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Full length article

Limits to graphite supply in a transition to a post-fossil society

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ABSTRACT

Transitioning to electric vehicles (EVs) powered by lithium-ion batteries (LIBs) aims at reducing emissions in the transportation sector, thereby decreasing fuel oil use and crude oil extraction. Yet, synthetic graphite, a crucial anode material for LIBs, is produced from needle coke, a byproduct of oil refining. This dependency could lead to bottlenecks in battery anode production. We found no obvious supply constraints for synthetic graphite in slow electrification scenarios based on different International Energy Agency scenarios. In contrast, net zero scenarios reveal drastic limitations in synthetic graphite supply, due to fast electrification and declining needle coke production. Natural graphite can mitigate supply limitations but faces environmental concerns, long development time and geopolitical concerns. Securing graphite supply while reaching the net zero goals requires comprehensive strategies combining (1) systematic graphite recycling, (2) overcoming current technical challenges, and (3) behavioral shifts towards reduced vehicle ownership and smaller vehicles.

1. Introduction

As the recent COP28 in the UAE called for "transitioning away" from fossil fuels ("COP28 UAE | COP28 delivers historic consensus in Dubai to accelerate climate action," 2023), the electrification of the transportation sector has been identified as a key to support this transition (IPCC, 2022), leading to growing demand for lithium-ion batteries (LIB). It is important to question the role of fossil fuels in the production of electric vehicles. Graphite, because of its conductivity, its stability, its capacity to intercalate lithium ions, and its availability, is the main industrial option for LIB anodes (Nzereogu et al., 2022), sometimes blended with a low share of silicon (Asenbauer et al., 2020). Graphite is also the first material in LIBs by mass (IEA, 2021a). As a consequence, graphite has been flagged as a strategic material for the energy transition by the US (USGS, 2017), the EU (European Commission, 2020) and China (UNEP, 2016). On the other hand, graphite production is heavily dependent on crude oil refining.

Graphite is either synthetic and graphitized from a carbon precursor, or natural and mined as an ore before purification. Graphite anodes usually comprise both natural and synthetic graphite (Abdollahifar et al., 2022). However, natural graphite usually exhibits lower performance in batteries than its synthetic counterpart (shorter lifetime, slower charging time), due to inconsistent purity (Abdollahifar et al., 2022). Furthermore, the development time (8–10 years) for opening new graphite mines and refining facilities (Buchert et al., 2020), the unequal distribution of graphite deposits, with China concentrating 65 % of global production (USGS, 2023), the health (Jara et al., 2019) and environmental impacts (CDC, 2022) related to graphite mining and refining limit the potential of natural graphite for future LIB anodes. Synthetic graphite also shows downsides, such as a higher carbon footprint due to high energy use in the production, with 4.86–13.8 kg CO_2-eq/kg for synthetic graphite compared to 2.1–7.75 kg CO_2-eq/kg for natural graphite (Buchert et al., 2020; Engels et al., 2022; Manjong et al., 2021; Rui et al., 2022; Surovtseva et al., 2022; Zhang et al., 2018). Because of rapid synthetic graphite production expansion, combined with the long development time of opening new graphite mines, the share of synthetic graphite in batteries has risen in recent years, reaching up to 90 % in 2023 (Abdollahifar et al., 2022; Pan, 2024; Schmuch et al., 2018). The main carbon precursor to synthetic graphite production is petroleum needle coke, a byproduct of petroleum refining (Harry, 1989). The development of electric vehicles, using graphite as the battery anode, will decrease the demand for petroleum production, therefore limiting the availability of petroleum needle coke required for producing graphite. As a result of growing concerns regarding synthetic

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graphite supply, it was recently added to the strategic raw material list from the European Commission (2023a). To understand to what extent supply constraints could arise with the development of vehicle electrification, it is important to quantify simultaneously the demand and supply of graphite.

Critical battery material value chains have been extensively studied using dynamic Material Flow Analysis (MFA), looking into cathode materials such as lithium (Hao et al., 2017), manganese (Sun et al., 2020) or cobalt (Sun et al., 2019). On the anode side, MFA of graphite has been used to show the importance of landfill stocks compared to in-use stocks in China (Rui et al., 2021) and to evaluate the performance of battery materials supply chains in the EU regarding efficiency and recycling (Ciacci et al., 2022). Often these analyses are backward-looking, focus on either natural or synthetic graphite and often exclude non-battery uses. Song et al. used MFA prospectively to estimate future graphite use in China (Song et al., 2019) and Zhang et al. included all graphite types and uses in their analysis of US graphite flows for 2018 (Zhang et al., 2023), but these studies are still constrained in their spatial and temporal scope. To inform governmental and industrial policies, battery development scenarios have been developed, showing that, in 2050, global graphite demand could be 4.8–24.7 times higher than in 2020 (IEA, 2021a). Using dynamic MFA, the MATILDA model was developed and used to determine the demand for several battery materials including graphite, in different scenarios (Aguilar Lopez et al., 2023). However, to our knowledge, no study has yet modeled simultaneously graphite supply and demand to anticipate potential production constraints.

