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Tanguy BONNET [1]

Abstract

Low-carbon technologies are highly intensive in critical minerals for which extraction and transformation generate heavy socio-environmental negative externalities. Global trade flows of such materials and technologies are part of a singular macroeconomy, filled with geopolitical stakes and national strategies. This paper aims to draw on environmental justice and ecological macroeconomics theoretical frameworks in order to assess the global material allocation of critical minerals and LCT and question its equity and efficiency in the lens of the ecologically unequal exchange theory.

Peripheral mining countries assume the heavy socio-environmental costs related to the extractive activities, while global trade flows enable an asymmetrical material allocation toward richer core countries. Two countries stand out : China, as the semi-periphery and the US, as the challenged core.

The paper also discusses how shifting geopolitics, geo-economic fragmentation and national strategies could modify such patterns of ecologically unequal exchange.

Keywords : critical minerals ; global trade flows ; ecologically unequal exchange ; environmental justice ; geo-economic fragmentation

JEL classification : Q42 ; L72 ; F18 ; Q37 ; Q56 ; Q57

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1 Introduction

Since several years, industrialized countries and advanced economies have engaged in an energy transition thought as a large-scale deployment of low-carbon technologies (LCT) as well as a massive electrification of different economic sectors. This transition is viewed as a way to decarbonize and maintain levels of energy production, but such a process requires huge amounts of minerals that will be extracted, refined, combined and used for their physical or chemical properties in LCT such as wind turbines, photovoltaic solar panels, and/or batteries electric vehicles. The demand for related minerals is therefore expected to surge in order to enable such an energy transition. Both researchers (Hache et al. (2019), Seck et al. (2020), Seck et al. (2021), Miller et al. (2023)) and international institutions (World Bank (2020), IEA (2021)) expect the related mineral demand to be multiplied by 2 to 13 depending on the minerals.

In this context of soaring demand for such critical materials, a specific and rather complex macroeconomy has quickly emerged. Several actors have set up national and international policies and strategies in their own interests, in order to manage domestic mineral resources, to gain control over the global value chains of transition-critical minerals (TCM) and LCT and/or in order to secure foreign supplies. First there is a strong economic dimension, as TCM and LCT represent a growing market with important profit opportunities. There is also a strong strategic dimension, with geopolitical, energetic, and material security issues. In addition, TCM macroeconomics includes an important ecological dimension around global socio-environmental justice, as at the basis of global material trade flows, the extraction of TCM leads to colossal negative externalities on local environments (soils, forests, biodiversity), but also potentially on local populations (workers, local inhabitants, indigenous people). TCM macroeconomics is therefore multifaceted, characterized by global material flows in economic, geostrategic, and socio-environmental dimensions. Therefore, in this paper, I aim to assess the TCM macroeconomics in a comprehensive way by drawing on the theoretical frameworks of environmental justice and ecological macroeconomics, and more specifically on the concept of ecologically unequal exchange (EUE).

1.1 Theoretical framework

Alf Hornborg, one of the key authors of this literature, considers that the EUE theory is the combination of the world-system theories and ecological economics (Hornborg (1998)). In a first place, theories of imperialism and dependency (Luxembourg, 1913) described international movements of capital and the imposition of market economy from capitalist to noncapitalist economies, either through violence or through several economic or socio-political mechanisms (foreign direct investment, private property, infrastructure, trade liberalization, debt, agricultural specialization (Vanel, 2003 ; Harvey, 2004 ; Burbaumer, 2022)), resulting in the permanent state of development in the first and underdevelopment in the second. In this line, world-system theories (Wallerstein, 1974 ; Arrighi, 1994) describe the global economy as a hierarchical international structure where core countries dominate and exploit periphery countries. core countries and monopolistic companies are geopolitically and commercially dominant on world markets. They can therefore secure favorable terms of trade, capture the most value-added in global value chains and profit from the low prices, wages and currencies of the periphery. The latter, despite its industrialization, is undergoing slow development due to its specialization, financial dependence, and inability to capture a large share of added value. There is therefore an asymmetric, hidden, and underpaid transfer of labor and value-added at a global scale, from periphery countries to core ones. This has been theorized by Emmanuel (1972) and Amin (1976) as the (economic) unequal exchange (Hickel et al., 2022).

Then, several ecological economists draw from this literature and add to the economic dimension of the unequal exchange an ecological one, in line with Georgescu-Roegen (1971), replacing the economic sphere within the biosphere and the associated physical, energetic and biochemical limits. This literature points out the fact that energy and natural resources are the basis and the precondition of any economic process, hence being one of the main driving forces of the economy, of capital accumulation and material development. As Hornborg, Frey et al. (2019) and Gellert (2019) trace this lineage from world-system theories to EUE and try to propose a unified theoretical framework linking closely related developments (world-ecology, metabolic rift, ecological imperialism).

In addition to the economic exploitation, the core benefits from the ecological exploitation of the periphery, reciprocally penalizing the latter. Economic growth and material development being enabled by energy and natural resources, the core will, in its endless drive for capital accumulation, expand its commodity frontier (Moore, 2000), including beyond national borders, in order to maintain and/or increase consumption of finite energy and materials. During history, these international resource access strategies take several forms : from colonization, to ecological imperialism, to liberal globalization of trade and finance. All these mechanisms, their nuances and their evolutions, have been explained and illustrated by several researchers (Musso et al., 2019 ; Frame, 2022). The core extends to the periphery, the exploitation not only of workers through labor, but also of nature through the extraction of comodified raw materials (agricultural, energetic, mineral). The latter, after transformation or not, is transferred to the core. These asymmetrical material flows are subject of insufficient monetary compensation, because of the core's domination on world markets ; this is the economic exploitation explained by the world-system theories. These asymmetrical material flows are also ultimately impossible to be fully compensated, or even measured in monetary terms, due to the fact that extractive peripheries must assume the negative socio-environmental externalities of the extraction of raw materials, without profiting from its material benefits. "Species, ecosystems and geological resources are ontologically incommensurable" (Althouse et al., 2023), so are the negative externalities of their exploitation on local populations, and so are the missed opportunities, in terms of material development, associated with the transfer of raw materials outside the national economy. In place, the energy and resources extracted benefit to the core's material accumulation and reinforce its position. Given the finitude of resources, in a "zero-sum world" (Hornborgh, 2009), economic growth and material accumulation in the core are achieved thanks to, and to the detriment of, the periphery. This is the ecological exploitation described by the EUE theory (Frey et al., 2019 ; Ciccantell, 2019).

