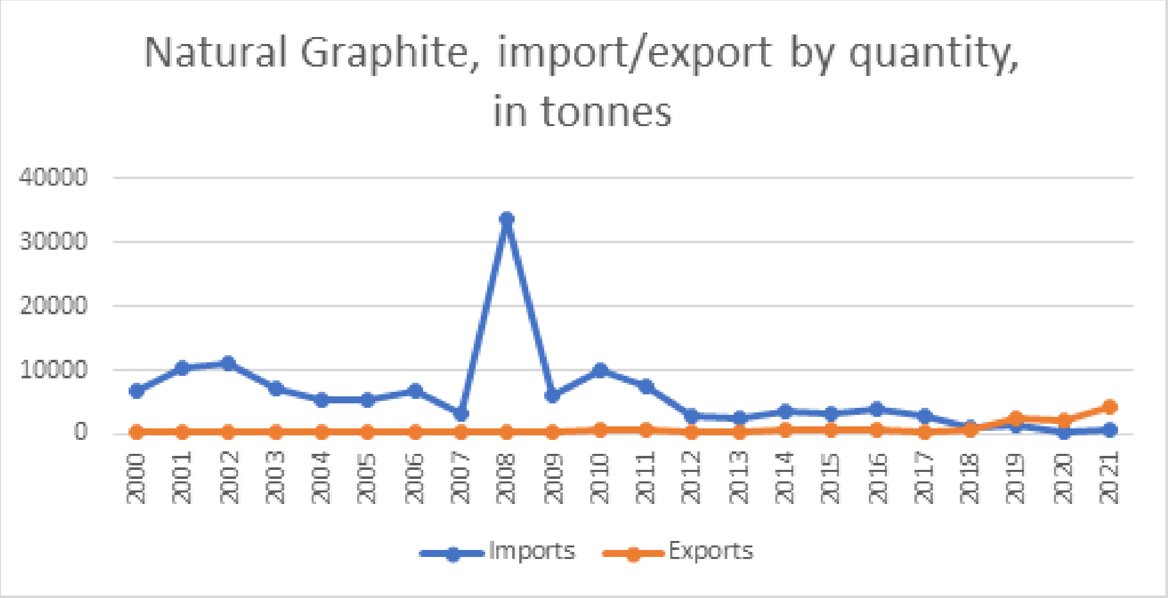

Figure 7. EU trade flows of Natural Graphite (CN 25049000) from 2000 to 2021 (based on Eurostat, 2022)

Almost 57% of the EU imports originated in China, 9% from Brazil and 7% from Norway for Natural graphite (CN 25041000) (Figure 3). Import from Mozambique has started in 2017 and increased from 740 t in 2017 to 12,545 in 2021. The import from China has been declining over the years from 43,039 t in 2000 to 30,600 t in 2021. In the same period, the EU exported small amounts of natural graphite (CN 25041000) at a yearly average of 4,949 t.

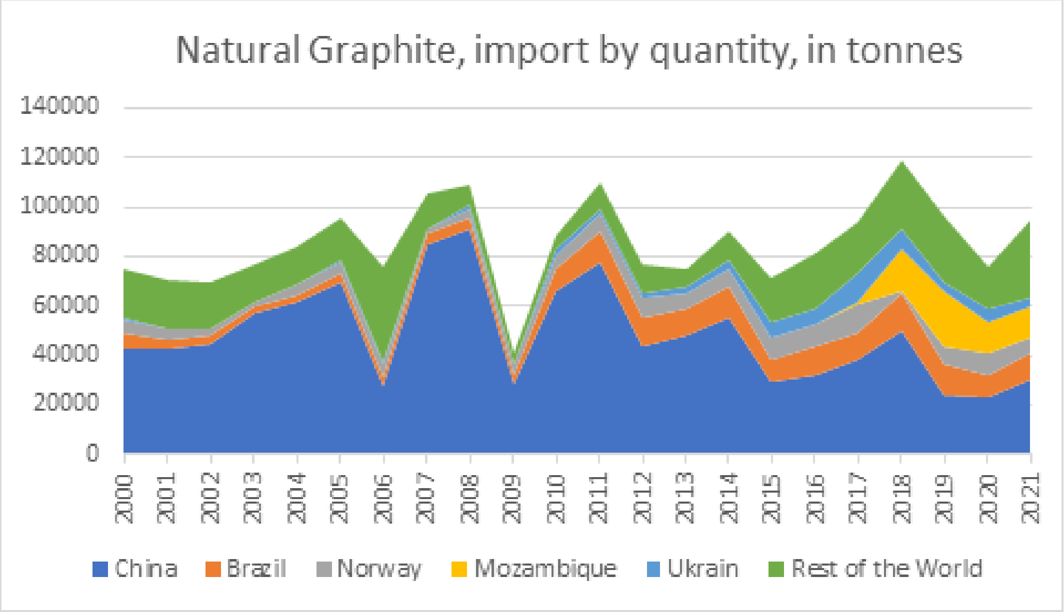

Figure 8. EU imports of Natural Graphite (CN 25041000) by country between 2000-2021 (based on Eurostat, 2022).

