The Evolution of Trade in 30 Energy Technology Materials Spanning Traditional and Clean Energy Technologies, and its Implications

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ABSTRACT

Deep energy decarbonization requires a shift in the materials used in energy technologies, or energy technology materials (ETMs). While many existing ETM studies are motivated by perceived supply chain vulnerabilities, the effect of changing demand on exporters of materials is relatively less explored. This study examines whether there are ETM products that exhibit characteristics in growth, volatility, and importer and exporter concentration in trade value and volume from 1999-2018 that are beneficial to exporters, and what the policy implications of these metrics may be. We systematically isolate and categorize 30 relevant traded products in UN Comtrade into clean and traditional materials, as well as into unrefined and refined materials; these outputs that can be re-used by other researchers for subsequent studies. The study finds that lithium carbonate exhibits the most beneficial metrics for exporters over time. Additionally, clean energy and refined materials are disproportionately represented in the high-performing products for exporters, compared to traditional and unrefined materials that developing countries tend to export more frequently. The results make a case for directed policy attention toward enhancing clean and refined ETM trade and capabilities in developing countries, although other policy options are also discussed.

Keywords: natural resources, trade, development, criticality, energy materials, minerals, commodities

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COVER IMAGE

Lithium mine at Bolivia´s Uyuni Salt Flat, the highest and largest salt flat in the World. Covered by a thick salt crust, appearing in white, it is completely flat. Lithium rich brine covered areas appear in green and light blue. Brine evaporation pools, part of lithium extraction process, appear in a checkered pattern. Attribution: Oton Barros (DSR/OBT/INPE), Coordenação-Geral de Observação da Terra/INPE, http://www.dsr.inpe.br, CC BY-SA 2.0, https://creativecommons.org/licenses/by-sa/2.0, via Wikimedia Commons.

1. Introduction

By 2050, the "Middle of the Road" Shared Socioeconomic Pathway used as input to the IPCC 6th Assessment Report conservatively predicts that modern renewables will grow to about 10% of the world energy supply from about their current 6%. Oil and gas will stay relatively constant, from about 57% to 58% (Riahi et al. 2017). As a result, even without accounting for Paris Agreement targets, oil and gas are likely to cede relative magnitude in world trade to materials (a general term that refers to the matter from which a thing is or can be made) for technologies that convert primary renewable sources (wind, solar, etc.) into secondary energy sources (electricity, heat, etc.), such as Rare Earth Elements (REE) for wind turbines. If we were to align with the Paris Agreement, then the Sustainable Development Scenario of the IEA predicts that oil and gas will need to decline to just over 20% of total energy supply (IEA 2020), thereby reinforcing the change to occur in energy technology materials (ETM) markets.

Climate goals coexist and interact with other policy priorities. These include boosting economic competitiveness and development, as well as maintaining fiscal sustainability (Anadón, Chan, et al. 2016; IPCC 2001; Mazzucato 2018; IMF 2019), in which a country's export base plays a central role. For the first time, we use trade data to interpret changes in the value and volume of traded products, defined as materials that cross country boundaries, and product groups along ETM supply chains. We ask: How have the characteristics of growth, volatility, and importer and exporter concentration in trade value and volume evolved for the products in the two decades between 1999-2018? What are the products (and product groups) that exhibit characteristics that are more beneficial to exporters?

In line with the policy priorities discussed, we interpret the trends from the point of view of main exporters and include both developed (defined here as those that are classified as both World Bank high-income and OECD members) and developing countries in our analysis, overall between 1999-2018 and comparing Decade 1 (1999-2008) and Decade 2 (2009-2018). We look in detail at major exporters, defined as those either within the top five in total value for a certain good during the 20 years, or those included in the cumulative top 90% of exporters, whichever comes first.

Considering the Paris Agreement targets, the related literature on supply chains, availability, and geopolitics of EMTs is blossoming. We frame our study within three inter-related existing ETM research streams: (1) Criticality studies (e.g. Erdmann and Graedel (2011), Achzet et al. (2013)); (2) Reserve and resource models (e.g. Speirs et al. (2014) and Olivetti et al. (2017)); and (3) Resource governance (e.g. Lee et al. (2020), and Sovacool (2019)).

The first stream is focused on understanding the extent to which developed countries may face challenges of mineral (defined by the United States Geological Survey, USGS, as "naturally occurring inorganic elements or compounds with an orderly internal structure and characteristic chemical composition, crystal form, and physical properties" (USGS 2021)) supply for their own industrial activity. The second is concerned with modelling reserves and resources necessary for different energy decarbonization scenarios. Data used for both streams includes production, consumption, reserves, and prices at international exchanges. The third stream discusses the complex relationship between exports and governance. To our knowledge, our work is the first one to ask whether there are existing discernible trade patterns over ETM products that can guide the intersection between climate, energy, and industrial policy for countries.

To this end, we first systematically identify 17 materials from the existing ETM literature and map these onto 30 traded products available in UN Comtrade, a comprehensive open-access dataset of bilateral trade flows spanning more than two decades, five thousand products, and hundreds of countries (UNSD 2020). While the dataset is already widely used, to the best of our knowledge it has not been employed to study the evolution of trade in traditional and clean ETMs over time, except in a study by Galeazzi, Steinbuks, and Cust (2020), and a descriptive industry report by UN Comtrade (only on products related to lithium-ion batteries and only 2010 onwards, from the point of view of importers and criticality) (UNCTAD 2020). The product code list may therefore be useful to other researchers willing to undertake subsequent ETM studies as broad as ours with trade data.

Having identified relevant UN Comtrade products, we categorize them according to their: (1) Role in energy decarbonization (Classification 1) and (2) Level of refinement

(Classification 2). Under Classification 1, products are either Clean Energy Materials (CEMs) or Traditional Energy Materials (TEMs, or those that facilitated the energy paradigm of the 19th and 20th centuries). We place platinum group metals in TEMs due to their historical role in internal combustion engines, though we acknowledge and discuss their future uses under CEMs. Under Classification 2, products are either raw ore and concentrates (OCs, defined as "the naturally occurring material from which a mineral or minerals of economic value can be extracted" (USGS 2016), or refined metals and chemicals (MCs). We compare groups within the same classification (CEMs versus TEMs and OCs versus MCs), or the same group over time (CEMs in Decade 1 versus CEMs in Decade 2).

Classification 2 shows how our perspective expands existing literature, which is mostly focused on minerals. We consider that each ETM is related to a range of traded products that involve different country exporters along the way. For example, an increase in the demand for "cobalt" for use in lithium-ion batteries will impact trade in minerals (unrefined cobalt ores and concentrates), and a range of refined chemicals derived from cobalt (cobalt oxide/hydroxide and cobalt metal). While existing literature discusses the implications related to the Democratic Republic of the Congo, (a major exporter of unrefined cobalt ores), we show that Europe and China surpass it in exporting cobalt chemicals, and include this in our discussion.

As the first study using historical trade data in the ETMs literature over all countries, we analyse and compare the following metrics: average of yearly growth rates of trade value, the volatility of growth in trade value, and the importer and exporter market concentration in trade volume (akin to the export and import market concentration index). We also identify major exporters by product, defined above. For the average growth and volatility analysis, we use parametric and nonparametric tests of statistical significance to gauge whether the differences in these metrics between groups and over time may be due to chance. For the importer and exporter concentration and major exporters analysis, we study changes over time dynamically (i.e., Decade 2 minus Decade 1).

Finally, we synthesize the results. Our interpretation of the results rests on the assumption that exporters benefit from exporting products that display high growth but low growth volatility in trade value (Renner and Wellmer 2019; McCullough and Nassar 2017). Exporters also benefit when products are highly concentrated over exporters (supply) and unconcentrated by importers (demand) in value. We discuss these assumptions with greater nuance in the Literature Review and Methods sections.

Our main results suggest that overall changes that occurred between Decades 1 and 2 have been unfavourable to exporters of ETMs. Growth rates were generally lower in Decade 2, and the statistical tests we ran to compare these metrics overall and within groups (e.g., CEMs in Decade 1 versus CEMs in Decade 2) imply that the differences are unlikely to be due to chance. In the Discussion, we consider why this might be and how this differs from what we expected given the existing literature. Additionally, in the dynamic analysis of concentration, there was an overall change towards exporter dispersal and importer concentration, exactly the opposite of what would benefit major exporters.

Second, CEMs are disproportionately represented in the products with high growth rates in Decade 2, a trend that mostly benefits developed countries. Our exporter analysis confirms existing literature indicating that major developed exporters of TEMs tend to be major exporters of other ETM products. However, developing TEM exporters tend to have less export diversification. This brings to the fore the importance of continued efforts in strengthening governance and capabilities for developing TEM exporters.

We also take a sub-sample of top-performer "notable" products. The sub-sample combines those with high growth during Decade 2, favourable importer and exporter concentration during 1998-2018, and favourable changes in importer and exporter concentration in the dynamic analysis. We find that MCs are overrepresented within "notable" products (as well as in the smaller group of top growth products in Decade 2). Additionally, our exporter analysis supports existing literature on industrialization and development, showing that developed countries tend to specialize in MCs (Behrens et al. 2007). Therefore, in line with the result pertaining to TEMs above, this leads us to argue that without coordinated, holistic, and sustained policy, it is likely that developed countries will benefit disproportionally from trade in ETMs in the transition towards decarbonized energy.

Third, we further identify the specific major exporters that stand to benefit the most from the trends in notable products: (1) The European Union (EU), because it is a major exporter of all the notable products (which is expected given the size of the trading bloc); (2) China, because it holds the highest average market share rank across all notable products; and (3) The United States (US), which plays a higher role in the notable products than in the overall sample, although we discuss subtleties. Of the 30 products, lithium [carbonate] exhibits the most beneficial trade patterns, putting its major exporters (Chile, Argentina, the European Union, and China) in a favourable position as energy decarbonization continues.

Our conclusions support the broader existing literature on the importance of efforts to create managed co-benefits of energy decarbonization in developing countries (Deng et al. 2018). We note that trade is only one of several issues related to ETMs. We encourage further research to explore the connection of ETM trade with topics such as the human rights implications of mining and domestic recycling that are outside the scope of our research questions.

Section 2 reviews relevant ETM literature and lays out the research questions; Section 3 details the methods we employ; Section 4 reviews the data; Section 5 presents the results; Section 6 presents the results; Section 6 discusses the results and limitations, and Section 7 concludes.

2. Literature Review

We consider three interrelated existing streams of research: 1. Criticality studies, 2. Reserve and resource models, and 3. Resource governance, and conclude with the key research questions that emerge as a result.

Given that the three literature streams span national security, supply chains (management and industrial organization), resources and reserves (geology), and governance, the papers and reports across these areas refer to different but related terms (like materials, raw materials, minerals, non-fuel minerals, raw minerals, commodities, metals, minor metals, major metals, etc.). A useful discussion comparing the listed terms can be found in Chapter 1 of the Critical Materials Handbook by Gunn (2014). To keep the review focused, we refer to materials and minerals using the definitions provided in the introduction. When necessary, we introduce and define new terms used in specific studies.

2.1. Criticality Assessments: Focus on Vulnerability to Supply Disruptions

In the past decade, the need to understand the dynamics and implications of decarbonization on energy technology supply chains has become increasingly clear. In 2010, China honoured existing export quotas for rare earth elements (REE) due to a conflict with Japan, and the world saw the price impacts of an interruption of ETMs (the underlying factors are more complex and discussed in detail in Renner and Wellmer (2019)). The disruption galvanized policy attention to ETMs, amongst other things, to the creation of the U.S. Department of Energy Critical Materials Institute in 2013 to "assure supply chains of materials critical to clean energy technologies" (Speirs, Houari, and Gross 2013).

Though they have been used for decades outside of the premise of the energy transition, "criticality" assessments dominate the ETM literature (Glöser et al. 2015). These assessments evaluate "the economic and technical dependency on a certain material, as well as the probability of supply disruptions, for a defined stakeholder group within a certain time frame" and tend to plot materials on a 'criticality matrix' where the risk of disruption in supply is plotted against the impact of that disruption (Schrijvers et al. 2020; Brown 2018). Such visualizations serve as an "early-warning" device and advise policymakers on priorities for basic research and development in material substitutes, processing, exploration, recycling, and more (Gunn 2014; Graedel et al. 2015; McCullough and Nassar 2017).

Criticality studies have usually been commissioned by institutions in large developed countries and each has its own methods (Speirs, Houari, and Gross 2013). Examples include National Research Council (2008) and Department of Energy (2011) in the United States; and Resnick Institute (2011) and European Commission (2010) in the

European Union, although there are more "international" perspectives, like UNCTAD (2020) on lithium-ion batteries.

ETM criticality assessments are also published in peer-reviewed journals. As opposed to government reports, peer-reviewed criticality assessments often: 1. Expand the geographical focus, 2. Compare results between assessments, and 3. Evaluate the suitability of different methodologies. These include Erdmann and Graedel (2011), Achzet et al. (2013), Dewulf et al. (2016), Brown (2018), Glöser et al. (2015), Zhang, Kleit, and Nieto (2017), and Nuss et al. (2014).

Measuring concentration

Although the methods behind criticality studies are diverse, there are some unifying themes. For instance, criticality assessments assume that high production concentration increases the risk of supply disruption for importers. The rationale is that exporter market power and competition for access between importers may cause prices to rise or become more volatile, making investments and future planning costly (De Groot et al. 2012).

Concentration is also a focus of this study. As opposed to criticality studies however, we use export quantity instead of production, because that is what is possible with our data. Observe as well that we take the opposite (exporter) perspective because we are interested in finding product characteristics that are beneficial for major exporters. We assume that a high exporter concentration translates to greater market power allowing for exporters to set terms of trade, as per standard trade theory (although to capture benefits, this must be coupled with stable growth in export value, which we discuss further in the Methods section).

Based on a methodological review for all markets by Acar and Bhatnagar (2003), Brown (2018) applies and compares seven concentration metrics by decades over the past century in five materials (fluorspar, lithium, coal, copper, and nickel). The aim is to understand what concentration metrics researchers should use.

Brown (2018)'s central argument is that "simple" metrics compared over decades should be the best practice in criticality assessments. We also apply simple metrics here as they tend to communicate more information than other more sophisticated concentration metrics calculated at only one point in time, as is often practiced in criticality assessments. Brown's results are summarized in detail in Table 1.

Table 1 Summary and comparison of concentration metrics used in criticality studies and evaluated in Brown (2018).

Index	Metric and reference	Description	Brown (2018) discussion	Calculated
1	Number of producers	The number of existing producers	**Does not consider** the size of producers relative to the total amount produced.	Calculated for the HHI, but not discussed
2	Percentage of the dominant producer	Percentage of the dominant producer	**Can only communicate** information on the largest producer.	Calculated and displayed, but only for the exporter analysis
3	Concentration ratio	Sums the market share (percentage of total) of the top producers	**Naturally closer to 100% when there are fewer producers**. Increasing the number of producers included in the calculation will result in higher percentages so the selection of how many is particularly important. Brown (2018) finds it is similar to the HHI (see next line).	Calculated and displayed, but only for the exporter analysis
4	Hirschman-Herfindahl Index (HHI) based on Hirschman (1945) and (Herfindahl 1951)	Sums the square of the market share of each market player.	**Fully discussed in the Methods section**. It is sensitive to the number of producers, and the result should be compared to the minimum possible for the number of players in the market. Monopolistic=0.25; Less concentrated=lower, minimum depends.	Calculated as a measure of concentration
5	Normalized Hirschman - Herfindahl Index (HHI*)	Normalizes the HHI to the number of players.	**Does not adequately capture changes** in the number of producers. Where the number of producers changes over time, there is a clear disadvantage to using HHI*. Monopolistic=1; Complete competition=0.	No
6	Kwoka's Dominance Index (Kwoka 1977)	Sum of the squares of market share differences when producers are ranked by size.	Measures 'inequality' in the size of companies within a market. **Like HHI, it is sensitive to the number of producers**, and the result should be compared to the minimum possible for the number of players in the market. High inequality=1; equality=lower	No

Index	Metric and reference	Description	Brown (2018) discussion	Calculated
7	Entropy measure of diversification	Sum of the multiplication of the market share of each producer by the logarithm of that market share, multiplied by negative one	Compared to the rest, **measures diversity, not concentration**. Like HHI, it is sensitive to the number of producers, and the result should be compared to the maximum possible for the number of players in the market. High diversity=maximum; low diversity=0.	No

Source: Author's elaboration based on Brown (2018).