Here, we address this gap using two models. First, we quantified the flows in the graphite value chain from 2020 to 2050, expanding the EV-fleet model MATILDA for battery demand, and using ECGA reports for non-battery demand. Second, we designed a simplified MFA of petroleum refineries to study and estimate the boundaries to needle coke production. In parallel, we conducted a qualitative assessment of natural graphite supply to evaluate its role in compensating synthetic graphite limitations. Using different scenarios concerning EV penetration, technological and social evolutions, we discuss the feasibility of producing enough graphite for the green transition. Section 2 describes the demand and supply models, Section 3 presents the main results regarding needle coke supply and demand whereas Section 4 discusses the main limitations to increasing the production of graphite.

2. Material and methods

2.1. System definition

This study covers the production and consumption of natural and synthetic graphite from 2020 to 2050, considering various sectors and including electric vehicle (EV) usage (Fig. 2).

Synthetic graphite originates from needle coke, i.e. the highest grade of coke with low impurity content and a low coefficient of thermal expansion (CTE), 80 % of which is of petroleum origin for availability and quality reasons (Clark, 2011; Jäger et al., 2010; Wagner da Silva and Clark, 2022). The coke is first heated to a temperature of around 1300 °C during calcination (process 7) to remove volatile matter and raise its carbon content. The precursor is then graphitized (process 10): heated at a temperature of 2500–3000 °C in an oxygen-free environment, the aromatic molecules of the material align to form a graphitic structure (Harry, 1989). Synthetic battery anode material (BAM) also requires spheronization and coating, whereas graphite for electric arc furnaces (EAF) electrodes is baked with a binder to reduce its porosity (Surovtseva et al., 2022).

Natural graphite originates from graphite ore mining and is then beneficiated (through several steps of flotation and grinding) to raise its graphite content from 3 to 52 % to 97–98 % (Ma et al., 2021; Schulze, 2014; USGS, 2017). BAM requires further processing steps. Spheronization consists of grinding and classifying to select particles of an optimal shape and size (15–30 μm) (Fischer et al., 2023). Purification (process 4), usually through hydrofluoric acid leaching, further raises the graphite content, and coating with coal tar pitch (CTP) improves conductivity, limits the irreversibility of the charge-discharge cycle and reduces reactions with the electrolyte (Han et al., 2015; Jo and Lee, 2019; Nozaki et al., 2009). We assumed that the byproduct of spheronization, graphite fines (small particles at >97 % graphite), can be used by all non-battery sectors.

Anode manufacturers aim to use the optimal mix of natural and synthetic graphite as a compromise between performance, price, and resource availability, as synthetic graphite is of more reliable quality but usually comes at a higher price (Abdollahifar et al., 2022; Schmuch et al., 2018). These are mixed and made into electrodes for EV batteries. After their use in vehicles, batteries can be recycled through various methods, but recycling incurs graphite losses and reduces its quality. Notably, pyrometallurgical recycling does not recover graphite (Sommerville et al., 2021).

Petroleum refining is a complex system that converts crude oil (or petroleum) into different products such as gasoline, diesel, jet fuel, and gases. Its goal is to maximize the output of the lighter, more valuable fractions: diesel and gasoline. As the simplified system in Fig. 2a shows, needle coke production (as a byproduct) includes the following processes: atmospheric distillation (AD), vacuum distillation (VD), fluid catalytic cracking (FCC), hydrocracking (HC), reforming, the delayed coking unit (DCU) and the gas plant. Some processes, such as hydrotreatment and isomerization, and some chemicals (ethylene, BTX) have been ignored as they were not considered relevant to study the needle coke production dynamics.

2.2. Mathematical model and data

As shown in Fig. 1, the "demand model" describes the dynamics of the global EV fleet and non-battery sectors to determine the demand for graphite and its raw materials, graphite ore and needle coke. All the processes in the graphite supply chain were characterized to determine the transfer coefficients between inflows and outflows as well as the carbon or graphite content of the different flows. The natural and synthetic graphite production figures were then validated against other studies. Scenarios for the graphite demand for new batteries and the available graphite scrap from EOL batteries were extracted from the MATILDA model (Aguilar Lopez et al., 2023). For non-battery sectors, the demand is extracted from the European Carbon and Graphite Agency (ECGA) outlook, estimating the annual demand based on the compound annual growth rate (CAGR) for the periods 2020–2030 and 2030–2050 (ECGA, 2022). The model and data are described in the SI – A.2. and are present in a Zenodo repository.

The supply model focuses on needle coke production. It calculates the upper boundary for needle coke production in future scenarios. Similarly to the demand model, the different processes were characterized to determine their inflows, outflows, and the yields in the system, in particular using the PRELIM model (Abella and Bergerson, 2012). To adjust the yield of the different processes and reduce uncertainty on the destination of flows, data reconciliation between crude oil input and petroleum production output was used. As an example, this reconciliation determined the share of atmospheric gasoil sent to the FCC and HC processes. The crude oil inflow as well as the different fuel outputs (diesel, gasoline…) were quantified using OECD statistics (OECD, 2019).

2.3. Scenarios

The scenarios for demand and supply are both built on the STEP, APS, and NZE from the IEA (2021b). In the different scenarios, the demand for needle coke can therefore be compared to the maximal theoretical production.

