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Critical Minerals and Countries' Mining Competitiveness: An Estimate through Economic Complexity Techniques

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Abstract

Minerals' criticality and countries' mining competitiveness are two dimensions that have gained relevance in the economic and policy agenda due to the key role of minerals in the energy transition. To a certain extent, these product-country dimensions can be seen as two faces of the same coin, which intertwine and simultaneously co-determine each other. Therefore, economic complexity techniques appear as a useful methodology to simultaneously estimate both dimensions.

This paper employs economic complexity techniques to build an unsupervised Fitness-Criticality algorithm, that allows simultaneously estimating countries' mining competitiveness (Fitness Mining Index) and minerals' criticality (Criticality Minerals Index). Our indexes are efficient in terms of the set of information employed, and do not rely on subjective perspectives and assessments. The results of the estimates suggest that South Africa, Russia, the United States, Norway, Canada, Australia and Chile are the most competitive countries. Moreover, the Platinum Group Metals, Lithium, Silicon and Rare Earths appear as the most critical minerals. These results are consistent with other methodologies employed by different organizations that separately estimate both dimensions and derive countries' and minerals' rankings.

J.E.L. Q30, Q37

Keywords: Mining Competitiveness, Economic Complexity, Critical minerals, Energy transition.

I. Motivation

There is a wide consensus on the increasing demand for minerals as a direct consequence of the current energy transition. For instance, the International Energy Agency (IEA) noted that meeting the Paris Agreement to limit the global temperature increase to "*well below 2°C*" would require a fourfold surge in the demand for minerals used in clean energy technologies by 2040 (International Energy Agency, 2021). Similarly, the International Monetary Fund estimates that the value of metal production would increase more than fourfold by 2040, which is explained by both quantity and price effects (International Monetary Fund, 2021).

The increasing demand for minerals is explained by the higher consumption intensity of minerals by the new technologies compared to the incumbent technologies. This amounts to stating that the clean energy technology paradigm is more intensive in minerals use than the fossil fuel paradigm. Moreover, low-carbon technologies require not only significantly larger quantities of minerals but also, a broader range of them (Bazilian, 2018). For example, a wind power plant requires nine times more minerals than a gas plant, and an electric car needs six times more minerals than a traditional gasoline-powered car. Likewise, a wind plant and an electric car use seven different types of minerals, meanwhile a gas plant and a conventional car use only two (World Bank Group, 2020; International Energy Agency, 2021). Consequently, the supply chains of the clean energy technologies are more complex than the fossil fuel technologies, and the disruption risks become a central issue.

In this vein, minerals employed by the new technologies become a critical input for the energy transition (Islam, Sohag, & Mariev, 2023) and, thus, the adoption speed of low-carbon technologies largely depends on how secure mineral supply chains are. Thereby, a clear trade-off between energy sustainability and energy security is emerging, with minerals at the center of tensions. Thus far, this trade-off has been mainly faced by developed countries pursuing the techno-economic transition, as revealed by the *Critical Raw Material Act* in the European Union (European Commission, 2023) and the *Inflation Reduction Act* in the United States of America (Bistline, Mehrotra, & Wolfram, 2023).

However, mineral-producing countries, that are mostly emerging countries, experience a trade-off of a different nature. On the one hand, they have the incentives to maximize mineral exports during the minerals boom; to exploit all the Ricardian rents related to both price and quantity effects. On the other hand, given the short-term rigidities of the supply of minerals, they also face the incentive to exploit their bargaining power to add value to minerals by exporting more processed goods and stop (slow) exporting only raw materials. Developing countries have addressed such trade-off with different strategies. For instance, Indonesia established a ban on nickel ore exports in 2019 to foster the national smelter and refinery industry (Widiatedja, 2021). Bolivia established by law that the lithium industry can only be developed by the State, and that private entrepreneurs may only participate in joint ventures focused on manufacturing lithium (Obaya, 2020).

As a result, the behavior and strategy of different countries, driven by their different incentives, affect both the "critical" nature of minerals and the competitiveness of the different countries: criticality and competitiveness become two crucial variables in the energy transition. In other words, achieving energy transition goals, e.g. carbon neutrality or net zero economies, implies affordable mineral prices and secure supply chains of critical minerals. No transition could be reached in their absence.

In this context, the present paper proposes a data-driven method with economic complexity techniques to measure minerals' criticality and countries' mining competitiveness. Specifically, we develop an unsupervised algorithm based on countries' specialization in raw minerals exports, which employs the diversity and the ubiquity of critical minerals exports. We obtain two vectors: the Mining Fitness Index (MFI), accounting for countries mining competitiveness, and the Criticality Minerals Index (CMI), accounting for the extent of minerals criticality. To the best of our knowledge, thus far no study has yielded together both dimensions empirically, using economic complexity tools.

On the one hand, diversity positively accounts for mining countries' competitiveness, since it reduces the inherent substitution risk of minerals uses. So, the more diversified a country is, the more resilient it is to technological changes that may potentially substitute for (current) minerals. On the other hand, ubiquity negatively accounts for the criticality of minerals since a more ubiquitous mineral implies that more countries are able to competitively export it. Thus, the more the mineral production is ubiquitous, the closer it is to a condition of perfect competition, with lower Ricardian rents. We calculate the Fitness-Criticality algorithm (FCa), that non-linearly combines the vectors of Mining Fitness Index and Critical Minerals Index.