As noted in the right-most column of Table 1, we calculate and/or discuss Indices 1-3 in this study, but outside the context of concentration. For the purposes of concentration, we use the most popular concentration metric, the un-normalized Herfindahl-Hirshmann index (HHI) (Index 4 in Table 1). It is less specialized than Kwoka's Dominance Index and the Entropy Measure of Diversification (Indices 6 and 7 in Table 1). The HHI also captures more information than, and has a high correlation to, the Concentration Ratio that Brown (2018) endorses (Index 3 in Table 1).

The ETM literature widely uses the HHI in criticality reports. For examples, see European Commission (2010, 2014), and Habib, Hamelin, and Wenzel (2016), who map primary ferrous, non-ferrous, precious, and specialty metals production in 1994 and 2013, finding a shift from developed economies to developing economies over this time period. We fully explain the application of the HHI in the Methods section of this study.

2.2. Resource/Reserve Assessments and Market Models

Another complementary ETM research stream deals with the availability and distribution of physical availability (resources), commercially viable resources (reserves), and production.

The Energy Transition Institute (2017) and Gruber et al. (2011) are examples of the large literature on resource assessments comparing estimates of future demand with the physical availability of ETMs.

As opposed to resource assessments, reserve assessments consider economic variables like production ability and recyclability. Examples of reserve assessments in the ETM space include Speirs et al. (2014) and Olivetti et al. (2017). Conclusions vary, Reuter et al. (2014) and Weil et al. (2018) conclude that lithium and/or cobalt markets could face supply constraints, but find these alleviated under time-varying assumptions of technology innovation in materials recycling or the development of substitute technologies. Others, like Narins (2017) take a more nuanced approach, pointing to the importance of the quality, not the quantity of metals, deeming there is the possibility of short, if not long-term, supply disruptions.

World Bank (2017) calculates the material demand expected to achieve the 2 degree, 4 degree, and 6 degree global warming targets for many technologies. Amongst other analyses, World Bank (2020) presents the results of an estimation of global demand growth to 2050 by ETM, according to the IEA Sustainable Development Scenario (SDS), with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100. The difference between World Bank (2017) and World Bank (2020) and many other assessments that attempt to predict demand (e.g. Watari et al. (2019)) is that like us they consider the role that all world regions will play in supplying materials for all renewable energy technologies.

Note that while resource, reserve, and demand assessments may aid in short-term public and private sector planning, the economics literature on exhaustible resources has successfully posited in theory and subsequent empirical analysis that demand and supply do not exist independently of each other. In a study of mineral imbalances over the last 100 years, Renner and Wellmer (2019) find that "short-term market imbalances are generally neutralized by a dynamic reaction on the demand side via substitution, efficiency gains or technological change."

Along these lines, some studies have estimated the future demand and supply of ETMs dynamically. Methods include spatial-temporal multi-product allocation, partial equilibrium models, and agent-based models. For instance, Zhang, Kleit, and Nieto (2017) present a bottom-up analysis of rare earth flows using agent-based modelling, which features interacting but autonomous agents in complex systems.

Other relevant work includes Labys and Yang (1991), Macal and Hill (1985), and Andriamasinoro and Angel (2012). These empirical and focused assessments show that while geopolitical supply risk should attract some concern from specific governments and industries, globally and in the long run, price signals and technological advances often circumvent physical shortages.

This result does not necessarily undermine criticality assessments, but highlights their role in "early-warning" screening (McCullough and Nassar 2017). Indeed, Solow (1974) notes that exhaustible resource pricing, demand, and supply depend on the "ease with which other factors of production […] can be substituted for exhaustible resources in production". And, while technological innovation is notoriously hard to predict, moments of acute prices can spur innovation within firms, in a process called "induced innovation" where "a change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive" Hicks (1932). Therefore, an example of endogeneity between innovation and perceived (or real) bottlenecks are the very efforts by developed countries to identify and substitute away from the materials that are most "critical."

Long-term evidence for induced innovation in the broader energy sector exists too. Fouquet (2015) uses 500 years of data for non-renewable energy resource use in the United Kingdom and finds that innovation, due to price increases, appears as the ultimate non-exhaustible resource. Popp (2002)'s seminal paper finds a strong and positive impact of energy prices on innovation.

Overall, while criticality, resources, reserves, and forecasting studies have contributed to an understanding of dynamics behind several ETM markets and actions that can help prepare supply chains for short-term disruptions, there is evidence that market forces tend to lead to innovation and bypass long-term shortages (Renner and Wellmer 2019). Our work contributes to our understanding of which countries are poised to benefit from energy decarbonization by assuming this endogeneity and focusing instead on relative benefits across different geographies from trade trends in ETMs in general and groups of ETMs (with a particular focus on CEMs vs TEMs and OCs versus MCs) between 1998-2018.

2.3. Resource Governance

Governance, defined as “the traditions and institutions by which authority in a country is exercised […including] the capacity of the government to effectively formulate and implement sound policies” (World Bank 2021) is central to and imbedded in ETM criticality literature. That literature infers that countries with low governance can generate supply shocks in importer countries (Bazilian 2018). Vulnerability to supply shocks leads Ali et al. (2017) to suggest a need for “environmental diplomacy” and a “planetary policy for metals.”

Renner and Wellmer (2019) question the “seller’s market” narrative. They find that “neither high country concentration nor poor governance seem to have a substantial or lasting impact on market balance” except in some contained examples with limited market impacts. They even find a “tendency of diminishing volatility with increasing country concentration.”

Instead, they posit that demand-side volatility has had noxious effects on exporters themselves. Demand-side price volatility interacts with the infamous Dutch Disease (in which, amongst other effects, real exchange appreciation from resource exporters weaken the country’s export competitiveness and industrial sectors) (Frankel 2012). Therefore, the importance of effective ETM governance can: (1) be framed around the benefits it provides to exporters; and, (2) links to the larger literature on governance in resource-rich countries.

Common policy suggestions include export diversification and turning mining (unrefined products, OCs) into manufacturing (including refined products, MCs). However, challenges include a lack of skilled labour and technological gaps, in addition to the macroeconomic challenges discussed above (Frankel 2012; Renner and Wellmer 2019). Other options include establishing a local industry around the extractive sector and using it for skilled knowledge development and an expansion of services (Renner and Wellmer 2019).

Renner and Wellmer (2019) make a distinction between minor metals (e.g., gallium, which may occur alone or coupled with others) and coupled elements (e.g. rare earth elements and platinum group metals that occur together in deposits), on the one hand, with major metals (e.g. copper, lead, zinc, and tin) on the other. In the case of minor and coupled elements, volatility and technological change may fail to translate into long-term demand, and fiscal returns from export taxes and royalties may be the extent of resource benefits to exporters.

Despite the issues that the burgeoning ETM literature has already touched upon, there is (yet) no study that attempts to answer questions on the changing characteristics of growth, volatility, and importer and exporter concentration in trade value and volume across the technologies that will play a role in energy decarbonization using historical data between 1999-2008, identifying patterns over groups and products.

The relationship between governance and institutional capacity and the evolution of competitiveness and exports is a rich area of literature. While this study does not try to explain the drivers behind the trends, it lays the groundwork for future governance research by trying to explain the key patterns that may be linked and driven by various governance characteristics.

3. Methods

Our methods consist of four parts. First, we refer to the existing ETM literature to select the most relevant energy technology materials according to pre-set requirements. Second, we match the key materials to the list of traded products. Third, we generate the product groups according to Classifications 1 and 2 introduced above. Fourth, we calculate the metrics for the analysis subject them to robustness checks with statistical tests.

3.1. Selecting Relevant materials

The ETM literature covers a vast set of materials, and the selection of ETMs included in each study is a function of the subject of analysis (for instance US criticality assessments select the ETMs that are relevant to US industry). World Bank (2020) is our main source of eligible ETMs. This is because the publication considers a wide range of energy technologies, it has a global outlook, and it is timely.

While World Bank (2020) contains several analyses, the most relevant to us is an estimation of global production growth to 2050 by ETM, according to the IEA Sustainable Development Scenario (SDS), with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100. Table 2 summarizes estimates for growth of demand in 2050 in comparison to 2018as well as the relevant energy technologies for each ETM.

To focus on the materials most likely to play a non-negligible role in the coming decades, we follow two criteria. Criterion 1: materials with an estimated non-negligible increase in annual demand, defined as at least 30%. Criterion 2: materials used in more than five technologies. Criteria 1 and 2 identify 13 materials located above the horizontal line in Table 2. The technologies in which the materials are found are marked in green.

Table 2. Materials analysed in World Bank (2020), including their projected annual demand from energy technologies as a percent of 2018 annual production, the technologies in which materials are used, and whether they were selected (green) or not selected (grey).

Number	Materials	Estimated percentage change 2018-2050*	Count of technologies (excluding coal)	Wind	Solar PV	CSP	Hydro	Geothermal	Energy storage	Nuclear	Gas	CCS	Coal (excluded)
1	Graphite	494	1						green				
2	Lithium	488	1						green				
3	Cobalt	460	3						green		green	green	green
4	Indium	231	2		green					green			
5	Vanadium	189	3						green	green			green
6	Nickel	99	8	green	green		green	green	green	green	green	green	green
7	Silver	56	3		green	green				green			
8	Neodymium	37	1	green									
9	Lead	18	5	green	green		green		green	green			
10	Molybdenum	11	7	green	green		green	green		green	green	green	green
11	Aluminum	9	5	green	green				green	green	green		green
12	Copper	7	9	green	green	green	green	green	green	green	green	green	green
13	Manganese	4	6	green			green	green	green		green	green	green
14	Chromium	1	8	grey			grey	grey	grey	grey	grey	grey	grey
15	Titanium	0	5				grey	grey		grey	grey		grey
16	Iron**	1	2										
17	Zinc**		5	grey	grey		grey		grey	grey			

Source: Adapted from World Bank (2020) Tables 3.1 and B.2.

Note: *2050 projected production from energy technologies to achieve under 2DS*, % of 2018 annual production. ** Information for iron and zinc are incomplete in the source. CCS = carbon capture and storage.

The two selection criteria ensure that our sample is comprehensive (Criteria 1 alone leads to eight materials) while excluding materials with negligible changes and roles in energy decarbonization. If we were to increase the stringency of the criteria, for instance increase Criteria 1 to 50%, the results would not change drastically. In that case, we would exclude neodymium. This is a rare earth element that is included in the sample through another route, explained below.

Second, note from Table 2 that World Bank (2020) considers minerals that are crucial for the use of oil, gas, and coal technologies (including carbon capture and storage), but not fossil fuels themselves. Due to our research question on the different groups of ETMs, we include oil and gas in our analysis. We exclude coal for two reasons: (1) the IEA SDS shows a marked phase-out of coal in several regions in accordance with government policies, and this decline is larger than the decline of other fossil fuels; and, (2) in comparison to other materials in this section, coal tends to be consumed domestically and the SDS forecasts that trade will decrease even further due to large coal regions primarily in Asia, led by India and China, prioritizing internal demand (International Energy Agency (IEA) 2020).

Last, we expand the materials used for oil and gas by considering platinum group metals (PGMs), which consist of platinum, palladium, rhodium, iridium, ruthenium, and osmium. While PGMs have a variety of uses today, half of their use is in catalytic converters for internal combustion engines. A smaller use of PGMs is as catalysts to create high-octane gasoline for cars from crude oil (Renner and Wellmer 2019). They also help improve the quality of hydrocarbons through processes like hydro processing and hydrocracking (Shaffer 2015). Throughout the text, we acknowledge and consider the fact that PGMs are also present in hydrogen fuel cells. Eventually they could become CEMs.

As the following sections will demonstrate, our ETM selection process makes it possible for us to explicitly compare trade trends between CEMs and TEMs across countries, as well as between refined and raw materials. In turn, it allows us to extract conclusions of short to medium-term impacts (or winners and losers) from the energy transition given historical trends as measured by key trade indicators.

Table 3. Final materials selection. Check=Sourced from World Bank (2020). X=Explained in the text.

Number	Materials	Sourced from World Bank (2020)
1	Graphite	✓
2	Lithium	✓
3	Cobalt	✓
4	Indium	✓
5	Vanadium	✓
6	Nickel	✓
7	Silver	✓
8	Neodymium	✓
9	Lead	✓
10	Molybdenum	✓
11	Aluminum	✓
12	Copper	✓
13	Manganese	✓
14	Rare earth elements	X
15	Oil	X
16	Gas	X
17	Platinum group metals	X

Source: Author's elaboration based on the methods described in this study and World Bank (2020).

3.2. Selecting Trade Products and Generating Product Groups

Methods for selecting relevant trade data

As briefly discussed in the introduction, we define materials as descriptive categories that contain a range of physically traded products.

When materials are traded, national custom offices log and classify them according to several pre-established international and national product nomenclatures. The UN Statistics Division (UNSD) gathers and standardizes self-reported annual customs data from over 170 countries since 1995 using two international trade product nomenclatures: the Harmonized System (HS) and the Standard International Trade Classification (SITC) (UNSD 2020). In this study, we use the HS nomenclature because it provides a more disaggregated product differentiation for our materials compared to the SITC.

The HS nomenclature is updated every four to five years to keep up with technological and other changes. In addition to compiling yearly data, the UNSD also converts the data reported in the most recent nomenclature into each previous nomenclature. Therefore, the longest data series is reported in the first HS version, called "HS 1992." The agency then converts all data reported by customs offices into metric tons (quantity) and current US dollars (USD) using exchange rates from customs offices (value). The data is accessible to all through the United Nations International Trade Statistics Database, also called UN Comtrade.

Despite the invaluable information provided by UNSD, data reported by customs is not checked for errors. There are several discussions of the size and effects of such errors. The methods of the Terms of Trade indicators used in the Integration and Trade Department of the Inter-American Development Bank contain an in-depth review of trade data errors (Galeazzi 2015). Additionally, in UN Comtrade, import data is reported in CIF format (which includes cost, insurance, and freight), and export data is reported in FOB (free on board) format. Usually, the researcher chooses the data format most aligned with the research question (here, we would use FOB).

A second database, the Database for International Trade Analysis (BACI), published yearly by the Centre for Prospective Studies and International Information (CEPII), reconciles importer and exporter declarations into freight on board (FOB) import values and weights the data by the reliability of its exporter (Gaulier and Zignago 2012), using differences between CIF and FOB to fix several issues in UN Comtrade data. Like UNSD, BACI provides the value of trade in thousands of current USD and the quantity in metric tons. Their longest nomenclature version is HS 1992, and the latest 2020 dataset ranges from 1995-2018. We, therefore, employ BACI as the direct data source.

BACI's dataset contains more than 1.5 million observations that reflect more than five thousand products, over more than 150 countries and more than 20 years. Selecting the relevant trade products for our study requires an explanation of the available typologies in the HS product classification system and a systematic identification of relevant product groups, described next.

The HS uses six digits to classify traded products. As an example, HS code 282520 refers to lithium oxide and hydroxide. While developed countries tend to disaggregate products into eight (and even 10) digits, data beyond six-digit HS codes is not comparable across countries. It becomes necessary to use only one country's data at a time or else harmonize across the developed countries that report data at that level, which would restrict the data only to developed countries. To the extent that we wish to define varieties as importers from a world demand, this option is not useful to us.