Demand scenarios are defined using six parameters: EV penetration, vehicle stock size, battery chemistries scenarios, recycling technology,

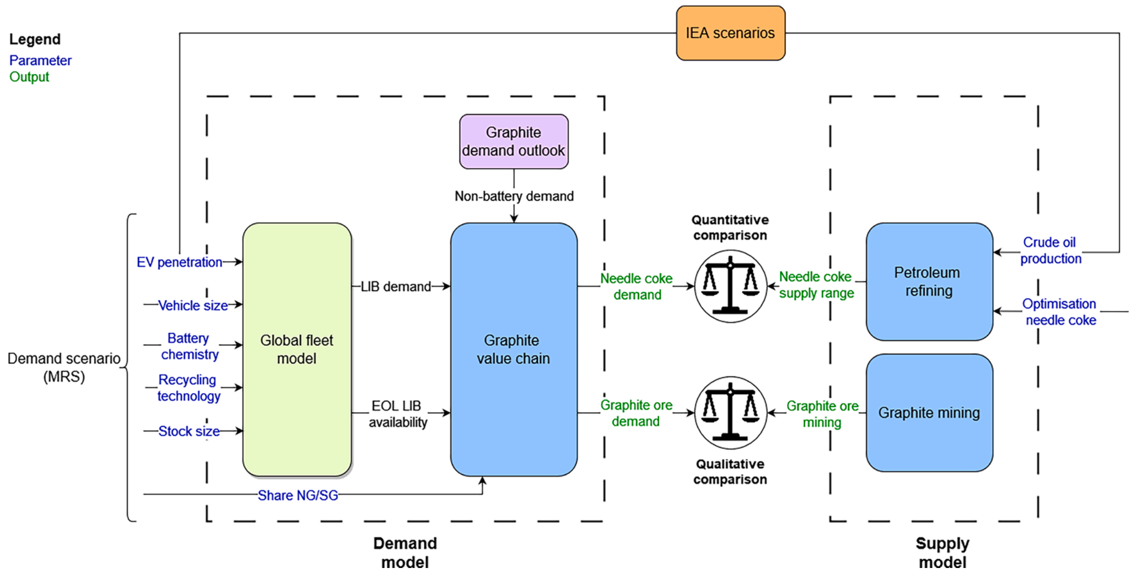

Fig. 1. Modeling flowchart. Graphite demand and supply are modeled independently, but both depend on the IEA scenarios. Graphite demand for batteries is calculated from the MATILDA model (Aguilar Lopez et al., 2023) whereas the demand outlook from the European Carbon and Graphite Association provides non-battery demand. Based on the graphite value chain, the demand for needle coke and graphite ore is then calculated. On the other side, an MFA of petroleum refineries provides a range for future needle coke supply, whereas a qualitative assessment of graphite mining was conducted to evaluate its potential limitations.

vehicle size (all MATILDA parameters) and the share of natural and synthetic graphite in batteries (additional parameter), possible values for the parameters are in supplementary table S3. All combinations of these parameters generate 4455 scenarios. To illustrate the results of the model, 6 scenarios were selected, built from the material requirement scenarios (MRS) in the original article describing MATILDA (Aguilar Lopez et al., 2023). The scenarios describe different storylines as shown in Table 1. Scenarios 1 and 2 are the least ambitious (STEP), the latter focusing on technological changes, scenario 3 is a baseline with moderate EV penetration (APS). Scenarios 4 (two variants) and 5 are Net Zero scenarios, the two first showing the high end of demand for natural and synthetic graphite and the latter describing an ambitious approach, where material demand is kept low thanks to high recycling and behavioral changes. The share of natural and synthetic graphite in the battery production was adjusted to the storylines and assumed constant over time (further described in the SI). Non-battery demand is identical in all scenarios. 2020 is the starting point for the different scenarios.

On the supply side, the input of crude oil was scaled depending on the IEA scenario. Faster electrification leads to lower crude oil production, as transportation is the main driver of crude oil production, which in turn limits the availability of needle coke. To consider variations in the refinery system, two limits to the supply are calculated, one assuming no changes in refining (baseline range), and one where refinery processes are modified to maximize the output of needle coke maximized (breakthrough range). For natural graphite, the USGS data for reserves and production of graphite ore were analyzed (USGS, 2023).

2.4. *Uncertainty analysis*

On the demand side, an uncertainty analysis was conducted on the 6 different MRS scenarios. The uncertainty analysis was only conducted on the graphite cycle, assuming no uncertainty on the primary data inputs. Here the goal is to give a range of uncertainty for the raw material demand (needle coke and graphite ore) for a given graphite demand. The uncertainty on the flows of graphite reflects potential knowledge gaps on the graphite system, but also how it could evolve in the future with technological improvements.

The Pedigree matrix approach was used to assign a probability distribution to each parameter (Ciroth et al., 2010; Funtowicz and Ravetz, 1990; Laner et al., 2016). The quality of each parameter is determined by 5 indicators: reliability, completeness, temporal correlation, geographical correlation and technological correlation, and an associated uncertainty is then calculated for each parameter. Using an Uncertainty Analysis tool for MFA (Dittrich, 2023), a Monte Carlo analysis was performed to determine the uncertainty of the flows in the system for every year of our six MRS scenarios. The method for the Uncertainty analysis is further detailed in SI A.3.

