Title

Releasing the Pressure: Understanding Upstream Graphite Value Chains and Implications for Supply Diversification

Authors
Ramji, Aditya
Dayemo, Kristi

Publication Date
2024-01-04

DOI
10.7922/G2GQ6W38

Releasing the Pressure

Understanding Upstream Graphite Value Chains and Implications for Supply Diversification

Prepared By:

Aditya Ramji and Kristi Dayemo

Institute of Transportation Studies, University of California, Davis

January 04, 2024

UC DAVIS
India ZEV Research Centre
Institute of Transportation Studies

ITS UC DAVIS
Institute of Transportation Studies

Ref. No. UCD-ITS-RR-24-04

Table of Contents

List of Tables

List of Figures

Glossary

Mining Term	Definition	Sources of Information
Reserves	The part of a mineral deposit that is economically viable for mining operations. Reserves can be categorized as inferred, indicated, or measured with an increasing level of confidence for economic viability. Reserve values are dynamic due to exploration, production, market conditions, technology advances, etc., which can change the amount of mineral that can be located and economically extracted. In this study, if a reserve value was not located for a mining project, a resource value was used (see below).	SEC filings, JORC filings, NI 43-101 filings, company websites, geological surveys, news reports, journal articles
Resource	A mineral deposit of economic interest where economic viability has not been explored. This value was used in this study when a reserve value was not located.	Company websites, geological surveys, news reports, journal articles
Grade	The average mineral content for a determined resource or reserve, established using a minimum grade. The average grade encompasses parts of the deposit that range from the minimum grade to higher grades considered to have economic interest or viability.	SEC filings, JORC filings, NI 43-101 filings, company websites, geological surveys, news reports, journal articles
Mining Project	A mine or collection of mines that are operated and reported on together by an owner or owners.	SEC filings, JORC filings, NI 43-101 filings, company websites, geological surveys, news reports, journal articles
Primary Owning Company	The company that has the largest ownership share of a mining project. Mining projects can be owned by multiple companies.	SEC filings, JORC filings, NI 43-101 filings, company websites, geological surveys, news reports, journal articles

1 Executive Summary

As countries ramp up lithium-ion battery (LIB) supply chains and production for the transition to a carbon free future, demand for the critical minerals LIBs contain has increased. Graphite is the largest unique component of LIB anodes by weight at 17 to 20% (kg/kWh) and by value at 8 to 13% ($/kg of LIB). It is also used in energy storage and many small electronic devices. Due to growth in end-uses as well as geographical expansion of markets, graphite demand is expected to rise. This will lead to significant pressure on supply chains.

Among major economies, the United States (US), China, India, and the European Union (EU) list natural graphite as a critical mineral. The EU also added synthetic graphite to its list in November, 2023, under the Critical Raw Materials Act. In October 2023, China tightened restrictions on exports of graphite types most suited to EV battery production. This has brought graphite to the center of supply chain discussions.

1.1 Graphite Sources

Unlike other critical minerals, which are mined from the earth and are naturally occurring, graphite can be either mined (natural graphite) or produced artificially (synthetic graphite). The choice of natural or synthetic graphite depends on three parameters: (1) battery performance (synthetic graphite is better), (2) cost economics (natural graphite is cheaper), and (3) resource availability (generally based on the available supply of natural graphite). Additionally, natural graphite has a smaller environmental footprint than synthetic graphite.

1.2 Methodology

Here, we analyze the dimensions of natural graphite availability as a resource. Our sources include:

- country geological surveys,
- mine-level data on production and reserves, and
- global trade and governance data among major natural graphite producers and consumer countries.

We assessed the criticality of natural graphite by reserves and production across countries, tracked production and corporate ownership of individual mines, analyzed trade flows, and modeled global graphite demand for all end uses through 2035.

1.3 Graphite Production and Reserves

In 2022, China produced about two-thirds of global graphite (62%), followed by Mozambique (12%), Madagascar (8%), Brazil (6%) and India (4%) — a total of 92%. Between 2019 and 2022, significant increases in natural graphite production occurred in Mozambique, Madagascar, and Tanzania in Africa, and India in South Asia.

Research shows that natural graphite availability (measured as global reserves and ore quality) is high. Although current production is concentrated mostly in China, investments in new mining projects are primarily in Africa. Of the 67 tracked individual graphite mines in this study, average production is around 60 kilotonnes (kt) per mine annually, indicating that many smaller mines are in operation. The average ore grade of producing mines tracked is around 3%, with more than half of the mines tracked having a grade higher than 9%.

1.4 Mine Ownership and Trade

Ownership of mines was mapped for 59 of the 67 tracked mining projects. These mines were owned by 41 parent companies operating mines in Africa, the Americas, Asia, and Europe. Ownership of mines is less geographically distributed than the mines themselves. Corporations registered in Australia, the United Kingdom (UK), and Canada own a significant portion of the mines tracked in this study.

Trade flows show that, after China, Mozambique and Madagascar are leading exporters of natural graphite, while Germany and Norway are leading exporters for synthetic graphite. In 2022, synthetic graphite was about 3.7 times more expensive than natural graphite in global markets. The average growth rate in the price of natural graphite among the major producers was about 10% between 2019 and 2022. For synthetic graphite, price growth was about 20%. This indicates a possibly higher increase in synthetic graphite demand relative to supply, in addition to the greater cost of production.

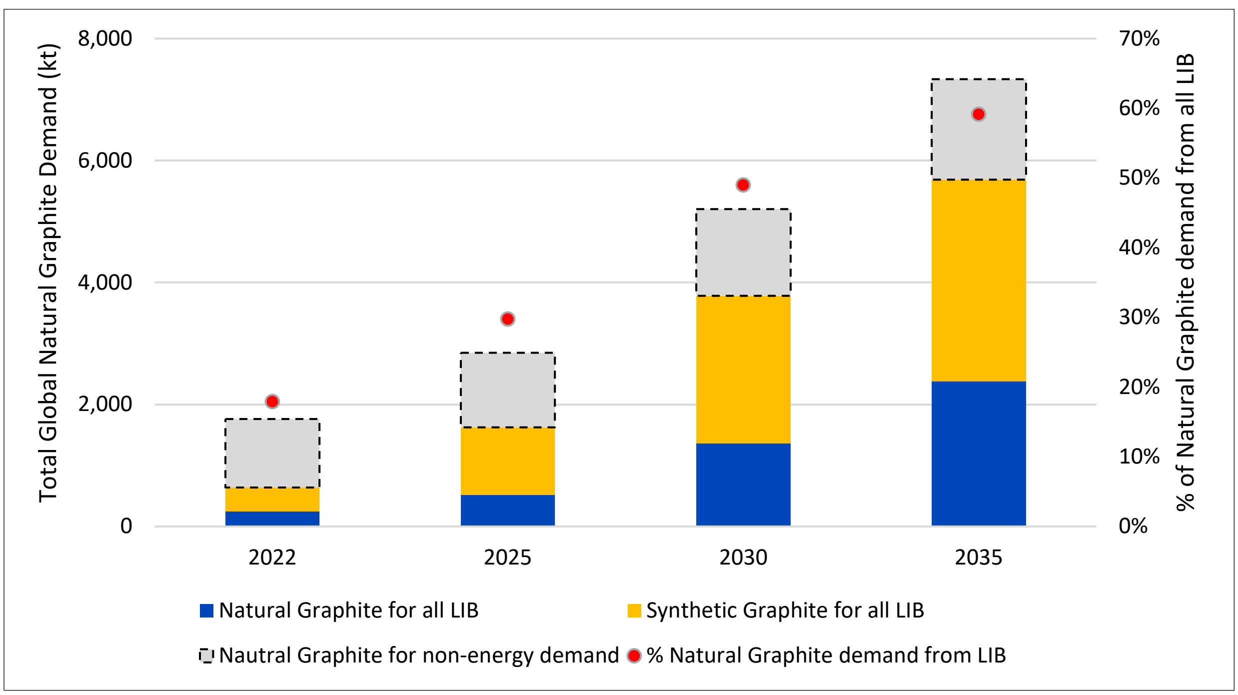

Figure 1. Estimated growth in supply and demand for natural and synthetic graphite from 2022 to 2025.

1.5 Global Demand, Alternative Supply Scenarios and Investment

As per our estimates, total graphite demand is expected to reach about 7,334 kt in 2035, growing at 11.6% compounded annual growth rate (CAGR) between 2022 and 2035 (Figure 1). This is a four-fold increase in demand over 2022. In 2022, LIBs made up around 36% of total graphite demand. By 2035, LIBs are expected to make up 78% of global graphite demand.

Through a scenario analysis, we found that reducing exports from China does not affect their status as the top graphite explorer. However, it does create a more geographically diverse supply chain.

Among the potential alternatives to China for both natural and synthetic graphite, Germany, Norway, Canada, and India are already members of the Minerals Security Partnership. This partnership includes 13 countries and the EU, and its purpose is to spur investment in responsible critical minerals supply chains globally. Mozambique, Madagascar, and Tanzania are being actively considered as possible investment destinations for expanding graphite production. This could have implications for compliance with the US Inflation Reduction Act (IRA) requirements, which require a certain percentage (increasing annually) of critical minerals in clean energy technologies including EV batteries to be sourced from countries that have a Free Trade Agreement (FTA) with the US. While neither of these have an existing agreement with the US, they are likely to adopt treaties to allow for IRA eligibility.

India has significant graphite production potential and could be a key trading partner among the MSP countries. In 2022, India was exporting synthetic graphite at $1,820/tonne and natural graphite at about $650/tonne, compared to China's synthetic graphite exports at $2,496/tonne and natural graphite exports at $1,574/tonne.

1.6 Social Responsibility

Notably, countries with dramatic increases in production are developing economies in the Global South, with African countries having the lowest economic development status. In terms of governance (defined as environmental regulations, political and economic stability), south Asian and Latin American countries rank better than African nations. Ensuring that overall resource, economic, and social governance are preserved or enhanced should remain a key consideration for sustainable value chains as investments in mining are ramped up, especially in African countries.

Minerals Security Partnership (MSP) countries have an opportunity to push for better practices as they look to diversify investments in natural graphite production outside of China. Given recent international developments with regards to graphite, five focus countries in three regions emerge: Mozambique, Madagascar, and Tanzania in Africa, India in South Asia, and Brazil in South America.

1.7 Looking Forward

Import dependence is difficult to identify through trade flows, geological surveys, and/or mine data due to lack of reporting and discrepancies between data sources. These discrepancies include differences in reported data across sources. A better system for tracking and reporting is needed in order to make accurate policy and research decisions.

Pressure to extract graphite has significant implications for environmental and social governance as production and investments ramp-up. Some concerns are overly lax permitting requirements, lack of consent of local communities impacted by land acquisition, and an array of possible impacts from new mining activities. Developed countries—and corporations with headquarters in these countries—play a key role in mineral extraction and value chains in resource-rich developing and less-developed economies.

2 Overview

As the deployment of clean energy technologies increases, so does the need for batteries. Over 10.5 million electric light duty vehicles (LDV) were sold in 2022, making up close to 13% of all new LDV sales (EV Volumes, 2023). In addition, global renewable energy capacity is expected to reach 4,500 GW in 2023 (Abdelilah et al., 2023). Use in vehicle batteries, energy storage, and small electronic devices are expected to drive global demand for lithium-ion batteries (LIB). Graphite is an essential component in LIBs and the parameters of its availability are important to consider as demand rises.

2.1 Graphite Applications

Lithium-ion batteries are made up of an anode, cathode, separator, electrolyte, and positive and negative current collectors (Minos, 2023). Graphite is the most commonly used material in LIB anodes due to its thermal and chemical stability and low cost (Lee et al., 2016; Novák et al., 2001; Simon et al., 1999; Zhao et al., 2022). It is expected to remain in-use for at least the next decade while there is ongoing research on alternatives including amorphous carbon, graphene, silicon, tin, and transition metal oxides (Collins et al., 2021; Ren et al., 2013). Graphite can constitute anywhere from 17 to 20% by weight of a LIB (kg/kWh), depending on the choice of cathode chemistry. Examples of cathode chemistry are lithium iron phosphate (LFP) and lithium nickel manganese cobalt oxide (NMC 622 or NMC 811) (Dunn et al., 2021a; Lebrouhi et al., 2022). In value terms ($/kg of LIB), the graphite anode makes up 8 to 9% in NMC chemistries and can go up to 13% in LFP batteries (BMI, 2023).

In addition to electric vehicle (EV) batteries and energy storage applications, graphite is a component of hydrogen fuel cells (Fan et al., 2021; Steele and Heinzel, 2001; Yu et al., 2023). With the growing push for a hydrogen economy in major markets such as the United States (US), European Union (EU), China, and India, further demand for graphite is expected in the coming decade (European Commission, 2020; International Energy Agency, 2023a; Office of Clean Energy Demonstrations, 2023; Raj et al., 2022). With competing uses in consumer electronics and other consumables (J. Zhang et al., 2023a), graphite demand is expected due to growth in end-uses as well as geographical expansion of markets, leading to significant pressure on supply chains.

2.2 Minerals Security Partnership and International Trade

Graphite is central to decarbonization of our energy systems. The US, China, the EU, and other countries list natural graphite as a critical mineral (Notice of Final Determination on 2023 DOE Critical Materials List, 2023; European Commission, 2023; International Energy Agency, 2022). The Minerals Security Partnership (MSP), a US-led coalition of major economies including Canada, Australia, Japan, India, the EU, and other countries recently announced three projects focusing on graphite, highlighting its importance in critical mineral supply chains (US Department of State, 2023b). The MSP countries are investing in graphite projects to develop a diverse and responsible critical mineral supply chain in accordance with environmental, social, and governance (ESG) standards (US Department of State, 2023a). More recently, the partial export ban on graphite by China in October 2023 has increased the focus on graphite value chains and diversification (Benson & Denamiel, 2023).

2.3 Natural vs. Synthetic Graphite

Unlike other critical minerals, which are mined from the earth and are naturally occurring, graphite can be either mined (natural graphite) or produced artificially (synthetic graphite) (Shi et al., 2021). As of 2020, natural graphite accounted for about 40% of the anode material market and the remainder was synthetic (Zhao et al., 2022).

Natural graphite is found in deposits formed from the metamorphism of carbonaceous sedimentary rocks (Lebrouhi et al., 2022). It is classified into three categories by grade: flake, amorphous, and vein (Deady et al., 2023). Synthetic graphite includes a broad group of essentially pure carbon materials. Synthetic graphite is produced when a carbonaceous precursor, like petroleum coke or coal, is heated to high temperatures (Kurzweil, 2015).

When natural graphite is used for LIBs, flake graphite is preferred. Flake graphite is typically found in deposits that range from 5-30% graphite content. Flake graphite is mainly produced by China, Australia, Mozambique, and Brazil while synthetic graphite is dominated by producers in China, India, Europe, and the US (Robinson Jr. et al., 2017). Vein graphite is higher in graphite content, and it is rare. It is found mostly in Sri Lanka and is costly to mine, restricting its applications (Duan et al., 2023).

In the case of LIBs, the preference for natural or synthetic graphite is based on three key factors:

- impact on battery performance: studies have indicated that synthetic graphite anodes deliver better LIB performance, and have fewer impurities compared to natural graphite (Xing et al., 2018);
- cost economics: natural graphite is preferred due its lower costs; and,
- resource availability: natural graphite is fairly abundant in terms of global resource endowment, but synthetic graphite can be made anywhere as long as primary inputs such as petroleum coke are available.

2.4 Graphite Demand

Historically, graphite demand was driven by end-uses in refractories, brake linings, batteries, steel, and lubricants (Robinson Jr., Hammarstrom, and Olson 2017; Rui et al. 2021; USGS 2000; Shaw 2013). In recent years, the growing clean technology transition has made batteries the second largest natural graphite end-use sector at 14% of total demand. For comparison, refractories account for 46% of natural graphite demand (USGS 2000; Shaw 2013).