From left to right, each two-digit pair classifies a good in increased detail. In our running example for lithium hydroxide and oxide, the first two digits (also referred to as a chapter), 28, indicate "inorganic chemicals; organic and inorganic compounds of precious metals; of rare earth metals, of radio-active elements and of isotopes." Chapters themselves are aggregated into the broadest possible product categories, sections. There 21 sections, ranging from Live Animals (Section 1) to Works of Art and Antiques (Section 21).

To narrow the scope of analysis, we first identify HS sections that correspond to our materials. These are: (1) mineral products; (2) chemicals or allied industries; (3) precious or semiprecious stones and metals; and, (4) base metals. The four relevant sections contain a total of 18 HS chapters for further review.

We use a UN Comtrade search functionality to identify products related to the materials in the ETM literature. The process allows us to break each HS chapter into its component products. For example, the next two digits in our running example, 25, indicate "hydrazine and hydroxylamine and their inorganic salts; other inorganic bases; other metal oxides, hydroxides and peroxides." The final two digits, 20, indicate "lithium oxide and hydroxide." Sections relevant to our analysis are summarized in Table 4. Table 4 also includes their chapters.

Table 4. HS Sections and chapters containing the materials we identified in the literature.

HS Section	Section summary	HS Chapter	Section summary
5	Mineral products	25	Salt; sulphur; earths and stone; plastering materials, lime and cement
		26	Ores, slag and ash
		27	Mineral fuels (oil, gas), mineral oils and products of their distillation; bituminous substances; mineral waxes
6	Chemicals or allied industries	28	Inorganic chemicals; organic or inorganic compounds of precious metals, of rare-earth metals, of radioactive elements or of isotopes
14	Precious or Semiprecious Stones, Precious Metals	71	Natural or cultured pearls, precious or semi-precious stones (diamond, etc.), precious metals (silver, gold, platinum, palladium etc.), metals clad with precious metal, etc.
15	Base metals and articles of base metals	74	Copper and articles thereof
		75	Nickel and articles thereof
		76	Aluminum and articles thereof
		78	Lead and articles thereof
		72-83	Rest of base metals, incl. iron and steel, zinc, tin, etc.; cermets and articles thereof

Sources: Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

We identify 30 trade products that contain references to the materials chosen from Table 4. Table 5 summarizes their codes and descriptions.

As described above, the more HS digits, the more specialized the product. The more specified the product, the fewer trade flows, and the less data available for the analysis, however. Therefore, we used the minimum level of aggregation to sufficiently define a product.

For example, 2709 is a 4-digit product that sufficiently defined "Crude oil" from others in its Chapter (27) of "Mineral products." It is necessary to use 6-digits, 282520, to identify lithium chemicals from the rest in its group, however. Overall, we have 19 four-digit HS and 11 six-digit HS products, placed in the top and bottom of Table 5, respectively.

Table 5. Selected UN Comtrade 4 and 6-digits products that correspond to materials identified in the literature.

Count	Chapter	HS Code	Harmonized System product description
1	25	2504	Graphite powders and flakes
2	26	2602	Manganese ores and concentrate
3		2603	Copper ores and concentrates
4		2604	Nickel ores and concentrates
5		2605	Cobalt ores and concentrate
6		2606	Aluminum ores and concentrate
7		2607	Lead ores and concentrate
8		2613	Molybdenum ores and concentrate
9		2615	Niobium, tantalum, vanadium, and zirconium ores and concentrates
10	27	2709	Crude oil
11		2711	Natural gas
12	28	2822	Cobalt chemical (oxide and hydroxide)
13		2846	Compounds, inorganic or organic, of rare-earth metals, of yttrium or of scandium, or of mixtures of these metals in unwrought, powder and waste and scrap form
14	74	7401	Copper matte
15	75	7501	Nickel matte
16	76	7601	Aluminum unwrought
17	78	7801	Lead unwrought
18	81	8105	Cobalt mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders and waste and scrap
19		8112	Beryllium, chromium, germanium, vanadium, gallium, hafnium, indium, niobium (columbium), rhenium and thallium metals; unwrought, waste and scrap, other than unwrought, including not elsewhere specified
20	26	261610	Silver ores and concentrates
21		261690	Rhodium, platinum and palladium (platinum group metals, PGM) ores and concentrates, and other precious metals
22	28	280530	Earth-metals, rare and scandium and yttrium, whether or not intermixed or interalloyed
23		282520	Lithium chemicals (oxide and hydroxide)
24		282530	Vanadium oxides and hydroxides
25		283691	Lithium chemicals (carbonate)
26	71	710691	Silver unwrought
27		711011 and 711019	Platinum unwrought, powder and semi-manufactured
28		711021 and 711029	Palladium unwrought, powder and semi-manufactured
29		711031 and 711039	Rhodium unwrought, powder and semi-manufactured
30	81	810291	Molybdenum unwrought, waste and scrap

Sources: Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

It is crucial to note that, while the HS nomenclature is usually more detailed than the materials identified in the ETM literature, the typology is a model, or abstraction, of the physical product space. Because of this, the HS nomenclature sometimes fails to differentiate products into the materials we identified. In the example used in the previous paragraphs, HS 282520, contains two types of lithium chemicals, oxide and hydroxide. As a result, it is impossible to differentiate between these two products in trade data. In practice, this is usually not a major issue. Both types of lithium are precursors for materials in the same energy technologies (UNCTAD 2020).

As another example, while dysprosium and neodymium are sometimes referred to separately in the ETM literature, the HS nomenclature groups several rare earth elements together (see 2846 and 8112 in Table 5). Therefore, as mentioned previously, our analysis includes all rare earth elements, despite World Bank (2020) excluding some of them.

Last, some of the identified materials are so diverse that they exist in dozens of 4 to 6 digit HS products. This is the case for copper, nickel, aluminum, and lead. In fact, each of these has its own HS chapter, and includes several derivative products. To keep our analysis manageable and focused, we keep only mattes (an unrefined stage) and no other associated derivative products such as scraps and alloys of these metals.

Generating product groups

Aside from looking at trade trends overall and by individual products, we look at groups of products.

We first classify products according to their role in the energy transition (Classification 1): Chemical and Mineral Clean Energy Materials (CEMs) versus Traditional Energy Materials (TEMs). In Classification 2, we classify products according to their level of refinement: Ore and Concentrates (OCs), versus refined Metals and Chemicals (MCs), summarized in Figure 1.

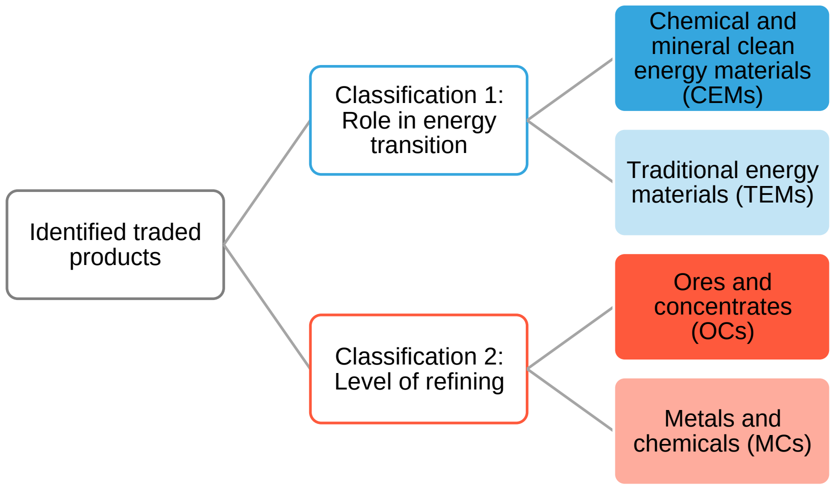

Figure 1. Classifications and product groups used in this study.

Source(s): Authors' elaboration based on the methods described in this study.

As we discussed in the Introduction and the Literature Review, we have not seen a division of the materials into unrefined versus refined products. This leads to a relevant clarifying question regarding Classification 2: Should MCs (like cobalt chemicals from China) theoretically display the same trends as their inputs (like unrefined cobalt from the Democratic Republic of the Congo)?

Consider that an increase in prices of raw materials may spur increased efficiency, recycling through induced innovation (discussed in the Literature Review), and stockpiling. This is especially true if the origin of a raw mineral is perceived to be an area of supply risk, like the Democratic Republic of the Congo (Lee et al. 2020). Indeed, the perceived supply risks of ETMs that spurred the criticality literature have also materialized into efforts by governments and private firms to localize and vertically integrate suppliers. Such an effort includes, for instance, the U.S. Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals "with the intention of progressing toward mineral independence" (Lee et al. 2020).

As a result, the relationship between OCs and their respective MCs may not easily be summed through a simple linear correlation and can be studied separately. In the Discussion section, we acknowledge another potential issue with our scope. An analysis of each market (for instance, lithium carbonate and not lithium oxide/hydroxide) is relevant but beyond the reach of the research questions posed in this study. Overall, the distinction between MCs and OCs remains valid.

We refer to product descriptions in Table 5, from UN Comtrade, as the main source in the categorization of products, shown in Table 6, following the same colours as Figure 1. CEMs make up 80% of the products according to Classification 1. OCs make up 40% of products according to Classification 2.

Table 6. Product, HS codes, and groups. Following the colours in Figure 1, Clean Energy Materials (CEMs) are blue, Traditional Energy Materials (TEMs) are light blue; Ores and concentrates (OCs) are red, Metals and chemicals (MCs) are light red.

<table>
<tr><th>Count</th><th>Chapter</th><th>HS Code</th><th>Harmonized System product description</th><th>CEMs (1) or TEMs (2)</th><th>OCs (1) or MCs (2)</th></tr>
<tr><td>1</td><td>25</td><td>2504</td><td>Graphite powders and flakes</td><td>1</td><td>2</td></tr>
<tr><td>2</td><td rowspan="8">26</td><td>2602</td><td>Manganese ores and concentrate</td><td>1</td><td>1</td></tr>
<tr><td>3</td><td>2603</td><td>Copper ores and concentrates</td><td>1</td><td>1</td></tr>
<tr><td>4</td><td>2604</td><td>Nickel ores and concentrates</td><td>1</td><td>1</td></tr>
<tr><td>5</td><td>2605</td><td>Cobalt ores and concentrate</td><td>1</td><td>1</td></tr>
<tr><td>6</td><td>2606</td><td>Aluminum ores and concentrate</td><td>1</td><td>1</td></tr>
<tr><td>7</td><td>2607</td><td>Lead ores and concentrate</td><td>1</td><td>1</td></tr>
<tr><td>8</td><td>2613</td><td>Molybdenum ores and concentrate</td><td>1</td><td>1</td></tr>
<tr><td>9</td><td>2615</td><td>Niobium, tantalum, vanadium, and zirconium ores and concentrates</td><td>1</td><td>1</td></tr>
<tr><td>10</td><td rowspan="2">27</td><td>2709</td><td>Crude oil</td><td>2</td><td>1</td></tr>
<tr><td>11</td><td>2711</td><td>Natural gas</td><td>2</td><td>1</td></tr>
<tr><td>12</td><td rowspan="2">28</td><td>2822</td><td>Cobalt chemical (oxide and hydroxide)</td><td>1</td><td>2</td></tr>
<tr><td>13</td><td>2846</td><td>Compounds, inorganic or organic, of rare-earth metals, of yttrium or of scandium, or of mixtures of these metals in unwrought, powder and waste and scrap form</td><td>1</td><td>2</td></tr>
<tr><td>14</td><td>74</td><td>7401</td><td>Copper matte</td><td>1</td><td>2</td></tr>
<tr><td>15</td><td>75</td><td>7501</td><td>Nickel matte</td><td>1</td><td>2</td></tr>
<tr><td>16</td><td>76</td><td>7601</td><td>Aluminum unwrought</td><td>1</td><td>2</td></tr>
<tr><td>17</td><td>78</td><td>7801</td><td>Lead unwrought</td><td>1</td><td>2</td></tr>
<tr><td>18</td><td rowspan="2">81</td><td>8105</td><td>Cobalt mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders and waste and scrap</td><td>1</td><td>2</td></tr>
<tr><td>19</td><td>8112</td><td>Beryllium, chromium, germanium, vanadium, gallium, hafnium, indium, niobium (columbium), rhenium and thallium metals; unwrought, waste and scrap, other than unwrought, including not elsewhere specified</td><td>1</td><td>2</td></tr>
<tr><td>20</td><td rowspan="2">26</td><td>261610</td><td>Silver ores and concentrates</td><td>1</td><td>1</td></tr>
<tr><td>21</td><td>261690</td><td>Rhodium, platinum and palladium (platinum group metals, PGM) ores and concentrates, and other precious metals</td><td>2</td><td>1</td></tr>
<tr><td>22</td><td>28</td><td>280530</td><td>Earth-metals, rare and scandium and yttrium, whether or not intermixed or interalloyed</td><td>1</td><td>2</td></tr>
</table>

Count	Chapter	HS Code	Harmonized System product description	CEMs (1) or TEMs (2)	OCs (1) or MCs (2)
23		282520	Lithium chemicals (oxide and hydroxide)	1	2
24		282530	Vanadium oxides and hydroxides	1	2
25		283691	Lithium chemicals (carbonate)	1	2
26		710691	Silver unwrought	1	2
27	71	711011 and 711019	Platinum unwrought, powder and semi-manufactured	2	2
28		711021 and 711029	Palladium unwrought, powder and semi-manufactured	2	2
29		711031 and 711039	Rhodium unwrought, powder and semi-manufactured	2	2
30	81	810291	Molybdenum unwrought, waste and scrap	1	2

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs =ores and concentrates; MCs=metals and chemicals.

3.3. Trade Value Growth and Volatility

Exporters prefer for their exports to experience a growth in value over time and to expand the number of products that they export, with the promotion of exports being a key role for government departments and ministries in many countries around the world. For example, the UK Department for International Trade aims to "enable the UK to trade its way to prosperity […] by helping businesses export […] opening up markets, and championing free trade" (Department for International Trade 2018).

To capture the importance of growth in trade value, we average annual growth rates in value (the "average growth rate"). While annual growth is the most disaggregated time unit our data allows, it also allows us to capture longer-term trends instead of shorter-term cycles driven, for example, by seasonality or speculation (Renner and Wellmer 2019). We calculate the average of value growth rates separately over twenty years (1999-2018) and over two ten-year periods (1999-2008 and 2009-2018, Decade 1 and Decade 2, respectively).

The growth in export value is important regardless of the differences in prices across products. Note that although their prices tend to be lower, unrefined products can be more profitable on a per unit basis than refined products, depending on the cost of production by product and exporter.

Also note from our description of trade data above that value is defined as price times quantity. Therefore, the data already captures the endogeneity between prices and quantity that we discussed in the Literature Review. Additionally, trade literature tends to make a distinction between large and small players, where large (small) set (and accept) trade terms, respectively. We assume that the major exporters in our dataset have already affected the value of the products that were traded, and that this point does not affect their preference for growth in traded value.

There is a nuance to the notion that exporters prefer export value growth, however. For exporters to reap long-term benefits, export increases must be stable. Amongst other detrimental effects, if the increase in the value of exports is driven by volatile increases in prices, importers may invest in product recycling, efficiency, or alternative sources. Such changes can be irreversible and are detrimental to exporters (Habib et al. 2016; Renner and Wellmer 2019). The importance of keeping prices accessible and stable stands in direct contradiction to some high-profile policy decisions, such as the Democratic Republic of the Congo declaring cobalt a 'strategic' mineral and nearly tripling its royalties in 2018 (Reuters 2018).

We consider the advantage of stability to exporters by using a straightforward measure of volatility, the standard deviation (SD). The SD is defined as the square root of the average of the squared differences from the mean. Metrics using the mean and SD have already been used to study the volatility of ETM in McCullough and Nassar (2017), but have been applied to prices and not trade values.

