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Green Energy Depends on Critical Minerals. Who Controls the Supply Chains?

Finance Working Paper N° 846/2022
January 2023

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ECGI Working Paper Series in Finance

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Abstract

In light of the transition away from fossil fuel–based energy, this paper highlights the importance of understanding who controls vital parts of the global supply chains of critical minerals and rare earth elements (REEs). Analysis of direct ownership does not reveal the real sources of control over the decisions of the company. To identify those sources, the authors use an index that measures the degree to which important shareholders can affect voting decisions. This analysis is not straightforward, because companies along the supply chain are not necessarily incorporated in the countries in which mining and production activities take place, and shareholders can exert influence through multiple layers of subsidiaries. The analysis reveals that China's control over the global value chains involving critical minerals and REEs extends beyond what is commonly assumed. It also sheds light on environmental, social, and governance issues in the countries in which mining and/or production take place. The paper advocates increasing transparency regarding the sources of control to better assess and manage economic and geopolitical risks; enhancing recycling, to reduce dependency on foreign supply; avoiding protectionist and trade-reducing reactions; and encouraging research and development in order to speed up the adoption of technologies of substitution.

Keywords: Ownership, voting power, corporate social responsibility, ESG, supply chain, recycling, rare earth elements, critical minerals, geopolitics
JEL Classifications: G3, L1, L7, Q3, Q5

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PETERSON INSTITUTE FOR INTERNATIONAL ECONOMICS

WORKING PAPER

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August 2022

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In light of the transition away from fossil fuel–based energy, this paper highlights the importance of understanding who controls vital parts of the global supply chains of critical minerals and rare earth elements (REEs). Analysis of direct ownership does not reveal the real sources of control over the decisions of the company. To identify those sources, we use an index that measures the degree to which important shareholders can affect voting decisions. This analysis is not straightforward, because companies along the supply chain are not necessarily incorporated in the countries in which mining and production activities take place, and shareholders can exert influence through multiple layers of subsidiaries. Our analysis reveals that China's control over the global value chains involving critical minerals and REEs extends beyond what is commonly assumed. It also sheds light on environmental, social, and governance issues in the countries in which mining and/or production take place. The paper advocates increasing transparency regarding the sources of control to better assess and manage economic and geopolitical risks; enhancing recycling, to reduce dependency on foreign supply; avoiding protectionist and trade-reducing reactions; and encouraging research and development in order to speed up the adoption of technologies of substitution.

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I INTRODUCTION

With the accelerating transition away from fossil fuels, awareness of the role of minerals critical to the production of clean energy (including cobalt, copper, lithium, nickel, and rare earth elements [REEs]) has increased. There is a sharper focus on rising prices and production and delivery delays as well as on the vulnerability of their supply chains.[1] The Russian invasion of Ukraine has intensified these concerns.

The International Energy Agency (IEA) has identified several factors that will increase the risks to the stability and reliability of these supply chains:

- *Geographical concentration:* Production and processing operations are concentrated in a small number of countries, including some with unstable political and social environments. For example, most of the increase in lithium and nickel output is expected to come from today's major producers, implying a higher concentration in the years to come, even though many countries are actively searching for deposits.
- *Degradation of resource quality:* In recent years, ore quality has continued to decline. This deterioration could increase both the cost of extraction and the level of pollution.
- *Climate risks:* Environmental degradation of production sites may hamper production. For example, more than half of lithium production is concentrated in areas with high water stress levels.
- *Environmental, social, and governance issues:* Concerns about environmental sustainability and good governance will tighten constraints on investments in and production of critical minerals, raising the cost of capital and production costs.
- *Derived demand for new infrastructure:* The rising demand for electric vehicles will put pressure on electricity grids, increasing demand for electricity infrastructure.

The concentration of production in one or a few countries makes the supply chains relying on those minerals vulnerable not only to market power and logistical risks but also to geopolitically induced disruptions, especially through trade restrictions.

Risks related to the geographic distribution of production are of special concern. The concentration of production in one or a few countries makes the supply chains relying on those minerals vulnerable not only to market power and logistical risks but also to geopolitically induced disruptions, especially through trade restrictions.

These risks become clear when comparing the supply chains of carbon-based energy and clean energy. As figure 1 (IEA 2021a) shows, for oil and gas, the United States dominates the supply chain (upstream, refining, and consumption). In contrast, the United States is only a minor player in the supply chains of clean technologies, in which China is the dominant actor.

There is also concern that reserves of critical minerals outside the European Union and the United States are owned largely by governments. Those governments, especially China, could interfere in the operations of private firms located in their countries (Gorodnichenko and Roland 2017). In contrast,

1 See Boer, Pescatori, and Stuermer (2021); IEA (2021a, 2021b); White House (2021); Wilson Center (2022); and World Bank (2020), among many others.

the controlling shares held by US-based companies belong to passive funds (investment funds that only follow a certain market index); the US government has no direct control over their operations unless it invokes legislation such as the Defense Production Act of 1950.[2]

The issue of government control has garnered increased attention since the Russian invasion of Ukraine.[3] Some countries are also taking new steps to protect their critical minerals against foreign control. In April, for example, Mexico announced plans to nationalize its lithium mines to limit Chinese or US influence.[4]

A major worry is governance issues (such as the opacity of beneficial ownerships) in both countries where critical minerals are produced and countries in which companies with interests or influence over mining activities are registered. These issues, especially lack of transparency, facilitate strategic behavior or market manipulation by firms. Governance structures and practices could entail substantial risks of corruption, which affect all stages of the value chains of extractive industries (OECD 2016).

Who ultimately controls the production of minerals and the governance context in which they operate are of critical importance. Production of a mineral could be widely dispersed globally, but a particular entity (a holding company or a few competing companies located in a country where authorities have the power to force a coalition if it suits their geopolitical interest) may have ultimate control (including through subsidiaries) over the decisions of the top firms producing that mineral, even if they are in different countries. That entity would then have a high degree of control, including market power, over the global production of that mineral and the supply chains that use it. More generally, there is a risk associated with imperfect information about entities that control a (mining) process, including their ultimate objectives, the geopolitical tendencies of the country in which they are located, and the length of time they intend to hold the controlling shares.

Assessing the fragility or vulnerability of supply chains requires identifying the parties that have a substantial degree of control over the producers of critical minerals. To do so, we use a game-theoretic concept that makes it possible to rigorously measure control. Although the concept dates to Banzhaf (1965, 1968), its application to the case of complex shareholding structures has been made possible only recently by advances in computer power and corporate finance. Using this approach, we reveal the extent of control by entities from China, Europe, and the United States, among others, over the supply chains of critical minerals and REEs, as distinct from the control that is associated with the location of the producing firms.

Assessing the fragility or vulnerability of supply chains requires identifying the parties that have a substantial degree of control over the producers of critical minerals.

2 Although the United States also has some reserves, unlike most other countries, it does not own subsoil resources. In addition, mining these minerals often faces stiff opposition from local populations. See https://insideclimatenews.org/news/07112021/lithium-mining-thacker-pass-nevada-electric-vehicles-climate/.

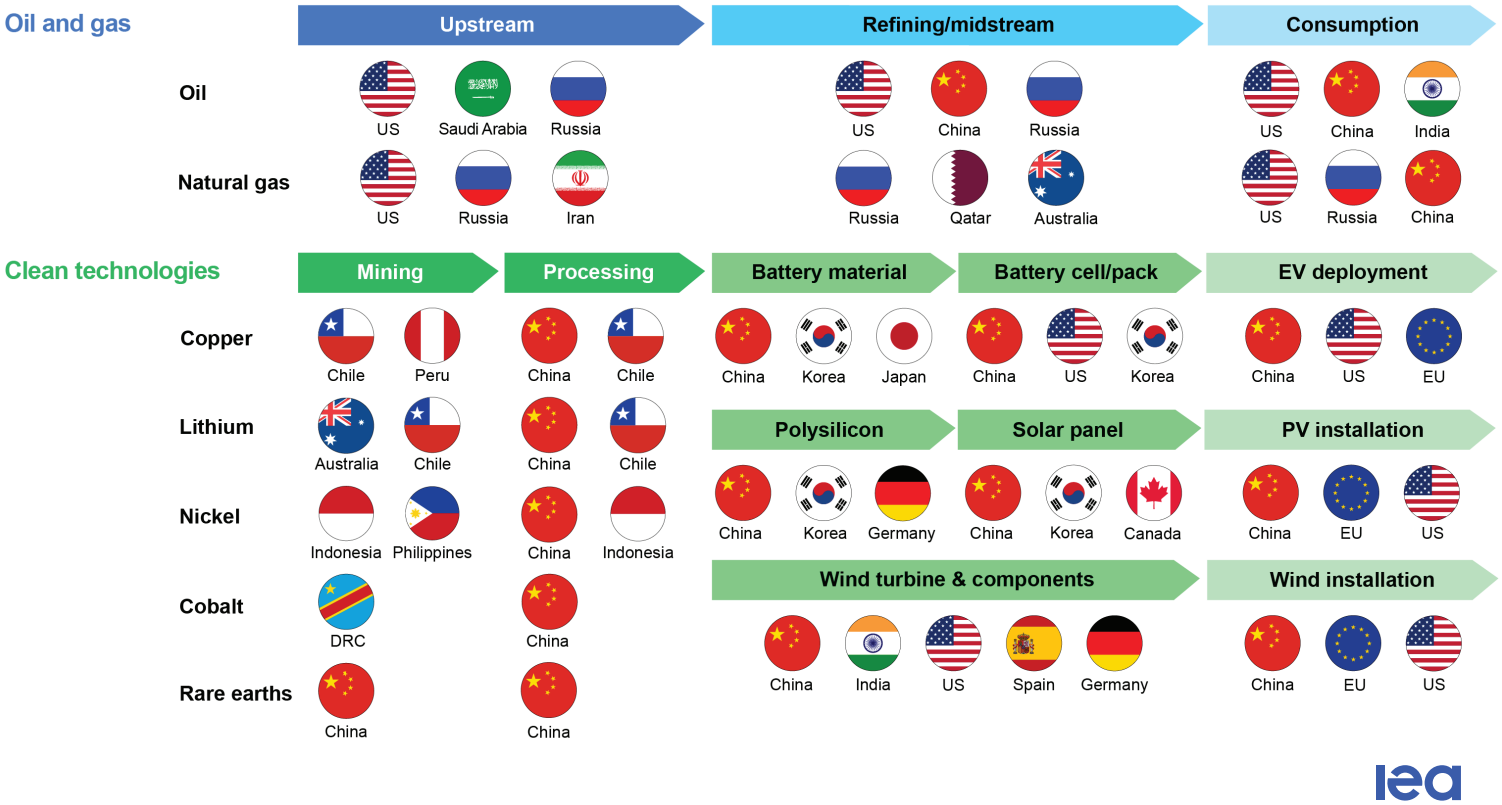
3 See the 2021 review of supply chain issues by the US government (White House 2021). For a general discussion of challenges natural resource economies pose to US foreign policy, see Hendrix and Noland (2014).

