Global Graphite Mining and Processing

Environmental and Social Impacts



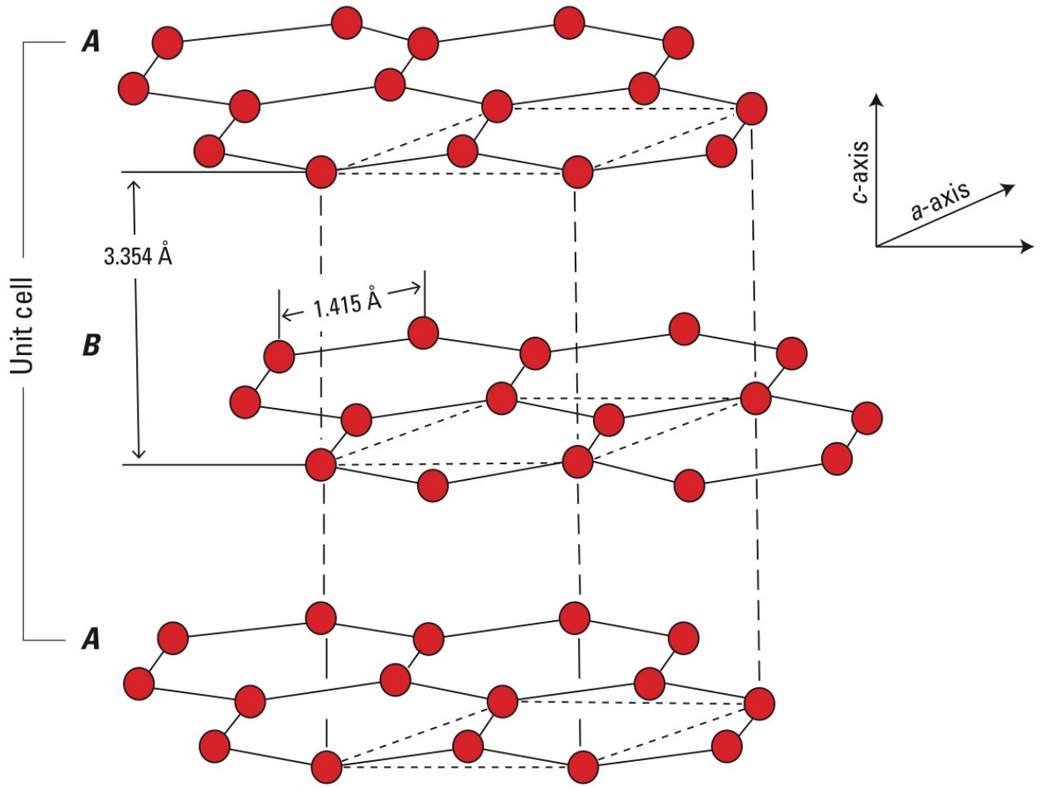
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About Graphite

- **Graphite is a compound made purely of carbon**, like diamonds, carbon nanotubes, and fullerenes
- Graphite and diamond were the first of the "ur-minerals"—the dozen or so mineral species that formed even prior to the first stellar nebulae, planets, and moons[1]
- **Graphite is composed of sheets of hexagonal arrays of carbon atoms, with weak attraction between the layers[7], contributing to its "slippery" feel**



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History of Graphite

- Graphite was first chemically characterised in 1779[4]
- It was later given it the term “graphite,” derived from the Greek word “grapho,” which means “I write”[3] — reflecting one of its initial uses as the “lead” in pencils[4]
- One of graphite’s first industrial uses, however, was actually to make cannonball molds, later expanding to include lubricant and refractory applications[4]
- **In the late 1800’s, means of converting carbon to graphite synthetically were discovered**[5]
-

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Abundance

- **Carbon is the fourth most abundant element in the solar system, and in terms of its abundance in Earth's crust, is ranked about 12th to 17th**[7]
- **The abundance of carbon in Earth's crust is difficult to determine** because carbon stores exist and cycle between rock, sediment, atmosphere, biosphere, and ocean reservoirs[7]
- More than 99% of carbon appears in the form of compounds with other elements[37]
- **Graphite makes up only a small proportion of the carbon in Earth's crust, probably less than 0.5%**[7] **making it — on its own — as having a crustal abundance roughly similar to tungsten (54th)**
- Of course, the ability to synthesize graphite increases its availability

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Elemental Properties

- Graphite exhibits the properties of both a metal and a nonmetal, which makes it suitable for many industrial applications[6]
- **The metallic properties include thermal and electrical conductivity. The nonmetallic properties include inertness, high thermal resistance, and lubricity**[6]
- The combination of conductivity and high thermal stability allows graphite to be used in many applications such as refractories, batteries, and fuel cells[6]
- For batteries specifically, **graphite forms intercalation compounds with alkali metal vapors**—usually potassium, lithium, rubidium, and cesium— **where the metal ions fit between the planar carbon sheets of the graphite structure**[7]

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Graphite in Batteries

- **Graphite when used as an anode in Lithium Ion Batteries (LiBs), can accommodate the insertion and de-insertion processes of lithium ions (Li+) thousands of times**[8]
- Due to its high electrical conductivity, inertness, reversible Li-ion intercalation between the basal planes of the crystal structure[9] and low cost to produce[10], graphite (either synthetic or natural) is a critical component of primary and rechargeable batteries[9]
- **Graphite is used in about 80% of LiBs today**[11]
- Despite extensive research efforts dedicated to discovering and developing alternative anode material candidates, **no widely commercially viable alternative to graphite anodes has so-far been identified**[12]