Global demand for batteries is expected to rise significantly in the next decade and will likely be the single largest contributor to the growth in overall graphite demand. There is uncertainty in the timing and total volume of future demand for graphite due to prospective advances in LIB technology as well as lack of clarity on the scale of deployment across regions. This uncertainty is furthered with a limited view on non-energy demand (other economic sectors) for graphite, especially in emerging economies that will likely see rapid infrastructure growth in the coming decade. While demand estimates provide a general sense of overall graphite tonnage requirements, they do not distinguish between natural or synthetic graphite.

With relatively higher cost and energy requirements for manufacturing synthetic graphite and life cycle emissions almost 10 times as high as natural graphite, there could be long-term challenges to expanding the synthetic graphite market, especially if regulations focus on value chain emissions. In the meantime, it is expected that both synthetic and natural graphite demand will continue to grow for LIB anode manufacturing, especially as the global regulatory environment evolves to decarbonize LIB value chains (Council of the European Union, 2022).

In a future where countries meet their announced pledges towards climate mitigation, annual graphite demand for lithium-ion batteries is estimated to reach 3.7 million tonnes (MT) by 2035 and about 2.5 MT by 2050 (International Energy Agency, 2023b). If the world meets net zero by 2050 target, annual demand for graphite increases to about 5.5 MT by 2035 and declines to about 2.7 MT in 2050.

3 Methodology

Research on graphite and its role in clean energy transitions has, so far, been limited in academia and the public and private sectors. Other LIB components, such as lithium and cobalt, have been studied more. To illuminate the path forward, we have analyzed natural graphite in terms of resource availability, corporate ownership, and market dynamics. We also forecast graphite demand for all end uses.

3.1 Resource Availability

In order to assess graphite resource availability, we identified estimated reserves, production, and mineral grade for key producing countries and mines. Country-level information came from national geological surveys. Mine-level information came from sources including Securities and Exchange Commission filings (US), Joint Ore Reserves Committee filings (Australia and Australasia), National Instrument 43-101 (Canada) filings, company websites, geological surveys, news reports, and journal articles.

Natural graphite production is reported from at least 21 countries, with varying estimates of production for the same year across different sources of data (Austrian Federal Ministry of Finance 2023; Idoine et al. 2023; USGS 2020; Stewart 2023). We provide reported natural graphite production estimates for 2019 across the US Geological Survey (USGS), the British Geological Survey (BGS) and the Austrian World Mining Data (WMD), to better understand variations in reported data. For 2022, we use USGS data as other sources have not published their updated estimates. Other sources of data include S&P Global, Geoscience Australia, Natural Resources Canada, and the Indian Bureau of Mines.

While the USGS is the most-referenced source for reserves information, data on reserves for countries with lower production shares are not reported by USGS. Information from other sources is also scarce. Thus, data from countries like Namibia, Zimbabwe, Germany, and Pakistan, all of which have reported graphite reserves, are not presented here.

A key contribution of our analytical framework is the criticality analysis of mineral production and reserves. Countries most often define critical minerals based on:

(1) market access, i.e., domestic availability and global distribution of a resource,

(2) requirements for key economic sectors, i.e., dependency of domestic manufacturing on the resource in question, and

(3) likelihood of disruption, e.g., political instability or unreliable transportation infrastructure.

We identify the criticality of the resource as a function of the annual production volume or reserves that are above the minimum threshold of mineral quality required for LIB manufacturing. In the case of graphite, the minimum grade found for flake graphite ore ranges from 2 to 5% according to industry sources. Since this is the natural graphite type used for LIB anodes, 3% was chosen as the measure for graphite ore grade criticality. Criticality status is based on the premise that, if the distribution of a resource is skewed towards lower grade ores, there will likely be higher associated costs of production due to additional processing and refining requirements. This imposes economic constraints on the production of these resources and, by extension, their affordability in global value chains.

We assessed the stability of graphite resources from major resource-endowed countries using the six World Governance Indicators (WGI) (Annexure I):

(1) voice and accountability,

(2) political stability,

(3) government effectiveness,

(4) regulatory quality,

(5) rule of law, and

(6) control of corruption.

We find the average percentile rank of the countries that report natural graphite production and reserves (Table 1 and Table 2) and rank them with country-wise scores (Figure 1) (Annexure II). This ranking is coupled with World Bank classifications of each country's economic status ranging from low to high. These rankings give insight into the likelihood of supply chain disruption due to factors such as infrastructure, corruption, and political stability.

3.2 Corporate Ownership

Given increasing international cooperation in critical mineral value chains—including graphite—and with countries signing mineral trade agreements, it is important to understand the interplay between countries where resources are located, mine ownership, and the location of corporation headquarters. These factors affect the geo-political dimensions of future resource supplies. Notably, most producing mines are auctioned to private sector corporations typically located in other countries.

This analysis brings forth four areas of peril and/or opportunity:

(1) the role of multinational corporations in driving global mineral supply chains through control of foreign production,

(2) the role of governments where corporations are headquartered in ensuring higher compliance standards for sustainable mining in overseas operations,

(3) the role of governments where mines are operated in ensuring the well-being of their citizens and environment, and

(4) the potential for industry engagement on improving compliance at mine-level or by corporation across its operations.

We assessed the corporate ownership and headquarters location of each mining operation. We filtered these data to assess which countries, through ownership of the mine, have access in regions according to mine locations. The mines are grouped across four regions, namely, Africa, the Americas, Asia, and Europe.

We further assessed corporate ownership by factoring in shareholders that own 20% to 50% of a mining project, subsidiaries, and recent mergers or acquisitions. These corporations are considered secondary entities in this report. Corporations that own more than 50% of a mining project are considered primary entities.

3.3 Market Dynamics

The market dynamics of graphite were analyzed using global trade data extracted from the World Customs Organization's Harmonized System (HS). The HS is a standardized numerical method of classifying traded products. It is used by customs authorities around the world to identify products when assessing duties and taxes and for gathering information. Country-level quantities and prices of exports and imports of both natural and synthetic graphite are available, as are major producers and consumers for the years 2019 and 2022. Given that prices of natural and synthetic graphite are difficult to access because most data are behind paywalls, we use trade data to provide insights into price trajectories.

These data were used to evaluate MSP member country activity and dependence on China. Dependence on China was calculated by comparing the share of Chinese imports to total natural graphite imports of each country.

3.4 Demand Forecast

We generated a demand forecast for natural graphite that considered all end uses through 2035. The model was based on data from Benchmark Mineral Intelligence (2023), IEA Critical Minerals Explorer (2023), EV-Volumes (2023) and (Dunn et al. 2021b). It estimates global demand for natural graphite across both energy and non-energy use and synthetic graphite for LIBs up to 2035. A caveat is that total graphite demand may be higher than our estimates, as synthetic graphite for non-LIB applications has not been considered in this analysis.

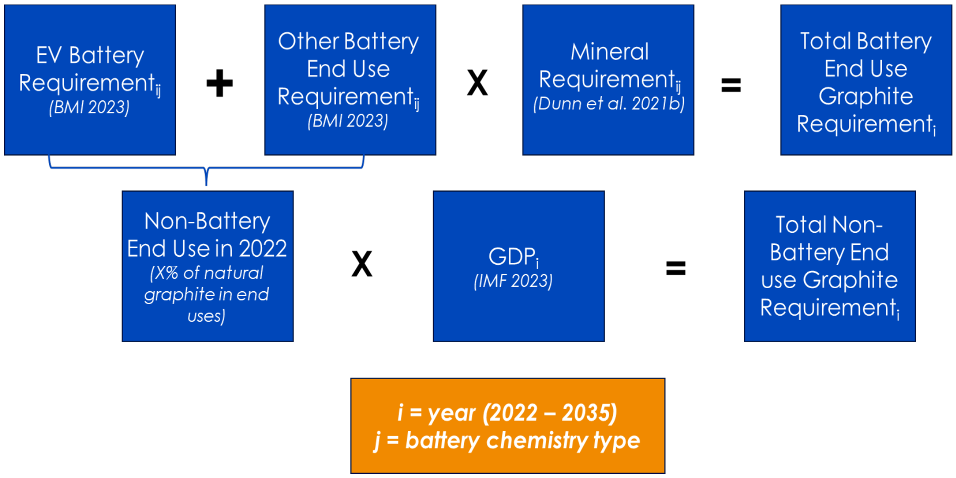

Figure 2. Graphite demand model for battery and non-battery end uses.

4 Natural Graphite Production and Reserves

Recent summaries of natural graphite production by country show some increases and suggest that key players are developing their supplies at different rates. Estimated reserves are also increasing as research and development continue.

Global natural graphite production was about 1.3 MT in 2022 (USGS 2023). Global natural graphite production has seen an estimated 3.3% compounded annual growth rate (CAGR) between 2018 and 2022, while global reserves have grown at 6.7% CAGR in the same period with additional exploration (Stewart 2023; USGS2017). Total global trade, excluding re-exports and re-imports, in 2022 of natural graphite was 3.2 MT, while that of synthetic graphite was 6.2 MT (Department of Economic and Social Affairs, 2023).

A World Bank Report (2020) estimated that annual production of graphite would have to total 4.5 MT by 2050, if the world were to be on track to achieve an under 2° Celsius scenario (Hund et al., 2020). Another estimate by Benchmark Minerals Intelligence (BMI) suggested that over 300 new mines would need to be built to meet the graphite demand for batteries by 2035, assuming the annual production of a typical graphite mine to be 56,000 tonnes and that most graphite demand will be met through natural graphite (Benchmark Mineral Intelligence, 2023).

The graphite market has experienced extreme shifts in supply and demand since the 1990s due to rapid expansion in production capacity (Ye et al., 2017). During this time, China ramped up production capacity significantly (USGS 2000; Robinson Jr., Hammarstrom, and Olson 2017). This led to a surplus of graphite on the global market, causing prices to plummet (Northern Graphite Corporation, 2020). Graphite prices remained low until 2005 when growing demand for steel in China caused prices to increase because graphite is the main electrode used in electric arc furnaces for heating and melting scrap to produce new steel. The price of graphite peaked in 2012 with shortages reported. This ushered in an era of graphite exploration and, between 2012 and 2020, estimates of graphite reserves more than tripled globally (USGS 2020). Before this exploration period, natural graphite reserves were considered to be concentrated in

China and Mexico (Mundszinger et al., 2017), however, reserves have since been identified in other countries including India, Mozambique, and Brazil (Stewart, 2023).

While estimates of overall global production of natural graphite from our three data sources are similar, there is some variation at the country-level. Notable examples are Mozambique, Canada, Brazil, Austria, South Korea, and Russia (Table 1). The disparity between sources is illustrated by production estimates for Tanzania. Estimates made by USGS suggest that Tanzania produced about 150 tonnes of graphite in 2019. However, BGS and WMD estimated zero production in the same year (Table 1). In the UN trade database, Tanzania reports exporting about 10,856 tonnes of natural graphite at an average value of $445 per tonne. This is significantly higher than the USGS estimate for 2019.

In 2022, China continued to produce about two-thirds of global graphite (62%), followed by Mozambique (12%), Madagascar (8%), Brazil (6%), and India (4%). These five countries produced 92% of global natural graphite for the year (Stewart, 2023). Between 2019 and 2022, significant increases in natural graphite production occurred in Mozambique, Madagascar, and Tanzania in Africa, and India in South Asia. Major producing countries are developing economies in the Global South, with African countries having the lowest economic development status (Weber, 2023).

Table 1. Global natural graphite production by country for 2019 and 2022 (kilotonnes).

Country	2019 (kt)			2022 (kt)	Production Share (%)	
	US Geological Survey	British Geological Survey	World Mining Data	US Geological Survey	2019	2022
China	700	700	700	850	62%	62%
Mozambique	100	114	153	170	11%	12%
Madagascar	47	53	45	110	4%	8%
Brazil	96	96	82	87	8%	6%
India	35	32	35	57*	3%	4%
South Korea	0	40	0.30	17	1%	1%
Canada	40	11	11	15*	2%	1%
Russia	25	17	18	15	2%	1%
Norway	16	10	10	10	1%	1%
North Korea	6	0	45	8	2%	1%
Tanzania	0.15	0	0	8	0%	1%
Vietnam	5	0	4	5	0%	0%
Ukraine	20	15	10	3	1%	0%
Turkey	2	10	10	3	1%	0%
Sri Lanka	4	4	3	3	0%	0%
Mexico	9	2	2	2	0%	0%
Austria	1	20	0.10	1	1%	0%
Pakistan	14	0		0	1%	0%
Namibia	4	0	0	0	0%	0%
Zimbabwe	2	0.10	0	0	0%	0%
Germany	1	0.21	0.14	0	0%	0%
Total	**1,126**	**1,124**	**1,127**	**1,364**		

**Estimates for Canada and India are obtained from Natural Resources Canada and Ministry of Mines and the Government of India, respectively.*

As per the latest updates from USGS (2023), the largest estimated reserves of natural graphite are in Turkey (26%), followed by Brazil (21%) and China (15%). The African nations of Mozambique (7%), Madagascar (7%), and Tanzania (5%) hold 19% of global natural Graphite reserves (Table 2). In 2019, USGS reported China as having the largest reserves with about 73 MT, revised to 52 MT in 2022. The largest increase in graphite reserves has been reported in Madagascar, with a jump from 1.6 MT in 2019 to 26 MT in 2022. While Sri Lanka is a key supplier of vein graphite, its reserves have been revised downward to 1.5 MT in 2022 from 7.6 MT in 2019.

A 2022 estimate from S&P Global indicates that Ukraine could hold about 17.9 MT of natural graphite; about 5% of global reserves. Russia is estimated to have about 4% of global graphite reserves. Supplies from this region will depend on the resolution of the ongoing geo-political tension. The recent war has resulted in a significant decrease in reported graphite production from both Russia and Ukraine, with Ukraine's production declining from about 17,000 tonnes in 2021 to about 3,000 tonnes in 2022. Australia, which is currently not a major producer of graphite, is reported to have about 7.1 MT of economic demonstrated reserves (Summerfield, 2019). This is the tenth-largest reserve, by country, after India which has an estimated 8 MT of reserves.

Table 2. Global reserves of natural graphite by country in 2022 (million tonnes).

Country	Million tonnes	% share	Source
Turkey	90.0	25.8%	USGS
Brazil	74.0	21.2%	USGS
China	52.0	14.9%	USGS
Madagascar	26.0	7.4%	USGS
Mozambique	25.0	7.2%	USGS
Tanzania	18.0	5.2%	USGS
Ukraine	17.9	5.1%	(Barich, 2022)
Russia	14.0	4.0%	USGS
India	8.0	2.3%	USGS
Uzbekistan	7.6	2.2%	USGS
Australia	7.1	2.0%	(Geoscience Australia, 2023)
Canada	5.7	1.6%	(Natural Resources Canada, 2023)
Mexico	3.2	0.9%	USGS
North Korea	2.0	0.6%	USGS
Vietnam	2.0	0.6%	USGS
South Korea	1.8	0.5%	USGS
Sri Lanka	1.5	0.4%	USGS
Norway	0.6	0.2%	USGS
Austria	0.2	0.1%	USGS
World Total	**356.5**		

5 Criticality of Natural Graphite

Graphite availability is a defining parameter for the success of clean energy technologies, especially LIBs, as global markets combat climate change. To better understand supply chain strengths and weaknesses, factors such as geography, governance, mine status, mineral grade, and resource ownership must be considered.

In this section, we assess the criticality of natural graphite in terms of:

- its geographical distribution,
- potential supply risks using 2023 World Governance Indicators (WGI) (Kaufmann and Kraay 2023) for graphite-producing countries,
- individual mine production or reserve status, grade of ore, and ownership.

These aspects of the supply chain provide a framework of criticality for mineral resource availability, insights into the potential quality of mineral resources available across key countries, and clarity about mine ownership structure.

