The Hague Centre for Strategic Studies

Graphite
Supply chain challenges & recommendations for a critical mineral

Amrish Ritoe, Irina Patrahau, Michel Rademaker

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Authors:
Amrish Ritoe, Irina Patrahau, Michel Rademaker (PL)

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Executive summary

The energy transition relies on secure supplies of raw materials for the large-scale deployment of low-carbon technologies. Graphite is a critical mineral for governments across Europe and the United States (US), given its importance to strategic sectors and the risks associated with its supply. The mineral plays an essential role in decarbonizing two economic sectors with high emissions of greenhouse gases: transportation and heavy industry. Technologies that enable the decarbonization of transport and steel production will rely heavily on a consistent supply of high-quality graphite, leading to an exponential growth in the demand for graphite over the coming decades. This paper analyses the practical, geopolitical and environmental challenges of sourcing graphite, and provides recommendations of how the European Union (EU) and the US can mitigate supply risks in the next decades.

As most countries strive toward carbon neutrality within the coming decades, the demand for graphite could increase up to 500% compared to 2018 levels.[1] The concentration of graphite production and processing in China, which accounts for approximately 80% of global graphite supply, leaves the EU and US vulnerable to supply chain disruptions.[2] When it comes to lithium-ion batteries, Chinese dominance becomes even more striking. China dominates the entire supply chain for lithium-ion batteries, not just those parts of the supply chain that rely on the production of graphite. As China is committed to decarbonizing its economy, the global supply of graphite and batteries will be placed under considerable stress.

There are two types of graphite: natural and synthetic graphite. Whereas natural graphite can be mined in multiple jurisdictions worldwide, synthetic graphite has a narrower supply base as it is produced from oil or coal-based needle coke. Synthetic graphite is preferred in the production electric arc furnaces (EAFs) for steelmaking, but battery producers can use both synthetic and natural graphite as their raw material. Due to its predictable, consistent performance and auspicious characteristics, synthetic graphite has long been preferred over natural graphite. However, its production is expensive, energy-intensive, and environmentally harmful. The use of synthetic graphite in 'green energy' technologies is highly problematic from an environmental, social, and governance (ESG) perspective and therefore becomes increasingly difficult to justify by producers. The increased demand for synthetic graphite from EAFs together with other ESG challenges could lead producers of lithium-ion batteries to move toward natural graphite and new processing methods.

The processing of natural graphite is becoming increasingly popular due to new and sustainable production processes and the potential to scale up in regions outside of China. Natural flake graphite mines exist in African countries like Mozambique and European countries like Ukraine and Norway. Companies in the EU and the US have developed cleaner methods to process natural flake graphite in an environmentally responsible and economically efficient manner. Producing countries in Africa, the EU and the US are in a unique position to bring together their capital, knowledge and raw materials and set up a solid supply chain that meets environmental and social standards, and that secures the graphite supplies required for the energy transition. Government initiatives could incubate an eco-system that reduces investment risks, increases public acceptance of industrial processes, and scales processing capacity at home.

1 Kirsten Hund et al., "Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition" (World Bank Group, 2020), 12.

2 USGS, "Mineral Commodity Summaries: Graphite," 2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-graphite.pdf; Govind Bhutada, "Visualizing the Natural Graphite Supply Problem," Elements, November 18, 2021, https://elements.visualcapitalist.com/visualizing-the-natural-graphite-supply-problem/.

List of abbreviations

ATVM	Advanced Technology Vehicles Manufacturing Loan Program
BEV	Battery electric vehicles
BNEF	Bloomberg New Energy Finance
CAGR	Compound annual growth rate
CO_2	Carbon dioxide
DOE	Department of Energy
EAF	Electric arc furnaces
EBA	European Battery Alliance
EGHAC	European Green Hydrogen Acceleration Center
ESG	Environmental, Social, Governance
ESI	European Solar Initiative
EU	European Union
EV	Electric vehicle
GHG	Greenhouse gas emissions
GWh	Gigawatt hour[3]
HF	Hydrofluoric acid
H_2SO_4	Sulfuric acid
ICE	Internal combustion engine
IEA	International Energy Agency
MIIT	Chinese Ministry of Industry and Information Technology
SDS	Sustainable Development Scenario
STEPS	Stated Policies Scenario
TGC	Total graphite content
TWh	Terawatt hour
US	United States

3 1 Gigawatt hour equals 1 million kilowatt hour (KWh).

1. Graphite as a critical mineral and its main uses

1.1. Introduction to graphite

Graphite's ability to leave marks on paper and other objects led German mineralogist Abraham Werner to officially name the mineral after the ancient Greek word *graphein,* which means 'to write'.[4] Werner's name choice in 1789 seems to be inspired by the initial relevance of graphite to humankind.[5] Whether it was for the marking of sheep in 16th Century England, the decoration of pottery in ancient Mediterranean civilizations, or making sketches in the Middle Ages, graphite initially served primarily decorative purposes. But this is only a small part of graphite's remarkable story. As people discovered how to benefit from the mineral's both metallic and non-metallic properties, graphite became increasingly important to civilizations.

Graphite became of military importance shortly after the English started to use the mineral to line the molds of cannonballs. It became clear that its resistance to extreme heat, its strength

Figure 1. On the left, flake graphite sample from the Molo project in Madagascar.
Source: Next Source Materials.
On the right, natural flake graphite after first grinding.
Source: Indiamart.

4 Sophie Damm and Qizhong Zhou, "Supply and Demand of Natural Graphite," DERA Rohstoffinformationen, 2020, 7, https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/Studie%20Graphite%20eng%20 2020.pdf?__blob=publicationFile&v=3.

5 University of Waterloo, "Graphite," Wat on Earth, 2006, https://uwaterloo.ca/wat-on-earth/news/graphite.

and flexibility made high-quality graphite very suitable for producing rounder cannonballs with a smoother surface. Consequently, cannonballs traveled at a higher speed and greater distance, giving the English navy a serious advantage during battle. Soon the production of graphite was strictly controlled by the English Crown itself, making graphite a critical mineral well before governments had classifications for minerals of strategic importance.[6]

Today, graphite is used across various industries such as automotive, steel-making, the nuclear industry, powder metallurgy, fuel cells, and flame retardants.[7] This wide use is the result of graphite's many different properties. Graphite is strong yet flexible, a good conductor of electricity and heat, but it is also fire and cold resistant.[8] Each of these is discussed below.

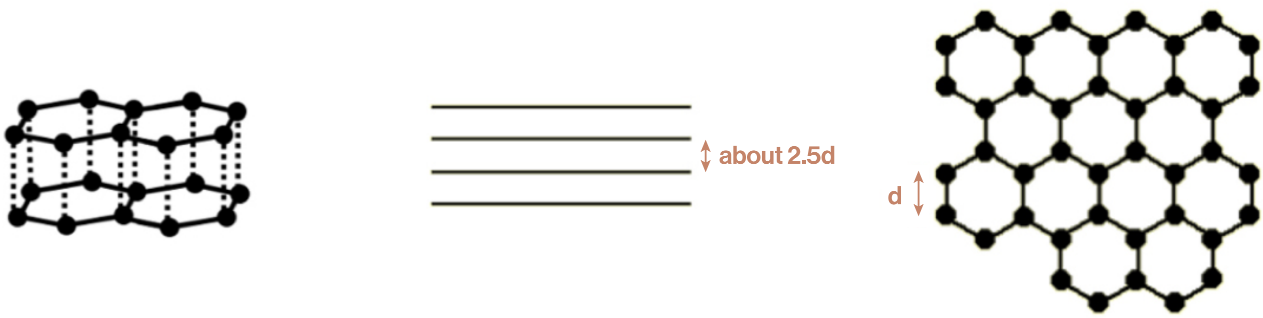
First, graphite's honeycomb-like molecular structure (see Figure 2) makes the mineral flexible and strong, allowing it to play an essential role in the production of steel. For instance, natural graphite is used to raise the carbon content in molten steel, increasing the strength of steel.

Graphite is also a good electrical conductor. It has a free electron to carry electrical charge, while the space between each graphite layer allows for the easy traveling of these free electrons.[9] This ability to carry, store and move electrical charge makes graphite the material of choice in the production of lithium-ion battery components and electrodes inside electric arc furnaces (EAF) for steel production. Both markets are growing fast, making graphite an essential mineral of the energy transition, as discussed below.

Lastly, graphite is used in applications that perform under extreme conditions. The steel industry uses graphite to paint the inside of foundry molds.[10] After leaving the graphite paint to dry, the inside of the mold gets a fine graphite coat, which will ease the separation of the

Figure 2. Structure of graphite.

Source: Matt Fernley, "Battery Materials Explained" (Battery Materials Review, 2020), 4.



Graphite structure **Graphite layers** **Graphite planar view**

6 For more information, see John Edward Proctor, Daniel Melendrez Armada, and Aravind Vijayaraghavan, *An Introduction to Graphene and Carbon Nanotubes*, 1st ed., vol. 43 (CRC Press, 2018).

7 Damm and Zhou, "Supply and Demand of Natural Graphite," 7; Matt Fernley, "Battery Materials Explained" (Battery Materials Review, 2020), 8–10.

