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How can liquid and transparent financial markets be created for lightly traded critical minerals?

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Executive Summary

This report assesses the challenges and opportunities in developing more liquid financial markets for lightly traded critical minerals. The growing global demand for critical minerals, driven by technological advancements and the green transition, has exposed structural weaknesses in existing mineral markets. Despite their strategic importance, markets for critical minerals remain illiquid, opaque, and highly volatile, limiting the ability of producers and consumers to hedge risks and accurately price these resources.

Key issues identified include price opacity, thin trading volumes, supply chain concentration, and the absence of standardized financial instruments like futures and derivatives. The dominance of certain countries in the mining and processing of critical minerals, particularly China, adds to geopolitical and economic vulnerabilities. Junior miners face significant barriers to entry due to high capital costs and limited access to financing.

This report identifies three categories that lightly traded minerals fall into: those ready for financialization (Category 1), those with potential for future financialization (Category 2), and those not yet ready for financialization (Category 3). Within these three categories, the report proposes a series of targeted policy recommendations for governments to help minerals move into the next stage of financialization which include:

- Resource surveying and mine development (Category 1)
- Grant funding and loans to incentivize private sector involvement (Category 1)
- Basic scientific research funding into graphite and vanadium (Category 1)
- Sectoral Hub creation for commercialization of graphite- and vanadium-utilizing technologies (Category 1)
- Government procurement of graphite- and vanadium-utilizing technologies (Category 1)
- Regulatory changes to spur financialization of graphite and vanadium (Category 1)
- Diversifying Supply Chains and Increasing Domestic Production (Category 2)
- Government Investment and Financial Support (Category 3)

As well, this report also offers recommendations for institutional investors, mining producers, and other financial actors to build out the financial mechanisms required in each stage of the process. They include:

- Collaboration within government-organized sectoral hubs (Category 1)
- Investment in commercialization and product development of graphite- and vanadium-utilizing technologies (Category 1)
- Creation of Spot Market in Partnership with Price Reporting Agencies (category 2)
- Investor Confidence and Market Transparency (Category 3)

Implementing these measures would reduce market volatility, improve liquidity, and enhance the resilience of critical mineral supply chains, supporting long-term economic and strategic stability.

High-level visual summaries of our findings are found through Figures 1 and 2. Figure 1 visualizes the categorization of the 13 critical minerals researched in our report, and where they fall in the stages towards market financialization. Figure 2 then takes the minerals that this report divides into three categories and illustrates how the report divided the minerals for categorization based on important economic and geopolitical factors such as market size, production concentration, and trade restrictions.

Figure 1. Degree of readiness for financialization among shortlisted minerals

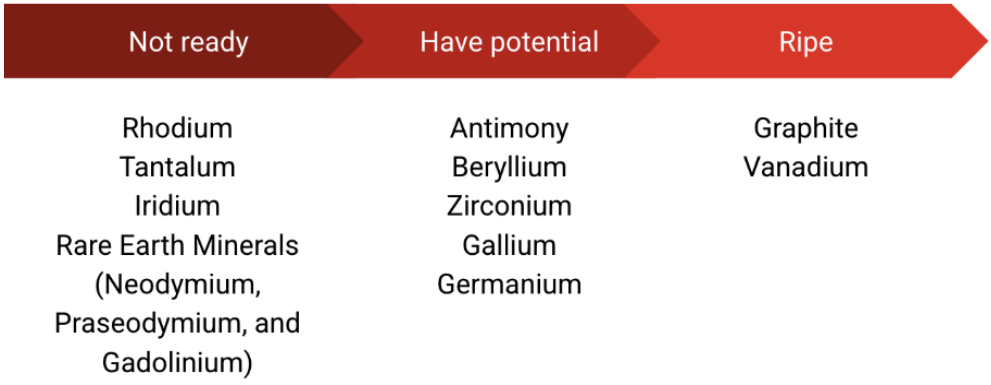


Figure 2. Heat map of shortlisted minerals' characteristics

Category	Minerals	Market Size	Physical production volume	Production concentration by company	Production concentration by country	Demand concentration by country	Trade Restrictions
Recently Financialized	Lithium						
Ripe for Financialization	Graphite						
	Vanadium						
Potential for Financialization	Antimony						
	Beryllium						
	Zirconium						
	Gallium						
	Germanium						
Not Ready for Financialization	Rhodium						
	Tantalum						
	Iridium					(N/A)	
	Rare Earth Minerals (Neodymium)						
	Rare Earth Minerals (Praseodymium)						
	Rare Earth Minerals (Gadolinium)						

Legend:

1. Market size
    a. Small Market (USD 1B – 5B)
    b. Medium Market (USD 5B – 15B)
    c. Large Market (USD 15B+)
2. Physical Production Volume (Metric Tons Annually)
    a. Low Production Volume (<10,000 metric tons)
    b. Medium Production Volume (10,000 – 500,000 metric tons)
    c. High Production Volume (500,000+ metric tons)
3. Concentration of Production by Company
    a. Low Concentration (No dominant producer, fragmented market, no company over 20%)
    b. Moderately Concentrated (4–6 companies hold ~30–50% market share)
    c. Highly Concentrated (1–3 major producers dominate production, >50% market share)
4. Concentration of Production by Country
    a. Lower Concentration (No single country produces >50%)
    b. Highly Concentrated (1 country produces >50%)
5. Concentration of Demand by Country
    a. Lower Concentration (No single country demands >50%)
    b. Highly Concentrated (1 country demands >50%)
6. Trade Restrictions
    a. Yes (Subject to Export/Import Restrictions, Bans, or Controls)
    b. No (No Major Trade Restrictions Noted)

Introduction

As global demand for critical minerals surges, especially for batteries and military uses, there is a growing need to create liquid and transparent markets for lightly traded minerals. These minerals are more lightly traded in volume and in major exchanges than minerals like gold, silver, copper, and nickel or other commodities like crude oil, natural gas, and coal.

Despite strong future demand projections, existing critical mineral markets remain volatile and opaque, posing significant challenges for North American and allied producers. Rising costs and unpredictable sales prices complicate long-term investment planning, while China's dominance in production and market infrastructure exacerbates these issues.

Establishing more liquid financial markets for critical minerals could mitigate these challenges by offering hedging opportunities and supporting the forecasted demand growth. Banks could better price risk to finance projects; manufacturers that use critical minerals could lock in commodity prices to price their end products and secure their profit margins; and producers of critical minerals could manage volatility to attract financing. However, these markets are still in their early stages and face significant hurdles. For investors and producers, the central question is whether better market structures could create a more stable investment climate and provide clearer demand signals.

This project explores the potential for more liquid financial markets for critical minerals, focusing on lithium and other lightly-traded metals.

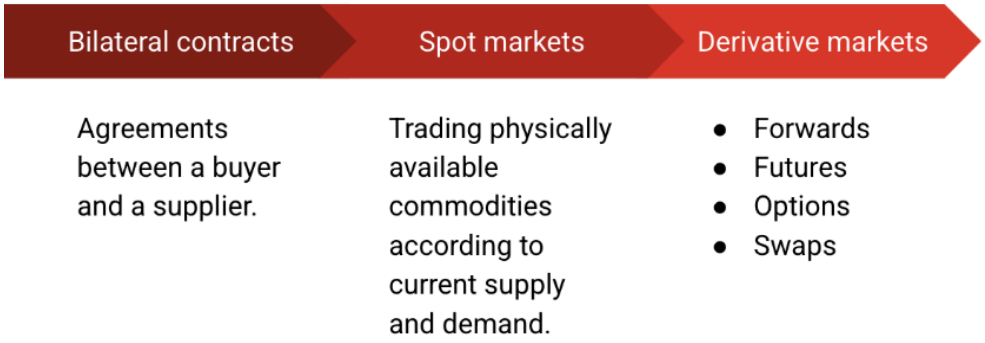
Research Questions

- What are the current gaps in the financial markets for critical minerals, and how do they affect investment in supply chains?
- Could the development of liquid financial markets improve access to capital and risk management tools for producers and investors?
- Are there specific financial instruments or channels that would be particularly beneficial for entities in this sector?

Typical process of commodity financialization

The financialization of commodity markets typically evolves from direct trading to the use of complex financial instruments.

Figure 3. Typical process of commodity financialization



Non-Derivatives

Commodity transactions are initially conducted through bilateral contracts privately agreed upon by suppliers and buyers. When prices agreed upon in these contracts can become the industry standard, a benchmark pricing system forms. This was the case with long-term iron ore pricing agreements between Australian miners (such as Rio Tinto and BHP) and Japanese steelmakers (such as Nippon Steel and JFE Steel) in the 1960s-70s. As these prices became standardized, spot markets developed for trading physically available commodities according to current supply and demand.

Derivatives

Companies can adopt derivative instruments as a form of financial insurance to manage price risk, especially considering the volatility of commodity prices. The development and evolution of these instruments in commodity markets are not necessarily linear, depending instead on the nature of the commodity and industry needs.

Forwards are generally considered the earliest form of commodity derivatives. They enable a buyer and seller to manage risk by establishing a bilateral over-the-counter agreement to buy or sell a commodity at a fixed price on a future date. Forwards are often more tailored to specific delivery dates and quantities of goods, making it preferable for companies that need to secure a certain amount of a commodity at a particular time in the future.

Futures were formalized in 1865 on the Chicago Board of Trade. They allow commodity buyers and sellers to lock in prices for future transactions. Futures are standardized contracts traded on exchanges, with central clearing to reduce counterparty risk and increase liquidity and transparency.

Options in commodity markets are contracts that grant a buyer or seller the right, but not the obligation, to buy or sell a commodity at a set price ('strike price') on or before a specific date. There are two options: 'call options' for buying and 'put options' for selling. By the 1980s, options on commodities became common because they avoided the inflexibility of futures contracts. Traders and investors could reduce losses from price movements while exploiting favourable price changes. For example, an electric vehicle (EV) battery manufacturer and a lithium mining company are worried about rising and declining lithium prices. The EV manufacturer can buy a call option on lithium at $20,000 per ton with an expiration in six months. If lithium prices rise to $25,000 per ton, they can exercise the option and buy at a lower price. If prices fall, they let the option expire and buy at market price. Meanwhile, the mining company can buy a put option to sell lithium at $20,000 per ton. If lithium prices drop to $15,000 per ton, they can exercise the option and sell at $20,000. If prices rise, they let the option expire and sell at market price.

Swaps were introduced in the 1980s and are settled periodically, unlike forwards, which are settled at contract maturity. In swaps, a buyer and seller agree on a fixed price, even though the prevailing market price may increase or decrease ('float') during the contract period. Returning to the example of the EV manufacturer and lithium mining company, suppose they agree on a swap contract where the EV manufacturer pays a fixed price of $20,000 per ton of lithium for the next 12 months. The mining company, in return, pays or receives the difference between this fixed price and the actual market price each month. If the market price rises to $25,000 per ton, the mining company pays the EV manufacturer the $5,000 difference, ensuring the EV manufacturer still pays only $20,000 per ton. If the price falls to $18,000 per ton, the EV manufacturer pays the mining company the $2,000 difference, so the mining company still receives $20,000 per ton.

Case study of commodity financialization–Lithium

To offer insight into the feasibility and marketability of lightly traded minerals, it is useful to first examine the case of lithium in its financialization development from a lightly-traded to moderately traded commodity. Examining the case of lithium is a necessary endeavor for it faced many of the same structural challenges pre-financialization that lightly traded minerals face today, and the recency of its financialization means that its development is a useful guide when determining what policies should be implemented for current lightly traded minerals.

This section will go in chronological order from lithium's pre-financialization, to its expansion as a financialized commodity and what the future holds for lithium, that might determine what the future holds for minerals not yet commoditized.

Lithium's Rise to Financialization

Lithium's importance has long been in the creation of EV batteries, and as EVs began to gain popularity in the mid-2010s, so did the demand for lithium. At this time, lithium transactions were through long-term (often multi-year) fixed-price contracts, the price set to the needs of the individual battery-makers (Wojewska et al., 2024). With these contracts, producers set prices, offering security against a volatile market and leverage in price-setting power, making the actual value of lithium disparate from what the market might have demanded had lithium been traded in a more robust market.