From a methodological point of view, the research related to the EUE theory studies the international economic structures that enable this mechanism, among which : i) the insertion of the periphery in the global value chains (Althouse et al., 2023) ii) the self-reinforcing loop between the international monetary hierarchy and the uneven flow of resources between the core and the periphery (Svartzman et al., 2022), iii) the global market prices, that fail to represent material and ecological realities, and that enable the net transfer of energy and materials (Hornborg, 1998).

The EUE theory also relies on qualitative and empirical analyses (with historical, socio-political and ecological perspectives) of case studies. The foundational works focused on historical colonial situations in which predation, violence and political domination structured the core-periphery relationships enabling massive unfair material transfers. These studies outline the violent colonial exploitation, of native populations and/or African slaves as well as natural resources in the Americas, resulting in a large net transfer of commodities of all types toward the European core. The latter benefited from EUE over rubber, spices, minerals or animal oils from the Amazon basin from the 16th to the 18th century, as shown by Bunker(1984) (the foundational paper of the EUE literature), sugar from the Carribeans in the 17th to 18th century (Moore, 2000) or guano/nitrates from Chile and Peru in the 19th century (Foster et al., 2009). Reciprocally, these extractive peripheries deeply suffered, from an economic, ecological and social point of view, from these uneven material flows. Recent papers, focusing on contemporary case studies illustrate the fact that the post-colonial neoliberal globalization still enables patterns of EUE due to the international economic structures mentioned above. Evidence for EUE are found by Infante-Amate et al. (2019), over different natural resources, between France and its former colonies since the 1970's ; by Bedford et al. (2020), over mineral resources, between Australia and South Africa since the 2000's ; by Frame (2019), over land and its different resources, between China (as well as other Asian countries) and Cambodia.

The empirical approaches use physical variables to measure material flows, like physical trade balances, or input-output matrices that account for the entire value chain and determine energetic or material footprint of finished or semi-finished traded goods. Therefore, the material flows from the periphery to the core are measured in quantity (i.e., volume) of goods, materials, embedded energy, water, or even land area or hours worked. Recent papers, attempting to measure EUE at a global scale, show that high-income countries in the core are net importers and consumers of embodied materials, energy, land and labor from the periphery, exceeding by far the domestic capacities (Dorninger et al., 2021). This appropriation of Global North (core) over the Global South (periphery) would account, for example in 2015, for footprints of "12 billion tons of embodied raw material equivalents, 822 million hectares of embodied land, 21 exajoules of embodied energy, and 188 million person-years of embodied labour" (Hickel et al. (2022)). The core materially benefits from these trade patterns while still generating a colossal monetary surplus because the economic dimension of the unequal exchange is still there, and the economic conditions in which this trade takes place are studied. There are indeed monetary flows from the core to the periphery, but, with regard to the prices and wages differentials, as well as the currency misalignments, the core benefits from the relatively cheap prices, currencies, manpower and nature of the periphery. These monetary flows would be far greater if the core's standards in terms of prices and wages, and/or if the purchasing power parity, were in force. Moreover the economic differentials represent a missed economic opportunity, in terms of revenue and in terms of material capacity for structural development, for the periphery ; while the core generates an exorbitant economic surplus of tens of trillions of dollars (Dorninger et al., 2021 ; Hickel et al., 2022) as well as the colossal material surplus mentioned above.

These approaches can have their limits, in regard to the above-mentioned "ontological issue of incommensurability" of nature, especially in monetary terms, but they still achieve to show asymmetrical material flows in uneven macroeconomic conditions, empirically verifying and illustrating the EUE phenomenon. These approaches support the theoretical and qualitative assessments of global economic and socio-political structures presented earlier. Finally, this literature offers important policy outputs - by critically questioning the dominant model of industrialized development on a global scale, and by assessing global imbalances as historically and politically constructed, economic and most importantly ecological inequalities – for alternate models for the global economy as well as for a global environmental justice (Martinez-Alier, 2012 ; Hickel et al., 2019 ; Althouse et al., 2020).

Some important theoretical developments around entropy and uneven transfers of energy and matter points the crucial role of technology. Indeed, grounding on Georgescu-Roegen's assessment of the economic process as highly entropic, some authors points at that technology is the modern form of capital accumulation. Technology is the result of a highly entropic international production process, where low-value and low-entropy inputs (natural resources), transformed into high-value and high-entropy outputs (technologies) (Althouse et al., 2022). As highly-sophisticated and highly-valued finished products, technologies embody high amounts of materials/energy and are highly priced by global markets, being therefore accessible only to countries with high purchasing power (Hornborg, 2014).

Technology, therefore, emerges as a product of an international production process that concentrates raw materials and energy extracted from the periphery, often to its ecological detriment. This process economically excludes the periphery through market mechanisms, while materially benefiting the wealthier core countries, as technology has high use-value, boosts material accumulation and productive capacities for structural development. As a result, it perpetuates structural economic and material imbalances between the two groups. Therefore, Hornborg clearly states that "modern technology is always and everywhere a matter of uneven distribution", "an asymmetric flow of embodied human time and embodied natural space between sectors where these assets are differently priced" and therefore ""Technological progress", in other words, is largely an index of capital accumulation and unequal exchange." (Hornborg, 2014).

Finally, regarding the latest theoretical developments on the international hierarchical structure of the EUE theory, more and more papers points at a multi-tiered system, with a core, a semi-periphery and a periphery. The semi-peripheral status was already analyzed by World-System theorists, although this concept has been mobilized only recently in the EUE theory. semi-periphery are countries characterized by both core and periphery features, and are therefore located between the two in the international economic hierarchy. A semi-periphery is an emerging economy positioned at the middle of the global value chains, and that, in the global production process, appropriates significant shares of economic surplus and embedded nature from foreign peripheries, while still transferring greater shares to core countries. Hence "they are both dominated by core countries and dominate peripheral zones" (Dunn et al., 1998 ; Frame, 2019). Therefore, several papers have classified China as a semi-periphery because of both i) core-like characteristics : major energy and materials imports (Svartzman et al., 2022) ; land-grabbing, investments and debt to promote natural resources exploitation in South-East Asia, Latin America or Africa (Frame, 2022 ; Brand, 2016 ; Dahir, 2019) ; a resulting surge of China's domestic material consumption (Svartzman et al., 2022) and ii) periphery-like characteristics : China is far from being a major imperialist power (no over-valued currency, weak wages, no major diplomatic or global military weight) (Herrera, 2023) ; large domestic natural resources extraction (see Table 10) ; large transfers of value-added and embedded labor toward the historical Northern core (Li, 2021). Recently, Tausch & Althouse (2025) have quantitatively illustrated and confirmed the semi-peripheral status of China. By assessing aggregated material flows, the authors show China benefits from the appropriation of the periphery's natural resources, while simultaneously being a net provider of biophysical resources exploited by the core.