4 See https://www.reuters.com/article/us-mexico-lithium-idUSKCN2MB12Z d1sss2&utm_source=selligent&utm_medium=email&utm_campaign=&utm_content=&utm_term=_220419-LLBeco-fthy_&M_BT=5243729005739.

Figure 1

The transition to a clean energy system brings new energy trade patterns, countries, and geopolitical considerations into play

Indicative supply chains of oil and gas and selected clean energy technologies



DRC = Democratic Republic of the Congo; EV = electric vehicle; PV = photovoltaic system

Note: Largest producers and consumers are noted in each case to provide an indication, rather than a complete account.

Source: International Energy Agency, The Role of Critical Minerals in Clean Energy Transition, 2021, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions. All rights reserved.

We also examine the implications of control on environmental, social, and governance (ESG) issues, using ESG data obtained from Refinitiv, one of the world's largest providers of financial markets data and infrastructure. We find that firms have very different ESG results depending not only on their location but also on the type of agents that control them and how concerned they are by ESG issues. For example, entities controlling mines in different countries can practice greenwashing by transferring polluting activities to countries in which environmental standards are lower. We focus our analysis on the formal sector, although we are aware that a sizable share of world mineral production comes from the informal sector (Delve 2021).

Our approach sheds light on several policy issues, including the need to increase transparency in shareholding structures and to identify their sources of control when devising policy measures to reduce the fragility of global value chains for critical minerals. These measures could increase the fragmentation of the global economy and protectionism, however, and slow the energy transition, if countries erect trade barriers, indulge in very costly industrial policies or focus too much on friend-shoring, and put at risk global trade and economic welfare. We hope that by making clearer the vulnerabilities in the supply chains of critical minerals, the approach used in this paper will facilitate targeted policy interventions and that such interventions will be implemented in ways that obviate the need for blanket protectionist measures.

The rest of the paper is organized as follows. Section II explains our framework for analyzing and measuring control over a firm. Section III reports on the application of the framework to four key minerals, cobalt, copper, lithium, and nickel. Section IV considers REEs separately because the data necessary for a full analysis are not available. Section V examines ESG issues and their relevance for better understanding the vulnerabilities of different types of critical mineral–producing firms. Section VI discusses some policy implications, including for competition and industrial policies. Section VII offers some concluding remarks.

We find that firms have very different ESG results depending not only on their location but also on the type of agents that control them and how concerned they are by ESG issues.

II FRAMEWORK FOR CAPTURING AND MEASURING CONTROLS

To identify the parties that control the companies involved in mining critical inputs, we need a rigorous and practical measure of the level of control by shareholders (direct or indirect through subsidiaries) over an entity. The concept we use is closely related to that of ultimate beneficial owners (UBOs), but UBOs do not provide all the relevant information for assessing control over a company, for two main reasons.

First, UBOs are defined by complex legal rules that differ across countries. Efforts by the international community to develop a UBO identification toolkit to help countries implement the method that best suits their legal and policy frameworks have shown their limits (OECD 2019a). Moreover, they will not lead to a global convergence toward an international standard that would be acceptable to all, or even most, countries (OECD 2019b). In addition, some legal persons who control complex groups of companies continue to fly under the radar, because the web of shareholding links that allows them to do so makes it difficult to identify them.

Second, control—whether exercised through direct or indirect stakes in a firm—is not a simple, linear (as implicitly assumed in the legal definitions of

UBOs), or even continuous function of the percentage of shares held. It depends, in a highly nonlinear fashion, on the global distribution of shareholdings, including the magnitude of the free float.[5] The level of control jumps from partial to total when a new purchase allows a shareholder to cross the majority threshold of 50 percent of ownership (e.g., move from 49.9 to 50.1 percent). But a high level of control can also be achieved with a percentage of shares (owned directly or indirectly through various subsidiaries) that is much below 50.1 percent—the case of most owners of Google (Alphabet), Apple, Facebook (Meta), Amazon, and Microsoft.[6]

To measure control, we first define the concept of sources of control (SOC). The methodology is founded on a well-established game-theoretic approach initially proposed by Penrose (1946), Shapley and Shubik (1954), and Banzhaf (1965, 1968) and closely related to the Shapley value (Shapley and Shubik 1969). It measures the ability of a direct or indirect shareholder to change the outcome of a vote by forming potential voting coalitions with other shareholders. It allows for the computation of a single index measuring the level of control that the shareholder could exercise over a company.[7]

The approach has been generalized to more complex situations and the framework enhanced to handle large datasets. It discriminates between financial links that are associated only with portfolio investments and those that can translate into significant control. It also addresses the top weaknesses of the indices traditionally used by researchers to measure concentration (such as the Herfindahl indices, which sum squared proportions of shares held by shareholders). Those weaknesses include the (incorrect but widely held) notion that diluting the capital of a company necessarily reduces the level of control held by the top shareholder.

The index of control that we use takes account of the presence of free float and associates it with an increased level of control by the largest minority (yet significant) shareholders.[8] The methodology also applies to multilayer shareholding patterns or cycles of ownership (Crama and Leruth 2007). For this analysis, we used the approach based on work done at the Haute Ecole de Commerce (HEC) of the University of Liège and data on shareholdings. It has been applied to financial markets (Crama, Leruth, Renneboog, and Urbain 2003; Crama and Leruth 2007, 2013). The data are processed using software made available by ZENO-Indices (a fintech spin-off of HEC Liège).[9] Appendix A

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5 *Float* refers to shares that can be publicly traded because they are not subject to restrictions.

6 To see this, consider the following part of an ownership cascade: company A, owned with 50.1 percent of the shares by company B, in turn owned with 50.1 percent of the shares by company C. Clearly, C directly controls A, as there is an uninterrupted control chain, but C has only 25 percent of the cash flow rights in company A.

7 While recognizing the virtues of the Banzhaf approach and having supported it, Supreme Court Justice John Marshall Harland regretted later that "[the Court] would become enmeshed in the haze of slogans and numerology which for 10 years has obscured its vision in the field" (Suzuki 2015). Applying the Banzhaf approach to corporate governance sheds light on rather than obscures the issue.

8 The founders of big US tech companies are very much aware of this. Several managed to retain a substantial control over their company while their percentage of ownership was diluted.

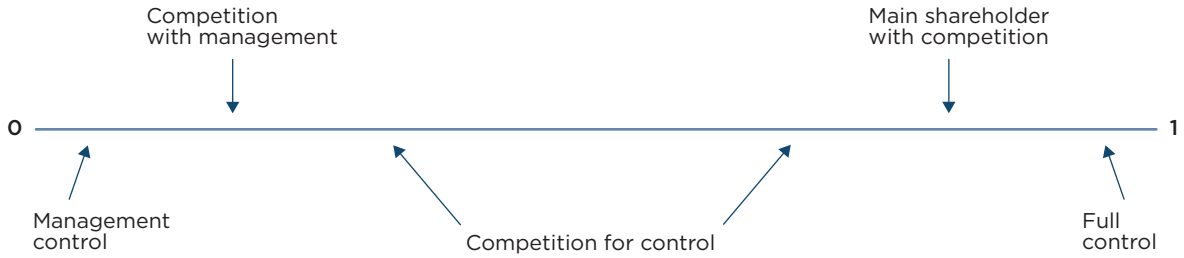
9 See www.ZENO-Indices.com. The software processed proprietary data on shareholdings made available to us by Refinitiv. The software used to identify the SOCs and measure their control on a target is still under development; ZENO-Indices does not yet offer a license for the use of its product.

briefly describes how the index is calculated and why traditional indices of control are not suitable.[10]

The ZENO Index measures the potential level of control that the top shareholders of a company can exercise through indirect shareholding, direct shareholding, or both. It ranges from 0 to 1, with 1 indicating full control (figure 2).[11] More specifically:

- If a ZENO Index (Z1) is equal to 1, the target is fully controlled by one top shareholder (called SOC1), which usually hires the management. There is no other SOC.
- If the highest ZENO Index is strictly below 1 but close to it (say, $0.7 < Z1 < 1$), one SOC (SOC1) has considerable influence, even when it owns substantially less than 50 percent of the shares, which is the case when there is a large float or many dispersed shareholders. The company could (but need not) have one or two additional top shareholders with low ZENO Indices (SOC2 with a small Z2).[12]
- If the highest ZENO Index Z1 lies between, say, 0.3 and 0.7, SOC1 faces competition for control from other SOCs (SOC2 and perhaps even SOC3), with $Z3 \leq Z2 \leq Z1$).
- If the highest ZENO Index falls below, say, 0.3 ($Z1<0.3$), management retains most of the control and becomes SOC1. The company is considered independent of external influence.