The paper is structured as follows. Section II reviews the literature on mining competitiveness and critical minerals. Section III introduces the economic complexity framework and the Fitness-Criticality algorithm (FCa). Then, the data and methodology are described in Section IV, and in Section V we show the results of the FCa and check on temporal consistency for two different windows of time. Section VI summarizes the concluding remarks.

II. Literature Review

This section summarizes the existent theoretical and empirical studies conducted on mining competitiveness and critical minerals, to set up the analytical framework we use and discuss the state of the art on these topics.

Mining Competitiveness

The traditional literature on mining competitiveness states that countries competitiveness is a function of the high quality – low cost of mineral deposits (Tilton, 1992). This view is related to the neoclassical international trade theory in which comparative advantages are defined by countries' factor endowments (Heckscher, 1991; Ohlin, 1933). Therefore, inter-country gaps in exports and export shares would exclusively obey to minerals endowments. Later on, the literature developed along alternative routes to state that mineral endowments are relevant, but they are not the only determinants of competitiveness. Other variables such as the institutional framework, infrastructure, tax burden, energy costs, regulatory framework, among other, also matter. Indeed, even if for some minerals the endowment of mineral reserves largely determines current production, as we move downstream along the supply chain the role of reserves becomes going weaker and other factors begin to matter (Tilton, 1983, 1992).

One straightforward method to measure countries' mining competitiveness is through their market share, which for commodities is mainly driven by production costs. However, in this case we need to make some considerations. First, market shares in the mining industry are highly path dependent, given the long lives of mining operations and the high sunk capital. Therefore, even if there were major changes in the competitiveness conditions of a mining leader country, the market share would not report them in the short term. Secondly, market shares do not only reflect natural competitiveness as given by endowments, labor, capital and technology, but also reveal policy distortions introduced by regulations and public policies. Thereby, countries with clear comparative advantages, as revealed by minerals' endowments, are not necessarily competitive in extracting minerals if governments impose inappropriate regulations, such as excessive royalties or permits compliances (Tilton, 1992).

Taking into account the previous considerations, the empirical literature on mining competitiveness has opted for measures that use the foreign direct investment (FDI) allocated into exploration in each country (Jara, Lagos, & Tilton, 2008; Jara, 2017; Vasquez & Prialé, 2021).[1] The argument for this approach assumes that lagged reserves explain the current production largely. Therefore, future production and market share will depend on new reserves, which in turn depend on the investments allocated for exploration. Furthermore, given that investments are very sensitive to institutional and macroeconomic contexts, they should automatically capture variations in these variables. Nevertheless, these studies have only performed cross-sectional econometric analyses and not time series, losing part of their attractiveness.

In sum, these empirical studies model competitiveness as a function of minerals endowments and the investment climate. The exploration budget by country is taken as

[1] Interestingly, the focus is almost exclusively on foreign investments, upon the implicit assumption that they play a much larger role than domestic investments in exploration.

proxy of mining competitiveness (dependent variable), the land area of countries and the market share are used as proxy for the geological endowment of countries (independent variable) and the Index of Economic Freedom[2] and the Governance Index from the World Bank as proxies for mining investment climate (independent variables). The results of these studies support the view of mining competitiveness that highlights the role of institutional variables in explaining competitiveness.

Critical Minerals

There is no unanimity in the literature on the definition of critical minerals (McNulty & Jowitt, 2021) as conceptualizations consider country-specificities. Among the many attempts to define these minerals, the one proposed by the United States Government in the Energy Act of 2020 stands out, which is based on three main characteristics: a critical mineral is essential to the economic and national security of a country; it is an input in the manufacturing of the key intermediate goods for the economy and for national security, and its supply chain is vulnerable to disruptions[3]. Moreover, a recent literature review has defined critical minerals as a "*valuable constituent element of a mineral commodity that is subject to the risk of supply disruption and which serves a purpose deemed as important based on the evaluators' perspective*" (Hayes & McCullough, 2018, p. 192).[4]

Although the critical minerals conceptualization dates back to 1939 with the United States Strategy and Critical Materials Stockpiling Act enacted in the WWII context, during the last decade new conceptualizations have been attached to the current energy transition. The reason is twofold: new technologies have a much higher minerals consumption intensity, and a boom of clean technologies adoption is expected (Bazilian, 2018). In addition, several of these minerals are produced in non-competitive markets with a highly concentrated supply in a few countries, many of them involved in socio-geopolitical conflicts, which introduces a high risk of supply disruptions and endorses the criticality denomination. For instance, D.R Congo owns 70% of the world supply of cobalt and China has 60% of the world supply of rare earth. Supply disruptions are not easily overcome since mining projects require several years to be developed, which makes the supply very inelastic in the short-medium term and constitutes a natural constraint for diversifying the sources of these minerals. Thus, most of the minerals intensively used by the new clean technologies, such as photovoltaic panels, wind turbines, electric vehicles, and power storage, can be considered critical minerals (Islam, Sohag, & Mariev, 2023).

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[2] https://www.heritage.org/index/ranking accessed July 12, 2023.
[3] Further information about the Energy Act of 2020: https://www.congress.gov/116/bills/hr133/BILLS-116hr133enr.pdf
[4] Yunxiong Li, Ascani, & Iammarino (2022) follow a different approach to define "Rare Metals" on the basis of their relevance for modern technologies, through a text mining exercise on 5,146,615 USPTO patents during the period 1976-2015.