5.1 Geographical Criticality for Natural Graphite

We rank the top 21 graphite-endowed countries according to production, reserves, the anticipated stability of their supplies, and governance indicators (Table 1, Table 2, Figure 3, and Annexure II). While all Global South countries rank lower than their developed counterparts, South Asian and Latin American countries, such as India, Vietnam, and Brazil, have relatively better percentile ranks than African countries (with exceptions, such as Namibia). The economic statuses of 71% of the countries (15 out of 21) are either middle- or low-income (World Bank, 2023). As MSP countries look to diversify investments into natural graphite production outside of China, the relationship between graphite reserves and economic disparity informs the work needed to meet ESG standards.

In their October 2023 Joint Statement, the MSP has identified three graphite projects that they will focus on advancing (US Department of State 2023b). These include a major investment in Balama, Mozambique, which is among the few mine locations outside of China to have a good combination of high-quality graphite ore and relatively higher reserves (see section 5.2).

Madagascar is another key graphite producer that has seen production more than double between 2019 and 2022 (Table 1) and is estimated to have about 7% of global natural graphite reserves (Table 2). Both these countries are among the lowest ranking in terms of overall governance indicators (Figure 3). The MSP is in a position to ensure that responsible mining standards and safeguards are adhered to as these countries ramp up production in the coming years.

Tanzania, Brazil, and India hold about 28% of global natural graphite reserves and rank relatively higher in terms of their overall governance indicators (Figure 3). These countries could be prioritized for investments in natural graphite.

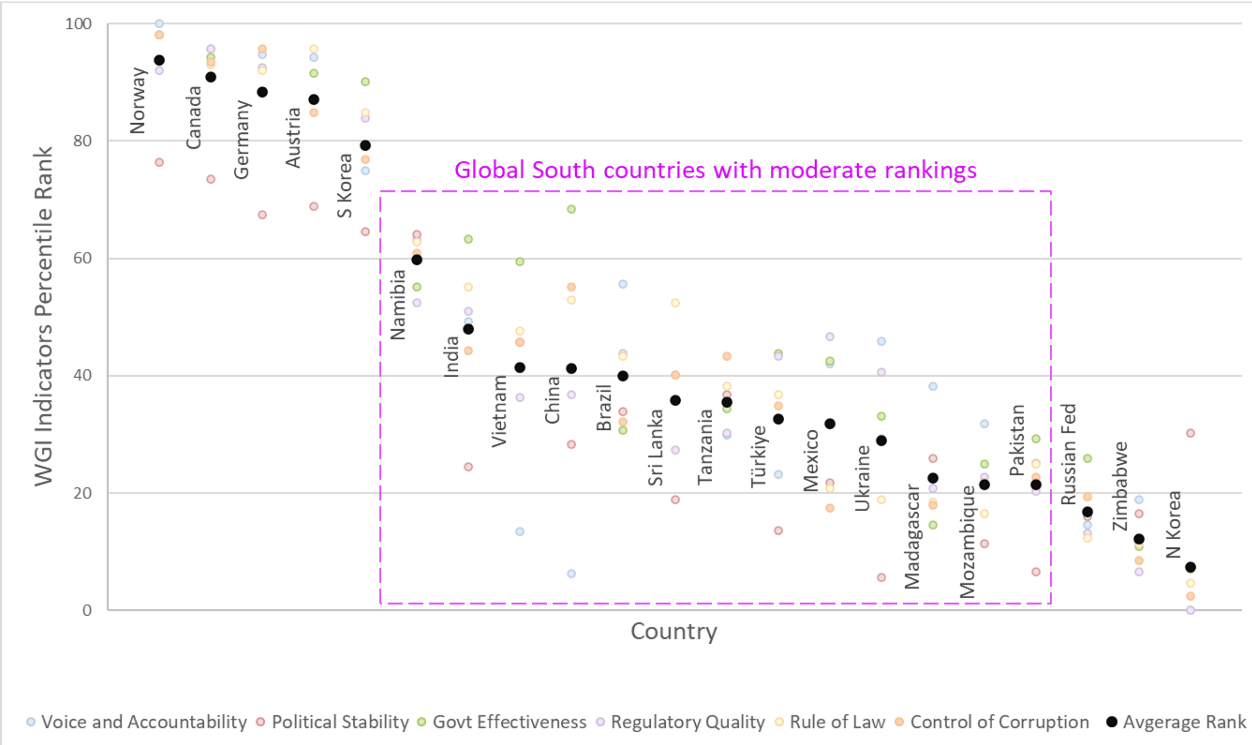

Figure 3. Worldwide Governance Indicator average percentile rank, by country.

5.2 Mine-wise Production, Reserves, and Ore Quality for Natural Graphite

In this study, the location, production or reserve status, grade of ore, and ownership for 68 mines were compiled. Most of the mines are in Africa, a region which has been a recent focus for graphite exploration (Stewart, 2023; US Department of State, 2023b). Information about mines in the Americas, India, and Europe was included, as well. Although China produces the most graphite, this report excludes Chinese mines due to poor data availability.

An economically viable graphite deposit usually has a minimum content of about 4 wt% C, with the graphite ore grade for lithium batteries ranging from 5 to 30% (Weber, 2023). Weber (2023) also finds that the global average grade from producing mines or explorations projects is about 13 wt% C. In our analysis, only 10 of 68 mines have a grade below 5%. This indicates that quality of ore is not a critical issue for graphite.

We assessed the average grade and total estimated reserves of graphite mines by country (Figure 4). Of the mines tracked in this analysis, Madagascar had the greatest number of mines. India had the highest average grade primarily due to one mine, Sivaganga, with an average grade of 84%. The largest reserves were in Africa, with Mozambique having the greatest estimated amount. Most African mines were in the exploration or project development phase, while 22 are active.

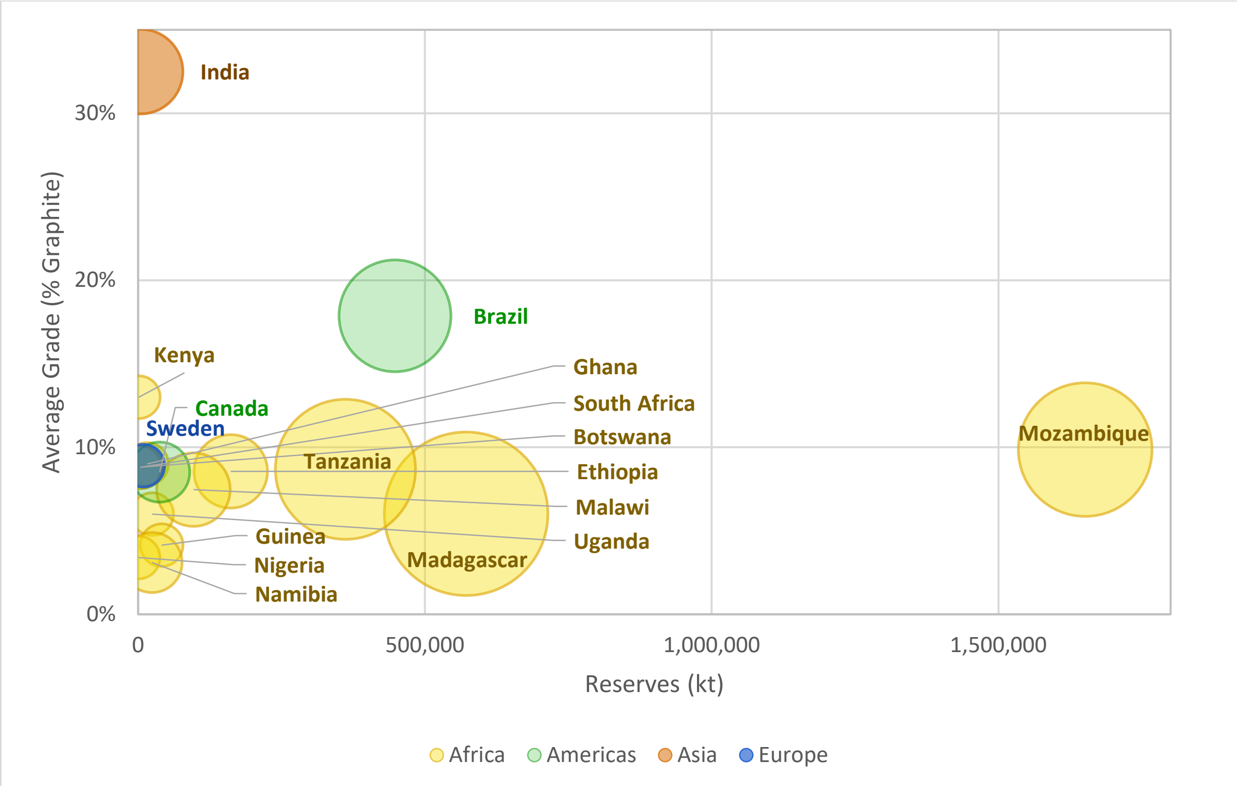

Figure 4. Average grade and graphite reserves of tracked mines, by country.

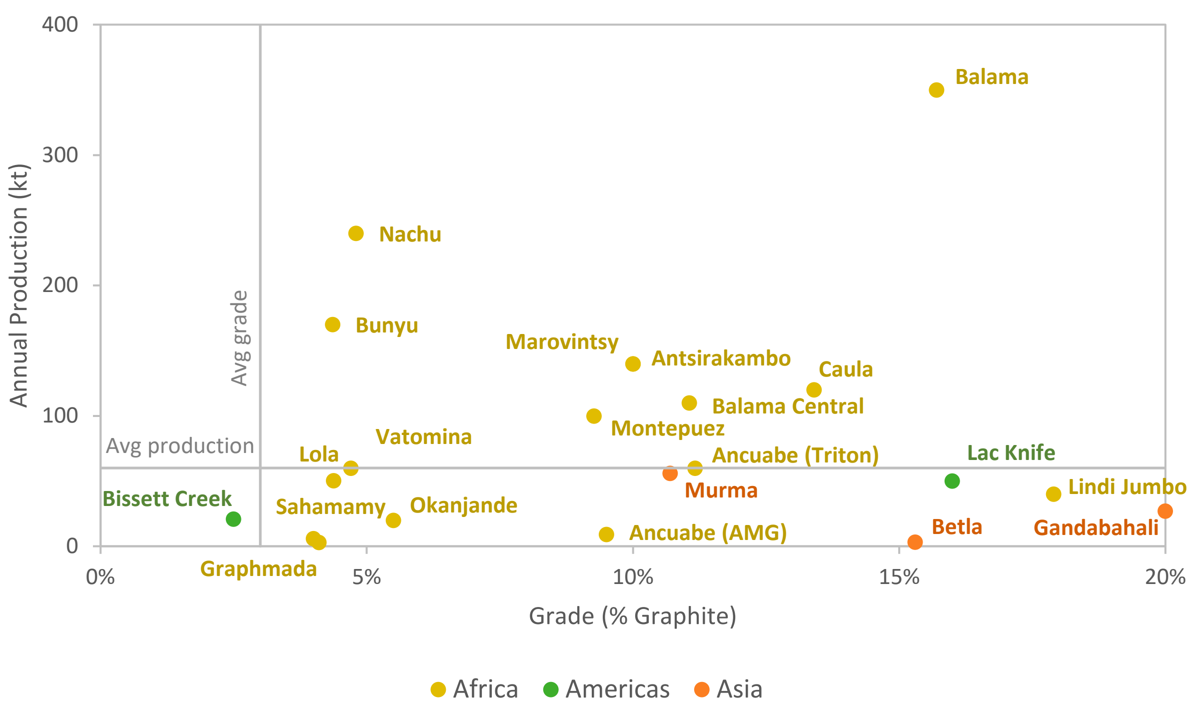

Figure 5. Natural graphite production and grade, by mine.

The Balama mine in Mozambique has the highest grade at 15.7% and the most production at 350 kt per year. Average production is around 60 kt per mine annually, indicating many smaller mines in operation (Figure 5). The average grade is around 3%, with more than half of the mines tracked having a grade higher than 9%.

Overall, geographical availability is likely to be the predominant limiting factor in graphite supply, rather than average grade of deposits (Figure 5 and Figure 6). The majority of the reserves tracked have a grade of 4 to 10% (Figure 6), which is above the 3% threshold we have set for criticality. The Nicanda Hill graphite mine in Mozambique stands out with a significantly higher reserve estimate (about 1,430 MT), compared to other mines (omitted from Figure 6 because it is an outlier). It is largely owned by a company headquartered in the UK, which means that the country in which the mineral deposit is located does not determine who owns and operates the mine.

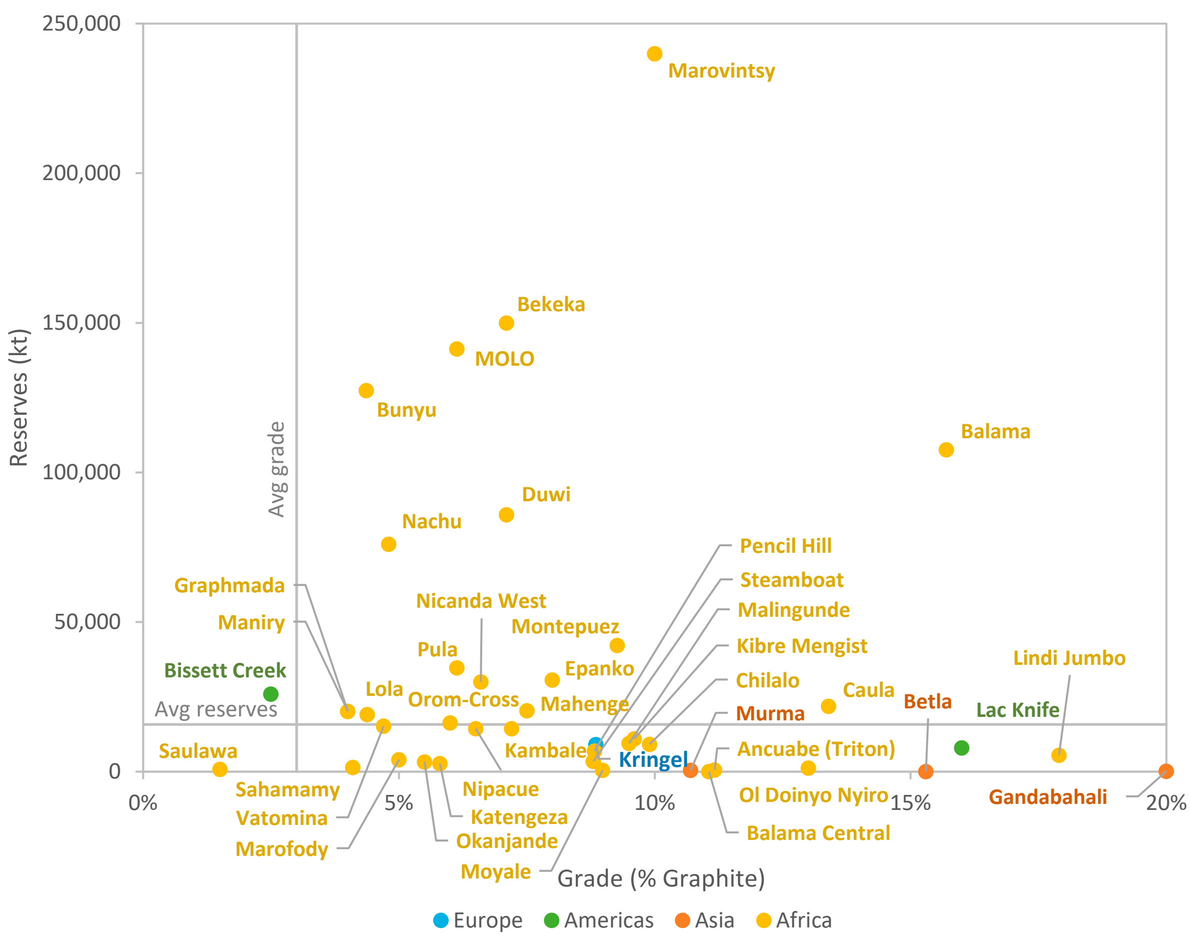

Figure 6. Grade and reserves of natural graphite, by mine. Nicanda Hill omitted (1,430 MT reserves and 11.1% grade).