1.2 Motivation, methodology and research question

As mentioned above, the EUE theory is relevant to apprehend TCM macroeconomics, in order to grasp the economic, geopolitical and ecological related issues, in the dialogue between resource-demanding and resource-supplying countries. There is an analytical interest in assessing this topic with an original and comprehensive theoretical framework, as well as a policy interest, by undertaking issues of equity in the global material allocation. Indeed, most of the studies on TCM focus on the latter as a source of economic or geopolitical risks for the demanding and decarbonizing high-income economies. Less research is done to articulate such stakes with the risks for, generally less wealthy, mining countries, in terms of socio-environmental costs, unsustainable development, and material imbalances. Therefore, this approach aims to highlight, in addition to the economic and geopolitical limits and tensions around the global TCM supply chains, a *political* limit in terms of equity and efficiency of global TCM allocation, in view of a more efficient and fair low-carbon transition at a global scale.

However, the classical framework of the EUE theory, and especially its core/periphery binarity must be adapted to the specific case of the TCM and LCT macroeconomics, the crucial role of China and its semi-peripheral status, as well as its relationship with the core countries, especially the US. Moreover, the TCM and low-carbon macroeconomics evolves in a moving international context deeply entangled with geopolitical stakes and national strategies. Such shifts in national and international geo-economics could therefore modify or modulate the potential EUE patterns at short to medium-term.

This paper aims at answering the following questions : is there a realization of EUE related to TCM global supply chains ? In which international strucutre does it materialize ? How could the potential EUE patterns be modified by the different national strategies and the shifting geopolitics in a context of geo-economic fragmentation ?
In order to answer to the first question, Section 2 will present the ecological and material distribution of the TCM , its associated ecological costs, and LCT, first by highlighting the heavy socio-environmental costs associated to the TCM supply chain with the mobilization of various socio-environmental indicators, then by assessing the global material trade flows for both TCM and LCT, using precise trade data, as well as the downstream technological deployment.
In order to answer to the second question, Section 3 will highlight the role of China as a semi-periphery, as well as the role of the US as an ultimate but challenged core, and the interaction between these two countries. This section will use once again key indicators, literature highlights and qualitative analysis, in order to assess not only the position of these two crucial countries in the ecological and material international structure, but also their economic and geopolitical position and relationships with the other demanding cores or supplying peripheries. Finally in order to answer to the third question, Section 4 will lead a qualitative and short-term prospective analysis of the different national and international economic and policy strategies in a context of shifting geo-economics, assessing how it could modify, reduce or redistribute the current EUE patterns. Section 5 concludes.

2 Ecological and material dimension of the TCM and LCT global supply chain

2.1 Materiality of the energy transition and socio-environmental costs of TCM supply

Economic growth, industrialization and material accumulation have always been conditioned by exponential extraction to match the demand for energy and materials (Vidal et al., 2017). The energy transition, based on electrification and LCT deployment, just like any other industrial process, is a source of additional or new demand for specific minerals. The latter are the main used materials, according to the IEA, [2] for the low-carbon electricity generation (wind turbines and solar panels), networks (electricity grid and other infrastructures), and storage (batteries) : Aluminum, Cobalt, Copper, Graphite, Lithium, Nickel, Silicon and Zinc. Table 1 below displays their content in the LCT, and the expected growth of demand between now and 2040.

Such an energy transition weighs a heavy material intensity as these technologies have important pure metal content. Therefore in this context, a surging demand is anticipated, whether it be by public or private institutions (World Bank's or S&P Global's scenarios also anticipate huge increases of critical minerals demand, close to the IEA) (Hund et al., 2023 ; S&P Global, 2023). This transition would only exacerbate the exponential trends of mineral production for these critical minerals, as displayed on Figure 8 in Appendix, with a significant acceleration of the mine productions for cobalt, lithium and silicium since 2016-17. Probably dozen of new mines would be needed to match such a demand growth. [3]

2. See the IEA critical minerals data explorer : https ://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer.
3. See https ://elements.visualcapitalist.com/how-many-new-mines-are-needed-for-the-energy-transition/

Table 1 – Metal content in low-carbon technologies

Materials	Onshore Wind (kg/MW)	Offshore Wind (kg/MW)	Solar PV (kg/MW)	EV (kg/EV)	Estimated growth of demand (STEPS)	Estimated growth of demand (SDS)
Aluminum	3221	1003	11283	251	×1.28	×2.2
Cobalt	/	/	/	13	×6	×21
Copper	2900	8000	2822	53	×1.7	×2.7
Graphite	/	/	/	66	×8	×25
Lithium	/	/	/	9	×13	×42
Nickel	/	/	/	40	×6	×19
Silicon	/	/	3948	/	×1.8	×2.3
Zinc	5500	5500	30	/	×1.8	×2.6

Sources : International Energy Agency, (2021) for contents in Photovoltaic panels (Solar PV) and in Wind turbines ; ADEME, (2022) for the contents in electric vehicles (EV). Scenarios based on IEA (2021) : STEPS = Stated Policies Scenario, an indication of where the energy system is heading based on a sector-by-sector analysis of today's policies and policy announcements ; SDS = Sustainable Development Scenario, indicating what would be required in a trajectory consistent with meeting the Paris Agreement goals.

Table 10 in Appendix displays the main mining countries for each critical mineral. The major TCM mining countries are mainly low to upper-middle income countries from the Global South, with the exception of Australia and Canada. Two exceptions should be mentioned : China, and, to a lesser extent the US, which are significant mining countries but are net importers of minerals and metals. Therefore, besides these two, the net exporting mining countries can be considered as extractive peripheries as they ensure net positive material outflows and assume huge socio-environmental costs related to mining activities.
Metallurgical activities (refining, transforming) are highly energy-intensive (Court et al., 2015) as well as being potentially extremely polluting depending on the materials (Bonnet et al., 2022). But the present section mainly focuses on the mining activities as most of the socio-environmental costs are spread around the different steps and times of the mine (exploration, extraction, on-site concentration). Indeed, mining is an inherently energy and material intensive industry that generates heavy socio-environmental negative externalities locally.