Figure 2
ZENO Indices and control level over firms



The ZENO Index identifies the SOCs based on a quantitative measure, whereas UBOs are defined based on legal texts. The two measures often share common elements, however, especially when there is little doubt as to who controls the company (when, for example, $Z1 > 0.8$). There are usually more UBOs than SOCs. A UBO that is also a SOC is a UBO with a significant level of control Z. A SOC that is not a UBO is a shareholder who has a significant level of control Z (e.g.,

10 Appendix A also discusses why control is not a simple function of the percentage of shares held and why the measure we propose is superior to the measures traditionally used that belong to the Herfindahl family.

11 The ZENO Indices of all top shareholders need not sum to 1.

12 In a case like this, SOC1 can occasionally lose a vote if SOC2 mobilizes a large set of small shareholders to form an anti-SOC1 coalition, a difficult task if Z2 is much smaller than Z1.

through subsidiaries), despite having a share stake that is below the legal reporting threshold for UBOs (e.g., 5 percent) or not meeting some other legal criteria.[13]

To summarize, the ZENO measures the level of control that all SOCs of a company can potentially exercise and ranks them, based on their corporate influence. The SOCs do not necessarily use that influence but could do so. To simplify the calculations, we limit the number of SOCs to two, such that $Z2 \leq Z1$, and consider the second SOC only when $Z2 > 0.2$.[14]

III APPLICATION TO FOUR KEY MINERALS

We use a three-step process to analyze four critical minerals. First, we look at the location of production (the first step in the value chain) and determine its share in global reserves of the mineral. Second, we identify the top companies producing that mineral and their shares of global production. Third, we identify who controls these companies by examining their SOCs.

The two largest players in cobalt are no longer the Democratic Republic of the Congo and Russia but the Glasenberg family (from South Africa) and China.

Cobalt

The Democratic Republic of the Congo is by far the largest producer of cobalt, followed by Russia in distant second place (table 1). Some countries have large cobalt reserves but have not yet commenced production (or production is not significant).[15] Indonesia, for example, has about 8 percent of global reserves but does not produce significant quantities of cobalt.

A different picture emerges when looking at where the firms operating cobalt mines are incorporated (table 2). The top producers are incorporated in the United Kingdom/Switzerland and China. Although 69 percent of cobalt production originates in the Democratic Republic of the Congo, firms incorporated there exploit only 3.5 percent of global output.

Who controls the companies listed in table 2? Chinese SOCs control two firms—China Molybdenum and Metorex—whose SOCs control 13.8 percent (10.8 percent + 3.0 percent) of the market (table 3). This share is larger than the share of output produced by the only firm incorporated in China (10.8 percent). About 57.9 percent of output is produced by firms that are active and known (100 percent – 42.1 percent) (little information is available about the "other" companies, making it more difficult to implement policies in them). Chinese SOCs thus control about 24 percent of the known and active market (13.8 percent/57.9 percent). The two largest players in cobalt are no longer the Democratic Republic of the Congo and Russia but the Glasenberg family (from South Africa) and China. Europe has no presence (Eurasian, although incorporated in the United Kingdom, is controlled by the government of Kazakhstan).

13 This complexity has led the Financial Action Task Force to adopt a risk-based approach to the identification of UBOs that was earlier suggested by Crama, Hubner, Leruth, and Renneboog (2021) in the context of the G20/T20 on the basis of ZENO Indices See G20–ZENO and www.fatf-gafi.org/publications/fatfrecommendations/documents/r24-statement-march-2022.html.

14 The computation of ZENO Indices requires shareholding data on the percent of voting shares. The index can be more sophisticated and integrate different types of voting rights; the nature of the top shareholders (e.g., investment funds, corporations, families, and individuals); collinearity between voting patterns; etc. The first cut, however, can be done with just shareholding data, which are available from any large data provider, including Bloomberg, Moody's, Refinitiv, and others. Refinitiv agreed to let us use its proprietary data.

15 For all minerals, proven reserves correspond to the economically mineable part of a measured mineral resource. For details on the definitions of mineral resources, mineral reserves, and mining studies, see CIM (2014).

Table 1
Top cobalt-producing countries, 2020

Country	Percent of global production	Percent of global proven reserves
Democratic Republic of the Congo	69.0	46.1
Russia	6.3	3.3
Australia	4.0	18.4
Cuba	2.7	6.6
Canada	2.6	2.9
New Caledonia (France)	1.2	n.a.
Other	14.2	—

— = Not reported by our sources

n.a. = Precise estimates are not available, but the top mine in New Caledonia (Goro, exploited by Vale) is estimated to hold 122.3 Mt of proven and probable reserves grading 1.42 percent nickel and 0.11 percent cobalt (see https://www.nsenergybusiness.com/projects/goro-nickel-cobalt-mine/).

Source: US Geological Survey 2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-cobalt.pdf. For New Caledonia, see https://www.nsenergybusiness.com/projects/goro-nickel-cobalt-mine. Data on New Caledonia are for 2019.

Table 2
Country of incorporation of top cobalt-producing companies, 2020

Company	Country	Percent of global production
Glencore	United Kingdom/Switzerland	19.3
Eurasian Natural Resources	United Kingdom	11.6
China Molybdenum	China	10.8
Norilsk Nickel (recently renamed Nornickel)	Russia	4.4
Gécamines	Democratic Republic of the Congo	3.5
Metorex	South Africa	3.0
Moa Nickel	Cuba	2.4
Prony Resources	New Caledonia (France)	1.5
Vale	Canada	1.4
Other		42.1

Source: Company annual reports.

Table 3
Sources of control (SOCs) of top cobalt-producing firms, 2021

Company	SOC1	Z1	SOC2	Z2
Glencore	Glasenberg family (South Africa)	0.4	Qatar Holding	0.3
Eurasian Natural Resources	Eurasian Res (government of Kazakhstan)[a]	1.0		
China Molybdenum	Cathay Fortune (China)	0.5	Luoyang Mining (China)	0.5
Norilsk Nickel[b]	Interros Ltd. (Russia)	0.7	Aktivium (Netherlands)[b]	0.3
Gécamines[c]	Democratic Republic of the Congo (government)	1.0		
Metorex[d]	Jinchuan Gr (China)	1.0		
Moa Nickel[e]	Cuba	0.5	Sherritt (Canada)	0.5
Prony Resources[f]	Prony (government of New Caledonia)	1.0		
Vale	Previ (Brazil)[g]	0.4	BlackRock	0.3

a. Eurasian Res is based in Luxembourg but controlled by the Kazakhstan government, https://www.eurasianresources.lu/en/pages/group-at-a-glance/group-at-a-glance. It is involved in extracting ore left by previous mining activity.

b. Not listed. Although its SOC2 (Aktivium) is based in the Netherlands, some of its shares are owned by Russian interests, and Refinitiv reports the Russian group MKPAO as the "ultimate parent."

c. Not listed; was a Belgian company that was nationalized.

d. Recently fully merged with Jinchuan of China.

e. Not listed; data source is http://www.rblrei-france.com/en/realisation/154-moa-nickel-1.

f. Not listed but controlled by the New Caledonia government.

g. Caixa de Previdência dos Funcionários do Banco do Brasil (pension fund for Banco do Brasil employees).

Source: Compiled by ZENO-Indices using Refinitiv data on shareholdings (except for unlisted firms, for which the sources were annual reports or other sources).

Copper

Chile is the world's top producer of copper, followed by Peru and China (table 4). However, UK companies are collectively the largest producers, followed by firms incorporated in Chile, the United States, and Mexico; China is in fifth spot (table 5). There is increasing worry about the availability of the supply of copper in the coming years (S&P 2022).

Who controls the top copper-producing firms? Unlike the market for cobalt, the copper market is not concentrated, possibly because copper is a well-established industry in which the top actors have long been involved in the sector. Production is geographically distributed. Even when firms such as Codelco of Chile and Southern Copper of Mexico have high ZENO scores (indicating important SOCs), SOCs control only a small share of global production (table 6). Nevertheless, by controlling several mining firms (Metorex, Zijin, Rio Tinto, First Quantum, and Jiangxi), China controls the largest share of copper production (11.2 percent) but by a small margin.

Table 4
Top copper-producing countries, 2020

Country	Percent of global production	Percent of global reserves
Chile	27.8	22.7
Peru	10.4	8.8
China	8.3	3.0
Democratic Republic of the Congo	7.8	3.5
United States	5.8	5.5
Australia	4.3	10.6
Zambia	4.1	2.4
Russia	3.9	7.0
Mexico	3.6	6.0
Indonesia	2.5	2.7
Poland	1.9	3.5
Other	19.5	24.3

Source: US Geological Survey 2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-copper.pdf.