5.3 Corporate Ownership of Natural Graphite Mines

Evaluating ownership provides insights into which countries will likely benefit from trade flows. We determined the primary company of ownership (holding a majority of the interest) for 60 of the 68 mining projects reviewed in this study. Since the recorded ownership of a mine could be through a secondary or subsidiary company, the country of origin of the owner may reveal the likelihood of regulatory compliance and international trade implications.

The 60 mines were owned by 41 primary companies located in Australia, the UK, Canada, and other countries (Figure 7 and Annexure III). These companies operated mines in Africa, the Americas, Asia, and Europe. Graphite mines are typically owned through a parent entity. All of the mines tracked in this analysis are privately owned, as opposed to state-owned corporations. Australian companies own twenty-one of the tracked mines, followed by the UK (eleven), Canada (nine) and Brazil (six) (Figure 7).

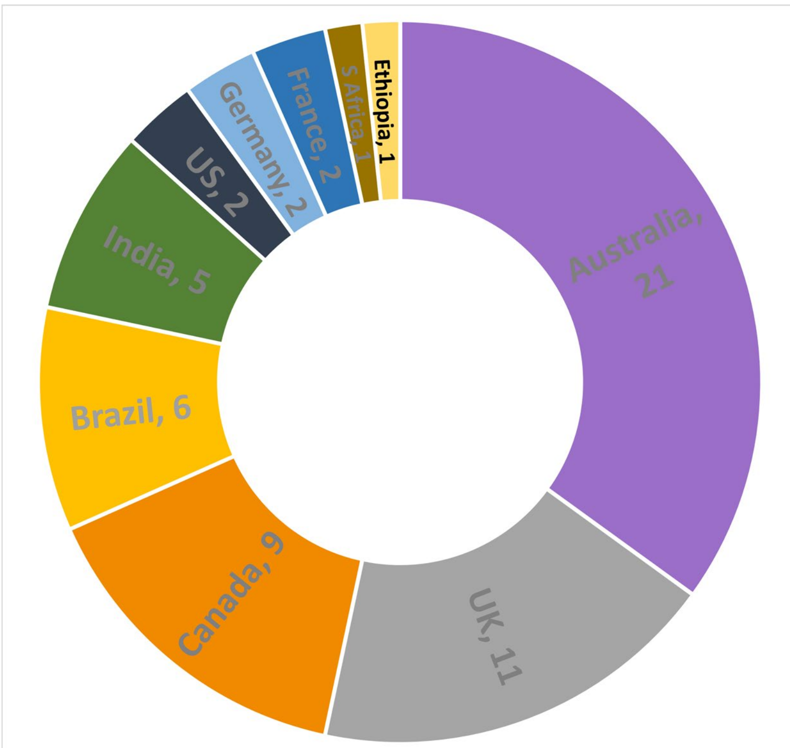

Figure 7. Primary country of ownership for 60 mines, globally.

Within Africa, Australian and UK-based corporations have the dominant presence in ownership and operation of natural graphite mines (Figure 8).

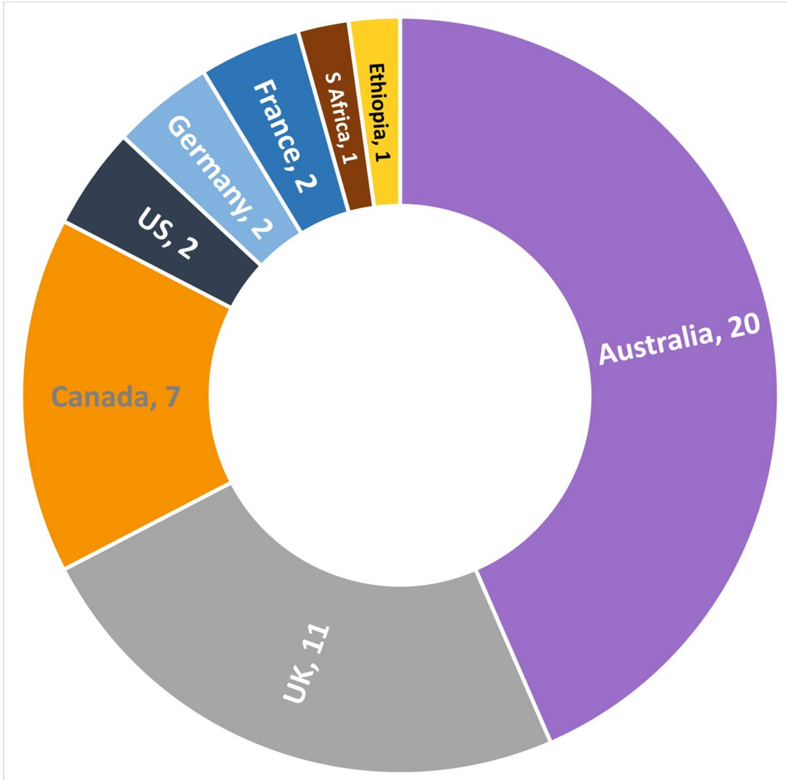

Figure 8. Country of origin of operating companies for 46 mines in Africa.

When looking at the number of corporations operating in each country, Australian-owned companies are most-represented with fifteen, followed by seven from the UK, five from Canada, five from India and three from Brazil (Figure 9).

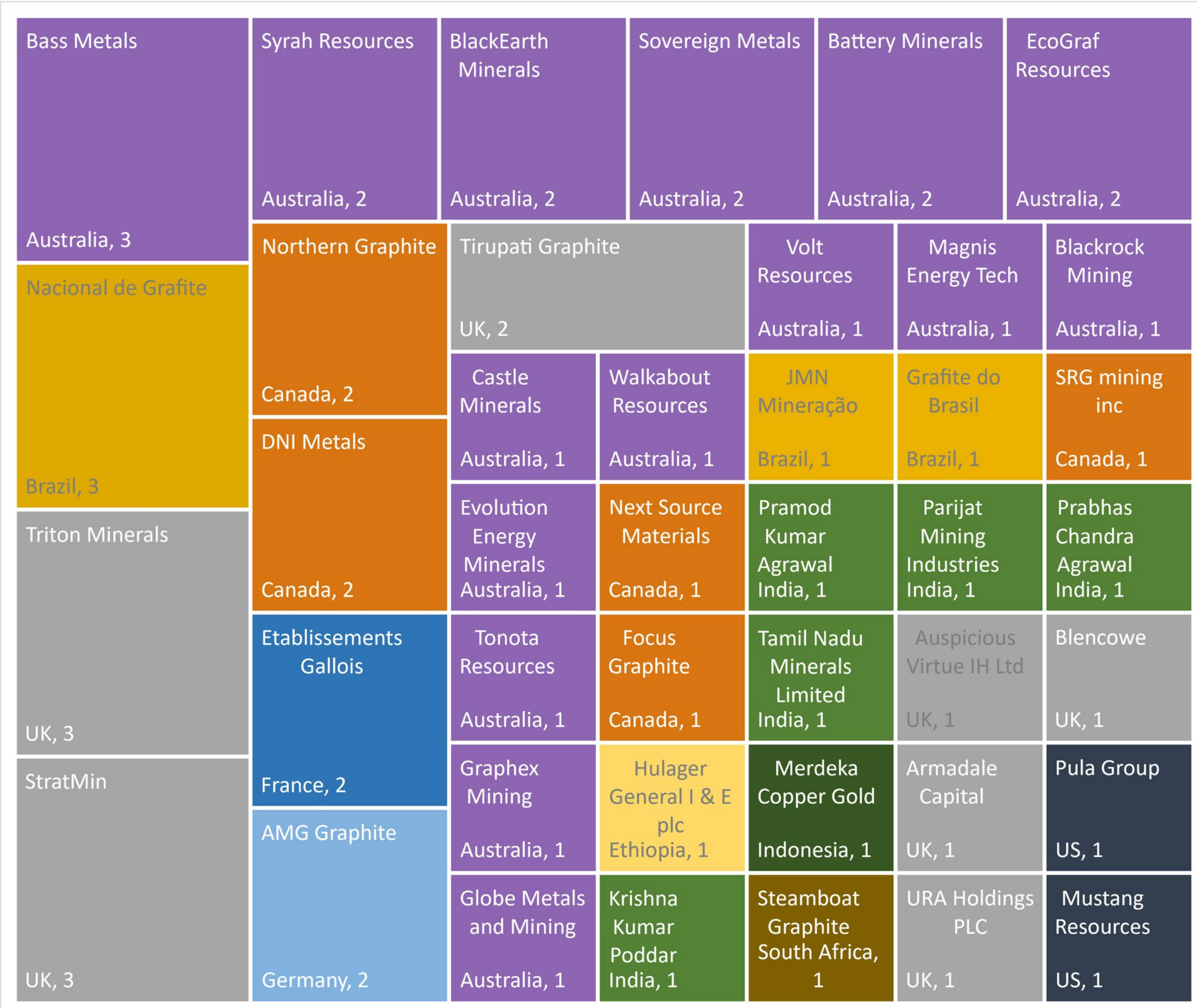

Figure 9. Ownership count of tracked graphite mines by company and country of origin. This graphic summarizes ownership by parent entities, only. Some companies have subsidiaries.

Of the 46 projects in Africa, 35 projects are in three countries, namely, Madagascar, Tanzania and Mozambique (Figure 10). Of 15 projects in Madagascar, dominant operations are by companies from Australia (three projects), UK (four projects) and Canada (five projects). Of the 10 projects in Mozambique, four are owned by the UK, three by Australia, two by Germany, and one by the US. Of the 11 projects in Tanzania, nine projects are owned by Australian companies and one each by the UK and the US.

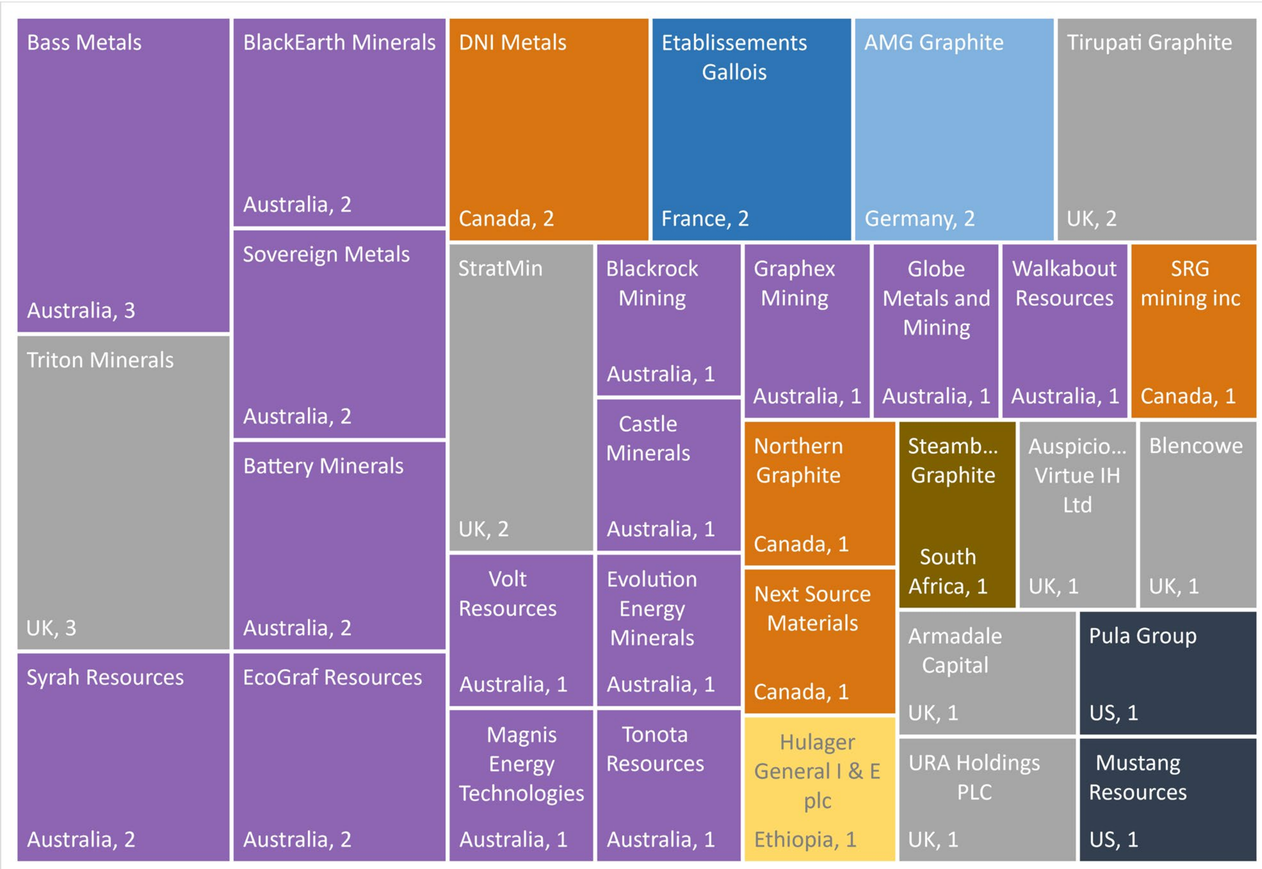

Figure 10. Ownership count of tracked graphite mines in Africa by company and country of origin.

In the Americas, major mine projects are owned by Brazilian or Canadian companies operated in their own countries (Figure 11). This was also the case for Asian mines, all of which were located and owned in India (Figure 9).

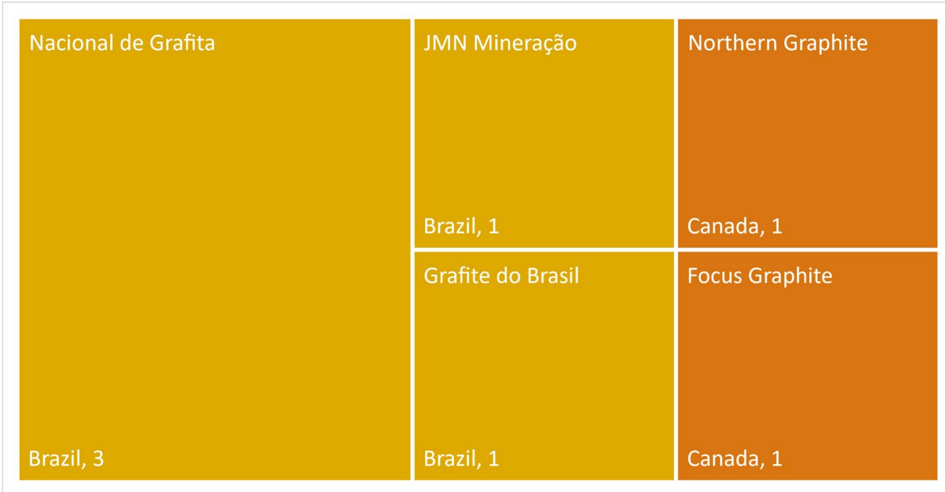

Figure 11. Ownership count of tracked graphite mines in the Americas by company and country of origin.

Often in the mining industry, mines are jointly owned by two or more corporations with different shares based on their investment, or the actual owning and operating entity is a subsidiary of a larger corporation. Ownership may change every few years due to mergers and acquisitions. Based on the 63 mining projects reviewed in this analysis we find that, in the case of natural graphite, none of these (i.e., joint ownership, subsidiaries or mergers and acquisitions) are very common.

However, in the cases of Finders Resources in Australia and Tirupati Graphite in the UK, the former is a subsidiary of another company, and the latter has other shareholders with a significant interest in their projects. Finders Resources is a subsidiary of Eastern Fields Development which is a joint venture between Procap Partners Limited, PT Saratoga Investama Sedaya Tbk, and PT Merdeka Copper Gold Tbk. In the case of Tirupati Graphite, a UK company called Stratmin has a 45% interest in Tirupati Graphite.

