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Competition, Cooperation, or Cartelisation?

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Document Version
Final published version

Publication date:
2025

License
Unspecified

Citation for published version (APA):
Sen, A., Jamasb, T., & Toba, N. (2025). *The Emerging Global Market for Energy Transition Critical Minerals: Competition, Cooperation, or Cartelisation?* Copenhagen Business School, CBS. CSEI Working Paper No. 2025-05Working Paper / Department of Economics. Copenhagen Business School No. 06-2025

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CSEI Working Paper 2025-05

CBS DEPARTMENT OF ECONOMICS
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WORKING PAPER

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The Emerging Global Market for Energy Transition Critical Minerals: Competition, Cooperation, or Cartelisation?

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Abstract

As the clean energy transition progresses, critical minerals and metals will be essential components in the deployment of clean energy technologies, with estimates of their demand set to soar. However, proven reserves, as well as processing facilities, are geographically concentrated in a small number of countries. This paper addresses the following research question: how will the emerging market structure for critical minerals develop: will producers and consumers compete, cooperate, or cartelise? We contribute to the literature by exploring frameworks to describe some possible outcomes of market evolution based on characteristics of the current critical mineral market, preconditions for competition, cooperation or cartelisation, and case studies. We draw on insights from collusive oligopolies in the international market for oil and gas.

Keywords: critical minerals, energy transition, supply chains, decarbonisation, industrial organisation, cartels, markets

JEL Classification: L13, O24, Q21, Q34, Q35, Q37, Q42, Q48

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1. Introduction

Critical minerals, metals and rare earth elements (hereafter, collectively referred to as "critical minerals") serve a vital role in the development of many strategic high-tech sectors as a key input (Guo and You, 2023). They are also central to the ongoing climate transition by serving as key inputs for various technologies.

As the clean energy transition progresses, the expected demand for critical minerals such as copper, lithium, nickel, and cobalt, as well as rare earth elements such as neodymium, praseodymium, dysprosium and lanthanum, are expected to significantly increase. These minerals are essential for essential components in rapidly growing clean energy technologies including wind turbines, solar panels, electrolysers, electricity networks, electricity storage, and electric vehicles (EVs) (IEA, 2023). As technologies advance, the demand for specific critical minerals may change (e.g. batteries), creating uncertainties. The supply of critical minerals is influenced by various factors, including mining activities, geopolitical considerations, market prices, and technological advancements. Ensuring a stable and sustainable supply of these minerals is essential for meeting growing demand and supporting the clean energy transition. Balancing the supply and demand of critical minerals is crucial for the successful deployment of clean energy technologies. Disruptions in the supply chain and market prices are likely to impact the investment, production and deployment of these technologies, potentially hindering progress towards climate goals.

The critical minerals industry is central to achieving global climate objectives, such as the Paris Agreement goal of limiting temperature rise to 1.5-2 degrees Celsius. In order to achieve the Paris goal, global carbon emissions need to halve from 2010 levels by 2030 and reach net zero by 2050 (Fankhauser et al., 2022; IPCC, 2018). For any global temperature objective, there is a finite budget of carbon dioxide that can be released into the atmosphere, alongside other greenhouse gases (GHGs); beyond this budget, any further release must be balanced by removal into sinks – that is, aggregate emissions are "net zero" (Fankhauser et al., 2022).

The energy sector, which accounts for a significant portion of global carbon emissions, relies heavily on these minerals for decarbonisation. It accounted for around 76% of global carbon emissions in 2021 (WRI, 2024), and its decarbonisation remains central to achieving net zero. Globally, the predominant approach to decarbonisation has included two areas of focus: first, the rapid scaling up of renewable energy, mainly solar photovoltaic (PV) and wind, in electricity production with the aim of displacing carbon-emitting fossil fuels, and, second, measures to improve the efficiency of energy use (Sen et al., 2021). A 2023 European Union (EU) scientific report establishes the criticality of rare earths for manufacturing in 12 key technologies in five strategic sectors, including renewable energy, electromobility, energy- intensive industry, digital, and aerospace/defence (Carrara et al., 2023).

The pace of the clean energy transition and the race to develop a competitive advantage in technologies has led to the reclassification of some resources as "critical". For instance, the EU in its recent critical minerals strategy classified "coking coal" (i.e., coal as a material input rather than as an energy source) as a critical mineral. Similarly, in 2023 the US Geological Survey reclassified copper as a critical metal, based on its three definitional criteria for a critical resource, namely, its essentiality to economic and national security: its key role in energy technology, defence, consumer electronics and other applications; and, the vulnerability of its supply chain to disruption. A mineral's criticality involves an economic (as well as national security-related) imperative apart from a purely scientific or chemical definition. Thus, the minerals that each state identifies as "critical" can differ according to that country's economic, industrial and security needs. For example the UK has identified 18 critical minerals (HoC, 2023). This paper uses the term 'critical minerals' to also refer to rare earths as well as strategic critical raw minerals and metals.

This paper focuses on the challenge of ramping up supply fast enough to decarbonise the global economy at the pace required. Specifically it explores whether the producers and consumers of critical minerals needed for a fully decarbonised energy system could coordinate over their production and procurement, and the likely forms and outcomes of this coordination. This paper's main research question is therefore*, how will the emerging market for critical mineral producers develop: through competition, cooperation, or cartelisation?* The next section presents an overview of the current market conditions and relevant literature on the topic. Section 3 explores frameworks for analysis; Section 4 outlines some case studies; and Section 5 concludes with some insights on future evolution of the market and areas for further research.

2. Overview of the market for critical minerals

The International Energy Agency (IEA) has projected an exponential increase in demand for critical minerals for clean energy technologies from 2023-2050. The IEA's Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS), and Net Zero Emissions by 2050 (NZE) Scenario all explore different energy futures (IEA, 2024a). In its STEPS scenario, demand doubles to 2030 with continued growth thereafter. In the APS estimates, demand more than doubles by 2030 and triples by 2050; and in the NZE Scenario, demand nearly triples by 2030, growing to over 3.5 times the 2023 levels by 2050 (IEA, 2024a).

These exponential critical mineral demand growth projections are mainly due to the increasing need for renewable electricity supply to the traditional electricity consuming loads and new types of electricity consuming loads whose energy needs previously relied entirely on fossil fuels. The new loads are transport, buildings and industry sectors (IEA, 2024b). The International Renewable Energy Agency projects that under its 1.5 Celsius scenario, the share of electricity in the global final energy consumption will increase from 22% in 2020 to 51% by 2050, with the share of renewables in electricity increasing from 28% to 91% in the same period (IRENA, 2024).

Furthermore, the critical mineral requirement to supply the initial buildout of renewable technologies is far higher relative to that with fossil fuels. For example, it is estimated that a typical EV requires 6 times the mineral inputs of a conventional car and an offshore wind plant requires 13 times more mineral resources than a similarly sized gas-fired plant (IEA, 2022). Since 2010, the average amount of minerals needed for a new unit of power generation capacity has increased by 50%, as the share of renewables has risen (IEA, 2022).

Critical mineral extractions require much larger volumes of ore compared to traditional mining for precious metals like gold or silver, often found in higher concentrations. For example, the production of 1 kilogram (kg) of cobalt necessitates the extraction of a minimum of 2.5–1.25 tonnes of magmatic sulphide ore, not including material losses in transport, processing and beneficiation (Ghorbani et al. 2024). Rare earths, for instance, do not naturally occur as metals, but in oxide form tightly bound with other rare earths so that producers cannot selectively produce just the one, two, or four high-value rare earths metals needed for permanent magnets (Thibeault et al., 2023). For context, an EV produced in 2021 required an average of 8 kg of cobalt (Mathieu and Mattea, 2021), among other critical minerals (Ghorbani et al. 2024).

Consequently, in the medium term the global demand for critical minerals for renewable energy technologies will likely grow and potentially reach a demand-to-supply disparity, which for some critical minerals could be much larger than that in the fossil fuels market (Ghorbani et al. 2024). From 2017 to 2022, demand from the energy sector was the main factor behind a tripling in demand for lithium, a 70% jump in demand for cobalt, and a 40% rise in demand for nickel (IEA, 2023).

The supply of critical minerals may not easily ramp up and down given high capital requirements with long lead times of mining projects. The main reason for price declines in 2023 after steep increases in 2021-22, was a strong increase in supply and ample inventories of technologies made with critical minerals. The recent fall in prices has affected investments in new mineral supply and reduced incentives for supply diversification, albeit investments are still growing. Thus, the boom and bust nature of the mineral industry and high market concentration implies there is a risk of significant shortfalls in supply if, for any reason, supply from the largest producing country is interrupted (IEA, 2024a).