8 Fernley, "Battery Materials Explained," 4.

9 Fernley, 4.

10 Damm and Zhou, "Supply and Demand of Natural Graphite," 14.

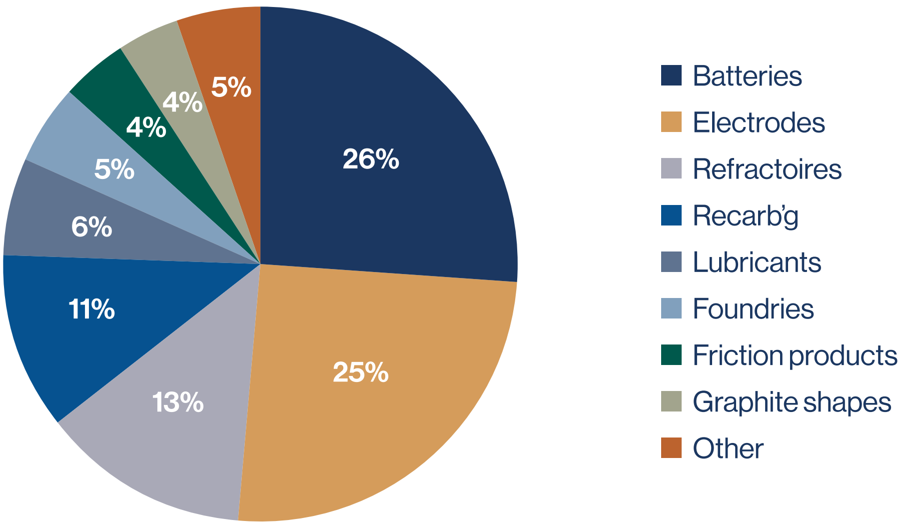
object cast once the hot metal poured into the mold has cooled off. Its ability to perform under extreme conditions makes graphite a widely used ingredient for lubricants as well. Graphite's heat resistance contributes to the inflammability of lubricants, whilst its ability to resist extremely low temperatures keeps the lubricant soft, smooth, and liquid in extremely cold environments.[11]

1.2. Graphite as a critical mineral

Graphite is a key mineral for the energy transition, contributing to cleantech solutions. The global demand for graphite could grow by up to 500% by 2050, compared to 2018 levels.[12] As shown in Figure 3, the bulk of this demand is coming from two industries: lithium-ion batteries and electrodes for electric arc furnaces (EAF), used in the production of steel.

The large expected increase in the demand for graphite introduces economic, strategic and climate considerations. Countries all over the world are committing to achieve net-zero emissions by 2050 and beyond. Given that road transport and heavy industries such as steel production are some of the largest producers of greenhouse gas emissions, these are also key priorities for governments in the EU, US and beyond to decarbonize.[13]

Figure 3. Graphite's projected demand distributed over end use by 2026.
Source: Matt Fernley, "Battery Materials Explained" (Battery Materials Review, 2020), 10.



11 USGS, "Graphite," Professional Paper, Professional Paper, 2017, J3.

12 Hund et al., "Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition," 12.

13 "Sources of Greenhouse Gas Emissions," Overviews and Factsheets, United States Environmental Protection Agency, 2019, https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions; Eurostat, "Oil and Petroleum Products - a Statistical Overview," August 2021, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Oil_and_petroleum_products_-_a_statistical_overview.

Expected sharp increases in demand combined with perceived high supply risks led to the categorization of certain minerals as 'critical minerals' (in the US[14] and Australia[15]) or 'critical raw materials' (in the EU[16]).[17] Graphite has been on these lists for quite some time, having been introduced by the EU as a critical raw material in 2014. The EU determines criticality based on a material's importance to the European economy and the risk of disruptions in supply chains.[18] The US focuses on gaining net import independence, the concentration of supply outside of the US, and the willingness or ability of suppliers to fulfill US domestic demand.[19] Graphite has become a strategically important commodity in the last years, with countries increasing their efforts to secure supplies to facilitate a smooth energy transition. The next two sections discuss the main uses of graphite: in batteries for electric vehicles and in electric arc furnaces for steel making.

1.3. **Batteries charging ahead**

Graphite, together with minerals like lithium and cobalt, plays an essential role in producing batteries. Almost all portable consumer devices such as laptops, cellphones and cameras use lithium-ion batteries. Batteries are rapidly moving into power tools and bigger devices such as battery electric vehicles (BEVs) and grid storage applications. Graphite contributes to a battery's longevity and performance, which is why it is the mineral of choice for lithium-ion batteries and their end applications. Specifically, the anode in lithium-ion batteries is made out of graphite.[20]

Over the last ten years, technological developments and large-scale production of lithium-ion batteries decreased overall costs by 90%.[21] However, higher raw material prices mean that in the short-term, average battery pack prices could rise in nominal terms. In the absence of other improvements that can mitigate this impact, the point at which BEVs reach cost parity with conventional internal combustion engine (ICE) vehicles would be delayed.[22] In turn, this would impact BEV affordability or manufacturers' margins, while also hurting the economics of large-scale energy storage projects. Therefore, securing raw materials like graphite is crucial given that governments aspire to an accelerated transition to clean energy systems.

In order to meet the demand from clean energy applications like BEVs and stationary (grid) storage, lithium-ion battery capacity needs to increase to 2000 GWh a year by 2030.[23]

14 "2021 Draft List of Critical Minerals," Federal Register, November 9, 2021, https://www.federalregister.gov/documents/2021/11/09/2021-24488/2021-draft-list-of-critical-minerals.

15 Commonwealth of Australia, "Australia's Critical Minerals Strategy" (Australian Government, 2019).

16 S Bobba et al., "Critical Raw Materials for Strategic Technologies and Sectors in the EU: A Foresight Study" (JRC, European Commission, 2020).

17 For more information, see Irina Patrahau et al., "Securing Critical Materials for Critical Sectors: Policy Options for the Netherlands and the European Union," HCSS Geo-Economics (The Hague Centre for Strategic Studies, 2020).

18 EU Commission, "Critical Raw Materials", 2021, https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en.

19 "2021 Draft List of Critical Minerals," 62201.

20 IEA, "The Role of Critical Minerals in Clean Energy Transitions," 2020, 5, https://iea.blob.core.windows.net/assets/24d5dfbb-a77a-4647-abcc-667867207f74/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf.

21 IEA, 11.

22 Veronika Henze, "Battery Pack Prices Fall to an Average of $132/KWh, But Rising Commodity Prices Start to Bite," *BloombergNEF* (blog), November 30, 2021, https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/.

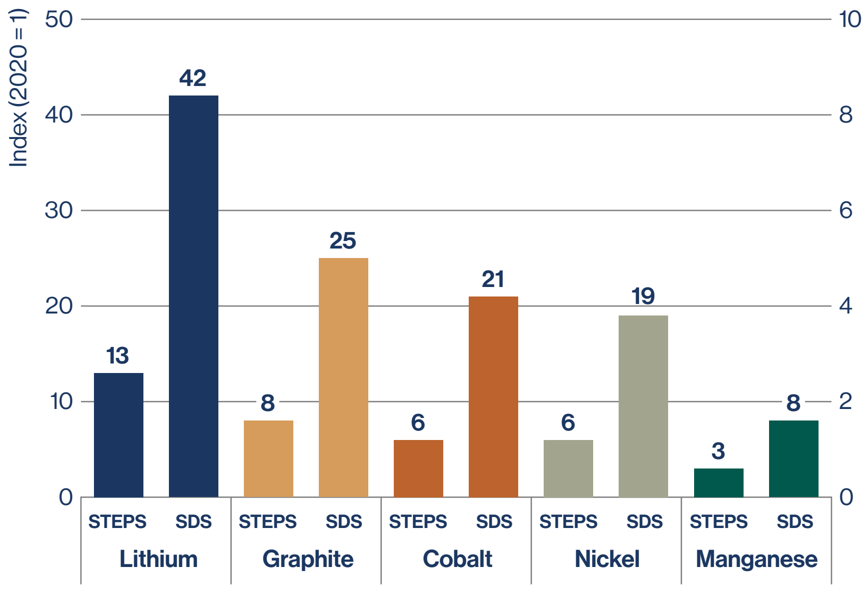
23 BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 2021, 6.

In terms of grid battery storage, the International Energy Agency's (IEA) Sustainable Development Scenario (SDS) expects a global annual capacity installation of 105 GWh by 2040.[24] As shown in the graph below, this would lead to a 25-fold increase in global graphite demand by 2040, relative to 2020, in order to reach climate goals (Figure 4).[25] After lithium, graphite is heading for the largest increase in consumption for minerals needed for the energy transition. Even in the less optimistic Stated Policies Scenario (STEPS) illustrated in Figure 4, which would entail a smaller decrease in greenhouse gas emissions, graphite demand would increase by eight times, relative to 2020.

Batteries, whether for electric vehicles or consumer electronics, are expected to see a 33% compounded annual growth rate (CAGR) in demand (see Table 1). The increased application of batteries in BEVs and grid storage solutions has significant implications for the battery and graphite markets. The batteries are larger and the potential demand for graphite very significant. By weight, graphite is the single largest component in lithium-ion batteries and thus electric cars. For each electric car, 66.3 kg of graphite is required, compared to 8.9 kg of lithium and 39.9 kg of nickel.[26]

Figure 4. Growth in demand for battery-related minerals, 2040 relative to 2020. STEPS is the IEA's Stated Policies Scenario, SDS is the Sustainable Development Scenario.

Source: IEA, "The Role of Critical Minerals in Clean Energy Transitions," 2020, 47.



24 IEA, "The Role of Critical Minerals in Clean Energy Transitions," 86.

25 IEA, "The Role of Critical Minerals in Clean Energy Transitions."

26 IEA.

Table 1. Projected global battery demand 2017-2025.

Data from Macquarie Research, "Lithium Market Outlook: Electrifying Demand," 2021, 2.

Global Battery Demand (GWh)	2017	2018	2019	2020	2021E	2022E	2023E	2024E	2025E	Compounded annual growth rate (2020-2025)
Power battery	**88**	**128**	**144**	**181**	**260**	**386**	**527**	**724**	**1014**	**41%**
EV	85	123	132	167	244	367	503	690	968	**42%**
Small power battery	3	5	12	14	16	18	21	24	28	**15%**
Electric ships	-	-	0	0	0	1	3	10	18	**146%**
Consumer battery	**70**	**68**	**71**	**73**	**76**	**79**	**83**	**86**	**90**	**4%**
Smartphones	17	17	17	16	19	20	22	23	24	**8%**
Laptop & Tablet	18	19	20	21	21	21	21	22	22	**1%**
Other products	35	33	34	35	37	38	40	42	44	**4%**
EES Battery	**4**	**9**	**15**	**21**	**27**	**33**	**40**	**48**	**56**	**21%**
Total Global Battery Demand (GWh)	162	205	230	275	363	498	649	858	1159	**33%**

When we look at Table 1, the growth potential for (processed) graphite becomes evident. The lithium-ion battery capacity is projected to grow to 1 TWh by 2025.[27] The expectations are that by 2030, capacity is expected to have doubled to 2 TWh. One TWh equals 1 billion kWh in energy storage capacity. So, by 2025, the world will require at least 1.2 million tons of processed graphite. By 2030 this volume is projected to double to about 2.4 million tons of processed graphite, just to produce lithium-ion batteries.[28]

1.4. Electric arc furnaces gaining ground in steel manufacturing

With so many countries committed to reducing their carbon footprint, heavy industries around the world are under pressure to decarbonize their production processes. The steel industry is no exception. The electric arc furnace (EAF), based on graphite electrodes as conductors, is a key technology allowing for a less energy-intensive production process.