We display the continuum of growth rates and volatility for all groups and products in graphs and tables in the main text and appendixes. We also focus on products that stand out in either metric, and especially on those that are high growth and low volatility. We focus on products that are among the top 20% (top quintile) products in either metric because the metric is broad enough to capture more than only potential outliers, but low enough to allow us to focus on top-performers. In the Discussion section, we focus on the products that stand out in the most recent decade and also discuss how this heuristic can affect our results.

Tests of statistical significance

In the analysis of trade value growth and volatility, we attempt to compare whether changes over groups or decades are statistically significantly different from one another. For this, we employ parametric and non-parametric paired and unpaired tests.

To compare the growth and volatility metrics over groups within the same Classification (for instance TEMs versus CEMs in Decade 1), we use two statistical tests for unmatched data. Specifically, we employ: (1) The Wilcoxon rank-sum test (often used as an alternative to the Student's t-test) and (2) the Nonparametric equality-of-medians test. Both tests are non-parametric inferential statistical methods, which means that amongst other characteristics, they do not assume anything about the underlying distribution of the data. This allows it to be applied to data that is not approximately normally distributed, or in small samples such as ours.

The two-sided Wilcoxon rank-sum test (also known as the Mann–Whitney two-sample statistic) tests whether two samples are likely to come from the same population using the following hypotheses:

> H0: The two independent samples are from populations with the same distribution
>
> H1: The two populations are not equal

Rejecting the H0 (when the p-value > 0.05) means that there is evidence the two populations have different distributions. If we obtain a p-value greater than 0.05 in this test, we can assume that there is a difference between the metrics of groups within a classification, for instance, a difference between growth rates of groups in Classification 1 (CEMs versus TEMs). We use the "ranksum" function in Stata (StataCorp 2021).

Tests that compare two groups that contain different items (as opposed to comparing the same items over time) have lower statistical power (StataCorp 2021). Therefore, we supplement the Wilcoxon rank-sum test with the Nonparametric equality-of-medians test. It tests the following hypotheses:

> H0: The k number of samples were drawn from populations with the same median
>
> H1: At least one sample was drawn from a population with a different median

In this case, rejecting the H0 (when the p-value > 0.05) implies that there is evidence the two populations have different medians. Like above, if we get a p-value greater than 0.05 in this test, we can assume that there is a difference between the metrics of groups within a classification, for instance, a difference in the volatility of growth rates of groups in Classification 2 (OCs versus MCs). We use the “median” function in Stata (StataCorp 2021).

Over decades within the same group, we make a different comparison. Here, we compare items within the same groups over time, for instance lithium carbonate within CEMs in Decade 1 versus lithium carbonate within CEMs in Decade 2. This allows us to use a paired test. If differences between pairs are normally distributed, it is possible to use the paired Student’s t-test on the equality of the means (a two-sample case of ANOVA), with the following hypotheses:

H0: The samples have equal means

H1: The samples have different means

Rejecting the H0 (when the p-value > 0.05) implies that there is evidence the two populations have different means, with the same implications as described for the previous two tests. We employ a Shapiro-Wilk test to confirm normality (“swilk” in Stata), and the “ttest” function (StataCorp 2021).

3.4. Export and Import Quantity Concentration

Following the literature we reviewed, we calculate the popular un-normalized Herfindahl–Hirschman Index (HHI-index) over exporters and importers, by ETM. In the trade literature, this metric is akin to the un-normalized Export (Import) Market Concentration Index that is usually calculated over value (UNCTAD 2018a, 2018b). However, we align ourselves with the existing ETM literature that we reviewed in the discussion on concentration indices, which uses production. The closest equivalent of production in our data is quantity of traded product.

The HHI is calculated by summing the square of the market share of each market player (Eq. 1).

$$HHI = \sum_{i}^{N} s_i^2 \qquad \textit{Eq. 1}$$

Where s_i is the market share of exporter i, and N is the number of exporters or importers.

It is desirable to be a major exporter of an ETM within a highly concentrated export market. This can be evidenced in the fluctuation of price-setting power by countries in the Organization of the Petroleum Exporting Countries (OPEC) over time (Fattouh and Mahadeva 2013). It is also evidenced in a variety of policy documents that consider the share of exports of a certain country in a certain product (UK Department of Business Innovation and Skills 2012). The same exporter prefers the opposite when it comes to the importer concentration of the same product.

Observe from Eq. 1.1 that the HHI depends partly on the number of exporters. This can make comparisons of the same product over time, or other products, difficult (Brown 2018). There are two ways to solve this. First, the researcher can cap the number of exporters included in the calculation. The U.S. Department of Justice tops it at 50. Second, they can calculate the difference between the HHI and the HHI minimum given the number of exporters for the given period, (1/ number of exporters).

At a large N, as is the case with trade, the minimum HHI is very small and there should not be much of a difference between the two options. So as not to lose any information, however, we opt for the latter. We, therefore, report the HHI score minus the minimum possible for the HHI (Eq. 2).

$$HHI = \sum_{i}^{N} s_i^2 - \frac{1}{N} \qquad \textit{Eq. 2}$$

Where s_i is the market share of exporter i, and N is the number of exporters.

We calculate both the importer and exporter concentration of products over the entire time period and dynamically. We consider how the products overall have shifted, what products are best positioned, and what products have had beneficial changes over the last two decades.

As explained in Brown (2018) the United States Department of Justice (2010) considers a score of more than 0.25 as high concentration, between 0.15 and 0.25 as moderate concentration, and lower than 0.15 as low concentration. For ease of interpretation, these are the cut-offs we adopt.

Nevertheless, they are necessary heuristics used to simplify analyses and they may be relatively arbitrary at the margins. For instance, the UK Competition and Market Authority (CMA) uses slightly different cut-offs. Ideally, the HHI is best discussed in a continuum and complemented with a market-by-market understanding of each of the 30 products (Brown 2018). As noted further in the Discussion section, is not possible to study each product in such depth due to the breadth of the products studied in this study.

3.5. Major Exporters

We identify and discuss the main exporters of our selected products. To do so, we rank exporters in descending order by value of exporters during the 20-year period, by product. We then choose either the top five, or those that cumulatively make up 90% of all the traded value for the particular product, whichever criterion occurs first. Like we did for concentration, we plot the number of goods each exporter was a top exporter in during the entire period (e.g., Brazil exported an average of three of the 30 products during the entire sample), and also the changes over decade in the number of products the exporters were major exporters (e.g., Brazil exported two products in Decade 1 and four in Decade 2).

For each major exporter, we also determine the percentage of the overall ETM products in each group within Classifications 1 and 2 (MC versus OC and CEMs versus TEMs). After doing so, we ask whether developing/developed countries are more likely to play a role as major exporters in some product groups, as expected based on the wider product space (Behrens et al. 2007). For instance, we expect that developing countries are more likely to be major exporters of OC (unrefined) and not MC (refined) products.

3.6. Summary of Metrics

Following the literature, we assume that exporters prefer to face high growth rates and low volatility for their products, as well as a concentrated market (by supply) and a dispersed market (by demand). We also assume that exporters prefer a change over time towards higher growth, lower volatility, higher export concentration, and lower importer concentration. Table 7 lists each metric and summarizes key characteristics discussed in this Methods section.

Table 7. Summary of assumptions and metrics used in the analysis of this study.

Item	Metric	Exporters prefer	Measured over	Measured using	Time period	Measured over
1	Growth rates	High	Value	Average of annual growth rates in time sample	1999-2018 1999-2008 2009-2018	Product groups and products
2	Volatility	Low	Value	Standard deviation of annual growth rates in time sample	1999-2018 1999-2008 2009-2018	Product groups and products
3	Importer concentration	Low	Quantity	HHI	1999-2018 and changes over decade	Products (product groups in Appendix 5)
4	Exporter concentration	High	Quantity	HHI	1999-2018 and changes over decade	Products (product groups in Appendix 5)
5	Identification of major exporters	NA	Value	Top five exporters, or those cumulatively make up 90% of all value for a particular product	1999-2018 and changes over decade	Products (product groups in Appendix 6)

Source(s): Authors' elaboration based on the methods described in this study.

We identify and discuss implications for the major exporters behind these products (Item 5). The Discussion section synthesizes the static and dynamic trends (overall, by product group, and by individual product) and it reflects on how trends may affect exporters.

4. Data

As described in the Methods section, UN Comtrade reports yearly bilateral flows of exporters, importers, value in thousand USD, and quantity in metric tons, by HS product code. Therefore, our dataset is composed of a panel of country exporters between 1995 and 2018. However, UN Comtrade reports some exporters in groups (Table 8). Additionally, we consider the Economic and Monetary Union of the European Union as one exporter because the bloc acts as one for trade purposes.

Table 8. Country groups in the trade dataset.

Country group	Countries in groups
Southern African Customs Union	Botswana, Lesotho, Namibia, South Africa and Swaziland
Belgium (irrelevant due to EU aggregation, see below)	Belgium and Luxembourg
France (irrelevant due to EU aggregation, see below)	France and Monaco
Switzerland	Switzerland and Lichtenstein
Taiwan	Not recognized by China, referred to as 'Asia, not elsewhere specified' in UN Comtrade
Economic and Monetary Union of the European Union (as of 2019)	Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and United Kingdom

Sources: Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

From now on, we simplify the product description in HS Comtrade in figures: (1) ores and concentrates are denoted by "[OC];" (2) oxides and hydroxides are denoted by "[OH]," (3) unwrought metals are denoted by "[UW];" and, (4) powders and flakes are denoted by "[PF]." Additionally, we denote REE compounds by REE1, and denote alloys by REE2 (Table 9).

Table 9. UN Comtrade description and simplified labels.

UN Comtrade description	Simplified label
Ores and concentrates	OC
Oxides and hydroxides	OH
Unwrought metals	UW
Powders and flakes	PF
REE compounds	REE1
REE alloys	REE2

Sources: Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

We deflate values to 2018 dollars using official US government statistics. The average trade value for the selected products is 120 million USD. The data for values has heavy tails and is highly positively skewed. In other words, the median is much lower than the average of 34 thousand USD, with a standard deviation of 1,460 million USD. The data for quantity displays the same pattern.

Figure 2 and Figure 3 show the value of TEMs and CEMs, respectively. Oil/gas dominate the aggregate trade value of our selected products and made up almost 90% of value in 2018.

World aggregate trade value for TEMs grew every year from 2001-2008, falling markedly after the 2008 financial crisis (Figure 2). From 2009-2012, TEMs experienced a period of growth and stabilization, reaching a 20-year peak in 2012. The aggregate values for TEMs decreased in the second half of 2014, hitting a nadir in 2016 due to the global collapse in commodity prices. A confluence of industry, macroeconomic, and financial conditions, including changing geopolitical risks and the U.S. dollar appreciation caused the commodity price collapse (World Bank 2015). Most recently, the aggregate value grew consistently from 2016-2018, approximating 2006 levels.

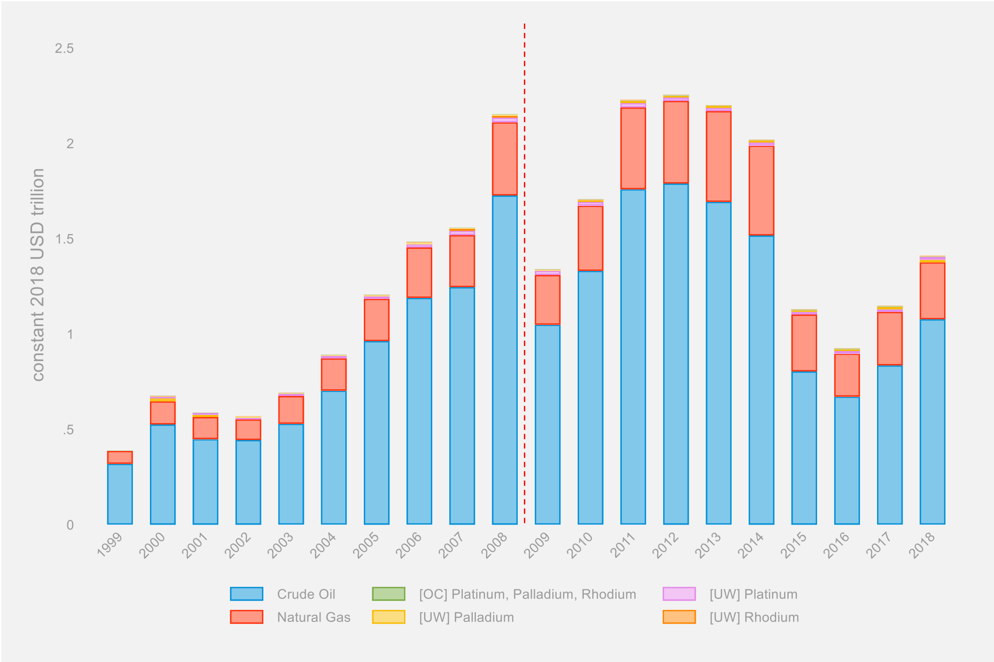

Figure 2. Traditional energy materials (TEMs), world trade value, 1999-2018, constant USD trillion. Left of vertical red line = Decade 1. Right of vertical red line=Decade 2. Source: Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020)

Note: OC=Ores and concentrates; UW=Unwrought metals.

Trends over time are similar for CEMs, except that the group reached its 20-year peak in 2011 (Figure 3). Copper [OC] and aluminium [UW] make up the biggest share of this group but are small compared to TEMs because they correspond to 4.66% and 4.44% of oil/gas in 2018, respectively. In the interest of space, we do not repeat the figures by cutting the data into OCs and MCs.

In both TEMs and CEMs, trade value mean and median grew over the decades of interest (Table 10). Volume decreased slightly in TEMs and increased in CEMs. The data is highly positively skewed, making a boxplot visualization of the metrics in Table 10 unwieldy. As an alternative, plotting logarithms and removing outliers yields very similar boxplots. Standard deviation (SD) increased in both groups over time. Appendix 1 contains the detailed statistics of the overall data, and summary statistics by product.

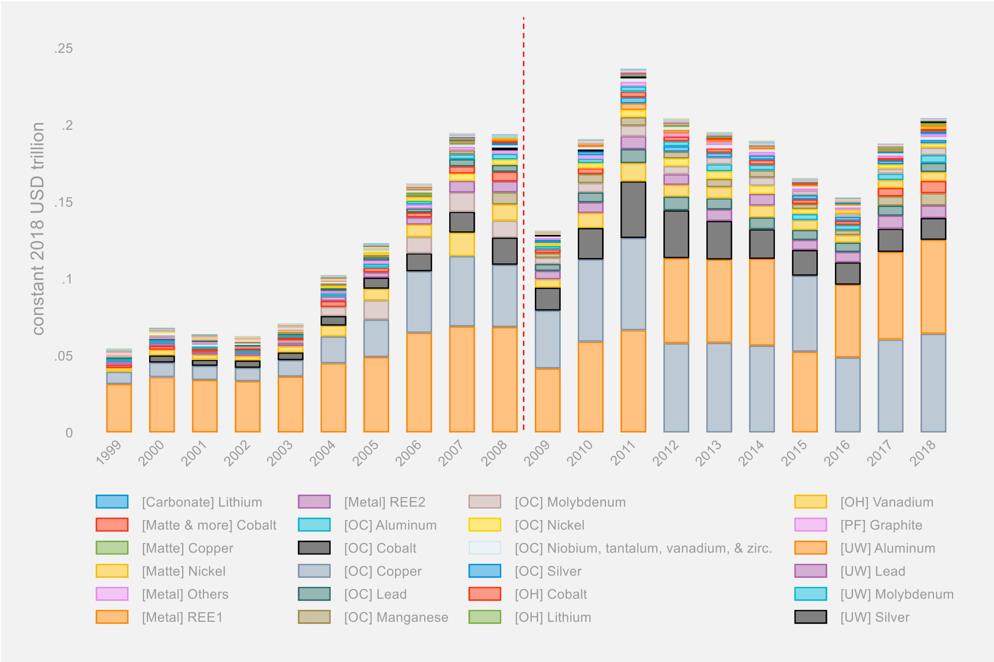

Figure 3. Clean energy materials (CEM), world trade value, 1999-2018, constant USD trillion. Left of vertical red line = Decade 1. Right of vertical red line=Decade 2.