As a lightly traded commodity with minimal market liquidity and price transparency, lithium's growing actual and perceived criticality made it susceptible to price bubbles (Restrepo et al., 2023). Beginning in 2016, price surges were witnessed in all lithium markets, explained by the increases in lithium demand from China due to the production and growing consumption of EVs, which caused a large market overreaction for the commodity.

As demand for lithium rapidly increased, supply became squeezed. With the help of price reporting agencies (PRA), in 2017/2018, the first spot markets for immediate delivery emerged to address the supply crunches, creating more frequent transactions at prices more reflective of lithium's market demand.

By late 2020, with PRA benchmarks and spot prices available, there was a significant influx of investors into lithium equity markets. This surge drove up stock prices, contributing to rising spot prices and enabling producers to sell at spot prices rather than long-term fixed contracts to

maximize profit margins (Wojewska et al., 2024). The criticality of lithium fueled high interest in the industry, prompting both major and junior producers to expand operations. At the same time, financial actors, such as hedge funds, mutual funds, and banks, increased their engagement in the sector.

In the absence of liquid derivative markets for direct exposure to lithium price movements, equity investment became the primary means for investors to capitalize on rising lithium prices. Large speculative inflows into lithium equities led to rapid stock price increases for major producers and facilitated record-high exploration spending in the sector. Junior producers, responsible for over two-thirds of lithium exploration, rely heavily on equity financing due to their limited access to bank loans and debt markets. Their financial viability depends on high-risk capital investments, given the uncertainties associated with exploration, project development, and fluctuating commodity prices (Wojewska et al., 2024).

A second important source in the lithium industry's financialization was debt financing. Debt is a significant source of finance for major mining companies. For example, prominent lithium producers like Albemarle and SQM have issued multiple bonds to fund the expansion of their operations in Chile and other locations. Lithium producers can also benefit from access to green finance through green bonds and debt securities issued to generate capital for climate-related or environmental projects. The first green bond was issued by the World Bank in 2008, and since then, the green bond market has rapidly gained traction. The high demand for green bonds highlights the increasing significance of green investments, whereby investors often accept a lower interest rate (known as the 'greenium') than traditional 'brown' or 'vanilla' bonds, thus providing more favourable lending conditions for green projects. (Wojewska et al., 2024).

However, spot prices differ with each transaction. They are highly volatile and continuously changing due to perceptions of supply and demand, shifts in geopolitical events, and strategies of global production network (GPN) actors. While producers increasingly rely on spot markets, they still face significant exposure to price risks due to the volatility of spot prices. As a result, they tend to prefer long-term contracts, though, since late 2021, many producers have shifted toward variable, short-term prices within these contracts rather than fixed prices. This transition was made possible by the emergence of short-term price benchmarks, which PRAs developed based on the growing frequency of transactions in the spot market. These benchmarks became essential for price-setting in contracts, enabling producers and their shareholders to demand more flexible, market-driven pricing structures to benefit from higher spot prices (Wojewska et al., 2024). However, the spot prices were still volatile, and there was a need for better hedging mechanisms to protect against risk exposure.

The emergence of spot prices marked an important step in lithium's path to financialization. Spot prices created in part from price reporting agencies helped legitimize the lithium market and allowed for the accurate reflection of lithium's price based on supply and demand factors. This, in turn, gave investors greater comfort and confidence in investing in the companies involved in the lithium sector and for lithium producers to sell their lithium based on true market value. Thus, a burgeoning lithium market was ripe for complete financialization with the development of derivative markets to protect against the speculative risk of spot price trading and became what was once a lightly traded mineral into a more heavily traded commodity.

Creation of derivative markets

Shortly after the increased trading of lithium spot prices and the influx of equity investment into lithium markets came the first derivative markets for lithium. The first derivative market was officially created on May 3, 2021, by the Chicago Metal Exchange (CME) for lithium hydroxide cash-settled futures contracts (Koralewski, 2024). Cash-settled futures means there is no physical exchange of the underwriting product once the contract expires. Instead, financial profits or losses come from the difference between the contract price and the market price in cash.

From their press release, several steps in the launch of the lithium derivatives market can be inferred (CME Group, 2021):

1. Market research and demand assessment: CME and industry experts analyzed the growing need for a lithium futures market driven by the rising demand for EVs.
2. Collaboration with industry actors: CME worked with battery manufacturers, miners, traders, and analysts to design a contract that meets industry needs.
3. Benchmark price selection: Fastmarkets' lithium hydroxide price assessments were chosen as the reference price for settling contracts.
4. Regulatory approval: Regulatory bodies like the U.S. Commodity Futures Trading Commission (CFTC) had to review and approve the contract.
5. Contract design and specifications: CME defined key contract details, such as contract size, pricing mechanism, expiration dates, and cash settlement method.
6. Implementation and promotion: CME launched lithium futures trading and promoted it to industry, traders, and investors.

The lithium derivative market further expanded later in 2021, when on July 19, 2021, the London Metal Exchange (LME) announced the launch of its own lithium hydroxide cash-settled

futures contract, with the express purpose of offering pricing and risk management tools to support the EV transition and a greener economy. LME's Chief Sustainability Officer, Georgina Hallet, explained that creating the lithium futures market is important in delivering transparency and access to metal markets. Moreover, the LME has been working with lithium market stakeholders for over "three years to gain an in-depth understanding of the commercial and technical nuances of an industry that is still in the preliminary stages of its maturation" (London Metal Exchange, 2021). Three years of derivative market development meant that lithium was only viewed as an economically viable commodity that required price risk management tools with the emergence of a spot price.

The introduction of derivative markets alongside PRAs' benchmarks allows for trading lithium futures, facilitating price risk management through hedging or speculation on lithium price trends. For hedging to be effective, physical market participants need to align their contract price benchmarks with those underlying the cash-settled futures. This alignment strongly connects PRA benchmarks, futures, and physical trade prices (Wojewska et al., 2024).

Amongst financial investors, cash-settled futures are attractive hedging tools. Investors are not burdened with the risks that come with the delivery or withdrawal of a metal to and from warehouses, just the change in price value at the end of the contract. Moreover, investors can gain exposure to lithium price developments without holding the lithium themselves or invest in the companies involved in the process, offering greater capital flexibility.

However, financial investors are not the only ones who see the attractiveness of trading on derivative markets. International traders, EV-actors, and lithium-producing and extraction companies have also increased their presence in the lithium derivative markets to adopt hedging strategies.

For players in the EV industry, barriers to hedging were low because they were already accustomed to managing risk across various other traded metals. So, they had high technical experience and the infrastructure required for hedging, making it easier to navigate lithium prices' volatility in their supply chains. For lithium producers, the increased volatility of prices at the onset of the emergence of PRA spot prices and the lack of credit provided by banks to those not engaged in financial hedging meant they had to adopt derivative trading as well (Wojewska et al., 2024).

Current state of the lithium futures market

The launch of lithium futures coincided with a period of price volatility in the spot market, highlighting the importance of using futures to manage volatility. Figure 4 shows how traded volumes and open interest in lithium futures gradually rose and peaked in June 2024, reflecting expanding market adoption and liquidity.

The evolution of the forward curve in the lithium futures market, shown in Figure 5, reflects growing trust in and maturity. Looking at the most recent data, there was a very steep contango in Q1 2024, and investors hesitated to buy forward at a 40% premium over the spot month for the March 2025 expiry. As the market continued to grow and mature in Q2 2024, the forward curve flattened, and open interest in the deferred months increased, meaning that investors interpreted the flattening curve as an opportunity to hedge.

Figure 4. CME lithium hydroxide volumes and open interest (Koralewski 2024; originally source: CME Group)

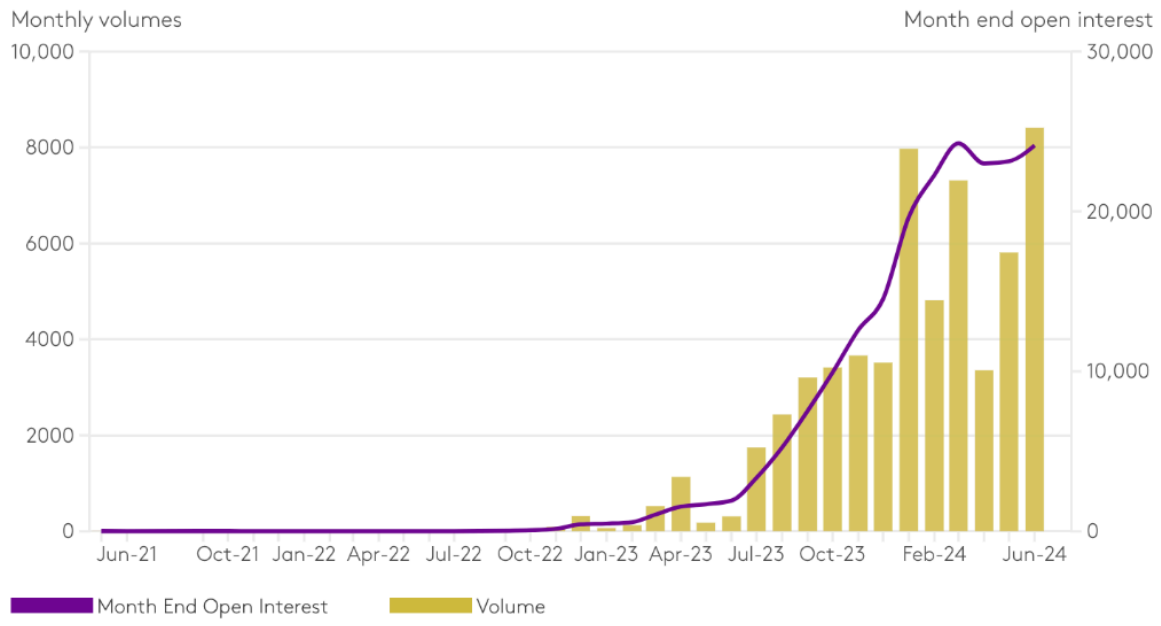
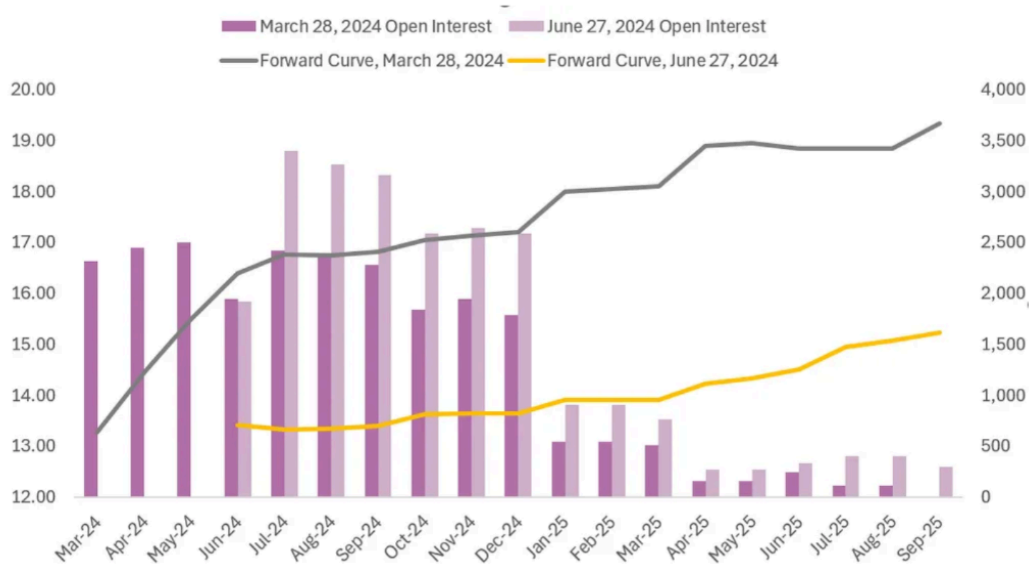


Figure 5. Lithium Futures Forward Curves. (Koralewski 2024; originally source: CME Group)



Similarities with the financialization of iron ore

The financialization of lithium is similar to that of iron ore, notably the transition towards spot-based, index-linked pricing. Iron ore experienced a significant transition in 2010 with the launch of futures trading on the Singapore Exchange (SGX), which facilitated the growth of the spot market by providing credible risk management tools. Lithium is now experiencing the same development, with financial instruments increasingly becoming part of its supply chain (Koralewski, 2024).