3. Results

3.1. *Global graphite cycle in 2022*

Fig. 2 shows the flows in the synthetic and natural graphite production in 2022, the use in battery and non-battery sectors as well as the recycling from EOL batteries. In 2022, batteries are not yet the main graphite consuming sector, but the electrification of transportation

Table 1
Summary of scenario parameters, as reported in Aguilar Lopez et al., 2023 with additional share parameter.

Scenario	Vehicle stock	EV penetration	Chemistry	Vehicle size	Recycling	Share NG
MRS1	Medium	Slow (STEP)	LFP	Constant	Pyrometallurgy	80 %
MRS2	Medium	Slow (STEP)	NCX	Shift to large	Pyrometallurgy	20 %
MRS3	Medium	Medium (SD)	BNEF	Constant	Pyrometallurgy	50 %
MRS4-SG	High	Fast (Net Zero)	Next gen BNEF	Constant	Hydrometallurgy	20 %
MRS4-NG	High	Fast (Net Zero)	Next gen BNEF	Constant	Hydrometallurgy	80 %
MRS5	Low	Fast (Net Zero)	Next gen BNEF	Shift to small	Direct	50 %

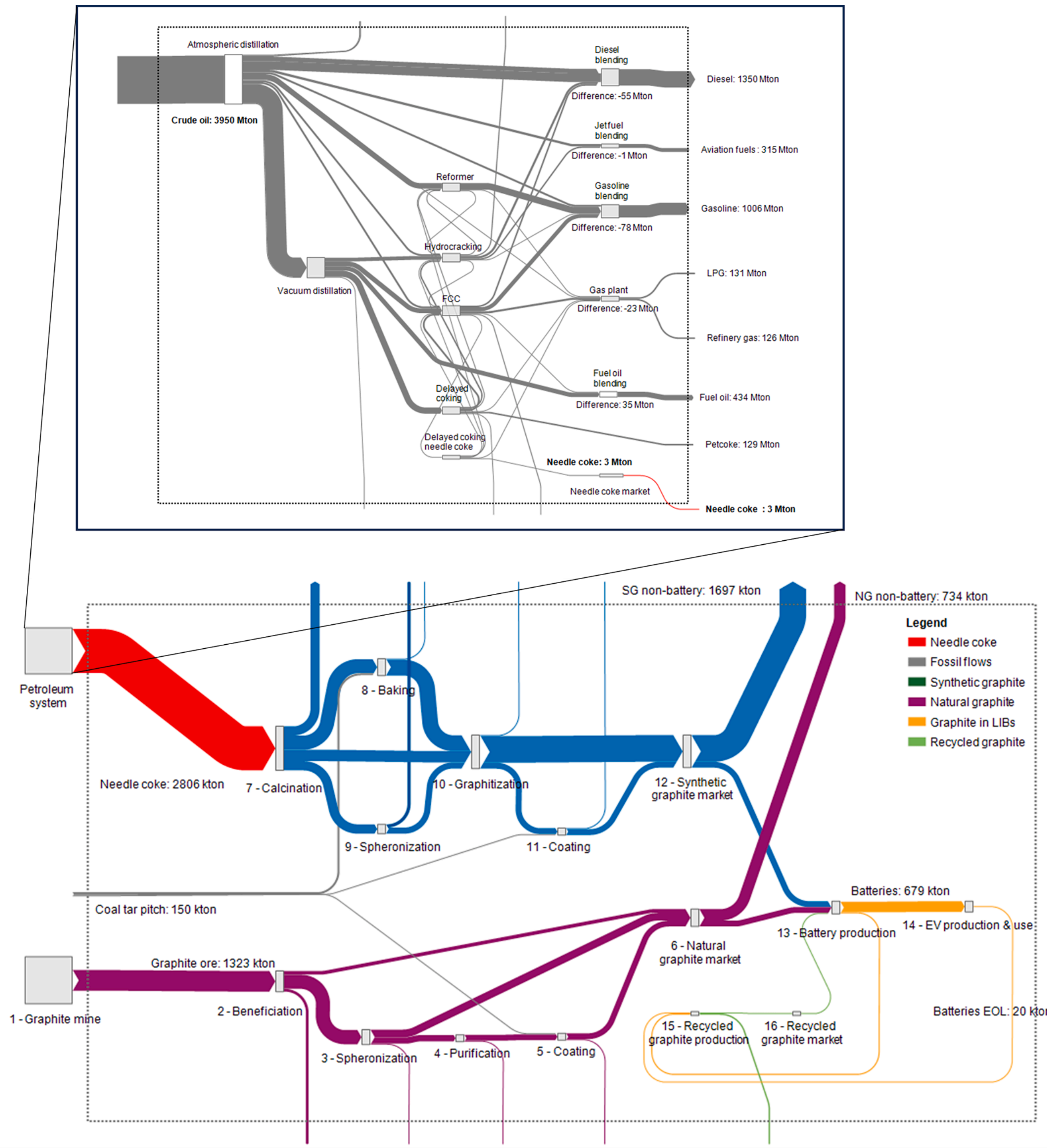

Fig. 2. Sankey diagram of the global graphite cycle quantified for 2022, with a zoom on needle coke production in petroleum refineries. The red flow in the top and bottom subfigures represent the same flow of needle coke but both figures are at different scales because the masses of the flows in both figures differ by 3 orders of magnitude. Unlabeled flows exiting the system are losses from the different processes. In 2022, more graphite is produced for non-battery uses, especially synthetic graphite for EAF electrodes.

transforms the graphite industry in all scenarios. The different routes for production relate to different end products, as the baking process for example is specific to EAF electrodes, whereas spheronization is specific to BAM.