6 Graphite Trade Flows among Major Producer Countries

To further understand global graphite flows, we analyze exports and imports of natural and synthetic graphite among major natural graphite producing countries. We use the UN Comtrade database to extract trade data for graphite at the four-digit level (Department of Economic and Social Affairs, 2023). The Harmonized System (HS) Codes[1] analyzed are 2504 for natural graphite and 3801 for synthetic graphite. The trade flows are analyzed for 18 countries (Table 3).

While China remains the largest exporter of natural and synthetic graphite, the share of Chinese exports of natural graphite declined from 50% to 44% while its share in exports of synthetic graphite increased from 60% to 77%, between 2019 and 2022. Mozambique is the second largest exporter of natural

[1] The Harmonized System (HS) is a standardized numerical method of classifying traded products. It is used by customs authorities around the world to identify products when assessing duties and taxes and for gathering statistics. The HS is administrated by the World Customs Organization (WCO) and is updated every five years.

graphite, with about a quarter of exports across both years. Madagascar shows the highest increase in export share of natural graphite, from 9% in 2019 to 21% in 2022. Germany and Brazil are two other key exporters of natural graphite with a share of around 3% each. In the case of synthetic graphite, apart from China, Germany and Norway are key exporters, followed by Brazil and India.

Table 3. Trade flows of natural and synthetic graphite by major graphite-producing countries *(orange indicates major exporters; yellow indicates key exporters in both years)*.

Country	Natural Graphite (Quantity)				Synthetic Graphite (Quantity)				Natural Graphite		Synthetic Graphite	
	Export		Import		Export		Import		% share of exports			
	2019	2022	2019	2022	2019	2022	2019	2022	2019	2022	2019	2022
Austria	5,766	4,733	16,837	21,690	5,527	7,263	13,114	8,036	1%	1%	1%	1%
Brazil	19,284	18,036	0	0	13,571	34,352	27,358	19,788	3%	3%	2%	3%
Canada	12,407	9,873	55,096	53,015	0	0	25,320	19,396	2%	2%	0%	0%
China	288,885	244,749	196,971	170,649	462,050	801,871	50,367	52,667	50%	44%	60%	77%
Germany	17,169	20,436	48,608	66,540	81,088	93,951	64,099	0	3%	4%	11%	9%
South Korea	341	203	41,667	48,432	15,682	0	66,851	64,144	0%	0%	2%	0%
Madagascar	53,960	116,721	944	0	0	0	0	0	9%	21%	0%	0%
Mexico	0	0	0	0	0	0	0	0	0%	0%	0%	0%
Mozambique	162,608	135,017	50	5	0	1,730	0	270	28%	24%	0%	0%
Namibia	0	105	0	3	0	0	0	15	0%	0%	0%	0%
Norway	0	0	49	373	78,580	66,604	22,209	22,846	0%	0%	10%	6%
Russia	2,236	0	3,825	0	38,864	0	19,656	0	0%	0%	5%	0%
India	459	2,089	45,003	52,172	24,422	29,842	51,788	77,670	0.1%	0.4%	3%	3%
Vietnam	1,293	0	1,443	0	100	0	14,800	0	0%	0%	0%	0%
Zimbabwe	0	501	0	0	0	0	8,564	9,831	0%	0%	0%	0%
Türkiye	1,609	2,459	10,584	15,954	560	556	24,811	0	0%	0%	0%	0%
Ukraine	3,619	1,166	817	147	46,861	4,451	0	7,194	1%	0%	6%	0%
Tanzania	10,856	6,120	299	0	73	250	11	9	2%	1%	0%	0%

While Mexico is estimated to have about 3.1 MT of natural graphite reserves, it does not indicate any recorded exports. Mexico could be a potential supplier, especially to the US, as corporations aim to meet compliance requirements for sourcing and value-add in accordance with US Inflation Reduction Act (IRA) legislation enacted in 2022.

Brazil, Germany, Norway, and India, which have natural graphite reserves, are also key exporters of synthetic graphite.

Tracking prices for natural and synthetic graphite is difficult because most data are behind paywalls. By analyzing export values in the trade database, average prices (USD/tonne) can be estimated. In this study, we use trade data to provide insights into price trajectories of both natural and synthetic graphite between 2019 and 2022 (Table 4). Tracked price changes between 2019 and 2022 are somewhat erratic, however, average prices increased by $530 for natural graphite and $148 for synthetic graphite.

Table 4. Export prices of natural and synthetic graphite by country in 2019 and 2022 *(For 2022, lower prices are pale orange and higher prices are dark orange)***.**

Country	Natural (USD/tonne)		Synthetic (USD/tonne)	
	2019	2022	2019	2022
Austria	1,401	1,644	6,511	4,388
Brazil	1,476	1,633	757	1,131
Canada	1,394	1,709	-	-
China	1,129	1,574	1,778	2,496
Germany	1,645	1,676	2,121	2,538
South Korea	2,515	7,729	7,432	-
Madagascar	364	437	-	-
Mexico	-	-	-	-
Mozambique	305	432	-	876
Namibia	-	294	-	36,818
Norway	-	-	825	1,406
Russia	477	-	771	-
India	745	653	1,955	1,822
Vietnam	1,487	-	10,059	-
Zimbabwe	-	5	-	-
Türkiye	870	691	2,489	3,556
Ukraine	660	719	760	841
Tanzania	445	412	46	400

The average growth rate in prices of natural graphite among the major producers was about 10% between 2019 and 2022, whereas price growth for synthetic graphite was about 20%. Further, in 2019, the average price of synthetic graphite was about 2.8 times the price of natural graphite. In 2022, the average price of synthetic graphite was about 3.7 times more than natural graphite. These indicators point to increasing demand for synthetic graphite relative to supply and the cost of production.

Among countries which are major producers of natural graphite, Mozambique and Madagascar were exporting natural graphite at about $435 per tonne in 2022, compared to $1,574 per tonne for Chinese exports, or $1,709 per tonne for Canadian exports. Among other potential producers, India ($653 per tonne) and Tanzania ($412 per tonne) could be price competitive sources for natural graphite. The prices of graphite in South Korea and Namibia are high largely due to low production volumes and limited capacity. These prices are expected to fall as production capacity and supply contracts expand in 2024 and beyond.

China's exports of synthetic graphite were priced at about $2,500 per tonne, with similar export values from Germany. In comparison, Norwegian synthetic graphite exports were around $1,400 per tonne and those from India were around $1,820 per tonne. Brazil, another key exporter of synthetic graphite, saw exports at around $1,130 per tonne in 2022.

Among potential alternative sources to China for both natural and synthetic graphite, Germany, Norway, Canada, and India are already MSP members, while Mozambique, Madagascar and Tanzania are being considered by MSP countries as key investment destinations for expanding graphite production. With Brazilian synthetic graphite exports more than doubling, and with its significant natural graphite reserves, it will also be a location of interest.

6.1 Graphite Imports and Exports among Mineral Security Partnership Countries

In this section, we analyze graphite imports and exports among MSP countries to better understand their dependency on international trade and China.

Among MSP countries, Germany, the US, and Canada are among the top exporters (in volume) of both natural and synthetic graphite (Table 5), although the US does not have any estimated natural graphite reserves. This indicates that the US is likely importing for other countries, and then re-exporting. France, Japan, and India are key exporters of synthetic graphite, as well.

Table 5. Export and Imports volumes for natural and synthetic graphite, MSP countries and China in 2022 (tonnes).

Country	Exports		Imports		Net Trade	
	Natural	Synthetic	Natural	Synthetic	Natural	Synthetic
Australia	127	0	383	20	-256	-20
Canada	9,873	0	53,015	19,396	-43,142	-19,396
Finland	3	22	1,251	5,271	-1,248	-5,249
France	140	40,919	5,646	43,067	-5,507	-2,147
Germany	20,436	93,951	66,540	0	-46,104	93,951
India	2,089	29,842	52,172	77,670	-50,083	-47,828
Japan	1,105	32,463	59,143	92,072	-58,038	-59,610
South Korea	203	0	48,432	64,144	-48,230	-64,144
Sweden	247	1,658	1,677	6,693	-1,430	-5,036
UK	0	0	6,562	0	-6,562	0
USA	9,917	41,336	89,409	165,174	-79,492	-123,839
China	*244,749*	*801,871*	*170,649*	*52,667*	*74,099*	*749,204*

The US is the largest importer of both natural and synthetic graphite, followed by Japan, India, South Korea, Canada, and Germany. All MSP countries are net importers of graphite, except Germany, which remains a net exporter of synthetic graphite. Within the MSP group of countries, India, Canada, and Australia could become suppliers of natural graphite, given their significant estimated reserves.

One of the MSP's key objectives is to diversify and de-risk mineral supply chains. We find that South Korea (97%) and Japan (89%) have the highest dependence on China for their overall natural graphite imports, followed by Australia, the US and, Finland (Figure 12). Both India and Germany acquire a little over a third of their natural graphite imports from China. The least dependence on China is among the UK, Canada, Sweden, and France.

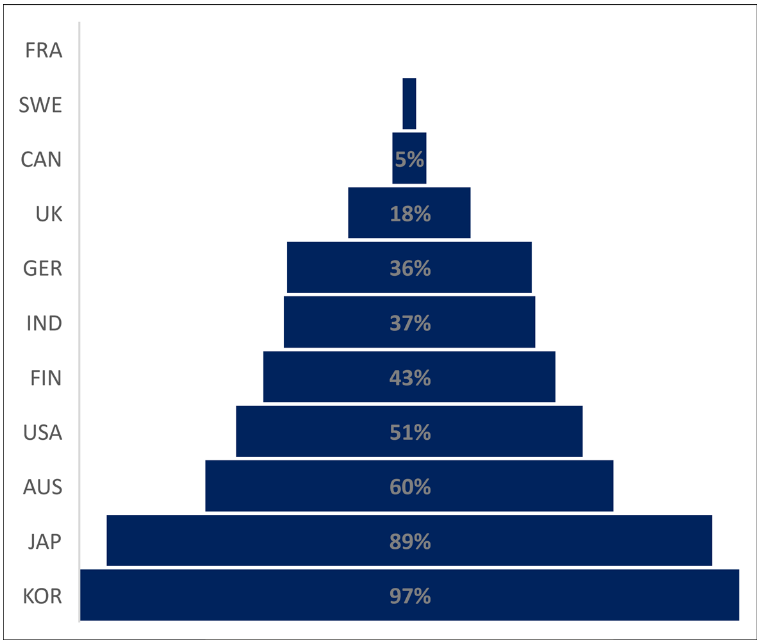

Figure 12. Share of Chinese imports of total natural graphite imports by country.

Trade data reported from Canada show that, in 2019, 73% of natural graphite imports were from China, whereas, in 2022, 93% of natural graphite imports were from the US (Figure 13, below). Total natural graphite imports have remained similar from 2019 through 2022. Given that the US has no significant natural graphite reserves, it is likely that Canada is importing a fair share from US direct imports. Trade data show that Canada imported about 53 kt of natural graphite in 2022, of which about 49 kt were imported from the US. In comparison, the US imported about 90 kt of natural graphite in 2022, which would indicate that over half of US imports went to Canada. However, the US reports exporting only about 10 kt of total natural graphite exports, with about 3 kt going to Canada. This follows the trend of reporting discrepancies from geological surveys. In this case, 46 kt of graphite trade between the US and Canada is not accounted for by trade data.

Average trade value per tonne of natural and synthetic graphite, classified as export or import value for different countries, varied from $90 to $9,113 over the study period (Table 6). China, a net exporter of graphite, has seen the value of its graphite exports increase by 12% CAGR between 2019 and 2022. China exported natural graphite at $1,574/tonne and synthetic graphite at about $2,500/tonne in 2022 while it imported synthetic graphite at about $7,700/tonne and natural graphite at about $706/tonne.

Table 6. Average global import and export value of natural and synthetic graphite for MSP countries and China.

Country	Measure	Natural ($/tonne)		Synthetic ($/tonne)		CAGR (2019-22)	
		2022	2019	2022	2019	Natural	Artificial
China	Export	1,574	1,129	2,496	1,779	12%	12%
China	Import	706	507	7,710	6,116	12%	8%
USA	Export	2,876	3,121	5,055	4,894	-3%	1%
USA	Import	2,181	1,189	3,911	5,136	22%	-9%
India	Export	653	745	1,822	1,955	-4%	-2%
India	Import	776	663	1,811	1,499	5%	7%
South Korea	Import	2,702	2,219	3,978	3,635	7%	3%
Germany	Export	1,676	1,645	2,539	2,121	1%	6%
Germany	Import	1,121	975	-	2,300	5%	-
Canada	Export	1,607	1,590	-	-	0%	-
Canada	Import	90	270	2,227	1,466	-31%	15%
Finland	Import	1,455	1,252	1,539	-	5%	-
Japan	Export	8,287	9,113	7,741	8,746	-3%	-4%
Japan	Import	1,800	1,740	1,452	1,508	1%	-1%
UK	Import	1,154	1,180	-	2,605	-1%	-
Sweden	Import	2,288	2,068	2,418	1,571	3%	15%
France	Export	2,484	6,221	3,448	3,427	-26%	0%
France	Import	976	794	2,258	1,841	7%	7%

The US, which is a net importer, had an average value of synthetic graphite exports of about $5,055/tonne. Prices of natural graphite imports have risen at 22% CAGR, reaching $2,180/tonne in 2022, while synthetic graphite import prices have come down from over $5,100/tonne in 2019 to $3,900/tonne in 2022, for the US.

Canada, which is also a net importer of graphite, saw synthetic graphite import costs increase by 15% CAGR reaching about $2,200/tonne in 2022. Canada's natural graphite exports were about $1,600/tonne in 2022.

In South and South-east Asia, both South Korea and Japan are key players in LIB manufacturing, with significant operational cell manufacturing capacity. South Korea's imports of natural graphite were about $2,700/tonne, while synthetic graphite was at about $3,980/tonne in 2022. Prices rose over the period. Japan, a key exporter of synthetic graphite, has seen prices fall but on a high base, with the 2022 average export value being about $7,740/tonne.

India, which has significant graphite potential and could be a key trading partner—especially among MSP—countries, was exporting synthetic graphite at $1,820/tonne, and natural graphite at about $650/tonne in 2022. As India begins to set up a base for LIB manufacturing, imports of natural graphite were priced around $776/tonne and synthetic graphite imports were around $1,800/tonne, seeing average import costs increase by 5 to 7% CAGR.

In Europe, France is a key exporter of synthetic graphite with stable export prices around $3,440/tonne. France's imports of graphite have seen prices increase by about 7%, with natural graphite imports at about $975/tonne and synthetic graphite imports at about $2,260/tonne. Within Europe, Sweden and Finland imported similar quantities of natural and synthetic graphite in 2022 and saw significant price differences in their imports. Sweden's landed import prices were about 1.5 times that of Finland. Finland did not import any synthetic graphite in 2019.

6.2 Natural Graphite and US IRA Compliance

The United States passed the Inflation Reduction Act (IRA) legislation in 2022. This law requires a minimum quota of value-based content in lithium-ion batteries to be sourced from eligible countries. The Act specifically requires that *"the applicable percentage of the value of the critical minerals contained in the battery must be extracted or processed in the United States or a country with which the United States has a free trade agreement, or be recycled in North America."* The percentage requirement increases from 40% in 2023 to 80% in 2027. The US Treasury has been working towards issuing further guidance on the methodology and approach to assess compliance with the regulations. More importantly, compliance with mineral content value requirements is necessary for original equipment manufacturers (OEMs) to qualify for half of the $7,500 EV tax credit while selling EVs to end-consumers. The IRA classifies graphite as a critical mineral, which is *"purified to a minimum purity of 99.9% graphitic carbon by mass."*

Lacking domestic reserves of natural graphite, the US produces synthetic graphite domestically, and this source remains the primary input for the anode of LIB cells manufactured in the US. The use of synthetic graphite is expected to increase as manufacturers aim to meet the compliance requirements of the US IRA, which will likely increase the cost of production of LIBs in the US. In 2022, as per trade data, the US imported about 51% of its natural graphite from China, followed by Mexico, Madagascar, Mozambique, and Canada (Figure 13).