Table 5
Country of incorporation of top copper-producing companies, 2020

Company	Country	Percent of global production
BHP Group	United Kingdom	8.4
Codelco	Chile	8.4
Freeport McMoRan	United States	7.0
Glencore	United Kingdom/Switzerland	6.1
Southern Copper	Mexico	4.9
First Quantum	Canada	3.8
Antofagasta	United Kingdom	3.6
KGHM	Poland	3.4
Anglo American	United Kingdom	3.1
Zijin Mining Group	China	2.8[a]
Rio Tinto	United Kingdom	2.6
Jiangxi Copper	China	1.7
Metorex	South Africa	0.3[b]

a. Figure is for 2021.

b. Figure includes Metorex's activities in the Kinsenda mine (located in the Democratic Republic of the Congo). It is estimated based on production of three mines (Chibuluma, Ruashi, and Kinsenda).

Sources: Company annual reports.

Table 6
Sources of control (SOCs) of top copper-producing companies, 2020

Company	SOC1	Z1	SOC2	Z2
Codelco[a]	Chile	1.0		
Freeport McMoRan	Fidelity Management & Research	0.3	Vanguard	0.3
BHP Group	Management	—[b]		
Glencore	Glasenberg family (South Africa)	0.4	Qatar Holding	0.3
Antofagasta	E Abaroa Foundation[c]	1.0		
Metorex	Jinchuan Gr	1.0		
Anglo American	BlackRock	0.4	PIC SOC[d]	0.3
Southern Copper	Grupo Mexico	1.0		
Zijin Mining Group	China	1.0		
Rio Tinto	Aluminum China	0.6	BlackRock	0.3
First Quantum	Jiangxi	0.7	Capital Group	0.3
Jiangxi Copper	Jiangxi	1.0		
KGHM	Poland	1.0		

a. Not listed. Shares held by Chile (100 percent).
b. No SOC emerges with an index higher than 0.3.
c. Foundation of the Abaroa family based in Liechtenstein.
d. Public Investment Corporation wholly owned by the South African government.
Source: Compiled by ZENO-Indices, using Refinitiv data on shareholdings.

Lithium

Australia produces more than half of the world's lithium, followed by Chile and China (table 7). This order is reversed when it comes to reserves, but there is an active effort by many countries to locate lithium reserves on their territory, and the numbers are likely to change substantially in the future.[16]

Unlike cobalt mines, lithium mines are incorporated where they are located (table 8). Should the lithium reserves in the Democratic Republic of the Congo prove economically viable, this would no longer be the case, as no mines incorporated there have the resources to exploit the resource.

16 For example, AVZ Minerals (an Australian company) has discovered large lithium reserves in the region of Manono in the Democratic Republic of the Congo (DRC), prompting a statement by the DRC authorities that it may hold some of the largest lithium reserves in the world (see https://www.africanews.com/2022/02/25/drc-lithium-exploitation-may-replace-tin-in-the-city-of-manono/).

Who controls these mines? Chinese SOCs control Talison and Ganfeng. Sociedad Química y Minera (SQM) is controlled by the Pampa Group. Albemarle's and Livent's top SOCs are passive investment funds incorporated in the United States. Allkem's two SOCs (at Z1 = Z2 = 0.2) have little control over the entity (table 9). Chinese SOCs thus control 33.1 percent (20.5 + 12.6) of the total market and about 50 percent (33.1/[100 – 33.0]) of the production of large firms. There are no SOCs based in Europe; the United States has a significant presence, but the channel of its influence is through large passive funds. Allkem, with two SOCs that have little influence on the company, is controlled by its management.

Table 7
Top lithium-producing countries, 2020

Country	Percent of global production	Percent of global reserves
Australia	54.2	25.9
Chile	16.3	41.8
China	12.6	6.8
Argentina	7.3	10.0
Other[a]	9.6	15.5

a. About 58 percent of the world's lithium reserves are in Bolivia, Argentina, and Chile (in that order), but only Chile has transformed its resources into economically viable production (see https://www.csis.org/analysis/south-americas-lithium-triangle-opportunities-biden-administration).

Sources: Data on production are from IEA (https://www.iea.org/data-and-statistics/charts/committed-mine-production-and-primary-demand-for-lithium-2020-2030), government of Australia (https://publications.industry.gov.au/publications/resourcesandenergyquarterlydecember2020/documents/Resources-and-Energy-Quarterly-Dec-2020-Lithium.pdf), and company annual reports. Data on reserves are from https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-lithium.pdf.

Table 8
Country of incorporation of top lithium-producing companies, 2020

Company	Country	Percent of global market
Talison Lithium	Australia	20.5
Sociedad Química y Minera (SQM)	Chile	16.3
Ganfeng Lithium	China	12.6
Albemarle	United States	10.3
Livent	United States	4.5
Allkem	Australia	2.8
Other		33.0

Source: Company annual reports.

Table 9
Sources of control (SOCs) of top lithium-producing companies, 2020

Company	SOC1	Z1	SOC2	Z2
Talison Lithium	Chengdu Tianqi	1		
Sociedad Química y Minera (SQM)	Pampa Group[a]	1		
Ganfeng Lithium	Li Liang Bin	0.8	Wang Xiao	0.2
Albemarle	Vanguard	0.5	BlackRock	0.2
Livent	BlackRock	0.6	Vanguard	0.4
Allkem	Management			

a. The Pampa Group corresponds to three shareholders that together own the majority of the shares in SQM. The Tianqi company (China) recently purchased a 24 percent stake in SQM. The ZENO Index was calculated under the assumption that the Pampa Group continues to vote as one. See https://www.reuters.com/article/chile-tianqi-lithium-idUSL2N1WP0GN.

Source: Compiled by ZENO-Indices, using Refinitiv data on shareholdings.

Nickel

Indonesia is the world's leading producer of nickel, with the Philippines and Russia a distant second and third (table 10). Indonesia also has a large share of the world's proven nickel reserves. That could change, however, as the search for more reserves is underway, especially in Africa.[17]

The country of incorporation of mining companies exploiting nickel is more dispersed than the country of production, except in the Philippines, where a Filipino mining company exploits nickel (table 11). Indonesia's nickel is extracted by foreign companies.

Who controls these mines? Vale, Norilsk, and Glencore are controlled by a mix of investment funds and industrial SOCs (table 12). BHP is run by its management (the top SOC is an investment fund with a low ZENO-Index) and the top SOC of Anglo American is a passive investment fund. The two other companies are controlled by SOCs in China or by the Indonesian government.

Like copper, nickel is an old and well-established industry in which the major players are well identified and have a long history. The emergence of China is still limited, but the presence of investment funds presents the risk that China could easily acquire controlling shares.

17 See, for example, the Kabulwanyele Nickel Project (KNP) in Tanzania by the Resource Mining Corporation Limited (https://resmin.com.au/projects/massive-nickel-projects-tanzania/).

Table 10
Top nickel-producing countries, 2020

Country	Percent of global production	Percent of global reserves
Indonesia	39.4	22.1
Philippines	12.5	5.1
Russia	8.9	7.9
New Caledonia	7.5	See note below table 1
Australia	5.8	22.1
Canada	5.5	2.1
China	3.9	2.9
Brazil	2.7	16.8
Guatemala	2.1	—[a]
Other	11.8	—

— = Not included in our sources.

a. Guatemala may hold some of the largest nickel reserves in the world, but mining there has faced stiff opposition from the indigenous community. See https://www.centralamericadata.com/en/search?q1=content_en_le:%22nickel+mines%22&q2=mattersInCountry_es_le:%22Guatemala%22.

Source: US Geological Survey 2022 (https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-nickel.pdf) for reserves and Refinitiv for production.

Table 11
Country of incorporation of top nickel-producing companies, 2020

Company	Country	Percent of global production
Vale	Brazil	6.7
Norilsk Nickel	Russia	6.4
Jinchuan[a]	China	5.6
Nickel Asia Corp.	Philippines	5.4
Glencore	United Kingdom/Switzerland	4.4
Aneka Tambang Tbk	Indonesia	3.0
BHP Group	United Kingdom	2.3
Anglo American	United Kingdom	1.9
Other		64.3

a. Detailed data on the production of nickel by China are not available, but NSEnergy lists the Jinchuan Group as the world's third-largest producer of nickel (https://www.nsenergybusiness.com/features/top-nickel-producing-companies/). The Tsingshan Group is also active in China and Indonesia and may plan to expand its activities to lithium (https://www.reuters.com/article/indonesia-nickel-huayou-eve-energy-idCNL3N2NB11O and https://www.reuters.com/markets/commodities/after-shaking-up-nickel-chinas-tsingshan-sets-sights-lithium-2021-11-26/).

Source: Refinitiv data for all companies except Jinchuan, where the ratio is based on data discussed in footnote a in this table.

Table 12
Sources of control (SOCs) of top nickel-producing companies, 2020

Company	SOC1	Z1	SOC2	Z2
Vale	Previ (Brazil)	0.4	BlackRock	0.3
Norilsk Nickel	Interros Ltd. (Russia)	0.7	Aktivium (Netherlands)	0.3
Nickel Asia Corp.	Sumitomo (Japan)	0.5	Mantra Resources	0.5
Jinchuan	China	1.0		
Glencore	Glasenberg family (South Africa)	0.4	Qatar Holding	0.3
Aneka Tambang Tbk	Indonesia	1.0		
BHP Group	Management			
Anglo American	BlackRock	0.4	PIC SOC	0.3

Source: Compiled by ZENO-Indices, using Refinitiv data on shareholdings.