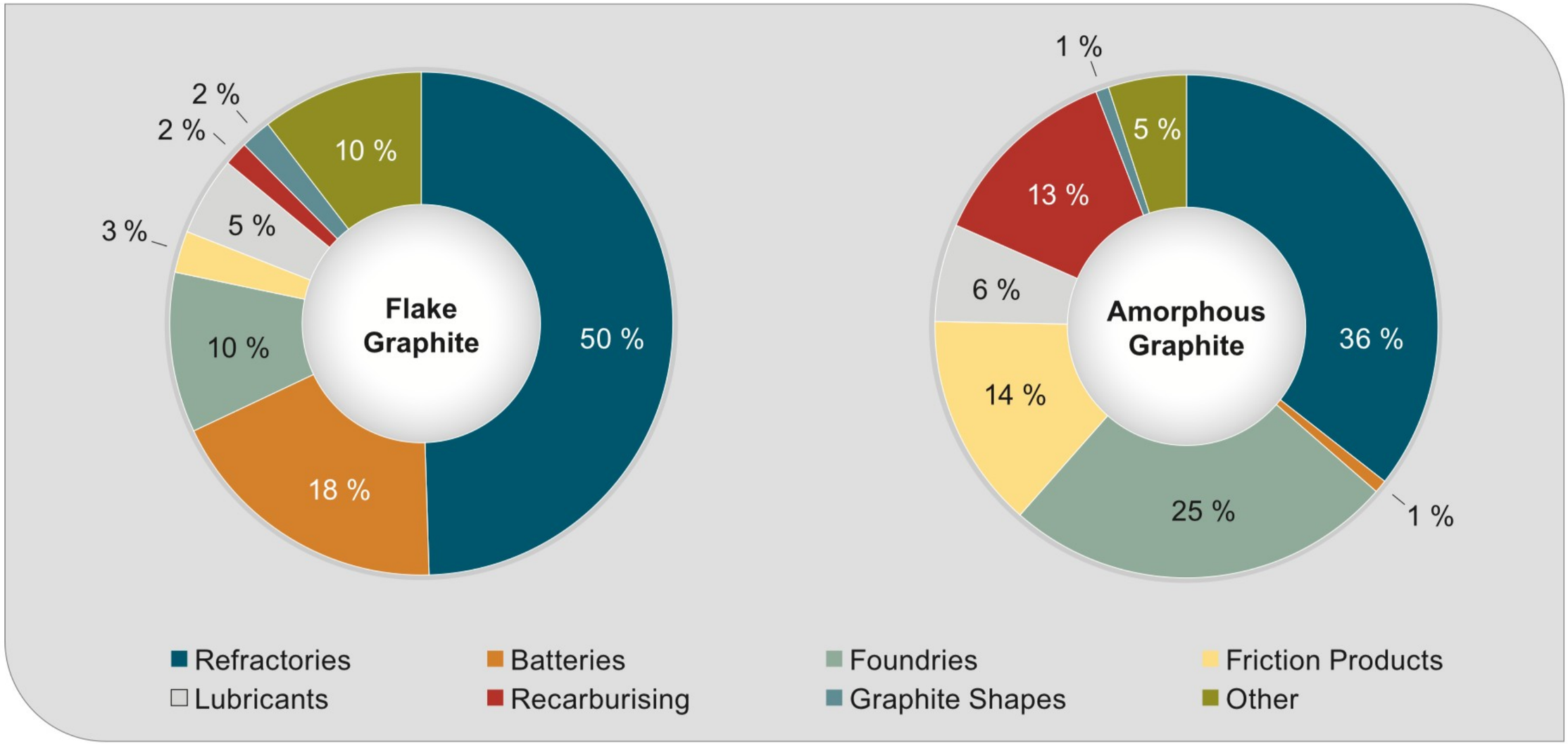
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Graphite Ores and Uses

- Natural graphite deposits come in three different forms: amorphous (micro-crystalline[7]), flake, and vein[5]
- Although higher purity, vein deposits are small[7] and rarely economically viable[5]
- "Flake graphite" is the commercial designation for crystal platelets of graphite that are between 40 micrometers and 4cm (but generally <=1 cm) in size[7]
- **Flake graphite — either natural or synthetic — is generally required for battery production**
- **On the other hand, synthetic graphite because of its greater porosity cannot substitute natural graphite in refractory applications[9], although both amorphous and flake graphite are used**

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Uses of the two primary forms of graphite[24]:

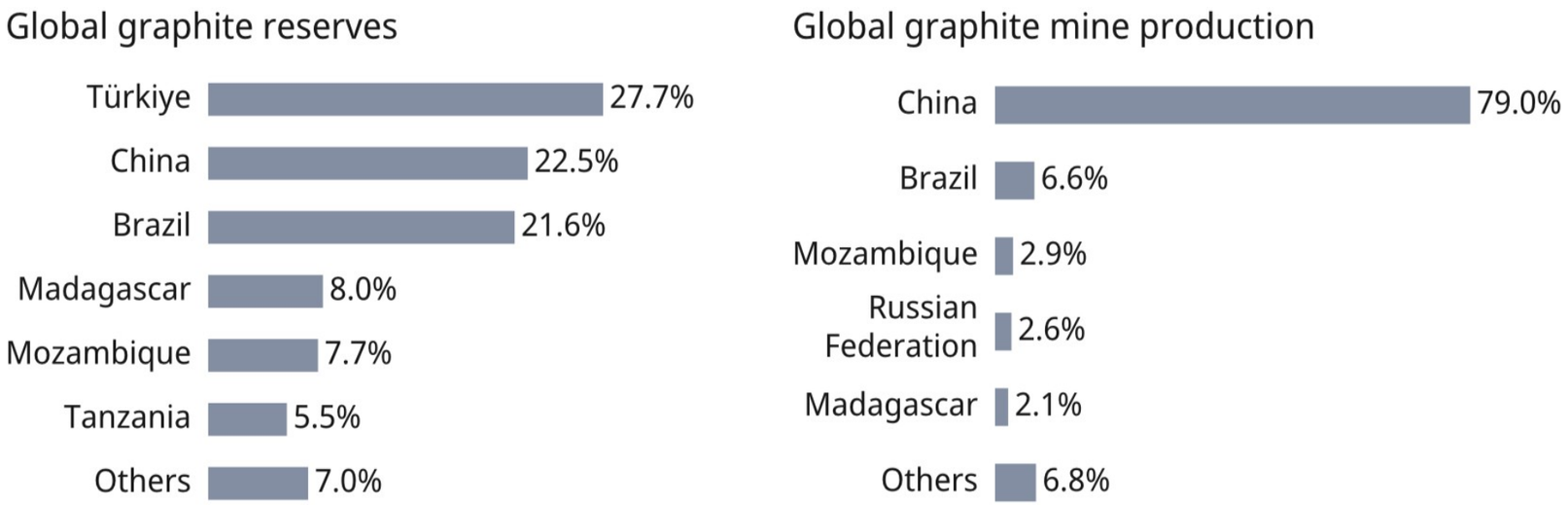


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Deposits and Reserves

- Global graphite resources are large relatixve to global consumption, but their extent is poorly known[7]
- **Complete estimates of graphite resources are likely not available for any single major graphite district in the world**[7]

Figure 1. **World graphite reserves and mine production.**
Global graphite mine production is concentrated in just a few countries, because of the uneven geographical distribution of graphite reserves.



Source: United States Geological Survey, Mineral Commodity Summaries 2022.