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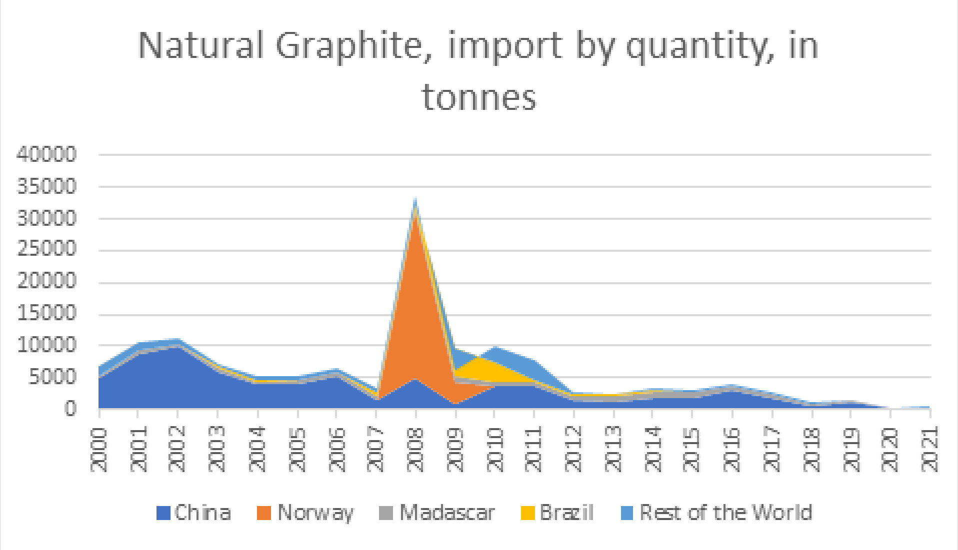

Figure 9. EU imports of Natural Graphite (CN 25049000) by country between 2000-2021 (based on Eurostat, 2022).

PRICE AND PRICE VOLATILITY

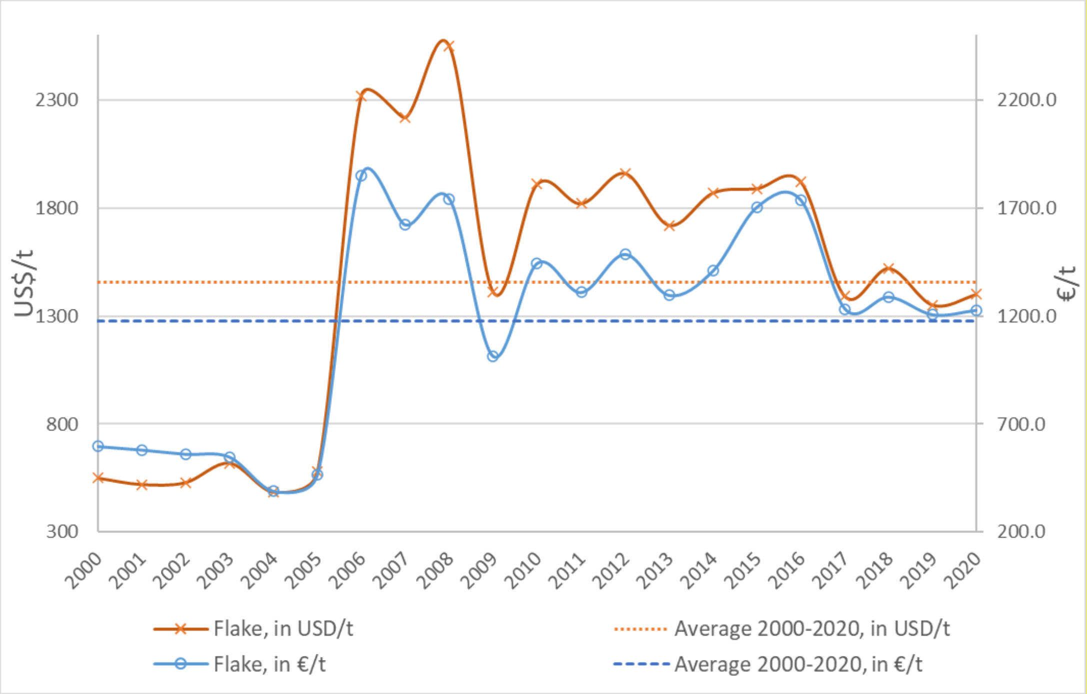

Figure 10. Annual average price of natural graphite (flake) between 2000 and 2020, in US$/t and €/t (based on USGS, 2021)2. Dash lines indicates average price for 2000-2020.

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[2] Values in €/t are converted from original data in US$/t by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

Natural graphite prices have been driven by the steel industry and the increasing demand for lithium-ion batteries sector (Brown et al., 2020; MineralInfo, 2021; NG, 2021). In general, graphite prices showed relatively low volatility as result of persistent oversupply and the type of price establishment, which is not traded on commodity exchanges but directly negotiated by suppliers and consumers on quarterly/monthly contracts (MineralInfo, 2021). During the first half of 2020, COVID-19 caused a reduction of natural graphite supply from China, which was the major graphite producer worldwide in this period (USGS, 2021). However, the Chinese production showed a quick recovery for the second half that allowed to maintain prices relatively constant (NG, 2021; Roskill, 2021; USGS, 2021). Moreover, natural graphite price for 2021 is expected to increase as a response to the expected demand of lithium-ion battery, new environmental policies for the Chinese industries as well potential COVID-19 impacts on the supply and demand of natural graphite (NG, 2021; Roskill, 2021). The price volatility of flake graphite was around 8% between February 2020 and January 2021 (DERA, 2021b). In this period, average monthly prices fluctuated less than the prices between 2016 and 2020, where price volatility was 18%. Thus, price volatility for 2020-2021 was reduced by more than a half of volatility reported between 2016 and 2020.

DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

Worldwide consumption of natural graphite was about 947,000 tonnes in 2018 (Roskill Information Services Ltd., 2019).

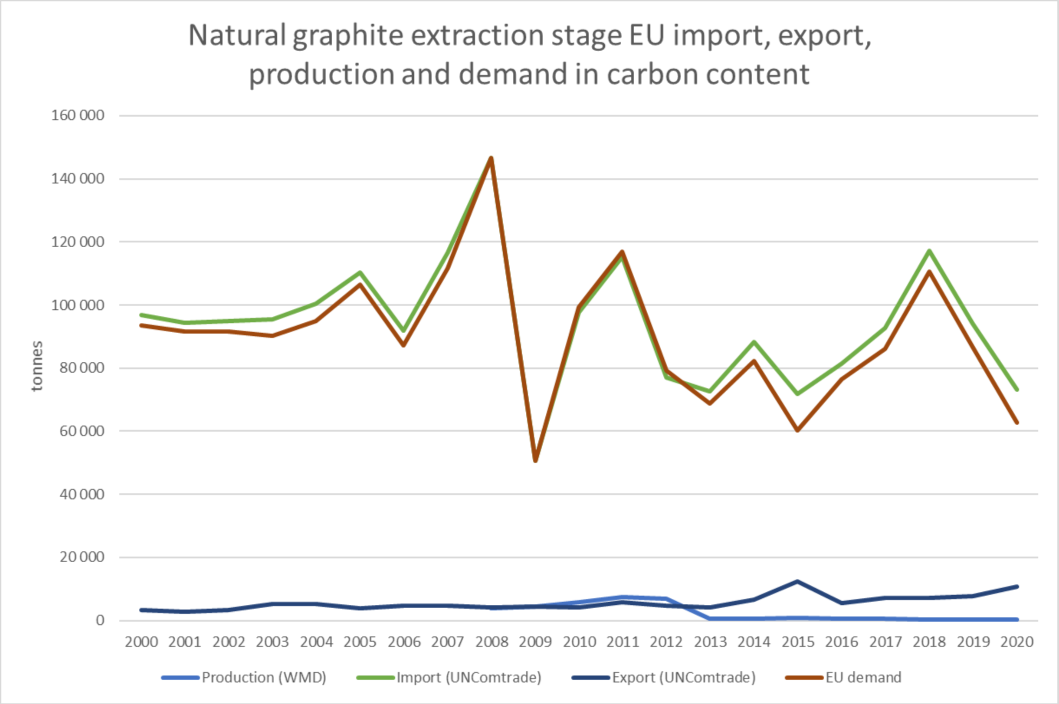

Figure 11. Natural graphite (CN 2504) extraction stage apparent EU consumption. Production data through WMD (2021) for natural graphite available for 2008-2020. Consumption is calculated in carbon content (EU production+import-export).

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Natural graphite extraction stage EU consumption is presented by HS code CN 2504 Natural graphite. Import and export data is extracted from UNComtrade (2021). Production data is extracted from WMD (2021).

Based on UNComtrade (2021) average import reliance of natural graphite at extraction stage is 97.1 % for 2008-2020.

EU USES AND END-USES

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.

In 2014, Ca. 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. Natural graphite was used in friction products (5%) and lubricants (5%), pencils (4%), graphite shapes (1%) and other applications (7%) (Figure 12).

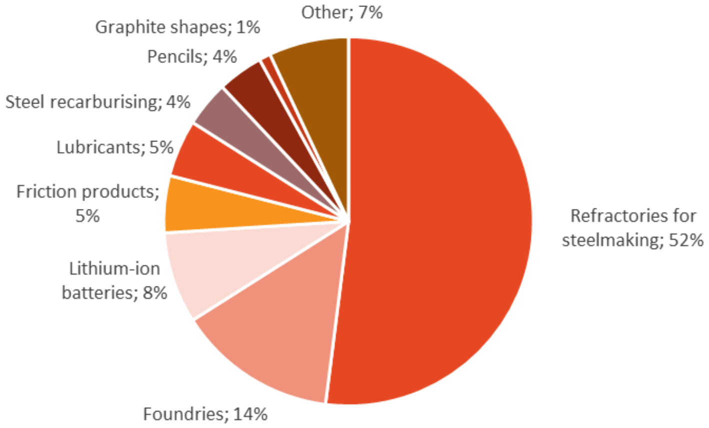

Figure 12. Global end uses of natural graphite in 2014. (BRGM 2016)

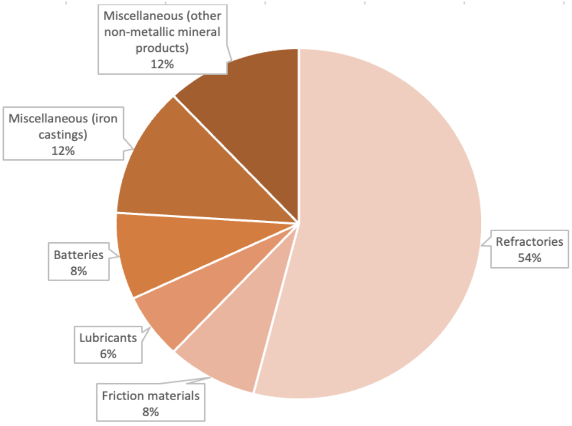

Figure 13. Estimated EU27 end uses of natural graphite in 2016. (SCRREEN experts input, 2022; MSA 2020 report)

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Figure 13 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 lithium-ion batteries (6%), friction products (8%), lubricants (5%), and other miscellaneous uses.