These two commodities also register high interaction between Chinese onshore futures markets and global exchanges. The launch of iron ore futures at the Dalian Commodity Exchange (DCE) did not compete with SGX; instead, it increased liquidity offshore. Similarly, physically delivered lithium carbonate futures launched by the Guangzhou Futures Exchange caused trading volumes to balloon, strengthening liquidity on the CME Group's COMEX exchange. This illustrates how domestic market activity could drive global financialization, sustaining physical and derivative markets (Koralewski, 2024).

Future projections of the lithium market

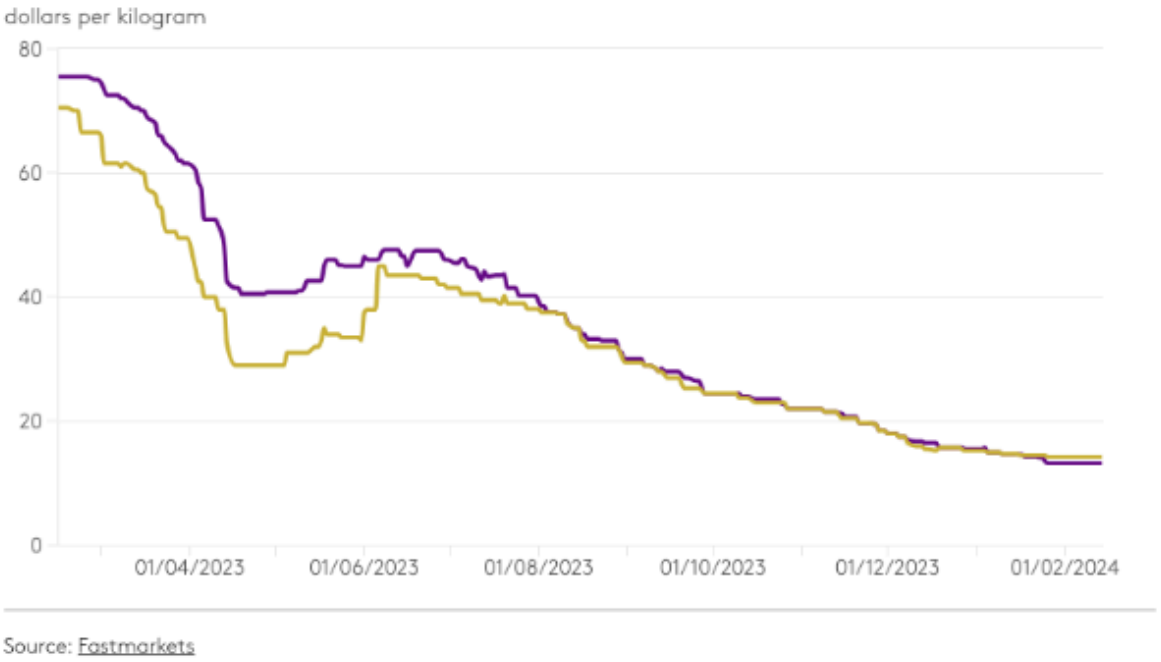
Based on the iron ore market's development, we could project the growth of the lithium futures market. If lithium futures develop as iron ore did in its first five years, future volumes could

reach 0.33 times and 0.71 times the physical market in 2025 and 2026, respectively. Moreover, iron ore futures are trading at 3.5 times the physical market, suggesting that the lithium futures market also has the potential to exceed the physical market (Koralewski, 2024). As an integral commodity to electric vehicles and energy storage systems, the global push towards decarbonization and net-zero emissions by 2050 means lithium will remain in the global economy for the foreseeable future.

However, for lithium markets to expand, demand growth, financing needs, bank participation, financial counterparties, broker engagement, and consumer hedging are all necessary. Greater producer participation is also essential. Important to consider is that these are still early days, and questions remain regarding the availability of necessary financial tools, the potential emergence of new contracts, and whether the market structure will follow a centralized liquidity model or a more segmented approach, similar to energy and some agricultural markets (Koralewski, 2024).

Challenges still exist in the lithium market for greater financial development, particularly in the Western world and their push for the energy transition. Despite long-term growth trends in EV and green energy sectors, they lag behind projected expectations due to lower-than-expected demand, causing prices to fall in sectors such as lithium, which are key in EV production. Moreover, the performance of EV sales is regional, where growth in the sector continues in China. However, there is weaker-than-expected growth in Europe and North America, and in South America and Africa, sales are marginal (Fastmarkets, 2024). The declines in prices seen in figure 6 after years of a precipitate rise in prices and the culmination of financialization, affect participants throughout the lithium supply chain, which can have devastating impacts on the future vitality of the lithium market. Price falls result in production halts, strategic reviews, staff cuts, and cost cuts that can make it hard for mineral industries to recover quickly (Ouerghi, Stibbs, & Perry, 2024).

Figure 6. Lithium hydroxide and lithium carbonate prices throughout 2023 and into 2024 (Ouerghi, Stibbs, & Perry, 2024)



Aside from price volatility and dramatic price changes, lithium can be a difficult market to invest in because lithium must be stored under specific conditions with a shelf life as low as six months. Users of lithium batteries are particular about their specifications, becoming more selective of what they are buying when there is a surplus in supply. These two factors can create distressed sellers looking to destock their holdings in lithium, making the commodity an unattractive market (Ouerghi, Stibbs, & Perry, 2024). Additionally, western governments that wish to meet environmental and socially desirable goals through laws and regulations that force companies to set up ESG and other sustainability programs can make entry into the market for lithium producers more difficult, constraining the market further.

While challenges exist, so do opportunities. To address the anticipated growth in industry demand by the decade's end, enhanced incentive pricing is necessary to facilitate the energy transition. Grasping market values is essential for spotting pricing opportunities and formulating growth strategies in the lithium sector. For instance, how much importance is placed on sustainability? Could it warrant the higher costs associated with processing technologies? Albemarle is testing closed bids while honing in on price discovery to evaluate product value based on sustainability, sourcing, and specifications. Norris anticipates that as the lithium sector expands, lithium traders will have greater chances to enter and enhance their market presence (Fastmarkets, 2024).

Members of the global south, such as Africa, are drawing significant interest as a growth region boasting large-scale, high-grade resources. Although the continent is rich in lithium resources conducive to cost-effective operations, it faces challenges like conflict, nationalism, and variable infrastructure across different areas. While electric vehicles dominate lithium demand, emerging technologies, such as advanced lithium metal batteries, present substantial value for the defence sector and national security. Governments increasingly recognize energy storage and access to such technologies as strategic assets, given their relevance beyond electric vehicles—like grid security and modern warfare—where lithium plays a pivotal role.

Lastly, emerging trading exchanges are looking to enter the lithium and commodities derivative markets, expanding the future potential of lithium's market liquidity and financialization. For example, in February 2025, Abaxx Exchange announced the forthcoming introduction of a lithium carbonate futures contract, set to begin trading on March 7, 2025. This contract aims to cater to the rising demand for battery metals vital for the energy transition, which is not found in traditional LME or CME exchanges (Reuters, 2025). This development signifies an increase in market liquidity for lithium, enabling investors to hedge against price fluctuations and attract more market participation. The financialization of lithium through such trading instruments allows for more effective resource allocation in the growing demand for battery metals, which is crucial for renewable energy technologies. Additionally, the emergence of new trading platforms like Abaxx reflects a shift in how commodities are traded, as traditional exchanges may not cater to the market's evolving needs. Overall, this indicates a significant advancement in the financial landscape surrounding lithium, which is vital for supporting sustainable energy initiatives.

Methodology of Original Research

Our original research followed a structured, multi-step approach to identify and analyze lightly traded critical minerals and assess their potential for financialization. Our methodology involved the selection of minerals based on defined parameters, case study analysis and categorization of selected minerals.

Selection of Critical Minerals

Our study began with the International Energy Agency's (IEA) list of critical minerals as a foundational reference. To refine our focus, we explored the concept of 'lightly traded minerals' and found that no formal definition exists. Consequently, we established our own parameters to define this category for the purposes of our research. The parameters included:

1. A global market size less than or equal to USD 1 billion

This threshold focuses on minerals with relatively small market sizes, which often lack deep liquidity, standardized trading mechanisms, and significant investor interest. A smaller market size may indicate that the mineral is still emerging in industrial applications, has limited production scalability, or is constrained by geopolitical or technological barriers. By targeting minerals within this range, policymakers and investors can identify opportunities to build market capacity and promote diversification.

2. Volatile price trends, indicating a lack of mature financial instruments

Price volatility suggests that the mineral market lacks stability, likely due to supply chain disruptions and limited hedging mechanisms through financial derivatives. This criterion highlights minerals where market intervention — such as government incentives, strategic reserves, or policy support — may help stabilize supply and demand dynamics. Addressing volatility also makes these minerals more attractive for long-term industrial use and investment, reducing risks for stakeholders in the supply chain.

3. Production concentrated in countries with feasible and transparent global markets

Ensuring that production occurs in transparent and well-regulated markets helps mitigate risks related to corruption, resource nationalism, and supply chain disruptions. Transparent markets provide clearer regulatory frameworks, lower geopolitical risks, and more predictable trade environments, crucial for long-term investment and industry adoption. This criterion also aligns with sustainability and responsible sourcing initiatives, ensuring ethical and stable supply chains for critical minerals.

However, China's dominant position in the production of many critical minerals presents a prominent caveat. Essentially, many minerals which were prioritized for current financialization or for future financialization were selected despite their high concentration of production in China. This is precisely because their value to key current and future technologies was considered very high. Recommendations for these compounds include focus not only on financialization, but also development of more diverse extraction and processing to help mitigate China's dominant role - a facet which if not addressed would prevent many of the benefits of financialization from being realized.

Applying these parameters enabled us to systematically filter the IEA's list and select 13 minerals that satisfied these criteria. In addition to meeting the requirements of the research paper, these minerals also exhibited high demand in current energy markets. They have diverse industrial applications, further reinforcing their relevance for financialization analysis.

Case Study Approach: Learning from Established Markets

To explore pathways for financializing lightly traded minerals, we analyzed lithium and iron ore as case studies. These minerals were selected due to their well-developed financial markets, providing a benchmark for understanding the processes and mechanisms contributing to a successful financialization framework. By examining these cases, we derived insights into the conditions, market structures, and regulatory considerations required to develop a financial market for other critical minerals.

Categorization of Selected Minerals

Following the selection and analysis phase, we further categorized the 13 identified minerals into three distinct groups based on their readiness for financialization and strategic importance:

1. Minerals Ready for Financialization
2. Minerals with Key Importance and Potential for Future Financialization
3. Minerals with Strategic Importance but a Complex Financialization Landscape

By systematically selecting minerals based on well-defined parameters, conducting case studies on existing mature markets, and categorizing the selected minerals, our research provides a structured approach to understanding the financial viability of market-relevant lightly traded critical minerals. This methodology ensures a comprehensive analysis of market conditions and identifies key pathways for integrating these minerals into global financial markets.

Mineral categorization

Category 1: Minerals ready for financialization

Minerals in this category have established and increasingly mature markets, driven by increasing industrial demand and the presence of transparent price discovery mechanisms. These minerals play a crucial role in sectors such as EV batteries, energy storage, and various industrial applications, where demand continues to rise due to technological advancements and global shifts toward sustainability. Their supply chains are diversifying, reducing dependence on a single country or region, and investment in production capacity is accelerating, particularly as governments and private entities recognize their economic and strategic value. Standardized pricing for some of these minerals further enhances their financialization potential, allowing them to be integrated into commodities exchanges, financial instruments, and investment products such as future contracts.

Several factors support the financialization of these minerals. High market demand and established uses ensure that these resources remain in consistent demand, particularly in industries driving the clean energy transition. Additionally, an emerging market infrastructure, including developing trading platforms and price benchmarks, contributes to market stability and facilitates broader participation from institutional and retail investors. Growing supply chain transparency is another key factor. Diversifying beyond dominant producers—such as China, which has historically controlled the market for many critical minerals—helps mitigate geopolitical risks and improve long-term price stability. Lastly, the potential for commodity-backed securities and futures contracts enhances liquidity in these markets, attracting greater investment and paving the way for full-scale financialization.