3.2. Scenarios for graphite demand

The range of raw material demand in the scenarios is very large, as shown in Fig. 3 most of the demand originates from EVs and there is still large uncertainty concerning the global development of EVs, as well as new battery technology which can impact the graphite content. The demand for needle coke and graphite ore follows the same trends in the different scenarios because we assume that the share of natural versus synthetic graphite is constant over time for a given scenario. The main difference between both is the demand from the non-battery sectors (area under the lowest scenario) which is significantly higher for needle coke than graphite ore due to synthetic graphite electrodes for EAFs. Social parameters, such as vehicle ownership or the evolution of vehicle size also have a large influence on the future demand for graphite and its precursors. In the 6 selected MRS, needle coke demand varies from 4.3 Mt (MRS5) to 24.1 Mt (MRS4-SG) in 2050 whereas graphite ore demand varies from 1.3 Mt (MRS5) to 25.7 Mt (MRS4-NG).

Uncertainties for the 6 MRS were also computed, these uncertainties regarding raw resources are large (Fig. 5), especially in the later years. This uncertainty accounts for the completeness and robustness of data sources, and to what extent they relate to the geographic and time scope of our study. In the future, there is growing uncertainty about how the processes in graphite production might evolve, and the uncertainties

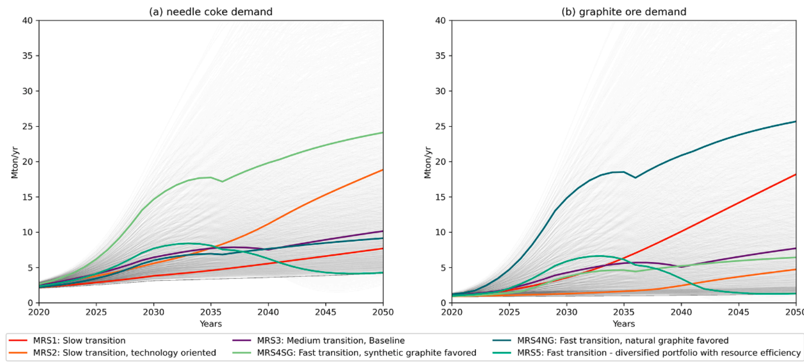

Fig. 3. Demand for (a) needle coke, (b) graphite ore in the 6 selected demand scenarios. All other possible combinations are shown in light gray in the background. The range for graphite demand in the future is wide, and multifactorial, depending on the extent of the transition to EVs but also technological and societal changes. The temporary decrease in demand around 2035 in MRS4 and MRS5 is due to changes in battery chemistries, see (Aguilar Lopez et al., 2023).

grow accordingly.

3.3. Scenarios for graphite supply

The top subfigure in Fig. 2 for needle coke production shows that petroleum needle coke production is a very small fraction of refineries output. Needle coke is only a byproduct, and refineries try to maximize gasoline and diesel output. Most refineries do not have a dedicated delayed coking unit for needle coke production. Increasing graphite demand will likely push refiners to produce more needle coke.

Fig. 5 shows the baseline and breakthrough supply ranges for needle coke in the background. The supply range for needle coke assumes that all feedstocks are redirected to needle coke production and ignores competition with other sectors. Due to the dependence of synthetic graphite production on crude oil extraction, the more ambitious the scenarios are in terms of climate mitigation and phasing out of oil, the higher the risk for supply constraints. In the STEP scenario, oil production is nearly constant until 2050 whereas the APS and NZE scenarios show decreasing needle coke availability due to decreasing oil production.

To lower the pressure on needle coke supply, anode manufacturers might be tempted to use natural instead of synthetic graphite, as reflected in the MRS4NG scenario. However, graphite ore mining is also subject to limitations. Production and reserves of graphite are unequally distributed (Fig. 4): China is currently the largest producer with 65 % of global graphite production, while Brazil and Turkey have the largest reserves with only medium and moderate production. When it comes to processing graphite for producing battery anodes, nearly 100 % of the production capacity is concentrated in China (International Energy Agency, 2023a). The rapid development of natural graphite production in Eastern African countries, especially Madagascar (+57 % in 2022 compared to 2021) and Mozambique (+136 %) could be a key to diversifying the supply of natural graphite (USGS, 2023).

