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THE POTENTIAL MACROECONOMIC RELEVANCE OF CRITICAL MATERIALS: SOME PRELIMINARY EVIDENCE

by Marco Taboga*

Abstract

The demand for key critical materials is expanding rapidly due to the growing adoption of renewable energy technologies. We explore whether the markets for these materials have reached, or will soon reach, an economic significance that would justify monitoring by central banks (e.g. for inflation forecasting purposes). Our findings indicate that the total value of critical materials produced globally remains relatively small, especially for those used in green technologies. However, in scenarios involving rapid progress towards net-zero emissions and strong demand pressures, the market for critical materials could reach a size comparable to that of the natural gas market. We discuss how, in such scenarios, characteristics of energy-critical materials such as substitution potential, price volatility, degree of criticality and demand elasticity will contribute to determine their macroeconomic relevance.

JEL Classification: Q3, Q4, E3, E5.

Keywords: critical materials, critical minerals, energy markets, clean energy.

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1. Introduction[1]

Critical materials are commodities that are essential to modern technologies and industries but are vulnerable to supply disruptions due to their scarcity, geographical concentration, or geopolitical challenges. These materials play a fundamental role in various strategic sectors, including electronics, renewable energy, defense and healthcare. The category of critical materials often includes rare earth elements (like neodymium and dysprosium), lithium, cobalt, nickel, and platinum group metals, among others.

Policymakers have focused on critical materials for decades because of their crucial role in economic growth, technological innovation, and national security.[2] The concentration of these materials in a limited number of countries – sometimes in regions prone to political instability or conflict – creates significant risks for supply chains.[3] For example, China dominates the global supply of rare earth elements, while cobalt production is heavily concentrated in the Democratic Republic of Congo (e.g., IEA 2024). These supply chain vulnerabilities can lead to price volatility, trade tensions, and potential shortages, posing risks to national economies and defense capabilities.

The importance of critical materials has surged in recent years, primarily driven by the global push for a green transition. As the world shifts away from fossil fuels toward cleaner energy sources, critical materials have become indispensable for producing renewable energy technologies like wind turbines, solar panels, and electric vehicle (EV) batteries. For instance, lithium, cobalt, nickel and graphite are key components in lithium-ion batteries, which power EVs and store energy from renewable sources. Similarly, rare earth elements are essential for the magnets used in wind turbines and the motors of electric vehicles.

By the very definition of criticality, large and persistent drops in the availability of a critical material – for example due to export bans imposed by a major producer country – can shut down entire supply chains and cause extensive economic damage, even when the material's cost typically represents only a small fraction of the total cost of its derivative products. After World War II, such extreme disruptions have never taken place.[4] However, the Russian invasion of Ukraine in 2022 and the resulting severe interruptions to natural gas supplies in several countries (Emiliozzi et al. 2023) have raised concerns that similar crises could affect critical material markets, prompting policymakers to build resilience against such risks (e.g., G7 2023, 2024).

As the green transition accelerates the demand for critical materials at an unprecedented rate, it is natural to ask whether these materials have become so significant that, even without

[1] The views expressed in this paper do not necessarily reflect those of Banca d'Italia. Helpful comments and suggestions were provided by Alessandro Borin, Riccardo Cristadoro, Fabrizio Ferriani, Michele Mancini, Luigi Federico Signorini and Giovanni Veronese.

[2] The US started its strategic-minerals program in 1939, during World War II.

[3] Beyond geographic concentration, ownership concentration of mining and refining companies also plays a role (Faubert et al. 2024).

[4] As documented by Kowalski and Legendre (2023), the number of export restrictions on critical minerals has steadily increased worldwide over the past two decades. However, most of the restrictions take the form of export taxes and licensing requirements, while export prohibitions play a minor role.

extreme and prolonged disruptions, their “ordinary” price volatility could substantially impact global macroeconomic outcomes. For instance, a central bank might consider whether monitoring the prices of critical materials – alongside those of energy commodities – could aid in predicting inflation. The first step in addressing these questions is to estimate the size of the markets for critical materials. To achieve this, we rely on and expand upon analyses published by the International Energy Agency (IEA) in its Global Critical Minerals Outlook 2024.

We focus on the six critical materials identified by the IEA as the most economically relevant for the green transition: copper, nickel, lithium, cobalt, graphite, and rare earths. We find that global demand for these materials amounted to 350 billion US dollars in 2023, of which 90 billion was for renewable energy technologies (hereafter referred to as cleantech). For comparison, total demand for fossil fuels in the same year was around 5 trillion dollars.

The distribution of cleantech demand across the six materials is uneven, with copper, lithium, and nickel accounting for 54, 19, and 10 billion dollars, respectively, and graphite, cobalt, and rare earths accounting for 2 billion dollars each.

The distribution across technologies is also concentrated, with most of the demand coming from the production of electric vehicles and from investment in electricity networks (30 billion each). The automotive sector appears highly exposed to price volatility, as its critical materials costs account for around 6% of the total retail value of EV sales. Significant changes in this proportion could hamper the profitability of an industry historically characterized by relatively low margins.

For future demand, we consider the IEA’s Net Zero Emissions (NZE) scenario for 2030 as a high-demand case. This scenario assumes that governments will not only meet all their climate-related commitments in full and on time, but also enhance these commitments beyond current levels to stabilize global average temperatures at 1.5°C above pre-industrial levels. We make the additional assumption that demand pressure will be strong enough to drive all critical material prices simultaneously to their historical maxima.[5] Under this scenario, we find that the total market value would increase to around 1.1 trillion dollars (approximately 1% of world GDP), with 650 billion attributable to cleantech demand. This is comparable to the current size of the natural gas market, whose volatile price developments are known to affect macroeconomic outcomes, particularly inflation.