Graphite

Graphite is a key strategic mineral that is ripe for financialization for a variety of factors. Firstly, graphite is an allotrope of carbon, and a factor contributing to its importance is its diverse applications (Mawlankar & Prasad, n.d.). These diverse applications directly result from its unique metallic and non-metallic properties, such as high electrical conductivity, thermal conductivity, stability at high temperatures, and lubricity. These unique properties are caused by the unique arrangement of carbon atoms within graphite, which are contained within a crystalline structure (ibid).

The diverse properties of graphite make it an essential material in electronics, with the compound widely used within batteries. Furthermore, graphite is central in steelmaking and other applications such as lubrication (Grand View Research, n.d.). The utilization of graphite in

these examples – among others – makes it a central mineral to produce a myriad of electronics, automobiles, aerospace products, within the construction sector, renewable energy, and many other arenas (Mawlankar & Prasad, n.d.; *Main Uses of Carbon and Graphite*, n.d.). Because of the geographic focus of many of these industries, China, South Korea, and Japan are all leading consumers of graphite. China also holds a dominant position within consumption, responsible for most global graphite production and up to 90% of refinement and reprocessing (Mawlankar & Prasad, n.d.; Pistilli, 2025). This gives the country an extremely influential position in the graphite supply chain and, thus, the production of all products which depend on it.

As a result of graphite's wide usage, it is unsurprising that the graphite market is very large. Estimates, however, vary depending on the current market size, ranging from $7 billion to $17 billion USD. In addition, market growth rates also vary – between 4.8-15.1% – but are united in all, showing moderate to strong positive growth within the next 5 to 10 years (Fortune Business Insights, 2025; Grand View Research, n.d.; Markets and Markets, n.d.; Mawlankar & Prasad, n.d.).

Currently, the graphite market is not financialized, as sales are only made through direct vendor-to-recipient sales. As a result, while spot prices are available, financial derivatives of graphite are not present (*Graphite Pricing*, n.d.). The size of the graphite market and the widespread economic importance of graphite to many products mean there is a great potential benefit for graphite purchasers for the creation of financialized commodity markets – as it would significantly increase the transparency of supply, demand, and pricing. As a result, graphite markets must be financialized, and in association with that, key consumers outside of China must pursue both domestic production and refinement/processing of graphite. The combined action of financialization with the de-focusing of China in the graphite production and processing supply chain is key to increasing the market's fluidity, transparency, and dependability. It is also key to preventing individual actors from limiting supply for individual geopolitical goals, a privilege China already exercises.

Vanadium

Vanadium, though currently not as widespread in its utilization as graphite, is also prominent as a critical mineral integral to existing technologies and prospective future systems. For a few key reasons, Vanadium is also being recommended as ready for financialization.

Firstly, Vanadium is a versatile transition metal that can be utilized to strengthen steel alloys while improving resistance to wear and corrosion. Aside from this application – the largest source of Vanadium consumption and for which the compound is often considered

irreplaceable – Vanadium is also used extensively in various aerospace, automotive, chemical, construction, pharmaceutical, and experimental applications (Fortune Business Insights, 2025). An example of a prospective application of Vanadium is within the Vanadium Redox Flow Battery (VRFB), a promising future battery technology which may be utilized for large-scale energy storage and allow for better integration of renewable power systems into electrical grids (Vanadium, 2017; *Vanadium and its Uses*, n.d.).

Vanadium's production is heavily concentrated in China, followed by Brazil, Russia, and South Africa (Pistilli, 2024; Vanadium, 2017). While this is a limiting factor to financialization, the production is still more diverse than other critical minerals, providing greater potential for immediate financialization with a more fluid market. Because of the diversity of Vanadium's production, price competition between key producers has already occurred (Fortune Business Insights, 2025). This showcases an environment that can take advantage of more free and open information, akin to what would be found in a financialized, open commodity market with financial derivatives. The Asia-Pacific region is also the largest consumer of Vanadium, with the large-scale industrial production and scientific development of growing Asian economies – especially China – being the largest factor for this regional consumption concentration (Fortune Business Insights, 2025). These economies, as well as those in North America and Europe, are taking significant steps to decarbonize, which will provide a new source of demand for Vanadium as it can be utilized in diverse and innovative technologies which are central to decarbonization (Fortune Business Insights, 2025; Vanadium, 2017; *Vanadium and its Uses*, n.d.).

The diverse applications and sources of future demand yield a current market size projection of about $4 billion USD. In contrast, the many sources of future demand reveal a healthy CAGR of approximately 4.4% until 2032 (Fortune Business Insights, 2025). The already competitive and large Vanadium market also demonstrates a strong basis for future growth. Combined with the fact that Vanadium trading already has adopted some market characteristics and the compound is key for future economic productivity, it is evident that the Vanadium market should be financialized to ensure free, open, and liquid purchase and sale of the resource.

Category 2: Minerals with potential for future financialization

These minerals are becoming increasingly strategic commodities due to their applications in emerging technologies, defence, and other critical industries. However, they currently lack essential conditions for financialization, such as liquid trading markets, diversified supply chains, and standardized pricing mechanisms. While their demand and technological significance are

growing, they are not yet mature enough for full-scale financialization. Factors such as limited market infrastructure, supply chain concentration, and price opacity prevent them from being easily traded as financial instruments. Despite these barriers, ongoing investment in domestic supply chains, expansion of alternative applications, and potential regulatory support indicate that these minerals could become viable for financialization in the future.

Key barriers to financialization are market immaturity and limited trading volume. Unlike widely traded commodities such as gold or lithium, these minerals do not yet have well-developed spot or futures markets, making it difficult for investors to engage with them on a large scale. Another major challenge is supply chain concentration, as the production of certain minerals, such as gallium and germanium, is dominated by a few countries, particularly China. This dependence increase the risk of market volatility, price manipulation, and geopolitical uncertainties, discouraging financialization. Additionally, these minerals lack standardized pricing mechanisms, meaning there is no globally accepted benchmark for their valuation, further complicating their entry into the financial market. Afinal challenge is uncertain long-term demand, as many of these minerals serve niche applications that may be disrupted or replaced by technological advancements.

Despite these obstacles, several factors suggest that these minerals may become financialized. One of the most significant drivers is increased government investment in domestic supply chains to reduce reliance on foreign producers and secure critical mineral supplies. Furthermore, developing alternative applications could expand the commercial use of these minerals, as seen with antimony in next-generation battery chemistries or gallium and germanium in the semiconductor industry. Additionally, creating industry-specific financial products, such as derivatives or other commodity-backed securities, could enhance market liquidity and pave the way for broader financialization. While these minerals are not yet ready for full-scale financialization, ongoing developments in supply chain diversification, technological applications, and market infrastructure indicate they could reach that stage shortly.

Antimony

Antimony is a mineral utilized in infrared detectors, light-emitting diodes (LEDs), semiconductors, batteries, ceramics, flame-retardant materials, paints, and other applications. The antimony market is estimated to be valued at approximately US$1.08 Billion as of 2024 and is projected to display a strong CAGR of 6.5% by 2032 (*Antimony Market Size*, 2025). China is a key producer of Antimony, creating about 48% of the world's supply, followed by Tajikistan and Russia (*Antimony Market Size*, 2025). The importance of Antimony to some key processes –

specifically in semiconductor manufacturing–has led to China'splacing export restrictions to reduce international supply (Baskaran & Schwartz, 2024).

While the above factors demonstrate that Antimony is an important compound in many supply chains, its financialization will not be pursued now. Firstly, its supply chain is insufficiently robust or diversified, with extensive concentration of production in a few countries such as China. Diversification of production and processing is key to creating the basis for a liquid market. Additionally, Antimony can be supplanted by alternatives in many of its current applications. Many of these alternatives – such as magnesium hydroxide, titanium, or zinc – often already possess extant financialized markets or are otherwise more readily available (*Antimony Market Size*, 2025). This reduces the urgency with which Antimony's market must be made more fluid and liquid, simply because the necessary research, financial, regulatory, and policy creation investment needed to create a market for Antimony is not commensurate with the relatively small increased benefit likely to be had by key stakeholders – especially buyers of Antimony for industrial production – if market financialization takes place.

Beryllium

Beryllium is a lightweight and highly conductive metal integral to many advanced technologies. As a result of its highly conductive nature and lightweight, it has many applications in aerospace structural materials, military technology, nuclear energy, medical devices such as CT scanners, and electronics such as capacitors (*Beryllium*, 2017). As a result, Beryllium also shows significant potential in future technologies associated with decarbonization. It has shown potential in many experimental applications – especially regarding the creation of exceptional metal alloys. The beryllium market is estimated to be valued at approximately US$3.8 Billion as of 2023 and is projected to display a significant CAGR of 4.2% by 2030 (Jaiswal, 2025). Unlike many rare Earth compounds, Beryllium is a rare example of China not being the leading or dominant producer. Instead, the United States is the largest producer of Beryllium, producing about 60% of the global supply, followed by China, Mozambique, and Brazil. The United States and, to a lesser degree, Europe and the Asia-Pacific regions are the leading consumers of Beryllium, largely due to the presence of aerospace and defence companies that utilize Beryllium in industrial processes in those regions (Jaiswal, 2025). The importance of Beryllium to key technologies – especially in the realm of advanced materials, aerospace, and novel electronics – has given it key importance in ongoing trade conflicts. The United States has introduced export restrictions in an effort to increase the international supply of Beryllium (Jaiswal, 2025).

Beryllium displays importance to key current and prospective technologies – signifying it is already being used as a pawn in trade disagreements. Nonetheless, its financialization is not to be pursued at this time. Akin to Antimony, its supply chain is insufficiently robust or diversified, with extensive concentration of production in a few countries such as the United States (Jaiswal,

2025). Diversification of production and processing is key to creating the basis for a liquid market. Additionally, Beryllium's longer-term utility, while significant, is still unclear. Many other elements – especially other light, ductile, and highly conductive metals – also have a propensity to be useful in electronics, aerospace, advanced materials development, and other applications currently held by Beryllium. As a result of a relatively large number of alternatives, Beryllium has less individual significance. This reduces the urgency with which Beryllium's market must be made more liquid, especially considering that infrastructural investment needed by governments, producers, processors, distributors, and consumers to create a market may not align with the relatively small increased benefit likely to be had by key stakeholders.

Zirconium

Zirconium is a greyish-white metal utilized in many diverse applications. It has strong corrosion resistance and can create advanced metal alloys with strong heat resistance. Thus, Zirconium is utilized in nuclear energy, aerospace applications, advanced metal alloys and ceramics materials manufacturing, various medical processes, the pharmaceutical sector, and many others. The zirconium market is estimated to be valued at approximately US$2.08 Billion as of 2024 and is projected to display a strong CAGR of 7.8% until 2034 (Kulkarni & Shivarkar, 2024). Australia is the largest producer of Zirconium, making about 40% of global production. This is followed by South Africa, which accounts for about 30% of the total, and China. Zirconium is consumed mainly in Asia-Pacific – about 50% of global demand, with the majority of the remaining half from North America and Europe (Kulkarni & Shivarkar, 2024).

While the above factors demonstrate that Zirconium is an important mineral to many supply chains, its financialization will not be pursued now. Firstly, its variety of production locations and the involvement of multiple mining companies means its extraction is quite diverse. Diversification of production and processing provides a strong basis for creating liquid markets. However, Zirconium does have the capacity to be supplanted by alternatives in a large number of its current applications (Kulkarni & Shivarkar, 2024). This reduces the urgency with which Zirconium's market must be made more fluid and liquid simply because the necessary research, financial, regulatory, and policy creation investment needed to create a market for Zirconium is not commensurate with the relatively small increased benefit likely to be had by key stakeholders – especially buyers of Zirconium for industrial production – if market financialization takes place.

Gallium

Gallium is a soft, silvery metal utilized in key technologies. It can make various alloys with low melting points and has shown great utility for creating semiconductors. Thus, Gallium – and specifically derivations of it which have been combined with other compounds such as Gallium arsenide and Gallium nitride – is integral to a vast array of different electronics. These include

items such as light-emitting diodes (LEDs), lasers, photovoltaic cells, electronics communications systems, and directly within the manufacturing of transistor architectures of semiconductors. Thus, Gallium is integral to many aerospace, military, and other sensitive applications (*Gallium Market Size and Research Report 2025-2034*, 2025). Gallium also has applications in biomedicine, such as in various testing mechanisms and therapeutics. The utilization of Gallium in these examples and the strong growth of many related sectors provide a wealth of demand for the compound. Nonetheless, the Gallium market has large variations in size estimates. These range from as small as $500 million to $7 to 8 billion (*Gallium Market Size and Research Report 2025-2034*, 2025). As expected, market growth values also vary significantly as a result, though virtually all information supports robust long-term growth from 4 to 7.5% per annum until about 2030 to 2035. Gallium is largely produced as a byproduct of the extraction of other compounds, often aluminum being a key example. China is by far the largest producer of zirconium, making about 80-98% of global production (*Gallium Market Size and Research Report 2025-2034*, 2025). The geopolitical importance of Gallium is also demonstrated by its application in some sensitive and breakthrough technologies and by the fact that China has introduced strong export restrictions to limit international supply (Cytera, 2023).