The empirical literature on critical minerals has employed different methodologies, but most of the approaches agree in considering the minerals concentration and the disruptions risks of supply chains as the two main determinants on the supply side. Meanwhile, economic importance appears as the main variable on the demand side (Hayes & McCullough, 2018). For instance, the European Union employs a methodology based on economic importance and supply risk criteria. Minerals substitution possibilities are the main determinant of economic importance, while concentration, countries' governance, trade restrictions and supply chain bottlenecks are the main drivers of supply risk (European Commission and Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs and Grohol, M and Veeh, C, 2023).

III. Economic Complexity Framework and the Fitness-Criticality Algorithm

Economic complexity is a data-driven framework that aims to explain the development of countries by employing network theory and machine learning techniques on big data (Hidalgo & Hausmann, 2009; Caldarelli, et al., 2012; Mealy, Farmer, & Teytelboym, 2019; Hidalgo C. , 2021; Balland, et al., 2022).

The economic complexity framework builds on three cornerstones. First, an ex-post and agnostic approach replaces the idea of a production function fed by a couple of inputs. Instead, highly granular economic outputs (e.g. exports, labor) are used to infer all unknown/hidden factors, such as domestic capabilities or local productive knowledge, to explain countries' economic performance. Second, it employs network theory and machine learning methods, such as matrix decomposition techniques, to capture these hidden features of countries and, thus, depict their economic performance. Third, the economic complexity computation is based on specialization matrixes (RCAs, RTAs, etc.) that connects location (i.e. country, region, etc.) with activities (i.e. products, patents, etc.), to derive countries' diversity and products' ubiquity.

Within the economic complexity literature, the diversity of export specializations reflects the variety of hidden local capabilities/knowledge of countries, whilst the ubiquity of goods across countries reveals products sophistication level. The evidence shows that developed countries export competitively a wider range of less common products, while developing countries are specialized in a scarce number of common products. This empirical fact has been linked to the nestedness property retrieved from network structural patterns (Mariani, Ren, Bascompte, & Tesso, 2019) and widely adopted to study location-activity networks. In summary, economic complexity proposes a framework that relates locations with activities, based on observable outputs (e.g. exports, labor). This allows us to capture useful insights on countries – their complexity and fitness - and products their complexity and sophistication - by employing machine learning techniques. In light of these characteristics, the economic complexity framework offers a suitable methodology to depict the relationship between countries' mining competitiveness and minerals' criticality. It provides a framework to connect countries with products and simultaneously infer their features from the economic system.

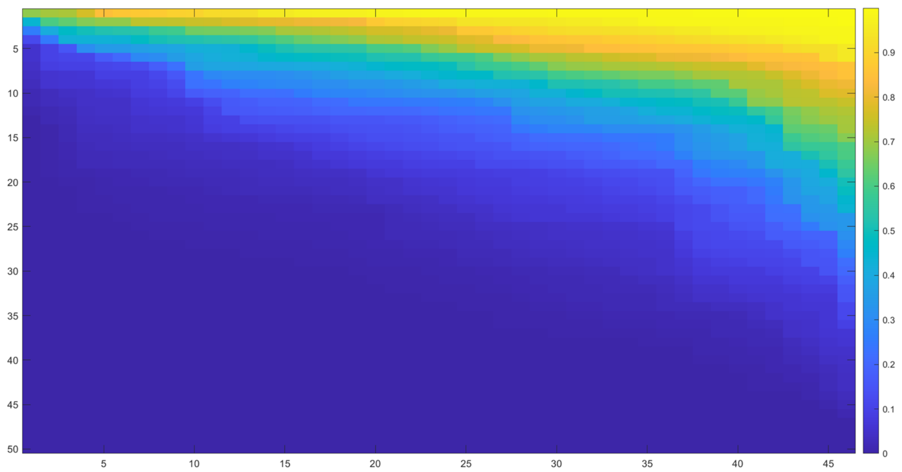
To build the Fitness-Criticality algorithm (FCa) we follow the non-linear algorithm proposed by Tachella et al (2013). Here, countries' fitness is the result of an iterative process in which export specializations reached by countries are weightedly added by using the complexities of their respective products as weights. In turn, the products' complexity is the result of an iterative process in which the product's ubiquities (inverses) are weightedly added by using the inverse of the countries' fitness, with which the non-linear relationship between both dimensions is incorporated (nestedness property). However, the interpretation of our FCa is totally different from the original algorithm of the mentioned authors since we take a straightforward interpretation of countries' diversity and products' ubiquity. In this sense, our paper differs from the classic economic complexity view as we dismiss the idea of inferring local capabilities or domestic knowledge from international trade.

From the perspective of competitiveness, a diversified portfolio of critical minerals reduces the demand substitution risks given by the inherent uncertainty of the ongoing technological races. This balances the risk given by the technological concentration of minerals (Markowitz, 1991). Two sources of demand substitution risk may be singled out. First, the modification of technology by substituting one mineral for another one to produce clean technologies and minimize costs. This risk is evident for the Li-ion batteries, in which different sub-technologies are competing for leading the market and the proportion at which minerals are employed represents the different risks. For instance, the NMC battery uses 33.3% of Nickel, 33.3% of Manganese and 33.3% of Cobalt, meanwhile, the NMC811 battery uses 80% of Nickel, 10% of Manganese and 10% of Cobalt (World Bank Group, 2020). Secondly, the substitution of one entire technology for another one, producing a lock-in of minerals used in the obsolete technology. This second risk is identified in less mature technologies, such as energy storage systems, in which the technological race still is in the initial stages, and there is no dominant technology yet. For instance, new prototypes of energy storage technologies are replacing lithium–cobalt batteries with salt batteries employing non (less)-critical minerals, such as sodium, nickel and chloride (Armand et al., 2023).