Conventional steel production relies on coal, limestone, or iron ore as feedstock and consists of two steps: iron making and steel making (see Figure 5 below). Contrastingly, EAFs allow steel producers to skip the iron making process, saving costs while significantly reducing the carbon output per ton of steel produced.[29] This is due to the usage of scrap steel as the primary feedstock, leading to a shorter and less energy-intense process.

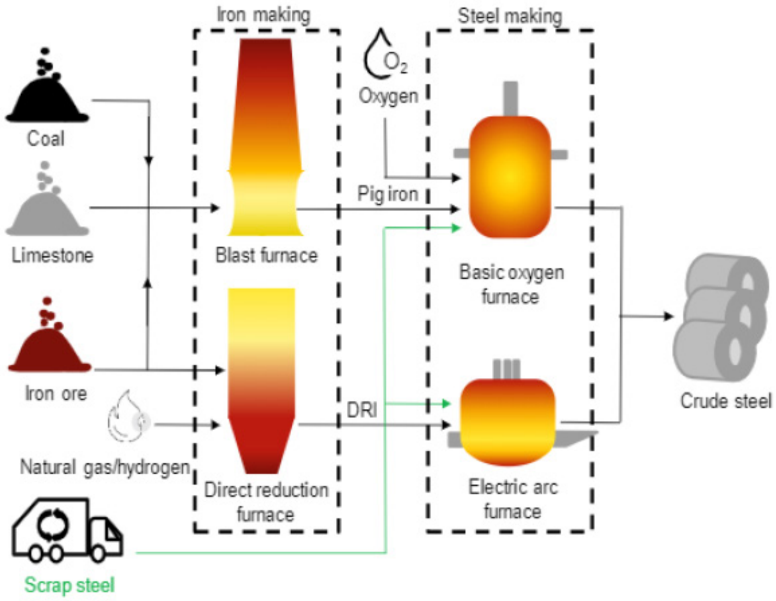
27 Macquarie Research, "Lithium Market Outlook: Electrifying Demand," 2021.

28 Data from Roskill.

29 BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 9.

Figure 5. Illustration of steel production processes.

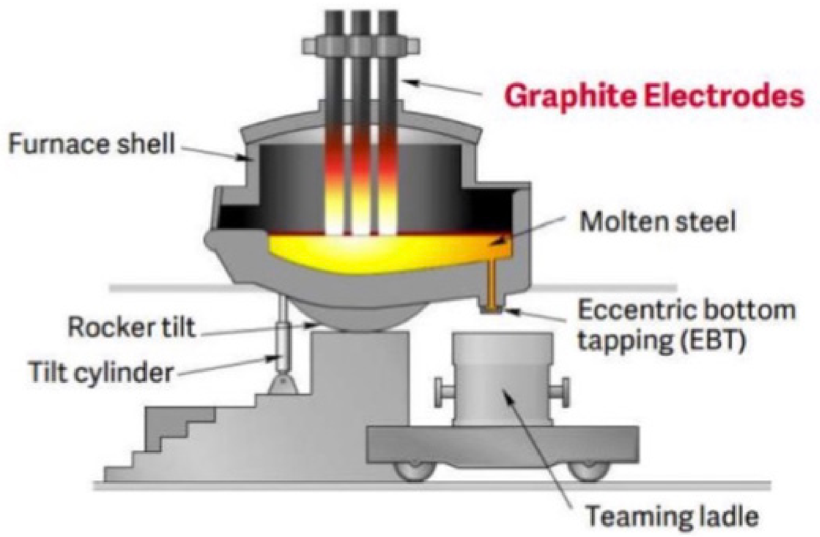
Source: BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 2021, 9.



As mentioned above, graphite electrodes are used as conductors inside an EAF. Electricity passes through the electrodes, forming an arc of intense heat that melts the scrap steel located in the furnace shell (Figure 6). The tip of the electrode can reach 3,000 degrees Celsius (for reference, this is approximately half of the temperature of the Sun's surface). Currently, graphite is the only commercially available material that can sustain such high heat levels within the EAF.

Figure 6. Schematic illustration of an EAF.

Source: BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 2021, 10.



Due to the tremendous heat that graphite electrodes are exposed to, their lifespan is relatively short. The high consumption rate of electrodes requires steel producers to replace the graphite electrodes regularly. Therefore, the larger the share of EAFs in total steel production, the greater the demand for graphite electrodes and the larger the demand for graphite. In 2020, total global crude steel production amounted to roughly 1.8 billion tons.[30] Roughly 74% of this volume was produced through the conventional process of steel making, and about 26% was produced using EAFs.[31] However, the share of EAFs in steel production is about to increase significantly as heavy industries across the globe are under pressure to reduce their carbon footprint.

In 2020, 49% of global steel production used EAF, though this number excludes China, which produces more than half of global crude steel, or 56% of the total.[32] While the use of EAFs in steel making is currently nascent in China, significant increases in EAF use are expected.[33] In December 2020, China's Ministry of Industry and Information Technology (MIIT) drafted new guidelines for the steel industry. The MIIT set a clear target for China's steel manufacturers to increase the contribution of EAFs in steel production from 10% of national steel production in 2020 to at least 15% of national steel production by 2025.[34] This would further strain the global supply of graphite.

Like in China, the pressure from governments to decarbonize is likely to lead to an increased share of EAFs in total steel production. The market share of EAFs in total steel production depends on two important factors: (i) the availability of sufficient steel scrap to serve as feedstock for EAFs and, (ii) successful alternatives to decarbonize steel manufacturing.

The latter depends on whether conventional steel makers (i.e., those who still have iron making as part of their production process) can switch to cleaner fuels such as hydrogen.[35] In that case, these alternatives will have a moderating effect on the growth of EAF and, consequently, the growth in demand for graphite from the steel industry. In its most optimistic scenario for EAF, BNEF projects that the share of EAF in total steel production will rise to 45-50% by 2050.[36] By 2030, demand for graphite to produce EAF electrodes could reach 1.7 million tons, further increasing to 5.7 million tons by 2050 (see Figure 7).

30 World Steel Association, "World Steel in Figures," 2021, 10.

31 World Steel Association, 10.

32 World Steel Association, 15; BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 10.

33 Min Zhang and Emily Chow, "China Plans to Increase Iron Ore Output, Boost Use of Steel Scrap," *Reuters*, 2022, sec. Commodities News, https://www.reuters.com/article/china-steel-idAFL1N2UI0FL.

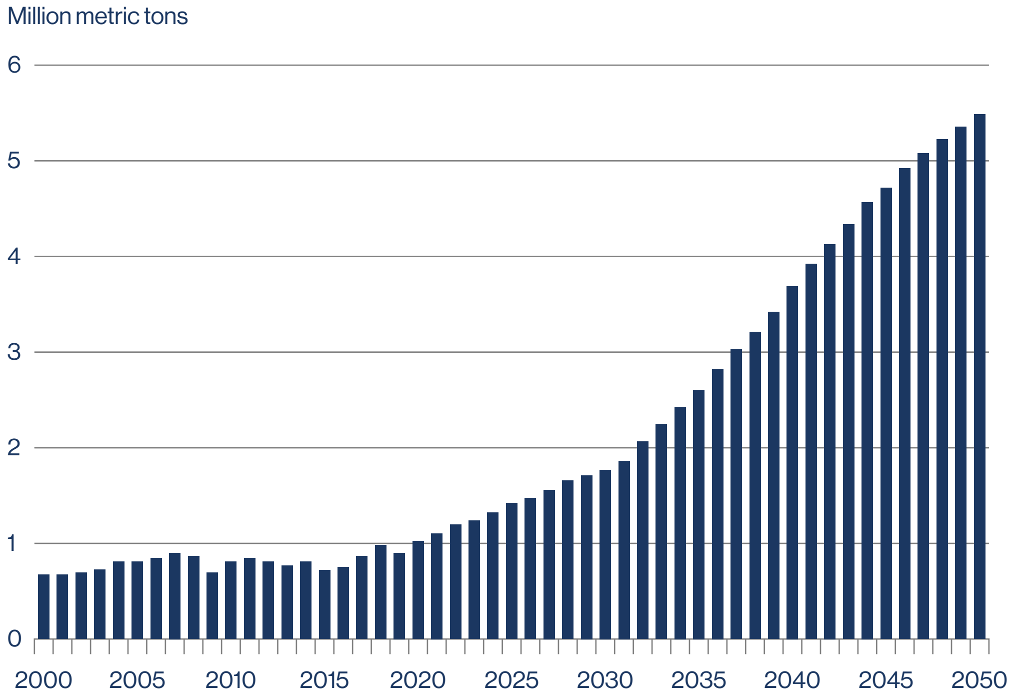
34 Zhang and Chow.

35 Energy Transitions Commission and Material Economics, "Steeling Demand: Mobilising Buyers to Bring Net-Zero Steel to Market before 2030" (Mission Possible Partnership, 2021), 16, https://www.energy-transitions.org/wp-content/uploads/2021/07/2021-ETC-Steel-demand-Report-Final.pdf.

36 BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 11.

Figure 7. Forecasted graphite demand from EAF electrodes.

Source: BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 2021, 12.