Relevant industry sectors are described using the NACE sector codes inTable 5.

Table 5. Natural graphite applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector, 2019 (Eurostat 2022)

Applications	2-digit NACE sector	Value-added of sector (millions €)	Examples of 4-digit NACE sector
Refractories for steelmaking	C24 - Manufacture of basic metals	71,390.80	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Refractories for foundries	C23 - Manufacture of other non-metallic mineral products	69,888.20	C2311 - Manufacture of flat glass
Batteries	C27 - Manufacture of electrical equipment	98,417.10	C2720 - Manufacture of batteries and accumulators
Friction products	C23 - Manufacture of other non-metallic mineral products	71,390.80	C2399 - Manufacture of other non-metallic mineral products n.e.c.
Lubricants	C20 - Manufacture of chemicals and chemical products	117,093.2	C2013 - Manufacture of other inorganic basic chemicals
Recarburising	C24 - Manufacture of basic metals	71,390.80	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Pencils	C23 - Manufacture of other non-metallic mineral products	69,888.20	C23.9.9 - Manufacture of other non-metallic mineral products n.e.c.
Graphite shapes	C28 - Manufacture of machinery and equipment n.e.c.	200,030.20	C2849 - Manufacture of other machine tools

APPLICATIONS

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 (accounting for Ca.15 kg per tonne of crude steel worldwide (Roskill 2015)).

Natural graphite used in refractories is selected for its high-temperature stability, chemical inertness and other important properties (flake size, carbon content, and impurity level).

Natural flake graphite with large crystals increases brick mechanical strength. Amorphous graphite powder can also be used, mostly for monolithic refractories.

Graphite flakes are primarily used 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.

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. Graphite, in the form of flakes or expanded graphite, offers the possibility of developing metal-graphite composites. Depending on the content and orientation of the incorporated graphite, it can be used as heat spreader material for thermal management, as a passive damping element for plant and mechanical engineering, or as bearing material for slowly rotating plain bearings. By combining materials, properties such as strength, thermal conductivity, damping factor, the coefficient of thermal expansion and Young’s modulus can be specifically matched to the intended application. Powder-metallurgical production allows the carbide content to be controlled in a targeted manner and graphite contents of up to 90% by volume to be realised without pores. Mechanical finishing is therefore possible even with very high graphite contents (Graphano Energy, 2022).

REFRACTORIES FOR FOUNDRIES

In foundries, natural graphite-based coatings and washings are employed as facings to protect refractory linings, troughs (and other equipment that convey molten metal) from erosion - as well as to ease the release of cast products from moulds.

Graphite is the main component in the manufacture of clay-bonded crucibles to handle molten metal (the mix contains up to 60% graphite).

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 fine-grained, low-grade flake graphite can also 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. TIn 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).

Graphite is needed for lithium-ion batteries used in electric vehicles ("EVs") and accounts for about 20-24% of the material needed in a battery.

The trend towards electro-mobility has the potential to become a growth driver for graphite. Forecasts estimate that demand will quadruple in the period up to 2030. In this field, graphite is used in the production of innovative energy storage and conversion systems. Graphite has proven itself as the best value anode material in modern lithium-ion batteries in terms of energy storage abilities, cyclical stability and cost efficiency. d (AMG, 2022).

FRICTION PRODUCTS

Due to their 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.

LUBRICANTS

With high thermal conductivity, thermal stability and lubrication properties, natural graphite is a critical component of friction linings, providing 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 %).

With its lubricating properties, graphite modulates the braking effect of friction linings and essentially contributes to braking comfort and to noise reduction.).

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 long used in pencil leads, due to its softness, non-toxicity and black streak, with flake graphite being favoured for higher quality in pencils.

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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.

These small parts are contained in almost all electrical motors in cars, such as windscreen wipers, fuel pumps and fan motors. They establish electrical contact to the rotating component of a machine via sliding rings or collectors. .

Due to its stability and high elasticity, graphene combines the hardness of a diamond with the bendiness of an ultra-thin film in one material. Due to its electrical hyper-conductivity, graphene has the potential to revolutionise microelectronics and computer technology. (AMG, 2022).

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. This retards the spread of fire and minimises one of the most harmful effects of combustion, the creation of toxic gases and fumes (AMG, 2022).

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

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.

Graphite is also an important raw material for lighter materials such as carbon fibres and reinforced plastics used in automobiles and in the manufacture of aircraft parts. Graphite is used as an alloy component in the semiconductor industry.

SUBSTITUTION

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).

Table 6. Substitution of natural graphite in main uses

Application	Share	Substitutes	SubShare	Cost	Performance
Refractories	54%	Graph free refractory materials	0%	Similar or lower costs	Similar
Refractories	54%	No substitutes	100%		No substitute
Friction materials	8%	No substitutes	100%		No substitute
Lubricants	6%	Molybdenum disulfide	25%	Similar or lower costs	Similar
Lubricants	6%	No substitutes	75%		No substitute
Batteries	8%	Synthetic graphite	80%	Similar or lower costs	Similar
Batteries	8%	No substitutes	20%		No substitute
Iron casting	12%	Synthetic graphite	30%	Very high costs (more than 2 times)	Similar
Iron casting	12%	Calcined petroleum coke	10%	Similar or lower costs	Similar
Iron casting	12%	Secondary synthetic graphite from machining shapes	10%	Similar or lower costs	Similar
Iron casting	12%	No substitutes	50%		No substitute

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 that 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).