From the perspective of minerals' criticality, rents from minerals differ according to the competition level of mineral markets. Critical minerals supplied only by a few countries (less ubiquitous minerals) tend to be traded in imperfectly competitive markets, which means that the mineral price is established at a markup over the marginal cost. This is the case of minerals such as Cobalt and Rare Earths. Instead, the price is determined on the basis of undisclosed contracts between a reduced numbers of economic actors. Therefore, less ubiquitous minerals provide higher rents, since suppliers have the market power to set price over marginal costs.

Finally, the nestedness property says that countries exporting a wider range of critical minerals are also able to export the most critical ones. Differently from the original complexity/fitness index, in which this property is explained by the availability of knowledge and capabilities, we state that the nestedness property is mainly a consequence of the geological formation since most critical minerals are byproducts of major industrial minerals. Therefore, if one country is endowed with copper and iron there are high chances it also produces cobalt, molybdenum, tellurium, rhenium, rare earths, niobium and vanadium (McNulty & Jowitt, 2021). Of course, technology also plays a role, since recovering byproducts requires specific technology and specialized knowledge. In this regard, the geological formation represents a necessary condition and the technological level a sufficient condition to explain the nestedness property of our country-critical mineral space. Figure 1 illustrates this property through the triangular specialization matrix that arises from mining countries and critical minerals.

Figure 1: Triangular specialization matrix (2008 – 2018).



Source: Own elaboration. Countries are on the Y-axis and critical minerals on the X-axis. The triangular shape of the specialization matrix reflects that more diversified countries (e.g., country 1) are also the countries able to competitively export less ubiquitous minerals (e.g., product 1) and vice versa.

In conclusion, we propose to consider the most competitive mining countries to face the energy transition those countries specialized in producing a wider variety of critical minerals and, among them also the less ubiquitous ones. In other words, these countries maximize the expected rents considering the substitution risks. At the same time, the most critical products are those that fewer countries can competitively export, being those countries the most diversified.

IV. Data and Methodology

Countries' mining competitiveness and minerals' criticality are estimated based exclusively on export data. Export flows are taken from the COMTRADE database of the United Nations and harmonized for the period 1995 – 2018. From these exports series, we estimate the revealed comparative advantages (RCA) for every product-country pairwise and for the last 23 years available. Thereby, our dataset is composed of 23 matrixes containing 5040 products and 147 observations (countries). The yearly matrices were averaged in two matrices, M1 = 1996 – 2007 and M2 = 2008 – 2018, to compute the algorithm for two different time periods and test its consistency.

After calculating the RCA for all products, we defined the sub sample of critical minerals to estimate their criticality level. In this regard, we adhere to the conceptualization that critical minerals are those widely used in clean technologies (Bazilian, 2018; Islam, Sohag, & Mariev, 2023). Specifically, we rely on previous studies carried out by the International Energy Agency and the World Bank (International Energy Agency, 2021; World Bank Group, 2020) to select a group of 10 technologies as the main clean technologies and 20 minerals[5] as "critical" minerals given their use for these technologies. The criterion for the selection of technologies was based on their expected deployment[6], whilst minerals were selected according to their consumption intensity by technology, range of employment across technologies and expected demand increment. Table 1 shows the matrix that relates technologies and minerals.

Table 1. Critical Mineral list and clean technologies

Minerals/Technologies	Solar PV	CSP	Wind	Geothermal	Hydro	Nuclear	Electricity Networks	Energy Storage	Hydrogen	Bio-energy
Iron Ore			X					X		
Bauxite	X	X	X		X	X	X	X	X	X
Copper	X	X	X	X	X	X	X	X		X
Lithium								X		
Silver	X	X				X				
Zinc	X	X	X		X	X		X		
Molybdenum	X		X	X	X	X				
Nickel	X	X	X	X	X	X		X	X	
Rare Earths			X					X	X	
Graphite								X		
Silicon	X									
Chromium		X	X	X	X	X				
Cobalt								X		
Manganese			X	X	X			X		
Niobium, tantalum and vanadium						X		X		
Lead	X		X		X	X				
Ruthenium, osmium and iridium									X	
Rhodium									X	
Palladium									X	
Platinum									X	

Source: Own elaboration based on (World Bank Group, 2020) and (International Energy Agency, 2021).

Once selected the critical minerals to be assessed, the next step consisted of identifying these minerals within the harmonized system of international trade categories. Specifically, we

[5] Some minerals have been grouped since their exports are accounted under the same HS code.