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: REE= Rare Earth Elements; OC= Ores and concentrates; PF= powders and flakes; REE1=REE compounds; RE2=REE alloys; UW=Unwrought metals.

Table 10. Descriptive statistics, value (in constant USD million) and volume, by decade and groups.

TEMs	Decade	N	Mean	Std. Dev.	skewness	p5	Median	p95
Value	Decade 1	26,315	387.27	2,764.74	18.80	0.00	1.31	1,159.22
Volume		26,315	1,002,092.00	6,914,507.60	15.05	0.00	81.58	3,066,373.60
Value	Decade 2	32,469	502.88	3,384.97	17.32	0.00	1.64	1,468.71
Volume		32,469	953,914.31	8,816,579.20	54.21	0.00	41.18	2,829,437.30
CEMs	**Decade**	**N**	**Mean**	**Std.Dev.**	**skewness**	**p5**	**Median**	**p95**
Value	Decade 1	69,182	16.04	159.47	35.36	0.00	0.15	42.16
Volume		69,182	15,355.13	201,989.92	49.37	0.05	30.00	26,336.00
Value	Decade 2	85,274	22.21	191.21	27.23	0.00	0.19	65.09
Volume		85,274	26,890.01	594,645.36	58.02	0.03	31.08	28,578.41

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials.

5. Results

5.1. Growth and Viability

Over the entire period of 1999-2018, the average growth rate for all products was 14.30%, and the standard deviation (or volatility) was 0.40. Figure 4 shows average growth rates in circles (left axis) and their volatility in diamonds (right axis). The average of yearly growth rates (which we call "average growth rates") were higher for CEMs (blue) than for TEMs (light blue) but CEMs were also more volatile. OCs (red) were best positioned than MCs (light red) in both metrics, with a higher average growth rate overall and a lower volatility. Appendix 2 contains the data at the product level.

To compare whether the groups are statistically different from one another, we use the nonparametric equality-of-medians test and the Wilcoxon rank-sum test. We compare growth and volatility in the CEMs versus TEMs, and OCs versus MCs and use two tests for robustness. Using the conventional cut-off p-value of 0.05, we fail to reject the null hypothesis that the groups are the same as one another (Table 11) suggesting that the differences between groups seen in Table 11 may be due to chance.

We also compare the growth and volatility of each group over the two decades of our data. In Figure 5, Decade 2 is differentiated from Decade 1 with a black outline. Like before, circles represent average growth rates and diamonds (in the right axis) represent volatilities. Green represents all products, blues represent Classification 1, and reds represent Classification 2. Solid arrows depict a change over time that was detrimental to exporters, and dashed arrows depict a change over time that was beneficial to exporters. Appendix 3 contains the data behind the figure.

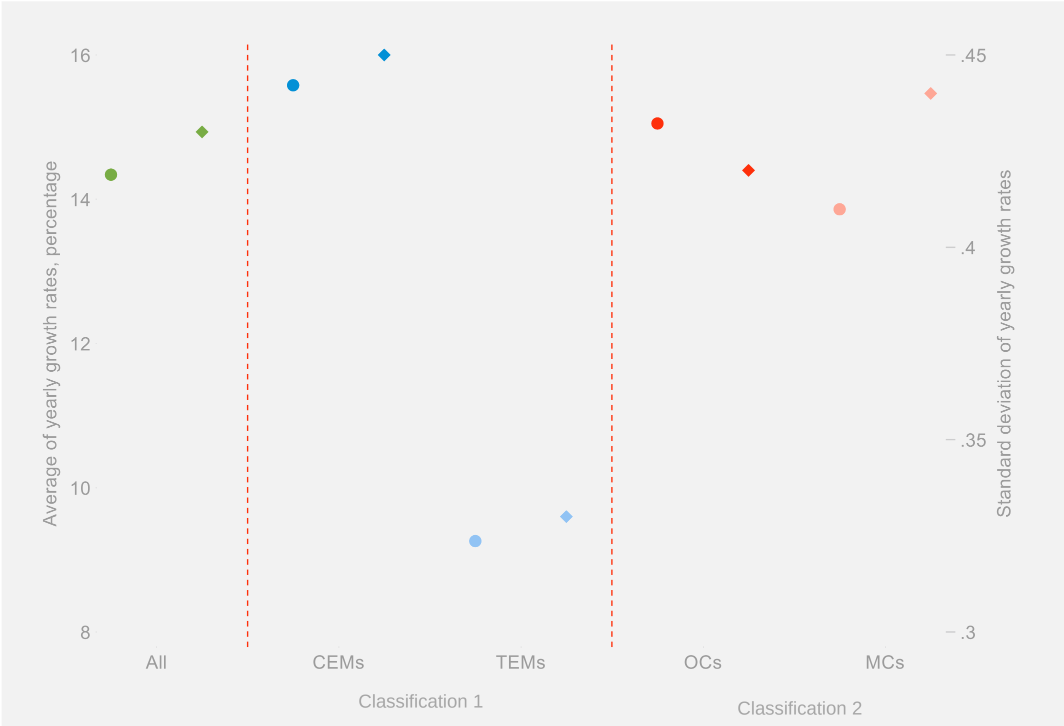

Figure 4. Average of yearly growth rates (circles) and the volatility of yearly growth rates (diamonds, right axis), by product groups. All products (green); CEMs (blue) versus TEMs (light blue); OCs (red) versus MCs (light red).

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals.

Table 11. P-values of nonparametric equality-of-medians test and Wilcoxon rank-sum test/Mann–Whitney two-sample statistic for the difference in growth rates and volatility of growth rates.

Group	Nonparametric equality-of-medians		Wilcoxon rank-sum test/Mann –Whitney two-sample statistic (exact p-value)	
	Growth	Volatility	Growth	Volatility
CEMs versus TEMs	0.539	0.648	0.442	0.210
OCs versus MCs	0.526	0.264	0.386	0.545

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals.

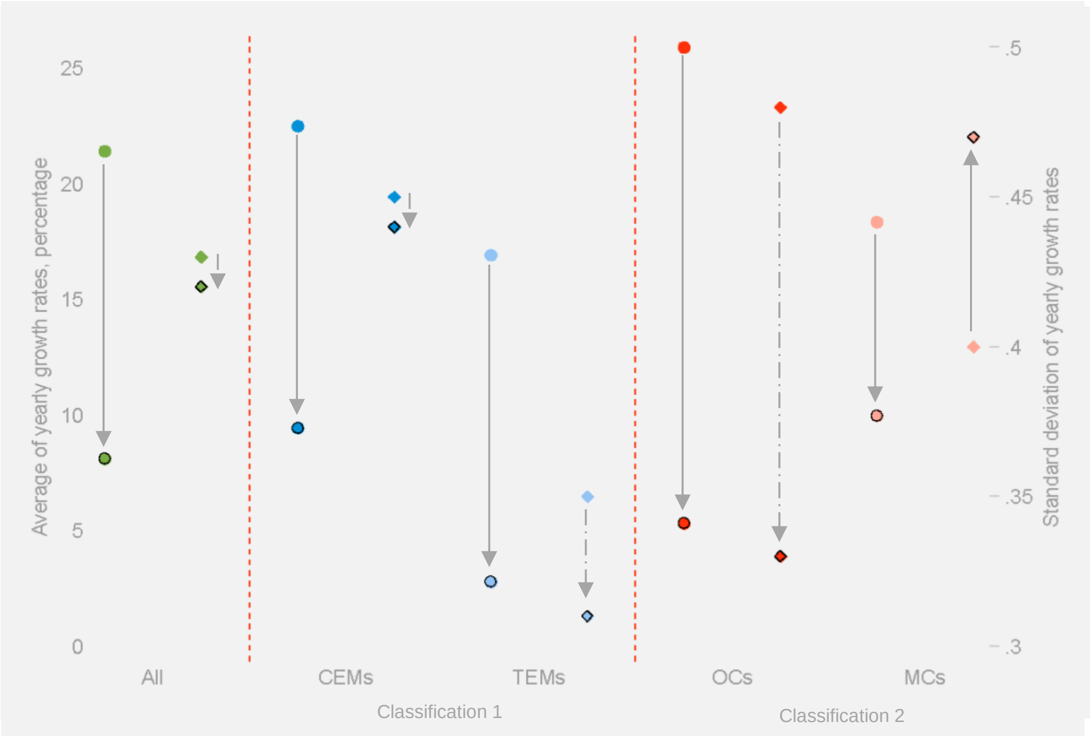

Figure 5. Average of yearly growth rates (circles) and volatility of yearly growth rates (diamonds, right axis), by product group and decade. All products (green); CEMs (blue) versus TEMs (light blue); OCs (red) versus MCs (light red). No outline= Decade 1. Black outline=Decade 2. Solid arrows = change between decades is detrimental to exporters. Dashed arrows = change between decades is beneficial to exporters.

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals.

Within groups, all changes in the average growth changes over decade were detrimental to exporters. We run the same tests as above, which compared the average growth and volatility across groups, by decade. The results of unpaired tests within decades are the same as in Table 11. In other words, the differences in growth rates and volatility across groups are not statistically significantly different from one another in either decade (see Appendix 4).

We subject the detrimental changes over time to statistical analysis by comparing the average growth rates of Decade 1 with the same metric in Decade 2

(Table 12). A Shapiro-Wilk test shows the differences between paired averages by product are normally distributed, so we employ paired t-Tests. These t-Tests show that differences over time are statistically significant in all groups at a p-value of 0.10, and all groups except TEMs at a p-value of 0.05. In other words, in Decade 2 the products experience less growth than Decade 1, and this change is unlikely to be due to chance.

Table 12. Paired t-Tests comparing Decades 1 and 2.

Indicator	Overall	CEMs	TEMs	OCs	MCs
Average of growth rates	0.000	0.000	0.0973	0.000	0.031
SD of growth rates	0.818	0.718	0.257	0.128	0.240

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals.

Admittedly, paired tests (comparing same item over time) are more powerful than unpaired tests (comparing different groups) (StataCorp 2021). Therefore, the difference in the statistical significance of the results of Table 11 and Table 12 could reflect the power of the tests themselves. We attempted to mitigate this by employing two tests for robustness when working with unpaired data.

The result of statistically lower growth in Decade 2 is visually supported in Figure 6, which displays all underlying data points. In Figure 6, CEMs are in green, TEMs are in red. OCs are marked in crosses, and MCs are marked in x's. Figure 6 shows that in Decade 2, no selected products surpass an average growth rate of 30%. It also shows that there is a positive relationship between growth rates and volatility. Therefore, products with high growth and low volatility would be positive anomalies for exporters.

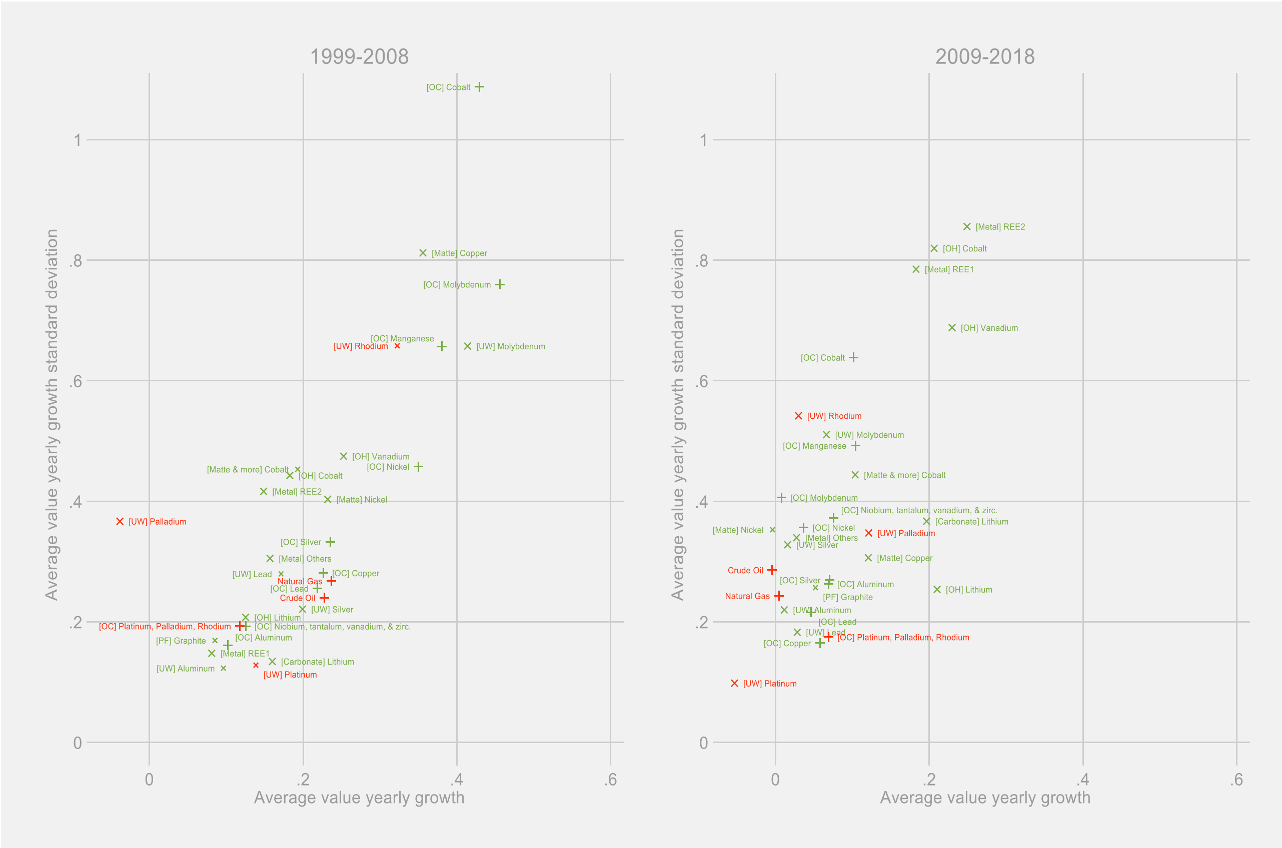

Figure 6. Average yearly growth (x axis), volatility of average yearly growth rates (y axis), Decade 1 (left); Decade 2 (right) Red = TEMs, Green=CEMS; + markers = OCs; X markers=MCs.

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in BACI (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals; OC= Ores and concentrates; PF= powders and flakes; REE1=REE compounds; RE2=REE alloys; UW=Unwrought metal

Table 13 lists the top 20% products in terms of growth and volatility, by decade, which can be visually verified in Figure 6. Note that there is no overlap between the top growers in Decades 1 and 2. All the top growers within Decade 1 lose their position to REE2 [Metal], vanadium [OH], cobalt [OH], lithium [OH], lithium [carbonate] and REE1 [Metal]. This change coincides with the adoption of smartphones (and the materials found in the lithium-ion battery found therein) in developed countries in 2007-08 (Gündüç 2019). Additionally, while in Decade 1, all high-growth products except for nickel [OC] were also highly volatile (Figure 6, left), lithium products stand out as top growers that are not in the top 20% by volatility in Decade 2.

Table 13. Top growth (green check) and top volatility (red X) products, in Decades 1 and 2. Ordered by growth in each decade. CEMs are blue, TEMs are dark blue; OCs are red, MCs are light red.