2. **Sources of graphite**

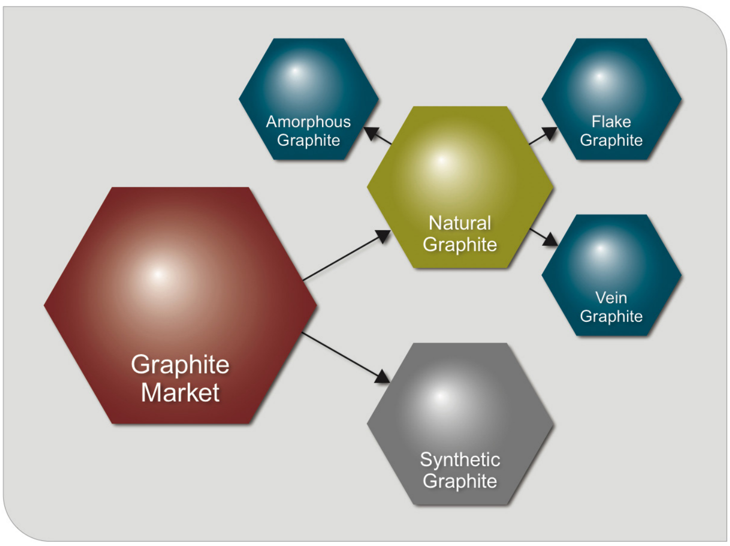
The demand for graphite for lithium-ion batteries and EAFs is expected to skyrocket in the coming decades. Without graphite, key economic sectors such as transport and industry would face difficulties decarbonizing. However, graphite comes in many different types. Whereas lithium-ion batteries can use both natural and synthetic graphite in their production processes, EAFs primarily rely on synthetic graphite. It is not only securing the right quantity of graphite that matters, although this is challenging enough on its own. Instead, it is the combination of having the right quantity of the right quality graphite that matters. This section describes the different types of graphite and discusses the leading players in graphite mining. Lastly, state of the art and new graphite processing methods are explained.

2.1. **Natural vs synthetic graphite**

There are two different sources of graphite: natural and synthetic graphite. Although both are called graphite, they are essentially very different commodities with unique properties. Natural graphite occurs in a variety of geological settings around the world. It is classified into three – physically distinct – deposit types: *amorphous graphite, vein graphite, and flake graphite.* Each of their characteristics makes them fit for use in different industries, as shown in Table 2.

Whereas flake graphite is considered the most desirable to produce lithium-ion batteries and EAFs, amorphous graphite is widely used in producing lubricants and paint, and vein graphite for automotive brakes. In sourcing natural flake graphite, battery and anode makers

Figure 8. The four types of graphite that supply the market.
Source: Sophie Damm and Qizhong Zhou, "Supply and Demand of Natural Graphite," DERA Rohstoffinformationen, 2020, 7.



are interested in whether the sourced material is suitable to make spherical graphite. Spherical graphite is flake graphite with higher concentrations of carbon content, produced by subjecting flake graphite from mines to a series of purification and shaping steps.[37]

The second type of graphite is synthetic graphite, which is not produced from natural graphite but from petroleum cokes. Synthetic graphite can be *primary* and *secondary.* Primary synthetic graphite is produced in a very energy-intensive way, known for its associated greenhouse gas emissions. However, its high quality and consistency among products make it desirable for energy transition technologies. Secondary synthetic graphite is produced from the residue of the primary graphite.

Table 2. Main characteristics of natural and synthetic graphite.

Source: BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 3–5; Damm and Zhou, "Supply and Demand of Natural Graphite," 7–9; Fernley, "Battery Materials Explained," 5–6.

Type of graphite		Main characteristics
Natural graphite	Amorphous graphite	• Lowest graphitic grades of the three types of natural graphite. Typically, it contains only up to 45% crystallized graphite. • Most abundant of the three types of natural graphite. It makes up almost 50% of global natural graphite supply. • Commonly used to produce refractory materials, paint coatings, lubricants, and pencil leads.
	Vein graphite	• Highest total graphitic grades and can sometimes reach over 90% of crystallized graphite. • Rare form of graphite, only mined in Sri Lanka. • Commonly used to produce automotive brakes.
	Flake graphite	• The natural graphite type that is the most desirable for the lithium-ion battery industry. • Commonly used to produce anode material for the batteries, as well as in industries such as the refractory industry.
Synthetic graphite	Primary synthetic graphite	• Produced from the refining of hydrocarbon residual products such as petroleum coke, needle coke and pitch coke. This production method is known for its high emittance of greenhouse gases (notably CO_2). • High quality graphite with significant electric and thermal conductivity. • Mainly used in end applications like lithium-ion batteries and to produce graphite electrodes for EAF.
	Secondary synthetic graphite	• Produced from residual product of primary synthetic graphite. • Generally considered lower cost material. • Some forms of it compete with vein graphite in applications such as brake linings.

2.2. **Graphite supply chain dominance**

In 2021, China remained the world's largest producer of natural graphite, with a global market share of 79%.[38] Europe[39] only provides about 3% of global natural graphite.[40] Notably, Ukraine is the largest natural graphite producer in Europe, providing approximately half of all European production, followed by Norway with 38%, Turkey with 8%, and Germany and Austria with only approximately 1% each.[41] Other important actors in the global mining of natural graphite are Mozambique, Brazil, Madagascar, India and Russia.[42] Flake graphite mining and production dominates in virtually all producers of graphite, except for Mexico and Russia. For energy technologies, natural flake graphite is considered the most desirable.

37 *Graphitic carbon*, *total graphitic carbon (TGC)* and *carbon content* are all used to describe a deposit's graphitic grade and may be used interchangeably in this paper.

38 USGS, "Mineral Commodity Summaries: Graphite," 1.

39 European producers are Austria, Germany, Norway, Turkey and Ukraine.

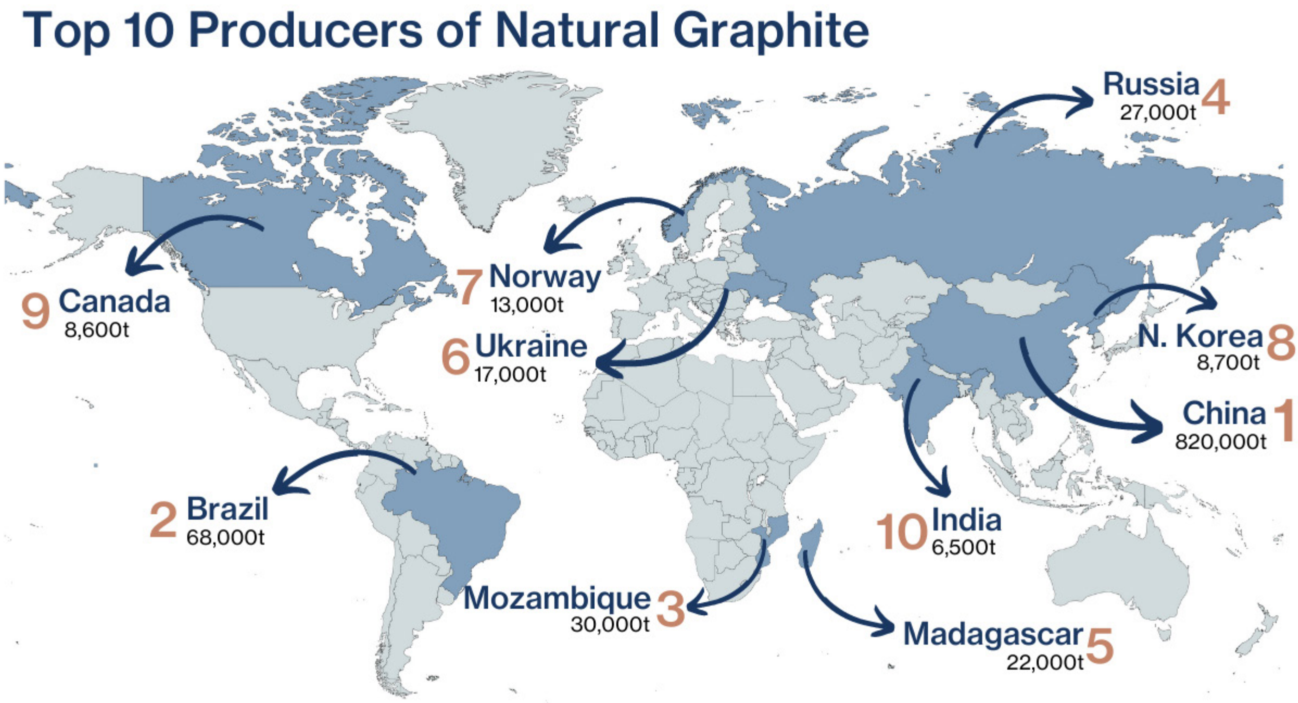
40 Calculation based on USGS 2022.

41 Calculation based on USGS 2022.

42 Bhutada, "Visualizing the Natural Graphite Supply Problem."

Figure 9. Production of natural flake graphite in 2021 (estimated).

Data from USGS, "Mineral Commodity Summaries: Graphite", 2022.