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Supply and Demand

- **China contains an abundance of natural graphite and is the largest graphite mining country**[15]
- **China is also the world's leading graphite producer, with an estimated 77% of total world production in 2023**[16]
- **In addition, China is practically the only global producer of spherical graphite**[9]**, the required form of graphite needed for battery anode materials**
- Changing environmental regulations and Chinese processing plant closures led to an increase in prices in early 2018[13]
- Not surprisingly, **European countries, China and the United States, together with many other countries and international organizations, have listed graphite as a critical/strategic material**[4]

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Natural Graphite Mining Process

- Natural flake graphite is mined in either open pits or underground[11]
- **The ore may contain between 2-30% by weight of graphitic carbon, and development of the deposits containing between 5-20% is most common**[11]
- The main mineral composition of graphite ore is quartz, plagioclase, and graphite[17]
- **Graphite ore contains impurities, primarily potassium, sodium, magnesium, calcium, and aluminium silicate minerals, which must be removed using purification methods**[18]

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Mining and Artisanal Small-scale Mining (ASM)

- Graphite is stable in the weathering environment; deposit grades and ease of mining are enhanced by weathering destruction of other minerals[7]
- Some deposits become so weathered that they can be mined with shovels and other hand tools[7]
- **Despite this, only one mention of ASM was found in the literature (a close to "moderate" association with ASM)**[14], and no particular details were listed

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Initial Natural Graphite Processing

- **Graphite separation from ores is achieved by a combination of careful crushing, milling, screening, tabling, flotation, magnetic separation, electrostatic separation, and leaching**[19]
- Given the high value and the scarcity of large-flake graphite ore resources, it is best to maximize the amount of large flakes and minimize processing that will reduce flake sizes[20]
- However, graphite is naturally hydrophobic, and the most used technique for ore separation is froth flotation[19]
- **One of the main reasons why graphite minerals are difficult to liberate is that the graphite flakes in the samples are interlocked with other minerals**[21]

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Natural Graphite Refining: Hydrometallurgy

- Hydrometallurgical purification consists of (a) flotation, (b) acid-base and (c) hydrofluoric-acid (HF in water) methods[22]
- Flotation is the lowest cost method[22]
- The acid-base method is an alkali fusion method where impurities react with NaOH under high temperature, producing water-insoluble hydroxides. These compounds are washed out with water[22]
- **The acid-base method is most widely used due to small-scale infrastructure investment, easy implementation, and strong universality. However, it is time-consuming and also causes serious pollution**[22]
- Lastly, hydrofluoric acid treatment is a purification method in which the acid reacts with almost all the impurities in graphite, generating water-soluble compounds that can be removed through rinsing with water[22]

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Natural Graphite Refining: Pyrometallurgy

- Pyrometallurgy purification includes (a) chlorination roasting and (b) high-temperature methods[22]
- **The chlorination roasting uses chlorine gas, heat, and pressure,** generating condensed complexes with chloride to eliminate impurities with low melting and boiling points[22]
- **The purification efficiency of this method is known to be high, reaching more than 98%. However, it is expensive and very difficult to deal with the expelling gas**[22]
- **In the high-temperature method, the graphite is heated to more than 8800F** where the impurities with low boiling points are vaporized and removed[22]
- The purity of graphite becomes more than 99.995%. However, **the drawback is large-scale infrastructure investment and high energy consumption**[22]

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Synthetic Graphite

- **Graphite can also be formed via synthetic processes from the heat-treatment of petroleum coke (highest quality[11]) or coal tar pitch[22]**
- This graphite is processed with heat treatment in the range of 4500– 5500F[22] for several days
- As a result of this treatment, synthetic graphite is more than 99.9% pure graphite, but it has slightly higher porosity, lower density, lower electrical conductivity, and a much higher price than natural flake graphite[7]
- **Synthetic graphite offers batch-to-batch property consistency[23]**
- **The drawbacks of synthetic graphite production are the use of fossil fuels as input materials and the high energy consumption to generate heat (not to mention the resulting price)**

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Synthetic Bio-graphite

- **Since graphite consists of carbon, non-fossil fuel carbon sources (e.g. biomass waste) have also been experimented with to produce synthetic graphite**[24]
- However, there are several challenges associated with the graphite production process from biomass waste materials, such as impurities, the processing conditions and production costs[25]
- **Agricultural bio-waste materials typically contain many volatiles and impurities, which can interfere with the synthesis process and reduce the quality of the graphitic carbon produced**[25]

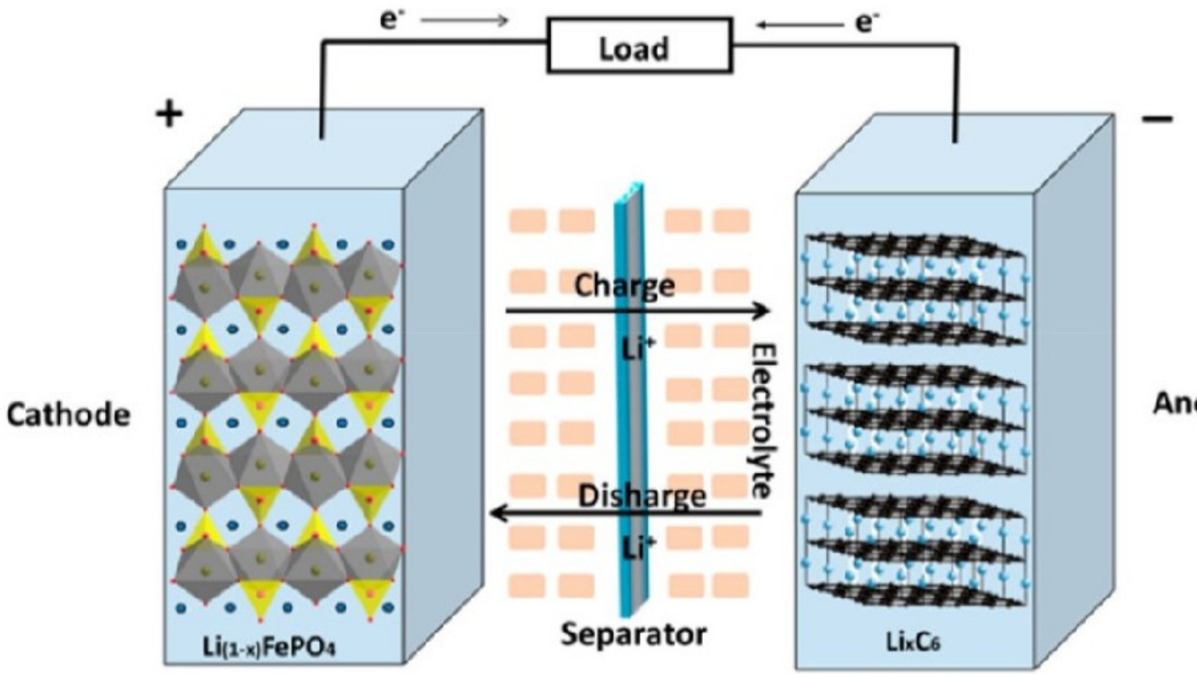
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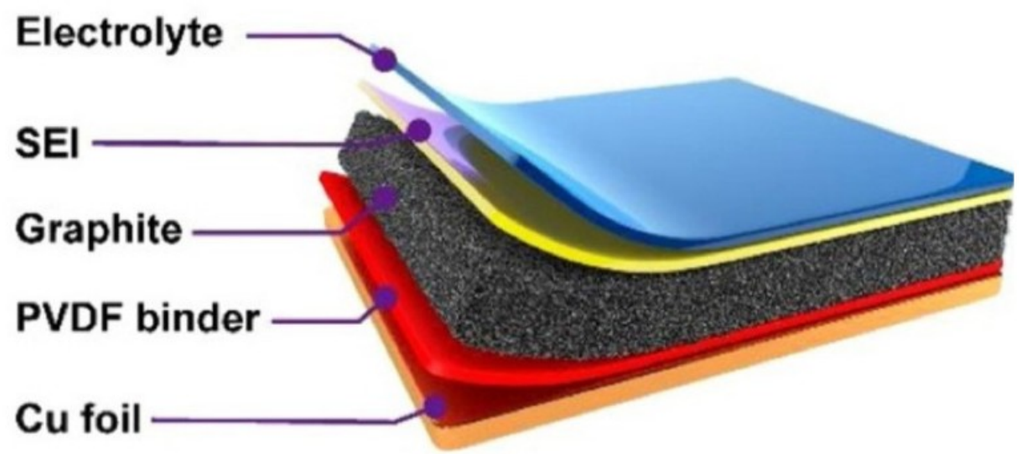
Carbonscape