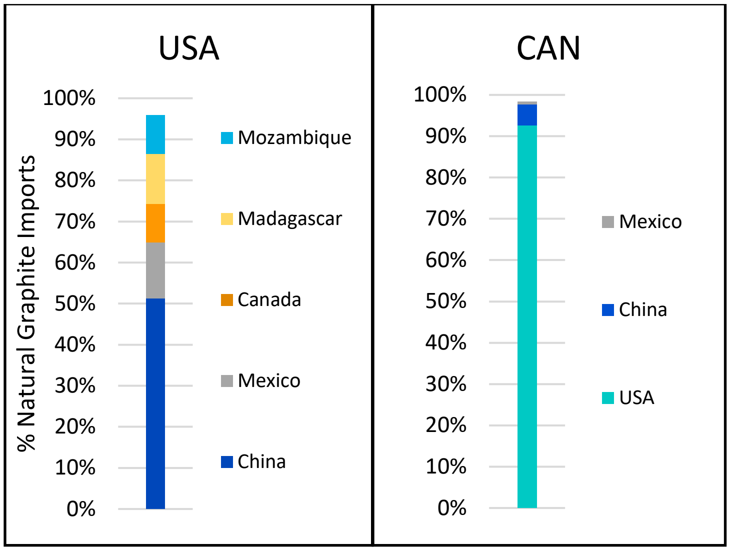

Figure 13. Share of natural graphite imports to the US and Canada in 2022.

In terms of 'compliance' sourced natural graphite, the US would have to ramp up its sourcing within North America from Canada and Mexico. These sources would, in all probability, be IRA-compliant given the assessment of procurement value chains, as proposed by the US Treasury. This would be the case as long as imported natural graphite were from mines in either Canada or Mexico.

6.3 Mineral Security Partnership Strategic Investments

As previously mentioned, the MSP Secretariat announced on October 10, 2023, seventeen strategic investments in critical minerals across upstream mining and extraction, midstream processing, and recycling. Three projects were announced on graphite including one in Mozambique (US Department of State, 2023b). Further, indicating the emerging strategic nature of graphite reserves in Mozambique, the US International Development Finance Corporation (DFC) approved a loan of $150 million to Twigg Exploration and Mining to further its graphite mining and processing in Balama, Mozambique.

The Balama mines currently have among the highest production and estimated reserves in Africa, as well as a high ore grade at around 16% (Figure 5 and Figure 6). These factors distinguish the area as a promising strategic investment location for ramping up current production rates to meet near-term natural graphite demand. Twigg's parent company is Syrah Resources. As identified in our corporate ownership analysis, Syrah Resources is headquartered in Australia (Figure 10 and Annexure III). This investment is likely to serve the graphite active anode processing facility in Louisiana, US, which has seen investment from Syrah Resources.

As OEMs aim to identify compliance mechanisms for the IRA as well as other emerging regulations in the EU, such as the recently approved Critical Raw Materials Act, the role of the MSP and potential critical mineral trade agreements will be of strategic importance to diversify supply chains. They will likely also attract greater investment both domestically and across strategic geo-political and economic partners. In the context of natural graphite, the US could leverage its other MSP partners such as India, Canada, Germany, and Norway to acquire both natural and synthetic graphite, and continue to refine and process graphite in the US to partially meet IRA compliance, as the US works towards potential trade agreements with India and Europe.

7 Global Demand for Natural Graphite and Supply Diversification Potential

Both natural and synthetic graphite supply chains can be diversified. Growing demand for graphite from clean energy transitions in the next decade could require a significant ramp-up of production and, at the same time, competing uses of graphite from non-energy sectors such as refractories and steel will continue to grow, especially among emerging and developing economies. Further, the challenge of diversifying supply streams away from China may pose additional supply risks and price challenges.

Various studies such as the IEA Critical Minerals assessment (2023), estimate graphite demand from EV battery demand. However, they do not estimate natural and synthetic graphite demand for specific end-uses.

We estimate graphite demand, both natural and synthetic, that will be likely required across sectors. From this basis, we consider:

(1) the global demand for natural graphite across both energy and non-energy use, and

(2) synthetic graphite demand for LIBs through 2035, and then

(3) explore potential supply diversification strategies.

Total graphite demand may be higher than our estimates, as we have not estimated synthetic graphite needed for non-LIB applications. Input data are from Benchmark Minerals Intelligence (2023), IEA Critical Minerals Explorer (2023), EV-Volumes (2023) and Dunn et al. (2021b).

7.1 Total Graphite Demand

We estimate that total graphite demand will be about 7,334 kt in 2035, growing at 11.6% CAGR between 2022 and 2035—an increase of about 4.2 times (Figure 14). In 2022, graphite demand from LIBs accounted for about 36% of global graphite demand. By 2035, LIBs are expected to contribute 78% of global graphite demand.

7.2 Natural Graphite Demand

Global natural graphite demand is expected to grow about three times by 2035 compared to 2022, with LIB-based natural graphite demand contributing 59% in 2035, as compared to 18% in 2022 (Figure 14). Total natural graphite demand is expected to reach a little over 4,000 kt in 2035 compared to 1,742 kt in 2025.

7.3 Lithium-ion Battery Graphite Demand from All Sectors

This analysis estimates demand from EV, Energy Storage Solutions, and from Portables / Consumer electronics. For 2022, we estimate the total graphite demand for all LIB cells was around 640 kt, of which about 38% (or 244 kt) came from natural graphite, and the remaining from synthetic graphite. For comparison, the IEA estimates a demand of 557 kt for EV batteries only in 2022.

Assuming global production is equal to demand, natural graphite demand for LIBs made up only 18% of natural graphite demand in 2022, and the balance was from other sectors including non-energy applications.

7.4 Graphite Demand Forecast and Diversification

For graphite forecast estimates through 2035, we use the following assumptions:

(1) Non-LIB demand of natural graphite grows at differential rates for developed and developing countries. While global GDP is estimated to grow at about 3% annually based on long-term IMF estimates, developing countries are expected to grow faster. While the US and Europe growth projections are estimated around 1.5 to 2% in the long term, the growth rates for Asia, Latin America and Sub-Saharan Africa are estimated between 3 and 5%, and

(2) LIB demand for natural graphite based on total LIB cell demand from BMI data, with mineral content assumptions for different battery chemistries drawn from Kendall (2020).

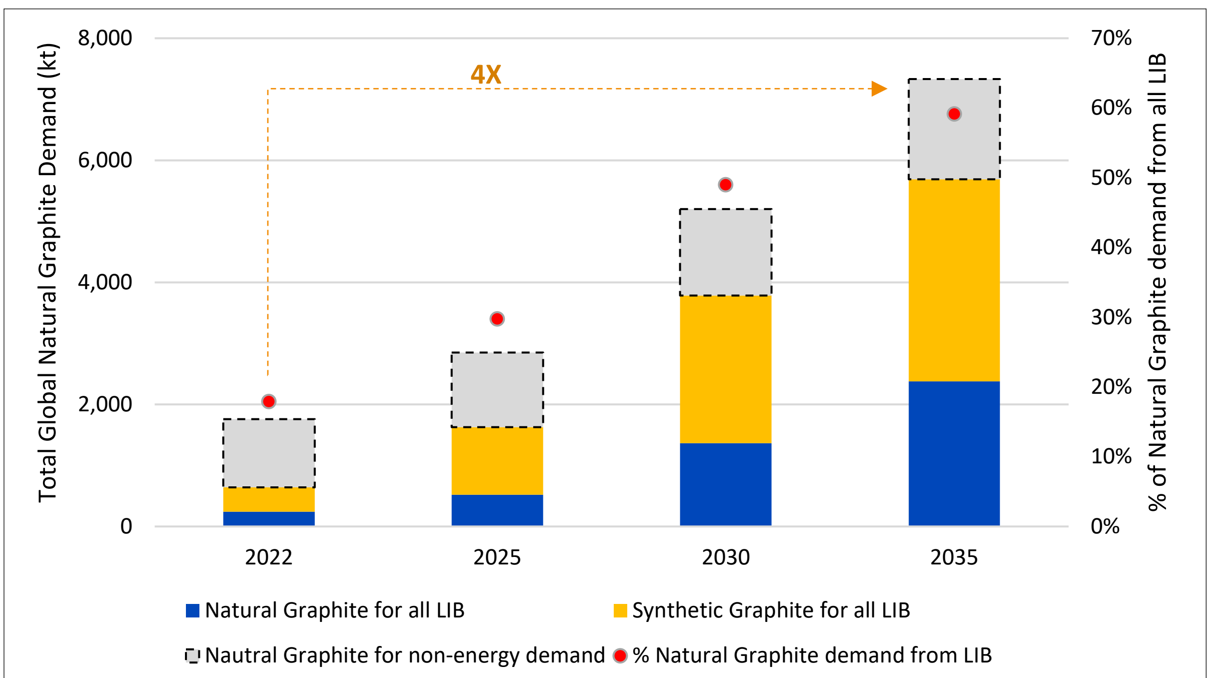

Figure 14. Estimated increases in global graphite demand from 2022-2035.

To further understand natural graphite production scenarios needed to meet estimated demand from resource-rich countries, we construct a business-as-usual scenario, wherein we assume that all countries retain their 2022 production shares through 2035. In light of recent graphite export restrictions from China and the focus on supply diversification, we assess alternative scenarios including:

(1) a 50% reduction in China's production,

(2) curtailed production from Russia given the ongoing conflict with Ukraine, and

(3) the opportunity for diversification among MSP network countries.

We present one key scenario here, where Chinese-produced graphite drops by 50% and MSP network countries and friendly nations, including Mozambique, Brazil, Madagascar, India, Canada, Mexico, and Tanzania ramp-up production to compensate. We find that China remains the largest producer with a 31% share, followed by Mozambique (23%), Madagascar (15%), Brazil (12%), India (8%), and then others (Figure 15).

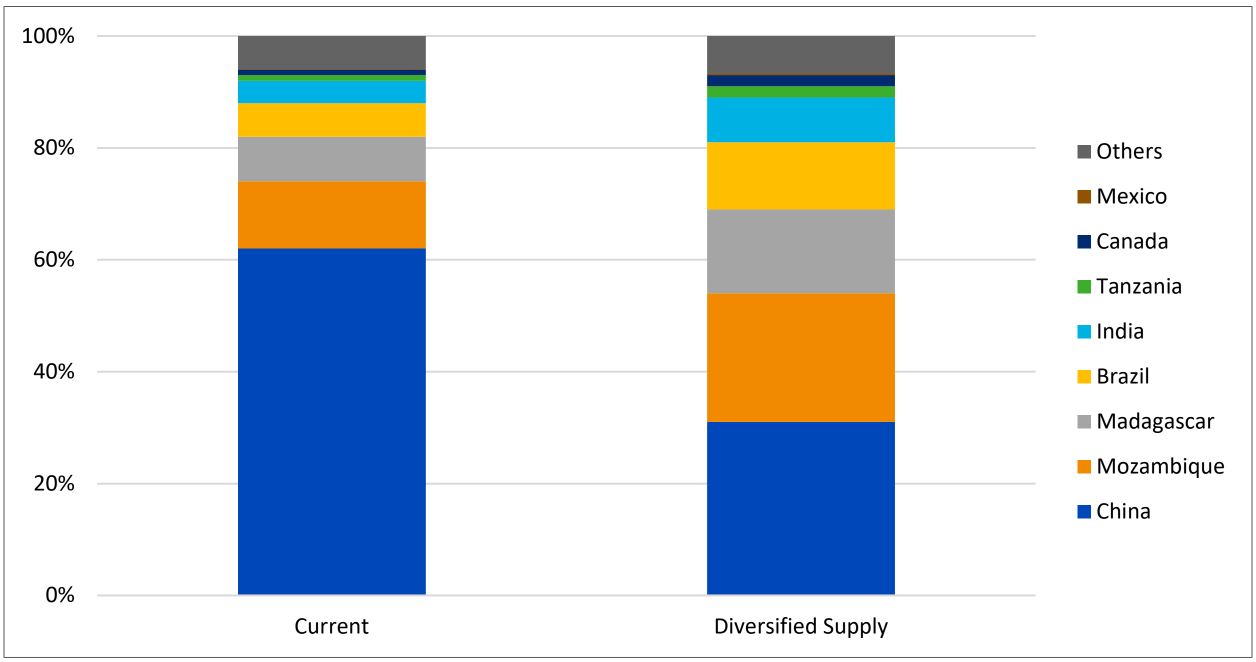

Figure 15. Potential for global supply diversification of natural graphite from 2022 to 2035.

With various geo-political efforts from the US-led MSP, the QUAD countries (US, Australia, Japan, and India), and the recently announced "critical minerals club" initiated by the EU Critical Raw Materials Act, there will be a focus on supply diversification for critical minerals including graphite. As already noted, the EU has listed both natural and synthetic graphite as a critical mineral.

India emerges as a key player in this landscape, given its participation in both the MSP and the QUAD. Australia, which is yet to commercialize its graphite reserves, will also remain a key potential partner as part of this supply diversification strategy. Brazil, which also participates in global graphite value chains similar to India, has the potential to ramp-up production for natural graphite, and takes significance as it will host both the G20 Presidency for 2024 and the COP30 Presidency in 2025. In Africa, apart from

Madagascar and Mozambique, Tanzania has potential as well, especially given its better performance across governance rankings. Overall, Brazil, India and Tanzania have better governance rankings as compared to Mozambique and Madagascar.

From only a resource security perspective, given the unique confluence of MSP partner countries, the MSP Investment Network countries as well as the dominance of Australian, Canadian and UK-based corporations in graphite mining, varied possibilities for alliances and pathways for supply diversification emerge, especially from the context of the US and the EU.

8 Environment, Social Equity, and Government Transparency

Environmental and social equity concerns for graphite mining are not well researched (Driver et al., 1993). This may be due to the focus on equity in relation to other critical minerals such as Lithium, Cobalt, and Nickel. What we do know about graphite mining points to the value of production standards in a new era of mining.

8.1 Environmental Impacts

Several studies have looked at the environmental effects of graphite mining. Pollution of water and air due to mineral dust and process inputs like hydrofluoric acid from Chinese spherical graphite production have been identified (Engels et al., 2022; Huang et al., 2022; Yang et al., 2017; L. Zhang et al., 2014). These studies have also found evidence of high levels of lead and mercury among other pollutants in the soil and water streams from graphite mining. Responsible mining principles adopted by MSP members include encouraging mining operations to “demonstrate responsible stewardship of the natural environment.” This includes water resources, air quality, biodiversity, and other natural resources, all of which merit more research. This same MSP principle states that responsible stewardship extends beyond communities to include global effects from greenhouse gas emissions.

8.2 Energy Inputs

Production of synthetic graphite is estimated to require about 7,500 kWh per tonne compared to 2,500 kWh per tonne for natural graphite (AMG Graphite, 2015). Synthetic graphite’s basic raw materials consist of petroleum coke and coal tar pitch, coproducts of the fossil fuel sector. The current interdependency between synthetic graphite and carbon fuels is concerning. It means that a key material input for decarbonization is inextricably linked with the continued operation of the fossil fuel industry. Even more troublesome, this means that there is a risk of decreasing availability of synthetic graphite as the fossil fuel industry shrinks. There are other, potentially renewable, carbon sources for synthetic graphite. For example, biomass could serve as a raw material (J. Zhang et al., 2023b). However, no commercial production from these pathways currently exists (Banek et al., 2022).

8.3 Health Impacts

Research on the health effects of graphite mining and processing focuses on a condition called graphite pneumoconiosis. This lung disease is characterized by inflammation, coughing, and fibrosis from inhaling graphite dust. It can lead to mortality (Gaensler et al., 1966; Hanoa, 1983). Postmortem examinations of graphite workers describe the lungs as indistinguishable from coal workers with progressive massive fibrosis (Akira & Suganuma, 2023). Furthermore, the dust can transmigrate within the body causing other health impairments (Driver et al., 1993). This concerning for workers who have long term exposure to high concentrations of mineral dust and also for communities located near mines or processing facilities. Reducing the harm to workers and communities exposed to graphite dust should be a priority for companies to “ensure safe, fair, inclusive, and ethical conditions in the workplace and promote the same in communities,” as indicated by the MSP’s Statement on Responsible Mining.