As Table 2 shows, mining generates huge amounts of wastes and consumes significant quantities of water as mines sink deep underground in order to extract, and then treat deposits. For example, on average, the extraction of 1 ton of copper ore generates 1.86 tons of waste rock, uses 32 cubic meters of water, and produces, after processing and refining, only 5.6 kilograms of pure copper metal. Regarding water use, this translates into important water pollution (IEA, 2021 ; Systext, 2021) as the water is contaminated by chemical components used in the extractive process or naturally present in the ore deposits extracted and treated. The total process, from raw ore extraction to pure metal refining, generates high levels of waste and pollution, and is highly energy intensive as displayed in Table 19 in Appendix. [4]
Low-carbon technologies and electrical infrastructures, mainly deployed in core countries, are critical mineral-intensive and have therefore huge energy, waste, water and pollution footprints, impacting mining and refining sites in extractive and productive Peripheries.

4. Moreover, most of the mining industry relies on carbonized energy, resulting in huge greenhouse gases emissions. The global mining industry, for all materials, would account for 7% to 10% of primary energy consumption (France Stratégie, 2020), resulting in 4% to 7% of global greenhouse gas emissions (Delevingne et al., 2020).

Table 2 – TCM extraction and associated waste, water use, and ore grade

Minerals	Main producing countries (2020, % of world total)	Total extraction (kt, 2020)	Waste ratio (waste/ore)	Water use (m^3/t)	Ore grade (% metal/ore)
Bauxite	Australia (27%), China (24%), Guinea (23%)	391 000	0.7	/	23.8%
Cobalt	D.R. Congo (73%), Russia (7%)	142	2.12	57	0.364%
Copper	Chile (32%), Peru (12%), China (9%)	20 600	1.86	32	0.56%
Graphite	China (79%), Brazil (6.5%)	966	/	/	/
Lithium	Australia (48%), Chile (26%), China (16%)	82.5 (hard rock and brine)	5.53 (hard rock)	773 (brine)	0.4% (hard rock)
Nickel	Indonesia (36%), Philippines (16%), Russia (13%)	2 510	1.36	53	0.9%
Silicon	China (70%), Russia (7%)	8 120	1.22	/	79%
Zinc	China (31%), Peru (10%), Australia (10%)	12 000	2.45	/	4.9%

Source : United States Geological Survey for production data ; Nassar et al. (2022) for the waste to ore ratio and the ore grade

Table 18 in Appendix shows the land use and deforestation related to mining activities. Mining activities expand on land with the generalization of open-pit mining, [5] and the growth of global mineral production (Figure 8) can cause deforestation in order to access new deposits, or to expand existing exploitations. However, these figures in Table 18 concern the whole mining industry in each country, for all minerals combined, therefore it must be nuanced when it comes to TCM. Indeed, only 25% of mining sites worldwide are reporting TCM extraction (Maus et al., 2022). Regarding deforestation, only 16% of mining-related deforestation is driven by TCM extraction while 71% of it comes from coal and gold extraction (WWF, 2023). But still, mining activity, regardless of the minerals extracted, is destructive of its local environment.

Therefore, mining threatens biodiversity and vulnerable ecosystems. Luckeneder et al. (2021) show that in 2019, 80% of global metal ore occurred in the most species-rich biomes, and approximately 8% were mined in officially protected areas. Sonter et al. (2020) made the same assessment regarding protected

5. Open-pit mining represents 57% of mining sites and 88% of ore production. Mining sites are larger and larger, and so are the waste generation and pollution levels (Systext, 2021).

areas, they also show that 7% of mining occurred in key biodiversity areas and 16% in remaining wilderness areas. TCM mining, just like any other type mining, threatens local ecosystems and a surge in TCM mining could exacerbate such pressure. Luckeneder et al (2021) find that, in 2019, around 25% of bauxite and 55% of nickel mining occured in tropical and subtropical moist broadleaf forests (the most species-rich biome), mostly in Indonesia which is indeed the country with highest mining-related deforestation (WWF, 2023). Sonter et al. (2020), focusing on critical minerals extraction, find that TCM mining overlaps with 12% of protected areas, 7.6% of key biodiversity areas and 14.3% of remaining wilderness areas.

Regarding TCM and water scarcity, whether it be research, public or private institutions, there is a strong water stress risk especially for cobalt, copper and lithium production. Luckeneder et al. (2021) show that 90% of mining occurs in areas of relative water scarcity and 13% within high water risk regions. Especially copper mining is exposed to important water stress as 40% of all copper ore is mined inside the two highest deciles of the water risk index used (AWARE). For the IEA (2024), approximately 50% of copper and lithium mines are located in high water stress areas. Finally, according to Pwc (2024) 2050 low emissions scenarios, 25% of copper production, 70% of cobalt production and 50% of lithium will face high drought risks, and 25% of lithium production would face extreme drought risk.

Land use, water use, environmental destruction and local pollution related to mining are, among others, source of local social conflicts. The heavy impact of the mining industry on its local environment logically triggers local population oppositions in order to protect their land, their water, their rights or to prevent polluting or destructive mining projects. Table 18 displays, for each country, the number of socio-environmental and ecological distribution conflicts related to mining and listed by the Environmental Justice Atlas (EJA) (Scheidel et al., 2020).[6] Scheidel et al. (2020) highlighted that, in 2020, mining was the most frequently reported sector, accounting for 21% (573) of all recorded cases (2743). They also underlined that mining-related conflicts are significantly more violent and deadliest than other conflicts as assassinations generally occur one out of five cases. According now to the late 2024 EJA dataset, there is a total of 4195 socio-environmental conflicts, mining accounts for 792 cases (18.9% of all recorded cases), and TCM related conflicts accounts for 366 cases (8.7% of all recorded cases, 46% of mining cases) (bauxite, cobalt, copper, lithium, nickel, zinc cases are recorded).