Despite Gallium's significant importance compounding to a myriad of technologies, its financialization is not to be pursued currently. Akin to Antimony, Gallium's supply chain is insufficiently robust or diversified. The extreme centralization of production in China with only a few key companies prevents the creation of a robust and open market. Diversification of production and processing is a strong prerequisite before the creation of liquid markets can be pursued. This is especially important for Gallium, as unlike many of the other compounds discussed, Gallium has relatively little capacity to be supplanted, with Germanium often being the only somewhat equivalent replacement (Cytera, 2023). There appears to be a large degree of chemical uniqueness offered by the compound, often meaning it cannot be replaced by many technological processes in which it is currently utilized (Cytera, 2023). As a result, even if Gallium is not currently ready for its market to be financialized, there is an urgent need for steps to be taken to develop and diversify the compound's production and processing locations, the number of companies involved, and the overall robustness of the supplier network. Only after such an increase in supply chain robustness can financialization be pursued.

Germanium

One of the few critical minerals quite similar to Gallium, Germanium is a lustrous, brittle and hard grayish-white metal. It physically resembles silicon and has semiconductor properties like silicon and Gallium. It can make various alloys with low melting points and has shown great utility for creating semiconductors. Thus, like Gallium, Germanium is integral to a vast array of different electronics – both current and prospective technologies in development (Nagrale, 2025). These include items such as light lenses and other optical systems, cameras, lasers,

photovoltaic cells, electronics communications systems, and directly within the manufacturing of transistor architectures of semiconductors (Nagrale, 2025). The overlap in utility for Germanium with Gallium is quite significant; as a result, Germanium is also integral to many aerospace and military applications. Gallium also has applications as a catalyst, making it useful for various chemical analysis and pharmaceutical and biomedical testing applications (Cytera, 2023).

The utilization of Germanium in these arenas and the substantial future growth of related sectors provide for strong demand. Nonetheless, just like Gallium, the Germanium market has significant variations in size estimates. These range from as small as $150 million to $3 billion. As expected, market growth values vary significantly, although all information supports significant long-term growth of about 3.5 to 7% annually until 2030 to 2035 (Nagrale, 2025). Germanium is primarily produced as a byproduct of the extraction of other compounds – just like Gallium, with zinc often being a key example. China is by far the largest producer of zirconium, making about 75-90% of global production (Nagrale, 2025). The geopolitical importance of Germanium is significant due to the many sensitive applications, and China has also implemented export controls to reduce international supply (Cytera, 2023).

Like Gallium, Germanium is important to diverse, militarily sensitive, or innovative technologies (Cytera, 2023). However, like Gallium, its financialization is not currently being pursued. Akin to Antimony and Gallium, Germanium's supply chain is insufficiently robust or diversified. The compound's extraction, processing, and overall production are centralized in China, with only a relatively small number of companies involved, preventing the creation of a strong, open market. Thus, just like Gallium, the first step should involve diversification of production and processing, as this is a strong prerequisite before creating a free, liquid market. Outside of Gallium, Germanium has few other compounds that can supplant it, and even then, Gallium is not a perfect one-to-one replacement by any means (Cytera, 2023). As a result, while Germanium is not currently ready for its market to be financialized, there is an urgent need for steps to be taken to develop and diversify the compound's production and processing locations, the number of companies involved, and the overall robustness of the supplier network.

Category 3: Minerals with Strategic Importance but Unready for Financialization

These minerals play a critical role in high-tech industries, defence applications, and energy technologies, yet their market characteristics make financialization challenging. Unlike more widely traded commodities, these minerals often suffer from supply chain opacity, extreme price volatility, and restricted production, making establishing a stable and investable financial market difficult. A handful of countries or companies often dominate their supply, creating

significant geopolitical and economic risks that deter broad market participation. Additionally, some of these minerals have low trading volumes and unpredictable pricing or are primarily extracted as byproducts of other mining operations, further complicating their potential for financialization. These factors collectively result in a lack of transparent pricing mechanisms, investment-grade data, and liquidity, making them unsuitable for integration into traditional financial markets.

A range of structural and market-related challenges hinder the financialization of these minerals. One of the most significant is extreme price volatility. The level of unpredictability makes it difficult to establish stable financial instruments such as futures contracts or commodity-backed securities. Another issue is opaque and restricted supply chains, as many of these minerals are mined in politically unstable regions or under the control of a few governments or private entities. This lack of diversification leads to supply manipulation, unpredictable export policies, and security-of-supply concerns, discouraging institutional investment. Furthermore, low market liquidity prevents the establishment of active trading markets, as production volumes and industrial demand are often too small to support significant financial transactions. Lastly, these minerals lack investment-grade transparency, meaning that investors have limited access to reliable production data, standardized pricing mechanisms, or clear regulatory frameworks — factors essential for creating a financialized market.

The financialization of these minerals faces deep-rooted geopolitical and structural challenges. Strategic and military sensitivities significantly restrict trade, as minerals like tantalum and iridium are essential for defence applications and subject to government control. Additionally, production constraints further complicate financialization, as many of these minerals are byproducts of larger mining operations, meaning their output depends on the production of more dominant commodities rather than direct market demand. This makes it difficult to scale production in response to price signals or investor interest. Finally, geopolitical risks pose a significant threat, as countries controlling these minerals may impose export bans, introduce restrictive trade policies, or nationalize mining assets, making it difficult to trade on open financial markets. Given these complex barriers, these minerals are unlikely to achieve full-scale financialization without significant changes in supply chain diversification, market transparency, and global regulatory cooperation.

Rhodium

Rhodium is one of the rarest and most valuable platinum group metals (PGMs), primarily used in automobile catalytic converters, chemical processing, and high-performance electronics. Its extreme resistance to corrosion and high melting point make it ideal for applications in

hydrogen fuel cells, jewelry, and advanced industrial processes (PR Newswire, 2020). Despite its industrial significance and high market value, rhodium remains illiquid mainly, with no futures market or standardized trading mechanisms, making financialization challenging.

The global rhodium market is valued between USD 2 billion and USD 4 billion, with demand primarily driven by the automotive industry's need for emission-control technologies (Business Research Insights, 2024). Unlike widely traded commodities, a publicly reported and responsive spot price for rhodium suggests active trading and price discovery within the market rather than relying on structured financial instruments such as futures.

Furthermore, South Africa dominates global rhodium production, supplying approximately 80% of the world's supply, followed by Russia and Canada (The Assay, 2024). The metal is not mined independently but is extracted as a byproduct of platinum and palladium mining, making its supply inherently dependent on the production rates of other PGMs (The Assay, 2024). This secondary production status complicates market forecasting, as platinum and palladium mining fluctuations directly impact rhodium availability. Additionally, the war in Ukraine and related sanctions have disrupted rhodium transportation, with airspace restrictions—such as those imposed by the United States on Russian aircraft—further straining a volatile supply chain (DeCarlo & Goodman, 2022).

One of the most significant barriers to rhodium's financialization is its extreme price volatility. Rhodium prices have historically fluctuated by several hundred percent within short periods, making it a high-risk asset for investors. For example, in March 2021, rhodium reached an all-time high of over USD 29,000 per ounce, falling to under USD 5,000 per ounce by late 2023 (The Assay, 2024). Such unpredictable swings deter institutional investors from developing structured financial products around rhodium.

Additionally, rhodium lacks a transparent, standardized pricing mechanism. Unlike gold or silver, which are actively traded on global exchanges, rhodium prices are privately negotiated between suppliers and buyers, reducing market liquidity and making it challenging to create futures contracts or ETFs (Business Research Insights, 2024). The absence of an established trading platform or exchange-listed financial instruments further limits investor participation.

Another major challenge is the geopolitical concentration of rhodium supply. With South Africa controlling the vast majority of global production, supply chain disruptions such as labour strikes, regulatory challenges, and energy shortages in the country have historically caused severe market fluctuations (Insider Monkey, 2024).

Furthermore, rhodium's status as a byproduct metal restricts its production flexibility. Unlike commodities such as lithium or copper, which can see increased mining activity in response to

higher prices, rhodium production is dictated by the mining trends of platinum and palladium. This means supply cannot be easily adjusted to market demand, making stabilizing prices and creating an investable asset difficult (The Assay, 2024).

Given its extreme price volatility, lack of standardized trading mechanisms, and concentrated supply chain, rhodium remains a highly challenging candidate for financialization. The absence of a futures market, limited market liquidity, and reliance on other PGM mining operations make it unsuitable for exchange-traded financial instruments. While its role in catalytic converters and hydrogen fuel technology ensures continued demand, rhodium will likely remain a strategically important but financially inaccessible metal for the foreseeable future. Unless supply chain diversification, pricing transparency, and market infrastructure improve, rhodium's financialization will remain out of reach.

Iridium

Iridium is one of the rarest and most valuable platinum group metals (PGMs), known for its extreme corrosion resistance, high melting point, and superior conductivity. It is used in high-performance electronics, medical implants, space exploration, and hydrogen production via electrolysis (Stanford Advanced Materials, n.d.). Despite its growing demand and critical role in emerging technologies, Iridium remains highly illiquid, lacks standardized pricing mechanisms, and is heavily concentrated within a few producing countries, making it unsuitable for financialization in the near future.

The global iridium market was valued at approximately USD 1.33 billion in 2024 and is projected to reach USD 2.07 billion by 2033, reflecting a steady increase in demand (Business Research Insights, 2024). However, Iridium is not actively traded on commodity exchanges, with prices primarily set through private contracts and industrial supply agreements. The market is highly concentrated, with South Africa being the most dominant producer, accounting for a significant portion of global iridium output, followed by Russia and Zimbabwe (Noble6, 2024). Unlike gold or lithium, Iridium does not have a well-developed futures market, and its trading remains opaque, further limiting its accessibility as a financialized asset.

Several key factors prevent Iridium from becoming a financialized commodity. First, its extreme rarity and low production volume make it difficult to trade at scale. Iridium is typically extracted as a byproduct of platinum and nickel mining, meaning its supply depends on demand for other metals rather than direct market forces (World Platinum Investment Council, 2023). This production constraint makes it difficult to scale supply in response to price signals, further complicating the development of a liquid trading market.

Another significant challenge is market opacity and pricing instability. Unlike widely traded commodities such as gold, silver, or lithium, iridium pricing is not standardized and is instead determined through long-term supply agreements between mining companies and industrial users (Business Research Insights, 2024). The lack of transparent trading platforms and publicly available price benchmarks prevents investors from participating in iridium markets, reducing its potential as a financial asset.

Iridium's high dependence on South African production also poses a major geopolitical risk. South Africa, which produces most of the world's Iridium, has experienced frequent labour strikes, regulatory uncertainty, and infrastructure challenges, all impacting supply stability (World Platinum Investment Council, 2023). Furthermore, Russia's position as a secondary producer adds an additional layer of geopolitical risk, as trade restrictions and sanctions could disrupt the market. With such a small number of producers controlling global supply, price manipulation and export restrictions are major concerns, reducing the feasibility of Iridium's financialization.

Lastly, Iridium's niche applications and limited market size restrict the development of large-scale trading. While Iridium plays a crucial role in hydrogen production, space technology, and medical implants, its demand remains too specialized and fragmented to support a broad investor base (Stanford Advanced Materials, n.d.). Unlike lithium or graphite, which are used in mass-market industries like batteries and electronics, Iridium's applications are primarily in high-tech and industrial sectors, limiting its appeal for large-scale financial investment.