- **A company called CarbonScape has bio-graphite pilot facility in New Zealand currently producing graphite with woodchips and sawdust for customer testing and validation**[26]
- So far, **the company reports its low-temperature process creates a biographite with a purity (99.5%)**, equivalent to costly high-temperature thermal treatments[26]
- **Furthermore, the company claims its unique microstructure allows more rapid movement of lithium ions, translating to superior fast-charge capacity compared to natural graphite**[26]

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Li-ion Battery Construction





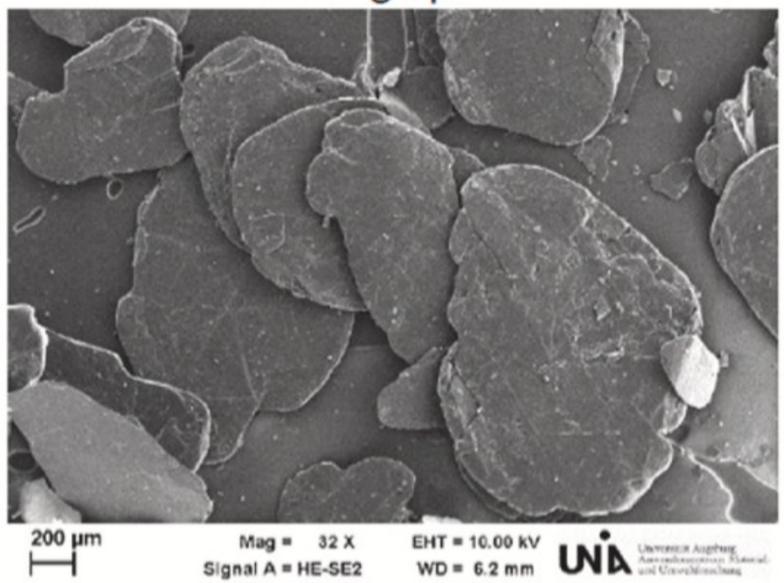
- LIBs consist of the **anode (spheroidized natural or synthetic[29] graphite on the copper sheet with a PVDF binder)**, a cathode (lithium metal oxide, metal: Co, Ni, Fe), electrolyte (concentrated lithium salts containing organic solvents), separator, casing and a small printed circuit board[27]

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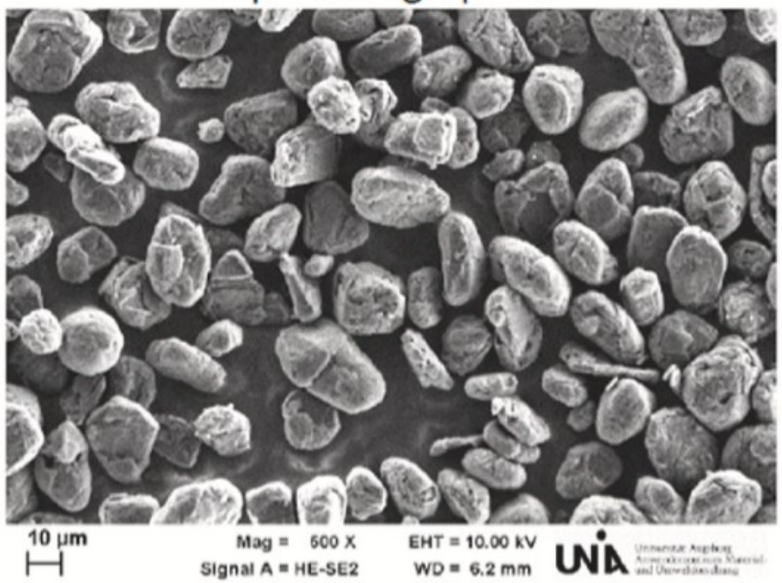
Spheronization

- **The spheronization process increases the surface area and conductivity making it highly suitable for use as anode material**[9]
- Spheronization happens before purification[30]

Flake graphite



Spherical graphite



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Coating

- **Coating happens after purification**[30]
- **The refined spherical graphite particles meld with a coating substance, commonly high softening point pitch**[10]
- **It is then subjected to furnace-based melting, yielding a uniform coating layer on the particles**[10]
- **In the concluding stage, the coated particles undergo carbonization, entailing heating in an inert atmosphere for a specific duration**[10]
- **This procedure heightens the performance and stability of the graphite anode within lithium-ion batteries**[10]
- According to one academic there is no data in the public domain confirming whether coating is always required[11]

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For both synthetic and natural graphite prepared for battery use, **the loss of initial graphite through the entire process is calculated at 30-70%**, most of which is generally used up by low-value uses of amorphous graphite, such as the recarburizing industry[9,11]

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Natural Graphite Mining: Health and Environmental Concerns

- Because of the chemically inert, nontoxic nature of graphite, **the main environmental concerns associated with graphite mining are (a) the presence of other minerals that can occur with graphite, and (b) inhalation of graphite particles or fine-grained silica minerals in graphite during mining and processing**[7]
- For example, **the iron sulfide minerals pyrite and pyrrhotite are present in amounts ranging from a trace to several percent in some graphite deposits which can cause acid-rock drainage if exposed to air and water**[7]
- Chronic exposure to graphite dust is associated with pneumoconiosis, a group of lung diseases associated with chronic exposure to mineral and metallic dusts[7]

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Natural Graphite Mining: Health and Environmental Concerns

- Because graphite ore always contains some quartz, a review was concluded and found that **although many years of occupational exposure to pure graphite may cause disease, mixed-dust inhalation is a more likely cause of lung disease**[7]
- Implementation of dust abatement protocols in mining and processing has resulted in decreased incidence of lung disease in graphite workers since the 1970s[7]
- **In Heilongjiang province (China), the world's leading flake graphite producing region (43% in 2012), graphite dust at one point contributed to severe air and water pollution, creating what was being described as 'graphite rain'**[31]