3.4. Comparison between supply and demand scenarios

Fig. 5 displays the demand for needle coke in the 6 MRS compared with supply ranges. In the STEP scenarios, needle coke supply is rarely constrained, electrification is limited. It can be observed that needle coke demand for MRS1 and for most of the other combinations (thin gray lines) remain within the baseline supply range. If the EV industry should not struggle with using graphite in the STEP, it is important to highlight that this scenario corresponds to a 2.6 °C global temperature increase by 2100 (IEA, 2021b), with dramatic consequences on global climate. These scenarios correspond to low ambition regarding the electrification of transportation. Both MRS1 and MRS2 do not include recycling of graphite and show few technological or societal changes. They illustrate a future where no systemic changes are needed in our

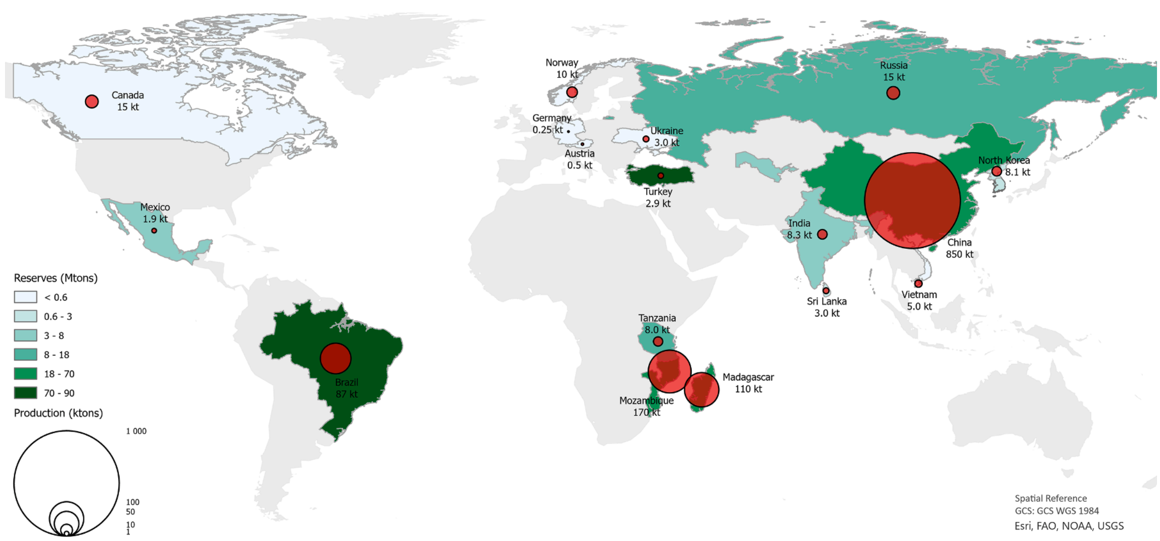

Fig. 4. . Production and reserves of natural graphite in 2023, from USGS Commodity survey (USGS, 2023). China, although it does not have the largest graphite reserves, is by far the largest producer for natural graphite. However, mining in East African countries (Madagascar, Mozambique, and Tanzania) is rapidly expanding.

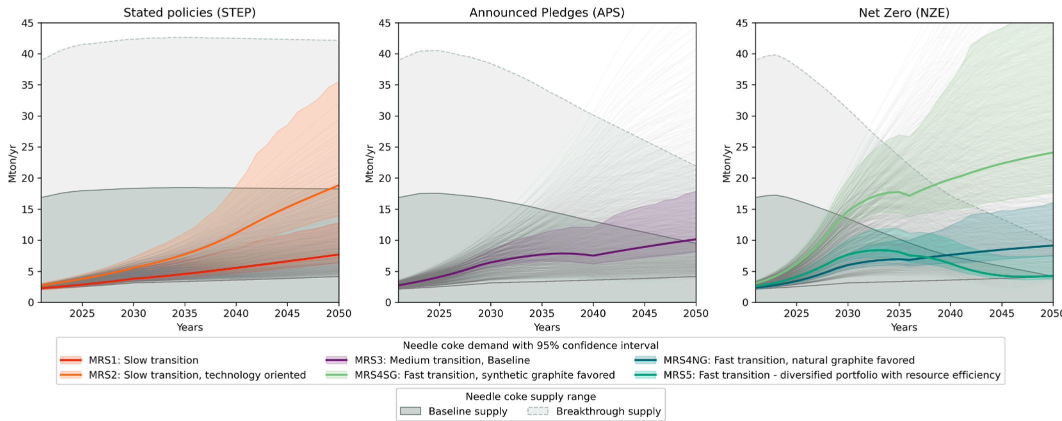

Fig. 5. Needle coke demand and supply range compared in the 3 IEA scenarios, with the 6 selected Material Requirement Scenarios (MRS) and all other combinations in the background. Two supply ranges are considered, the baseline range where refineries dynamics remained unchanged and the breakthrough supply where refinery processes maximize needle coke output. Faster transitions result simultaneously in higher needle coke demand and lower needle coke supply potential, increasing the risk of supply shortages.