A recent publication by Walter et al. (2024) focus on TCM and "green extraction frontiers in the Americas", but its scope is limited to conflicts related to copper, lithium and graphite in nine countries of the Americas. The interesting point of this study is that in these cases, the need for minerals for the energy transition and the struggle against climate urgency are explicitly mentioned by the public and private mining promoters in order to motivate and justify such projects. These case-studies deal with conflicts related to water use, cultural heritage sites, lack of local participation as well as confrontation with local Indigenous peoples. Regarding the latter, Owen et al (2022) map the TCM related mining projects and find that 29% of these TCM mine projects are located on or close to Indigenous peoples' lands.[7] These alarming proportions point toward a potential multiplication of land use and socio-environmental conflicts with already vulnerable populations. Moreover, Scheidel et al (2020) highlight the fact that conflicts are significantly more violent when Indigenous people are involved, the latter being more exposed to criminalization, violence and even assassinations compared to non-Indigenous protestors. In a

6. These figures concern conflicts related to "Mineral ore exploration and/or extraction" which is one of the 52 subcategories of the EJA, it concerns all minerals and not specifically TCM, but it does exclude oil, coal and uranium extraction. Then, the EJA being an ongoing collaborative global inventory of ecological struggles, it is necessarily incomplete and it might lack data on some conflicts happening in some countries. Consequently, countries with high levels of environmental standards and organization can appear over-represented. Still, the EJA is an impressive and crucial tool for studying ecological conflicts, environmental justice and the EUE. The numbers displayed here are therefore a lower-bound for socio-environmental conflicts related to mining in general.

7. Depending on the minerals, the proportion of mine projects overlapping with Indigenous peoples' lands can be more or less important but are always significant : 32% of bauxite projects, 28% of cobalt projects, 66% of copper projects, 8% of graphite projects, 85% of lithium projects, 57% of of nickel projects and 64% of zinc projects.

related way, there is a growing critical literature on "green colonialism" and the "decarbonization consensus". The latter studies on a colonial upturn around land and resource grabbing using the rhetoric of energy transition and the struggle against climate change to justify TCM mining and low-carbon infrastructure projects, disregarding the socio-environmental consequences for local populations, while also motivated by profit opportunities (Voskoboynik et al., 2022 ; Svampa et al., 2023). While territories in the Global South "are (inevitably) 'sacrificed' for the sake of ecological modernization" (Dietz, 2024). Table 3 sums up the limits and risks associated to each mineral in terms of biodiversity pressure, water stress, environmental justice conflicts and overlap with Indigenous Peoples' land.

Table 3 – Socio-environmental risks by minerals

Mineral	**EJA conflicts**	**Mining overlap with biodiversity (for the 4 species-richest biomes)**	**Drought risk (Pwc low-emissions 2050 scenario)**	**Reserves and resources overlap with Indigenous People lands**
Bauxite	54	65% (25% in the most rich)	26%	32%
Cobalt	4	/	74%	28%
Copper	232	60%	54%	66%
Graphite	/	/	/	8%
Lithium	36	/	74%	85%
Nickel	6	60% (55% in the most rich)	/	57%
Silicon	/	/	/	/
Zinc	80	75%	18%	64%

Source : Environmental Justice Atlas (Temper et al., (2018) ; Luckeneder et al., (2021) ; Pwc, Climate risks to nine key commodities (2024) ; Owen et al., (2022)

Finally, in a systematic review, Lapeyronie et al (2023) examine the links between TCM mining territories and the 2015 United Nations sustainable development goals. They find that, when considering all United Nations' Sustainable Development Goals, there are more or less as many positive as negative impacts of TCM mining on such objectives. However, when focusing on SDGs related to health (Goal 3 : Good Health and Well-Being) and environment (Goal 13 : Life on Land), TCM mining has an overwhelmingly negative impact. This confirms the destructive character of mining activities on local environments, land, forest and biodiversity, as well as the health risks related to the toxicity of the minerals extracted or the mining techniques used.
Therefore, all TCM mining countries have faced such negative socio-environmental externalities due to mining activities ; water issues and Indigenous territories land-grabbing around copper and lithium extraction in Latin America (Jerez et al., 2021 ; Vasquez et al., 2023 ; Walter et al., 2024) ; corruption issues, armed conflicts, human rights abuse and disastrous working conditions in bauxite, copper and cobalt mines in Africa and especially in D.R. Congo (Amnesty International, 2016 ; Prause 2020 ; Amnesty International, 2023 ; Gourdon et al., 2024) ; heavy environmental pollution in Russia (SystExt, 2021) ; deforestation and Indigenous rights abuse, to say the least, in Indonesia (O'Brien, 2010 ; WWF, 2023) ; negative impacts on Indigenous people in post-colonial contexts such as in Australia, Canada or the US (Rodeiro, 2023 ; Horowitz et al., 2024). Although it is impossible to list all cases, this section has provided an unexhaustive review of the negative socio-environmental externalities related to mining that shows the heavy impacts of such activities in TCM extracting countries. All these impacts are expected to be multiplied in this context of global TCM extraction surge.