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Tailings

- **Each year, China generates over 6 million tons of graphite tailings**[17]
- The traditional method of storing graphite tailings not only consumes significant land resources but also results in the release of dust and leakage from the tailings reservoir, leading to severe environmental pollution during adverse weather conditions[17]
- **At the same time, due to the natural graphite ore in the flotation process being mixed with a large number of complex toxic heavy metals, such as As, Ba, Cd, Cr, Cu, Ni, Pb, Se, and oxygenated anions, the massive accumulation of graphite tailings also causes heavy metal pollution in the soil and water around the mine**[32]

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Natural Graphite Processing: Environmental Impacts

- The environmental impact of graphite mining, especially natural graphite, is significant. **Issues like deforestation, habitat degradation, and water contamination are often underrepresented in LCAs due to limited data**[10]
- Graphite production requires substantial water usage[10]
- **Flotation, for example, requires 100 tons of water and 10 tons of raw graphite ore on average to generate 1 ton of (unrefined graphite)**[17]
- In addition, **roasting-leaching treatment (most common process used in China) of 1 ton graphite flotation concentrate needs 450–500-kg NaOH (lye), leading to environmental issues especially in wastewater**[19]
- The hydrofluoric acid method, on the other hand, produces a large amount of acidic wastewater with fluoride ions due to the large amount of acid used (purification of 1 ton of graphite requires 1 ton of 40% hydrofluoric acid)[33]

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Synthetic Graphite Production: Environmental Impacts

- The environmental impacts of oil and coal mining to produce the input materials of needle coke and coal tar pitch are already well-documented[11] and are not reviewed here
- **One study — while admitting that no quality inventory exists for synthetic graphite — indicates that the GHG emissions and energy consumption for synthetic graphite may be more than double the values reported in prior work[11]**
- **Because of the high energy consumption required for synthetic graphite production, it has been estimated that natural graphite has 62–89% lower GHG emissions than synthetic graphite[23]**

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Including Spheronization and Coating in the Calculations: an LCA Study

- **A 2022 study of the purified spherical natural graphite anode production process using industrial data for a Chinese producer found GWP more than four times higher than battery-grade graphite in the ecoinvent database[30]**
- **The main reason for such high CO2 emissions, they state, is the energy-intensive coating step, which has been neglected or under- estimated in many previous publications[30]**
- **Interestingly, according to Pehnt (the source before 2020 for GaBi data), the majority of the energy consumption occurs in mining, but this study's investigations found the mining process requires the least energy[30]**
- **They conclude that natural graphite should be regarded as an environmental hotspot similar to cobalt and lithium[30]**

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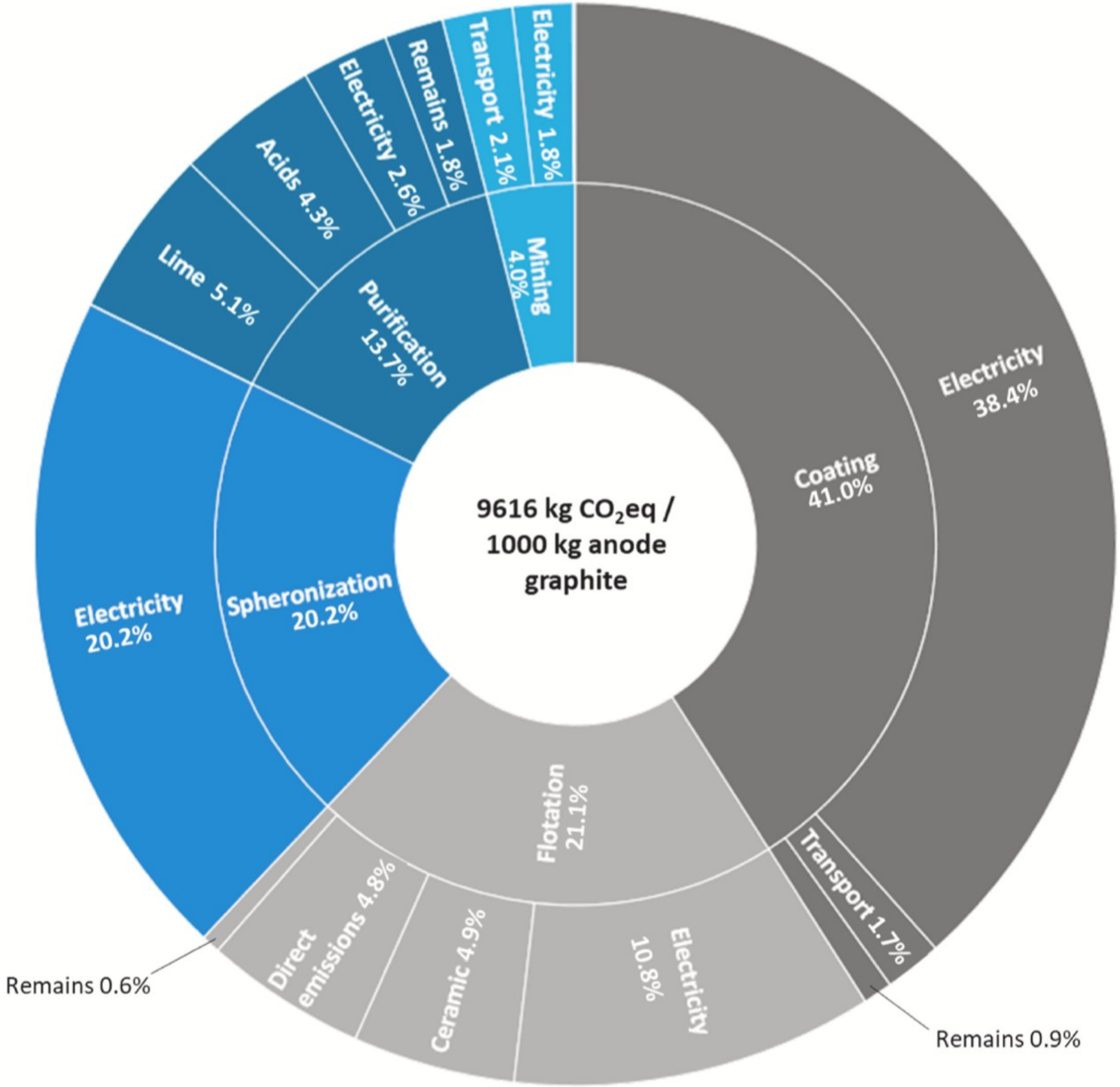


Fig. 5. GWP results for each production steps of 1000 kg anode graphite according to primary data collection at a Chinese graphite manufacturer (CML method).