				Decade 1		Decade 2	
		Classification 1	Classification 2	High growth	High volatility	High growth	High volatility
1	Molybdenum [OC]	CEM	OC	✓	X		
2	Cobalt [OC]	CEM	OC	✓	X		
3	Molybdenum [UW]	CEM	MC	✓	X		
4	Manganese [OC]	CEM	OC	✓	X		
5	Copper [Matte]	CEM	MC	✓	X		
6	Nickel [OC]	CEM	OC	✓			
7	REE2 [Metal]	CEM	MC			✓	X
8	Vanadium [OH]	CEM	MC			✓	X
9	Lithium [OH]	CEM	MC			✓	
10	Cobalt [OH]	CEM	MC			✓	X
11	Lithium [Carbonate]	CEM	MC			✓	
12	REE1 [Metal]	CEM	MC			✓	X
13	Rhodium [UW]	CEM	MC		X		X

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals; UW=Unwrought metals.

Observe also that in Decade 2, TEMs played a smaller role as high-growth products (overall and by decade) than they do in the overall sample (0 versus 20%). OCs played a larger role within high-growth products than within the product sample in Decade 1 (66.67 versus 40%), but this fell to zero in Decade 2. Within high-growth products, CEMs and MCs are the winners of Decade 2.

This result suggests that there has been a measurable change in trends of top growing materials traded over the past decades, and energy decarbonization may play a role. Given the direction of change in energy technologies and the materials used in them, energy decarbonization may reinforce these trends in the coming years. Additionally, if our upcoming exporter analysis supports the literature in that developing countries tend to export more TEMs and OCs, then this first result may help strengthen the rationale for targeted policy consideration to help balance industry towards CEMs and MCs.

5.2. Importer and Exporter Concentration

Figure 7 shows the results of the import and exporter HHI metrics. Area 1, in green, contains the most favourable metrics for exporters because it represents high exporter market concentration and low importer market concentration. Higher numbers indicate worsening conditions for exporters with area 5, in red, being the most unfavourable.

Figure 7 shows that exporter HHI is more spread out than importer HHI, and that importer HHI is relatively more concentrated, opposite to the interests of exporters. In fact, 28 products are either concentrated or highly concentrated by importers, compared to 18 by exporters (see the Methods section for a discussion on the cut-offs for concentration that we chose. Additionally, there are no products in the first-best combination (Area 1) for exporters, and there are products in the worst possible combination for exporters (Area 5).

The products in Area 2 (the second-best section) are palladium [UW], platinum [UW], lithium [carbonate], graphite [PF], and cobalt [OH]. Of these, lithium [carbonate] and cobalt [OH] were within the top 20% growers in Decade 2 of the growth and volatility analysis. Appendix 5 contains the results by groups.

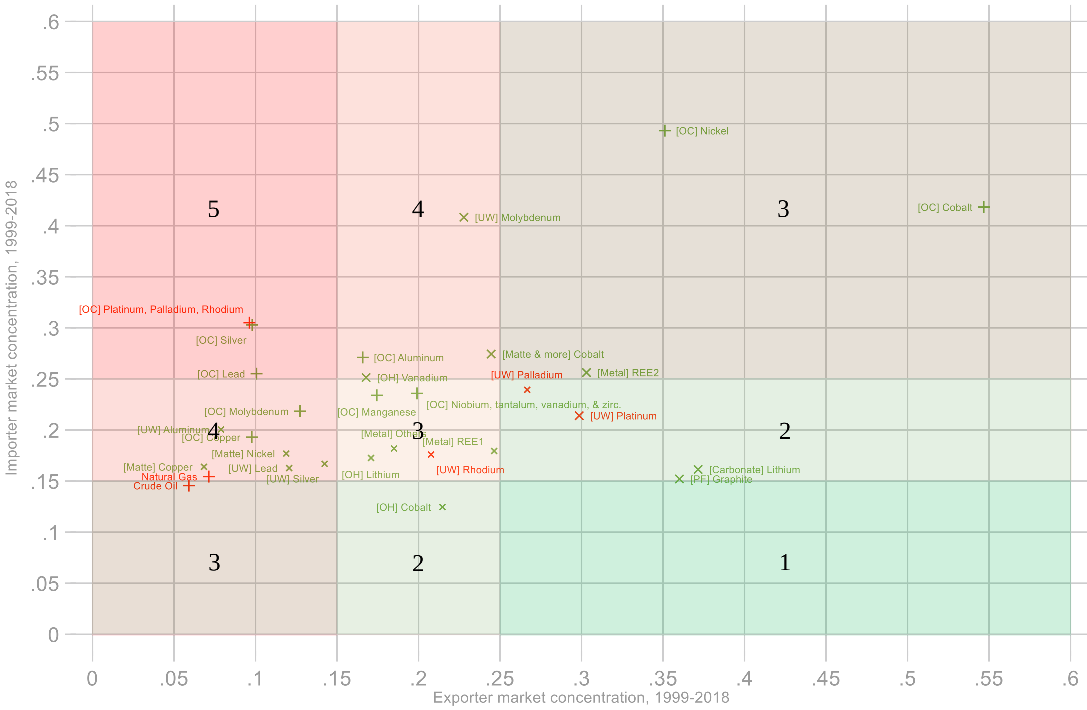

Figure 7. Exporter and importer concentration (HHI), by product, 1999-2018; Red = TEMs, Green=CEMs; + markers = OCs; X markers=MCs.

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals; OC= Ores and concentrates; PF= powders and flakes; REE1=REE compounds; RE2=REE alloys; UW=Unwrought metals.

We turn to a dynamic analysis of changes in the HHI in quantity traded between Decades 1 and 2 in Figure 8. The horizontal axis of Figure 8 shows the change in exporter concentration, Decade 2 minus Decade 1. A positive value on the x-axis means that exporter concentration in the second decade grew in comparison to the first decade. Likewise, the vertical axis shows the change in importer concentration. Hence, a positive value on the y-axis means that importer concentration in the second decade is higher than in the first decade.

Like before, colours help us understand the results. Favourable conditions for exporters are found in Area 1 (green), representing increasing exporter market concentration and decreasing importer market concentration. The opposite is true for products in the top left quadrant (red, Area 3).

The products are disproportionately found to the left of the y-axis (17 versus 13), suggesting an overall decrease in exporter concentration, which is detrimental to exporters. Products are also disproportionately found on the top quadrants (18 versus 12), suggesting an increase in importer concentration, also detrimental to exporters. The top quadrants each share 9 products, more than each of the bottom two quadrants.

In addition to being highly concentrated by exporters, and relatively unconcentrated by importers in the static analysis, the changes in concentration over the last two decades have been beneficial to exporters of lithium [carbonate]. Molybdenum [OC], natural gas, and rhodium [UW] have also benefited from changes in importer and exporter concentration in these decades.

Figure 8. Change in market concentration by exporter (x-axis), importer (y-axis), Decade 2 minus Decade 1. CEMs are in green, TEMs are in red. OC markers are crosses, and MC markers are x's. The colours of quadrants represent the preference for exporters. Green indicates an increase in the export concentration and a decrease in the import concentration. The opposite happens on the red quadrant.

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in BACI (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals; OC= Ores and concentrates; PF= powders and flakes; REE1=REE compounds; RE2=REE alloys; UW=Unwrought metals.

5.3. Major Exporters Over Time and Over Product Groups

To pinpoint major exporters of each product, we rank exporters in descending order by export value during the 20-year period, by product. We then choose the top five, or those that cumulatively make up 90% of all value for the particular product, whichever criterion occurs first. Figure 9 summarizes the top exporters per product, and individual market shares.

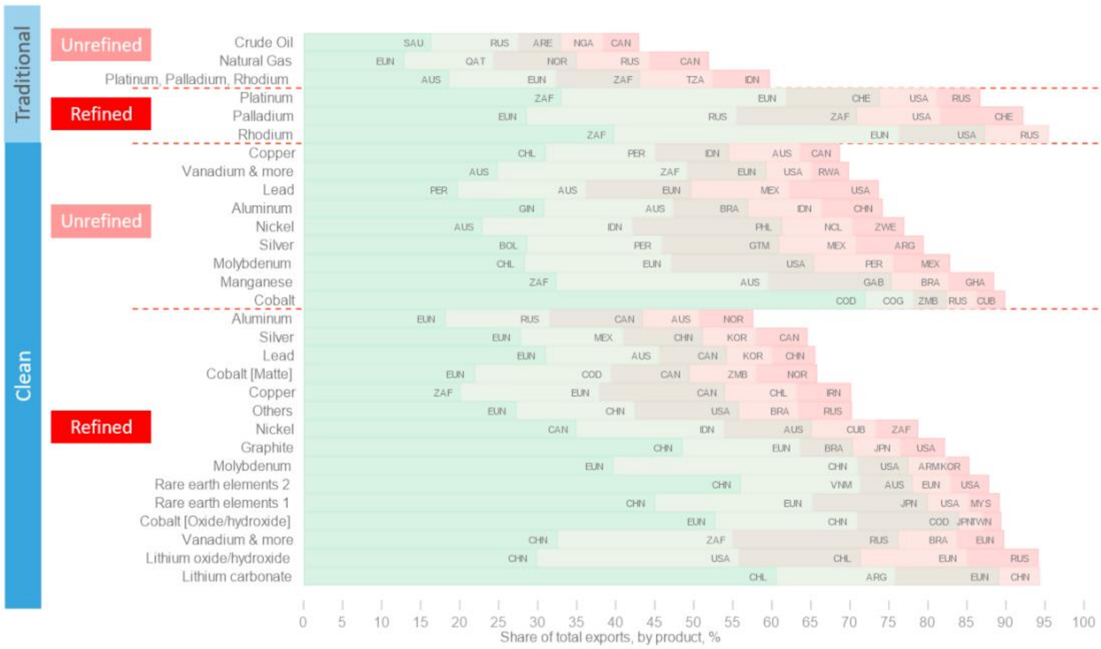

Figure 9. Major exporters by product 1999-2018. Exporters are ordered in descending order of exporter size in the market, left to right. Green = first, light green= second, grey= third, light red= fourth, and red= fifth major exporter.

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: ARE, United Arab Emirates; ARG, Argentina; ARM, Armenia; AUS, Australia; BOL, Bolivia; BRA, Brazil; CAN, Canada; CHE, Switzerland; CHL, Chile; CHN, China; COD, Democratic Republic of the Congo; COG, Republic of the Congo; CUB, Cuba; EUN, European Union; GAB, Gabon; GHA, Ghana; GIN, Guinea; GTM, Guatemala; IDN, Indonesia; IRN, Iran; JPN, Japan; KOR, Korea; MEX, Mexico; MYS, Malaysia; NCL, New Caledonia; NGA, Nigeria; NOR, Norway; PER, Peru; PHL, Philippines; QAT, Qatar; RUS, Russia; RWA, Rwanda; SAU, Saudi Arabia; TWN, Taiwan; TZA, Tanzania; USA, United States; VNM, Vietnam; ZAF, Southern Africa Customs Union; ZMB, Zambia; ZWE, Zimbabwe.

There are 40 major exporters for the 30 selected products. It is worth noting that some developing countries have a big share of exports in several products, for instance, note the Republic of the Congo and the Democratic Republic of the Congo's position in cobalt [OC], Bolivia's position in lead [OC] and silver [OC], or Guinea's position in aluminum [OC]. In all products except crude oil, the top five exporters made up more than 50% of the total world traded value for the product. Although we do not employ it for this purpose in this study, Figure 9 could also be used as an alternative to the HHI as a measure of concentration because it is the equivalent of the Concentration Ratio recommended in Brown (2018) that we discussed in the Literature Review.

Looking at the composition of major exporters by product, we find that developed countries tend to have a lower representation of OCs as part of their exports, as opposed to processed MCs (see Appendix 6 for a visualization of this). This finding is in line with the relatively higher level of industrialization in developed countries and it supports existing literature (Behrens et al. 2007). The one exception is Australia, a global mining hub.

Appendix 6 also shows that major oil and gas exporters that are not in the OECD (Saudi Arabia, Nigeria, United Arab Emirates, and Qatar, as opposed to Canada, Europe, Norway) tend to have less diversification of goods and are 100% made up of TEMs. The only OECD country that is 100% made up of TEMs is Switzerland, which is a major exporter of unwrought palladium and platinum. These are refined products that may also become CEMs over time however, as discussed in the Methods section.

Last, we perform a dynamic analysis of major exporters. The vertical axis of Figure 10 shows the average number of goods for which a country was a major exporter by value during the two decades included in our analysis. We find that most countries are major exporters of fewer than five goods. There are seven countries that export more than five goods, however. These countries are: Australia, Canada, China, the European Union, Russia, the Southern African Customs Union, and the United States. The European Union outperforms all countries.

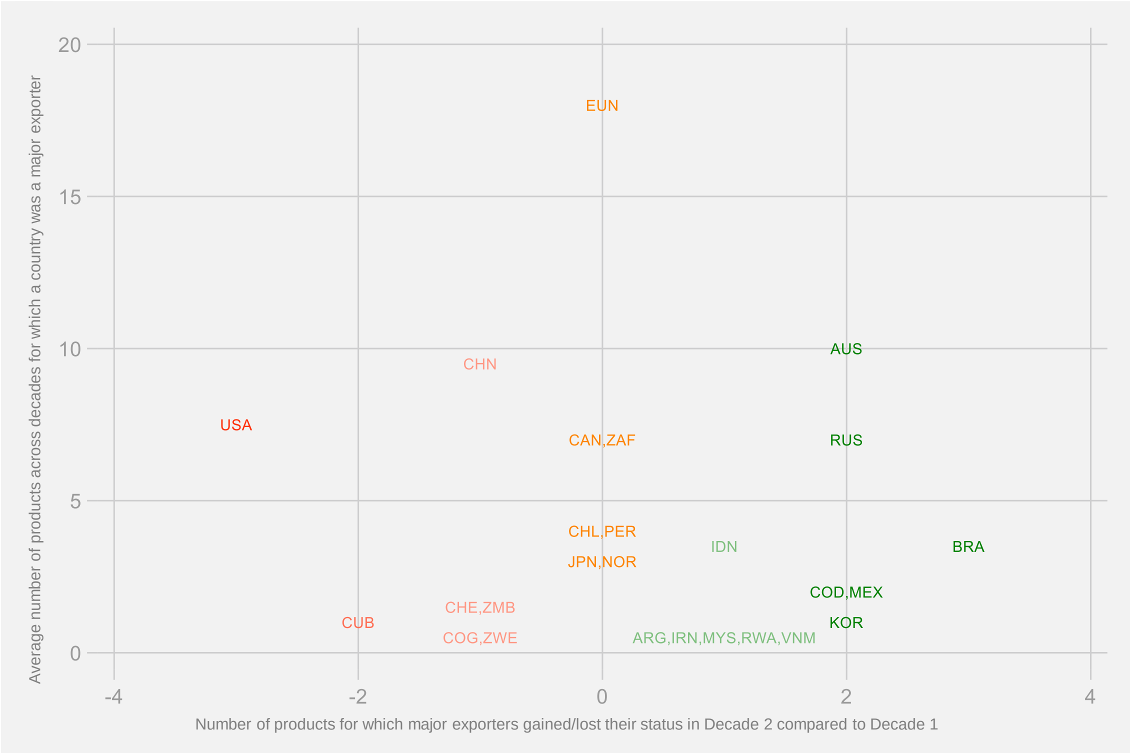

Figure 10. Number of products for which major exporters gained/lost major exporter status, Decade 2 minus Decade 1 (x-axis) and average number of products across decades for which each country was a major exporter (y-axis). Red labels=country lost products; orange=no change; green labels=country gained products.

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: ARE, BOL, GAB, GIN, GTM, NCL, NGA, PHL, QAT, SAU, TZA are missing from the graph because they are major exporters in one product, and have not seen a change in that over the decades. See Figure 9 for country legend.

The horizontal axis of Figure 10 shows the change in the number of products for which the country saw a status change (turning into or stopped been a major exporter) over the decades of interest. Red labels indicate that an exporter lost products; orange indicate no change; green labels indicate that a country gained products over time. Most countries gained or lost their position as a major exporter in at most one good. However, the United States stands out as a top major exporter that lost major exporter status in three goods over the decades of interest. This result may help support the motivation behind the growing criticality literature.