IV THE CASE OF RARE EARTH ELEMENTS

REEs are widely used in high-tech production, from medical devices to military defense systems.[18] As they are indispensable in the transition to clean energy, global demand is expected to increase. Pressure on the supply chain can already be felt in various sectors.

Unlike other minerals discussed above, China has considerable control over both the reserves and the production of key REEs (e.g., neodymium and dysprosium). The three countries with the largest reserves (China, Vietnam, and Russia) hold 70 percent of global reserves (figure 3). China also controls much of the rest of the chain (as shown in figure 1).

China sometimes partners in new projects launched in other countries.[19] The situation in the market for REEs is therefore different from that in the market for other critical minerals, where China is not a main source of reserves but hosts the SOCs of the mines that exploit them. From a strategic point of view, a key consideration is China's position in global value chains. A country could host a mine site or a company interested in processing goods that require REEs, but it would still need to either import REEs from China or depend on China for some part of the process down the chain. In 2020, Mountain Pass (a US-based company that claims to be the largest producer in the West) acknowledged that it produces an REE concentrate that it sells to Shenghe Resources (Singapore) International Trading Pte. Ltd., an affiliate of Shenghe Resources Holding Co. Ltd., a leading global REE company that is publicly listed in China.[20] Myanmar, which also holds some REE reserves, is reported to sell all of its production to China.[21] Chinese operators took advantage of the opportunity to be first movers, which has implications for policy issues, as discussed below.

Unlike other minerals discussed above, China has considerable control over both the reserves and the production of key REEs.

18 The most important REE is perhaps neodymium, because of its magnetic properties and its use in wind turbines, mobile phones, and electrical vehicles.

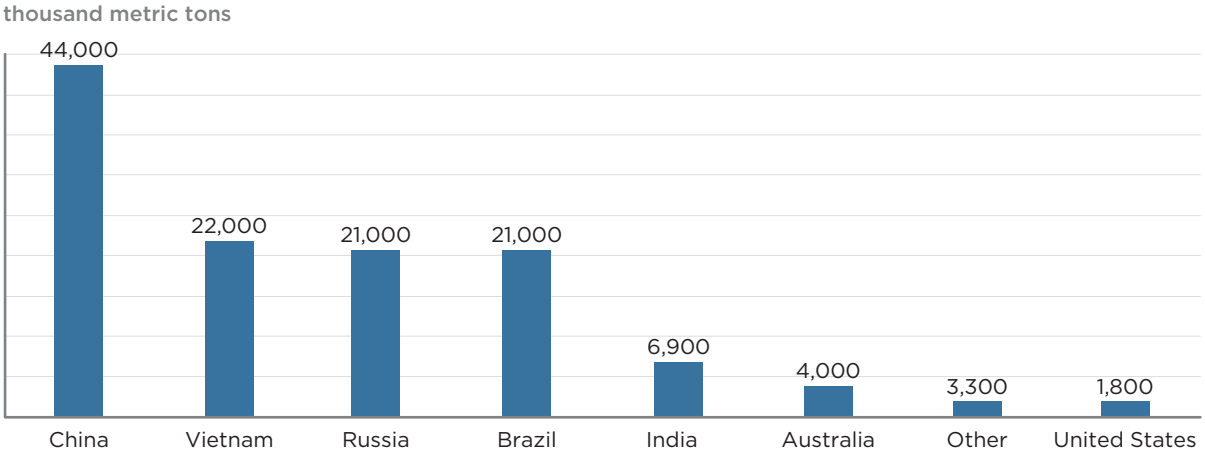
19 On the processing side, a plant in Malaysia run by Lynas is the only large non-Chinese facility in operation today, but several others are under development.

20 See https://d18rn0p25nwr6d.cloudfront.net/CIK-0001801368/7c83b453-4580-4c19-935a-5d198af27e58.pdf.

21 See https://www.reuters.com/business/energy/china-hikes-2021-rare-earth-quotas-by-20-record-highs-2021-09-30/.

Production data are difficult to obtain. Table 13 gives a sense of production levels by companies based on the quotas imposed by the Chinese government on its three largest companies; data for Mountain Pass and Lynas Rare Earth were obtained from various sources.

Figure 3
Global reserves of rare earth elements, by country, 2020



Source: US Geological Survey, Mineral Commodity Summaries, January 2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-rare-earths.pdf.

Table 13
Country of incorporation of top producers of rare earth elements, 2020

Company	Country	Total rare earth ore (metric tons)	Percent of global output
China Northern Rare Earth Group[a]	China	100,350	41.0
China Southern Rare Earth Group[a]	China	42,450	17.3
Mountain Pass[b]	United States	36,750	15.0
Chinalco[a]	China	17,050	7.0
Lynas Rare Earth[c]	Australia	14,170	5.8
Other Chinese companies[a]		8,150	3.3
Other		26,080	10.6
Total world production		245,000	

a. See https://www.reuters.com/business/energy/china-hikes-2021-rare-earth-quotas-by-20-record-highs-2021-09-30/.

b. Mountain Pass estimates its production at 15 percent of global consumption of REEs, which we approximate by the level of global production (15 percent * 245,000). For the 15 percent figure, see https://d18rn0p25nwr6d.cloudfront.net/CIK-0001801368/7c83b453-4580-4c19-935a-5d198af27e58.pdf. For the total world production figure, see https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-rare-earths.pdf.

c. See Annual Report for FY2021 available at https://lynasrareearths.com/investors-media/reporting-centre/annual-reports/.

Note: We did not calculate SOC figures for REEs, because all but two of the top producers are Chinese companies. One of those companies, Mountain Pass (now Molycorp Minerals), is not a listed company; the other is Lynas, whose shares are held by investment funds, including Vanguard, BlackRock, and an Australian asset manager (Caledonia Private Investments Pty Ltd.).

Sources: US Geological Survey 2022 (https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-rare-earths.pdf) for total world production (calculated as the sum of all its components, which yields 245,000 metric tons) and sources indicated in the table notes.

V ENVIRONMENTAL, SOCIAL, AND GOVERNANCE ISSUES

Interest in ESG is growing. Investments in ESG–related funds have skyrocketed, attracting net inflows of $71.1 billion between April and June 2020—more funds than they attracted in the previous five years. As of August 2020, ESG assets under management exceeded $1 trillion.[22]

ESG issues are important in mining and refining because they are inherently polluting activities (E), and the industry is often accused of treating its workers poorly (S). Governance (G) is arguably the most critical dimension of ESG, because, as a private banker, noted, "There is no successful E or S without a functioning G."[23] To a large extent, a company's ESG policies and its level of corporate social responsibility will determine its overall risk profile and long-term viability.

For many companies, mainly listed ones, ESG scores are available from various data providers. Also available are subscores on product safety investments; employee engagement affecting labor productivity and human rights issues in the supply chain; and inclusion of minorities, the absence of gender discrimination, and the composition of the board.[24]

The measurement of E and S is generally more robust (and more correlated across data providers) than the measurement of G, as it relies on more accurate and comparable indicators, such as carbon dioxide emissions.[25] The measurement of G is subject to much greater debate. For example, the indices often exclude important corporate governance issues, such as concentration of control, which they often measure by simply aggregating perceptions and self-assessments.[26,27]

We first consider the importance of transparency regarding the global reach of SOCs for ESG policies. A firm's ESG policy could be determined largely by the relative power of shareholders and managers. For instance, a large shareholder with a strong preference for investing in firms with strong environmental performance could force an investee firm to adopt sustainable projects (Barko, Cremers, and Renneboog 2021). An ill-intentioned or careless SOC could also use its subsidiaries to engage in unethical practices, such as moving pollution to developing countries with weaker environmental regulation to obtain good ESG scores for its subsidiaries in places where regulation is stricter. This possibility is one of the disadvantages of corporate networks created by so-called "common

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22 https://www.ft.com/content/27025f35-283f-4956-b6a0-0adbfd4c7a0e. See also Renneboog, Ter Horst, and Zhang (2008) or Gibson Brandon, Glossner, Krueger, Matos, and Steffen (2021).

23 See https://www.natwest.com/corporates/insights/sustainability/theres-no-successful-e-or-s-without-a-functioning-g-in-esg.html.

24 We use Refinitiv data for ESG aggregates of E, S, and G.

25 This does not imply that the measure of E and S is not controversial, as obvious from the recent controversies in Davos (see https://www.reuters.com/breakingviews/hsbcs-jarring-esg-message-davos-spring-podcast-2022-05-26/, https://time.com/6180638/tesla-esg-index-musk/ or https://news.bloomberglaw.com/esg/goldman-investment-unit-finds-huge-subjectivity-in-esg-ratings).

26 See, for example, https://www.thegoldensource.com/understanding-esg-data-challenges/#:~:text=Specific%20ESG%20Data%20Challenges&text=There%20is%20a%20lack%20of%20data%2C%20so%20one%20needs%20multiple,ratings%20are%20dependent%20on%20methodologies.