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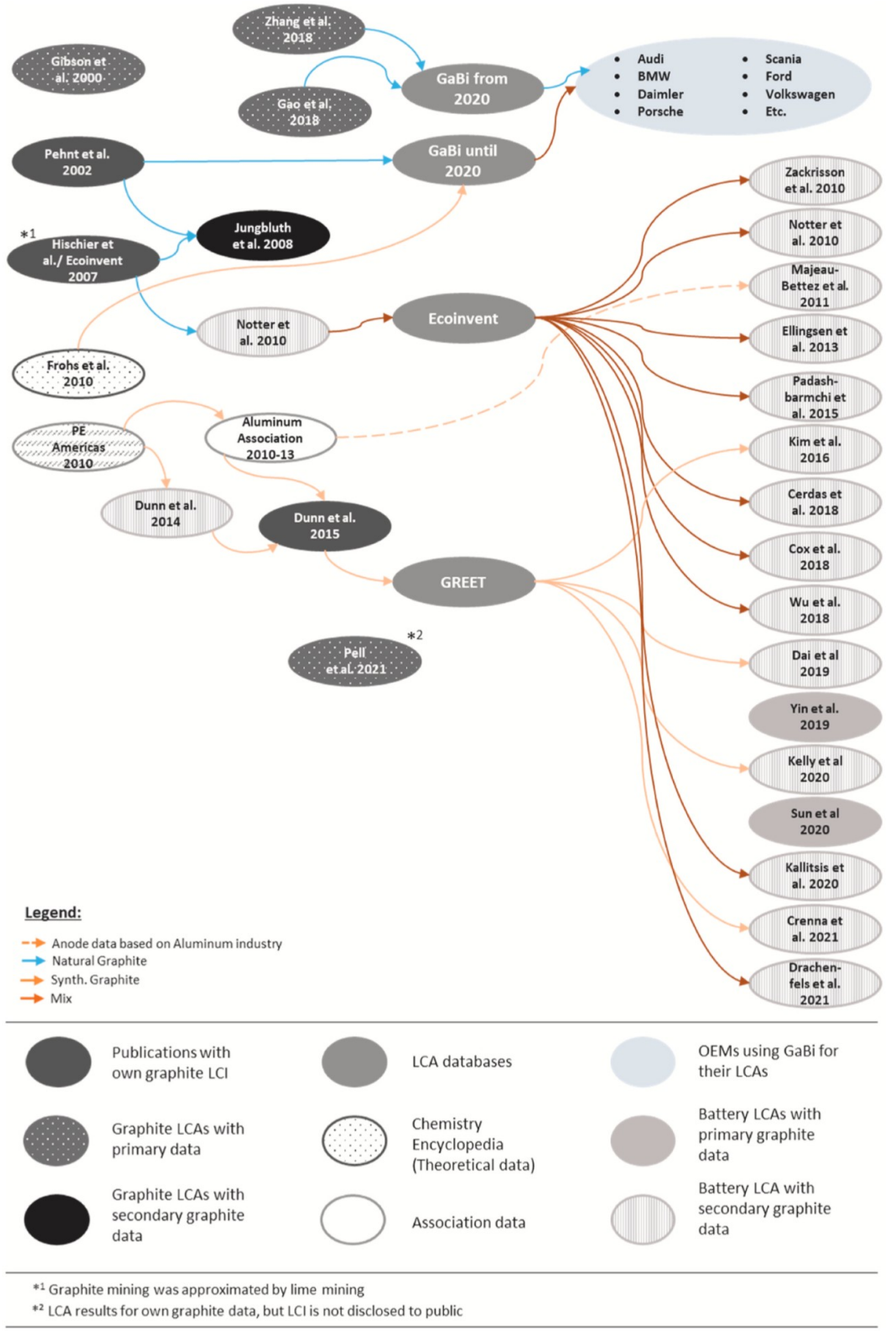


Fig. 1. Data network of LCI data for graphite, their sources and their further usage in different publications.

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Recycling Graphite

- **Recycling of graphite from end-of-life products is limited as a significant amount is dissipated during use**, e.g. lubricants, pencils, friction pads, foundry washes, carbon brushes and, to some extent, refractories[9]
- In addition, **recycling of graphite from end-of-life products is inhibited by its relative abundance in nature and lack of economic incentive due to the prevailing low prices**[9]
- Currently, **there is no reported industrialized process to recycle graphite from the spent lithium-ion batteries**[9]
- **Pyrometallurgical recycling of batteries, for example, does not target graphite, which is oxidised to CO2**[9]

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Recycling Graphite (cont.)

- **Overall, the end of life recycling rate for natural graphite is estimated at less than 1%**[5]
- However, 77% of recycled graphite from refractories and foundries in the US is used as low-value roadbed materials,[23] **indicating that most recycling today may not generate original-quality graphite**
- In addition, much of the academic research focuses on similar "downcycled" applications[34] or conversion to other materials

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Graphite Alteration after Battery Use

- Spent graphite from lithium-ion batteries (LIBs) is no longer pure graphite and has a complex composition including various metal and organic impurities[35]

Impurities of spent graphite.

Species	Impurities
Metal impurities	Ni, Co, Mn, Li_2CO_3, LiF, CuO, Fe, Al_2O_3, Na
Organic impurities	Polyvinylidene fluoride binder, LiPF, Electrolyte

34

- This is due to the natural process of how battery chemistry changes during use
- Removing and separating these components — even from a separated anode — to obtain pure graphite again can be a complex and energy-intensive process[35]
- Having said that, at least the anode formulation is relatively consistent for Li-Ion batteries, compared to the many varied cathode chemistries

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Table 2. Global retired LIBs recycling market research.[72]

	Manufacturers	Countries	Approaches	Details
First-tier (Processing capacity (spent LIBs) >3 000 t $year^{-1}$)	Umicore	Belgium	Main Pyro (high temperature)	Ni-Co alloys, Li compounds Processing capacity (spent LIBs) 7000 t $year^{-1}$ [72b]
	Brunp	China	Thermal + Mech + Hydro	Ternary precursors Processing capacity (spent LIBs) 120 000 t $year^{-1}$
	GEM	China	Mech +Pyro + Hydro	NCM and NCA ternary precursor Processing capacity (spent LIBs) 10 000 t $year^{-1}$
	Taisen Recycling	China	Hydro	Processing capacity (spent LIBs) 6000 t $year^{-1}$
	SungEel HiTech	South Korea	Mech+ Hydro	NCM precursor, Li_3PO_4 Processing capacity (spent LIBs) 8000 t $year^{-1}$
	Glencore	Norway	Hydro	Ni, Co, Cu Processing capacity (spent LIBs) 7000 t $year^{-1}$
	Accurec GmbH	Germany	Thermal+Mech+ Pyro + Hydro	Co-Mn alloys, Li compounds Processing capacity (spent LIBs) 3000 t $year^{-1}$
	Nickelhütte Aue	Germany	Thermal + Pyro + Hydro	NiCoCu-Matte Processing capacity (spent LIBs) 7000 t $year^{-1}$