As market size alone is not sufficient to assess macroeconomic relevance, we take other characteristics of energy-critical materials into consideration: substitution potential, price volatility, degree of criticality and demand elasticity.

We document that recent years saw the emergence of production-ready substitutes of copper, nickel, lithium, cobalt and natural graphite for cleantech applications, while alternatives to rare earths remain at an experimental stage. Overall, these favorable developments could decrease the likelihood that critical materials markets become a major source of macroeconomic volatility.

[5] Computed over the 2016-2024 sample analyzed in this paper.

We demonstrate that both after 2020 and over a longer time span, the volatility of critical material prices has, on average, been significantly lower than that of fossil fuels, particularly natural gas. This difference can be partly attributed to the relative ease and lower cost of storing critical materials, a factor that both empirical and theoretical studies identify as a key determinant of commodity price volatility. The low volatility of critical materials, especially when considered as a group (where idiosyncratic volatilities partially offset one another), may reduce their macroeconomic impact, even in scenarios where the size of their markets equals that of the natural gas market.

However, the volatility-mitigating factors considered above might be compensated by several unfavorable developments, among which increased disruptions due to climate stress, and increased risks of manipulation and speculation (IRENA 2023). Policy work to keep criticality in check will remain essential to reduce the likelihood of extreme price spikes.

Boer et al. (2024) conduct a study comparable to ours. They incorporate IEA's demand scenarios into a structural vector auto-regression model to derive endogenous price trajectories for copper, nickel, cobalt, and lithium. They estimate that in the NZE scenario, the cumulative production of these metals would be valued at around 11 trillion dollars over the 2021–2040 period. Our analysis complements theirs in several ways: we include two additional materials (graphite and rare earths), break down demand projections by industrial application, provide point-in-time market size estimates rather than cumulative values, use updated IEA scenarios (2024 vs. 2021), and offer a detailed discussion of other critical material market characteristics – beyond size – that are relevant for assessing their macroeconomic significance.

While the analyses presented in this paper are simple and mostly descriptive, they may help to start a debate on the role of critical materials in macroeconomic monitoring. Our preliminary conclusion is that critical materials markets have not yet reached a size such that their price volatility is able to substantially influence macroeconomic outcomes, barring the risk of extreme and to date unobserved events leading to shut-downs of entire supply chains. However, if rapid progress toward net zero is achieved over the next 5 to 10 years, critical materials markets could become large enough to justify monitoring by central banks, especially if some of the volatility-mitigating factors mentioned above are weakened by structural changes. Moreover, adverse developments in critical material markets may already be highly consequential for specific sectors in which critical materials represent a large fraction of total costs (e.g., the automotive sector; Section 3; see also Panon et al. 2024).

The rest of the paper is organized as follows: Section 2 introduces the data and the methodology; Section 3 presents the estimates of market size; Section 4 discusses other relevant characteristics of critical materials markets; Section 5 concludes.

2. Data and methodology

For the quantities demanded of the six main materials (copper, nickel, lithium, cobalt, graphite, and rare earths), we rely on the IEA's Critical Minerals Data Explorer, which provides estimates of demand in kilotonnes (kt) for 2023 and projections through 2050 across the IEA's three standard scenarios, including the NZE scenario considered in this paper and described in the introduction. For each material, there are estimates of total demand and demand specifically related to the production of clean technologies, broken down by application: electric vehicles, wind energy, solar photovoltaic, stationary electricity storage, electricity networks, and other cleantech.

As the methodology used by the IEA to estimate quantities demanded is mostly undocumented and undisclosed, we cross-checked their data with numerous other sources, including the US Geological Survey. This also allowed us to infer the technical assumptions made by the IEA and roughly reproduce their 2023 estimates.

The quantities demanded refer to purified materials, not to minerals or raw materials. In some cases, they refer to abstract statistical concepts. For example, lithium demand is expressed in kt of pure lithium. In order to be priced, it must be converted to quantities of commercially available products such as lithium hydroxide monohydrate, using conversion factors derived from atomic masses. For rare earths, the IEA uses an unspecified mixture of praseodymium, neodymium, terbium and dysprosium. Based on estimates of the relative abundance of these elements at various mining operations (Gielen and Lyons 2022), we set the weights of the mixture at 73%, 21%, 4% and 2% (for Nd, Pr, Dy and Tb respectively). The statistical concept for graphite "includes all grades of mined and synthetic graphite". In the absence of further information, in our calculations we use the IEA's graphite quantities as if they were quantities of XL graphite flakes, that is, battery-grade processed graphite.[6]

We convert quantities to dollar amounts using the prices of high-grade materials traded on public exchanges: grade A copper (99.9% pure), B39-79 nickel (99.8% pure), lithium hydroxide monohydrate (99.2% pure; 6.05 conversion factor from pure lithium), standard cobalt (99.8% pure), XL graphite flakes, high-grade rare earths (between 96% and 99% purity for praseodymium and above 99% for the other rare earths). This procedure might lead to over-estimate total market value when significant amounts of low-grade material are produced and traded (e.g., in the cases of copper and graphite). The IEA did not release data about prices or dollar amounts, except for an unnumbered chart published in its Global Critical Minerals Outlook 2024. Comparison of this chart with a subset of our results reveals only small discrepancies.

3. Market size

Table 1 presents our estimates of the 2023 market size, both for total global consumption and for demand generated by cleantech applications. To create the table, we use the average daily prices of the materials recorded in 2023. Global demand for these materials amounted to 350 billion US dollars in 2023, with copper and nickel accounting for 63 percent (221 billion) and 19

[6] Although it would be desirable to exclude synthetic graphite from the calculations, as it is produced in scalable industrial processes that use fossil fuels as inputs.

percent (67 billion) of the total, respectively. For comparison, total demand for fossil fuels in the same year was around 5 trillion dollars, with crude oil making up 57 percent of that total (Table 2).[7]

Aggregate lithium demand was valued at approximately 34 billion dollars, a figure influenced by the price spike observed between 2021 and 2023. As its price has now reverted to a significantly lower level (Figure 1), we expect the value of lithium consumed to be around 15 billion dollars in 2024, despite a rise in demand. The other three materials considered in this study contributed relatively little to the total, with values of 13, 8 and 7 billion dollars for rare earths, cobalt, and graphite, respectively.