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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).

For the individual application of natural graphite, the following summarises the substitutes possible: be listed

REFRACTORIES

Refractories for steelmaking is one application in which there is no competition by synthetic graphite (Leguérinel and Le Gleuher 2017), (Tercero et al. 20158). 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 is required to form a dense graphite structure. However, these 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).

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. 2018), (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).

To achieve a further increase in the energy density of lithium-ion batteries, conventional graphite can be replaced by lithium-metal alloys on the anode side due to increases in the specific capacity of the anode (for this, the element silicon is a promising candidate).

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. 2018), (USGS 2019b), (Roskill 2015).

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Graphite / lubricants / replacement is possible with water-based synthetic lubricants for forging steel and aluminium. These graphite-free lubricants provide a clean working environment and are particularly suitable for the manufacture of forgings such as connecting rods (CONDAT, 2022).

FRICTION MATERIALS AND CARBON BRUSHES

Synthetic graphite can be used instead of natural graphite, if the price matches the application (Roskill 2015, Tercero et al. 2018);

RECARBURISING

High-carbon scrap from discarded graphite shapes and, calcined petroleum coke, synthetic graphite powder or anthracite can substitute the use of natural graphite to increase the carbon content in molten iron and steel (Tercero et al. 2018), (USGS 2019b). However, substitution with synthetic graphite is possible, but not applied in practice because of the higher costs (Roskill 2015).

FIRE-PROOFING MATERIALS, SEALS AND GASKETS

Synthetic graphite does not compete with natural graphite in applications using expandable natural graphite (Roskill 2015).

SUPPLY

EU SUPPLY CHAIN

Figure 14 shows the simplified Sankey diagram for natural graphite flows for the year 2016.

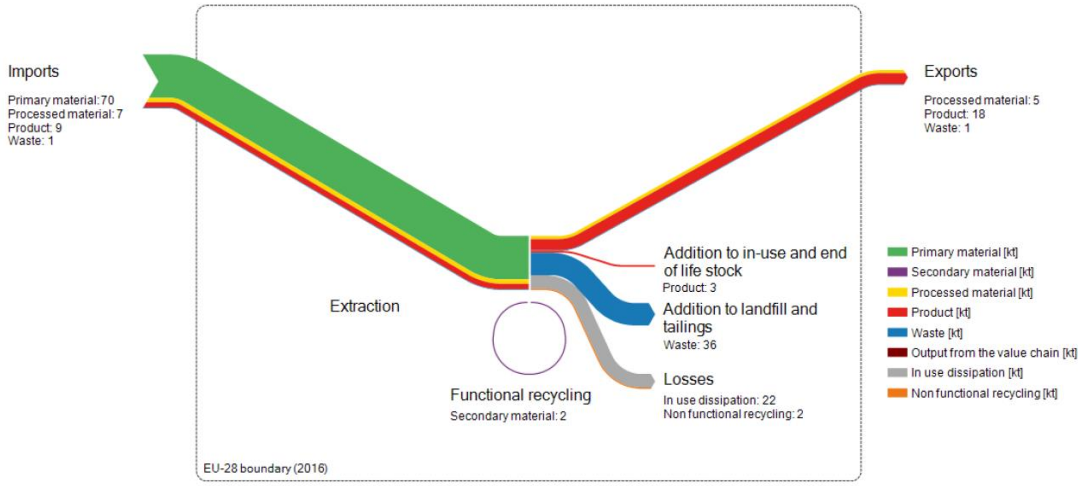

Figure 14: Simplified MSA of natural graphite flows in the EU in 2016 (Draft natural graphite MSA 2019)

The import reliance of the EU for natural graphite is 97%. 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).

However, 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).

SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES OF 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).

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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 are 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:

Table 7: Global reserves of natural graphite in 2019 and 2020. (USGS 2020, 2021)

Country	2 019,00	% 2019	2 020,00	% 2020
Brazil	72 000 000,00	23,9%	70 000 000,00	21,6%
China	73 000 000,00	24,3%	73 000 000,00	22,5%
India	8 000 000,00	2,7%	8 000 000,00	2,5%
Korea, North	2 000 000,00	0,7%	2 000 000,00	0,6%
Madagascar	1 600 000,00	0,5%	26 000 000,00	8,0%
Mexico	3 100 000,00	1,0%	3 100 000,00	1,0%
Mozambique	25 000 000,00	8,3%	25 000 000,00	7,7%
Norway	600 000,00	0,2%	600 000,00	0,2%

Sri Lanka			1 500 000,00	0,5%
Tanzania	18 000 000,00	6,0%	17 000 000,00	5,3%
Turkey	90 000 000,00	29,9%	90 000 000,00	27,8%
Uzbekistan			7 600 000,00	2,3%
Vietnam	7 600 000,00	2,5%		
TOTAL	300 900 000,00		323 800 000,00	

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)[3]. 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 320,000 kt of graphite content (Table 7Table 8).

EU RESOURCES AND RESERVES[4]

The most important natural graphite deposits in the EU and their associated resources and reserves are summarised below and listed in Table 8:

- 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),

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[3] 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

[4] For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for natural graphite. Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for natural graphite does not provide a complete picture for Europe.

flake graphite (Český Krumlov-Městský vrch, Lazec-Krenov, Koloděje nad Lužnicí-Hosty) and mixed (amorphous and flake) (Spolí) (Czech Geological Survey 2017).