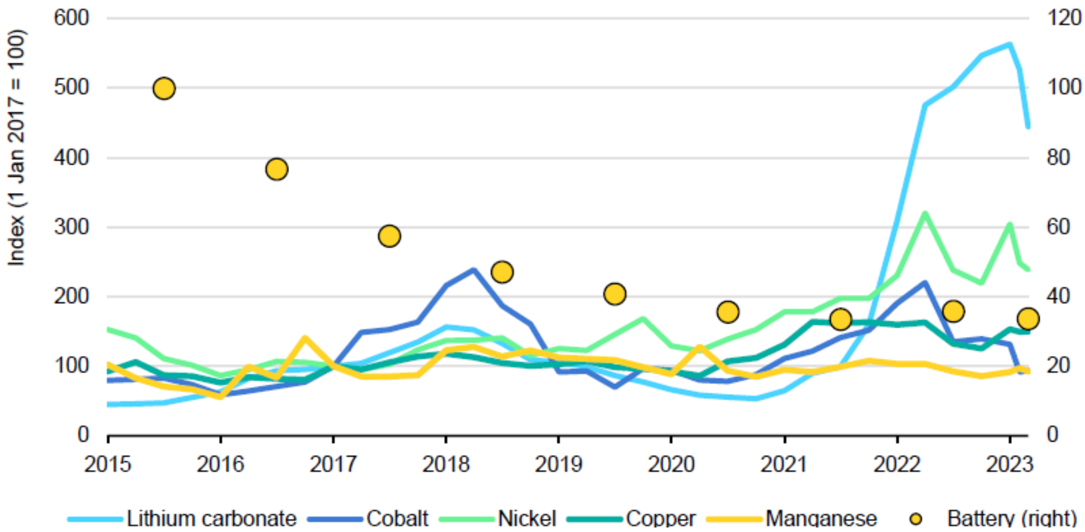
The proven reserves of many critical minerals are geographically concentrated (Umbach, 2021). For example, Brazil produces 98% of the world's active niobium reserve; global cobalt reserves are concentrated in the Democratic Republic of Congo (DRC); Argentina, Bolivia, and Chile, known as the "lithium triangle", together hold half of the world's lithium reserves; Indonesia controls over 20% of the world's nickel reserves; Mozambique controls more than half of the global graphite reserves; Russia has nearly half of global palladium deposits; and China holds reserves of rare earth oxides, and 34% of the world's copper reserves (HoC, 2023; Romani et al., 2024). China, Chile, Japan and the US are producers of mined and/or refined copper (Umbach, 2021).

The critical minerals supply chain can be broadly bifurcated into *extraction* (of the raw material) and *processing* (of the critical mineral). Processing involves separation, purification and refining. Processing stages are the most technically complex and costly, and require highly skilled resources to manage production (Thibeault et al., 2023). The need to separate low-value rare earths first before being able to separate high-value rare earths may cause an over-supply of the low-value rare earths, resulting in prices lower than their cost of production and thereby driving up the cost of the high-value rare earths (Thibeault et al., 2023). In mining, dominant positions are held by Australia (lithium), Chile (copper and lithium), China (graphite, rare earths), DRC (cobalt), Indonesia (nickel) and South Africa (platinum, iridium) (IEA, 2024). For mining, assessing production by ownership (based on the leading owner company's headquarter location) shows that companies in the US and Europe play a much greater role in the supply of all critical minerals than what the geographical location of mines may suggest (IEA, 2024). Production is carried out in small number of large multinational corporations and state-owned or -controlled enterprises operating across multiple countries (IRENA, 2023).

Much of this is from some of the largest multi-national mining majors (IEA, 2024). Although the majority of copper production occurs in Chile, European companies are the leading copper producers with over 10% of production and US companies controlling the second-largest amount of production. For lithium, Australia and Chile are the primary locations of raw material production, whereas US companies are a major shareholder of over 40% of producing mines (IEA, 2024). Although Indonesia is the leading location of nickel mining, Indonesian companies hold less than 10% of production (IEA, 2024). Chinese companies are the owners of major nickel mine, accounting for around 40% of production (IEA, 2024). European companies also have a sizeable share with over 20% of supply, predominantly due to operations in Indonesia (IEA, 2024). For cobalt, the majority of mines are located in DRC, whereas European and Chinese companies each own a third of the supply (IEA, 2024). Notably, DRC-owned companies account for less than 5% of production (IEA, 2024). The concentration of the supply chain becomes even more pronounced in the processing stage, with China currently accounting for 100% of the refined supply of natural graphite and dysprosium (a rare earth element), 70% of cobalt, and almost 60% of lithium and manganese (IEA, 2024).

Although most critical minerals are not widely traded (for instance, on international exchanges), the evidence suggests the existence of a supply response in the mining supply chain (Maranon and Kumral, 2019). For example, as shown in Figure 1, a commodity price cycle since 2015 which peaked in 2023 has occurred alongside a (lagged) expansion in lithium exploration: exploration spending rose by 20% in 2022 alone, driven by record growth in lithium exploration (IEA, 2023). A subsequent drop in prices in 2024 resulted in miners cutting back on some planned expansions, for instance in China and Australia. Trade (measured by the value of net exports) in critical minerals is many orders of magnitude smaller (around US$200 billion/year) than trade in the fossil fuels (in excess of US$1 trillion/year) that they will eventually replace (IRENA, 2023). However, as the energy transition to net zero progresses through decarbonisation and electrification of multiple economic sectors, critical minerals trade is expected to scale up significantly.

Figure 1: Selected critical mineral price indices, 2015-2023



Source: Data and graph from IEA (2023b)

Between 2022–2050, the energy transition could require the production of 6.5 billion tonnes of end-use materials, 95% of which would be steel, copper and, with smaller quantities of critical minerals/materials such as lithium, cobalt, graphite or rare earths; this cumulative material extraction compares with the over 8 billion tonnes of coal extracted annually in 2023 (ETC, 2023).

According to the Energy Transitions Commission (see https://www.energy-transitions.org/who/), there is no fundamental shortage of any of the raw materials to support a global transition to a net-zero economy; geological resources exceed the total projected cumulative demand from 2022-50 for all key materials, whether arising from the energy transition or other sectors (ETC, 2023). The three key issues are therefore: ramping up supply fast enough to decarbonise the global economy at the pace required; ensuring that mining for key materials occurs in a sustainable and responsible way which manages and minimises local environmental impacts; and, reducing primary material requirements through innovation and recycling (ETC, 2023). Thibeault et al. (2023) similarly identify production concentration and aggregate production as the two pressing challenges of the critical mineral transition.

3. Literature Review

Over the past four decades, since the establishment of modern institutional and governance structures to shape world trade, the organisation of global supply chains based on market liberalisation has increased the efficiency of production, trading, and consumption across economies (Beck et al., 2024). In the conventional energy sector, the efficiency-promoting organisation of global supply chains is fairly well established within the markets for hydrocarbons (Fattouh, 2011). One example of this efficiency is a persistent decline in emissions intensity of global economic output dominated by fossil fuels (measured in GDP terms) since 1990 and as material intensity of economies while total output has continued to expand (Sen et al., 2021). In the oil sector, the development of a deep and liquid physical (barrels) and financial (paper derivatives) market for both crude oil and refined (processed) products has meant that the price of oil is set by the marginal cost (of the most expensive oil resource) in a highly complex market serving around 100 million barrels/day of demand.

For the critical minerals sector that is expected to underpin a future net zero economy, it is not as yet clear how a global market will develop into efficiency-promoting well-organised supply chains across geographies, specifically due to the complexities of extraction and processing (Srivastava and Kumar, 2022). This literature review covers studies across three relevant strands of critical mineral transition literature that attempt to predict this evolution: competitive advantage, trading blocs and industrial policy.

3.1. Competitive advantage

Broad evidence (including that in Section 2) suggests that it is not singularly the resource endowment of a nation that might determine how the market for critical minerals evolves. This strand of literature draws heavily on Porter's (1990) hypothesis on what makes firms and nations successful in international supply chains, as an underpinning explanator of how critical mineral markets might evolve. This posits that classical explanations of the comparative advantage of nations, namely, that nations gain factor-based advantage in industries that make intensive use of the factors (land, labour and capital) they possess in abundance is redundant. Instead, a competitive advantage theory may be more relevant, particularly as in the sophisticated industries that form the backbone of any advanced economy, "a nation does not inherit but instead creates the most important factors of production – such as skilled human resources or a scientific base" (Porter, 1990). Moreover, the stock of factors that a nation enjoys at a particular time is less important than the rate and efficiency with which it creates, upgrades and deploys them in particular industries (Porter, 1990). Key literature in this strand includes Thibeault et al (2023), which analyses how firms and nations compete in the rare earth sector applying Porter's (1990) theory through the concepts of cost leadership, differentiation, and focus strategies, in the context of rare earth elements. It addresses the challenges posed by the rare earth supply chain, including the concentration of resources, trade barriers, and environmental concerns, and explores how countries and companies aim to overcome these challenges through resource substitution, supply chain diversification, and the development of new mining and recycling methods. Innovation plays a role in gaining a competitive advantage, such as advancements in rare earth extraction, recycling technologies, and substitution of rare earth materials in critical applications. In order for firms and nations to gain a lasting competitive advantage in the rare earth sector, they need to combine technological innovation, sustainable practices, and strategic diversification of supply chains (Thibeault et al., 2023).