[6] IEA scenarios.

made text analysis over the United Nations COMTRADE database, disaggregated to six digits, searching for the name of our 20 minerals. Then, we classified all products containing these minerals between raw and processed minerals. Given that our interest is in the extractive industries rather than metallurgic industries, we selected only products made of raw minerals. Thereby, our sample contains 46 products, mainly ores, ashes, residuals, powder, flakes and/or unwrought minerals.[7] Specifically, this sample contains: iron products (6), zinc products (6), aluminum products (5), copper products (5), nickel products (4), molybdenum products (3), lithium products (2), graphite products (2), chromium products (2), silver products (1), rare earths product (1), cobalt product (1), silicon product (1), niobium product (1), tantalum & vanadium product (1), manganese product (1), lead product (1), ruthenium product (1), osmium and iridium product (1), rhodium product (1), palladium product (1) and platinum product (1).[8]

Finally, we delete observations on countries without a relevant production of any critical mineral during the last two years to compute the Fitness-Criticality algorithm (FCa). This adjustment is needed because export data include re-exports, which distort mining competitiveness, otherwise a country without mining production could be considered competitive. For this purpose, we employ data from the United State Geological Service (USGS) that allows us to know the main countries' producers by type of mineral. Thereby, our final database to compute the FCa consists of two matrices of 46 products (critical minerals) and 50 countries (mineral producers) covering 23 years.

Formally, the FCa is defined by the following system of equations:

$$(1)\quad \widehat{F_c^{(n)}} = \sum_p M_{cp} C_p^{(n-1)}$$

$$(2)\quad \widehat{C_p^{(n)}} = \frac{1}{\sum_c M_{cp}(1/F_c^{(n-1)})}$$

$$(3)\quad F_c^{(n)} = \frac{\widehat{F_c^{(n)}}}{\left\{\widehat{F_c^{(n)}}\right\}_c}$$

$$(4)\quad C_p^{(n)} = \frac{\widehat{C_p^{(n)}}}{\left\{\widehat{C_p^{(n)}}\right\}_p}$$

Where F_c is the fitness of country$c$, M_{cp} is the country-product specialization matrix based on the RCA of each product and C_p is the criticality level of the product (mineral) p. Thereby, Equation (1) computes the country fitness as the specialization sum in exporting critical minerals (diversity) weighted by the criticality level of exported mineral one iteration back.

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[7] The only processed mineral included was copper cathode.

[8] See the Annex, Table 1 for further information regarding the products selected.

In turn, Equation (2) computes the minerals' criticality level as the sum of minerals' ubiquity inverse weighted by the inverse fitness of the exporting country. In this way, the criticality depends on how ubiquitous the mineral is, i.e., how many countries can export it competitively, but also on the mining competitiveness of those exporters. The non-linearity is given by the mineral ubiquity normalization by the fitness of the exporting country, which reflects that countries with higher mining competitiveness are those able to produce and export the less ubiquitous critical minerals. Finally, Equations (3) and (4) state the fitness and criticality values of order n, in which each vector is normalized by its average value.

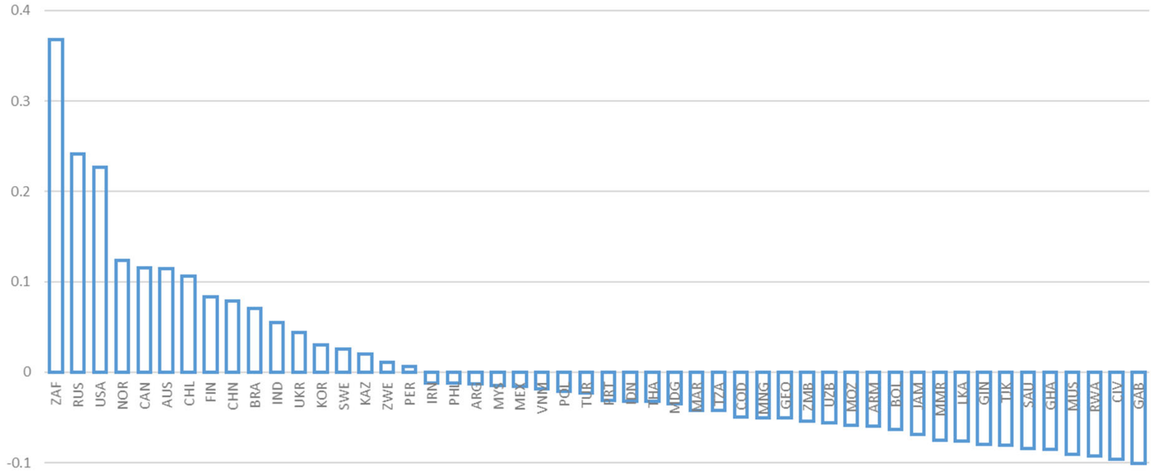
V. Results

The Mining Fitness-Criticality algorithm (FCa) provides two vectors. On the one hand, the Mining Fitness Index (MFI) assigns a value to each country according to the diversity of exported critical minerals and the type of exported critical minerals (i.e. more or less ubiquitous). Thus, the MFI allows us to approximate the competitiveness of mining countries in producing critical minerals since it captures the minerals substitution risks and the extent of competition faced. On the other hand, the Mining Criticality Index (MCI) assigns a value to each critical mineral according to its ubiquity, which is inversely weighted by the mining fitness of producer countries. In this sense, the MCI captures how common or not the mineral is, and the fact that rarer minerals are produced by countries with higher fitness. The higher the value is the lower its ubiquity: the mineral is exported competitively by a small number of countries. In this regard, a high MCI implies a mineral market far from perfectly competitive conditions and, hence, higher potential rents.

It is worth mentioning that to assess minerals criticality we only consider the factors on the supply side: how many countries export them competitively and their specialization. However, demand factors are implicitly considered through the sample selection, based on the higher expected demand due to the energy transition estimated by the International Energy Association and the World Bank (International Energy Agency, 2021; World Bank Group, 2020).