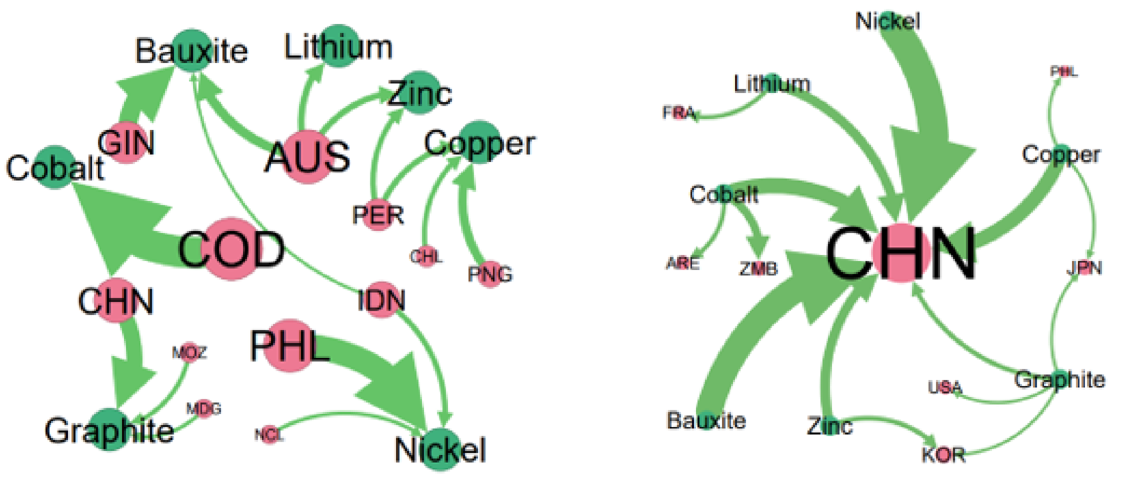
2.2 Global TCM and LCT material flows

To asses material flows, trade flows expressed in volume (in tons) are extracted from the bilateral trade flows database BACI (Gaulier et al., 2010) that uses UN Comtrade data. This data is used to measure and represent global material flows as well as bilateral supply flows and physical trade balances. For each selected TCM, two forms have been considered : i) minerals : extracted materials that have undergone an initial treatment, processed into ores and concentrates (low purity, raw materials necessitating further refining in order to be used as industrial input), ii) metals : a purer refined, but unalloyed or untransformed, form (80%-99% purity). Then, the components for the most important and widely deployed LCT that incorporate these metals will be studied : i) photovoltaic cells, ii) wind-powered electricity generating sets, and iii) lithium-ion electricity storage batteries. With these three steps, minerals, metals and LCT components, the following assessment accounts for the entire TCM/low-carbon technologies global value chain. For each products, the HS 6 digit codes and denominations used under BACI are available in Table 11 in Appendix. [8]
The following network graphics display the mean global material trade flows for each products over the 2017-2022 period. The period 2017–2022 has been chosen both for data availability reasons and for its economic relevance. The industry of LCT, the extraction of critical minerals, and the large volume of the international trade of these materials, truly began to emerge in the late 2010s. However, during this more recent period, (i) the macroeconomic environment (industry, extraction, trade) surrounding critical minerals and LCT has become more established, mature, and stable, and (ii) this same macroeconomic dynamic has entered an acceleration phase since 2017. This acceleration is particularly evident in the deployment of LCT, accompanied by a surge in mining activities, notably for copper, cobalt, lithium, and zinc. Finally, from 2017 onwards, critical minerals have gained significant geopolitical and geostrategic visibility, with the publication of critical mineral lists and the revival of national policy initiatives, especially in the United States and Europe.
Only the countries that meet a minimum trade threshold are represented in the network graphs. Specifically, a country is included at a given stage of the value chain if its exports or imports account for at least 10% of global trade for at least one critical mineral or metal, or at least 5% of global trade for at least one low-carbon technology, on average over the 2017–2022 period. This selection criterion ensures that the graphs highlight the key players in global material trade flows, while maintaining clarity and readability.
The links represent the mean share of the world trade for the product in question over the 2017-2022 period and the size of the nodes represent the total of the mean shares for all the traded retained products. The detailed data of these graphs are available from Table 12 to Table 17 in Appendix.

Figure 1 displays network graphs representing the global import/export flows for TCM minerals (ores and concentrates or unprocessed materials). Regarding the supply side of minerals, when all minerals are taken as a whole the supply is quite diversified with several countries, from all around the world, playing an important supplying role on the global scale. Most of the supplying countries are from the "Global South". Developing countries typically considered as productive or extractive peripheries, however there is a heterogeneity between the latter, some are low-income and less-developed economies (Guinea, D.R.

8. UN COMTRADE data for cobalt under HS code 810510 ('unwrought and mattes') lacks sufficient product disaggregation. This category combines both "unwrought", i.e. refined cobalt metal (typically >80% purity) and cobalt "mattes", which are semi-processed intermediates with much lower cobalt content (10–30%). As a result, trade figures under this code should be interpreted with caution, as they may not exclusively reflect flows of refined cobalt metal but also flows of cobalt "mattes".

FIGURE 1 – Exports and imports of TCM minerals



Source : BACI data. Australia (AUS), Chile (CHL), China (CHN), D.R. Congo (COD), Guinea (GIN), Indonesia (IDN), Madagascar (MDG), Mozambique (MOZ), New-Caledonia (NCL), Peru (PER), Philippines (PHL), Papua New Guinea (PNG), United Arab Emirates (ARE), France (FRA), Japan (JPN), South Korea (KOR), United States (USA), Zambia (ZMB).

Congo, Mozambique, Madagascar, Papua New-Guinea, Philippines) while other are important emerging economies asserting an upper-middle to high income position (Indonesia, Peru, Chile) and, of course, China which is now a major global economic actor. Finally, the main exception is Australia, which is a high-income developed country generally considered in the “Global North”, ensuring here an important extractive role for different minerals.

However, when taken individually, the global supply of some minerals can be very concentrated. D.R. Congo exports 80% of the world’s traded cobalt ores ; Philippines and Indonesia respectively 64% and 16% of the world’s traded nickel ores ; Guinea exports 49% of the world’s traded bauxite ; China 43% of the world’s traded natural graphite. This concentration of the supply side is a displayed source of concern for demanding core countries wishing to secure inflows of TCM.

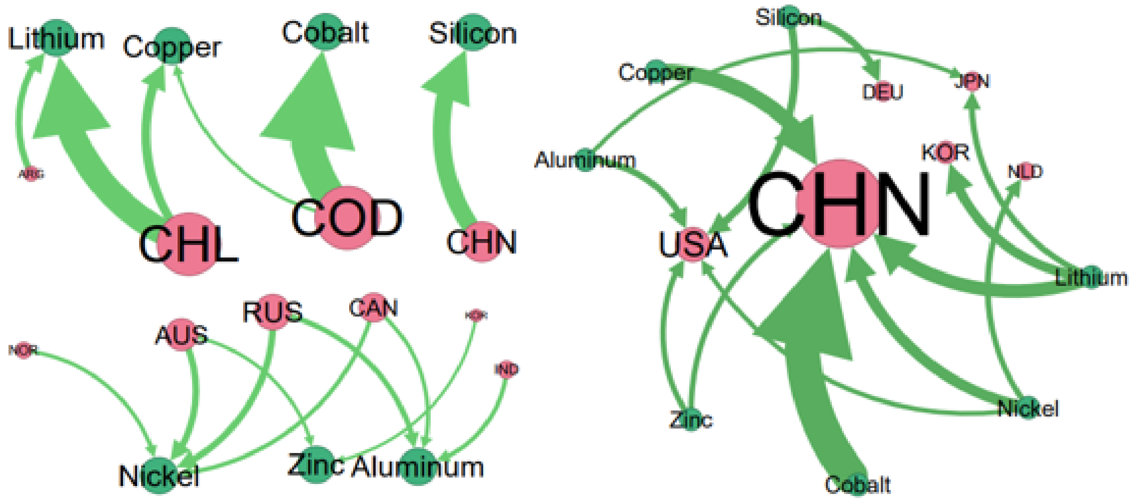
Looking at the demand side, China clearly dominates and absorbs the vast majority of the global minerals trade flows. Its imports account for 28 to 83% of global trade for all minerals, except graphite, for which China is by far the largest producer (see Table 10 in Appendix). At this stage of the GVC, China attracts a huge share of the global material flows and acquires large parts of foreign extracted natural resources, a core-like pattern that we will discuss later.