The value of critical materials used in cleantech applications was 90 billion dollars in 2023, or 26% of the total. When examining individual materials, cleantech demand constituted a predominant share of overall demand only for lithium (56 percent), while for all other materials, the proportion was well below 30%.

Table 3 shows the breakdown of cleantech demand into six application types: 1) electric vehicles; 2) wind generation; 3) solar photovoltaic generation; 4) stationary electricity storage; 5) investments in electricity networks; 6) other renewable-energy products or investments goods not belonging to the previous categories. The last row of the table reports estimates of the critical materials bill in each category as a proportion of the value of sales in the same category.

The two cleantech applications providing the largest contribution to the demand for critical materials are electric vehicles and electricity networks, at 35 and 39 per cent of the total dollar value respectively. In these two categories, the cost of critical materials also represents a significant fraction of sales (6.5 and 10.9 per cent). The highest incidence, however, is found in electricity storage applications (about 50 per cent).

While market size alone is not a sufficient measure of macroeconomic relevance, the current value of demand for critical materials (approximately 0.35% of global GDP) appears too small to allow for a significant transmission of their price volatility to consumer inflation, GDP, or other macroeconomic indicators relevant to central banks.[8] Although this conclusion is likely accurate today, based also on further evidence presented in the following sections, it may not hold in the near future if there is a substantial increase in demand for cleantech applications due to progress toward net-zero emissions. For this reason, we compute estimates of market value in a future high-demand scenario.

We consider the IEA's Net Zero Emissions (NZE) scenario for 2030, which assumes that governments will not only meet all their climate-related commitments in full and on time but

[7] We use the quantities and prices of various qualities of crude oil to compute this aggregate. However, an apples-to-apples comparison with our aggregate of critical materials (which includes only refined materials) should instead include pricier distillates of oil (such as diesel and gasoline).

[8] As explained in the introduction, this statement encompasses "normal" episodes of high volatility and price spikes, and not catastrophic supply disruptions and prolonged shut-downs of entire supply chains, that could ideally happen but have never been observed in the recent past.

will also strengthen these commitments beyond current levels to stabilize global average temperatures at 1.5°C above pre-industrial levels. In this scenario, according to the IEA's estimates, production and investment in all cleantech categories increase significantly. For example, lithium, graphite, and copper used in the production of electric vehicles increase more than six-fold.

The fast increase in demand envisaged in the scenario may put strong upward pressure on prices. We take this possibility into consideration by assuming that all critical material prices simultaneously return to their historical maxima, which are in most cases multiples of today's prices (Figure 1).[9] Under this scenario, we find that the total market value increases to around 1.1 trillion dollars (approximately 1% of world GDP), with 650 billion attributable to cleantech demand (Table 4). This is comparable to the current size of the natural gas market (Table 2).

With this result in mind, several questions arise. How likely is it that we end up in such a scenario? Price developments in the natural gas market are known to influence macroeconomic outcomes, particularly inflation. If markets for critical materials reach a scale comparable to that of the natural gas market, should we expect a similar macroeconomic relevance? Would the transmission channels of price shocks be analogous? In the following sections, we analyze and discuss key aspects of critical materials markets to provide preliminary answers to these questions.

4. Market characteristics

We now discuss key features of the six critical materials involved in the computation of market size: substitutability, price volatility, degree of criticality, elasticity of demand.

4.1 Substitutability

A distinguishing feature of critical materials is that they are difficult or outright impossible to substitute in the industrial processes in which they are used. However, their degree of substitutability can change significantly over time, due to innovation and technological progress (e.g., Ku et al. 2018).

Assessing the degree of material substitutability is generally challenging, as substitution potential is highly specific to individual use cases (Lütkehaus et al. 2022). However, in the IEA scenario discussed above, the rise in demand for critical materials is driven by few specific applications. This narrower scope allows us to offer some insights into the potential for substitution.

[9] Our assumed price levels are not dissimilar from those found endogenously with a structural VAR by Boer et al. (2024) in a high-demand scenario. We choose the historical maxima over our 2016-2024 sample as simple and objective measures of price stress, corresponding to historically observed supply/demand imbalances on critical material markets. The maxima are higher than average 2023 prices by 28% for copper, 122 for nickel, 127 for lithium, 98 for graphite, 174 for cobalt, and 47 for rare earths.

The first major application is the production of batteries used in electric vehicles and stationary electricity storage. Frequently, the cathodes of these batteries contain nickel and cobalt, the anodes are made of graphite, and lithium ions serve as energy carriers. Based on these facts, the increased production of batteries is a key driver of the surge in demand for cobalt, graphite, lithium, and nickel in the IEA scenario. However, due to significant investments in battery research and development, several production-ready technologies have recently emerged that will at least partially reduce the use of these materials.

First, abundant and inexpensive sodium has become a viable substitute for lithium in lower-performance electric vehicles and stationary storage (e.g., Froese 2024, Iberdrola 2024, Johnson 2023, Manthey 2024). Second, natural graphite can be replaced by synthetic graphite, which is produced through scalable industrial processes that do not rely on critical materials as primary inputs (Giesige 2024, Young 2024). Third, cobalt is increasingly being substituted by cheaper alternative cathode materials, such as iron and phosphorus (Abuelsamid 2023, Pollard 2023, Sriram 2024). Finally, nickel is not required in most of the emerging battery chemistries mentioned above, such as those based on sodium ions and cobalt-free cathodes. Overall, when it comes to battery applications, the potential for substituting critical materials appears high.