Fikru and Awuah-Offei (2022) offers insights on whether countries might choose to specialise in extraction of the main 'ores' that contain critical minerals, or to further process and separate critical minerals from these ores. This choice is predicated on the fact that most critical minerals are produced as joint products after or with another mineral processing or recovery. For example, at least 23 of the 50 critical minerals in the US are predominately produced as joint products (Nassar and Fortier, 2021). A joint production system allows mining companies to use a single ore deposit as an input (or raw material) to produce multiple mineral goods, the primary of which is the main mineral (Fikru and Awuah-Offei, 2022). A further processing of the ore deposit is required to produce one or more critical minerals (Jordan, 2018). Fikru and Awuah-Offei (2022) proposes an economic framework for producing critical minerals as joint products – it presents a two-stage optimisation model: in the first-stage, firms minimise cost to choose input levels, including the extraction of a common ore to produce a critical mineral with or after the production of a main mineral; and, in the second stage, it models the production decision of firms by maximising profits to examine the role of geological, market, and technology parameters on critical minerals production under several scenarios. The joint product nature of critical minerals can inform resource management strategies. For instance, joint production can lead to efficiency gains, allowing producers to optimize the extraction of multiple minerals with minimal additional cost (Fikru and Awuah-Offei, 2022).

Valverde-Carbonell et al. (2024) highlights the interconnection between mineral criticality and mining competitiveness. While critical minerals are essential for global industrial activities, countries that have a competitive mining sector are better positioned to extract these minerals efficiently and sustainably. Countries with high 'mineral criticality' but low mining competitiveness may face challenges in exploiting their resources; conversely, nations with competitive mining sectors can leverage their resources to meet both domestic and global demand for critical minerals (Valverde-Carbonell et al., 2024). The paper deploys an endogenous system of equations in which countries' mining competitiveness and mineral criticality are simultaneously co-determined. The results show that South Africa, Russia, the US, and China are the most competitive mining countries; meanwhile, the platinum group metals, silicon, rare earths, and lithium are the most critical minerals assessed in the study (Valverde-Carbonell et al., 2024).

3.2. Trading Blocs

A second strand of relevant literature is organised around the development of critical mineral markets through "trading blocs" (groups of countries that establish rules for trade between all participating countries). Vivoda et al. (2024) critically examines the evolving landscape of global trade, characterized by the stratification of nations into competing groupings, and considers how intense geopolitical concentration and competition between two trade groupings impacts on the governance of critical mineral supply chains. The trading bloc hypothesis is supported by anecdotal evidence. For instance, Norway's 2005 "Oil for Development" policy was shaped around assistance provided to partner countries, tailor-made to promote sustainable mining and improve local economic development in the short and long run (Vakulchuk, 2023).

Vivoda (2023) analyses "friend-shoring", referring to the spatial reordering of supply chains under the criterion of political convergence – a strategy adopted by some critical mineral producers such as the US, through its Mineral Security Partnership. Again, friend-shoring is supported by anecdotal evidence. For example, the US Defence Production Act (DPA) is a 1950 law that allows the President to order mass production of certain products to enhance national security (Vivoda, 2023). In May 2022, the Pentagon requested the US Congress to amend the DPA to enable direct investment in Australia and the UK (Scheyder, 2022). According to the US Department of Defence (DoD), it is "unnecessarily" constrained by the requirement to invest only in the US and Canada. Combining the resources of two "closest allies" would "increase the nation's advantage" in an environment characterised by increased strategic competition (Scheyder, 2022).

Hegde et al. (2021) argue that powerful economies such as the US, China and EU are moving away from multilateralism in different ways, in order to shape novel approaches. Non-transparent practices like informal trade instruments, geoeconomics, and the domestication of international trade rules are appearing as new tools of global economic governance (Hegde et al., 2021). Vivoda et al. (2024) examine the emergence of the "BRICS+6" group in relation to the emergence of strategic critical minerals. The initial BRIC grouping, comprising Brazil, Russia, India and China, was launched in 2009, with South Africa joining in 2010 (Vivoda et al., 2024). Aimed at replacing the Western dominated trading system with a model more sympathetic to the needs of developing states, the operational impact of the original BRICS has been marginal (Pant, 2013). The enlarged BRICS+6 group, comprising the original members plus a further six nations, Argentina, Egypt, Ethiopia, Iran, Saudi Arabia and the UAE represents the shifting dynamics of international economic power (Vivoda et al., 2024).

Ghorbani et al (2024) explores the emergence of an Organization of Petroleum Exporting Countries (OPEC)-style organisation for green energy minerals and metals (GEMMs), due to three factors: a clear and essential role in the green energy transition, geographically concentrated in a manner that facilitates production coordination, and, production that is overwhelmingly consumed by developed nations but supplied by developing nations. As long as the cost-benefit ratio favours the formation of GEMM organisations, such organisations could potentially emerge (Ghorbani et al., 2024). The cost-benefit situation may be proxied by the demand to supply ratio of GEMMs and purchaser behaviour; when demand is high and suppliers are few, a loss in production autonomy is not as noticeable, because profit is likely to be rewarding in any case (Ghorbani et al., 2024). However, the governance of such GEMM organizations is crucial to avoid manipulation of production and quality to exploit consumers in advantage of the members of the organizations or their connected entities/individuals.

3.3. Industrial policy

A third strand of literature relates the evolution of the critical mineral market closely to countries' domestic industrial policy. Governments have traditionally used targeted interventions in the form of industrial policy to make domestic producers more competitive or promote growth in selected industries. While some countries had continued to use it, industrial policy had fallen out of favour across most of the world for years, because of its complexity and uncertain benefits (Ilyina et al., 2024). However, this trend is being reversed.

A review of industrial policy during 2009-2020 by Juhász et al (2023) illustrates that industrial policy is a prominent feature of the global economy and completely different from industrial policies of the past, highlighting four findings: first, industrial policy is common and has expanded since 2010; second, industrial policy is granular and technocratic - countries tend to use subsidies and export promotion measures, often targeted at individual firms; third, the countries engaged most in industrial policy tend to be wealthier liberal democracies; and fourth, industrial policy is targeted toward a subset of industries and is highly correlated with an industry's revealed comparative advantage.

As industrial policy examples since 2020, EU and US efforts to reverse previous offshoring, including in mineral related sectors, are discussed in terms of contributing to domestic employment and welfare (Zhou and Manberger, 2024). This was also explicit in the text, framing and other measures around the US's Inflation Reduction Act: to offer infrastructure and clean energy related jobs; similarly, the EU's Green Deal Industrial Plan is a "growth strategy", which marks a shift towards greater enthusiasm for public financing and state aid in support of clean energy and decarbonisation targets, with provisions also to protect social welfare in legacy carbon intensive sectors (Zhou and Manberger, 2024). The UK's "Invest 2025" industrial strategy is rooted in 'net zero objectives" including to capture the growth opportunities of the clean energy mission and net zero transition, identify and support clean energy industrial sectors with the greatest growth potential, and, align sector plans with net zero and environmental objectives (DfBT, 2024).

The assessment of UK industrial policy aimed at shaping the industrial composition of the economy during 2019-2022 confirms that industrial policy needs to be tailored to idiosyncratic situations across sectors, within and across countries and time (CMA 2025). Following are the UK Competition and Markets Authority's findings (CMA 2025). Compared to peer economies, the UK has historically been more likely to use industrial policy in mining, trade, information and communication technologies, arts and entertainment, and the hospitality sector, reflects the strategic priorities of past UK governments. The sectors with industrial policy have some overlap with the eight growth-driving sectors of the new industrial strategy. The UK has favoured tax credits reflecting its comparatively service-driven economy, which the assessment finds to be more effective on average than other tools. Based purely on the average of recent policies, a one percentage point increase in industrial policy spending as a share of GDP leads to about a 0.25% increase in labour productivity in the targeted industries (CMA 2025). Employment, investment, research and development (R&D) or market power has no significant impact. Industrial policies also appear to be more effective in production (that is, manufacturing, mining and utilities) than services (CMA 2025).

Liu (2024) discusses the challenges of measuring the effectiveness of industrial policy and suggests using network theory to assess its aggregate effects. It highlights four key economic mechanisms within networks, recommending targeting upstream sectors when market imperfections arise, addressing cross-region externalities, leveraging knowledge spillovers in central sectors, and focusing on downstream sectors to resolve coordination problems along the supply chain.

Zhu et al. (2022) looks at the structure of critical mineral trade in influencing renewable energy development in a country. It constructs global critical mineral trade networks from 2000 to 2019 to quantitatively analyse their topological characteristics, then using a dynamic econometric model to analyse the effect of critical mineral trade pattern on renewable energy development. It finds that a country's trade strength and central influence (in a resource trade network) is beneficial for renewable energy development. Variations of this relationship are examined in Fikru and Kilinc-Atta (2023), Feng et al. (2023) and Chang et al. (2023), among others. Pangestu (2023) argues that industrial policy aimed at onshoring or building supply chains with allies is unlikely to reshape the industrial geography of critical minerals. It contends that the required investments face uncertainties from increased demand, shifting industrial policies, geopolitics, long lead times, and reliance only on allies. Even if onshore extraction increases in developed countries, environmental concerns may hinder progress. It adds that industrial policy could disrupt or raise the cost of access to critical minerals and transition technologies, especially for developing countries. Expanding and diversifying investment in resource-rich developing countries could reduce reliance on a few countries and firms (Pangestu, 2023).