Due to its production constraints, market opacity, geopolitical risks, and limited trading volume, Iridium remains far from financialization. Its supply chain is too concentrated, its pricing mechanisms too opaque, and its market size too small to support the development of exchange-traded products such as futures contracts. While increasing demand in hydrogen electrolysis, space exploration, and medical technology may expand its industrial significance, Iridium will likely remain a strategic material rather than a tradable financial asset. Unless supply chain diversification, price transparency, and trading liquidity improve significantly, Iridium will remain inaccessible to financial markets.

Tantalum

Tantalum is a rare, corrosion-resistant metal widely used in electronics, aerospace, medical implants, and superalloys. It is a key component in capacitors for smartphones, laptops, and other high-performance electronic devices, as well as in jet engines and nuclear reactors due to its ability to withstand extreme temperatures and resist chemical degradation (Thomasnet, n.d.). Despite its critical role in advanced technologies, tantalum remains lightly traded, suffers

from extreme price volatility, and lacks a standardized market, making it unsuitable for financialization in the near future.

In 2024, global tantalum production was approximately 2,100 metric tons, with a market valuation of USD 400-500 million (USGS, 2024; NextMRC, n.d.). However, the tantalum market is highly fragmented and lacks transparent trading mechanisms. Unlike other industrial metals, the bid-ask spread for tantalum is not standardized, and buyers and sellers often negotiate prices privately (Global Advanced Metals, 2023).

Tantalum production is highly concentrated in a few countries, with the Democratic Republic of the Congo (DRC) being the largest producer, accounting for approximately 41% of the world's supply (USGS, 2024). Other notable producers include Rwanda, Brazil, Nigeria, and China. This heavy reliance on politically unstable regions creates significant supply chain risks, as mining operations in the DRC and Rwanda are frequently linked to conflict minerals and ethical concerns (OECD, 2023). Furthermore, geopolitical restrictions have been placed on acquiring tantalum from certain countries due to national security concerns (U.S. Department of Commerce, 2023). Under U.S. regulations, Section 301 tariffs were implemented on September 27, 2024, imposing a 25% tariff on tantalum imports from China (Argus Media, 2023). Additionally, the U.S. Department of Defense has restricted the acquisition of tantalum from specific sources to prevent funding for armed conflicts (U.S. Department of Defense, 2022). Similarly, the European Union enforces the Conflict Minerals Regulation, which requires tantalum, tin, tungsten, and gold importers to ensure their supply chains do not finance armed conflicts, particularly in the Democratic Republic of Congo (European Commission, n.d.).

Tantalum faces several structural barriers to financialization, the most significant being its extreme price volatility. The price of tantalum concentrate (Ta_2O_5) fluctuates significantly based on market conditions, supply chain disruptions, and geopolitical events (USGS, 2024). Unlike gold, lithium, tantalum does not have a well-established exchange or transparent pricing mechanism, making it difficult for investors to engage with the market.

Another major challenge is the opaque nature of the tantalum supply chain. Since prices are often privately negotiated rather than determined through open-market trading, there is limited price transparency, preventing the development of structured financial products such as futures contracts, ETFs, or commodity-backed securities (OECD, 2023). Additionally, tantalum's classification as a potential conflict mineral has led to strict regulatory oversight, particularly in the U.S. and EU, making financialization even more complicated.

Furthermore, tantalum's production constraints pose additional risks. Unlike bulk commodities such as copper or iron ore, tantalum is often mined as a byproduct of tin or lithium extraction, meaning its supply is not easily scalable or responsive to price movements (Global Advanced

Metals, 2023). This lack of independent production makes establishing a liquid and investable market for tantalum difficult.

Given its high price volatility, limited market transparency, and ethical sourcing concerns, tantalum remains unsuitable for financialization. The absence of futures contracts, standardized pricing mechanisms, and exchange-based trading platforms means that tantalum is primarily traded through private agreements rather than open markets. Furthermore, the geopolitical risks associated with its supply chain, particularly its dependence on the DRC, create additional barriers to investor participation.

While tantalum is essential for advanced electronics, aerospace, and medical applications, its low trading volume, ethical sourcing challenges, and supply chain restrictions prevent it from becoming a widely traded financial asset. Unless greater supply chain transparency, improved market liquidity, and ethical sourcing initiatives are implemented, tantalum will remain a strategically important but financially inaccessible mineral.

Rare Earth Elements (Neodymium, Praseodymium, and Gadolinium)

Rare Earth Elements (REEs) such as Neodymium (Nd), Praseodymium (Pr), and Gadolinium (Gd) are critical materials used in high-tech applications, including EVs, wind turbines, medical imaging, and defense systems. Despite their growing demand and strategic importance, these minerals face significant barriers to financialization. The lack of transparent pricing mechanisms, market illiquidity, extreme price volatility, and geopolitical risks make it difficult to establish structured financial instruments such as futures contracts or exchange-traded funds (ETFs) for these materials. Additionally, the dominance of China in rare earth extraction and processing creates further uncertainty, as supply chain disruptions and government-imposed export restrictions can lead to severe market fluctuations. The following sections explore the challenges facing neodymium, praseodymium, and gadolinium, highlighting why these REEs remain far from financialization.

Neodymium

Neodymium is a critical rare earth element primarily used in neodymium-iron-boron (NdFeB) magnets, which power electric motors in electric vehicles (EVs), wind turbines, and industrial automation. These magnets are among the strongest permanent magnets available and are essential for energy efficiency and miniaturization in advanced technologies such as robotics, hard disk drives, and medical devices (U.S. Geological Survey, 2023). Neodymium is integral to the transition towards green energy, with its demand driven by the growth of the renewable energy sector and the increasing adoption of EVs.

The global neodymium market was valued at USD 5.52 billion in 2023 and is projected to reach USD 8.77 billion by 2032, reflecting a compound annual growth rate (CAGR) of 5.3% (Fortune Business Insights, 2023). The production market is highly concentrated, with China dominating the supply chain, accounting for over 85% of global production. Other notable deposits are located in countries such as the United States, Myanmar, and Australia (Investing News, 2023). China's control over producing rare earth elements, including neodymium, significantly shapes global market dynamics. The country has established a near-monopoly over the refining process, which gives it substantial leverage over pricing and market access.

While there is insufficient evidence to confirm the existence of a formal spot market for neodymium, a publicly reported and responsive spot price suggests active trading and price discovery within the market. In particular, prices are often influenced by supply disruptions, regulatory changes, and shifts in demand, such as the acceleration of electric vehicle production. As such, a spot price does exist, though its formation remains somewhat informal, primarily through direct contracts rather than transparent market exchanges (Reuters, 2023).

Neodymium faces significant price volatility, which complicates efforts toward its financialization. The commodity experienced an all-time high price of 1,520,000 CNY/T in February 2022 before dropping to 512,500 CNY/T in early 2025 (Trading Economics, 2025). This extreme volatility presents a challenge for investors, as the erratic nature of the prices undermines risk management strategies and reduces investor confidence. The absence of standardized global pricing mechanisms further contributes to the market's instability, as neodymium is predominantly traded via bilateral contracts rather than on open exchanges.

Moreover, China's dominance over neodymium production and refining introduces a significant geopolitical risk. Government-imposed export restrictions or regulatory changes, such as China's tightening of rare earth element exports in recent years, can lead to disruptions in global supply chains and price fluctuations (Reuters, 2023). For instance, export restrictions or tariffs could exacerbate price volatility and disrupt the market's stability, deterring potential investors.

In conclusion, while the neodymium market holds potential for financialization, significant barriers remain. The supply chain must diversify to facilitate broader financial market participation, and stable pricing mechanisms and increased liquidity in trading platforms are essential. Without these factors, neodymium is unlikely to be considered for broader financial instruments in the near future.

Praseodymium

Praseodymium is another key rare earth element used in high-strength magnets, aircraft engines, fiber optics, and specialized glass manufacturing. This element is essential for

advanced technologies, particularly in industries such as aerospace and clean energy (Stanford Materials, n.d.). While there is insufficient evidence to confirm the existence of a formal spot market for Praseodymium, the presence of publicly reported prices suggests that active trading and price discovery are occurring within the market.

The global praseodymium market was valued at USD 1.2 billion in 2024, with projections to reach USD 2.5 billion by 2033 (Verified Market Reports, 2023). Despite Australia and the United States contributing to global production, China remains the leading supplier, which introduces geopolitical and supply chain risks. China's near-monopoly over rare earth element production and refining raises concerns over potential price manipulation and export restrictions, which could disrupt the global supply (Reuters, 2024). In addition, the concentration of production in a few countries limits the market's resilience, making it vulnerable to political instability or shifts in regulatory policies.

While Praseodymium's trade is limited on global commodity exchanges, there is a growing interest in the element due to its critical role in the transition to clean energy. The increasing demand for Praseodymium in producing magnets used in wind turbines and EVs has generated significant market activity, albeit somewhat fragmented.

However, Praseodymium faces several challenges that hinder its financialization, particularly its high price volatility and market concentration. Firstly, the absence of a standardized global trading platform for praseodymium limits transparency and price discovery, discouraging broader participation in financial markets (Reuters, 2024). In 2023, praseodymium oxide prices dropped by 37%, followed by another 26% decline in 2024 (Reuters, 2024). Such sharp fluctuations complicate the development of stable financial instruments like exchange-traded funds (ETFs) or futures contracts. These tools rely on market stability to mitigate risk, and Praseodymium's volatility creates significant uncertainty for investors. Additionally, the lack of standardized pricing and transparent market mechanisms exacerbates this issue, as bilateral contracts dominate the market and lack an established spot market for trading.

Moreover, China's near-monopoly over praseodymium production and refining raises concerns about supply chain disruptions, price manipulation, and the potential for government-imposed export controls. These factors create an unstable environment for potential investors and make it challenging to introduce broader financial instruments. The ongoing geopolitical risks and a lack of liquidity in the market limit the ability to structure financial products that could attract a broader range of investors. Praseodymium will likely remain unsuitable for financialization until there is greater diversification in production sources, price stability, and increased market transparency.

Gadolinium

Gadolinium is a rare earth element with essential applications across several high-tech industries, including MRI contrast agents, X-ray machines, neutron moderators in nuclear reactors, fiber optics, magnets, and capacitors (Stanford Advanced Materials, n.d.). It is particularly valued for its ability to enhance imaging in medical diagnostics and its role in improving the efficiency and safety of nuclear reactors. Despite its critical role in medical, nuclear, and high-tech industries, gadolinium remains one of the least financially accessible rare earth elements, with no futures trading and highly restricted market data. This lack of transparency and trading options significantly limits its financialization potential.

The estimated global market value of gadolinium varies widely, ranging from USD 530 million to as high as USD 1.2 billion, reflecting a lack of transparency in pricing and market size (Industry ARC, 2023; Maximize Market Research, 2023; Future Market Insights, 2023). Like other rare earth elements, China remains the dominant producer, controlling most gadolinium extraction and refining capacity (Minor Metals Trade Association, n.d.). China's control over the global supply chain for gadolinium, including its near-monopoly on refining, creates substantial supply risks and geopolitical challenges for international markets.

Although gadolinium is extracted as part of broader rare earth mining operations, it is often produced as a byproduct of the extraction of other REEs, such as lanthanum and cerium. This dependence on other rare earth elements for its supply further complicates its market dynamics, making it more susceptible to demand fluctuations. The limited transparency in the market has made it challenging for investors to gauge the actual market value of gadolinium and predict future supply and demand trends (Maximize Market Research, 2023).

Gadolinium faces several structural barriers to financialization, primarily due to the absence of a dedicated trading market beyond spot transactions. Currently, there are no futures contracts or commodity-backed securities available for gadolinium. This lack of formal trading mechanisms and the absence of standardized global pricing makes it difficult for investors to manage risk or enter the market. Additionally, China's control over gadolinium production and refining raises concerns over potential export restrictions, which could destabilize the market. These geopolitical uncertainties further limit the attractiveness of gadolinium as an investable asset.

Low market liquidity and inconsistent production data further reduce its viability for financial instruments. The lack of robust market infrastructure and limited demand-driven price discovery makes gadolinium less accessible for speculative investment. Additionally, its strategic applications in sectors like nuclear power and medical imaging mean that governments may impose trade restrictions or take actions to limit speculative investment in these resources, further complicating financialization efforts (Industry ARC, 2023).

Moreover, because gadolinium is often produced as a byproduct of other REEs, its production is tied to broader market forces, which adds another layer of complexity to its financialization potential. For example, shifts in demand for other rare earth elements may impact gadolinium production levels and availability.