Table 8: Natural graphite resources and reserves data in the EU

Deposit	Country	Reserves (Mt)	TCG_grade %	Contained (tonnes)	Company	Reference
Jalkanen	Sweden	31.5	14.9	4,693,500	Talga Group Ltd	Talga PR Aug 27, 2015
Vittangi	Sweden	19.5	24	4,686,000	Talga Group Ltd	Talga PR Sept 17, 2020
Woxna	Sweden	13.28	7.83	1,039,824	Leading Edge Materials Corp.	Leading Edge Materials PR June 6, 2021
Raitajärvi	Sweden	4.3	7.1	307,300	Talga Group Ltd	Talga PR Aug 26, 2013
Aitolampi	Finland	26.7	4.8	1,275,000	Beowulf Mining	Beowulf PR Oct 30, 2019
Skaland	Norway	1.78	22	397,000	Mineral Commodities Ltd	USGS mineral commodities 2021
Kaisersberg	Austria	0.16	NA	NA	-	Lauri et al. 2018

WORLD AND EU MINE PRODUCTION

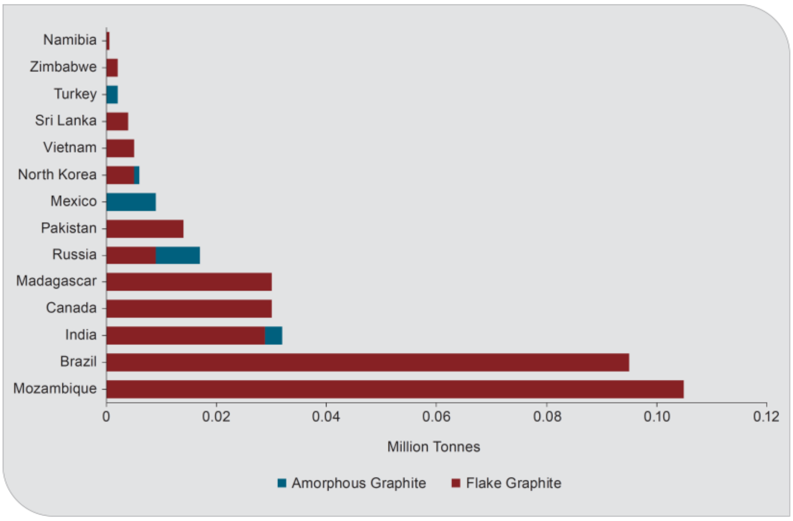

Figure 15: World production of flake (red colored) and amorphous (blue colored) graphite in 2018 excluding China and EU (Roskill 2019, German Mineral Resources Agency 2020).

China remains the main natural graphite producer. According to recent data, graphite production in 2018 in China reached 1.25 million tons. About the 1/3 of total production was amorphous graphite and 2/3 of the total production was flake graphite (ICMNR 2019, German Mineral Resources Agency 2020). World natural graphite production excluding China and EU did not exceed 0.5 million tons in 2018 (Figure 15) while production in EU and EU-linked countries between 2015-2019 remains low (Table 9).

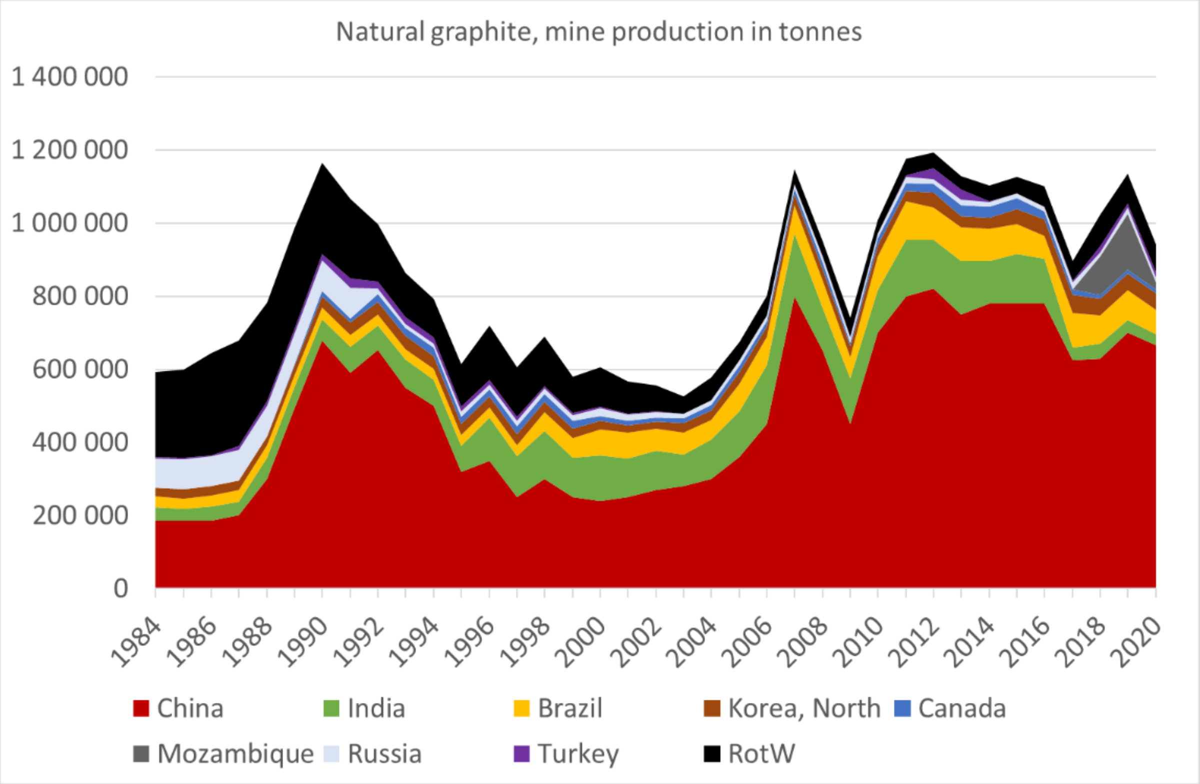

Figure 16. Natural graphite mine production by country since 1984 (WMD, since 1984).