While the literature provides some insight into the strategic behaviour of countries involved in the critical minerals space, it does not provide further insight into organising frameworks for possible interactions among different actors in the critical minerals space under differing conditions. Given the heterogeneity of this market relative to markets for other traded natural resources (as commodities), this paper sets out three broad categories of such interactions and their enabling conditions, in the next section.

4. Frameworks for assessing future market evolution

In the search for a framework to assess evolution of market structure, a useful starting point is to consider the existing structures of commodity markets, followed by examining the incentives of market participants, which might then shape market outcomes.

4.1. Evolution of commodity market structures

Typically, commodity markets comprise of so-called "hard" commodities (energy or fuels, metals, minerals), and "soft" commodities (agricultural produce and livestock, nature and carbon offsets). For all commodities, the range of participants involved in market transactions is similar and includes: producers, consumers, agents involved in trading arbitrage or hedging risks, and regulators. These market participants operate at varying scales (national, regional, and international) contingent on the scope of the market. Transactions (sales and purchases of commodities) are determined through an archetypal set of pricing instruments underpinned by some physical unit of the commodity: they include unregulated/negotiated bilateral or multilateral contracts between agents; over the counter (OTC) bilateral contracts, for physical deliveries or financial (paper) settlements; and, exchange-traded contracts (using global commodity exchanges such as the London Metals Exchange or Chicago Mercantile Exchange). Contracts can broadly be categorised as "spot" (for immediate or day ahead physical delivery at a benchmark price), "futures" (derivatives contracts which mainly serve to hedge against price movements), and "options" (a right, rather than obligation, to buy at a set price). Table 1 provides examples of the structure of commodity markets across select commodity types.

Table 1: Structure and organisation of commodity markets

Market type	Commodities traded	Market participants	Trading exchanges (examples)
Energy	Oil, natural gas, low carbon fuels	Producer companies/groups, wholesale and retail fuel marketing companies, traders/trading companies, investors/financial institutions	New York Mercantile Exchange, Intercontinental Exchange (ICE), Dubai Mercantile Exchange, Tokyo Commodity Exchange, Shanghai International Energy Exchange, Multi Commodity Exchange of India
Metals	Copper, aluminium, zinc, nickel, cobalt	Mining companies, refiners/processing companies, traders (arbitrage), industry, investors/financial institutions, exchanges	ICE; London Metals Exchange, Shanghai Metals Exchange, Guangzhou Future Exchange (GFEX)

Agriculture	Grains and cereals, livestock and dairy, cash crops, oilseeds and edible oils.	Producers/suppliers (farmers, cooperatives, agribusiness), food processing corporations, governments, storage and providers, exchanges	Chicago Board of Trade; Intercontinental Exchange (ICE); National Commodity & Derivatives Exchange; B3 (Brazil Exchange)
Nature	Carbon credits and offsets, carbon removals	Carbon credit/offset developers (from technology-based and nature-based projects), corporations (buyers of credits and offsets), trading platforms, standards/certification bodies, exchanges	ICE; Chicago Mercantile Exchange (CME); European Energy Exchange

Source: Authors; Note: the list is illustrative and not exhaustive.

There are four key features which determine competitive trading in commodity markets: liquidity, volatility, anonymity, and transparency, summarised below from Heather (2015):

- "Liquidity" is a measure of the ability to trade volume at a given price without causing a substantial price movement or swing in the market. Standardisation of traded contract terms and conditions tends to concentrate liquidity.
- "Volatility" is a measure of price movement in relation to market activity. Historically, financial markets have high liquidity and fairly low and consistent volatility, whereas energy markets are typically very volatile yet may also be very liquid.
- "Anonymity" underpins futures trading and for instance requires a Clearing House that acts as the counterparty to all trades and this allows both "big" and "small" participants to trade alongside each other.
- "Market transparency" implies that traded volumes and prices are quickly disseminated in the public arena, with accurate, reliable and timely market data.

Based on the development of North American, British and Continental European natural gas commodity markets, the process of developing a mature commodity market around a "hub" (such as US Henry Hub or the UK National Balancing Point) takes around 10-15 years (Heather, 2015). Such development requires the adoption of rules/regulations governing the physical side of the business, alongside the emergence of standardised contracts for the commercial aspects. Then, bilateral trading follows, aided by brokers creating trading opportunities between counterparties. Trades start to be reported in the trade press, creating information to enable market transparency. Price disclosure and price discovery attracts more players into the market, such as smaller physical traders and early financial players. The creation of exchange products (futures), based on the underlying physical contracts, offers greater access to the market, especially by non-physical players (who close out their trading positions before maturity), and could also mitigate market powers or volatility in the spot markets. As increasing numbers of varied participants enter market trading, a forward curve develops for risk management purposes. The final stage of maturity is when the market develops sufficient liquidity for traders to use specific traded products (such as the Day Ahead or the Month Ahead) as indices on which to price their physical transactions (Heather, 2015).

Critical minerals as commodities traverse the "energy" and "metals" markets, given their pivotal role in both, described in Section 2, and thus the market infrastructure to facilitate the development of a mature market arguably exists. There are three main exchanges on which critical mineral futures already trade: the Chicago Mercantile Exchange (CME), the London Metal Exchange (LME), and the Guangzhou Future Exchange (GFEX) in China (Collins, 2024). Minerals such as aluminium and nickel are widely traded and well-established, but lithium and cobalt futures contracts are in their nascent stages of development; the majority of deals for these are thus OTC contracts, which are largely unregulated (Collins, 2024).

4.2. Market organisation – competition, cooperation, cartelisation

Market evolution is partly contingent on the incentives of different market participants, given an existing market structure. Perfectly competitive markets are characterised by homogenous products traded between multiple buyers and sellers, symmetry of information, and very low/no barriers to market entry/exit. Under a situation of perfect competition, numerous producers/producing countries operate in the resource market, all facing equal marginal extraction costs and subject to the same royalties, tax rates and stock constraints (Romani et al., 2024). Producers set the same output, for any given price, under the constraint that the change in cumulative output i.e. the marginal output, cannot exceed initial reserves (Romani et al., 2024). The market price is exogenous to each producer, who then determines its production plans as a function of price, and the market is brought into equilibrium purely through the price signal which equates price with the marginal cost (i.e. the cost of the last unit that needs to be produced for supply to meet demand) (Romani et al., 2024). Perfect competition, which represents a set of idealised conditions, is rarely found in reality in markets for commodities (or in any market, in general). Instead, the incentives of market participants deviate from the competitive or efficient optimum, on both the producer and the consumer sides. In the case of critical minerals, this paper propose that these incentive structures could lead to one or more of three potential outcomes: cooperation among producers, cooperation (or collaboration) among consumers, and collusion among producers (i.e. through cartels/collusive oligopoly).

Cooperation among producers. This outcome could be driven by incentives to lower the transaction costs of market participation, to achieve collective outcomes (that cannot be achieved by individual market participants, such as enhanced bargaining power) and allocate collective gains from those outcomes, to achieve economies of scale (e.g. rapid scaling up and deployment of capital), and to internalise externalities. Cooperation among producers for many of the above reasons is typically observed in markets for agricultural commodities, in which producer cooperatives play a visible role, such as ‘Zen Noh’ in Japan or ‘Dairy Farmers of America’ in the US (Bijman and Wijers, 2019; Falkowski, 2021). In critical mineral markets, the cooperative producer model could be used to generate competitive advantages for market participants (e.g. through joint ventures), for instance, when de-risking supply chains by relocating production increases costs and inefficiencies. There are some arguments that producer cooperation might lead to an inefficient vertical integration (e.g. through bundling extraction of minerals, their processing into intermediate inputs, and their use in end-product manufacturing, such as EVs), especially when such integration takes place between corporations in different parts of the value chain (Tan and Keidling, 2024). Unlike collusion, cooperation among producers may not necessarily influence the market price of a commodity. For instance, the Gas Exporting Countries Forum (GECF), established in 2001, acts as a cooperative platform for gas exporters, with little to no influence over prices.