Due to these challenges, gadolinium is unlikely to be financialized in the near future unless significant improvements are made in price transparency, trading volume, and supply chain diversification.

Policy Recommendations

This section presents key policy recommendations designed to address the challenges identified in the preceding analysis. These recommendations are tailored to both public and private sector actors, ensuring a comprehensive approach to fostering a robust and investable market for critical minerals. On the government side, federal agencies, regulatory bodies, and trade and investment organizations must implement policies that enhance market transparency, incentivize investment, and mitigate financial risks. Meanwhile, private sector actors—including institutional investors, mining companies, commodity exchanges, and technology firms—must drive market liquidity, innovation, and the adoption of financial instruments such as futures contracts and price indices. By working together, public and private stakeholders can establish a resilient and efficient financial ecosystem for critical minerals.

Recommendations for minerals ready for financialization

1. ***Analytical basis for recommendations: using the financialization of iron ore to guide potential financialization of graphite and vanadium***

Graphite and Vanadium were chosen as key critical compounds for financialization because of their diverse applications, relative diversity of their production and processing, and high market demand. Nonetheless, actioning financialization requires varied transformations of policy, investment, and graphite production and sale. Surveying past examples of commodities which have been financialized with similar pre-existing facets is key, as it can provide a blueprint to follow for graphite.

The financialization of iron ore could serve as a reference for financializing vanadium and graphite. Iron ore underwent financialization mainly in the 2000s. This was led first and foremost by a boom in demand of the 2002-2012 commodity super-cycle. The vast increase in demand for various commodities – led by iron ore – from development in Asian economies – and mainly by China – drove prices up immensely. This also introduced volatility, as supply chains struggled to keep up with changing market dynamics. To combat this, financialization of

the iron ore commodity market was pursued. Iron ore previously functioned based on long-term contracts – like many other commodities – but this changed as financialization took place. To simplify, this shift was driven by the potential risk of long-term contracts locking stakeholders – whether they are buyers, sellers, or commodity traders – into contracts which have unfavourable prices as compared to spot prices in short-term sales. This resulted in a push for the creation of new sectoral norms with shorter-term – specifically quarterly – contracts. Eventually, a path was paved for the creation of prices based on indices – themselves based on a collation of spot prices – and the creation of financial instruments, such as futures. Iron ore's financialization is complicated, as there remain financial instruments which are geographically limited – such as some derivatives only available in China, the largest market for iron ore by far – and in other ways the iron ore's market could use increased robustness.

Nonetheless, due to the similarity of graphite and vanadium's current markets to that of iron ore before financialization, the latter is a strong commodity case study to follow. Firstly, graphite and vanadium, like iron ore possess large, rapidly growing markets. Graphite and vanadium also cannot be supplanted by alternatives for many of their applications, another quality shared by iron. These factors ensure strong and long-term demand. Graphite also displays many of the characteristic facets of iron ore during the 2002-2012 commodity super-cycle, such as variable prices due to rapidly shifting supply and demand.

2. Volatility – the key to catalyzing financialization of graphite and vanadium

Graphite and vanadium are currently bought and sold from producers and users directly via off-take agreements. These direct agreements between consumers and sellers are generally for a period of one or more years and are secretive. As a result, while it is known that volatility is present, greater market average prices are difficult to assess. Vanadium prices are more open than graphite, as the earlier appears to have sufficient availability of public data that markets such as the Shanghai Metals Market can estimate day-to-day price variations. However, even for Vanadium, the level of price and supply clarity pales in comparison to what is seen for fully financialized commodities.

Curiously, the presence of volatility is key to establishing a financialized derivative market for a commodity market. Volatility of price creates inherent instability for all market players and reduces reliability of the cost-efficiency of long-term contracts. Buyers of a commodity become more concerned that they are likely to overpay, while sellers may worry that they may have lower profits than otherwise possible. As a result, the inherent undesirability for all parties in a situation of price volatility within a bilateral contract trading framework incentivizes the creation of an open, liquid market. This is because an open market can allow for prices to be openly set in real-time through public trading and provides more information for all players. A

commodity market then allows for financial derivatives to be created, as the higher information environment allows derivatives to be created – derivatives which can be used to shield both buyers and sellers from experiencing the negative implications of short-term price fluctuations. Essentially, short-term volatility is key to catalyzing financialization, which will then create a more transparent and financially stable market with greater public knowledge regarding compound demand and supply. Graphite and vanadium are in a similar, price variable paradigm as iron ore was in the late 2000s, priming both for a similar transformation.

As graphite and vanadium will be integral to key twenty-first century technologies, the creation of a financialized commodity exchange is crucial for ensuring robust supply chains and to reduce geopolitical leverage of individual players. As a result, governments in the developed and developing World which wish to have safe, reliable, and cost-effective access to graphite and vanadium long-term, must embark on policy interventions to increase competition and short-term volatility. This will first involve investment in greater mining, processing, and transportation logistics to increase supply. Doing so will result in greater competition between producers and shift the focus of production away from China. Additionally, demand through already growing industries which utilize graphite and vanadium must be further incentivized. Green technologies, while growing, are lagging far behind global needs for decarbonization. An influx of investment in technologies utilizing graphite and/or vanadium will further bolster demand, increasing short-term market volatility.

Essentially, while such an influx of market volatility is not favourable for market players in the short-term, it will cause sectoral shifts to recognize the need for the creation of financial derivatives – the exact tools necessary to reduce volatility long-term. As a result, governmental policy mechanisms to increase in both the supply-side and demand-side for both graphite and vanadium are key for financialization, and thereby central to ensuring stable long-term demand for both compounds.

3. Supply-side interventions

Supply-side interventions must be focused on diversifying graphite production and processing, namely away from China where it is largely focused. Currently, about 78% of global graphite production is in China. However, this is not due to China being the location of the majority of graphite reserves, with the nation only estimated to have about 27.9% of the global share. China's production is so high due to high levels of Chinese government investment in development of graphite extraction and processing - as is the case with many other rare Earth compounds. This is partially due to China's high usage of the compound. While estimates vary, the country is estimated to make up anywhere from 28-51% of global graphite demand. As a result, while a large portion of even the majority of China's graphite production is likely for

domestic consumption, the country nonetheless has a stranglehold on the global graphite market, as often the dominant supplier for other countries as well.

Nation states which aim to foster a robust, financialized graphite market must investigate avenues to increase production of graphite in other regions so that they become viable exporters of the compound. Brazil is a prominent example which may be able to rise as a major exporter, as it is estimated to have the World's second largest graphite reserves – at about 26.4% of the global share. Its current production however, pales in comparison to China's. In addition, discovery for graphite reserves is not pursued nearly as fervently as for other, more currently lucrative resources – such as oil and natural gas – meaning that it is quite likely that many more graphite reserves exist globally but simply are undiscovered.

a. Resource Discovery and Mine Development (Government-led)

A two-pronged approach regarding resource discovery and mine development could be pursued by countries aiming to diversify graphite production away from China and financialize the compound's trading so as to make its market more transparent and fluid. The discovery process would involve direct investment in geological surveying. This would require development of the technological, scientific, and institutional subcomponents which would facilitate such investigation. As a result, a country's government bureaucracy, scientific research institutions such as universities, as well as private sector players should be involved in a collaborative framework. This process will likely be quite straightforward, as most countries of at least middle-income status and moderate political stability already have sufficiently stable institutions which are able to conduct such a task, and the task itself – geological surveying – is one mainly of basic scientific research.

b. Grant Funding and Concessional Loan Incentivization Schemes to incentivize private sector engagement (Government-led)

The second step, mine creation, is more complicated. It involves direct investment by a country in large-scale extraction, refinement, and often also processing to be able to utilize a compound. Depending on highly variable geographic or geological factors, this investment can vary in cost vastly, anywhere from hundreds of millions to billions of dollars. Extensive, case-by-case analyses will be necessary to complete such tasks, and will require extensive collaboration between governments, research/scientific/academic institutions, and the private sector. Countries lacking domestic players – especially in the realm of large private sector mining companies – will face further barriers and will have to either create state-owned enterprises for such tasks or foster private sector development. Due to the high barriers to entry posed by the high costs of creating a mine and the relatively long periods of time needed before returns are gotten, it is inevitable that extensive direct funding through grants or concessional loan

arrangements will have to be created by governments to spur the creation of or entry of private players. Such costs will still largely be present if a country aims to create a state-owned mining corporation, though the potential for long-term dividends to be more directly returned to the state is a potential benefit. As a result, embarking on such a long-term and potentially loss-making investment requires a robust and long-term political consensus within a country of the strategic, economic, or geopolitical importance of such an intervention.

Nation states must evaluate whether they possess sufficient domestic capacity to extract and process graphite or vanadium domestically and if there is geopolitical incentive for them to invest in such a proposition. If a nation state does not have sufficient domestic reserves but does see other incentives to financial and reorient away from Chinese dependence, the country must secure key partners that do have sufficient reserves and have sufficiently aligned long-term goals that they would be willing to collaborate on cooperative development of resource extraction.

4. Demand-side interventions

While supply-side interventions are key, they are only one part of the creation of a more robust market for graphite and vanadium. Investment in the creation of large-scale supply will only be viable if there is sufficient demand for both graphite and vanadium. As a result, the development of relevant sectors which will utilize the newly abundant domestic supply of both compounds is of strong necessity. Such demand for both compounds may develop independently due to stochastic innovations spurring technological developments for products utilizing one or both compounds. However, many such demand-creating innovations are not simply random, but due to the existence of prosperous economic environments which will be fruitful for the creation of companies, attraction of talent, and technological development.

a. Basic scientific research in technologies likely to use graphite and vanadium (Government-led)

Basic scientific research conducted at research institutions and universities are the key driver of the development of both novel technologies and breakthrough scientific discoveries. Such opportunities are mostly supported through direct government grant funding which is aimed to give researchers space to explore prospective and viable scientific opportunities. Ensuring a high degree of investment in such research is key for a country to maintain its domestic capacity to investigate new technologies, applications of those technologies, and potential avenues for development.

The relevance of this type of investment is that for there to be viable demand in the usage of graphite and vanadium, a nation must establish a strong capacity to research each compound

for its potential uses to elucidate current and potential future technological applications which may be commercialized. Essentially, such grant-based funding of basic research will be able to create a large supply of technological opportunities, indicating to market players that there will be long-term demand for both graphite and vanadium. This will give greater confidence for government and private players in the need to maintain earlier supply-side interventions which must take place over a long-period of time – as they would be indeed valuable investments of public and private funds for technological development.

Additionally, technological innovation cannot occur without investment in potential enhancements to existing technologies, and investigation of radical new technological opportunities. Thus, such research funding is not only needed to understand what current applications of graphite and vanadium exist, but also what potential future applications may exist – and thus why ensuring high demand for both compounds is useful for future systems. Due to the low potential of many individual research projects to unveil technologies which may be commercialized, the private sector is generally averse to basic scientific research investments. As a result, it is highly pertinent for government-led funding in this arena.

Specifically, governments must invest in scientific research in the chemical properties of graphite, vanadium, and compounds containing either compound to support such knowledge growth. Furthermore, research regarding technologies such as electrodes, batteries, lubricants, refractories, energy storage systems, semiconductors, carbon composite materials, anodes, advanced metal alloys, and other high performance materials should be pursued, as these all show potential for usage of graphite and vanadium.

b. Commercialization of technologies using graphite and vanadium through Sectoral Hubs (Government + Research + Business/Financial Actor collaboration)

The capacity for basic scientific findings to be developed into technologies requires strong levels of collaboration between all key players. Essentially, fertile environments for scientific advancements to not only be created, but then be transferred to the private sector to create products requires robust capacities for cross-sectoral communication. Completing this requires direct integration of the disparate players within the realm of specialization of collaborators. More practically, this requires the private sector to be able to directly collaborate, learn of, investigate, and be capable of developing new findings within scientific research into technologies within real time.

The creation of geographically-focused and integrated sectoral hubs regarding vanadium and graphite-utilizing technologies is a prime mechanism by which such collaboration can take place. It creates an environment primed to allow transfer of knowledge within organizations of a sector and between workers as well. Such knowledge transfer is central to continued technology

development, as it ensures a diverse and deep base of workers with relevant expertise which continually can attract talent and reduces transaction costs – both direct monetary but also greater social costs of doing business – thereby incentivizing innovation.