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	Manufacturers	Countries	Approaches	Details
Second-tier (Processing capacity (spent LIBs) <3 000 t $year^{-1}$)	Kyoei Seiko	Japan	Pyro	Ni, Co, Cu
	Dowa	Japan	Thermal + Pyro + Hydro	Ni, Co, Cu
	AEA	UK	Electrodeposition	product CoO
	Recupyl	France	Mech+ Hydro	product Li_2CO_3, $Co(OH)_3$
	SNAM	France	Thermal + Pyro + Hydro	Co, Ni, Cu
	EDI	France	Mech+Uknown	Co, Cu
	Batrec	Switzerland	Hydro	product Ni, Co, MnO
	Duesenfeld	Germany	Mech+ Hydro	Co/Li/Ni/Mn salts, graphite
	IME	Germany	Pyro + Hydro	Alloys, Ni/Co hydroxide
	GRS Batterien	Germany	Pyro	Alloys
	Redux	Germany	Thermal+Mech+ Uknown	Co/Ni salts
	Fortum	Finland	Hydro	Co/Li/Ni/Mn salts
	AkkuSer	Finland	Mech+Uknown	Co alloy, Li_2CO_3
	Northvolt	Norway	Hydro	ternary
	Mitsubishi	Japan	Pyro	product LCO
	4R Energy Corp	Japan	Laddering	Focus on laddering 10–24 kWh, 100 kWh
	Li-Cycle	Canada	Pyro + Hydro	Co/Li/Ni salts
	Retriev	United States/Canada	Mech+ Hydro	Li_2CO_3
	OnTo Technology	United States	Supercritical recovery	Recovery of formance battery
	Redwood	United States	Hydro	Co/Li/Ni salts, graphite

Mech: mechanical, Hydro: hydrometallurgy, Pyro: pyrometallurgy.

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Industrial Graphite Retrieval Processes

- **Per the previous table, only two companies focus on retrieving graphite from LiBs: Dusenfeld in Germany and Redwood Materials in the US**[36]
- Also it is not clear if these processes are limited to EV batteries
- Another paper mentions that "the extraction of graphite from the mixture of shredded anode and cathode can be performed via selective flotation. This common technique is part of the processes patented by Retriev Technologies and Warner Babcock Institute for Green Chemistry"[2]
- However, the previous table does not mention Retriev as focusing on graphite retrieval[36]
- Tesla is collaborating with various industries to create the Global Battery Alliance (GBA)[36] to try to standardize battery labeling, etc. which may assist in battery recycling

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Summary

- Graphite is a pure carbon compound composed of sheets of hexagonal arrays of carbon atoms
- Multiple chemical properties of both metals and non-metals make it an ideal Li-Ion battery anode material
- While graphite isn't seen as particularly harmful itself to humans or the environment, graphite mining comes with risks such as acid mine drainage and dust pollution
- Graphite purification is where most of the environmental impacts exist, as the processes of refining natural graphite or creating synthetic graphite consume large quantities of energy and chemicals, especially given the spheronization and coating processes used to make graphite ready for anode use
- Some of the uses of graphite are dissipative, but for the remainder, scaled industrial processes to recycle graphite do not exist today, resulting in a global recycling rate in the low single digits
- For LiBs in particular, because of the relatively low cost of graphite compared to other materials like cobalt and lithium, existing battery recycling processes either consume graphite during smelting or generate mixed "sludge" waste with carbon and other contaminants
- While China's dominance of the graphite market (all the way from mining to anode material creation) create globally recognized supply risks, more work will need to be done to develop graphite recycling technology and infrastructure

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References (1 of 4)

[1] Hazen, R. M., Downs, R. T., Kah, L., & Sverjensky, D. (2013). Carbon mineral evolution. Reviews in Mineralogy and Geochemistry, 75(1), 79–107.

[2] Larouche, F., Tedjar, F., Amouzegar, K., Houlachi, G., Bouchard, P., Demopoulos, G. P., & Zaghib, K. (2020). Progress and Status of Hydrometallurgical and Direct Recycling of Li-Ion Batteries and Beyond. Materials, 13(3), Article 3. https://doi.org/10.3390/ma13030801

[3] Vasumathi, N., Sarjekar, A., Chandrayan, H., Chennakesavulu, K., Reddy, G. R., Vijaya Kumar, T. V., El-Gendy, N. S., & Gopalkrishna, S. J. (2023). A Mini Review on Flotation Techniques and Reagents Used in Graphite Beneficiation. International Journal of Chemical Engineering, 2023, e1007689. https://doi.org/10.1155/2023/1007689

[4] WIPO. (2023). Patent Landscape Report—Graphite and its applications. https://doi.org/10.34667/tind.47589

[5] United Nations Conference on Trade and Development. (2020). Commodities at a Glance: Special Issue on Strategic Battery Raw Materials. UN. https://doi.org/10.18356/9ba5e76c-en

[6] Wang, H., Feng, Q., Tang, X., & Liu, K. (2016). Preparation of high-purity graphite from a fine microcrystalline graphite concentrate: Effect of alkali roasting pre-treatment and acid leaching process. Separation Science and Technology, 51(14), 2465–2472. https://doi.org/10.1080/01496395.2016.1206933

[7] Robinson, Jr., G. R., Hammarstrom, J. M., & Olson, D. W. (2017). Graphite USGS. https://pubs.usgs.gov/publication/pp1802J

[8] Wang, H., Huang, Y., Huang, C., Wang, X., Wang, K., Chen, H., Liu, S., Wu, Y., Xu, K., & Li, W. (2019). Reclaiming graphite from spent lithium ion batteries ecologically and economically. Electrochimica Acta, 313, 423–431. https://doi.org/10.1016/j.electacta.2019.05.050

[9] European Commission. (2020). Study on the EU's list of Critical Raw Materials (2020). https://op.europa.eu/en/publication-detail/-/publication/c0d5292a-ee54-11ea-991b-01aa75ed71a1/language-en

[10] Robin, R. J. (2024). Viability and Eco-Consequences of Synthetic and Natural Graphite for Li-ion Battery Anodes in the US. IEEE Engineering Management Review, 1–16. https://doi.org/10.1109/EMR.2024.3372697

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References (2 of 4)

[11] Surovtseva, D., Crossin, E., Pell, R., & Stamford, L. (2022). Toward a life cycle inventory for graphite production. Journal of Industrial Ecology, 26(3), 964–979. https://doi.org/10.1111/jiec.13234

[12] Andersen, H. L., Djuandhi, L., Mittal, U., & Sharma, N. (2021). Strategies for the Analysis of Graphite Electrode Function. Advanced Energy Materials, 11(48), 2102693. https://doi.org/10.1002/aenm.202102693

[13] Damm, S., Zhou, Q. (2020). Supply and Demand of Natural Graphite - DERA Rohstoffinformationen. https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/Studie%20Graphite%20eng%202020.pdf?__blob=publicationFile&v=3