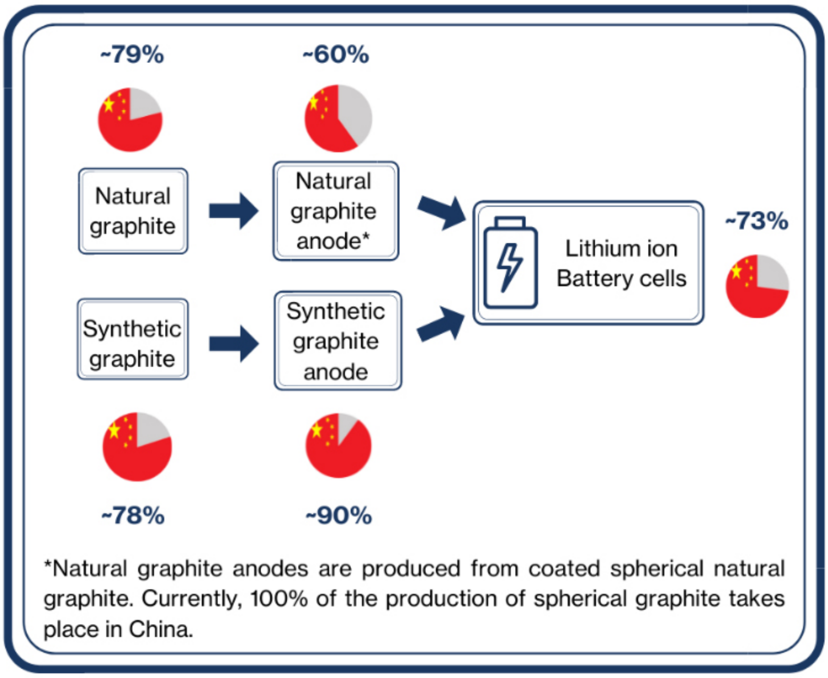


When it comes to synthetic graphite, China's position is dominant as well. Synthetic graphite is made from needle coke, and China produces the most petroleum and coal-based cokes in the world.[43] In 2018, 78% of global synthetic graphite originated in China.[44]

Yet the country's dominance expands further than solely producing and exporting graphite as a raw material. China controls the processing of both natural and synthetic graphite as well. Figure 10 illustrates the Chinese dominance along the lithium-ion battery supply chain. About 60% of the production of natural graphite anodes and 90% of synthetic graphite anodes are concentrated in China.[45] Until natural graphite anodes are manufactured, the natural graphite goes through additional phases like purifying, processing into spherical graphite and coating, discussed in more detail in the next section. As of 2022, the production of purified spherical graphite is 100% taking place in China.[46]

43 BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 22.
44 Bhutada, "Visualizing the Natural Graphite Supply Problem."
45 BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 18.
46 Data from Next Source Materials, 2022.

Figure 10. China's dominance of the graphite and battery supply chain.
Data from Benchmark Mineral Intelligence, 2020; BloombergNEF, 2021; USGS, 2022; Bhutada, 2021; Next Source Materials, 2022..



2.3. Graphite processing: why size, shape and purity matter

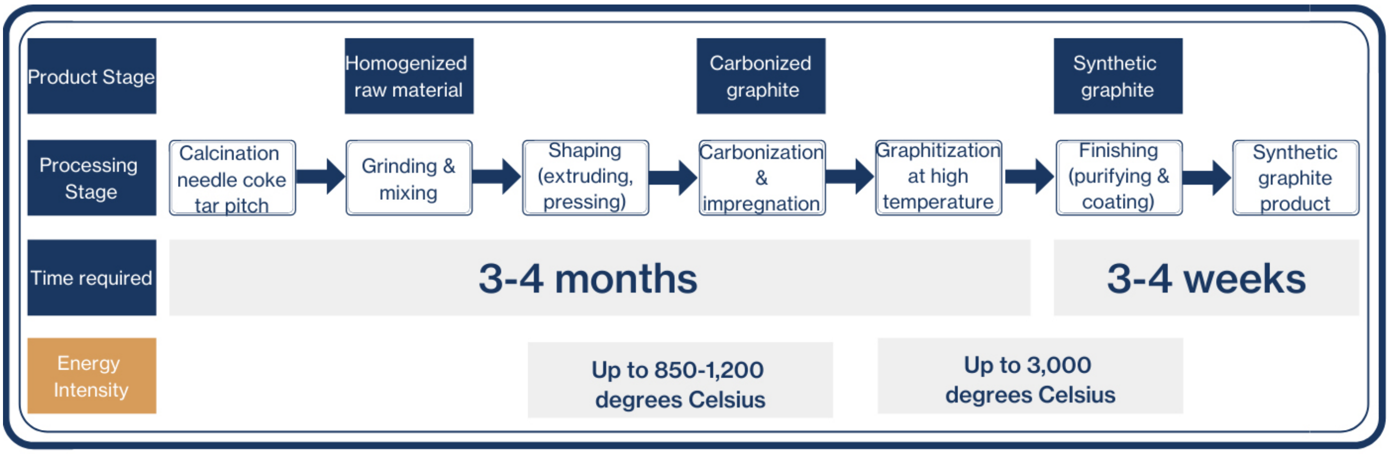
Like any other critical mineral, graphite needs to be processed before it can be used in cleantech end applications. This section discusses two types of graphite, synthetic and flake natural graphite, that are used in the two fastest growing markets, i.e., EAFs and lithium-ion battery anodes.

2.3.1. How is synthetic graphite made?

The production of synthetic graphite involves three elements that producers in any industry try to reduce: energy, capital and GHG emissions. As shown in Figure 11 below, the process of making synthetic graphite requires calcined petroleum needle coke as feedstock. Calcined petroleum needle coke is an environmentally harmful product, as it is a residual product from petroleum refining. It needs to be heated at high temperatures to pre-process it and make it eligible for its production process.

Figure 11. A simplified overview of the process flow for the production of synthetic graphite.

Data from BloombergNEF, 2021; Battery Materials Review, 2020; Monsoon Resources Group, 2021.



The graphitization cycle (i.e., the final step before the final product) is the most significant manufacturing process. During this step, the preprocessed needle coke is heated to temperatures of almost 3,000 degrees Celsius. Graphitization takes place in purpose-built furnaces to withstand the extreme heat required for this process. The main purpose of this step is to convert the carbon in the needle coke into graphite. Graphitization removes impurities from the needle coke feedstock, further improving its total graphite content (TGC) and strengthening its structure. Although battery anodes and EAF electrodes use synthetic graphite as feedstock for their respective manufacturing processes, each end application requires different processing steps, illustrated in Figure 12 and 13 for EAFs and batteries, respectively.

Figure 12. Processing synthetic graphite for EAF graphite electrodes.

Data from BloombergNEF, 2021; Monsoon Resources Group, 2021.

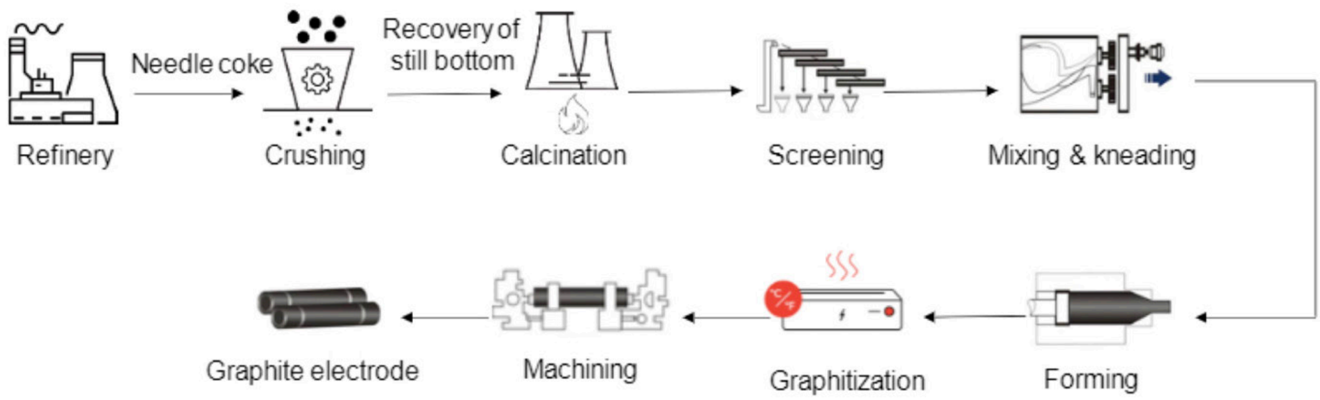
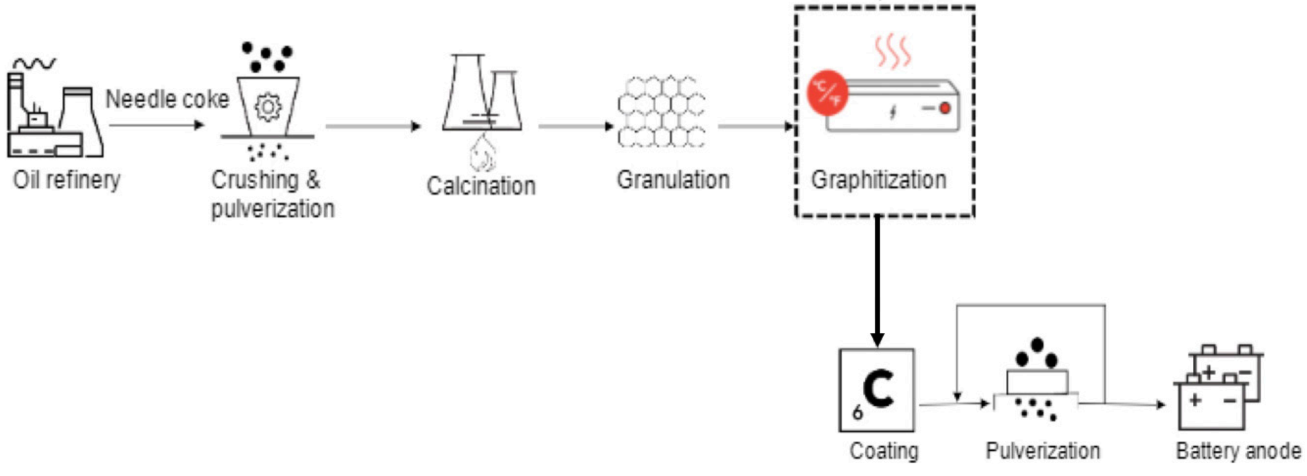


Figure 13. Processing synthetic graphite for battery anodes.

Data from BloombergNEF, 2021; Monsoon Resources Group, 2021.



The biggest difference between the two processes is that the production of anode active material for batteries requires some additional steps, including the coating of graphitized synthetic graphite. Coating graphite particles happens through a thin-film deposition on the particles. Coating adjusts surface chemistry and provides protection in order to reduce electrode resistance, side reactions and heat generation during cycling. This can lead to improvement in cycle life, rate capability, reversible capacity and efficiency.

The process of coating can be compared to varnishing wooden furniture. In the process of varnishing, wood becomes stronger, and its longevity is increased by adding a protective layer. By coating graphite particles, you provide them with a protective layer which makes them less vulnerable to side reactions with other parts of the battery. Since graphite is a key anode active material, the more it is protected the better it serves the longevity of the battery. The coating of graphite particles also enhances their (electrochemical) characteristics of increasing the energy density of the anode active material and thereby increasing the performance of the battery.