Governments could set up regulatory, tax, grant, and/or loan-based incentives to foster entry of private players into a regional hub. Often, such a hub would be ideal around existing research institutions, such as universities, as the already present scientific research basis can serve as a strong core for hub development. Additionally, both through direct government investment and additional regulatory incentive schemes, the state has a secondary role of incentivizing the creation of financial entities which may invest in novel technologies. Thus, Governments must facilitate the establishment of venture capital and private equity dedicated to the hub or encourage existing private enterprises to increase their investment in it. Such private capital is central to funding prospective technologies and creating new businesses. The creation of such an environment focused on technologies using vanadium and/or graphite will create economic feedback loops that increase economic investment in the sector and justify the economic necessity of the earlier discussed supply-side interventions.

c. Government-led procurement with a focus on creating economic spillovers

The creation of a sectoral hub is a difficult task with its own risks. Government procurement could spur success of not only an individual hub, but technologies within an entire sector. Pioneered by the DARPA Model of the United States, governments have been shown to play a pivotal role in jumpstarting technologies. This is a direct result of the capacity for governments to invest in and procure technologies in large-scale if there exists a relevant political imperative. Through the DARPA Model, the United States pioneered what is known as mission-oriented innovation – the development of advanced technologies with particular performance targets – for military projects. Such mission-oriented development focused upon vanadium and graphite-utilizing technologies is a central mechanism by which demand for both compounds will be fostered. A key focus must be for these investments to be in technologies which can allow for economic spillovers – essentially the process by which technological development in one arena can allow for new technologies to be developed in different by related applications. In fact, DARPA's investment in semiconductors for development of computers was a prime example of a technology which resulted in large economic spillovers, helping to create the modern semiconductor sector – which is invaluable to the modern economy. While such spillovers are difficult to predict, government procurement should prioritize technologies that are most likely to create spillovers.

d. Regulatory changes to spur financialization of graphite and vanadium (Government-led)

Government procurement is needed to create large-scale demand for graphite and vanadium-utilizing technologies. This would also incentivize private original equipment manufacturers – companies which actually create the commercialized technologies – and financial players such as investment firms to enter the market. However, to further incentivize this, governments must also make regulatory changes to further lubricate the process of financialization. This includes regulatory loosening as needed to make trading more viable, partnerships with existing commodity exchanges to create financial derivatives and development of local commodity markets if necessary. Development of new commodity markets and ensuring trading information meets sufficient standards of accuracy requires investment in logistics. Efficiency of logistics will be ensured by data collection and surveying regarding the supply chain of graphite and/or vanadium, thereby preventing artificial shortages and greater price liquidity. Partnerships between commodity markets, mining companies, transportation companies, as well as buyers is of key focus to ensure success of logistics frameworks. Finally, government stockpiling must also be prioritized, as it will ensure demand can be met in case of supply gaps. Essentially, the above items represent a collation of more granular regulatory and policy changes which are needed to help incentivize commodity market development and financialization of both graphite and vanadium.

Recommendations for minerals with potential for future financialization

Government-Directed Policies/Considerations

Government Policies must focus on creating the foundation for market development by reducing geopolitical risk, stabilizing supply chains, and supporting infrastructure development.

1. ***Reducing Geopolitical Risk through Trade Policy and Diplomatic Engagement***

   One of the challenges associated with these minerals is that they are often at the forefront of geopolitical tension due to their strategic importance in military applications, and because mining of such minerals is often concentrated in adversarial actors such as China that have placed export controls on said minerals, making liquid and transparent markets difficult to create. Where mineral concentration offers greater flexibility, Western governments should:

   - **Pursue multilateral agreements** to secure reliable access to these critical minerals.
   - **Reduce the impact of export controls** imposed by dominant producers like China.

- **Integrate mineral supply chain security into defense-linked agreements** with key allies would strengthen geopolitical stability and ensure access to materials essential for military and technological applications.

2. ***Diversify Supply Chains and Increase Domestic Production***

Just as important as reducing geopolitical risks in the financialization of such minerals, is the greater diversification of where the minerals can be extracted.

- **Increasing mineral supply** amongst western-aligned nations reduces the risks associated with high concentration of production in adversarial countries.
- Governments should look towards **direct procurement,**
- Commit to **long-term purchasing contracts at fixed premium prices** to support the development and increase demand of new mining operations,
- Create **national reserves** of minerals to reduce supply shocks and stabilize market volatility.

3. ***Build Regulatory & Legal Frameworks for Financialization***

Establishing a robust regulatory and legal framework is essential for the successful financialization of critical minerals. Governments should:

- **Strengthen laws governing** mineral trading, property rights, and tax structures to create a stable and predictable investment environment,
- Collaborate to **outline clear requirements for futures and options contracts,** ensuring that trading mechanisms are transparent, consistent, and aligned with international standards,
- **Establish oversight mechanisms** to monitor and prevent excessive speculation and market manipulation to safeguard orderly price discovery, reduce market volatility, and build confidence among institutional investors.

4. ***Institutional and Government Support***

Governments can incentivize domestic and allied production by offering:

- **Tax breaks, royalty relief, and grants** to stimulate mining investments. State-backed financing, such as low-interest loans, equity stakes, and sovereign guarantees, has proven successful, as demonstrated by the U.S. Department of Energy's $700 million loan to the Rhyolite Ridge Lithium-Boron Project (U.S. Department of Energy, 2023).

Private Sector and Investor Considerations

1. ***Creation of spot market in partnership with price reporting agencies***

   As seen in the case of lithium, the development of transparent spot markets was one of the most important actions taken in its evolution towards the creation of lithium derivative markets and its complete financialization. Financial actors and industry stakeholders should:

   - **Support price reporting agencies (PRAs) in creating independent price benchmarks** based on frequent and publicly reported transactions, increasing market transparency and reducing reliance on opaque bilateral contracts.
   - Producers and traders should also be encouraged to **report transaction prices** to improve market transparency and ensure consistent valuation.

2. ***Balancing Long-Term Stability with Market Flexibility***

   Transitioning from fixed-price contracts to more flexible pricing structures is essential for increasing market liquidity and improving price discovery in critical mineral markets. While long-term contracts play a crucial role in securing supply stability—particularly in the early stages of market development through government-led initiatives—the private sector should support a gradual shift toward more dynamic and market-responsive pricing mechanisms.

   Financial actors and industry stakeholders can facilitate this transition by:

   - **Promoting variable or index-linked pricing models** that reflect real-time market conditions and evolving spot prices.
   - **Adopting standardized contract terms** that evolve alongside spot market dynamics enabling smoother participation in the market and more effective price risk management.

3. ***Conduct a Pilot & Test Derivative Markets***

   One of the desired outcomes of financialization is the creation of derivative contracts for these minerals. However, with minerals not yet ready for full financialization, or in a position where there is risk associated with investing, introducing derivative markets for critical minerals requires a phased approach to minimize risk and build market confidence. Financial actors should:

   - **Launch trial hedging programs** that allow producers and traders to experiment with risk management tools, offering clear assessments on where in the

development stage these minerals are and what needs improvement so that full financialization can be possible.

- Trial hedging programs can include **forward contracts and swaps,** before moving to full-scale adoption.
- **Developing over-the-counter (OTC) derivatives** provide flexibility by enabling customized contracts tailored to specific market needs, helping participants manage exposure to price volatility.
- To support the growth of these markets, it is essential to ensure that the necessary market infrastructure—**such as clearinghouses and settlement systems**—is in place and capable of handling derivative trading efficiently and securely.

Recommendations for Minerals with Strategic Importance but a Complex Financialization Landscape

Government-Directed Policies/Considerations

Access to capital remains a significant barrier for mining exploration and development, especially in minerals that lack liquid and transparent markets. Governments play a crucial role in building an investment ecosystem to support critical mineral development.

1. ***Government Investment Incentivization***

   Establishing public-private investment funds will help de-risk projects, making them more appealing to financial investors. To encourage private sector participation, governments should:

   - Introduce **tax rebates** on capital investments;
   - Provide **1:1 matching funds** for critical mineral exploration and development;
   - Public investment guarantees, such as **sovereign-backed assurances** to cover investment losses, can further reduce financial risk and attract investors.
   - **Sovereign green bonds** could be issued to raise capital for environmentally sustainable mineral projects, ensuring responsible resource development while drawing private investment.

2. ***Institutional and Government Support***

Efficient permitting and regulatory frameworks can help de-risk projects and attract private investment. This can be achieved through:

- **A single-window approach** could consolidate regulatory approvals, environmental assessments, and stakeholder consultations, significantly reducing lead times and administrative costs.
- These agencies would **coordinate across federal, provincial, and municipal levels** to provide clear timelines and regulatory expectations.
- **Digital platforms** should be implemented to allow real-time tracking of **permit applications and regulatory approvals.**

3. Strengthening Supply Chains & Infrastructure

To enhance market efficiency, governments should:

- **Invest in logistics and warehousing capacity**, ensuring efficient rail and port links, as well as certified storage facilities.
- Creating **trade hubs**;
- **Simplifying customs procedure**s;
- **Harmonizing international standards** to facilitate smoother transactions;
- Support the **development of centralized trading platforms** to improve price discovery and liquidity.

4. Sustainability & ESG Compliance

Governments should align financial support with sustainability frameworks such as OECD Due Diligence Guidance and UN Guiding Principles on Business and Human Rights. Public financing and incentives should be:

- **Tied to ESG performance**, ensuring that projects adhere to environmental and social responsibility standards.
- **Implement traceability systems** using blockchain technology and conducting third-party audits to maintain transparency in mineral sourcing.
- **Integrate community and environmental safeguards**, such as biodiversity protection and land reclamation planning, making mineral outputs more attractive to buyers who prioritize sustainability.

Private Sector and Investor Considerations

For financial investors, transparency, risk mitigation, and liquidity are key factors in determining investment viability. Strengthening investor confidence through reliable market data and government-backed risk-sharing mechanisms will be critical to scaling critical mineral markets.

1. ***Investor Confidence & Market Transparency***

   To improve market transparency, governments and industry associations should regularly publish data on production, trade volumes, and pricing:

   - **Establish price indices and benchmarks** will allow investors to make informed decisions.

   Create risk-sharing mechanisms, such as:

   - **Political risk insurance**;
   - **Loan guarantees**;
   - And **co-investments** can help mitigate financial uncertainties in illiquid mineral markets.
   - Encouraging **long-term offtake agreements** between miners and end-users, such as EV manufacturers, can provide revenue stability and enhance investor confidence.
   - **Regulatory oversight** should prevent excessive speculation and market manipulation through measures such as circuit breakers and position limits.

2. ***Strategic Partnerships & Market Development***

   Fostering collaboration between miners, governments, and end-users will promote investment and align regulatory standards across jurisdictions. Engaging with commodity exchanges to explore the feasibility of derivative markets will improve financial accessibility:

   - **Expanding the investor base** by allowing commodity funds or ETFs for critical minerals can enhance liquidity and reduce risk.
   - **Development banks and industry actors** can also **act as market maker**s in the early stages to further bolster investor confidence.

3. ***Infrastructure & Market Readiness***

   To support the financialization of these minerals, private sector actors must take a proactive approach to infrastructure development and market preparedness. Companies

and investors should focus on strategic investments that enhance supply chain efficiency, market transparency, and financial viability. Specifically, efficient transportation, storage, and refining would prove essential for improving the profitability and scalability of critical mineral projects. Therefore, private sector players should:

- **Invest in Midstream and Downstream Infrastructure**: Companies can expand refining and processing capacity to reduce reliance on foreign facilities, increasing control over supply chains. Joint ventures with manufacturers and technology firms can secure long-term demand and ensure supply stability.
- **Develop Private Logistics Networks**: Strategic partnerships with transportation providers can optimize shipping routes and reduce costs. Investors should prioritize infrastructure projects that enhance access to ports, rail, and storage facilities in key mining regions

4. ESG-Driven Investment Strategies

Investors are increasingly prioritizing ESG performance as a condition for funding. Mining companies should adopt:

- **Robust ESG standards** to qualify for financial backing from both public and private sources.
- **Implement robust traceability systems and independent certifications** ensuring transparency in mineral sourcing. Aligning financialization efforts with ESG compliance will not only improve market credibility but also attract institutional investors, expand access to green financing, and unlock premium pricing in regulated markets.

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