6. Discussion

Energy decarbonization is a crucial objective but it cannot be pursued in isolation from other priorities. It interacts with other areas, including economic competitiveness and development, in which trade plays a central role. The energy transition will bring about a change in trade patterns in the materials that are used in energy but current literature on the materials for energy decarbonization has focused on other issues.

Our study advances the literature by using trade data to interpret changes in the value and volume of traded products and product groups along ETM supply chains across developed and developing countries with a unique exporter perspective. We consider products that are either traditional or clean energy materials (CEMs or TEMs). We also distinguish between unrefined (OCs, ores and concentrates) and refined products (MCs, metals and chemicals). We engage with the following questions: How have the characteristics of growth, volatility, and importer and exporter concentration in trade value and volume evolved for the products in the two decades between 1999-2018? What are the products (and product groups) that exhibit characteristics that are more beneficial to exporters?

We find that changes over time do not benefit the exporters of the selected ETM products. Growth rates were generally lower in Decade 2, and the changes are statistically significant. This is likely to be the result of the deep crisis in commodities during 2014, seen in the Data section. At the same time, the results point to an overall change towards exporter dispersal and importer concentration.

The movements in both metrics are exactly the opposite of what would benefit major exporters. They also seem to be in direct contradiction to the premise and findings of the criticality literature, in which importing countries will suffer from demand jumps and supply bottlenecks in materials for clean energy technologies (Ali et al. 2017). The contradiction may be explained by differences in methods (estimation of historical metrics instead of forecasting), data (trade instead of reserves and production), perspective (exporters instead of importers), and material coverage (narrow [i.e., minerals for clean energy technologies] instead of broad [i.e. refined and unrefined materials for clean and traditional energy technologies]).

Table 14 helps synthesize some of our main results for the purposes of discussion. In the most recent decade, CEMs appear disproportionately represented in the products with higher growth rates (Table 14, column 2). This result is an indication that the transition to decarbonized energy may already be affecting the trade of materials.

Table 14. Notable products that stand out in the static and dynamic analyses.

	High growth, Decade 2[1]	High growth and not high volatility, Dec 2[2]	Favorable concentration[3]	Favorable concentration changes[4]	Technologies	2050 growth %[5]	CEMs/ TEMs	OCs/ MCs
Graphite [PF]			✓		1	494	CEM	MC
Lithium [OH]	✓	✓			1	488	CEM	MC
Lithium [Carbonate]	✓	✓	✓	✓	1	488	CEM	MC
Cobalt [OH]	✓		✓		1	460	CEM	MC
Vanadium [OH]	✓				3	189	CEM	MC
REE1 [Metal]	✓				1	37	CEM	MC
REE2 [Metal]	✓				1	37	CEM	MC
Molybdenum [OC]				✓	8	11	CEM	OC
Palladium [UW]			✓		1		TEM	MC
Platinum [UW]			✓		1		TEM	MC
Rhodium [UW]				✓	1		TEM	MC
Natural gas				✓	1		TEM	OC

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals. [1] Table 13; [2] Table 13; [3] Area 2 in Figure 7; [4] Area 1 in Figure 8; [5] See description in Table 2.

Viewed in conjunction with the analysis of exporters, the result shows that developing country exporters of TEMs must continue to strive towards capturing enriching the opportunities around TEMs, such as services and knowledge, if not export diversification, as discussed in Renner and Wellmer (2019).

The rest of Table 14 summarizes the sub-sample of top-performing "notable" products across the analyses of the Results section. Of the 30 products, lithium [carbonate] exhibits the most beneficial trade patterns, putting its major exporters (Chile, Argentina, the European Union, and China) in a position to benefit the most from current trade trends as energy decarbonization continues.

Making up 10 of the 12 products, MCs are more highly represented in Table 14 than in the overall product sample. MCs are also disproportionately represented in the group of top growth products in Decade 2 (column two). These patterns reinforce the importance of thorough planning for developing countries, which are more likely to be exporters of OCs. We found this result is not borne out in the existing literature, but this may be because, to the best of our knowledge, we are the first to divide ETMs between unrefined and refined products while the existing literature concentrates on minerals, or unrefined materials.

Table 15 further summarizes the results by showing the countries that stand to benefit the most from the trends in these specific notable products. The results are ordered by the number of notable products for which a country is a major exporter.

The European Union is a major exporter of all notable products, although this finding was expected due to the size of the trading bloc and analysis of major exporters. Also expectedly, China and the United States come next. Certainly, it is unreasonable to compare these countries with the other major exporters without considering the sizes of their economies.

Table 15. Major exporter market share rank, by notable product. Count of notable products for which each main exporter is a main exporter, and average rank across notable products. Green = first, light green= second, grey= third, light red= fourth, and red= fifth major exporter.

Major exporter†	Count of notable products‡	Average exporter rank across the notable products	Cobalt [Oxide/hydroxide]	Graphite	Lithium [Carbonate]	Lithium [Oxide/hydroxide]	Rare Earth Elements (1)	Rare Earth Elements (2)	Vanadium & more	Palladium	Platinum	Rhodium	Molybdenum	Natural gas
Classification			C	C	C	C	C	C	C	C	C	C	T	T
			R	R	R	R	R	R	R	U	U	U	R	U
EUN	12	2.4												
USA	8	3.8												
CHN	7	1.6												
RUS	6	3.8												
ZAF	4	1.8												
CHL	3	1.7												
JPN	3	3.7												
BRA	2	3.5												
CHE	2	4.0												
ARG	1	2.0												
VNM	1	2.0												
QAT	1	2.0												
COD	1	3.0												
NOR	1	3.0												
AUS	1	3.0												
PER	1	4.0												
TWN	1	5.0												
MEX	1	5.0												
CAN	1	5.0												
MYS	1	5.0												

Source(s): Author's elaboration and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: †A major exporter is defined as either one of the top five exporters of a particular product, or one of the exporters that accounts for 90% of the total value of the product when in descending order, whichever criterion is met first. ‡The "notable" products sub-sample combines the products within the top 20% of all products in value growth during the most recent decade, those that have had favorable importer and exporter volume concentration during the entire time sample, and those that have had favorable changes in importer and exporter volume concentration when comparing the two decades

ARG, Argentina; AUS, Australia; BRA, Brazil; CAN, Canada; CHE, Switzerland; CHL, Chile; CHN, China; COD, the Democratic Republic of the Congo; EUN, European Union; MEX, Mexico; MYS, Malaysia; NOR, Norway; PER, Peru; QAT, Qatar; RUS, Russia; TWN, Taiwan; TZA, United States; VNM, Vietnam; ZAF, Southern Africa Customs Union.

However, observe two additional points. China holds the highest average market share rank compared to all countries that export any of the notable products (column 3). And, on top of coming second to the European Union, the United States plays a higher role in the notable products than in the overall sample (75% versus 25%). These two points show that these two countries are not only large exporters generally (which is expected) but also that they are relatively well-positioned for changes in ETM trade. To its benefit, the Southern African Customs Union closely follows China in column 3 due to its role in the platinum group metals. This is an exceptional position to be in, as we discussed that those products may shift from TEMs to CEMs.

It behoves developing countries to consider strengthening policy towards CEMs and MCs export capabilities. However, comparable policy advice has proven difficult to materialize in the past (Renner and Wellmer 2019). If the trends found in this study have any bearing on the future, then the chances of success may become even slimmer, especially for TEMs exporters because TEMs have historically been a potential long-term and growing source of state assets that could be used to invest, direct, and develop industrial capabilities.

We consider three limitations to our work, mostly related to the tradeoffs between broad and detailed analyses. First, as mentioned in the Methods section, the level of detail with which we can study ETMs in a wide range of countries over several decades using trade data depends on the product differentiation provided by trade product classifications. This means that there may be products that we cannot isolate as well as other ETM studies (for example, those that differentiate some REE).

Simplifications do not only come from the structure of our primary dataset. As we explained in the Methods, the breadth of the data leads us to create predetermined rules to translate continuous data into discrete data for analysis (e.g., HHI into low, medium, and high concentration products or average product growth into top-performers and the rest). However, while the definitions we created may affect some of the top-performer and notable products that may lie on the margin, they do not affect the overall results of the discussion.

Second, UN Comtrade data provides information on the quantity and value of traded products at the equilibrium between supply and demand, and we do not attempt to identify and isolate demand or supply sources of change. For instance, the high volatility in cobalt [OC] could be related to the fact that it is a by-product of copper (Nassar, Graedel, and Harper 2015).

Third, cross-comparisons of equilibrium value and volume are challenging in absence of a detailed discussion of each market and substitution between ETMs under current technological conditions, which is not possible when covering 30 products over two decades. We discuss future avenues for research that address this in the Conclusion.

7. Conclusion

According to our analysis of historical ETM trade data, we find that CEMs and MCs hold relatively larger promise than TEMs and OCs for exporters as energy decarbonization advances. However, in accordance with existing literature and our own data, these are markets in which developing countries are generally underrepresented. While some developing countries may still benefit from trade trends in individual OC and TEM products, it is imperative to further consider and evaluate policy that strengthens trade capabilities in refined and clean energy materials.

Future research could narrow the scope of analysis of trade patterns in greater granularity. For instance, it could use the same data to analyse and compare countries in specific regions (e.g., Sub-Saharan Africa) and specific technologies (including a detailed consideration of possible substitutions between different ETMs by technology). It could otherwise veer closer towards focused topics in resource economics and macroeconomic policy. In this case, it could engage with considerations on fiscal resources and terms of trade in a given country and ETM market, and be accompanied by a discussion on the extent, direction, and results of existing export, industrialization, and innovation policies.

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APPENDIX 1. Data, Additional Statistics

Table 16. Detailed statistics, value (constant 2018 USD mil) and quantity, 1995-2018, all selected products.

	value, USD mil	quantity, metric tons		value, USD mil	quantity, metric tons
N	213,240	213,240	iqr	4	1,184
Mean	120	284,646	1st Perc.	0	0
Std. Dev.	1,460	4,251,106	p5	0	0
range	129,345	838,800,000	p10	0	0
min	0	0	p25	0	1
max	129,345	838,800,000	Median	0	34
variance	2,131,649	18,070,000,000,000	p75	4	1,185
cv	12	15	p90	56	44,161
skewness	35	82	p95	213	278,607
kurtosis	1,854	13,321	p99	2,336	4,899,092

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Table 17. Summary trade statistics v (value, in constant 2018 USD million) and q (quantity), 1995-2018, by product.

Product	HS		Mean	SD	Median
Graphite [powders/flakes]	2504	v	0.762	4.79	0.026
		q	1372.44	10353.161	22.5
Manganese [ore/concentrate]	2602	v	10.2	61.057	0.148
		q	68943.35	467951.87	458.239
Copper [ore/concentrate]	2603	v	102.353	411.604	1.331
		q	56853.04	220256.85	1301.478
Nickel [ore/concentrate]	2604	v	19.053	86.964	0.085
		q	276674.25	2443238.3	56.777
Cobalt [ore/concentrate]	2605	v	6.888	46.291	0.1
		q	3115.311	19142.672	28.344
Aluminum [ores/concentrates]	2606	v	8.412	54.619	0.15
		q	206533.78	1614446.8	320.212
Lead [ore/concentrate]	2607	v	20.293	65.348	0.36
		q	14374.702	41253.776	537.157
Molybdenum [ore/concentrate]	2613	v	23.766	106.335	0.731
		q	1489.077	4980.633	83.96
Niobium tantalum vanadium zirconium [ore/concentrate]	2615	v	3.11	14.199	0.196
		q	3043.089	17675.03	84.15
Silver [ore/concentrate]	261610	v	15.018	45.82	0.436
		q	2716.031	11222.395	20.336
PGM [ore/concentrate]	261690	v	13.112	47.324	0.149

Product	HS		Mean	SD	Median
		q	3448.922	16752.099	3.447
Crude oil	2709	v	1220.069	5038.755	72.284
		q	2841234.2	10754529	173312
Natural gas	2711	v	188.431	1540.974	0.783
		q	630825.72	8985540	1269.115
Earth-metals, rare and scandium and yttrium, whether or not intermixed or interalloyed	280530	v	1.95	15.937	0.037
		q	145.595	1436.489	1.741
Cobalt chemical [oxide/hydroxide]	2822	v	2.752	20.069	0.062
		q	152.763	1299.757	3.555
Lithium chemicals [oxide/hydroxide]	282520	v	0.911	6.087	0.05
		q	124.042	669.026	7.75
Vanadium chemical [oxide/hydroxide]	282530	v	2.778	12.357	0.083
		q	257.26	909.721	8
Lithium chemicals [carbonate]	283691	v	2.018	12.389	0.028
		q	339.758	1601.662	4.635
Compounds, inorganic or organic, of rare-earth metals, of yttrium or of scandium, or of mixtures of these metals [unwrought, powder, waste/scrap]	2846	v	2.87	20.185	0.036
		q	259	1556.228	2.688
Silver [unwrought]	710691	v	28.005	177.77	0.274
		q	147.813	3772.52	0.77
Platinum [unwrought, powder, semi-manufactured]	711011	v	28.535	127.973	0.366
		q	2.499	46.908	0.029
Palladium [unwrought, powder, semi-manufactured]	711021	v	20.507	91.247	0.268
		q	3.844	72.106	0.036
Rhodium [unwrought, powder, semi-manufactured]	711031	v	15.094	68.022	0.236
		q	0.696	4.583	0.023
Copper [matte]	7401	v	3.577	18.382	0.052
		q	1351.567	5159.475	23.637
Nickel [matte]	7501	v	37.321	163.291	0.089
		q	4028.672	14754.092	13.187
Aluminum [unwrought]	7601	v	37.392	296.009	0.576
		q	18514.265	134500.4	267.8
Lead [unwrought]	7801	v	6.645	55.221	0.312
		q	4025.006	28643.756	200.584
Molybdenum [unwrought]	810291	v	1.826	8.874	0.067
		q	71.298	323.231	3.51
Cobalt mattes and other intermediate products of cobalt metallurgy [unwrought, powders, waste/scrap]	8105	v	5.953	46.975	0.114
		q	314.716	4412.124	3.425
Beryllium, chromium, germanium, vanadium, gallium, hafnium, indium, niobium (columbium), rhenium and thallium [metals]	8112	v	2.8	14.6	0.053
		q	209.873	2106.129	2.821

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

APPENDIX 2. Growth and Volatility Results, by Product

Table 18. Average yearly growth and average yearly growth standard deviation, 1999-2018, Decade 1, and Decade 2.