27 The way governance is measured also explains why the correlation between estimates of G across providers is low and lower than for E and S (about 0.4 for ESG as a whole). The correlation of financial data across suppliers is about 0.99 (see Liang and Renneboog 2021).

ownership" (in which one SOC controls or influences several investee firms). Although such practices may be legal, they are socially costly to the country in which the polluting activity takes place and globally harmful.[28]

Of the 29 mining companies we examined, ESG data were available on 21. We divided these companies into the following groups:

- *Chinese SOCs*. Chinese SOCs are the key SOCs that emerge from our analysis. They include both government and privately run companies. They have a reputation for having little interest in social and environmental issues.[29]
- *Other (non-Chinese) government-run companies (financial or not)*. Some companies have a sovereign wealth fund or another government entity as a top SOC. These firms are expected to be less efficient (unless they are in countries in which corruption levels are low) but more concerned about public welfare than other firms. They could put pressure on management to focus on long-term performance and make stronger E and S choices.
- *Management-run companies*. In these firms, the balance of power between shareholders and management is tilted toward the latter and there is no prominent SOC (Z1 < 0.3). One expects high agency costs to lead to poor performance in E and S.[30] Two companies in our sample (BHP Group and Allkem) are in this category.
- *Combined investment funds and industrial/family-run companies*. In these entities, both Z1 and Z2 ≥ 0.3. Industrial or family partners are expected to care about the long-term interests of their company and the industry. They are therefore likely to believe that E and S that support long-term investments generate long-term value although they might reduce short-term profits (Sahut, Peris-Ortiz, and Teulon 2019). Partnering with a financial partner adds a rigorous approach to the balance sheet; one would expect such companies to perform better than other companies on E and S.
- *Institutional Investors (passive funds)*. Passive funds are reputed to be driven by short-term considerations and maximization of their own portfolios. They are flexible and can move in and out of capital more rapidly than other investors. A question is whether passive funds should be considered SOCs. We think they should, for two reasons. First, they are large shareholders, and nearly all institutional investors (and passive funds) exercise their voting rights on the management and shareholder proposals that are tabled at

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28 This practice, called greenwashing, is akin to transfer pricing. A similar situation can occur with the issuance of green bonds by one subsidiary to raise capital that will ultimately be used by another, not so clean, subsidiary (for a recent example, see https://www.esgtoday.com/deutsche-bank-dws-offices-searched-by-authorities-on-greenwashing-claims/). Yet another example of the dangers of common ownership could be illicit international financial flows that are detrimental to the common good, such as recouping losses made by one subsidiary through transfers from another.

29 Their lack of interest in and action on ESG does not prevent Chinese firms from touting their corporate social responsibility at home and abroad (https://youmatter.world/fr/csr-in-china-future-of-corporate-social-responsibility)/.

30 For a discussion of agency costs in the relationship between boards and management, see Liang and Renneboog (2018).

annual meetings.[31] Their influence extends beyond their own voting behavior, because proxy advisory services (such as ISS and Glass Lewis) offer advice to shareholders on how to vote and can cast votes on behalf of institutional shareholders.[32] Second, the largest funds (such as BlackRock, Vanguard, or State Street, which are often referred to as having "universal" ownership) can influence the voting behavior of other institutional shareholders by their leadership on ESG issues.[33,34] The United States is involved in critical minerals through its institutional investors (passive funds); the two largest US SOCs are investment funds.

Table 14 presents the average ESG scores according to type of governance.[35] The scores vary considerably across types, reinforcing the notion that who controls a company (which can be interpreted as a measure of G in the logic of this paper) will have an impact on E and S indicators.[36]

Passive funds and management-run companies—firms in which agency problems are potentially large, given the absence of an important SOC—have the lowest E scores.[37] The combination of an investment fund and an industrial SOC is associated with a high E and the highest S. Non-Chinese government SOCs perform well on S and E. China performs poorly on S. Companies may give priority to growth at the expense of other considerations, especially when production facilities are in foreign countries in which governments are expected to take responsibility for environmental and social conditions.[38] SOCs that are

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31 See, for example, Appel, Gormley, and Keim (2016); Bebchuk and Hirst (2019); and Fichtner, Heemskerk, and Garcia-Bernardo (2017).

32 See, for example, https://www.jdsupra.com/legalnews/quick-guide-to-iss-and-glass-lewis-2022-3019913/.

33 For instance, BlackRock states that "ESG integration is the practice of incorporating material ESG information . . . with the objective of improving the long-term financial outcomes of our clients' portfolios. We do this across our active portfolios. . . . In index portfolios where the objective is to replicate a predetermined market benchmark, we engage with investee companies on ESG issues to enhance long-term value for our clients" (https://www.blackrock.com/corporate/literature/publication/blk-esg-investment-statement-web.pdf). Vanguard states that "with more than 30 million investors globally who look to us to both safeguard and grow their investments, we think about. . . [ESG] issues in the context of delivering long-term value to our investors and helping them to meet their objectives" (https://www.nl.vanguard/professional/investment-capabilities/esg/our-approach-to-esg).

34 Funds' ESG policies can be inconsistent with and depend on economic circumstances. For example, the post-COVID situation and the economic disturbance in the food supply following the Russian invasion of Ukraine changed institutional investors' attitudes to ESG. "Environmental advocates targeted BlackRock for a wave of protests in mid-April, holding up images of giant eyeballs to signal that 'all eyes' were on BlackRock's voting decisions" (https://www.lexology.com/library/detail.aspx?g=efa88552-14df-42c9-9c8d-6c94e3b90180). In 2022, BlackRock warned that it would vote against more climate resolutions (https://www.ft.com/content/4a538e2c-d4bb-4099-8f15-a28d0fefcea2).

35 We use the latest ESG scores; data on production are mostly from 2020. These figures were subject to revision by Refinitiv, because of "new data measures" in 2020 and after.

36 For a discussion of this issue, see https://www.hl.co.uk/news/articles/governance-the-most-important-esg-factor. Institutional investors that signed the Principles for Responsible Investment (PRI), the largest responsible investment initiative, exhibit better portfolio-level ESG scores than firms that did no (Gibson, Krueger, and Schmidt 2021).

37 We do not claim to have established causality.

38 In China, there are issues linked to environmental preservation by Chinese firms. Kostka (2014) points to an environmental implementation gap in which environmental goals and policies at the national level are ambitious and comprehensive but suffer from inadequate and inconsistent implementation.

passive funds perform worse than average on E and better than average for S and G. A closer look at the data shows that performance is uneven, but it may be that the impact of passive funds' "active" policy to push the ESG agenda indeed had a positive impact.

Table 14
Average environmental, social, and governance scores, by source of control

		Score		
Governance type	**Number of companies with ESG data**	*Environmental*	*Social*	*Governance*
China	7	68.0	55.7	70.1
Other government	4	76.5	78.6	65.9
Management	2	67.3	77.7	83.9
Combined investor fund and industrial/family SOC	4	72.0	81.0	74.5
Passive funds	4	62.9	74.6	89.3
Average		69.3	70.6	75.1

Source: Refinitiv data provided by Tilburg University.

VI POLICY CONSIDERATIONS

Economic and political dependency are relevant for both firms and investors, who prefer not to be at the mercy of a single set of interconnected suppliers or exposed to the vagaries of international events.[39] They are also relevant for sovereign states anxious to protect their economies from unexpected shocks or international blackmail.

A firm or state can be dependent on a private supplier or another state. State-on-state dependence arises either because foreign states can affect the behavior of the companies controlled by their nationals or because they can restrict the activities of any undertaking on their territory. Whether economic or geopolitical, the private and public costs of dependency are not the same.[40]

When considering policy options, one should keep in mind some similarities in the positions of the European Union and the United States. In many countries, including China, critical reserves are owned by the state, or states have controlling interests in mineral-producing companies. In the United States, the controlling shares held by US-based companies belong to passive funds, and the

39 Investors in private firms are increasingly interested in knowing whether their governance structure is conducive to good financial and ESG performance, compatible with a reasonable level of risk (see https://www.ft.com/ftfm/responsible-investing).

40 The state benefits from diversification of sourcing across its firms, but each individual firm might have an excessive incentive to diversify sources. The state needs to consider the repercussion of dependency throughout its economy, whereas individual firms factor in only the impact on their own business and may care less about geopolitical blackmail or supply shocks.

US government has no direct control over the operations of these funds except by invoking legislation such as the Defense Production Act of 1950. The positions of the United States and Europe are therefore not that different. Compared with China, which has vast reserves of critical minerals, especially REEs, the European Union and the United States are not in a strong position.[41] The European Union and the United States therefore face some common issues when confronting policy choices.

The effectiveness of many of the policies discussed below would benefit greatly from identifying the SOCs in global value chains, especially as companies and countries are unlikely to be fully aware of the intricate webs of direct, indirect, and cross-ownerships that determine ultimate control. Doing so involves collecting and analyzing the kind of information discussed in this paper for all industries. We focused on the first stage of the supply chain, but the analysis should be extended further downstream.

The first policy lever is to publicize the web of ownership and the resulting control structure in industries that the state judges to be sensitive.[42] Of course, greater transparency does not by itself eliminate strategic or harmful behavior by SOCs. Identifying the SOCs of systemically important firms (including from the fiscal stability or protection of small shareholders point of view) is also critical because in case of financial distress, it is the SOCs that would potentially bear most of the risks. Several other policy actions could be considered, though some of them have the potential of being misused to protect incumbents.

Compared with China, which has vast reserves of critical minerals, especially REEs, the European Union and the United States are not in a strong position.

Governance

Increased global reliance on critical minerals is likely to exacerbate governance problems—especially corruption—in producing countries. For example, the critical mineral reserves in Afghanistan make the country highly vulnerable to corruption, supported by foreign firms or countries. Increased transparency coupled with enhanced anti-corruption procedures in producing and consuming countries are critical to address these problems (EITI 2022).

Regulation of Mergers

Mergers between producing firms and/or consuming firms can help prevent the emergence of critical bottlenecks. But policymakers need to consider networks of control when examining the impact of mergers, including in markets in which neither of the merging parties is directly involved.[43] Merger authorities should consider the full set of ownership relationships involved (including by identifying the SOCs before and after the merger).