production systems, which makes them easily attainable, but not ambitious enough to mitigate climate change. Under the APS scenario which corresponds to 2 °C global warming (IEA, 2021b), the slow shifting out of crude oil leads to possible needle coke supply constraints in the later years of the model, as shown by the intersection of the demand in MRS3 (baseline scenario) and the baseline supply around 2049. In this scenario, the transition to electric vehicles is more ambitious and allows for decreasing global oil production. In the NZE scenario, which is the only scenario that limits temperature increase to 1.5 °C by 2100 (IEA, 2021b), needle coke is quickly constrained, which can lead to supply shortages starting in 2030. Both MRS4-SG and MRS4-NG exceed the baseline supply range, around 2030 and 2040 respectively. The former even exceeds the breakthrough supply range before 2040. Even when considering the uncertainty range, all fast transition (NZE) scenarios exceed baseline supply, except for MRS5. However, the uncertainty has an impact on estimating when these shortages might occur. For example, in MRS4SG, shortages are expected between 2027 and 2032, depending on whether we consider the low end or the high end of the uncertainty range. Of the selected scenarios, only the MRS5 combines ambitious climate goals and secure needle coke supply for graphite production.

4. Discussion

4.1. Model assumptions

In this paper, we have adopted a conservative approach to the modeling parameters of supply and demand. When observing how supply and demand compare in Fig. 5, it is important to keep in mind that the supply scenarios tend to overestimate the range of needle coke production. It is assumed that all the available feedstock of fluid catalytic cracking decanted oil is used for producing needle coke. In contrast, a large share is currently used by the shipping industry as heavy fuel, accounting for 35Mtons or 8.8 % of shipping fuel supply (Wagner Da Silva and Clark, 2022). For all decanted oil to be used in needle coke, the shipping sector would have to find alternative fuels. Besides, a large share of this decanted oil might not be suitable for producing needle coke, because of its sulfur content. High sulfur content in needle coke leads to sulfur puffing during graphitization, damaging the structure of the graphite, and reducing its performance in battery anodes. But sulfur is also a constraint for the maritime sector, facing regulations (IMO, 2020). Because of quality concerns and competition with other sectors, needle coke supply constraints could emerge earlier than our model suggests.

The one exception to our conservative approach is the assumption that only petroleum needle coke can be used as a graphite precursor. This type of needle coke makes up for 80 % of all precursors, the other 20 % mainly being coal-based needle coke (Wagner da Silva and Clark, 2022). As coal is even more targeted by climate regulations than petroleum and given that all IEA scenarios predict a phasing out of coal in the next decade, this assumption is not likely to significantly affect the results for the later decades.

The uncertainty analysis highlights that technological changes in graphite production can have a large impact on the demand for needle coke and subsequently on the occurrence and timing of graphite shortages in the different scenarios. On the supply side, the breakthrough scenario was introduced to model a situation where refiners prioritize needle coke production, driven by its increasing value. This scenario implies systemic changes to refining as it would require large investments targeted towards synthetic graphite production. It should therefore be interpreted as an exceptionally optimistic scenario for needle coke supply.

4.2. Strategies for avoiding supply disruptions

As observed in Fig. 5, most of the net zero scenarios lead to production bottlenecks in the next decade due to the phasing out of petroleum, yet crucial to produce synthetic graphite. One strategy to reduce synthetic graphite supply constraints is to use more natural graphite in batteries (scenario MRS4NG). Graphite ore reserves are plentiful (USGS, 2023) and most of the scenarios never exceed them, graphite ore depletion is not a major concern. On the other hand, the distribution of resources and infrastructure raises geopolitical issues, 65 % of global graphite mining and most of the refining capacity is concentrated in China. As the demand for LIBs is global, dominated by China, Europe and the US (International Energy Agency, 2023b), many countries view the reliance on a single third country supplier as a strategic issue. This is for example highlighted in the EU by the European Critical Raw Materials Act (European Commission, 2023b). Beyond geopolitical considerations, expanding the production of natural graphite faces environmental and social concerns. While graphite is an inert material, its processing is not exempt from environmental issues: mining tailings are usually released in water bodies, graphite refining releases dust that causes respiratory issues (CDC, 2022) and its purifying uses harmful chemicals (Jara et al., 2019). More importantly, it will be challenging to increase natural graphite production at the speed required for net zero scenarios: it typically takes 8–10 years to establish new natural graphite production, whereas synthetic graphite production can be scaled up in less than 2 years (Buchert et al., 2020). In the meantime, the EU has enacted a ban on thermal vehicles starting from

2035 (European Parliament, 2022), leaving little time to develop new natural graphite projects. This may benefit countries with lower environmental, social, and governance standards (Mancini et al., 2020). The decarbonization of the transportation sector could then result in a delocalization of environmental and social impacts to less advanced economies. As it exhibits lower quality than synthetic graphite, the competitive advantage of natural graphite historically relied on a lower price (Abdollahifar et al., 2022). Shifting the production to mostly natural graphite would therefore have consequences on battery performance, and most importantly lifetime (Glazier et al., 2017). Decreasing battery longevity would raise the demand not only for graphite but for all battery materials, some of which are already constrained. Another issue with the production of natural graphite for batteries is the overproduction of graphite fines, small graphite particles, which are a byproduct of spheronization. Graphite fines have been consumed by the pencil and recarburizing industries, but these sectors can no longer absorb the growing production. We conservatively assumed that all non-battery natural graphite can be replaced by graphite fines in our scenarios, but the production of graphite fines will still exceed demand from these sectors in less than a decade in most scenarios. To avoid serious waste production of a valuable byproduct and extend the availability of natural graphite, it would be crucial to develop processes to revalorize graphite fines into anode material (Abrego-Martinez et al., 2023) to reinject them in the battery value chain.