In the IEA scenario, all major clean energy applications are expected to require large quantities of copper. Most of this demand is for wiring (in electric vehicles, solar and wind power plants, stationary battery storage, and electricity networks). However, many experts, including cable industry executives we consulted, believe that copper wires can be substituted with aluminum ones in most cases (e.g., Hoekstra 2023), and there is ample evidence of ongoing substitution (e.g., Hamon 2021, Prasad and Sayyad 2024, Weber 2023). In simple terms, while there are technical trade-offs between the two materials, aluminum becomes an appealing alternative when prices are considered, especially when copper prices are higher than usual.

Finally, in the NZE scenario, demand for rare earths rises rapidly, driven by their use in the magnets found in EV motors and wind turbines. Several substitutes are currently being researched, including tetrataenite (Bloomberg 2022), iron-based magnets (Ida 2023), and manganese-aluminum-carbon compounds (McKenzie 2023). However, none of these technologies has yet reached the level of maturity required for cost-effective large-scale production.

Overall, despite the uncertainties in assessing innovation and predicting the pace of adoption of new technologies, it seems reasonable to conclude that the substitutability of critical materials is increasing rapidly in most energy applications (with the notable exception of rare earths used in magnets). This improved substitutability could reduce the likelihood of the demand-driven price spikes projected in our 2030 scenario.

4.2 Price volatility

In the high-demand 2030 scenario, the market size for critical materials approaches that of the natural gas market. But does this automatically make critical material prices a source of macroeconomic volatility, as we see with natural gas prices? The answer depends, in part, on their expected variability. Paradoxically, if critical material prices were completely stable, their impact on global inflation and economic activity would arguably be minimal. In other words, for critical materials to have comparable macroeconomic effects, both market size and price volatility must mirror those of natural gas.

Motivated by this line of reasoning, we analyze the time series of critical material (Figure 1) and fossil fuel prices and compute estimates of their volatility. We focus on the 2016-2024 period, during which time-series data for all six critical materials under analysis are available. Volatility is calculated as the sample standard deviation of the percentage monthly price changes, then annualized by multiplying by the square root of 12. The estimates are presented in Table 5.

The main result of this analysis is that, historically, the prices of critical materials have been, on average, much less volatile than those of fossil fuels, particularly natural gas. Copper, which holds the largest weight in both the 2023 and 2030 consumption baskets, has an annual volatility of 20 per cent, compared to 78 for natural gas[10] and 38 for oil.

We calculate two critical-material price indices as weighted sums of the prices of the six materials, with weights proportional to the quantities consumed in 2023 and in the 2030 scenario. The volatilities of these indices, which provide a measure of the variability in overall market size, are 19 and 20 per cent respectively, four times lower than the volatility of natural gas.

To address concerns that the accelerated pace of the green transition may have caused structural breaks, we also calculate volatilities using a shorter sub-sample starting in 2020. We find that this has a minor impact: the estimated volatilities of the critical material indices increase slightly, to 21 and 24 percent, respectively.

There are several reasons for the relatively low volatility of critical material indices. One key factor is the diversification effect: since the prices of different critical materials are not perfectly correlated, their individual volatilities tend to offset each other when combined in a basket of materials. The literature on commodity volatility supports this view, noting that despite the influence of common factors, much of the volatility of individual commodities is idiosyncratic (e.g., Frankel and Rose 2010; Erb and Harvey 2006; Daskalaki and Skiadopoulos 2011; Nguyen and Walther 2020).

Second, the theory of storage – supported by strong empirical evidence – suggests that storage costs are a major determinant of commodity price volatility. When it is difficult and costly to store a commodity, stockpiles tend to be small. As a result, even minor imbalances between supply and demand can trigger significant price changes, as these cannot be mitigated by available inventories (e.g., Ng and Pirrong 1994; Cifarelli and Paesani 2012; Geman and Smith 2013; Legrand 2019). For some of the critical materials analyzed in this paper, storage fees are regularly published by metal exchanges. For instance, at the London Metal Exchange, the storage fees for copper from April 2023 to March 2024 were approximately 50 USD cents per

[10] If we exclude the 2022-2024 period, influenced by the effects of the Russia-Ukraine war, from the calculation, the estimated volatility of natural gas decreases to 66.

tonne per day, equivalent to about 2 percent of the price of copper per year; analogously, the fees for nickel and cobalt were around 1.4 percent and 0.8 percent of their prices, respectively. By contrast, storage fees for natural gas in Europe typically range from 2 to 8 EUR/MWh per year (UN 2013; REKK 2013; VIS 2023), which amounts to 5 to 20 percent of its current price. Moreover, storage capacity for critical materials is generally easier to provision compared to that for natural gas, which requires significant investment in infrastructure.

Finally, demand elasticity is another key determinant of commodity price volatility (e.g., Baumaister and Peersman 2013, Chen and Mu 2021). Intuitively, if demand is very inelastic, small shifts of the supply curve cause large changes in prices, making their volatility higher. As we explain in more detail in Section 4.4, there are reasons to believe that the demand elasticity for critical materials may be higher than that for fossil fuels.

Based on the evidence and the theoretical considerations above, we conclude that the relatively low volatility of critical material prices, when considered as a group, may reduce their macroeconomic impact, even in scenarios where their market size matches that of the natural gas market. However, this conclusion could be invalidated by structural breaks – not observed so far – that may significantly alter price volatilities. Some factors that could increase volatility include more intense speculation and market manipulation activity (e.g., IRENA 2023) and more frequent disruptions of mining activities due to climate stress (e.g. PwC 2024). The effects of (higher) cartelization – which is also a material risk according to IRENA (2023) – on volatility is ambiguous, as cartelization usually compresses volatility, though with exceptions (Harrington and Chen 2006, Bolotova et al. 2008, Blanckenburg et al. 2012).