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).

Table 9: EU (and EU-linked) natural graphite producer (metric tons), source: WMD.

Country	2015	2016	2017	2018	2019	2020
Austria	150	150	150	150	100	100
Germany	398	502	422	222	207	108
Sweden	295	-	-	-	-	-
Total	**843**	**652**	**572**	**372**	**307**	**208**
Norway	*9185*	*9600*	*9600*	*10000*	*9780*	*5549*
Turkey	*0*	*0*	*4000*	*16752*	*9990*	*15205*
Ukraine	*10000*	*12000*	*13000*	*15000*	*10000*	*10000*

OUTLOOK FOR SUPPLY

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958211

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).

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

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 primary 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, graphite recycling by spent Li-ion batteries is not industrially applied as dismantling at large scale is challenging, while graphite content in batteries is relatively low. (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).

Recycling graphite from spent lithium-ion batteries is expected to have a significant techno-economic importance due to the limited primary resources of graphite and the positive environmental impact of the recycling. Various studies have been focused on the simultaneous recovery of Li and graphite by spent Li-ion batteries. A typical recycling methodology comprises the combined acid leaching (using sulfuric acid), for the dissolution of impurities, and the calcination processing at high temperatures >1500 °C to obtain a solid product. Generated graphite has a maximum purity > 99.5%, while it exhibits acceptable electrochemical performance in terms of charge capacity and cycle (Gao et al. 2020). A limited number of non-EU based recycling Companies have reported the successful industrial recovery of natural graphite from spent lithium-batteries anodes (ecograf.com.au/business/recycling/, lithionrecycling.com/contact/).

Kish graphite is a potential additional secondary natural graphite resource which is produced from the steel making process. It is formed on the free surface of molten iron and grows in a foliated dendritic manner. Graphite flakes are formed in varying quantities, sizes and purities in steel plants. Flotation has been tested as effective methodology for the purification of kish graphite. Purification degree over 90% was observed using single flotation in case of large flake sizes (>500µm), while in case of smaller flake sizes (<500µm), multiple froth floats are required. A technical-economic assessment has been performed for a 10,000 tonne per year process plant, indicating that the exploitation of this secondary resource could be economically possible (Frost, 2014).

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PROCESSING

NATURAL GRAPHITE MINING

Natural graphite 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. extra large (+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

OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES

Natural graphite is an inert and non-toxic material (Leguérinel and Le Gleuher 2017), it is not subject to restrictions by the REACH regulation (ECHA 2019). Internationally, graphite is regulated in occupational health legislation with threshold limit values ranging from 0.3 mg/m³ to 15 mg/m³ for dust and aerosols (IFA 2021). No safety issues could be found.

ENVIRONMENTAL ISSUES

- Battery Grade Graphite: It’s not all about Carbon (MINVIRO 2020)
  There is more graphite than lithium in a lithium-ion battery, with an estimated 54 kg required for a Tesla Model S. The major limitation of LCA studies is the quality of the environmental performance data for raw material production. This is especially true for graphite. Graphite is often overlooked when assessing the environmental profile of battery materials. There is an obvious need for new LCA studies with good quality project-level data. There is an urgent need in particular for the development of a product category rule to ensure that we can have a fair and representative comparison for the environmental performance of different production routes, enabling policymakers and purchasers to make informed decisions. The following life cycle assessment studies have been made to evaluate the substance technology impact:
- (Pizza et al. 2014) performed a life cycle assessment on epoxy-based composites, filled with graphite nanoplatelets (GnP). Raw material extraction and filler and resin preparation phase exhibit the highest environmental impact while the composite production is negligible. Thermosetting resin remains the highest primary energy demand when used as a matrix for GnP fillers.
- (Wu et al. 2018) conducted a comparative life cycle assessment of lithium-ion batteries with lithium metal, silicon nanowire, and graphite anodes. Lithium metal and silicon nanowires are the most promising alternative advanced anode materials. By comparing three batteries designed, respectively, with a lithium metal anode, a silicon nanowire anode, and a graphite anode, the authors analyse the life cycle of different negative electrodes. Batteries with a lithium metal anode have a lower environmental impact than the battery with a graphite anode. The production of a battery with silicon nanowires causes a higher environmental impact than the production of a battery with graphite. Batteries with lithium metal anodes are the most environmentally friendly lithium-ion batteries.

STANDARDISATION AND NORMATIVE REQUIREMENTS

This substance is not registered under the REACH and no standards could be found in the scientific literature review.

CONTRIBUTION TO LOW-CARBON TECHNOLOGIES

Due to its different properties, natural graphite is a material applied in a broad spectrum of industrial sectors. In the field of green technologies, natural graphite is used to manufacture the anode in batteries and fuel cells for electric vehicles and energy storage systems. In this field, it is worth to note also the use of natural graphite in the brushes of electric motors. In this contest, the uptake of electromobility is expected to decarbonise the transport sector, especially in combination with the decarbonisation of power generation. On the other hand, energy storage systems are essential for the exploitation of renewable, intermittent energy sources in order to decarbonise the power production sector.