Our model shows that it is possible to achieve high electrification of the transportation sector using mostly synthetic graphite, but only when combining systematic recycling with resource efficiency measures (see Fig. 5). In the fast transition scenario that illustrates this possibility (MRS5), vehicle ownership decreases, meaning that alternative modes of transportation are developed (walking, cycling, public transportation). Vehicles tend to be smaller, and batteries are reused. At the same time, 90 % of the graphite from end-of-life LIBs is recycled for the battery sector (no downcycling). Recycling plays a key role in improving value chain circularity, mitigating the environmental impacts of graphite production, and securing material supply, particularly in regions like Europe with high battery usage but low graphite production. With 90 % graphite recycling, the graphite system exhibits a nearly circular graphite value chain, aligning fast electrification and adequate needle coke supply. Reaching such a high recycling rate means overcoming technological challenges, especially concerning the degradation of the graphitic structure during battery use such as disordering, lithium intercalation and solid electrolyte interphase formation (Buchert et al., 2020; Moradi and Botte, 2015). Today, battery anodes cannot contain more than 10 % recycled graphite ("Personal communication with Gunstein Skomedal and Robin Hansson, VIANODE," 2023), a limit which will be reached within a decade in the most ambitious scenarios.

4.3. Graphite alternatives

The tension on the supply of natural and synthetic graphite could also be relieved by using alternative anodes in LIBs. Extensive research explores the conversion of biocarbons into biographite to diminish the dependency of graphite production on hydrocarbons. Lab-scale experiments demonstrate the feasibility of producing high-quality biographite from diverse biocarbons, such as lignocellulosic feedstocks, glucose, and medium-density fiberboard (Banek et al., 2018; Gomez-Martin et al., 2018; Sagues et al., 2020; Zhao et al., 2017). Despite promising performance in lithium-ion cells, challenges in scalability and cost may limit the widespread adoption of these methods at an industrial scale.

Hard carbon or silicon are already used as graphite alternatives for battery anodes. The former is however less popular than graphite due to its lower coulombic efficiency and cycling underperformance (Guo et al., 2023). The latter is promising due to its extraordinary capacity — 10 times higher than graphite — but it undergoes high volume change during cycles (He et al., 2021). Silicon is only used blended with graphite, rarely making up for more than 10 % of the anode mass (Asenbauer et al., 2020), and is therefore not an alternative to fully replace graphite in the short term.

Beyond these graphite alternatives, the shift to battery chemistries less reliant on graphite, such as sodium-ion batteries (NIB) or potassium-ion batteries (KIBs), emerge as promising solutions. Sodium is much more abundant than lithium, making it 30 times cheaper (Slater et al., 2013). While NIBs currently face challenges such as lower capacities, limited cycling performance, and safety concerns (Xie et al., 2020), ongoing research suggests that their potential use in specific applications could increase. As graphite does not intercalate sodium ions, hard carbon or conversion materials are privileged for SIB anodes (Perveen et al., 2020; Xiao et al., 2019). Potassium is also an abundant element and KIBs demonstrate a higher energy density than their sodium counterparts, but they are limited by large volume variations, low reversible capacity, and safety hazards (Min et al., 2021; Zhang et al., 2019). The development of SIBs and KIBs, driven by factors such as lithium supply constraints and increasing LIB price, could negatively impact the demand for graphite. Considering the limitations of KIBs and NIBs, LIBs with graphite anodes would probably remain the dominant chemistry for high-performance batteries. Still, lithium and graphite supply constraints may encourage vehicle manufacturers to explore more diverse chemistries. The fates of graphite and lithium are therefore interlinked and the supply constraints for one material might impact the demand for the other.

5. Conclusions

This study modeled graphite demand and supply under different scenarios. The range of the results is high, and largely depends on the level of ambition regarding the electrification of the transportation sector, but also on the developments of natural graphite mining and petroleum refineries. A common result to all Net Zero Scenarios is however that phasing out of oil while increasing the use of synthetic graphite will most likely lead to supply constraints. There exists no technological silver bullet for producing battery anode material in sufficient quantities in the next decades while meeting climate goals. To ensure a fast electrification of the transportation sector, our results show that technological solutions, such as systematic recycling and the development of alternative anodes, are necessary but not sufficient. Behavioral, policy and cultural changes leading to lower vehicle ownership and smaller vehicles are crucial to ensure that graphite demand remains within limited bounds. Facilitating societal changes instead of relying solely on uncertain technological advances is also key to reducing risk in the transition to carbon-free transportation.

CRediT authorship contribution statement

Francis Isidore Barre: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Romain Guillaume Billy:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Fernando Aguilar Lopez:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Daniel Beat Müller:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The Python code is available on Zenodo (https://doi.org/10.5281/zenodo.10973890) including the database with the used data. The supporting information contains the remaining data. The results can be visualized at http://129.241.153.168:8052.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107709.

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