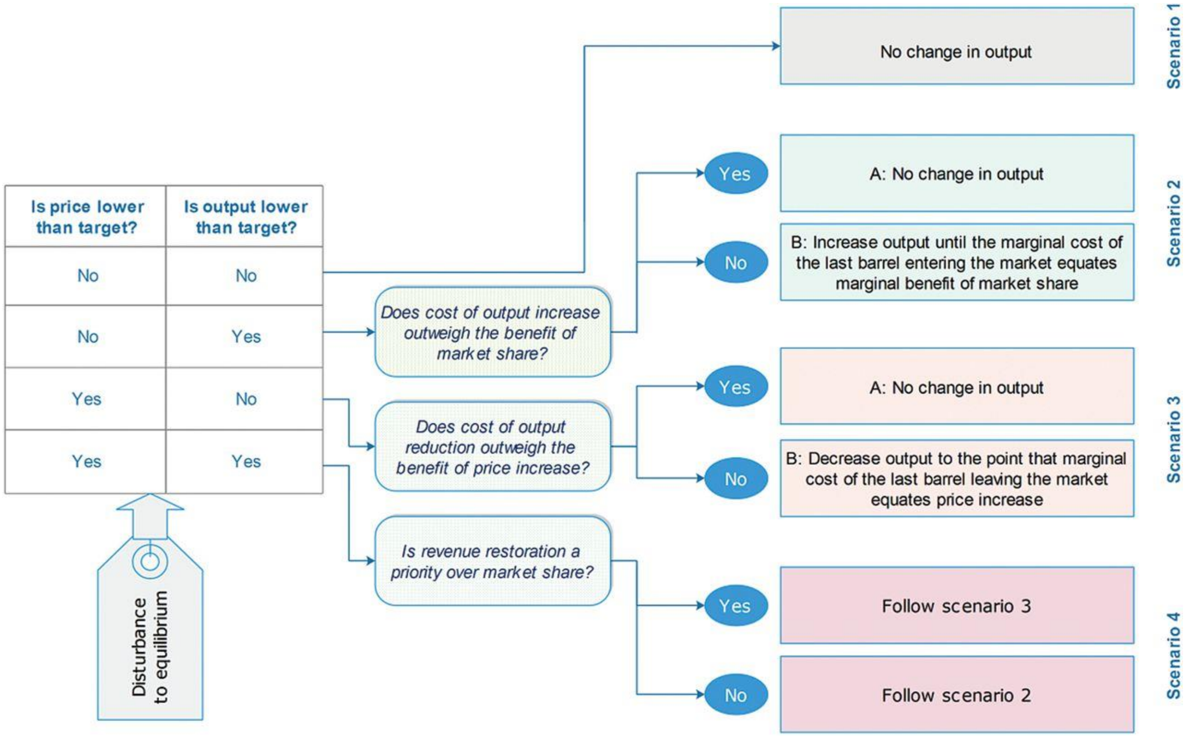
Cooperation between consumers. This outcome mirrors cooperation among consumers, except that it takes place on the demand side. It is driven by factors such as the existence of information asymmetry, increased price volatility in one or more linked commodity markets (e.g. energy and metals/minerals), shared objectives around the development of value chains, an inelastic supply of labour, and shared environmental objectives. Cooperation could take place among countries that are net consumers or net importers (e.g., the Minerals Security Partnership consisting of 14 countries seeking to secure supplies; similarly, the IEA was set up originally as a response by net oil importing countries in the Organisation for Economic Co-operation and Development (OECD) to develop collective strategies mitigating the impact of oil supply shocks), or among corporations across different industries, which use critical minerals as a shared input (e.g., companies that require rare earths to manufacture magnets, electronics, etc.) (Mamula and Adams, 2017).

Collusion between producers. A form of strategic cooperation between producers, precedents since the 1960s suggest that an outcome of collusive oligopoly, or cartelisation, of mineral commodity markets particularly on the extraction of raw minerals, is a possible outcome. A prominent example is found in the oil market, where the geographical concentration of deposits granted near-monopoly power to the group of countries holding some of the world's largest crude oil reserves that formed OPEC (Romani et al., 2024), which later expanded its membership to OPEC+. Geographical concentration is a necessary but not sufficient condition for this type of collusion; cartel members must also effectively coordinate in controlling production quotas and ensure that this coordination is enforced and generates sufficient additional profit, compared to a competitive market scenario, to justify the effort (Romani et al., 2024). Cartelisation assumes certain preconditions: the production of a reasonably homogenous commodity (e.g. crude oil or natural gas, albeit of different grades); shared objectives of cartel members on building and/or maintaining market share, versus maximising revenues from production and export; the use of spare production capacity to influence the price elasticity of supply; the existence of a "leader" in the cartel (e.g. Saudi Arabia in OPEC); the ability to coordinate on and enforce production quotas; and, an adherence to the fundamental rule guiding investment and output decisions (Fattouh et al. 2016).

4.3. Strategic cooperation between crude oil producers

The international market for crude oil presents a salient case of cartelisation. Formed in 1960 and made up of oil producing/exporting countries, OPEC expanded its membership in 2016 in response to dramatically falling oil prices (as a result of the advent of US shale oil production adding to supplies in the market) to OPEC+ through signing agreements with 13 other oil producing countries that were not part of the core group, taking its share from around 40% of the market to 60% of global crude oil production by 2023, approximately 29 million barrels/day (mb/d) from OPEC and a further 17 mb/d from the "plus" producers (EIA, 2023). Saudi Arabia, the largest producer in OPEC/OPEC+ has also acted as its *de facto* leader, as the member of the group with the largest amount of "spare capacity" (~3 mb/d) that enables it to ramp up its output of crude or conversely cut its oil output over a relatively short period of time (Fattouh, 2011). OPEC holds around 5 mb/d of spare capacity (~5% of global oil demand). A vast literature exists on the effectiveness of OPEC production quotes, enforcement mechanisms, "cheating", and the ability of the leader to "punish" cartel members that deviate from agreed production levels by using its spare capacity to influence the output (and hence market price) of crude oil (Fattouh et al., 2016). Figure 2 illustrates the framework of the OPEC behaviours.

Figure 2: Revenue maximisation vs. market share objectives in oil cartels



Source: Fattouh, B., Poudineh, R. and Sen, A. (2016). 'The dynamics of the revenue maximization–market share trade-off: Saudi Arabia's oil policy in the 2014–15 price fall,' Oxf Rev Econ Policy, Volume 32, Issue 2, Summer 2016, Pages 223–240, https://doi.org/10.1093/oxrep/grw010. Used with permission from Oxford University Press.

Figure 2 provides a framework describing 4 scenarios based on a shock to the market which affects price and output targets, and the strategic response of the leader in each scenario (Fattouh et al., 2016). The four scenarios are: "within target variations" which refer to normal market fluctuations and in which no strategic response is action required; "output drop" in which market share decreases, but revenue remains within target and the decision to increase output depends on potential revenue loss (i.e. increasing output in the market could led to a lower price); "price fall" in which revenue drops due to decline in the price of crude oil and the decision to cut output to restore the price depends on the balance between price recovery and market share loss (cutting output in the market could lead to a drop in demand); and "price–output fall" in which both revenue and market share fall, requiring a strategic response (Fattouh et al., 2016). The elasticity of non-OPEC supply (e.g., US shale oil supply) also determines how effective a strategic response might be in terms of meeting output and revenue targets: for instance, if non-OPEC supply has a relatively high elasticity, a cut by OPEC and the resulting lower output will be substituted by increased non-OPEC production; conversely if non-OPEC supply is relatively inelastic, an output cut could potentially impact the crude oil market price (Fattouh et al., 2016).

As the *de facto* leader, Saudi Arabia has to balance its domestic objectives with the objectives of the cartel and the anticipated reaction of other members in relation to maintaining cartel cohesion. Fundamentally, as an economy which depends on oil exports accounting for around half of GDP and 85% of overall exports, it faces a trade-off between maximising the revenues from its output and maintaining market share for its crude oil reserves (Fattouh et al., 2016). This trade-off is managed at any time with two instruments: adjustments (increases or decreases) in its output using its spare capacity, and investments in long-term output and spare capacity. Consequently, it has targets on revenues (e.g. determined by government budget requirements), targets on market share, and targets on the optimal amount of spare capacity that it desires to hold (determined by the cost of maintaining spare capacity vs. its benefit) (Fattouh et al., 2016). Outcomes of these instruments reduce to a target price and target output. It is assumed that Saudi Arabia acts as a rational economic player; the goal is to achieve higher revenue than in a competitive market, not absolute revenue maximisation.; multiple trade-offs exist; not all objectives can be met simultaneously; and, the oil market is subject to uncertainties, such as the elasticity of oil supply determined by new non-OPEC sources (Fattouh et al., 2016).

Studies show that the average duration of cartels is about five years; some (like OPEC) have lasted decades (Levenstein and Suslow, 2006). Limited evidence suggests that cartels are able to increase prices and profits, to varying degrees; they can also affect other non-price variables, including advertising, innovation, investment, barriers to entry, and concentration (Levenstein and Suslow, 2006). Cartels break up occasionally because of cheating or lack of effective monitoring, but the biggest challenges cartels face are entry and adjustment of the collusive agreement in response to changing economic conditions. Cartels that develop organizational structures that allow them the flexibility to respond to these changing conditions are more likely to survive (Levenstein and Suslow, 2006).

4.4. Case studies of potential market evolution

The frameworks described above are not deterministic, but serve as a guideline towards understanding the objectives, incentives and behaviour of participants in commodity markets, such as critical minerals. Empirical evidence does not provide purist examples, either. Below this analysis outlines some case studies, which set out ground realities.