Regarding metals (processed and refined materials), Figure 2 shows a quite similar picture for the supply side, with an overall diversified supply, but highly concentrated for some metals taken individually. Aluminum, nickel and zinc are historically widely traded metals, their global offer is quite diversified, and notably ensured by industrialized developed economies.

Chile exports raw copper ores (15% of global trade) but also, and most importantly, refined copper metal (23% of global trade). In addition, Chile dominates the lithium carbonates global supply, its exports accounting for 63% of global trade. Finally, China exports 43% of world traded silicon carbides.

Regarding D.R. Congo, a nuance must be made as it most likely exports cobalt "mattes" and not pure cobalt metal properly speaking (see footnote 8). However, the fact is that the cobalt global trade is extremely concentrated from D.R. Congo to China, the latter being the top refining country for this material, as discussed later in section 3.2.

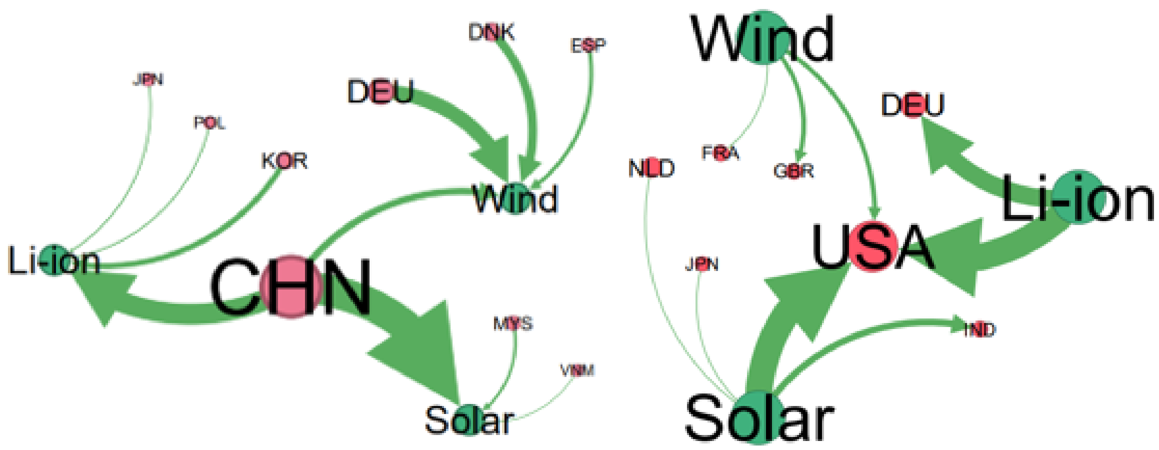
FIGURE 2 – Exports and imports of TCM metals



Source : BACI data. Australia (AUS), Canada (CAN), Chile (CHL), China (CHN), D.R. Congo (COD), Germany (DEU), India (IND), Japan (JPN), South Korea (KOR), Netherlands (NLD), Norway (NOR), Russia (RUS), United States (USA).

Looking at the demand side, China is clearly the biggest importing country, acquiring 25 to 35% of global traded nickel, lithium and copper metals, and especially 79% of world traded cobalt ores, mattes and unwroughts, confirming the tight link between D.R. Congo and China. Once again, China plays a core-like role acquiring large amounts of foreign transformed materials. However, other countries appear as major metal importers, unsurprisingly Germany, Japan, South Korea and the US. The latter are closer to traditional core countries that acquire foreign embedded nature in order to integrate it in their more sophisticated and value-creating domestic production chain.

FIGURE 3 – Exports and imports of LCT



Source : BACI data. China (CHN), Denmark (DNK), France (FRA), Germany (DEU), India (IND), Japan (JPN), Malaysia (MYS), Netherlands (NLD), Poland (POL), South Korea (KOR), Spain (ESP), United Kingdom (GBR), United States (USA), Vietnam (VNM).

Finally, at the last stage of the global value chain, for TCM-using low-carbon technology components, there is a major shift, as Figure 3 shows. China dominates the global supply chain and exports respectively 18%, 41% and 60% of world traded wind-powered generators, lithium-ion batteries and solar photovoltaic panels. Other important exporters are notably Denmark and Germany for wind-powered generators. However, globally, China dominates the downstream TCM and low-carbon technology GVC, and ensure a huge share of the global offer.
On the demand side, from the many countries importing these technologies, almost all of them are advanced economies from the Global North. The US is by far the most important, its imports accounting for 9% of wind-powered generators global trade, and 19% of global lithium-ion batteries and solar PVs global trade, appearing as the ultimate core country of this long and complex GVC. Its supplies significantly depend on China, especially regarding li-ion batteries for which 51% of US imports over the 2017-2022 period are directly from the latter (according to BACI data). Reliance is less important regarding the other technologies especially for wind turbines, however regarding solar PVs, the US indirectly relies on Chinese PVs components that are assembled in Malaysia or Vietnam in order to bypass the US tariffs on Chinese PVs (Basore et al, 2022). This direct or indirect reliance point at the "Chimerica" relationship we will describe later.

If China exports LCT to the US and to other advanced northern economies, it also provides for its own needs. Indeed, IEA data, presented below in Table 4, shows that China has the world's largest deployment of LCT, and by far, in absolute terms. It has the biggest manufacturing capacity and largely deploys its own technologies in addition of exporting them abroad. The US come second in terms of absolute deployed capacity. However, it is important to note that, on a per capita basis, deployment is higher in the United States than in China. Most importantly, unlike China, the US do not assume the socio-environmental and energetic costs associated with the transformation of TCM and the manufacturing of the technologies.