8.4 Equity

Most graphite production occurs in developing nations that have low to middle range governance scores with regards to parameters such as economic status, political stability, government effectiveness, regulatory quality and control of corruption (Section 5.1). There is an opportunity for Global South countries to benefit from well-regulated mining, but many of these countries have a history of economically, socially, and environmentally exploitative resource extraction. This is especially true in Africa where international alliances like the MSP and industry are currently focusing investments.

Countries with above average governance indicator scores that produce graphite tend to be net graphite importers. This indicates that much of the graphite produced in developing nations is used in developed nations that do not experience the impacts of mining and processing to the same degree. Countries that score high in governance indicators and are key exporters, like Germany and Norway, tend to export synthetic graphite as opposed to natural graphite. Given the different processes to produce synthetic vs. natural graphite, there is a need to estimate the compensation for pollution attribution, which can have impacts on regulatory policy for sustainable value chains.

The financial benefits of natural graphite mining, compared to the burdens, are skewed to benefit developed countries. Australian, Canadian, and British companies, in particular, will financially benefit from mining projects that are planned in Africa, given their strong presence in mining operations. This means that, not only are natural graphite resources leaving developing nations in Africa–the profits are, too.

Principles for Responsible Critical Minerals outlined by the MSP state that projects should provide “economic benefit for local communities, including through local employment, local sourcing, and corporate social responsibility measures.” However, without mandatory regulatory requirements and a clear intent of international policy to result in greater value-addition in the country where the resource is located, mining is unlikely to benefit communities near mines.

Brazilian and Indian companies are well-represented in the company analysis. All of the operations of these companies occur in their home country so, even if resources are exported, the financial benefits remain in the country. However, this does not necessarily mean that mining results in benefits to local communities. Thus, these countries would also benefit from best practices in terms of environmental and social regulations with regards to mining.

8.5 Transparency

Tracking data at both the mine-level as well as global trade flows is difficult, partly due to discrepancies between reporting bodies. Geological surveys often report varying production and reserve amounts for the same country in the same year, most notably for Mozambique, Canada, South Korea, Austria, and Turkey. Trade data also contain discrepancies, as with US exports to Canada, wherein about 46 kt of graphite are unaccounted for. Mine-level data were extremely difficult to find. Simply locating mines and determining their names is difficult, which makes it challenging to find documents associated with them.

The MSP indicates "transparent and ethical business operations" are a core principle for responsible CRM supply chains. If transparency is important, more access to basic information about mining operations should be available for researchers, policy makers, communities and investors. A standard reporting system for mine and country level operations would make comprehension and assessment much clearer and also enable more accurate evaluation of ESG and equity considerations.

9 Summary and Next Steps

At the recently concluded COP28 in December 2023, there was a significant push for enhanced climate action acknowledging that current country efforts are not sufficient to meet the 1.5°C target. This will require a rapid scale-up of clean energy technologies in the next decade. Significant effort will be needed to make these technologies accessible and affordable to developing countries, for many of whom the cost of the impending energy transition already is a barrier. This speed and scale, in turn, puts pressure on supply chains, requiring production ramp-ups in existing mines, additional exploration, and new mining to meet accelerated demand requirements in a climate-constrained time frame.

The analysis in this paper of resource availability, market dynamics and demand forecast for graphite provides analytical insights and highlights key policy considerations.

We estimate that total graphite demand will be about 7,334 kt in 2035, growing at 11.6% CAGR between 2022 and 2035—an increase of about 4.2 times. In 2022, graphite demand from LIBs accounted for about 36% of global graphite demand. By 2035, LIBs are expected to contribute 78% of global graphite demand.

9.1 Limits and Opportunities

Overall, geographical availability is likely to be the predominant limiting factor in graphite supply, rather than average grade of deposits. Potential countries that could add to global supply include Brazil, India, Tanzania, Madagascar, Mozambique, who are already producing graphite but could increase their pace, given their sizeable reserves. Mexico, Australia, Vietnam, and Namibia also have the potential to ramp-up production. India emerges as a key player in this landscape as a participant in both the MSP and the QUAD.

Among potential alternative sources to China for both natural and synthetic graphite, we find that Germany, Norway, Canada, and India are already MSP members, while Mozambique, Madagascar and Tanzania are being considered by MSP countries as key investment destinations for expanding graphite production. With Brazilian synthetic graphite exports more than doubling, and with its significant natural graphite reserves, it will also be a location of interest.

9.2 Equity and the Environment

We should be careful in in ensuring that the speed and scale of graphite production is not at the cost of environmental and social compliance. Most graphite production occurs in developing nations that have low to middle range governance scores with regards to parameters such as economic status, political stability, government effectiveness, regulatory quality and control of corruption. There is an opportunity for Global South countries to benefit from well-regulated mining, but many of these countries have a history of economically, socially, and environmentally exploitative resource extraction. This is especially true in Africa where international alliances like the MSP and industry are currently focusing investments. We do find that some of the developing countries like Brazil, India and Tanzania have better governance indicators as compared to Mozambique and Madagascar.

Although the MSP countries have committed to sustainable mining through their investments in Africa, these are voluntary commitments and are not enforceable. MSP member countries, especially the US, Australia, and Canada who have significant corporations and capital being deployed in Africa and Latin America for mining, can play a key role in ensuring that their companies meet certain compliance standards even as part of their overseas operations, which could be rewarded through market mechanisms through the domestic market regulator.

There needs to be a larger international framework on how international trade and critical minerals need to be dealt with. A resource competition should not leave developing countries, especially producer countries, as just raw material suppliers but also benefit from downstream diversification and economic value add.

9.3 Developing a Cohesive Strategy

As EV manufacturers aim to identify compliance mechanisms for the US IRA as well as other emerging regulations in the EU, such as the recently approved Critical Raw Materials Act, the role of the MSP and potential critical mineral trade agreements will be of strategic importance to diversify supply chains. They will likely also attract greater investment both domestically and across strategic geo-political and economic partners.

Lacking domestic reserves of natural graphite, the US produces synthetic graphite domestically, and this source remains the primary input for the anode of LIB cells manufactured in the US. The use of synthetic graphite is expected to increase as manufacturers aim to meet the compliance requirements of the US IRA, which will likely increase the cost of production of LIBs in the US. At the same time, it should be noted that synthetic graphite has a higher environmental footprint compared to natural graphite.

In terms of 'IRA compliant' sourced natural graphite, the US would have to ramp up its sourcing within North America from Canada and Mexico in the short to medium term. These sources would, in all probability, be IRA-compliant given the assessment of procurement value chains, as proposed by the US Treasury. While Mexico is estimated to have about 3.1 MT of natural graphite reserves, it does not indicate any recorded exports.

We expect that, as mineral exploration increases, new graphite deposits will be identified. To ensure sustainable mining practices and ESG compliance while accelerating critical mineral production, we need greater data sharing between agencies, more transparency in mine-level data and ownership patterns, and comprehensive geological surveys—especially in developing countries.

References

Abdelilah, Y., Bahar, H., Criswell, T., Bojek, P., Briens, F., Moorhouse, J., & Martinez, L. M. (2023). *Renewable Energy Market Update - June 2023*.

Akira, M., & Suganuma, N. (2023). Imaging diagnosis of pneumoconiosis with predominant nodular pattern: HRCT and pathologic findings. *Clinical Imaging*, *97*, 28–33. https://doi.org/10.1016/j.clinimag.2023.02.010

AMG Graphite. (2015). *AMG Investor Day Graphite Presentation*. https://amg-nv.com/wp-content/uploads/Graphite-2015-Investor-Day-Presentation-FINAL.pdf

Austrian Federal Ministry of Finance. (2023). *World Mining Data 2023*. https://www.world-mining-data.info/?World_Mining_Data

Banek, N. A., McKenzie, K. R., Abele, D. T., & Wagner, M. J. (2022). Sustainable conversion of biomass to rationally designed lithium-ion battery graphite. *Scientific Reports*, *12*(1), 8080. https://doi.org/10.1038/s41598-022-11853-x

Barich, A. (2022, May 11). *Ukraine aims to become major graphite supplier — when the war ends*. S&P Global. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/ukraine-aims-to-become-major-graphite-supplier-8212-when-the-war-ends-70113612

Benchmark Mineral Intelligence. (2023, September 6). *More than 300 new mines required to meet battery demand by 2035*. BMI. https://source.benchmarkminerals.com/article/more-than-300-new-mines-required-to-meet-battery-demand-by-2035

Benson, E., & Denamiel, T. (2023, October 23). China's New Graphite Restrictions. *Center for Strategic & International Studies*. https://www.csis.org/analysis/chinas-new-graphite-restrictions

BMI. (2023). *Benchmark Minerals Intelligence Database*. BMI Lithium-Ion Battery Database.

Collins, G. A., Geaney, H., & Ryan, K. M. (2021). Alternative anodes for low temperature lithium-ion batteries. *Journal of Materials Chemistry A*, *9*(25), 14172–14213. https://doi.org/10.1039/D1TA00998B

Council of the European Union. (2022). *Towards a sustainable, circular, European battery supply chain*. European Council. https://www.consilium.europa.eu/en/infographics/battery-supply-chain/

Deady, E., Goodenough, K., Currie, D., Lacinska, A., Grant, H., Patton, M., Cooper, M., Josso, P., Shaw, R., Everett, P., & Bide, T. (2023). *Potential for Critical Raw Material Prospectivity in the UK*. https://ukcmic.org/downloads/reports/ukcmic-potential-for-critical-raw-material-prospectivity-in-the-uk-cr23024.pdf

Department of Economic and Social Affairs. (2023). *UN Comtrade Database*. UN Comtrade. https://comtradeplus.un.org/

Notice of Final Determination on 2023 DOE Critical Materials List, Pub. L. No. 88 FR 51792, US DOE (2023). https://www.federalregister.gov/documents/2023/08/04/2023-16611/notice-of-final-determination-on-2023-doe-critical-materials-list

Driver, C. J., Ligotke, M. W., Landis, W. G., Downs, J. L., Tiller, B. L., Moore, E. B. Jr., & Cataldo, D. A. (1993). *Environmental and health effects review for obscurant graphite flakes. Final report, 1991 July--1993 May*. https://doi.org/10.2172/10182257

Duan, S., Wu, X., Wang, Y., Feng, J., Hou, S., Huang, Z., Shen, K., Chen, Y., Liu, H., & Kang, F. (2023). Recent progress in the research and development of natural graphite for use in thermal management, battery electrodes and the nuclear industry. *Carbon*, *206*, 434–435. https://doi.org/10.1016/j.carbon.2023.02.028

Dunn, J., Slattery, M., Kendall, A., Ambrose, H., & Shen, S. (2021a). Circularity of Lithium-Ion Battery Materials in Electric Vehicles. *Environmental Science & Technology*, *55*(8), 5189–5198. https://doi.org/10.1021/acs.est.0c07030

Dunn, J., Slattery, M., Kendall, A., Ambrose, H., & Shen, S. (2021b). Circularity of Lithium-Ion Battery Materials in Electric Vehicles. *Environmental Science & Technology*, *55*(8), 5189–5198. https://doi.org/10.1021/acs.est.0c07030

Engels, P., Cerdas, F., Dettmer, T., Frey, C., Hentschel, J., Herrmann, C., Mirfabrikikar, T., & Schueler, M. (2022). Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data. *Journal of Cleaner Production*, *336*, 130474. https://doi.org/10.1016/j.jclepro.2022.130474

European Commission. (2020, July). *A hydrogen strategy for a climate-neutral Europe*. European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

European Commission. (2023, March 16). *Establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020*. EU Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0160

EV Volumes. (2023, September). *EV Volumes*. EV Volumes. https://www.ev-volumes.com/

Fan, L., Tu, Z., & Chan, S. H. (2021). Recent development of hydrogen and fuel cell technologies: A review. *Energy Reports*, *7*, 8421–8446. https://doi.org/10.1016/j.egyr.2021.08.003

Gaensler, E. A., Cadigan, J. B., Sasahara, A. A., Fox, E. O., & MacMahon, H. E. (1966). Graphite pneumoconiosis of electrotypers. *The American Journal of Medicine*, *41*(6), 864–882. https://doi.org/10.1016/0002-9343(66)90046-5

Geoscience Australia. (2023, December). *Graphite*. Australian Government. https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/graphite

Hanoa, R. (1983). Graphite pneumoconiosis. A review of etiologic and epidemiologic aspects. *Scandinavian Journal of Work, Environment & Health*, *9*(4), 303–314. https://doi.org/10.5271/sjweh.2407

Huang, S., Wang, W., Cui, Q., Song, W., & Jiao, S. (2022). Assessment of Spherical Graphite for Lithium-Ion Batteries: Techniques, China's Status, Production Market, and Recommended Policies for Sustainable Development. *Advanced Sustainable Systems*, *6*(11). https://doi.org/10.1002/adsu.202200243

Hund, K., Porta, D. La, Fabregas, T. P., Laing, T., & Drexhage, J. (2020). *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*. https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf

Idoine, N. E., Raycraft, E. R., Price, F., Hobbs, S. F., Deady, E. A., Everett, P., Shaw, R. A., Evans, E. J., & Mills, A. J. (2023). *World mineral production 2017-21*. https://nora.nerc.ac.uk/id/eprint/534316/

International Energy Agency. (2022, October). *National Plan for Mineral Resources (2016-2020)*. IEA. https://www.iea.org/policies/15519-national-plan-for-mineral-resources-2016-2020

International Energy Agency. (2023a, January). *Hydrogen Industry Development Plan (2021-2035)*. IEA. https://www.iea.org/policies/16977-hydrogen-industry-development-plan-2021-2035

International Energy Agency. (2023b, July 11). *Critical Minerals Data Explorer*. IEA. https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer

Kaufmann, D., & Kraay, A. (2023). *Worldwide Governance Indicators 2023*. https://www.govindicators.org/

Kurzweil, P. (2015). Lithium Battery Energy Storage. In *Electrochemical Energy Storage for Renewable Sources and Grid Balancing* (pp. 269–307). Elsevier. https://doi.org/10.1016/B978-0-444-62616-5.00016-4

Lebrouhi, B. E., Baghi, S., Lamrani, B., Schall, E., & Kousksou, T. (2022). Critical materials for electrical energy storage: Li-ion batteries. *Journal of Energy Storage*, *55*, 105471. https://doi.org/10.1016/j.est.2022.105471

Lee, C., Han, Y.-J., Seo, Y. D., Nakabayashi, K., Miyawaki, J., Santamaría, R., Menéndez, R., Yoon, S.-H., & Jang, J. (2016). C4F8 plasma treatment as an effective route for improving rate performance of natural/synthetic graphite anodes in lithium-ion batteries. *Carbon*, *103*, 28–35. https://doi.org/10.1016/j.carbon.2016.02.060

Minos, S. (2023, February 28). *How lithium-ion batteries work*. US Department of Energy. https://www.energy.gov/energysaver/articles/how-lithium-ion-batteries-work#:~:text=The%20Basics,vice%20versa%20through%20the%20separator

Mundszinger, M., Farsi, S., Rapp, M., Golla-Schindler, U., Kaiser, U., & Wachtler, M. (2017). Morphology and texture of spheroidized natural and synthetic graphites. *Carbon*, *111*, 764–773. https://doi.org/10.1016/j.carbon.2016.10.060

Natural Resources Canada. (2023, February 28). *Graphite facts*. NRCan. https://natural-resources.canada.ca/our-natural-resources/minerals-mining/minerals-metals-facts/graphite-facts/24027

Northern Graphite Corporation. (2020). *The Graphite Supply Problem*. Northern Graphite Corporation. https://www.northerngraphite.com/about-graphite/the-graphite-supply-problem/