Critical Raw Minerals Buyers' Clubs. A salient example of a critical minerals "buyers' club" is from the EU, which in 2024 passed legislation to coordinate its member states towards the procurement of critical raw minerals. This club was prompted by a doubling in some critical mineral prices due to export restrictions places on them by China, the main supplier to the EU of several strategic critical minerals. This club included non-binding benchmarks for the overall capacity at EU level to be achieved by 2030 (in terms of annual consumption of 17 strategic critical minerals): the EU should mine 10% of its annual needs, process 40% of its needs, and cover 25 % of its needs through recycling. Additionally, the EU should diversify its imports of strategic minerals and, for each one, should not depend on any single third country for more than 65% of its supply (Ragonnaud, 2024). Modelled on "Aggregate EU", the joint purchasing mechanism established to procure natural gas supplies after the Russian invasion of Ukraine, the EU will launch a similar joint purchasing platform for critical mineral, closely linked to its public procurement.

Similarly, the Minerals Security Partnership (MSP) which builds on the EU critical raw minerals policy, aims at expanding coordination among countries in developing resilient supply chains, with members including the EU countries, US, Australia, Canada, Estonia, Finland, France, Germany, India, Italy, Japan, Norway, Republic of Korea, Sweden, UK, Argentina, Ecuador, DRC, the Dominican Republic, Greenland, Kazakhstan, Mexico, Namibia, Peru, the Philippines, Serbia, Türkiye, Ukraine, Uzbekistan and Zambia. Notably, the MSP is not a buyers' club, but is driven by buyers looking to secure future procurement of the critical minerals that they need for the energy transition. Arguably, this is a novel mechanism where the objective may be to secure market shares for critical minerals on the demand and supply sides through coordination across all market participants, but notably excluding the world's largest supplier of critical minerals, i.e., China, upon which the EU is for instance 100% dependent for most of its 14 strategic critical raw minerals. While unlikely to have any direct influence over the market price or on output, the heterogeneous pool of participants in such a club could enable the development of more commodity markets for critical minerals (as described in Section 4.1).

Lithium Producer Cartels. Argentina, Chile and Bolivia form the so-called "lithium triangle" in South America and together account for 30% of lithium mining and around 50% of reserves. Within Latin America, there are countries with smaller lithium reserves such as Brazil, Mexico, and Peru (Fornillo and Lampis, 2023). The concept of a lithium cartel was reportedly floated by the three countries in

2022; and some studies have argued that national sovereignty over resources was a key driver of this cartel. However, of the three countries, only Bolivia already has a national (publicly-owned) company involved in lithium extraction, *Yacimientos Litíferos Bolivianos,* with both Chile and Argentina having announced plans to create national public companies (Fornillo and Lampis, 2023). In Argentina, the government aims to increase production, involve smaller businesses, generate employment, and encourage foreign investment through incentives and simplified procedures, while in Bolivia, the government aims to commercialise lithium, targeting 40% global supply by 2030 (Ghorbani et al., 2024). Given its higher share in lithium production, Chile might be envisaged as a *de facto* leader of a cartel.

Elsewhere in the world, Zimbabwe, Namibia and DRC hold the top three lithium reserves in Africa, with Mali and Ghana following behind (Ghorbani et al., 2024). An African lithium cartel is driven by the potential for regional cooperation on refining and production. For instance, Namibia has minimal capacity for lithium mineral beneficiation, and processing and production. This limited capacity could lead to mineral concentrate being exported, value added elsewhere, and products using lithium imported back into the country, as happened in some developing countries exporting crude oil and importing diesel fuel and other petroleum products at higher prices (Ghorbani et al., 2024). A cartel needs to have market power, either through a swing producer or a small group of members, and it must convince non-members who are major producers to refrain from undermining cartel policy; having reserves alone does not automatically translate into production (Mares, 2022).

The sources of lithium (a niche commodity) among potential members varies, for instance, Argentina produces lithium from salt lake brines and some hard rock, Peru and Brazil are set to produce from hard rock, Chile and Bolivia from salt lake brines, and Mexico from both lithium clay and geothermal brines. Thus, costs of production across cartel members could also be very different, influencing the potential for cohesion (Mares, 2022). Given the differing incentives of lithium producers and the small number or producers with widely differing production capacities, it could be difficult for a lithium producers' cartel to arrive at a strategic optimum; if cartels were to emerge, smaller producers might have the incentive to maximise revenues, whereas larger producers or reserve-holders could prefer maintaining market share (preserving demand) in the medium to long-term (Mares, 2022).

Table 2: Illustrative characteristics of the markets for hydrocarbons (crude oil and natural gas) vs. critical minerals

	Hydrocarbons	Critical minerals and metals
Resource concentration	80% of conventional oil reserves in 12 OPEC countries (UAE, KSA, Iraq, Iran, Venezuela, Nigeria, Kuwait, Libya, Algeria, Gabon, Congo, Eq. Guinea). OPEC+: 13 further countries.	Nineteen countries across continents – critical minerals and rare earths.
Split between physical & financial market to manage price risk	Global crude oil consumption is 100 mb/d. Daily trading volume of petroleum futures, options, and OTC derivatives >5 bb/d. (around 50 times production). Established channel between physical and financial market.	Contracts in traditional metals markets, 3-5 yrs forward markets. Futures markets in some critical minerals: daily traded volumes of *Li* and *Co* account for <1% of their annual production; nickel, zinc and copper have traded volumes from 10-30%. Immature financial market.
Split between raw material extraction & processing (intermediate) product	Crude oil and natural gas vs their refined products (gasoline, diesel fuel, jet fuel, heating oil, naphtha, Liquefied Petroleum Gas, kerosene, Natural Gas Liquids).	Product complexity and lack of fungibility; not all critical minerals are the same. Less homogeneity across minerals as well as within grades of the same mineral.
Lead times to production	Ranging from several months (unconventional sources such as US shale oil) to 5.5 years (new conventional fields).	10-15 years to make new production chains operational, from opening mines to building the reprocessing and refining facilities.
Coordination among producer countries	OPEC & GECF suppliers' cartels. OPEC influence has been challenged by the entry of new producers at the margin and diversification by importers. GECF acts as a cooperative platform for gas exporters, with little to no influence over prices.	High concentration of trade (Chile, South Africa, Australia, Peru, Russia, China, Indonesia, DRC), but no formal coordination on the supply side. Attempts to coordinate on the demand side.
Trade positions of consumer countries	OECD/IEA member countries' 90-day strategic reserves.	EU "Critical Raw Materials Club" (US-IRA and EU Green Deal).
Geopolitical conditions	Frequent energy price shocks from geopolitical conflict; however, a deep and liquid market helps manage volatility.	Concentration of extraction and processing in singular countries – price volatility from supply chain disruption.
Elasticity of supply and demand	Inelastic demand; elastic supply with new non-OPEC member sources and spare capacity (potential for substitution).	Inelastic demand, inelastic supply (low substitution) – unless entry of new source of supply (or development of spare capacity). Uncertainties given technological changes (e.g., batteries nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP), sodium-ion, etc.)

Source: Authors

Nickel Producer Cartel. Indonesia, which accounts for around 60% of the global refined nickel supply up from just 6% in 2015, is an emerging leader in nickel production, with its market share expected to grow to 74% by 2028 (Lakshmi and Hodgson, 2025). The industry has been developed through initial export restrictions, a ramp up in overseas (from China) investments into Indonesia's nickel processing capabilities, and a strategic government policy focus. It is estimated that Indonesia now controls more of the world's supply of nickel than OPEC did of oil at the cartel's peak in the 1970s — then around half of global crude oil output (Lakshmi and Hodgson, 2025); supply from Indonesia pushed the price down to below US$16,000/tonne, whereas it is estimated that prices would need to rise and stay above US$22,000/tonne for a period of time for nickel mines outside Indonesia to be viable producers. In contrast, Indonesian policymakers have indicated a price target of $18,000/tonne, which is presumably high enough to meet its revenue targets but low enough to preclude competition from other countries (Lakshmi, 2024). This indicates that a level of spare capacity might exist.

In 2022, Indonesian policymakers floated the idea of an OPEC-like cartel for nickel alongside other producing countries. A nickel cartel potentially meets several of the preconditions for cartelisation: a reasonably homogenous product, the use of spare capacity to influence the price elasticity of supply, the existence of a "leader" in the cartel (i.e. Indonesia), and the ability to enforce production quotas (e.g., the use of spare capacity by the leader to drive down prices and "punish" member who deviate from quotas). However, the substitutability of nickel with other alternatives and technological changes (e.g., lithium iron phosphate and/or sodium-ion batteries) creates uncertainty around the viability of this model. Faced with a substitute, the optimal strategy for a nickel produce could be to maximises revenues by flooding the market, undermining coordination and cohesion in such a cartel.

Historically, producer groups and governments have made various attempts to influence mineral markets through collusion (IRENA, 2023). In the early 20th century, there were active producer cartels in the aluminium, copper, nickel, steel, zinc and lead industries (IRENA, 2023). A number of these cartels were created in the 1930s in response to the extremely low prices that prevailed during the Great Depression (IRENA, 2023). The 1960s to 1970s saw another wave of cartelisation, in the aftermath of decolonisation and a booming world economy, with the creation of several cartels and producer clubs to govern metal markets such as for bauxite, copper, iron ore, tin, tungsten and uranium (IRENA, 2023). Table 3 summarises three of these metal producer clubs.