More in detail:

CONTRIBUTION TO PREVENTED CARBON DIOXIDE EMISSIONS

- **Technology 1: Batteries**

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. 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 electric generation. The energy storage infrastructure is considered essential to maintain a more flexible energy system and sustain the exploitation of intermittent renewable energy sources, especially wind and solar.

- **Technology 2: Fuel cells**

Natural Graphite is the primary filler material in bipolar plates for fuel cells. The graphite used in bipolar plates must be processed specifically for fuel cells and batteries. Natural flake graphite is usually the raw graphite that is processed for this purpose. 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. As example Fuel Cells are employed in Electric Vehicles powered by hydrogen which is the most prominent technologies employed for substituting the fossil fuels in the transport vehicles preventing carbon dioxide emissions.

- **Technology 4: Graphene**

Generally, Graphene and Graphene Related Materials can be employed in all green technologies whose components or part of them work in presence of graphite replacing it. As example Lithium ion Battery, Fuel cells or Supercapacitor.

USE OF RECYCLED MATERIAL IN LOW-CARBON/GREEN TECHNOLOGIES WITH CURRENT TRL (DOWNGRADE ANALYSIS IF ANY)

- **Batteries** → Silicon Nanopowders (TRL 4)
    a) derived from EoL PV panels (TRL 3)
    b) derived from Electronic Wastes (TRL 3)
- **Batteries** → Hard Carbon, Coal Char, Carbon Derived Biomass (TRL 3)

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SOCIO-ECONOMIC AND ETHICAL ISSUES

China is the leading supplier of natural graphite, both to the 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).

Li metal anode has long been considered as one of the most ideal anodes. However, safety concerns, low efficiency, and huge volume change are severe hurdles to the practical application of Li metal anodes, especially in the case of high areal capacity. Graphitized carbon fibre (GCF) electrodes can serve as a multifunctional 3D current collector to enhance the Li storage capacity. The multifunctional 3D current collector promisingly provides a new strategy for promoting the cycling lifespan of high areal capacity Li anodes.

Environmental and socio-economic challenges in battery supply chains: graphite and lithium (Dolega et al. 2020). Innovative solutions along the value chain of lithium-ion technology and to validate them in demonstrators in preparation for cell manufacturing in Germany.

RESEARCH TRENDS

Graphene Technologies: In the past few years, different methods of synthesis have been developed starting from graphite in order to produce different types of 2D graphene-like materials as pristine graphene, graphene oxide, or reduced graphene oxide. 2D graphene-like materials were employed in many technologies and green technologies. As example:

- Energies generation and storage: Fuel Cells, Hydrogen generation, batteries, supercapacitors, photovoltaic.
- Electronics & Photonics: Hybrid systems Silicon-Graphene, where the graphene is added to deliver additional functionalities. Prominent for applications in the flexible technologies. Sensors, flexible and printed electronics, optoelectronic and photonic devices.
- Additive to composites and coatings to enhance their mechanical properties for energy saving. Typical host materials are polymers, carbon-reinforced polymers, ceramics, concrete, etc. where the addition of graphene/2D materials shall improve particular mechanical and functional properties usually addressing a weakness of the host material. (from Graphene Flagship Technology and Innovation Roadmap https://graphene-flagship.eu/)

Recycling of graphite anodes for the next generation of lithium-ion batteries (Moradi et al. 2015): Graphite is currently the state-of-the-art anode material for most of the commercial lithium ion batteries. Flake graphite could become a critical material in the near future for countries such as the United States and members of the European Union with no graphite production. Recycling of flake graphite from its different waste resources is proposed as a potential solution to meet the future demand of graphite. The limitation of current technologies and a new perspective towards the future concept of "battery recycling" were also pointed out. Challenges in recycling battery grade flake graphite from spent lithium ion batteries and possible research opportunities in this regard were introduced.

Environment Impact Analysis of Natural Graphite Anode Material Production ((Zhang et al. 2018): A quantitative LCA of natural graphite anode material shows that the main environment impact categories are human toxicity potential, particulate matter formation potential and marine ecotoxicity potential, which account for 26 %, 19 % and 15 % of total environment impacts, respectively. The processes of production, purification and surface modification cause the strongest impact on the environment, because they consume a large number of electricity. Under the current electricity structure of China, improving the production technology and reducing the energy consumptions of purification and surface modification, are the effective methods of environment impact reduction for LIB anode materials.

Environmental impact, life cycle analysis and battery performance of upcycled carbon anodes (Hicks et al. 2018): For rechargeable lithium ion batteries, natural and synthetic graphite anodes come with great economic and environmental costs. Carbon microsheets, developed from used starch packing peanuts, are a carbonaceous alternative with great electrochemical performance and quantifiable environmental footprint. Synthesis route (E.G., ambient inert gas or vacuum) influences microsheet electrochemistry and environmental impact. Carbon microsheets show gravimetric capacity greater than conventional graphite, with argon-derived microsheets demonstrating gravimetric capacity up to CA. 30 % greater than vacuum-derived ones. Midpoint LCA illustrates that the impact of the vacuum process is sensitive to the origin of utilized energy. For instance, with respect to ozone depletion, vacuum pyrolysis produces less emission equivalents than its argon analogue – assuming conventional domestic energy profile. In this sense, the context of energy should be considered alongside environmental impact in evaluation of process sustainability.

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