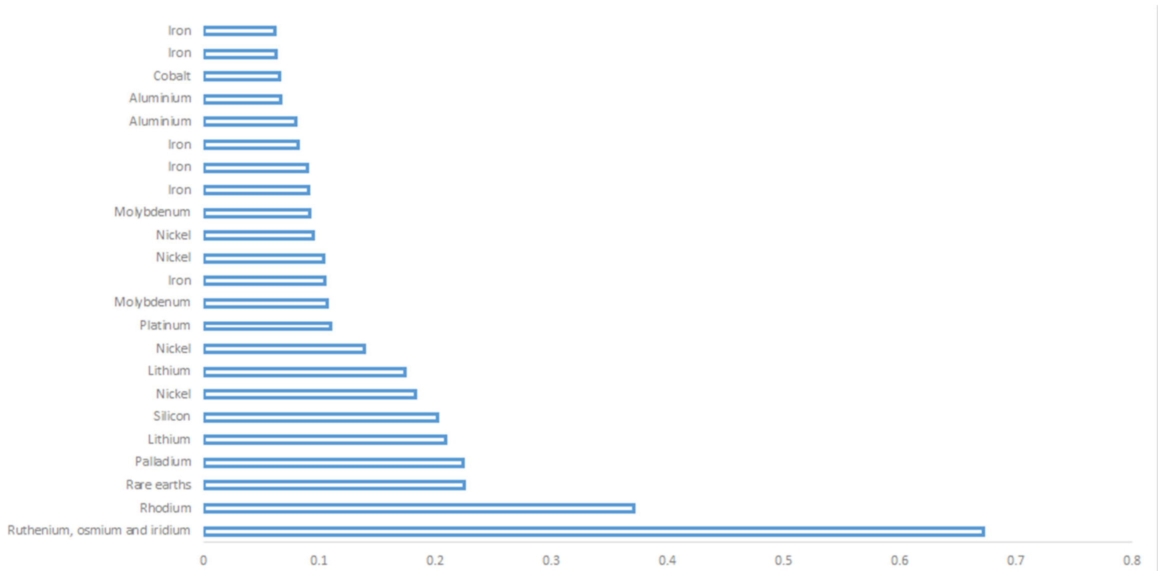
Figures 2 and 3 show the estimated results by the algorithm for the period 2008-2018. Figure 2 displays countries ordered by their Mining Fitness Index, measured as deviations from their average fitness value. South Africa appears to be the most competitive country by far, followed by Russia and United States. Then, Norway, Canada, Australia and Chile emerge as a third group, with Finland, China and Brazil further behind. At the opposite extreme, the five least competitive countries are Gabon, Ivory Coast, Rwanda, Mauritius, and Ghana.

Figure 2: The Mining Fitness Index (2008-2018)



Source: Own elaboration.

Figure 3: Minerals Criticality Index – Top 50% (2008-2018)



Source: Own elaboration.

Figure 3 displays products ordered by the value of the Minerals Criticality Index, measured as deviations from their average criticality value. The platinum group metal (PGM) composed by platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), osmium (Os) and iridium (Ir)) occupies the first positions. The main mineral is platinum and the rest of them are by-products. The world reserves of PGM concentrate in five countries: South Africa

(90.1%), Russia (6.4%), Zimbabwe (1.7%), United States (1.3%) and Canada (0.4%).[9] Next in criticality are Lithium minerals, found in brines and rock. Lithium resources from brines are concentrated in South America with Argentina, Bolivia and Chile, however, only Argentina and Chile have a relevant participation in reserves and production. Lithium reserves and production from rock (pegmatites) is mainly concentrated in Australia, representing more than the 50% of the world production. China also is a major player in this market with 17% and 13% of the Lithium production and reserves respectively (Economic Commission for Latin-America and the Caribe, 2022).

These results are in line with those provided by methodologies that separately estimate countries' mining competitiveness and minerals' criticality. However, some divergences are explained by the variables used to measure the competitiveness and criticality. For instance, the Fraser Institute Annual Surveys[10] ask mining and exploration companies about their perception regarding the main factors affecting the investment in exploration. This report dates from 1997 and ranks the competitiveness not just of countries but districts/regions of countries. The ranking for our window of time (1996-2018) is partly different, but there are some regularities. The United States, Canada and Australia systematically lead the rankings, and other countries such as Chile, Finland and Sweden are also among the most competitive, coherently with our ranking illustrated in Figure 2. Instead, countries like Venezuela, Bolivia, Argentina, D.R. Congo and Indonesia appear often at the bottom, and this also coincides with our ranking, since all of them are ranked below the mean. Nevertheless, for some countries we get opposite results. For instance, India and China rank above the mean in our ranking, while the Fraser Institute classify them as among the least competitive. This discrepancy may be explained because the Fraser Institute focuses on investment attractiveness, and therefore biases the analysis against non-Western countries such as China, India and Russia. Instead, our MFI that is based on the RCAs of countries exporting critical minerals, i.e., accounts for actual output produced by each country.