Additionally, we emphasize that our analysis does not account for war-like scenarios, in which significant portions of the global production of a critical material become inaccessible to major regions for prolonged periods, severely disrupting their value chains. Such episodes have not occurred in recent history.[11] Instead, export restrictions on critical minerals, though increasing in number, have primarily taken the form of export taxes and licensing requirements, with outright export prohibitions playing a minor role (Kowalski and Legendre 2023). This aligns with the political incentives of exporting countries to maintain high tax revenues, avoid harming local businesses, and extract benefits from controlling the issuance of licenses.

4.3 Degree of criticality

As previously discussed, our estimates of market size depend significantly on the inclusion of copper in the IEA's list of critical materials, as copper accounts for 63% of total demand in 2023 and 34% in 2030. This choice hinges on its extensive use in the energy sector and on concerns about potential undersupply if demand for cleantech investments grows rapidly. However, the degree of criticality of copper is usually deemed low because its market is large and mature, production is not highly concentrated, a significant portion of demand is met by recycling, and

[11] This statement applies to the critical materials discussed in this paper. However, as we have already explained in the introduction, the Russian invasion of Ukraine in 2022 and the resulting severe interruptions to natural gas supplies in several countries (Emiliozzi et al. 2023) have raised concerns that similar crises could affect critical material markets.

it is highly substitutable with aluminum in many applications. For instance, while copper is considered critical by the US Department of Energy, it is not included in the main list of critical minerals compiled by the US Department of the Interior and the US Geological Survey. Similarly, the European Commission designates copper as strategic, but not critical. A meta-analysis by Hayes and McCullough (2018) found that only 3 out of 32 surveyed criticality studies deemed copper critical.[12]

For our purposes, that is, for assessing macroeconomic relevance, it seems reasonable to include a material in the analysis if it has a large market size but a low degree of criticality. Ultimately, market maturity, lower production concentration, and good substitutability should be reflected in lower price volatility, which is also factored into the analysis.

The degree of criticality for the other materials in our analysis is higher, mainly due to the geographic concentration of their production. For this reason, all of them are included in the critical materials lists compiled by the U.S. Department of the Interior and the European Commission, with the sole exception of nickel, which the EU considers strategic but not critical.

As criticality may change over time, several points are worth noting. First, authorities worldwide have intensified their efforts to reduce criticality by incentivizing the development of more robust and diversified supply chains. According to the IEA's Critical Minerals Policy Tracker, by the end of 2023, over 450 policy measures had been adopted by more than 35 countries to ensure supply reliability and resilience, promote exploration, production, and innovation, and encourage sustainable and responsible practices. Second, recycling of critical materials, which naturally reduces strategic dependencies and increases resilience, is set to play a larger role in the future. For example, battery recycling technology has advanced rapidly (Crownhart 2023), and a significant portion of the demand for battery-critical materials is likely to be met by recycled materials in the near future (Tong et al. 2024). Third, as illustrated in Section 4.1, the substitutability of critical materials is rapidly increasing in most energy applications, further contributing to a reduction in criticality.

Overall, while criticality remains high for the majority of materials analyzed in this paper, progress on both policy and technological fronts is likely to reduce it, or at least keep it in check despite increasing demand for energy applications. This should help lower the likelihood of the extreme price spikes projected in our 2030 scenario.

4.4 Demand elasticity

We conclude our discussion of critical materials' characteristics with a brief consideration of demand elasticity.

[12] The case of copper highlights the uncertainty surrounding the criteria for determining criticality, due to a lack of widely accepted scientific standards (e.g., Daw 2017, Helbig et al. 2021) and limited debate within policy circles. Additionally, the quantitative frameworks used to rank materials by their criticality depend on numerous parameters and modeling choices that are often set arbitrarily, based on expert judgment (Erdmann and Graedel 2011, Machacek 2017).

Although, to our knowledge, academic research on demand elasticity in critical materials markets is currently very limited,[13] we note that, particularly in energy applications, a significant portion of the demand is driven by the production of investment goods (e.g., power plants and grids) and durable goods (e.g., electric vehicles). Since investments and durable purchases are easier to postpone during price spikes than the consumption of nondurables (e.g., Wong and McDermott 1990, Barsky et al. 2007), the elasticity of demand for critical materials may be higher than, for example, that of fossil fuels, which are primarily used in consumption activities that are difficult, if not impossible, to delay. This could mitigate the impact of critical material shortages on their prices. However, such shortages may have negative repercussions on economic activity overall and on the green transition specifically, by slowing down investments. The magnitude of these effects is uncertain and could be the subject of future research. Moreover, it may be worthwhile to model how investment slowdowns induced by high critical material prices could differ between the transition phase – when investment in fossil-based energy sources is still a viable alternative – and a steady state where fossil fuels have been completely phased out. In the latter scenario, demand could become less elastic, as postponing the replacement of depreciating green energy plants becomes more challenging.

5. Conclusions

The demand for critical materials has surged in recent years, primarily driven by the global push for a green transition. We ask whether these materials have become so economically significant that their "ordinary" price volatility could substantially impact global macroeconomic outcomes, even without extreme disruptions in which significant portions of the global production of a critical material become inaccessible to major regions. Answering this question could be useful, for instance, to a central bank needing to decide whether monitoring critical material prices – alongside those of energy commodities – might aid in predicting inflation and other macroeconomic variables.

Policy-oriented studies on critical materials often focus on issues related to supply security,[14] specifically, how to monitor and mitigate the risk of entire supply chains being disrupted by the sudden unavailability of one or more critical materials, triggered, for example, by extreme geopolitical events. While the importance of this work cannot be overstated, as evidenced by recent G7 Communiqués (2023, 2024), we focus on a different aspect: the potential macroeconomic impacts of critical materials during normal times.