41 The United States also has some reserves, but the government does not own subsoil resources, and mining these resources often faces opposition from local populations (see https://insideclimatenews.org/news/07112021/lithium-mining-thacker-pass-nevada-electric-vehicles-climate/).

42 Investors are typically not fully aware of ownership connections (Ginglinger, Hebert, and Renneboog 2018), especially when SOCs have a controlling interest in (mining or other) operations across borders.

43 These networks matter because effects can significantly affect the level of control exercised by the merging parties. Considering these effects could help prevent mergers that would create a dominant position for a SOC that a purely legal approach could miss.

Trade

Tariff and nontariff trade barriers are a key risk to GVCs, including those for critical minerals. Take the case of the China-US trade dispute filed by the United States with the World Trade Organization (WTO) alleging that China had imposed export taxes on some of its mineral products (antimony, cobalt, copper, graphite, lead, magnesia, talc, tantalum, and tin) (Bown 2016). More effective WTO dispute resolution mechanisms are needed to counter such practices. Trade disputes and their resolution should consider not only trade restrictions by one country on another but also the possibility that a country channels such restrictions through companies it controls, wherever they are located.

Procurement

Safety of supply is a legitimate criterion when designing procurement tenders. It should not be used as an excuse for protectionism, however. A transparent analysis of who controls suppliers would provide a measure of the risks associated with potential suppliers while avoiding protectionism.

Financial and Fiscal Risks

Countries must assess the risks to their economies, including the effects on fiscal stability, and how major changes in SOCs for critical stages of the supply chain would affect them. Investors are also interested in the risks associated with their investments.[44] Identifying SOCs is much more relevant to a good risk assessment than compiling lists of UBOs.

State Support

Countries can subsidize economic activities to resolve a well-identified market failure. For example, efforts by the US Department of Energy to secure supply chains in the context of energy transitions explicitly identify the need to "Increase federal government financial support to eligible US companies investing in or exporting to foreign countries to secure supply chain inputs that fill challenging domestic gaps and support growth of other domestic segments of the supply chain."[45] Identifying the SOCs is critical to targeting the right companies by countries that use a similar instrument or a specific legislation to help develop "first of a kind" production facilities.[46]

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44 Macroeconomic concerns go beyond fiscal risks. A key concern for countries producing critical minerals is how to address the revenue volatility that may arise from market movements or geopolitically induced interruptions, as well as political economy problems associated with natural resource rents (such as the lower level of political accountability associated with creating non-tax revenues). These problems are akin to the macroeconomic management issues that commodity producers experience, including debt transparency and management (Gelpern, Horn, Morris, Parks, and Trebesch 2021) and Dutch disease. They may become more pronounced when energy transition accelerates, increasing demand for critical minerals (Hendrix 2022). In addition, the usual arsenal of fiscal policies related to primary commodities (taxation, fiscal rules, and sovereign wealth funds) should apply.

45 See US Department of Energy (2022).

46 An example is the European Chips Act (see https://ec.europa.eu/commission/presscorner/detail/en/ip_22_729).

Recycling

The recycling of critical minerals reduces the exhaustibility of natural resources and could considerably increase their supply.[47] A key feature of recycling is that the primary input tends to be found in the same place as the demand for the refined product. This correspondence is likely to be stronger for metals, where the time between original use and recycling is short. Appendix B provides some illustrative calculations showing how recycling critical minerals can help reduce dependence on new supplies but can be only a partial solution.

The recycling of critical minerals reduces the exhaustibility of natural resources and could considerably increase their supply, but it can only be a partial solution.

Substitution

Policies—particularly to encourage research and development (R&D) and stimulate substitution away from critical minerals—can help reduce vulnerability. Countries may have a substitute (existing or to be found) in which they are better endowed than the mineral they import. Even if they do not find one domestically, R&D might facilitate greater diversification across supplying countries and companies. Substitution can also arise at others stages of the global value chain. For example, companies could substitute away from lithium by moving to batteries that rely on another element. They could move from electric cars to hydrogen-powered engines, eliminating demand for car batteries altogether.[48]

Other Considerations

Other considerations include strategic reserves, onshoring, and direct government participation in the extraction of critical minerals:

- For storable commodities, such as minerals and their derivative products, strategic reserves might provide a cushion against shocks to foreign supply, politically motivated or not (an example is the United States' strategic petroleum reserves).
- Mining companies can operate only where mineral deposits are located, but onshoring could affect other parts of global value chains.[49]
- Governments could participate directly in critical mineral extraction companies in producing countries. Critical minerals are produced mostly in developing or emerging-market economies, where mining is undertaken largely by foreign companies. The domestic industry typically remains small;

47 At least since *United States v. Alcoa*—the landmark decision that determined the relevant market for market share analysis—economists understand that producers of a durable good face competition not only from each other but also from the "supply overhang" resulting from their previous levels of production. See, for example, https://law.justia.com/cases/federal/appellate-courts/F2/148/416/1503668/.

48 Such substitution efforts are under way. For example, the European Union has financed two Important Projects of Common European Interest (IPCEIs) on batteries and is about to approve a large IPCEI on hydrogen. (IPCEIs are programs that address market failures by offering subsidies for worthwhile innovative projects that would otherwise not be pursued.) IPCEIs must also Involve significant synergies between individual projects and ensure ex post diffusion of knowledge. They typically cover innovation from basic research to scaling up for industrial deployment. See https://ec.europa.eu/commission/presscorner/detail/es/ip_19_6705.

49 See, for example, recent efforts by the US administration on semiconductors (https://www.voanews.com/a/biden-pushes-expansion-of-domestic-semiconductor-manufacturing/6407527.html).

as more deposits are found, the lack of resources will increasingly marginalize the domestic industry as large foreign firms will move in. A government could become a shareholder in ventures that exploit mines (without nationalizing the companies), making it a substantial SOC. Such shareholdings are a potential source of risk to the operations of those ventures and to government finances, but they also give a say to the owner of the resource (through the government).

VII CONCLUDING THOUGHTS

The transition away from carbon-based energy has brought to light the fragility of global value chains that rely on critical minerals. The Russian invasion of Ukraine has increased the urgency of the energy transition. But countries could increase global fragmentation and hurt welfare if they try to address this vulnerability by undertaking very costly industrial policies and relying excessively on friend-shoring.

Public policy interventions may be needed to reduce the risks to the energy transition posed by hold-ups by geopolitically intended restrictions on trade in critical minerals. These interventions need to take into consideration not only where those critical minerals are produced but who controls their production (often nontransparent webs of ownership and influence). Doing so would help make supply chains more resilient and contribute to the fight against the harmful policies countries may adopt as part of their efforts to enhance resiliency.

Ownership and control relations and shareholding webs can change frequently and quickly. Therefore, analysis of the type done here needs to be conducted regularly, to shed light on the risks in value chains and to allow policy makers to craft more effective responses. The increased transparency that could come from knowledge of SOCs in the production of critical minerals would help reduce the need for broad protectionist and trade-reducing actions by governments in consuming countries.

The approach proposed in this paper would allow mineral-producing countries identify and manage risks. Such knowledge could be particularly helpful in improving transparency, governance, and macroeconomic management.

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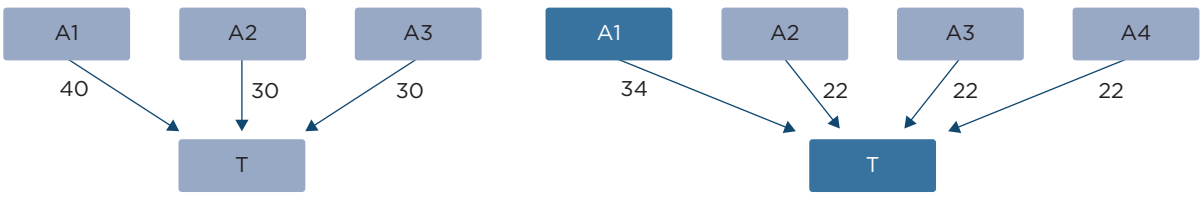
APPENDIX A
ZENO INDICES

ZENO Indices measure the ability of a direct or indirect shareholder of a firm to change the outcome of a vote at the firm's level by changing its own vote. They allow for the computation of a single index measuring the level of control a shareholder can exercise over a company (called here a target T).

To see how the indices work, assume that a firm has several shareholders, A1 to A*n*, and that an issue is being put up for a "yes" or "no" vote to these shareholders. We focus on A1 and assume that the other shareholders all vote independently from each other, so that there are 2^{n-1} possibilities (called *strings of possible votes* by these shareholders). A decision by A1 to change its vote from "yes" to "no" may swing the outcome. It will always do so if A1 has a full majority (the Banzhaf power Index, or Banzhaf value, is equal to 1). If it does not hold a majority of the company's share and its change never affects the final result, the Banzhaf power index of A1 in T is equal to 0. In the general case, a change of vote by A1 will sometimes change the final outcome. The Banzhaf power index is measured by the proportion of cases in which by changing its vote, A1 changes the final outcome (for details on the Banzhaf value, see Banzhaf 1965 or 1968.) The original approach has been generalized to more complex situations and a methodology proposed to handle large datasets (for calculating these values with many players) by Crama and Leruth (2007).