This example illustrates delicate but important differences in processing. Although both end applications use synthetic graphite as feedstock, the product used in the end application is different. This is why even the final steps of the process (see Figure 11) take 3-4 weeks to finalize. Each end customer requires a different product which in turn requires a specific processing flow sheet.

2.3.2. **How is natural flake graphite processed?**

Natural flake graphite can replace synthetic graphite in the production of batteries. To meet the ever-growing demand, flake graphite coming from the mine needs quite some modifications. Battery anodes require coated spherical graphite with at least *3N* purity. The *N* stands for "Nine", 3N therefore referring to 99.9% purity. Figure 14 shows two types of graphite processing, the current state of the art, used largely in China, and an emerging method based on environmentally friendlier techniques and a higher yield of final product.

In state of the art techniques, approximately 3 tons of natural flake graphite yield 1 ton of purified spherical coated graphite. This process is expensive and wastes up to 70% of the initial graphite, which is why coated spherical graphite sells for over 10 times the price of micronized graphite concentrate. The low yield shows the need for the continuous improvement of processing techniques.

Graphite ore is processed from a low TGC (about 2%) to a 54-97% TGC after it has been submitted to the flotation process. This material is called flake concentrate. The concentrate is chemically treated using hydrofluoric acid (HF) to elevate to a purity higher than 99%. The next step involves the micronizing of flake graphite by reducing it in size to 10-20 micron particles (for reference, a human hair is about 70 microns in diameter). This is done in a step-by-step process as the flakes move through a cascading series of mills. They are crushed by impact, collision, friction, and shearing using a high-speed rotating plate and classified to separate the target size range, which then goes into the next mill. Micronized and rounded material is then chemically purified to produce graphite with even higher TGC levels, from approximately 95% TGC to 99.9% TGC. The chemicals used in this step are typically hydrofluoric and sulfuric acid. These acids are aggressive enough to remove impurities that affect battery performance. The use of acids such as HF is one of the reasons why almost all of today's spheroidized coated graphite is produced in China.

Since HF is a very hazardous substance, the regulation around it is extremely tight, making the costs to use it in processing operations substantially higher in jurisdictions like the EU's. China certainly has a competitive advantage when it comes to applying wet chemistry to graphite processing, but there are no companies outside of China that have developed proprietary technology that does not use acids.

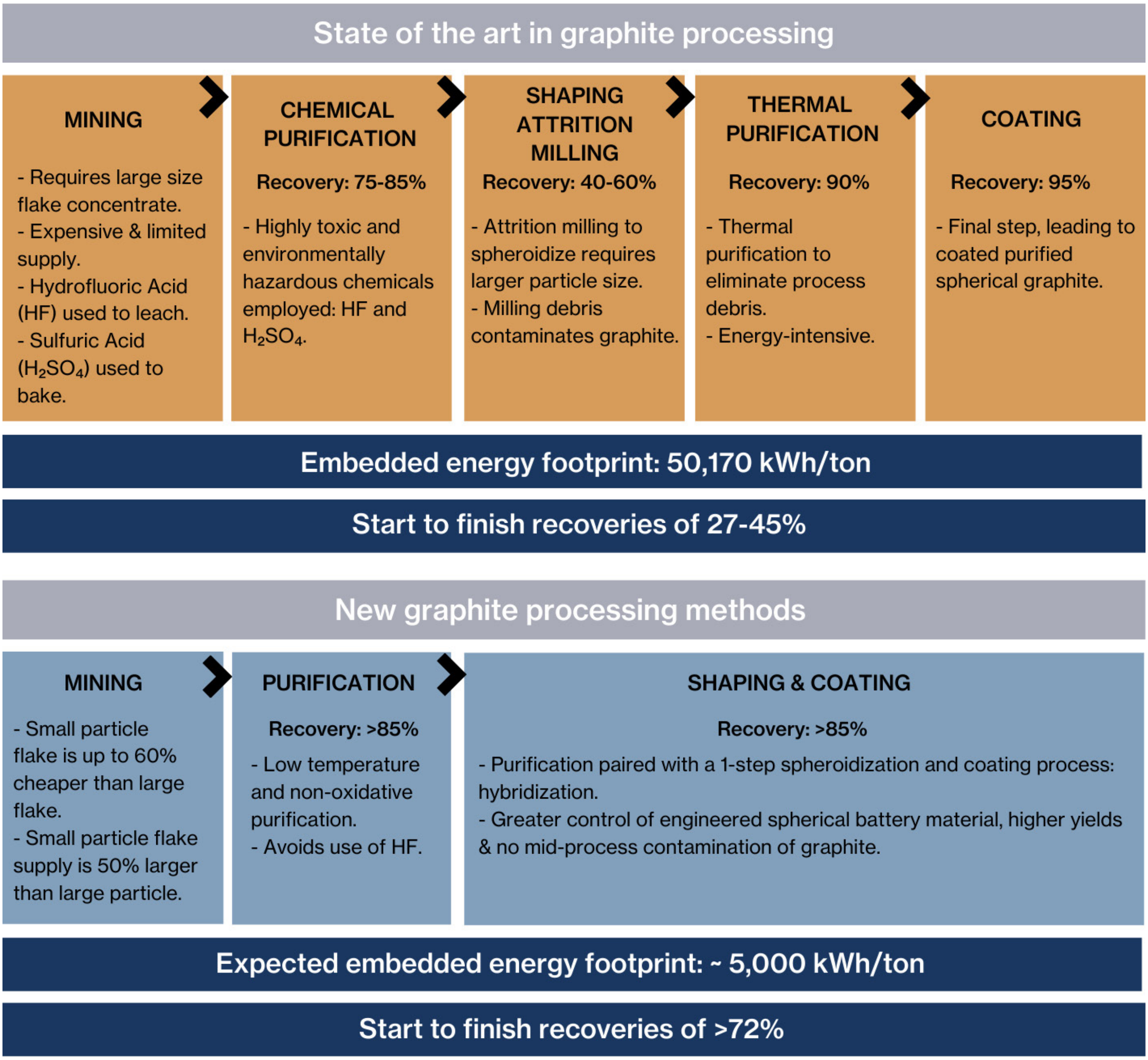
US based Urbix Inc. has developed a processing method that limits the environmental impact and energy intensity, while also improving the yield (the new processing method in Figure 14). The company is already producing coated spherical graphite in its demonstration plant in Arizona which uses only 6% of acids compared to the conventional processes used in China today, leaving HF entirely out of its process. On top of this, Urbix's way of producing coated spherical graphite consumes only a fraction of the energy used by its average Chinese counterpart (see Figure 14 for the details). It does so while improving the yield from natural flake graphite processing, from a recovery rate of up to 45% in current methods to more than 72%.

Developing a mine and bringing critical minerals to market is a time and cost intensive process.[47] Graphite is no exception. Homegrown Western companies like Urbix are the living proof that the West possesses the ability to become a leader (again) in innovative technical solutions for the processing of critical minerals like graphite. It has the ability to deliver those *quality* products in a manner that is aligned with its environmental, social and governance (ESG) standards.

47 Jeff Amrish Ritoe, "The New Great Game: Securing Critical Minerals Today for a Clean Energy System Tomorrow" (Bangkok: The Hague Center for Strategic Studies, 2021), https://hcss.nl/wp-content/uploads/2021/08/The-New-Great-Game-August-2021.pdf.

Figure 14. A simplified overview of the process flow for the production of coated spherical graphite.

Data from Urbix Inc, 2021.

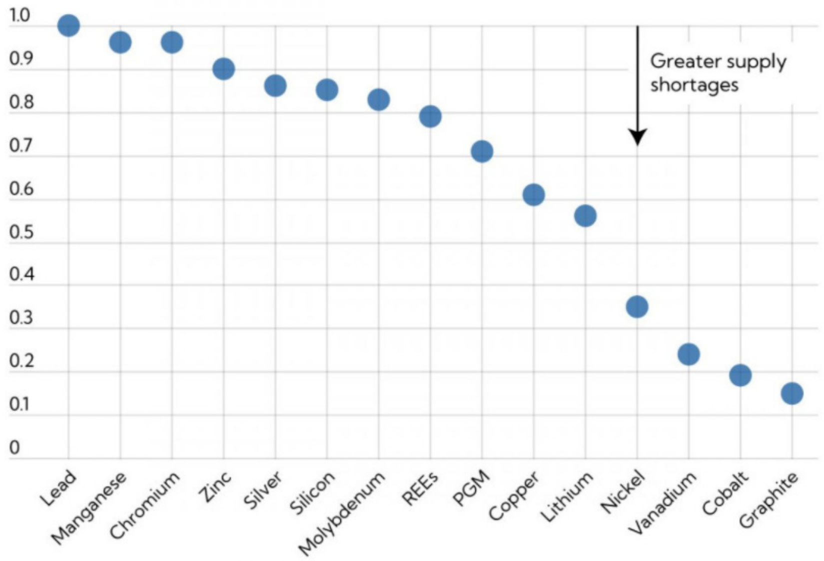


3. Graphite supply challenges: economic, security and climate considerations

Graphite could experience significant supply/demand disruptions in the coming decades.[48] Figure 15 shows the supply/demand ratio for metals considered critical for the energy transition. The lower the ratio for a metal, the greater the supply shortage. With a supply-demand ratio of 0.1, graphite is expected to experience the most significant supply challenges. Demand for graphite could exceed supply as early 2023.[49] Three main factors make it challenging to bring supply and demand for graphite in balance within this decade: the fact that not all graphite is suited to meet demand in certain industries, the energy-intensive, and 'dirty' production process for synthetic graphite, and China's hegemony over not only graphite mining but entire value chain. These are discussed below.

Figure 15. Supply-demand ratio for metals critical to the energy transition under a net-zero scenario.

Source: Nico Valckx et al., "Metals Demand From Energy Transition May Top Current Global Supply", 2021.