Novák, P., Joho, F., Lanz, M., Rykart, B., Panitz, J.-C., Alliata, D., Kötz, R., & Haas, O. (2001). The complex electrochemistry of graphite electrodes in lithium-ion batteries. *Journal of Power Sources*, *97–98*, 39–46. https://doi.org/10.1016/S0378-7753(01)00586-9

Office of Clean Energy Demonstrations. (2023). *Regional Clean Hydrogen Hubs*. US Department of Energy. https://www.energy.gov/oced/regional-clean-hydrogen-hubs

Raj, K., Lakhina, P., & Stranger, C. (2022). *Harnessing Green Hydrogen: Opportunities for Deep Decarbonization in India*. https://rmi.org/insight/harnessing-green-hydrogen/

Ren, J.-G., Wu, Q.-H., Hong, G., Zhang, W.-J., Wu, H., Amine, K., Yang, J., & Lee, S.-T. (2013). Silicon-Graphene Composite Anodes for High-Energy Lithium Batteries. *Energy Technology*, *1*(1), 77–84. https://doi.org/10.1002/ente.201200038

Robinson Jr., G. R., Hammarstrom, J. M., & Olson, D. W. (2017). *Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply*. https://pubs.usgs.gov/publication/pp1802J

Rui, X., Geng, Y., Sun, X., Hao, H., & Xiao, S. (2021). Dynamic material flow analysis of natural graphite in China for 2001-2018. *Resources, Conservation and Recycling*, *173*, 105732. https://doi.org/10.1016/j.resconrec.2021.105732

Shaw, S. (2013, April). Graphite demand growth: the future of lithium-ion batteries in EVs and HEVs. *37th ECGA General Assembly*. http://saintjeancarbon.com/data/graphite-research-articles/Graphite_demand_Li-ions_April_2013.pdf

Shi, M., Song, C., Tai, Z., Zou, K., Duan, Y., Dai, X., Sun, J., Chen, Y., & Liu, Y. (2021). Coal-derived synthetic graphite with high specific capacity and excellent cyclic stability as anode material for lithium-ion batteries. *Fuel*, *292*, 120250. https://doi.org/10.1016/j.fuel.2021.120250

Simon, B., Flandrois, S., Guerin, K., Fevrier-Bouvier, A., Teulat, I., & Biensan, P. (1999). On the choice of graphite for lithium-ion batteries. *Journal of Power Sources*, *81–82*, 312–316. https://doi.org/10.1016/S0378-7753(99)00211-6

Steele, B. C. H., & Heinzel, A. (2001). Materials for fuel-cell technologies. *Nature*, *414*(6861), 345–352. https://doi.org/10.1038/35104620

Stewart, A. A. (2023). *Mineral Commodity Survey 2023: Graphite (Natural)*. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-graphite.pdf

Summerfield, D. (2019). *Australian Resource Reviews: Graphite 2018*. https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/graphite

US Department of State. (2023a). *Minerals Security Partnership (MSP) Principles for Responsible Critical Mineral Supply Chains*. https://www.state.gov/wp-content/uploads/2023/02/MSP-Principles-for-Responsible-Critical-Mineral-Supply-Chains-Accessible.pdf

US Department of State. (2023b, October 10). *Joint Statement on the Minerals Security Partnership Announce Support for Mining, Processing, and Recycling Projects*. US Department of State. https://www.state.gov/joint-statement-on-the-minerals-security-partnership-announce-support-for-mining-processing-and-recycling-projects/

US Geological Survey. (2000). *Graphite*. https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/graphite/310300.pdf

US Geological Survey. (2017). *Mineral Commodities Summary 2017*. https://pubs.usgs.gov/publication/70180197

US Geological Survey. (2020). *MINERAL COMMODITY SUMMARIES 2020*. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf

Weber, L. (2023). On the security of graphite supply. *Mineralogy and Petrology*, *117*(2), 387–399. https://doi.org/10.1007/s00710-023-00816-3

World Bank. (2023). *World Development Indicators 2022*. https://datatopics.worldbank.org/world-development-indicators/the-world-by-income-and-region.html#:~:text=The%20World%20Bank%20classifies%20economies,%2Dmiddle%2C%20and%20high%20income.

Xing, B., Zhang, C., Cao, Y., Huang, G., Liu, Q., Zhang, C., Chen, Z., Yi, G., Chen, L., & Yu, J. (2018). Preparation of synthetic graphite from bituminous coal as anode materials for high performance lithium-ion batteries. *Fuel Processing Technology*, *172*, 162–171. https://doi.org/10.1016/j.fuproc.2017.12.018

Yang, Q., Geng, Y., Dong, H., Zhang, J., Yu, X., Sun, L., Lu, X., & Chen, Y. (2017). Effect of environmental regulations on China's graphite export. *Journal of Cleaner Production*, *161*, 327–334. https://doi.org/10.1016/j.jclepro.2017.05.131

Ye, Z.-H., Li, Y.-K., & Yang, X. (2017). An Analysis on Chinese Graphite Resource and Its Development Suggestions. In *ESSE 2017* (pp. 395–400). De Gruyter. https://doi.org/10.1515/9783110540048-041

Yu, S., Zhou, P., Hao, J., & Zhou, Y. (2023). Research progress of functionalized graphite oxide based alkaline anion exchange membrane for fuel cells. *Polymer*, *283*, 126256. https://doi.org/10.1016/j.polymer.2023.126256

Zhang, J., Liang, C., & Dunn, J. B. (2023a). Graphite Flows in the U.S.: Insights into a Key Ingredient of Energy Transition. *Environmental Science & Technology*, *57*(8), 3402–3414. https://doi.org/10.1021/acs.est.2c08655

Zhang, J., Liang, C., & Dunn, J. B. (2023b). Graphite Flows in the U.S.: Insights into a Key Ingredient of Energy Transition. *Environmental Science & Technology*, *57*(8), 3402–3414. https://doi.org/10.1021/acs.est.2c08655

Zhang, L., Liu, X., Wan, H., & Liu, X. (2014). *Luobei graphite mines surrounding ecological environment monitoring based on high-resolution satellite data* (A. M. Larar, M. Suzuki, & J. Wang, Eds.; p. 92632N). https://doi.org/10.1117/12.2069232

Zhao, L., Ding, B., Qin, X., Wang, Z., Lv, W., He, Y., Yang, Q., & Kang, F. (2022). Revisiting the Roles of Natural Graphite in Ongoing Lithium-Ion Batteries. *Advanced Materials*, *34*(18). https://doi.org/10.1002/adma.202106704

Annexure I: World Governance Indicators – Definitions

Indicator	Definition
Voice and Accountability	Reflects perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media.
Political Stability	Political Stability and Absence of Violence/Terrorism measures perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism.
Govt Effectiveness	Reflects perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.
Regulatory Quality	Reflects perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development.
Rule of Law	Reflects perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.
Control of Corruption	Reflects perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests.

Annexure II: World Governance Indicators - Country Percentile Ranks

Country	Economic Status by Income	Voice and Accountability	Political Stability	Govt Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption	Avg. Rank
Norway	High	100	76	98	92	98	98	94
Canada	High	96	74	94	96	93	93	91
Germany	High	95	67	88	92	92	96	88
Austria	High	94	69	92	87	96	85	87
South Korea	High	75	65	90	84	85	77	79
Namibia	Upper Middle	63	64	55	52	63	61	60
India	Lower Middle	49	25	63	51	55	44	48
Vietnam	Lower Middle	14	46	59	36	48	46	41
China	Upper Middle	6	28	68	37	53	55	41
Brazil	Upper Middle	56	34	31	44	43	32	40
Sri Lanka	Lower Middle	40	19	36	27	52	40	36
Tanzania	Lower Middle	30	37	34	30	38	43	35
Türkiye	Upper Middle	23	14	44	43	37	35	33
Mexico	Upper Middle	42	22	42	47	21	17	32
Ukraine	Lower Middle	46	6	33	41	19	29	29
Madagascar	Low	38	26	15	21	18	18	23
Mozambique	Low	32	11	25	23	17	22	22
Pakistan	Lower Middle	25	7	29	20	25	23	21
Russia	Upper Middle	14	16	26	13	12	19	17
Zimbabwe	Lower Middle	19	17	11	7	11	8	12
North Korea	Low	0	30	7	0	5	2	7

**Blue highlight indicates high supply potential countries*

Annexure III: Mine-wise details of tracked projects

Name	Mine Project Location	Operating Status	Production (ktpa)	Reserves (kt)	Grade (%Gr)	Owner Type	Owning Company	Company Location
Nicanda Hill	Mozambique	Exploration	-	1,400,000	11.10%	private	Triton	United Kingdom
Antsirakambo	Madagascar	Active	4.80	240,000	10.00%	private	Etablissements Gallois	France
Marovintsy	Madagascar	Active	3.60	240,000	10.00%	private	Etablissements Gallois	France
Itapecerica	Brazil	Active	90.00	209,600	9.79%	private	Nacional de Grafita	Brazil
Bekeka	Ethiopia	Exploration	-	150,000	7.10%	-	-	-
Bunyu	Tanzania	Project Development	23.70	127,000	4.40%	private	Volt Resources	Australia
Balama	Mozambique	Active	350.00	110,000	16.00%	private	Syrah Resources	Australia
Mateus Leme	Brazil	Active	2.00	91,700	14.00%	private	JMN Mineração	Brazil
Duwi	Malawi	Exploration	110.00	85,900	7.10%	private	Sovereign Metals	Australia
Nachu	Tanzania	Exploration	130.00	76,000	4.80%	private	Magnis Energy Technologies	Australia
Mahenge	Tanzania	Project Development	340.00	70,000	8.50%	private	Blackrock Mining	Australia
Salto de Divisa	Brazil	Active	6.00	52,000	10.00%	private	Nacional de Grafite	Brazil
Montepuez	Mozambique	Exploration	100.00	41,400	8.80%	private	Battery Minerals	Australia
Lola	Guinea	Exploration	94.00	41,000	4.14%	private	SRG mining inc	Canada
Peresopolis	Brazil	Exploration	-	40,000	12.00%	-	-	-
Pula	Tanzania	Exploration	40.00	34,700	6.13%	private	Pula Group	United States
Maiquinique	Brazil	Active	54.00	33,300	9.60%	private	Grafite do Brasil	Brazil
Nicanda West	Mozambique	Exploration	-	30,000	6.60%	private	Triton	United Kingdom
Bissett Creek	Canada	Project Development	20.00	28,300	2.06%	private	Northern Graphite	Canada

Name	Mine Project Location	Operating Status	Production (ktpa)	Reserves (kt)	Grade (%Gr)	Owner Type	Owning Company	Company Location
Balama Central	Mozambique	Exploration	110.00	26,600	10.30%	private	Battery Minerals	Australia
Ancuabe 2	Mozambique	Active	60.00	24,900	6.20%	private	Triton	United Kingdom
Orom-Cross	Uganda	Project Development	101.00	24,500	6.00%	private	Blencowe	United Kingdom
Okanjande	Namibia	Active	31.00	24,200	3.10%	private	Northern Graphite	Canada
Maniry	Madagascar	Project Development	30.00	20,200	6.51%	private	BlackEarth Minerals	Australia
Graphmada	Madagascar	Active	11.80	20,200	4.00%	private	Bass Metals	Canada
Pedra Azul	Brazil	Active	90.00	19,100	12.29%	private	Nacional de Grafita	Brazil
Vatomina	Madagascar	Exploration	6.00	18,400	4.50%	private	Tirupati Graphite	United Kingdom
Merelani	Tanzania	Active	6.00	17,700	6.50%	private	EcoGraf Resources	Australia
Kambale	Ghana	Exploration	-	15,611	9.00%	private	Castle Minerals	Australia
Nipacue	Mozambique	Exploration	9.00	14,360	6.50%	private	AMG Graphite	Germany
MOLO	Madagascar	Exploration	17	14,170	7.00%	private	Next Source Materials	Canada
Kibre Mengist	Ethiopia	Exploration	-	11,000	9.60%	-	-	-
Epanko	Tanzania	Active	40.00	10,900	8.60%	private	EcoGraf Resources	Australia
Liandu	Tanzania	Exploration	-	10,900	8.60%	private	Armadale Capital	United Kingdom
Nanzeka Malingunde (Dowa)	Malawi	Project Development	52.00	9,500	9.50%	private	Sovereign Metals	Australia
Lac Knife	Canada	Project Development	47.80	9,310	14.97%	private	Focus Graphite	Canada
Vohitsara 2	Madagascar	Active	6	9,200	4.10%	private	Bass Metals	Canada
Kringel	Sweden	Active	-	9,000	8.85%	private	Finders Resources	Australia
Chilalo 1	Tanzania	Exploration	52.00	7,962	10.50%	private	Evolution Energy Minerals	Australia
Pencil Hill	Botswana	Exploration	-	6,900	8.82%	private	Tonota Resources	Australia
Chilalo 2	Tanzania	Project Development	108.00	5,300	10.90%	private	Graphex Mining	Australia

Name	Mine Project Location	Operating Status	Production (ktpa)	Reserves (kt)	Grade (%Gr)	Owner Type	Owning Company	Company Location
Vohitsara 1	Madagascar	Project Development	-	4,000	5.00%	private	DNI Metals	Canada
Marofody	Madagascar	Project Development	-	4,000	5.00%	private	DNI Metals	Canada
Steamboat (Cuchron)	South Africa	Exploration	500.00	3,500	8.80%	private	Steamboat Graphite	South Africa
Caula	Mozambique	Exploration	-	2,933	13.40%	private	Mustang Resources	United States
Sao Benedito	Brazil	Inactive	-	2,100	57.43%	private	Sao Benedito	Brazil
Sahamamy	Madagascar	Active	3.00	1,400	4.10%	private	Tirupati Graphite	United Kingdom
Ol Doinyo Nyiro	Kenya	Exploration	-	1,200	13.00%	-	-	-
Katengeza	Malawi	Exploration	5.00	1,000	5.80%	private	Globe Metals and Mining	Australia
Lindi Jumbo	Tanzania	Project Development	40.00	987	17.90%	private	Walkabout Resources	Australia
Ancuabe 1	Mozambique	Active	6.00	900		private	AMG Graphite	Germany
Saulawa	Nigeria	Exploration	-	770	3.40%	-	-	-
Moyale	Ethiopia	Exploration	-	460	8.98%	private	Hulager General Import and Export plc	Ethiopia
Loharano	Madagascar	Active	12.00	235	-	private	StratMin	United Kingdom
Mkonda &Mvuye	Zambia	Exploration	-	-	6-12%	-	-	-
Njoka	Zambia	Exploration			10-13%	private	URA Holdings PLC	United Kingdom
Aukam	Namibia	Exploration	22.00	-	-	-	-	-
Antsirabe	Madagascar	Exploration	-	-	-	private	StratMin	United Kingdom
Caula	Mozambique	Exploration	-	-	-	private	Auspicious Virtue Investment Holding Ltd	United Kingdom (British Virgin Islands)
Andapa	Madagascar	Exploration	-	-	-	-	-	-
Mahela	Madagascar	Exploration	-	-	-	private	Bass Metals	Australia

Name	Mine Project Location	Operating Status	Production (ktpa)	Reserves (kt)	Grade (%Gr)	Owner Type	Owning Company	Company Location
Ianapera	Madagascar	Exploration	-	-	-	private	BlackEarth Minerals	Australia
Nachingwea	Tanzania	Project Development	-	-	-	private	Syrah Resources	Australia
Murma	India	Active	55.9	475	10.7%	private	Krishna Kumar Poddar	India
Nawapar	India	Active	-	-	20%	private	Pramod Kumar Agrawal	India
Betla	India	Active	3.3	65	15.3%	private	Parijat Mining Industries	India
Gandabahali	India	Active	27.1	197	20%	private	Prabhas Chandra Agrawal	India
Sivaganga	India	Active	1050	3,407	84%	state owned	Tamil Nadu Minerals Limited	India