HS code	Product	Avg growth			Avg growth standard deviation			TEMs (1)	OCs (1)
		1999-2018	Decade 1	Decade 2	1999-2018	Decade 1	Decade 2	CEMs (0)	MC (0)
2709	Crude Oil	10.55	22.76	-0.44	0.28	0.24	0.29	1	1
2711	Natural Gas	11.43	23.66	0.42	0.28	0.27	0.24	1	1
283691	[Carbonate] Lithium	17.92	15.99	19.65	0.28	0.13	0.37	0	0
8105	[Matte & more] Cobalt	14.58	19.28	10.35	0.44	0.45	0.44	0	0
7401	[Matte] Copper	23.21	35.59	12.07	0.60	0.81	0.31	0	0
7501	[Matte] Nickel	10.78	23.19	-0.40	0.39	0.40	0.35	0	0
2846	[Metal compounds/mixtures] REE	13.75	8.10	18.27	0.58	0.15	0.79	0	0
280530	[Metals, incl intermixed/alloyed] REE	20.14	14.85	24.91	0.67	0.42	0.86	0	0
8112	[Metals, incl. waste/scrap] Others	8.86	15.69	2.72	0.32	0.31	0.34	0	0
2606	[Ore/concentrate] Aluminum	8.44	10.18	6.88	0.22	0.16	0.26	0	1
2605	[Ore/concentrate] Cobalt	25.69	42.93	10.17	0.87	1.09	0.64	0	1
2603	[Ore/concentrate] Copper	13.75	22.64	5.75	0.24	0.28	0.16	0	1
2607	[Ore/concentrate] Lead	12.78	21.87	4.59	0.25	0.26	0.22	0	1
2602	[Ore/concentrate] Manganese	23.49	38.06	10.38	0.58	0.66	0.49	0	1
2613	[Ore/concentrate] Molybdenum	22.02	45.62	0.78	0.63	0.76	0.41	0	1
2604	[Ore/concentrate] Nickel	18.50	34.99	3.67	0.43	0.46	0.36	0	1
2615	[Ore/concentrate] Niobium, tantalum, vanadium, & zirc.	9.91	12.54	7.55	0.29	0.19	0.37	0	1
261690	[Ore/concentrate] Platinum, Palladium, Rhodium	9.22	11.79	6.90	0.18	0.19	0.17	0	1
261610	[Ore/concentrate] Silver	14.82	23.51	7.00	0.30	0.33	0.27	0	1
2822	[Oxide/hydroxide] Cobalt	19.51	18.26	20.63	0.65	0.44	0.82	0	0
282520	[Oxide/hydroxide] Lithium	16.99	12.51	21.02	0.23	0.21	0.25	0	0
282530	[Oxide/hydroxide] Vanadium	24.05	25.25	22.97	0.58	0.47	0.69	0	0
2504	[Powders/flakes] Graphite	6.76	8.52	5.18	0.21	0.17	0.26	0	0
7601	[Unwrought] Aluminum	5.15	9.62	1.13	0.18	0.12	0.22	0	0
7801	[Unwrought] Lead	9.59	17.12	2.82	0.24	0.28	0.18	0	0

HS code	Product	Avg growth			Avg growth standard deviation			TEMs (1)	OCs (1)
		1999-2018	Decade 1	Decade 2	1999-2018	Decade 1	Decade 2	CEMs (0)	MC (0)
810291	[Unwrought] Molybdenum	23.09	41.40	6.61	0.60	0.66	0.51	0	0
711021	[Unwrought] Palladium	5.02	-3.85	12.12	0.35	0.37	0.35	1	0
711011	[Unwrought] Platinum	3.18	13.85	-5.34	0.15	0.13	0.10	1	0
711031	[Unwrought] Rhodium	15.99	32.24	2.98	0.60	0.66	0.54	1	0
710691	[Unwrought] Silver	9.72	19.91	1.56	0.29	0.22	0.33	0	0
	Mean	14.30	21.27	8.10	0.40	0.38	0.39		

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: REE= Rare earth elements; TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals.

APPENDIX 3. Growth/Volatility, Additional Visualization

In Figure 11, products are plotted along a horizontal axis representing average growth rates, and the vertical axis representing volatility. CEMs are in green, TEMs are in red. OCs are marked in crosses, and MCs are marked in x's.

Those in the top 20% by growth overall are: cobalt [OC], vanadium [OH], manganese [OC], copper [matte], molybdenum [UW] and molybdenum [OC]. Half of these, vanadium [OH], manganese [OC], and molybdenum [UW] were not among the top 20% by volatility.

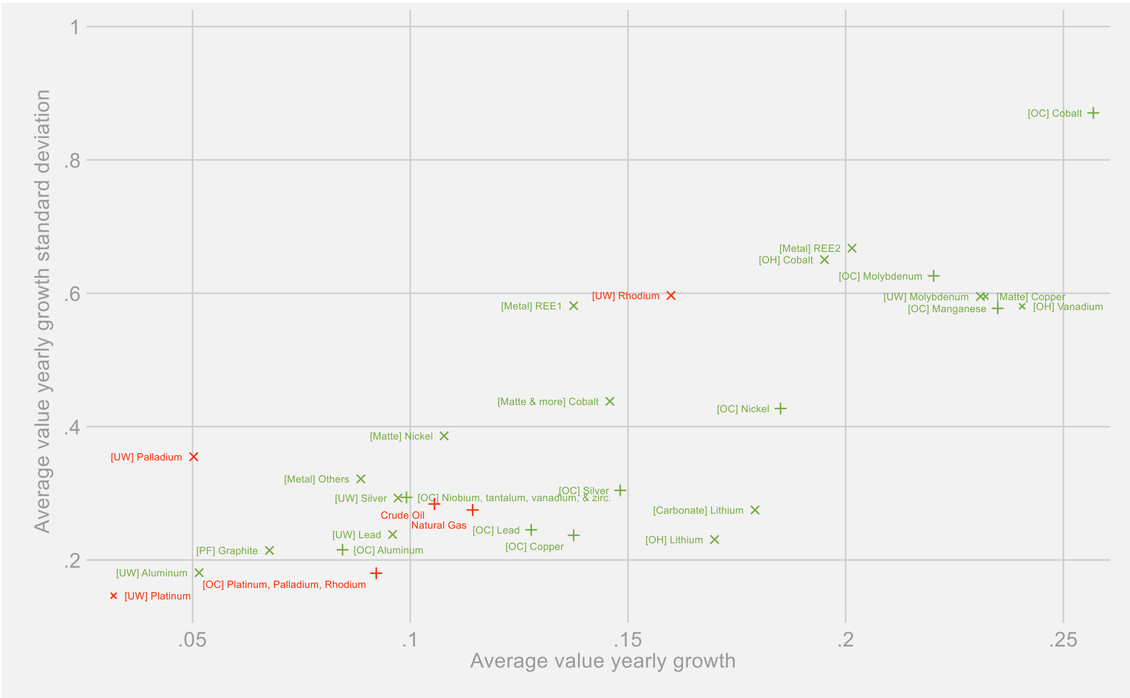

Figure 11. Average yearly growth (x axis), average yearly growth standard deviation (y axis), 1999-2018; Red = TEMs, Green=CEMs; + markers = OCs; X markers=MCs.
Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).
Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals; OC= Ores and concentrates; PF= powders and flakes; REE1=REE compounds; RE2=REE alloys; UW=Unwrought metals.

APPENDIX 4. Growth and Volatility, Additional Statistics and Tests

Table 19. Average growth rates and volatility by groups, 1999-2018.

	Average of growth rates	Volatility
All	14.34	0.43
TEMs	9.26	0.33
CEMs	15.58	0.45
OCs	15.05	0.42
MCs	13.86	0.44

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals.

Table 20. Average growth rates and volatility by groups and decade.

	Average of yearly growth rates			SD of yearly growth rates		
	Decade 1	Decade 2	Dec2-Dec1	Decade 1	Decade 2	Dec2-Dec1
All	21.4	8.1	-13.31	0.43	0.42	-0.01
TEMs	16.9	2.78	-14.12	0.35	0.31	-0.04
CEMs	22.48	9.43	-13.05	0.45	0.44	-0.01
Difference	-5.58	-6.65		-0.1	-0.14	-
OCs	25.88	5.31	-20.57	0.48	0.33	-0.14
MCs	18.33	9.96	-8.37	0.4	0.47	0.07
Difference	7.55	-4.65	-	0.08	-0.13	-

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals.

Table 21. Differences in growth rates and volatility of growth rates, P-values of nonparametric equality-of-medians test and Wilcoxon rank-sum test/ Mann –Whitney two-sample statistic.

		Nonparametric equality-of-medians		Wilcoxon rank-sum test/ Mann –Whitney two-sample statistic (exact p-value)	
		Decade 1	Decade 2	Decade 1	Decade 2
Growth	CEMs versus TEMs	0.976	0.665	0.818	0.563
	OCs versus MCs	0.240	0.906	0.203	0.964
Volatility	CEMs versus TEMs	0.648	0.648	0.494	0.143
	OCs versus MCs	0.709	0.709	0.755	0.249

Source(s): Author’s elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals.

APPENDIX 5. Importer and Exporter Concentration, Group Comparisons

Figure 12 shows the percentages of products within each group that are in each area of Figure 7. The colours of the stacks in the bars are the same as the colours in the areas of Figure 7.

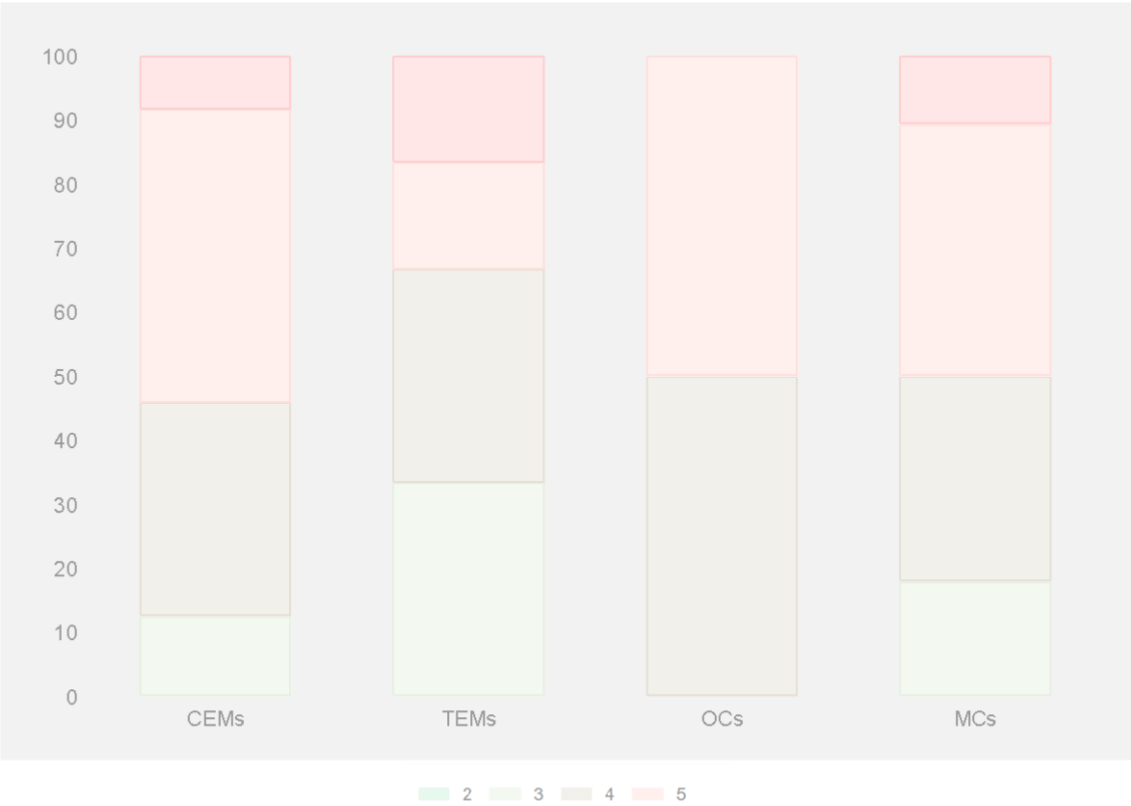

Figure 12. Export and import concentration by CEMs and TEMs and OCs versus MCs, using the same Area colours as Figure 7.

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals.

The results are nuanced. Observe that TEMs have more than double the percentage of products than CEMs in Area 2 (the second-best overall). However, as can be seen in Figure 7, this pattern is likely led by the platinum group metals (which may become CEMs over time, see the Methods section). Additionally, CEMs have a smaller fraction of materials in Area 5. Relatedly, neither OCs nor MCs are better positioned. MCs have a wider range of exporter and importer HHI combinations, whereas OCs are evenly split between the extremes.

We also discuss the products by Classifications 1 and 2 based on Figure 7, 30% of CEMs are in Area 3, which is opposite to the interests of major exporters. Yet no TEMs are found here. Instead, 33% of TEMs are in Area 1 (the first-best option), compared to about 7% of CEMs. We alternatively cut the data by Classification 2. OCs are less likely to lie in Area 3 (25% versus 33.33%), and they are more represented in Area 1 (17% versus 11%).

APPENDIX 6. Exporter Analysis, Additional Visualizations

Figure 13 summarizes the percentage of a country's products that belong to each product group within the 30 products selected in the Methods section of this study. As discussed in the text, CEMs versus TEMs and OCs versus MCs make up different proportions of exporters' product portfolios, and generally run along developed/developing country lines.

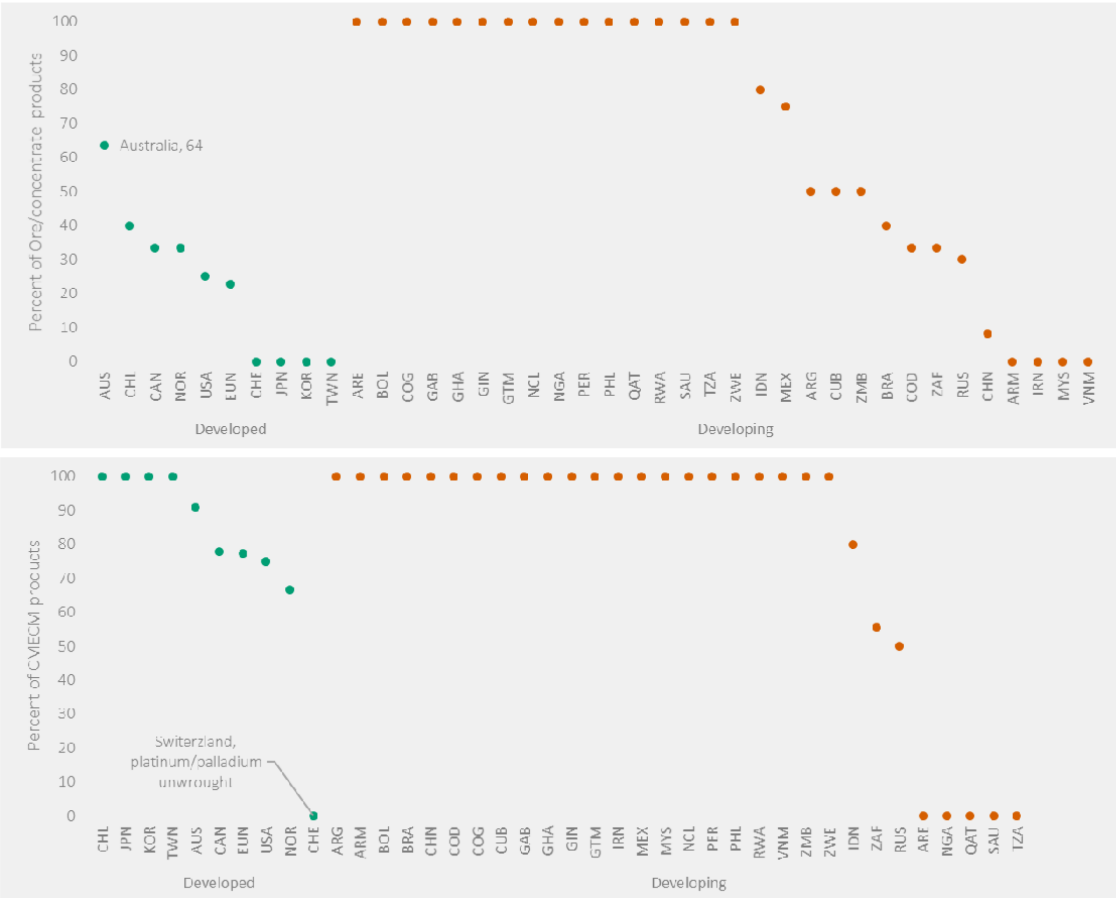

Figure 13. Percentage of a country's export made up of OCs versus MCs (top) and TEMs versus CEMs (bottom), by developing (orange) or developed countries (green).

Source(s): Author's elaboration based on the methods described in this study and UN Comtrade version HS92; cleaned by CEPII published in the BACI database (2020).

Note: TEMs=traditional energy materials; CEMs=clean energy materials; OCs=ores and concentrates; MCs=metals and chemicals.