Source: International Energy Agency, US Geological Survey 2021, and IMF staff calculations.
Note: PGM = Platinum-group metals. REEs = Rare-earth elements. Supply-demand ratio is the ratio of supply to demand. Supply = cumulative production volume for 2021–2050, fixed at 2020 output level. Demand = total metal demand 2021–2050 for renewable energy and other uses.

48 Nico Valckx et al., "Metals Demand From Energy Transition May Top Current Global Supply" *IMF Blog* (blog), 2021, https://blogs.imf.org/2021/12/08/metals-demand-from-energy-transition-may-top-current-global-supply/.

49 Benchmark Mineral Intelligence, "Graphite Special Report," April 2020, 4, https://www.benchmarkminerals.com/wp-content/uploads/Graphite-COVID-19-Special-Report.pdf.

Challenge 1:
Not all graphite is suited to meet the rising demand

Even though different graphite sources exist, each industry has its preference for the type of graphite they use in their end applications. As illustrated in Figure 3, more than 50% of the projected demand for graphite up to 2026 comes from the EV battery industry and the steel industry. Today, EAF producers prefer to use only synthetic graphite.[50] Battery makers can use both synthetic and natural flake graphite, although synthetic graphite anodes have been preferred for EVs due to longer lifecycles and fast charging capabilities.[51] With the exponential growth in demand expected from EAF electrodes and batteries, the market for synthetic graphite will become increasingly tight. The shortage of synthetic graphite paired with the other environmental issues could lead battery producers to shift their focus toward natural graphite and new processing methods. Recently, EV battery makers have acknowledged this issue and increased efforts to source alternatives to synthetic graphite such as spherical graphite. However, as discussed in the previous section on graphite processing, spherical graphite production has its challenges, demanding skillful processing to meet the end user's qualification requirements.

Challenge 2:
Expensive, energy intensive and dirty production process

Most anode technologies used by battery makers employ a blend of natural-based spherical graphite and synthetic graphite, in varying percentages, depending on the end user's requirements. However, producing synthetic graphite is a power-intensive, costly, and environmentally harmful activity (see Figure 16). The graphitization cycle is an emission-intensive process due to its reliance on carbon-rich needle coke and complex processes to bring it to the desired form, including very high temperatures. As a result, it is becoming harder to justify using materials like synthetic graphite in end products (batteries and EVs) that are promoted as 'green and clean'.

Today's Chinese production process for synthetic graphite is highly energy-intensive, placing EV automakers in the EU between a rock and a hard place. On the one hand, they can source synthetic graphite from China, effectively keeping China's dominant position intact despite inefficient production methods. Given that China's energy system relies on coal, as shown in Figure 17, energy intensive activities such as graphite production are environmentally harmful, leading to large scale GHG emissions. Synthetic graphite produced in China and used in EVs that sold in Europe is not a sustainable material. Increasingly strict environmental, social, and governance (ESG) norms across the EU, together with the development of the carbon border tax and the EU Taxonomy for sustainable finance, will cause issues for European EV producers.

50 BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 10.

51 BloombergNEF, 8.

Figure 16. Schematic overview of the flowsheet from raw material to battery component for natural (flake) graphite and for synthetic graphite.

Source: Urbix, Inc., Let's Talk Science, Benchmark Minerals Intelligence

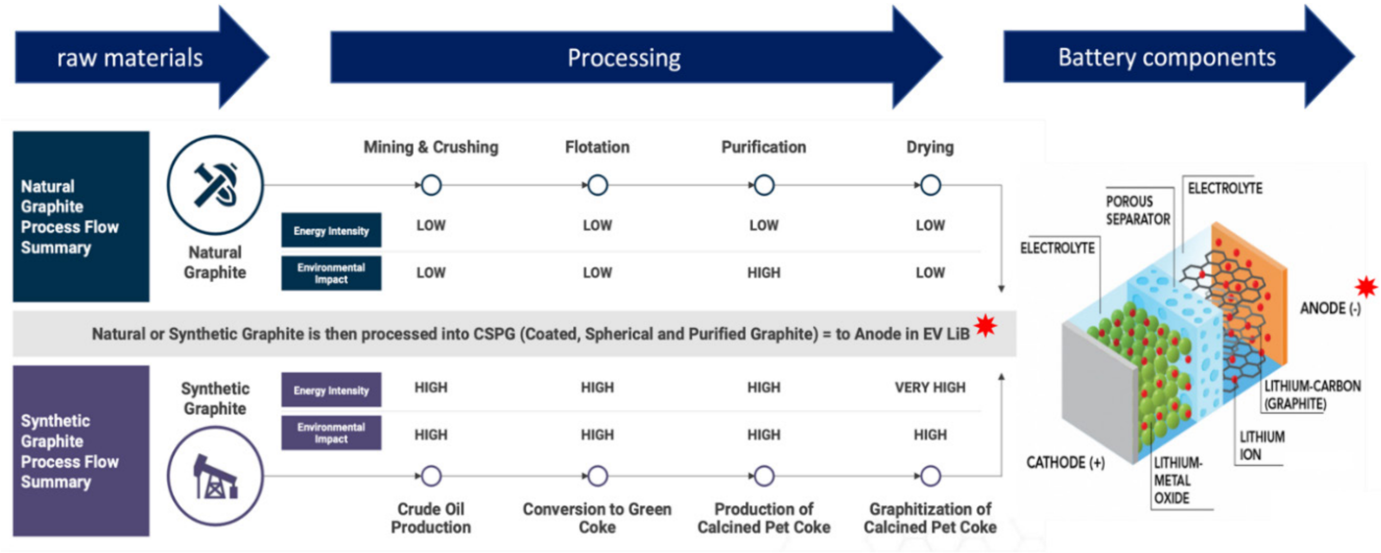
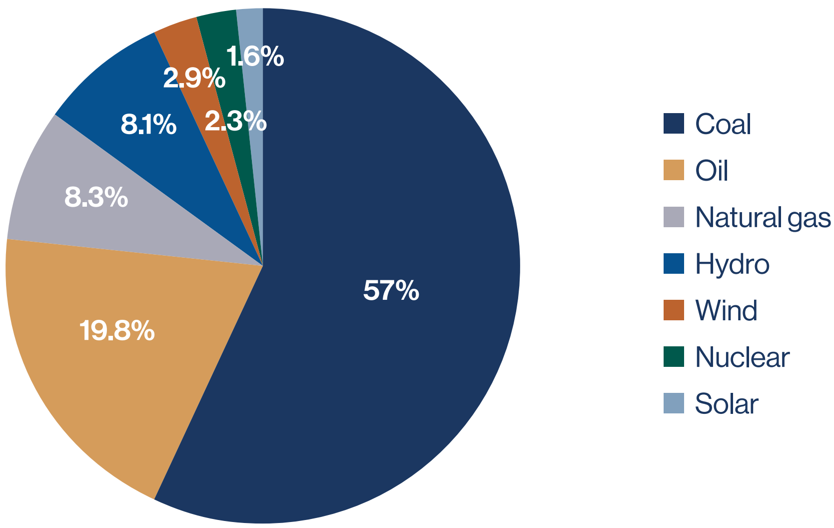


Figure 17. China's energy consumption by source in 2020.[52]

Data from BP, 2021.



On the other hand, they could refuse sourcing graphite from China and instead wait for Western companies to set up graphite production and processing facilities. This, however, imposes risks of stalling the EV revolution and slowing down climate action. The reality today, unfortunately, is that EV automakers tend to be rather pragmatic and prioritize a steady supply of graphite over refusing synthetic graphite material with a large carbon footprint.

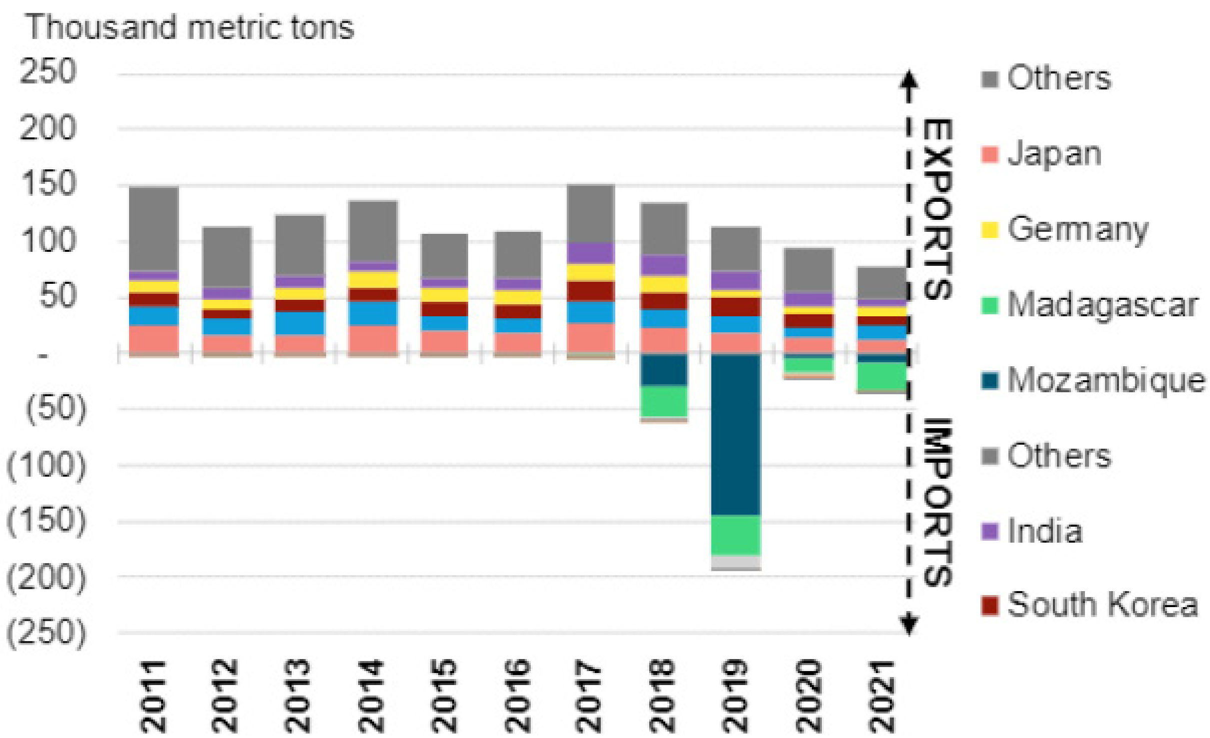
52 Biofuels, biomass and other types of energy sources do not show, but they make up less than 1% of total energy consumption. Data from Hannah Ritchie and Max Roser, "China: Energy Country Profile," Our World in Data, November 28, 2020, https://ourworldindata.org/energy/country/china.