We find that the overall size of the market for critical materials is still small but could, over a five- to ten-year horizon, reach the scale of macroeconomically relevant markets such as that for natural gas. Even so, some factors may limit the macroeconomic impact of developments in critical material markets: the substitutability of critical materials is increasing rapidly in most energy applications, their price volatility remains significantly lower than that of traditional

[13] For estimates of supply elasticity, see Boer et al. (2024).

[14] Other important issues include market transparency, the environmental and social sustainability of the sourcing of critical materials, cartelization and market manipulation. See, e.g., IRENA (2023) and the Framework for Critical Raw Materials laid out by the United Nations Economic Commission for Europe (UNECE).

energy commodities, and many countries are adopting policy measures to ensure supply reliability and resilience. The primary tail risk is that export restrictions on critical materials, which have increased in number and have so far mostly taken the form of export taxes and licensing requirements, could evolve into the less benign form of outright export prohibitions. While incentive-compatibility considerations suggest that this risk remains low (at least outside war-like scenarios), its realization could have significant macroeconomic consequences, particularly in sectors where critical materials constitute a large share of total inputs (Panon et al. 2024).

While our contribution is simple and primarily descriptive, its aim is to stimulate the debate on the role of critical materials in macroeconomic monitoring. In particular, we highlight a gap in the literature regarding the price elasticity of the demand for critical materials. We hypothesize that it may be higher than that of other commodities, given the widespread use of critical materials in the production of investment goods, which can be more easily delayed during price spikes. Whether this is true, and how shock transmission channels differ as a result, remains to be explored.

References

Abuelsamid, S., 2023. Lithium Iron Phosphate Set To Be The Next Big Thing In EV Batteries. Forbes.

Barsky, R.B., House, C.L. and Kimball, M.S., 2007. Sticky-price models and durable goods. American Economic Review, 97(3), pp.984-998.

Baumeister, C. and Peersman, G., 2013. The role of time-varying price elasticities in accounting for volatility changes in the crude oil market. Journal of applied econometrics, 28(7), pp.1087-1109.

Blanckenburg, K.V., Kholodilin, K.A. and Geist, A., 2012. The influence of collusion on price changes: New evidence from major cartel cases. German Economic Review, 13(3), pp.245-256.

Bloomberg, 2022. Researchers Find Possible Replacement for Rare Earth in Magnets. Bloomberg News.

Boer, L., Pescatori, M.A. and Stuermer, M., 2024. Energy Transition Metals: Bottleneck for Net-Zero Emissions? Journal of the European Economic Association, 22, pp.200-229.

Bolotova, Y., Connor, J.M. and Miller, D.J., 2008. The impact of collusion on price behavior: Empirical results from two recent cases. International Journal of Industrial Organization, 26(6), pp.1290-1307.

Chen, Y.F. and Mu, X., 2021. Asymmetric volatility in commodity markets. Journal of Commodity Markets, 22, p.100139.

Cifarelli, G. and Paesani, P., 2012. An Assessment of the Theory of Storage: Has the Relationship between Commodity Price Volatility and Market Fundamentals Changed Over Time? Dipartimento di Scienze Economiche, Università degli Studi de Firenze, Working Paper, 12/2012.

Crownhart, C., 2023. Battery recycling: 10 Breakthrough Technologies 2023. MIT Technology Review.

Daskalaki, C. and Skiadopoulos, G., 2011. Should investors include commodities in their portfolios after all? New evidence. Journal of Banking & Finance, 35(10), pp.2606-2626.

Daw, G., 2017. Security of mineral resources: A new framework for quantitative assessment of criticality. Resources Policy, 53, pp.173-189.

Emiliozzi, S., Ferriani, F. and Gazzani, A., 2023. The European energy crisis and the consequences for the global natural gas market. Bank of Italy Occasional paper, 824.

Erb, C.B. and Harvey, C.R., 2006. The strategic and tactical value of commodity futures. Financial Analysts Journal, 62(2), pp.69-97.

Erdmann, L. and Graedel, T.E., 2011. Criticality of non-fuel minerals: a review of major approaches and analyses. Environmental science & technology, 45(18), pp.7620-7630.

Frankel, J.A. and Rose, A.K., 2010. Determinants of agricultural and mineral commodity prices. HKS Faculty Research Working Paper Series, 10-038.

Froese, M., 2024. First-ever commercial-scale production of sodium-ion batteries in the US. EV Engineering.

G7, 2023. Five-Point Plan for Critical Minerals Security. G7 Ministers' Meeting on Climate, Energy and Environment. Sapporo.

G7, 2024. Climate, Energy and Environment Ministers' Meeting Communiqué. Torino.

Gielen, D. and Lyons, M., 2022. Critical materials for the energy transition: Rare earth elements. International Renewable Energy Agency, Abu Dhabi, pp.1-48.

Faubert, V., Guessé, N. and Le Roux, J., 2024. Capital in the Twenty-First Century: Who owns the capital of firms producing critical raw materials? Banque de France Working Paper, No. 952.

Geman, H. and Smith, W.O., 2013. Theory of storage, inventory and volatility in the LME base metals. Resources Policy, 38(1), pp.18-28.

Giesige, J., 2024. Synthetic anode confirmed. What are the implications? The Limiting Factor

Hamon, M., 2021. Aluminum Conductors in Solar Applications: How to Save Costs without Sacrificing Reliability. PurePower Engineering.

Hayes, S.M. and McCullough, E.A., 2018. Critical minerals: A review of elemental trends in comprehensive criticality studies. Resources Policy, 59, pp.192-199.

Harrington Jr, J.E. and Chen, J., 2006. Cartel pricing dynamics with cost variability and endogenous buyer detection. International Journal of Industrial Organization, 24(6), pp.1185-1212.