[14] Material Insights. (n.d.). Graphite (Natural). Retrieved from https://www.material-insights.org/graphite

[15] Bai, Q., Zhang, S. T., Wang, W. L., & Wang, Z. J. (2015). Variance of graphite import–export volume and price in China for 2003–2012: A time-series analysis. Resources Policy, 44, 65–70. https://doi.org/10.1016/j.resourpol.2015.01.004

[16] USGS. (2024). Mineral Commodity Summaries 2024. https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-graphite.pdf

[17] Zhang, J., Wei, Q., Zhang, N., Zhang, S., & Zhang, Y. (2023). Comparative Study of Iron-Tailings-Based Cementitious Mortars with Incorporated Graphite Ore and Graphite Tailings: Strength Properties and Microstructure. Materials, 16(10), Article 10. https://doi.org/10.3390/ma16103743

[18] Al-Sairafi, F. A., Jiang, C., Zhong, Z., & Saleh, B. (2022). Study on purification of flake graphite by heat activation and hydrofluoric acid. Advances in Materials and Processing Technologies, 8(4), 4564–4578. https://doi.org/10.1080/2374068X.2022.2079172

[19] Chehreh Chelgani, S., Rudolph, M., Kratzsch, R., Sandmann, D., & Gutzmer, J. (2016). A Review of Graphite Beneficiation Techniques. Mineral Processing and Extractive Metallurgy Review, 37(1), 58–68. https://doi.org/10.1080/08827508.2015.1115992

[20] Sun, K., Qiu, Y., & Zhang, L. (2017). Preserving Flake Size in an African Flake Graphite Ore Beneficiation Using a Modified Grinding and Pre-Screening Process. Minerals, 7(7), Article 7. https://doi.org/10.3390/min7070115

Global Graphite Mining and Processing: Environmental and Social Impacts © 2024 by More Than Sustainability is licensed under CC BY-SA 4.0

References (3 of 4)

[21] Ma, F., Song, B., & Tao, Y. (2023). Study on mineralogical characteristics of fine flake graphite ore. Particulate Science and Technology, 41(3), 411–419. https://doi.org/10.1080/02726351.2022.2106331

[22] Jara, A. D., Betemariam, A., Woldetinsae, G., & Kim, J. Y. (2019). Purification, application and current market trend of natural graphite: A review. International Journal of Mining Science and Technology, 29(5), 671–689. https://doi.org/10.1016/j.ijmst.2019.04.003

[23] Zhang, J., Liang, C., & Dunn, J. B. (2023). 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

[24] Shi, Z., Wang, S., Jin, Y., Zhao, L., Chen, S., Yang, H., Cui, Y., Svanberg, R., Tang, C., Jiang, J., Yang, W., Jönsson, P. G., & Han, T. (2023). Establishment of green graphite industry: Graphite from biomass and its various applications. SusMat, 3(3), 402–415. https://doi.org/10.1002/sus2.139

[25] Yap, Y. W., Mahmed, N., Norizan, M. N., Abd Rahim, S. Z., Ahmad Salimi, M. N., Abdul Razak, K., Mohamad, I. S., Abdullah, M. M. A.-B., & Mohamad Yunus, M. Y. (2023). Recent Advances in Synthesis of Graphite from Agricultural Bio-Waste Material: A Review. Materials, 16(9), Article 9. https://doi.org/10.3390/ma16093601

[26] CarbonScape Renewable Biographite Anode Material Ready to Scale. (n.d.). Retrieved from https://www.batterytechonline.com/materials/carbonscape-s-renewable-biographite-anode-material-ready-to-scale

[27] Sunil, S. R., Vishvakarma, S., Barnwal, A., & Dhawan, N. (2019). Processing of Spent Li-Ion Batteries for Recovery of Cobalt and Lithium Values. JOM, 71(12), 4659–4665. https://doi.org/10.1007/s11837-019-03540-6

[28] Sun, J., Chen, W., Jia, K., Li, S., Jia, P., Wang, W., Song, Z., Zhao, X., Mao, Y., & Chen, S. (2023). Progress on the Microwave-Assisted Recycling of Spent Lithium Battery Graphite. Processes, 11(5), Article 5. https://doi.org/10.3390/pr11051451

[29] Vanderbruggen, A., Gugala, E., Blannin, R., Bachmann, K., Serna-Guerrero, R., & Rudolph, M. (2021). Automated mineralogy as a novel approach for the compositional and textural characterization of spent lithium-ion batteries. Minerals Engineering, 169, 106924. https://doi.org/10.1016/j.mineng.2021.106924

Global Graphite Mining and Processing: Environmental and Social Impacts © 2024 by More Than Sustainability is licensed under CC BY-SA 4.0

References (4 of 4)

[30] 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

[31] Li, A., & Miller, S. A. (2014). China graphite pollution fears spread to Heilongjiang. Industrial Minerals, 557, 5.

[32] Jiang, R., & Wang, Z. (2024). Performance and Heavy Metal Analysis of Graphite Tailings Cured Using Cementitious Materials. Buildings, 14(2), Article 2. https://doi.org/10.3390/buildings14020537

[33] Liu, Y., Fu, Y., Zheng, L., Wang, M., Wang, Z., Yang, S., Liu, J., & Gong, X. (2023). Leaching characteristics and solidification strategy of heavy metals in solid waste from natural graphite purification. Environmental Science and Pollution Research, 30(11), 30892–30904. https://doi.org/10.1007/s11356-022-24298-6

[34] Liu, J., Shi, H., Hu, X., Geng, Y., Yang, L., Shao, P., & Luo, X. (2022). Critical strategies for recycling process of graphite from spent lithium-ion batteries: A review. Science of The Total Environment, 816, 151621. https://doi.org/10.1016/j.scitotenv.2021.151621

[35] Kosenko, A., Pushnitsa, K., Pavlovskii, A. A., Novikov, P., & Popovich, A. A. (2023). The Review of Existing Strategies of End-of-Life Graphite Anode Processing Using 3Rs Approach: Recovery, Recycle, Reuse. Batteries, 9(12), Article 12. https://doi.org/10.3390/batteries9120579

[36] Tian, H., Graczyk-Zajac, M., Kessler, A., Weidenkaff, A., & Riedel, R. (2023). Recycling and Reusing of Graphite from Retired Lithium-ion Batteries: A Review. Advanced Materials,, 2308494. https://doi.org/10.1002/adma.202308494

[37] Liang, C., Chen, Y., Wu, M., Wang, K., Zhang, W., Gan, Y., Huang, H., Chen, J., Xia, Y., Zhang, J., Zheng, S., & Pan, H. (2021). Green synthesis of graphite from CO2 without graphitization process of amorphous carbon. Nature Communications, 12(1), 119. https://doi.org/10.1038/s41467-020-20380-0

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