Challenge 3:
China's graphite hegemony

China's dominant position across the graphite supply chain creates significant challenges for economic powers like the EU and the US. Depending on a single country to supply a material that is considered critical for clean energy technology and other strategic industries is a risk. China is able to restrict the export of (processed) graphite, either for geopolitical reasons or purely for its domestic consumption, cutting other economic powers like the EU and the US off from essential graphite feedstock.

Natural flake graphite offers an alternative that is cheaper to produce, less energy-intensive, and has a better environmental footprint than synthetic graphite. China's position as a major exporter of natural flake graphite is declining. Such a trend is due to the quality of this type of locally produced graphite decreasing while demand from domestic battery makers is increasing.[53] The decline in high-quality flake production has forced China to start sourcing natural graphite from mines abroad, making China a net importer of natural flake graphite in 2019 (Figure 18).

Figure 18. China's trade flow of flake graphite, 2011-August 2021.
BloombergNEF, "Global Graphite Outlook 2021-2030: China's Dominance Unchallenged," 15.



53 Fernley, "Battery Materials Explained," 34.

In addition, the energy-intensive manufacturing process and the concentration of production in China make consumers of synthetic graphite vulnerable to disruptions in the energy sector. Increasing price volatility in energy markets has been observed in the last few years due to geopolitical tensions or regular supply chain disruptions. Should an energy crisis occur, energy-intensive heavy industries can be shut down to secure energy supply for households and other necessary societal functions. For instance, in the second half of 2021, China was forced to curtail the supply of electricity to heavy industries, including synthetic graphite producers.[54] Given that China is the world's biggest producer of synthetic graphite, the electricity curtailment led to production disruptions which, together with the already high energy prices, created a 'double whammy' for synthetic graphite producers and their customers worldwide.

With the recent hike in electricity prices in mind, more battery makers will consider increasing the share of natural flake graphite in their production processes at the expense of synthetic graphite. This would decrease China's control over graphite production and ensure a more sustainable production process for EV batteries and other applications.

54 Davide Ghilotti and Sybil Pan, "Rising Synthetic Graphite Costs May Push Battery Makers to Rely on Natural Material," Fastmarkets, January 12, 2022, https://www.fastmarkets.com/insights/rising-synthetic-graphite-costs-may-push-battery-makers-to-rely-on-natural-material.

4. What does it take to secure the right quantity and quality of graphite?

The commitment of the EU and US to climate goals puts pressure on mining and processing companies to find innovative ways of producing critical minerals in the most environmentally friendly manner. Achieving such goals would ensure a more sustainable production process and would mitigate supply chain risks for graphite and associated technologies. It would also reduce dependency on China.

Given the environmental impact and associated costs with synthetic graphite production, the EU and US should focus on producing natural flake (spherical) graphite. The latter can be mined all over the world. Moreover, innovative and sustainable processing techniques have already been developed. In other words, the ability to deliver *quality* exists. Now, policymakers in the West should ensure that sufficient *quantity* (i.e., the required volumes) of product is available to meet national ambitions in the energy transition. To achieve this, at least two things are required:

- An environment in which graphite processing companies are encouraged to scale up their operations and provide responsibly produced and high-quality graphite for countries in the West;
- A system whereby direct access to graphite ore is ensured, to feed processing facilities in the EU and US, from mines outside of China.

The creation of a scale-up ecosystem

A junior processing company today may well be considered a tech startup. Although Chinese companies today produce active anode material at the lowest cost, it is equally true that their processes are neither clean nor efficient. Under today's conventional methods of producing coated spherical graphite for battery anodes, up to 70% of natural flake graphite can be lost in the process (as shown in Figure 14). Western companies that find new, innovative ways to improve the processing yield significantly improve graphite's ESG footprint. If they wish to scale up in their own countries in partnerships with domestic players, then the EU and US government should nourish this as much as possible.

A good initiative contributing to lowering barriers to entry for European companies is to create organizations like EIT InnoEnergy. EIT InnoEnergy is spearheading the way to a decarbonized Europe by 2050 through the leadership of three industrial alliances: European Battery Alliance (EBA) for battery storage, European Green Hydrogen Acceleration Center (EGHAC) for green hydrogen, and European Solar Initiative (ESI) for solar photovoltaics.[55] The organization has developed several programs to act as a "one-stop shop" for companies that have developed innovative technologies that can help Europe's decarbonization efforts.

The Bipartisan Infrastructure Deal under the Biden Administration is providing support for American companies involved in the production, sourcing and recycling of battery minerals and other materials. More than $7 billion has been announced as available funding for the battery supply chain.[56] At the same time, the Department of Energy's (DOE) Loan Program will support projects that increase the domestic supply of critical minerals and the manufacturing of zero-carbon transportation modalities such as EVs.[57] Under the Advanced Technology Vehicles Manufacturing Loan Program (ATVM), the DOE is providing loans and loan guarantees for companies building innovative projects within the battery supply chain, based in the US.[58] The Loan Program seeks to bridge the gap between necessary cleantech investments and the lack of investment incentives in the private sector. The DOE has direct lending facilities at its disposal. Additionally, by providing federal loan guarantees, the DOE reduces market uncertainty and helps companies attract capital from other market actors.

Attracting investments can also be a challenge for junior processing or mining companies, given the bad reputation of industrial processes in Europe and the US. However, financing opportunities can be linked to platforms like EIT InnoEnergy or other governmental initiatives, to reduce investment risks and encourage the funding of companies that could move parts of the graphite supply chains to Europe or the US. The EU Taxonomy for Sustainable Activities is a useful categorization tool of economic activities, allowing companies to prove their contribution to the European Green Deal. It can also serve as a reputational tool to increase public acceptance of industrial processes. Platforms like EIT InnoEnergy and other governmental initiatives are key in building a scale-up ecosystem, whereby junior companies with clean production methods can develop and support the energy transition.

Securing access to graphite ore

Securing raw materials is crucial in building new supply chains. Although China is by far the largest producer of natural flake graphite at the moment, that does not mean that Europe and the US cannot mitigate risks associated with supply chain politics. Europe, for instance, has some sources of natural flake graphite close to or within its borders, with Norway and Ukraine as largest producers. In order to become less dependent on a single source, the US and EU should explore options of closer cooperation in order to:

1. Include graphite producing countries in the process of value addition further downstream;
2. Include producers of end applications (i.e., EV automakers) from both sides of the Atlantic into the mining process of graphite at an earlier stage;
3. Increase the inflow of graphite and mitigate disruptions through international free trade agreements;

55 "EIT InnoEnergy- Accelerating Sustainable Energy Innovations," accessed February 9, 2022, https://www.innoenergy.com/.

56 "DOE Fact Sheet: The Bipartisan Infrastructure Deal Will Deliver For American Workers, Families and Usher in the Clean Energy Future," Energy.gov, November 9, 2021, https://www.energy.gov/articles/doe-fact-sheet-bipartisan-infrastructure-deal-will-deliver-american-workers-families-and-0.

57 "DOE Fact Sheet."

58 "Critical Materials: Loans & Loan Guarantees" (Loan Programs Office), accessed March 15, 2022, https://www.energy.gov/sites/default/files/2021-06/DOE-LPO_Program_Handout_Critical_Materials_June2021_0.pdf.

4. Include foreign expertise to build a graphite supply chain at home (while keeping ownership and control over it);
5. Include large institutional investors like pension funds in the financing of early graphite mining opportunities; and
6. Involve the public at an early stage to gain stronger support for mining projects at home.

By working together in these six areas, a truly trans-Atlantic platform can be set up with the US, Canada, and Brazil as leaders in the Americas, producing countries like Mozambique and Madagascar as leaders in Africa, and the EU in strong collaboration with countries like Norway and Ukraine.[59] Combined, the three regions (i.e., the Americas, Africa and Europe) are home to sufficient natural resources, technical expertise, and capital to reduce their dependence on Chinese graphite. It will certainly take time to create an alternative supply chain to the one that is centered around China today. However, a holistic approach in which collaboration is sought in all the six above-mentioned areas will decrease dependency on a single supplier.

Although initiatives like EIT InnoEnergy are important to start collaboration in the graphite supply chain on European soil, a broader international collaboration that is open to graphite players from (one of) the other Atlantic regions is recommended. This demands a collaborative rather than a protective mindset. Although it is key that European projects in graphite mining and processing get a fair chance to develop and scale-up, the thought that European projects alone will reduce the EU's dependence on Chinese graphite in a significant way is naïve. The same applies to the US, where foreign players sometimes cannot even get qualified due to so-called 'national security' interests. But if economic powers like the US, the EU and Canada work towards setting up a supply chain that is more detached from China, it is essential that the three regions start building *virtual airlifts* in which capital, expertise, and natural resources flow (more) freely between them.

Partnerships on a *quid pro quo* basis, whereby the US and EU open their markets for each other's technology and capital, and sign agreements to develop new upstream assets jointly, could be a collaborative way to create new opportunities. The world will need all the critical minerals and processing capacity it can get to support the energy transition. Chopping up the world in 'spheres of influence' to secure access over assets that hold critical minerals only makes sense if you have the know-how, capacity, and funding to develop these assets independently. If you do not have that (yet), working with those who do is an essential first step.

59 For a more detailed explanation on how policies around these five areas could be executed we suggest reading Jeff Amrish Ritoe, "The New Great Game: Securing Critical Minerals Today for a Clean Energy System Tomorrow" (The Hague Centre for Strategic Studies, 2021), https://hcss.nl/wp-content/uploads/2021/08/The-New-Great-Game-August-2021.pdf.

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