Helbig, C., Schrijvers, D. and Hool, A., 2021. Selecting and prioritizing material resources by criticality assessments. One Earth, 4(3), pp.339-345.

Hoekstra, A., 2023. Copper scarcity will not materially slow down the energy transition. Neon Research.

Iberdrola, 2024. Sodium-ion batteries: the revolution in renewable energy storage. Iberdrola.

Ida, M., 2023. Japanese Advances in Rare Earth Alternatives Bring Many Advantages. Japan Forward.

IEA, 2024. Global Critical Minerals Outlook 2024. International Energy Agency.

IRENA, 2023. Geopolitics of the Energy Transition: Critical Materials. International Renewable Energy Agency.

Johnson, P., 2023. Volkswagen-backed EV maker rolls out first sodium-ion battery powered electric car. Electrek.

Legrand, N., 2019. The empirical merit of structural explanations of commodity price volatility: Review and perspectives. Journal of Economic Surveys, 33(2), pp.639-664.

Lütkehaus, H., Pade, C., Oswald, M., Brand, U., Naegler, T. and Vogt, T., 2022. Measuring raw-material criticality of product systems through an economic product importance indicator: a case study of battery-electric vehicles. The International Journal of Life Cycle Assessment, pp.1-16.

Kowalski, P. and Legendre, C., 2023. Raw materials critical for the green transition: Production, international trade and export restrictions. OECD Trade Policy Papers, 269.

Ku, A.Y., Loudis, J. and Duclos, S.J., 2018. The impact of technological innovation on critical materials risk dynamics. Sustainable Materials and Technologies, 15, pp.19-26.

Machacek, E., 2017. Constructing criticality by classification: Expert assessments of mineral raw materials. Geoforum, 84, pp.368-377.

Manthey, N. 2024. CATL gears up for next-gen SIBs and global licensing. Electrive.

McKenzie, J., 2023. Powering the green economy: the quest for magnets without rare earths. PhysicsWorld.

Ng, V.K. and Pirrong, S.C., 1994. Fundamentals and volatility: Storage, spreads, and the dynamics of metals prices. Journal of Business, pp.203-230.

Nguyen, D.K. and Walther, T., 2020. Modeling and forecasting commodity market volatility with long-term economic and financial variables. Journal of Forecasting, 39(2), pp.126-142.

Panon, L., Lebastard, L., Mancini, M., Borin, A., Caka, P., Cariola, G., Essers, D., Gentili, E., Linarello, A., Padellini, T. and Requena, F., 2024. Inputs in distress: Geoeconomic fragmentation and firms' sourcing. Banca d'Italia Occasional Papers, No. 861.

Pollard, J., 2023. LFP Becoming the Battery of Choice for Electric Vehicles. Asia Financial.

Prasad, E., Sayyad, A., 2024. Aluminum Wire Battery Market Size, Share, Competitive Landscape and Trend Analysis Report, by Type, by Application: Global Opportunity Analysis and Industry Forecast, 2024-2033. Allied Market Research.

PwC, 2024. Climate Risks to Nine Key Commodities: Protecting People and Prosperity. PricewaterhouseCoopers.

REKK, 2013. Natural Gas Storage Market Analysis in the Danube Region. Regional Centre for Energy Policy Research.

Sriram, A., 2024. Tesla to bring LFP battery supply chain to US. Reuters.

Tong, Z., Wang, M., Bai, Z., Li, H. and Wang, N., 2024. Advances in lithium-ion battery recycling: Strategies, pathways, and technologies. ChemPhysMater, in press.

United Nations, 2013. Study on Underground Gas Storage in Europe and Central Asia. United Nations Economic Commission for Europe.

VIS, 2023. Study on the impact of the measures included in the EU and National Gas Storage Regulations. Final Report prepared for The Agency for the Cooperation of Energy Regulators.

Weber, A., 2023. High-Strength Aluminum Wire Helps Address Lightweighting. Assembly.

Wong, A.Y.T. and McDermott, C.J., 1990. Consumption of durables, non-durables and services in New Zealand: A system-wide analysis. New Zealand Economic Papers, 24(1), pp.115-127.

Young, T., 2024. Panasonic secures US graphite supply. EVinFocus.

Tables

Table 1 – Size of critical materials markets in 2023 (USD billion)

	Total	Cleantech
Copper	220.9	54.3
Nickel	67.4	10.4
Lithium	34.1	19.0
Graphite	6.9	1.9
Cobalt	7.5	2.2
Rare earths	13.1	2.3
Total	349.8	90.1

Note: market size is the product of the quantities demanded in 2023, as estimated by the IEA, and their respective prices (computed as averages of the daily prices recorded in 2023). Cleantech refers to the portion of demand that is attributed to the production of renewable-energy and other green technologies.

Table 2 – Size of fossil-fuel markets in 2023 (USD billion)

	Total
Crude oil	2973
Natural gas	1268
Coal	939
Total fossil fuels	**5180**

Note: market size is the product of the quantities demanded in 2023, as estimated by the IEA and the US Energy Information Administration, and their respective prices (computed as weighted averages of the daily prices of regional benchmarks, recorded in 2023).