Table 3: Metal Producer Clubs of the 20th century – failed attempts at producer coordination

Metal producer club	Members	Outcome
Intergovernmental. Council of Copper Exporting Countries (CIPEC) (1967-88)	Chile, Peru, Zaire, Zambi, Yugoslavia, Indonesia. Associate members: Australia and Papua New Guinea	High elasticity of demand for copper, limited market share (37%), and problems with cohesion prevented CIPEC from cutting output to raise prices.
Association of Iron Ore Exporting Countries (APEF) (1975-89)	Australia, Algeria, India, Liberia, Mauritania, Peru, Sweden, Venezuela.	Lack of cohesion between member over setting export prices meant that APEF reduced its role to collecting market information.
Primary Tungsten Association (PTA) (1975-87)	14 governments and private enterprises from Australia, Bolivia, Brazil, France, Peru, Portugal, Rwanda, Spain, Sweden, Thailand, Zaire.	Main driver was revenue preservation, primarily to act as counter the US selling excess volumes into the market from its strategic stockpile. Industry mine closures meant the PTA eventually ceased to exist.

Source: IRENA (2023).

5. Conclusion

Critical minerals are central to the clean energy transition, as this paper has shown. As the transition progresses, the need for a massive buildout of the clean energy system to 2050 could require significant amounts of capital invested in new production of critical minerals while the resource efficiency, recycling and technological changes could offset. The data suggests significant potential for recycling, for example after consumption, about 69% of the cobalt is sent to landfills and the remainder is partially recycled (Ghorbani et al. 2024; Dehaine et al., 2021). Experience in the evolution and maturity of markets for hydrocarbons can serve as a basis upon which to draw insights for the development of the critical minerals market traversing the commodity markets for energy and metals. While data shows that the exponential increase in demand for critical minerals over the next few decades will likely be an order of magnitude greater than what we have seen for hydrocarbons, there are some important differences between the two commodities: the main one being that hydrocarbons represent a flow of resources in a high variable cost energy system, whereas critical minerals represent a stock of resources needed to build out a high capital cost energy system, and could be recyclable.

Furthermore, ongoing technological changes may dictate the kind and the amount of critical minerals are needed in the future. Therefore, at some point, new technologies and policies around recycling and the minimisation of waste could act as a natural cap on critical minerals demand growth, placing a limit on the size of the market for critical minerals, which will be determined by the natural turnover of assets (i.e. the life of clean energy assets). Another important distinction is the higher degree of heterogeneity across and within grades of critical minerals, relative to crude oil which is a reasonably homogenous commodity and categorised into “heavy/sour” and “light/sweet” grades. Given these two distinctions, it seems unlikely that a cartelisation (or collusive oligopolies) based on targeting market shares would be sustainable over time. Monopolisation strategies may also carry risks for supply and demand. High market concentration indicates a risk of significant shortfalls in supply if, for any reason, supply from the largest producing country is interrupted. These risks could be exacerbated if suppliers have a high dependence on critical mineral export revenues.

On the other hand, the inherently localised nature of clean energy (i.e., clean energy production facilities are built close to markets) and synergies with “green” industrial objectives suggest that some form of cooperation is desirable. |Ideally, this should be targeted at building resilient and responsive supply chains, rather than at attaining singular objectives on market share or output. An extended critical mineral buyers’ club which includes or closely collaborates with producers (either countries or corporations) could be a way forward in enabling the development of mature markets to minimise information asymmetry and the transaction costs for market participants. The critical minerals market is unlikely to develop the depth of financialisaton seen in markets for crude oil and natural gas in the medium term. However, overlaps with clean energy and climate goals imply that there is potential for existing financial markets to integrate critical mineral commodities in their products or operations. Such integration would serve the dual goal of raising the substantial capital needed to deploy clean energy technologies, and mitigating risks and volatility as the critical mineral market develops, which is a potential area of further research.

Building the new energy system will also result in some initial CO_2 emissions as the first generation of new clean technology has to be built using fossil fuel-based energy (ETC, 2023). However, some estimates suggest that the production of materials to support the energy transition will result in total global cumulative life cycle emissions of 15-30 $GtCO_{2e}$, compared with the ~40 $GtCO_{2e}$ produced every year from the current fossil-fuel-based energy system; and while the former will fall towards zero as the mining and refining sectors decarbonise, emissions from fossil fuels would continue in perpetuity if there was no transition to a new system (ETC, 2023).

This paper is yet to identify or assess how or if such collective actions were able to efficiently transform countries with abundant natural resources such as critical minerals from exporting raw materials into exporting high value commodities. Temporary minimum distortions might be a feature for this transformation period, with clear existing strategies. This paper earlier alluded to this question in the discussion on Porter (1990). The role of collective actions in such a transformation is another research area.

Finally, environmental impacts (or emissions footprint) of critical minerals could gain greater prominence as markets develop, which both producers and consumers should consider in their strategies. This environmental consideration is already observed in markets for hydrocarbons, with "carbon neutral LNG" and low-emissions-intensity crude oil gaining popularity particularly in countries with lowest marginal costs of extraction. The underpinning rationale is that in a carbon-constrained world, only the lowest carbon emitting producers will be able to compete; hydrocarbon producers with the lowest costs of production (e.g., in the Gulf Cooperation Council or GCC countries) could therefore retain their competitiveness if they invest in reducing their emissions from the production of crude oil or natural gas. An evolving market in which critical minerals are traded more widely on exchanges could account for varying levels of emissions ("clean" or "dirty" grades of minerals or metals), making this an important potential consideration for producers and consumers.

Acknowledgments

Tooraj Jamasb acknowledges financial support by Copenhagen School of Energy Infrastructure (CSEI), Copenhagen Business School, and energy sector partners.

References

Barbezat, D. (1989), "Cooperation and Rivalry in the International Steel Cartel, 1926–1933", The Journal of Economic History, vol. 49/2, pp. 435–47.

Beck, R., Di Nino, V. and Stracca, L. (2024). 'Globalisation and the efficiency-equity trade-off.' Journal of International Money and Finance, Volume 148, October 2024, 103157.

Bijman, J. and Wijers, G. (2019). 'Exploring the inclusiveness of producer cooperatives,' Current Opinion in Environmental Sustainability, Vol. 41, pp.74-79.

Bray, M. (1997), "Meddelanden från Ekonomisk-historiska institutionen vid Göteborgs universitet (Eliminating the Competition: Price-fixing and Market-sharing in the Nickel Industry 1895–1929)", in European Business History Association and Göteborgs universitet (eds.), Business and European integration since 1800: regional, national, and international perspectives, Graphic Systems, Göteborg.

Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C., Lyons, L., Malano, G., Maury, T., Prior Arce, A., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., Pennington, D. and Christou, M . (2023). Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study. Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/386650, JRC132889.

Chang, L., Taghizadeh-Hesary, F., Mohsin, M. (2023), 'Role of mineral resources trade in renewable energy development,' Renewable and Sustainable Energy Reviews, Volume 181, 113321.

Collins, G. (2024), 'Critical Mineral Futures Markets: A Brief Introduction.' Commodity Insights Digest, Colorado School of Mines.

Competition and Markets Authority of Government of the United Kingdom (CMA) (2025). Industrial policies: New evidence for the UK. CMA Microeconomics Unit 9 April 2025. Report no. 3.

Dehaine, Q., Tijsseling, L.T., Glass, H.J., T¨orm¨anen, T., Butcher, A.R. (2021). Geometallurgy of cobalt ores: a review. Miner. Eng. 160, 106656

DfBT (2024). Invest 2035: the UK's modern industrial strategy. Department for Business and Trade. Gov.uk.

EIA (2023). What is OPEC+ and how is it different from OPEC?. US Energy Information Administration.

ETC (2023) Material and Resource Requirements for the Energy Transition. Energy Transitions Commission.

Falkowski, J. Chlebicka, A. (2021). 'What product mix do they offer and what marketing channels do they use? – Exploring agricultural producer organisations' heterogeneity,' Journal of Rural Studies, Vol.85, pp. 1-12.

Fankhauser, S., Smith, S.M., Allen, M. et al. The meaning of net zero and how to get it right. Nat. Clim. Chang. **12**, 15–21 (2022).

Fattouh, B., Poudineh, R. and Sen, A. (2016). 'The dynamics of the revenue maximization–market share trade-off: Saudi Arabia's oil policy in the 2014–15 price fall,' Oxf Rev Econ Policy, Volume 32, Issue 2, Summer 2016, pp. 223–240.

Fattouh, B. (2011). An Anatomy of the Oil Pricing System. OIES Paper WPM40. Oxford Institute for Energy Studies.

Feng, C., Yang, X., Afshan, S., Irfan, M. (2023) 'Can renewable energy technology innovation promote mineral resources' green utilization efficiency? Novel insights from regional development inequality,' Resources Policy, Volume 82, 103449.

Fikru, M.G. Kilinc-Ata, N. (2024) 'Do mineral imports increase in response to decarbonization indicators other than renewable energy?' Journal of Cleaner Production, Volume 435, 140468.