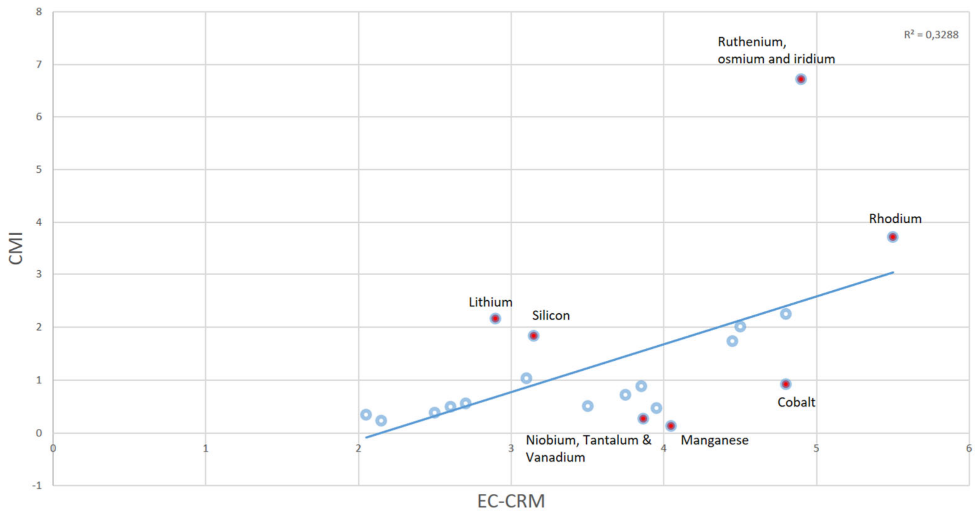
Similarly, the European Commission has elaborated a ranking of minerals criticality for its countries based on the economic impact their (limited) availability could have on EU economies and the supply risk of each mineral. Although this report has a wider scope than the present research, since it studies 70 possible critical minerals, and not only those minerals linked to the energy transition, it represents a good benchmark for our study. In the last version of this report (European Commission and Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs and Grohol, M and Veeh, C, 2023), 34 out of the 70 minerals assessed are considered critical. Within these 34 minerals, 14 fall into our critical list. Only 6 of the minerals included in our list are not considered critical by the European Commission, which means a matching of 70%. In both assessments Platinum

[9] https://natural-resources.canada.ca/our-natural-resources/minerals-mining/minerals-metals-facts/platinum-facts/20520 accessed on July 10, 2023.
[10] https://www.fraserinstitute.org/categories/mining accessed July 12, 2023.

Group Metals and Rare Earths appear as most critical, meanwhile, copper, lead and zinc appear as the least critical.

We estimate the correlation between our Critical Minerals Index (CMI), and the simple average between the economic importance index and supply risk index reported by the European Commission (EC-CRM), and we obtain a positive linear correlation of 0.57 (Figure 4). Here, we also can appreciate those minerals that appear as very critical in one ranking but not in the other one. All minerals highlighted in red are outliers with significant differences between the two estimates. For instance, ruthenium, omnium and iridium appear considerably more critical in our assessment, meanwhile, cobalt emerges as one of the most critical based on the European Commission assessment.

Figure 4: European Commission Critical Raw Material Index (EC-CRM) versus our Critical Minerals Index (CMI)



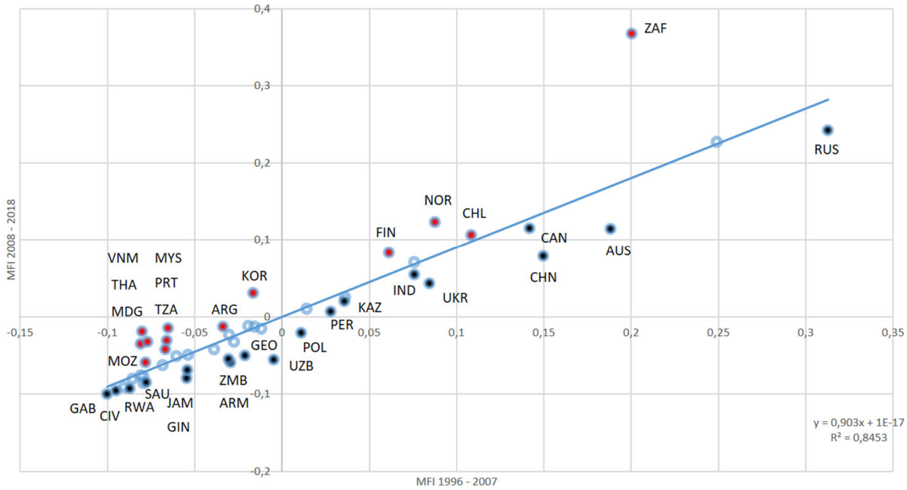
Source: Own elaboration.

We also test if the MFI and CMI indicators have changed over time, as a way to test the consistency of the Fitness-Criticality algorithm. Indeed, changes in the criticality level of minerals and countries competitiveness are expected, but they should be rather limited since the mining industry needs long periods of time to develop new projects. In other words, substantial path dependence is expected in mining competitiveness and minerals criticality.

For this purpose, we execute the algorithm for two different periods and, then, we run two linear regressions: MFI_t versus MFI_{t-1} and CMI_t versus CMI_{t-1}. We expect a high intertemporal correlation for both indexes due to the long-term nature of mining activity. Moreover, outliers' observations offer interesting information on countries deviating from the past trend in a relatively short period. We explain this deviation as significant positive or negative shocks shifting competitiveness out of the trend.