This is a complex problem because control is not a simple, linear, or even continuous function of the percentage of shares held. To see why this is the case, consider the left-hand part of figure A.1. The numbers on the arrows represent the percentage of T's shares held by each shareholder A. Although this number is higher for A1 (40 percent) than for the other shareholders (A2 and A3), A1 does not actually have more control over T than they do, as it needs to collude with either A2 or A3 to ensure a majority (more than 50 percent). However, both of the smaller shareholders are in the same situation: If A3 colludes A2, the two shareholders jointly hold a majority. Intuitively (and correctly), the control of each shareholder over T is identical.

Figure A.1
Control and dilution of capital



Note: A1 to A4 are shareholders of T and the percentage of shares held is indicated on the arrows.

Therefore, all three ZENO Indices of control (and the Banzhaf values) are equal (Z1 = Z2 = Z3 = ½), and all three shareholders are correctly identified as equal SOCs. Let us now dilute the capital of T (see the right-hand part of figure A.1). This dilution increases A1's control although the percentage of shares held has decreased. Indeed, if A1 joins forces with any other shareholder, the coalition

has a majority. The situation is no longer the same for the other shareholders, all three of which needing to join forces in order to create a coalition with a majority. Diluting the capital thus increases A1's control. In the case of the left-hand part of figure A.1, a Herfindahl-type index would yield $(4/10)^2 + 2\times(3/10)^2 = 0.34$. In the case of the right-hand part of figure A.1, the Herfindahl index would (misleadingly) suggest that the concentration of control decreased: $(34/100)^2 + 3\times(22/100)^2 = 0.2608 (< 0.34)$.

APPENDIX B
RECYCLING ISSUES

The numerical example we develop below aims at illustrating the potential of recycling to mitigate dependency issues depending on the combination of demand growth and the time lapse between product sale and recycling.

Consider one of the metals that we have analyzed, say nickel. As of today, there is a stock (S) of refined nickel incorporated in various products. Assume that these products become obsolete after T years, at which point they can be recycled. Also assume that output has been constant over time and there was no recycling in the past.

Now assume that recycling becomes feasible for a proportion, α, of the available scrap nickel. This proportion reflects two factors: the loss of metal during the recycling process and the fact that not all sources of scrap can be recycled on economically attractive terms. In this simple example, the supply of recycled nickel is equal to $\alpha\frac{S}{T}$ every year.

How does this new source of nickel affect dependency? A key feature of recycling is that the primary input tends to be found in the same place as the demand for the refined product. This correspondence is likely to be stronger for metals than for other goods, because the time between original use and recycling is shorter (it depends on the nature of the final products in which the metal has been embedded).

We also need to account for growth in demand. So far, we have implicitly assumed that yearly demand is constant, at $\frac{S}{T}$. We now assume that demand grows at a yearly rate equal to g. This means that demand today (time t) is larger than the demand (and hence output) that existed earlier (time t-T) and that has become the current nickel scrap (time t) that can possibly be recycled (in proportion α).

We define R as the share of today's demand that can be satisfied through recycling.[50] We start at the point at which there is no accumulated scrap and annual demand is equal to S/T. After T periods, the supply from scrap is $\alpha\frac{S}{T}$. The next period, it is $\alpha(\frac{S}{T})(1+g)$ after $T+t$ periods, it is $\alpha(\frac{S}{T})(1+g)^t$. Demand at time $T+t$ is equal to $(\frac{S}{T})(1+g)^{t+T}$. Hence the ratio is $R = \frac{\alpha}{(1+g)^T}$.

The competitive constraint attenuated by recycling is thus stronger the higher the recycling rate (α), the shorter the expected life of the final products in which the metal is used, and the slower the growth in the demand for the metal, as illustrated in table B.1.

The potential of recycling to mitigate dependency issues depends on the combination of demand growth and the time lapse between product sale and recycling. Without market growth, the only limit is recycling technology (α). As soon as there is market demand growth, the share of demand covered by recycling can drop sharply, even if there are no technical obstacles ($\alpha = 1$). Of course, recycling faces several constraints, from the loss of material during the industrial process (essentially zero for copper and nickel, higher for cobalt) to inefficient collection to the difficulty of recycling inputs that contain different types of metals. We should therefore consider values of α that are significantly smaller than one.

50 The formula can be modified to account for varying rates of growth over time.

Table B.1
Shares of recycling as a function of demand growth and product lifecycle

	Annual increase in demand (percent)			
Time	*0*	*3*	*5*	*10*
3	α	0.92α	0.86α	0.75α
5	α	0.86α	0.78α	0.62α
10	α	0.74α	0.61α	0.39α
15	α	0.64α	0.48α	0.24α

Note: The parameter α indicates the proportion of available scrap that can be recycled.

Table B.2 reports the percentage of demand currently met through recycling. For copper, both the United States and the resource-poor European Union have managed to cover significant portions of their own needs through recycling, providing a buffer against unexpected shocks and geo-political issues. The United States also achieves significant levels of recycling in lithium, where the European Union is currently trailing. Cobalt recycling provides little protection against dependency.

Table B.2
Percentage of demand for four minerals met through recycling in the European Union, the United States, and globally

Mineral	European Union	United States	Globally
Cobalt	n.a.	15[b]	n.a.
Copper	44[c]	34[d]	30[e]
Lithium	n.a.	n.a.	50[a]
Nickel	n.a.	47[f]	25[g]

n.a. = not available

Sources:

a. https://www.pv-magazine.com/2019/07/12/lithium-ion-recycling-rates-far-higher-than-some-statistics-suggest/.

b. https://www.investingnews.com.

c. https://www.euric-aisbl.eu.

d. https://www.copper.org.

e. https://www.investingnews.com.

f. https://pubs.usgs.gov.

g. The figure was obtained from "Asian Metal" but their website has now been taken down. However, it is in line with the 35 percent as projected for 2040 in https://www.mining.com/recycled-metals-could-meet-a-significant-part-of-the-rising-demand-from-evs-report/.

The view that emerges from table B.2 may be too rosy, for two reasons. First, current levels of recycling benefit from the existence of potential scrap overhangs. As recycling at scale is still a relatively recent phenomenon, the stock of metal that can be collected is large. Available scrap will eventually be limited by the volume of products that become obsolete and hence scrapable in any

given year. Second, the rate of demand growth expected over the next 5–10 years is significant. It is therefore important to assess the steady-state role of recycling based on the likely rate of growth of demand and the expected lifetime of products containing the relevant metal.

Table B.3 shows the implied proportion of demand that can be satisfied through recycling under the assumption that the recycling process is perfectly efficient ($\alpha = 1$). We use two methods to compute the share of demand that could be met by recycling. In the first, the growth rate is assumed to be the same for demand and supply and is equal to the growth rate observed in the past.[51] In the second, the supply growth rate is assumed to be equal to past demand growth rate, and the growth rate for demand is assumed to be equal to predicted future growth rate. The share of recycled metal is then computed for 5 years and 10 years from now.[52]

Table B.3
Maximum percentage of demand that can be met through recycling

		Annual demand growth (percent)			Share of demand met by recycling (percent)		
Mineral	**Current level of technical difficulties**	*Past*	*Forecast*	**Expected average lifetime of product (years)**	*Method 1*	*Method 2 (5 years)*	*Method 2 (10 years)*
Cobalt	Intermediate	4.3 (2010-21[c]	7[d]	8-10 (batteries only)	66-71	45-51	51-58
Copper	Moderate	3 (2010-21)[e]	6[f]	25[g]	48	20	17
Lithium	High	18 (2014-21)[a]	24[b]	3	61	52	52
Nickel	Moderate	5 (2011-20)[h]	4.8[i]	57 percent of all nickel ever mined is still in use[j]	38	40	40
Rare earth metals	High	n.a.	6[k]	n.a.	n.a.	n.a.	n.a.

n.a. = not available.

Sources:

a. https://www.statista.com/statistics/606684/world-production-of-lithium/.

b. https://www.barrons.com.

c. https://www.statista.com/statistics/339759/global-cobalt-mine-production. See also Zele (2018).

d. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/021622-global-light-duty-ev-sales-to-rise-to-268-mil-by-2030-platts-analytics.

e. https://www.statista.com/statistics/254839/copper-production-by-country/.

f. https://www.mordorintelligence.com/industry-reports/copper-market.

g. Gloser, Soulier, and Tercero Espinoza (2013).

h. https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/nickel-facts/20519.

i. https://www.mordorintelligence.com.

j. https://nickelinstitute.org/media/2273/nickel_recycling_2709_final_nobleed.pdf.

k. https://www.arultd.com.

51 If today's demand is X and the projected growth rate is g, we estimate last year's demand as $X(1 + g)^{-1}$ and next year's demand as $X(1 + g)$.

52 As lithium products have an expected lifetime of only three years, the two methods produce the same result.

The difference between the two methods is especially significant for copper, where past and future growth rates differ markedly. The first estimate is a better reflection of the likely future steady state; the second is a better approximation for the next few years, at least for metals with long expected lifetimes of products. We do not have direct information about expected lifetimes for nickel; we know only that it must be substantial and hence use $T = 20$ as an approximation. The numbers in the last three columns are derived results.

The conclusion is that recycling can mitigate dependency issues for mineral poor countries but is not a panacea. The rate of coverage for lithium and cobalt might look encouraging, but the technical difficulties faced by recyclers of both metals are substantial, so the shares in table B.3 should be multiplied by a value of α well below one. The issue is of a different nature for copper and nickel, for which the combination of high growth rates and long expected lifetimes means that if growth remains high, recycling can provide only a partial solution to the problems raised by dependency.

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