Fikru, M.G., Awuah-Offei, K. (2022), 'An economic framework for producing critical minerals as joint products,' Resources Policy, Volume 77,102753.

Fornillo, B. and Lombis, A. (2023). 'From the Lithium Triangle to the Latin American quarry: The shifting geographies of de-fossilisation.' The Extractive Industries and Society, Vol. 15.

Ghorbani, Y., Zhang, S.E., Bourdeau, J.E., Chipangamate, N.S., Rose, D.H., Valodia, I., and Nwaila, G.T. (2024). The strategic role of lithium in the green energy transition: Towards an OPEC-style framework for green energy-mineral exporting countries (GEMEC)Resources Policy, 90(2024), 104737.

Guo, Q., You, W. (2023) 'A comprehensive evaluation of the international competitiveness of strategic minerals in China, Australia, Russia and India: The case of rare earths,' Resources Policy, Volume 85, Part A, 2023.

Heather, P. (2010). The evolution of European traded gas hubs. OIES Paper NG104. Oxford Institute for Energy Studies.

Hendrix, C. (2022) Why the proposed Brussels buyers club to procure critical minerals is a bad idea,' Policy Brief, Peterson Institute.

HoC (2023) A rock and a hard place: building critical mineral resilience, First Report of Session 2023–24 UK, House of Commons Foreign Affairs Committee.

Hotelling, H. (1931) The Economics of Exhaustible Resources. Journal of Political Economy, 39, 137-175.

IEA (2024a) Global Critical Minerals Outlook. International Energy Agency, OECD: Paris.

IEA (2024b). World Energy Outlook. International Energy Agency, OECD: Paris.

IEA (2023a) Critical Minerals Market Review, International Energy Agency, OECD: Paris.

IEA (2023b) Global EV Outlook, International Energy Agency, OECD: Paris.

IEA (2022) The Role of Critical Minerals in Clean Energy Transitions, International Energy Agency, OECD: Paris.

IPCC (2018). Special Report: Global Warming of 1.5°C – Summary for Policymakers. Intergovernmental Panel on Climate Change, UNFCCC.

IRENA (2024). Geopolitics of the Energy Transition – Energy Security. International Renewable Energy Agency.

IRENA (2023) 'Trade, security and interdependence' in Geopolitics of the Energy Transition – Critical Minerals. International Renewable Energy Agency.

James, A., Retting, T., Shrogen, J.F., Watson, B., Wills, S. (2022). Sovereign Wealth Funds in Theory and Practice, Annual Review of Resource Economics, Vol. 14:621-646.

Jordan B. (2018). Economics literature on joint production of minerals: a survey. Resour. Policy, 55 (2018), pp. 20-28.

R., Juhász, N., Lane, E. Oehlsen, and V. C. Pérez. 2023. The Who, What, When, and How of Industrial Policy: A Text-Based Approach. Available at SSRN: https://ssrn.com/abstract=4198209 or http://dx.doi.org/10.2139/ssrn.4198209

Hegde, V., Wouters, J. and Raina, A. (2021). Is the rules-based multilateral trade order in decline? Current practices, trends and their impact. EE Elgar Online, 10 (1). pp. 32-53. https://doi.org/10.4337/cilj.2021.01.02

Ilyina, A., Pazarbasioglu, C. and Rute, M. (2024). Industrial Policy is Back But the Bar to Get it Right Is High. International Monetary Fund, Washington D.C.

Lakshmi, A.A.. and Hodgson, C. (2025). 'The OPEC of nickel: Indonesia's control of a critical metal,' Financial Times, 13 February.

Lakshmi, A.A. (2024). 'Indonesia to accelerate nickel output despite low global prices,' Financial Times, 29 March.

Levenstein, Margaret, C., and Valerie Y. Suslow. 2006. "What Determines Cartel Success?" Journal of Economic Literature 44 (1): 43–95.

Liu, E. Industrial Policy. 2024. Presentation at Markus Academy of Princeton University. https://economics.princeton.edu/events/ernest-liu-on-industrial-policy/

Mamula, N. and Adams, J. (2017). A rare earth cooperative for critical minerals could be just what America needs, The Hill, 27 July.

Mares, D.R (2022). 'Understanding Cartel Viability: Implications for a Latin American Lithium Suppliers Agreement.' Energies, 15, 5569.

Maranon, M., Kumral, M. (2019) 'A review of competitive advantage theory applied to the global rare earth industry transition,' Resources Policy, Volume 85, Part A, 103795.

Mathieu, L., Mattea, C., 2021. From Dirty Oil to Clean Batteries: Batteries vs. Oil: a Systematic Comparison of Material Requirements. Transport & Environment, pp. 1–75.

Nassar N.T., Fortier S.M. (2021). Methodology and Technical Input for the 2021 Review and Revision of the US Critical Minerals List (No. 2021-1045).

Nature Editorial (2023) The global fight for critical minerals is costly and damaging, Nature, 619, 436.

Pangestu, M. (2023). Industrial policy not the right answer to securing critical minerals and the green transition. East Asia Forum. https://doi.org/10.59425/eabc.1693173655

Pant., H.V. (2013). The BRICS fallacy. Wash. Q., 36 (3) (2013), pp. 91-105.

Porter, M.A. (1990). The Competitive Advantage of Nations. Harvard Business Review.

Poudineh, R. Fattouh, B., West, R. (2018) 'The rise of renewables and energy transition: what adaptation strategy for oil companies and oil-exporting countries?' Energy Transitions, Volume 3, pp. 45–58.

Poudineh, R. Sen, A. and Fattouh, B. (2016) 'The dynamics of the revenue maximization–market share trade-off: Saudi Arabia's oil policy in the 2014–15 price fall', Oxford Review of Economic Policy, 32 (2), pp. 223–240.

Romani, I.G., Comincioli, N. and Vergalli, S. (2024). Climate Policy and Cartelization Risk for Critical Minerals: An Application to the Copper Market. CEEPR WP 2024-18, MIT-CEEPR Working Paper Series.

Ragonnaud, G. (2024). Implementing the EU's Critical Raw Materials Act European Parliamentary Research Service, European Parliament.

Scheyder, E. (2022). Pentagon asks Congress to fund mining projects in Australia, UK, Reuters.

Srivastava, N., Kumar, A. (2022) ‘Minerals and energy interface in energy transition pathways: A systematic and comprehensive review,’ Journal of Cleaner Production Volume 376, 134354.

Storli, E. (2014), "Cartel Theory and Cartel Practice: The Case of the International Aluminium Cartels, 1901–1940", Business History Review, vol. 88/3, pp. 445–67.

Teece, D.J., Sunding, D., Mosakowski, E. (1993) ‘Natural Resource Cartels’ in Handbook of Natural Resource and Energy Economics, Volume 3, pp. 1131-1166.

Thibeault, A., Ryder, M., Tomomewo, O., Mann, M. (2023) ‘A review of competitive advantage theory applied to the global rare earth industry transition,’ Resources Policy, Volume 85, Part A, 103795.

Tsokhas, K. (2000), “The Rise and Decline of an International Zinc and Lead Cartel, 1945–75”, Australian Economic History Review, Vol. 40/3, pp. 263–86.

Umbach, F. (2021) ‘Critical raw materials: Assessing EU vulnerabilities’, Raw Materials, March 30, GIS Reports Online.

Vakulchuk, R. (2023) Critical Materials for Development: A New Trajectory for Norwegian Foreign Aid Policy, Technical Report, Norwegian Institute of International Affairs.

Vakulchuk, R. and Overland, I. 2021. Central Asia is a missing link in analyses of critical materials for the global clean energy transition. One Earth, 4(12), 1678–1692.

Valverde-Carbonell, J., Pietrobelli, C. and Menendez, M.M. (2024). Minerals’ criticality and countries' mining competitiveness: Two faces of the same coin. Resources Policy, Volume 98, November 2024, 105359.

Vivoda, V., Matthews, R., McGregor, N. (2024) ‘A critical minerals perspective on the emergence of geopolitical trade blocs,’ Resources Policy, Volume 89, 104587.

Vivoda, V. (2023) ‘Friend-shoring and critical minerals: Exploring the role of the Minerals Security Partnership,’ Energy Research & Social Science, Volume 100, 103085.

Walters, A. (1944), ‘The International Copper Cartel’, Southern Economic Journal, vol. 11/2, pp. 133.

Woodward, M., Walton, B., Hamilton, J., Alberts, G., Fullerton-Smith, S., Day, E., Ringrow, J. (2020). Electric vehicles: setting a course for 2030. Deloitte insights.

WRI (2024) ‘Where Do Emissions Come From? 4 Charts Explain Greenhouse Gas Emissions by Sector.’ World Resources Institute.

Zhou, J., and Manberger, A. (2024) Critical Minerals and Great Power Competition. Stockholm International Peace Institute.

Zhu, X., Ding, Q., Chen, J. (2022) ‘How does critical mineral trade pattern affect renewable energy development? The mediating role of renewable energy technological progress,’ Energy Economics, Volume 112, 106164.