Figure 5 shows the linear relationship between the $MFI_{1996-2007}$ and $MFI_{2008-2018}$, measured as deviations regarding their respective means. The Pearson correlation between both MFIs reaches the high level of 0.92, which reflects a high persistency. Countries above the regression line (red dots) are countries that performs better than expected from the linear relationship, and the opposite applies to countries below the regression the line (black dots). In this regard, South Africa is the country with the highest improvement in the MFI between periods. Although there are not negative outliers, Russia, Australia, China, Uzbekistan and Guinea appear as countries losing mining fitness.

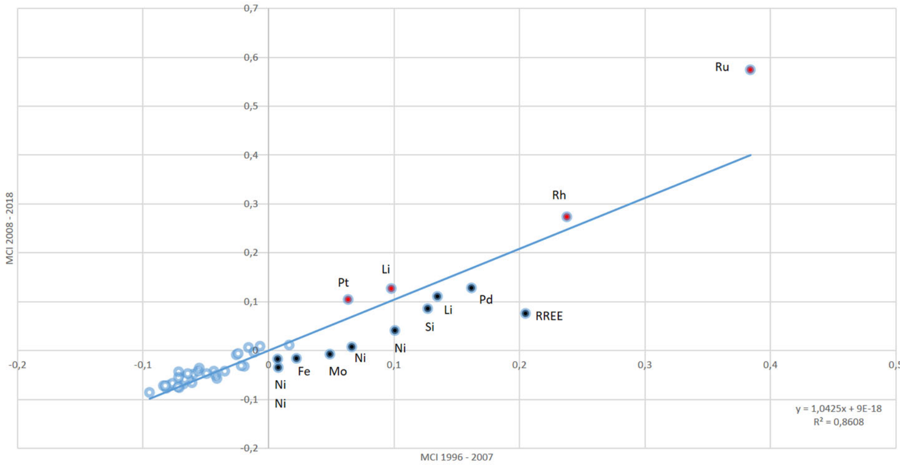
Figure 5: Mining Fitness Index over time (1996-2007 vs. 2008-2018)



Source: Own elaboration.

We replicate the analysis for minerals' criticality to measure the criticality consistency over time. Figure 6 illustrates the linear relationship between both $CMI_{1996-2007}$ and $CMI_{2008-2018}$, which reaches a 0.93 Pearson coefficient. Highly critical minerals in the first period remain highly critical in the second period, and the same applies to minerals with low criticality level, that remain little critical. The red dots in Figure 6 above the regression line show those minerals that significantly gained criticality, meanwhile, the black dots illustrate minerals that significantly lost criticality between periods. Ruthenium, Osmium, Iridium and Lithium increased their criticality over time. In contrast, the figure shows the loss of criticality of Rare Earths, that however still remain among the top five most critical minerals. Similarly, also nickel products lost criticality.

Figure 6: Minerals Criticality Index over time (1996-2007 vs. 2008-2018)



Source: Elaborated based on our own estimates.

VI. Final Remarks

The Fitness-Criticality index contributes to the literature by providing a straightforward methodology to assess countries' mining competitiveness and minerals' criticality. The results are in line with other methods employed in the past to evaluate both dimensions separately. However, while mainstream methods take the exploration investment as a proxy of competitiveness (indirect measure), we employ revealed comparative advantages as a primary information source, i.e. a direct measures of competitiveness Moreover, while existing analyses assess minerals' criticality based on a large set of variables accounting for their economic importance in countries and regions and for the supply chain risks of each mineral, we exclusively use export data to estimate countries' diversification and minerals' ubiquity, the two cornerstones of our algorithm. This explains why some discrepancies with our index emerge, since we do not perform an ad-hoc demand-side analysis. In sum, our proposed indexes are more efficient in terms of the quantity of information needed, are less influenced by country-specific perspectives and assessments and rely on widely available public statistical sources.

The results show that South Africa, Russia, the United States, Norway, Canada, Australia, Chile, Finland, China and Brazil are among the top 10 most competitive countries in the critical minerals industries, with the highest levels of the Mining Fitness Index. It is not surprising to find countries like the United States, Canada or Australia in this group. However, the presence of Russia and China represents a novelty relative to other indexes and may be explained by our use of a direct measure of competitiveness instead of the indirect measure used by the mainstream literature, that crucially hinges on foreign direct investments in exploration. Moreover, according to our Critical Minerals Index, the most critical minerals are the Platinum Group Metals, Lithium, Silicon and Rare Earths, which is pretty much in line with other technical assessments

Some preliminary policy insights can be gained from our analysis. The Critical Minerals Index provides a signal to mineral producer countries on how strong their bargaining power is. In this regard, mining countries using industrial policies to foster adding value to their resourced-based exports should be aware that the policy results would depend on the criticality extent of their minerals. For instance, an export ban on copper ore in Chile or Peru, similar to the recent Indonesia's export ban on nickel ore, would probably not be successful since copper ore is low in criticality compared to nickel, thereby enjoying limited market power. Indeed, copper is in the fourth quartile of the Critical Mineral Index, meanwhile, nickel is in the first one.

On the other hand, our Fitness Mining Index shows that polymetallic countries are more competitive than countries specialized in single minerals and metals. Indeed, this makes them more resilient to substitution risks. However, their higher competitiveness is also due to the more diversified countries being able to produce the more critical (less ubiquitous) minerals. Although the capacity to produce the most critical minerals is largely determined by the geological formation - most critical minerals are byproducts of major industrial minerals -, there is also a relevant technological component associated with the capabilities of countries to recover and valorize discarded byproducts.

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