Table 3 – Cleantech demand in 2023 by technology (USD billion)

	EVs	Wind	Solar	E storage	E network	Other	Total
Copper	3.4	4.3	10.3	0.3	35.3	0.7	54.3
Nickel	6.5	1.0	0.0	0.3	0.0	2.6	10.4
Lithium	17.1	0.0	0.0	1.9	0.0	0.0	19.0
Graphite	1.7	0.0	0.0	0.2	0.0	0.0	1.9
Cobalt	2.1	0.0	0.0	0.1	0.0	0.0	2.2
Rare earths	0.9	1.3	0.0	0.0	0.0	0.0	2.3
Total	31.8	6.6	10.3	2.8	35.3	3.3	90.1
% of sales or investments	6.5	3.8	3.3	49.3	10.9	NA	6.9

Note: EVs = electric vehicles; Wind = wind turbines; Solar = solar photovoltaic plants; E storage = stationary electricity storage; E network = investments in electricity networks; Other = other renewable-energy products/investments not belonging to the previous categories. The quantity of a material demanded in 2023 for each category of green technology, as estimated by the IEA, is multiplied by the average of the material's daily prices recorded in 2023. The last row reports the estimated incidence of critical materials' costs on the total value of sales/investments in each category.

Table 4 – Market size in a high-demand scenario in 2030 (USD billion)

	Total	Cleantech
Copper	364.2	163.8
Nickel	267.8	134.3
Lithium	330.8	289.0
Graphite	39.1	25.2
Cobalt	39.1	23.1
Rare earths	30.6	12.8
Total	1071.6	648.4

Note: market size in the high-demand scenario is computed under the hypothesis that governments step up their commitments to mitigate climate change, and the resulting increased demand for critical materials exerts substantial upward pressure on their prices. For each material, market size is the product of the quantity demanded in 2030 in the IEA's NZE scenario and the maximum market price recorded in our sample.

Table 5 – Annual price volatility of critical materials and fossil fuels (per cent)

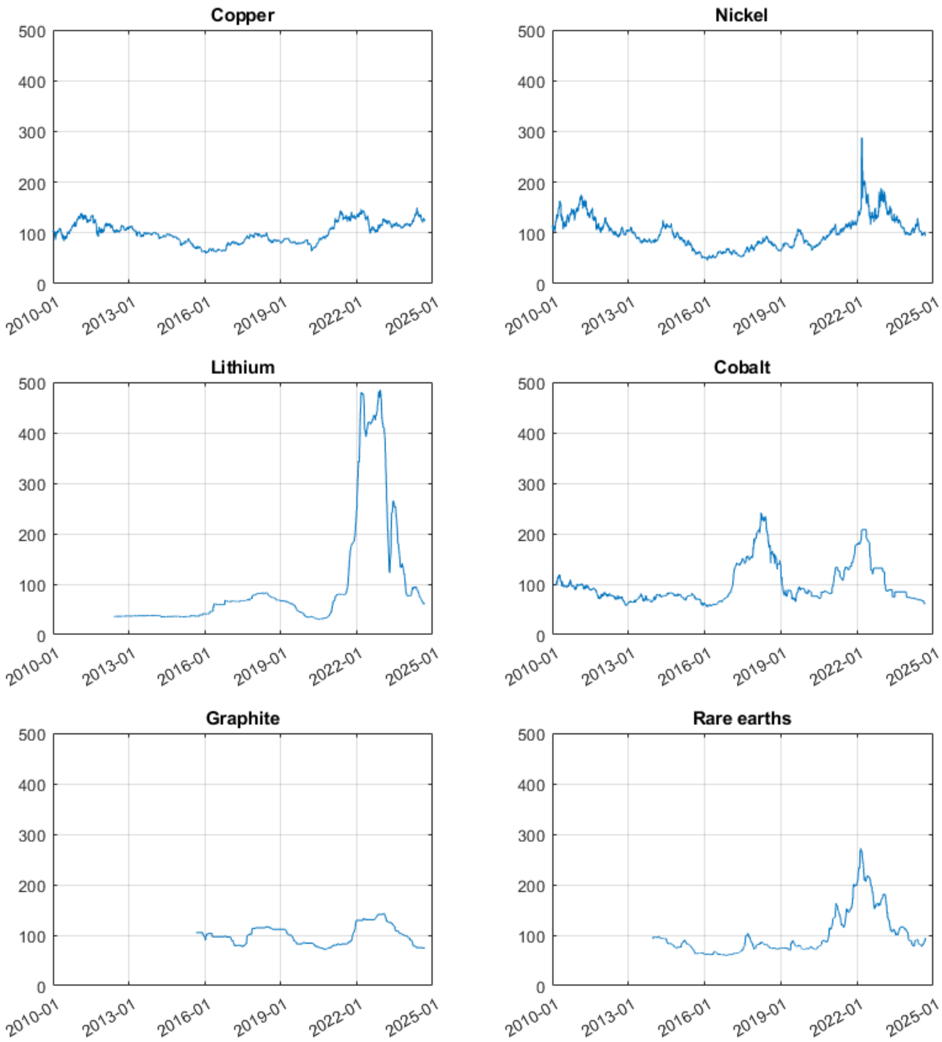
Critical materials	Volatility		Fossil fuels	Volatility
Copper	19.5		Oil (Brent)	38.0
Nickel	37.4		Natural gas (TTF)	78.0
Lithium	49.6		Coal (API2)	37.5
Graphite	15.2			
Cobalt	33.4			
Rare earths	28.6			
CM Index 2023	18.6			
CM Index 2030	19.6			

Note: price volatilities are estimated on the 2016-2024 sample. CM Index 2023 is a weighted average of the prices of the six critical materials, with weights proportional to the quantities demanded in 2023. In the 2030 version of the index, the weights are the quantities demanded in the 2030 NZE scenario.

Figures

Figure 1 – Prices of critical materials

(indices; sample average = 100)



Note: price indices are obtained by dividing each price series by its sample average (and then multiplying by 100). Indices are displayed on the same scale so as to facilitate a visual assessment of their different volatilities.

Figure 2 – Critical material price indices

(indices; sample average = 100)

Note: The two critical material indices are weighted averages of the prices of the six critical materials (copper, nickel, lithium, cobalt, graphite, rare earths), with weights proportional to the quantities demanded (in 2023 and in the 2030 NZE scenario).