TABLE 4 – Electricity generation in 2023 in the United States and in China

Electricity generation	**United States**		**China**	
	Absolute	Per Capita	Absolute	Per Capita
Solar Photo-voltaic	183,812,000 MWh	0.55 MWh	427,270,000 MWh	0.3 MWh
Wind Turbine	439,270,000 MWh	1.87 MWh	762,672,000 MWh	0.54 MWh
Battery Electric Vehicle (Electricity Demand)	22,000,000 MWh	0.066 MWh	38,000,000 MWh	0.027 MWh

Source : IEA Energy Statistics Data Browser for electricity generation from solar PVs and wind turbines. IEA Global EV Data Explorer for EV-related electricity demand.

At first sight, the TCM GVC can therefore be broken down as follows : i) the Global South ensures the global TCM supplies (with the exception of important mining countries such as Australia or Canada), ii) China absorbs a huge majority of these supplies in order to transform them (metallurgical and manufacturing activities), iii) then China ensures most of the global LCT supplies, mainly flowing toward the Global North countries, especially the US, while still benefiting from a vast low-carbon technology deployment. This global structure composes an international transformation chain that acts as an impressive tool of displacement and concentration of matter, to the material benefit of the core, and reciprocally, to the ecological detriment of the periphery.
Regarding the extremes of the TCM GVC described above, the peripheries from the Global South are extractive peripheries that assume socio-environmental costs of extraction but do not materially benefit from technological deployment. Reciprocally, cores from the Global North do not assume the socio-environmental costs of extraction but do enjoy the material benefits of technological deployment.

As explained in the literature review, technology is an important index of EUE. This uneven global distribution between cost and benefit, extraction and technology, is the very basis of the EUE mechanism. Schematically, huge amounts of rocks, with low content of pure metal, are extracted and transformed in the periphery, in order to deploy technologies, with high content of pure metal, in the core. This massive energetic process, and material displacement, is not, and cannot be, perfectly compensated by monetary flows, because of uneven macro-economic conditions (that we will assess later on) and because of the absolute impossibility of compensating for socio-environmental externalities (shown earlier), and results in an uneven and uncompensated global technology deployment.

Therefore, this assessment clearly confirms that the TCM and LCT global supply chain constitutes an important case of EUE realization between TCM extracting peripheries and LCT deploying cores.
In that sense, this section 2 answers the first research question presented in the introduction. However, this preliminary investigation reveals two important countries around which this EUE is structured, namely China and the US as they have by far the highest deployment of LCT, pointing out at a specific three-tiered international hierarchy that we need to assess to complete the analysis.
There are two points to elaborate : i) China, which is central in the TCM and LCT GVC, and which seems to play the role of a semi-periphery ; and ii) the important role of geo-economics, particularly illustrated by the US relationship with China, that could modify or reshape the classical accumulation pattern of the core countries. We now focus on these two countries, their respective strategy, and their geopolitical and economic relationships with suppliers.

3 China and the US in the TCM and LCT macroeconomics

3.1 China material supply sources and macroeconomic conditions

China is a major mining country and exploits its vast and rich subsoil. In 2022, China accounted for 22.5% of world's bauxite extraction, 8.8% of world copper extraction, 72% of world graphite extraction, 15% of world lithium extraction, 70% of world silicon materials extraction and 32% of world zinc extraction (USGS, 2024). China thus assumes the related socio-environmental costs related to mining. However, it exports few raw materials as it ensures the processing and refining stage for its domestically extracted minerals as well as for the minerals that it produces little or none, and that it largely imports. Hence, China accounts for 58% of world aluminum refining, 78% of world cobalt refining, 43% of world copper refining, 15% of world lithium refining, 27% of world nickel refining, 80% of world silicon refining and 48% of world zinc refining (European Commission, Raw Materials Information System). In addition to be a major mining country, China is by far the most important refining one.
In order to reach this position, China has put in place a global strategy to access mineral supplies from several suppliers, by largely importing from, and investing in, foreign mining countries.

Table 5 shows China's main supplier for each selected TCM, [9] with i) the share of suppliers in Chinese imports of a material, and (ii) China's share in the suppliers' exports of the same material, in order to display mutual reliance. All these suppliers are net exporters of these products with China.
Generally, China has quite concentrated supplies as for several materials (bauxite, raw and refined cobalt, refined lithium, raw nickel) only one or two suppliers represent more than half of Chinese imports. For the other materials (aluminum, raw and refined copper, refined nickel) Chinese imports are more diversified. However, if China heavily relies on some suppliers for certain materials, on the other side,

9. Except graphite and silicon for which China dominates the world supply and does not really imports any

TABLE 5 – China's main TCM suppliers

Products	China Suppliers	% of China Imports	% of Supplier's Exports
Bauxite	Indonesia	58.6%	67.17%
	Australia	26%	63.7%
Aluminum	Russia	18.6%	3.11%
	Australia	18.4%	2.5%
Cobalt ore	D.R. Congo	69%	53.3%
Cobalt unwrought	D.R. Congo	56.3%	51.1%
Copper ore	Peru	20%	42.3%
	Mongolia	17%	92.3%
Copper cathodes	Chile	33.4%	27.4%
	Japan	10.17%	37.6%
Lithium unprocessed	Australia	42.3%	62.1%
Lithium carbonates	Chile	75.15%	15.9%
	Argentina	18.76%	21%
Nickel ore	Philippines	57.3%	71.2%
	Indonesia	30.8%	65.2%
Nickel unwrought	Russia	23%	18.4%
	Canada	23%	12.3%
Zinc ore	Australia	34.8%	27.6%
	Peru	15.6%	19.9%
Zinc unwrought	Kazakhstan	37.4%	42.1%
	Australia	17%	18.6%

Shares of the total on the 1995-2022 timespan. Source : BACI

some countries heavily rely on China to export their minerals (Indonesian bauxite and raw nickel, Australian bauxite and raw lithium, Mongolian raw copper or Philippines raw nickel). Overall, there are quite balanced interdependencies between China and its suppliers, the first rely on the second to secure material supplies, and the second rely on the first to secure export revenues.

The evolution of China's physical trade balance and import reliance for each material is available in Appendix 2. Globally, Chinese imports of minerals have largely increased over the last 20 years, illustrating the commodity boom driven by China's industrialization. This pattern is very strong since 2015 for materials that are specifically used in LCT, as 2015 is more or less the starting point for a large deployment of such technologies, following the COP 21 Paris Agreements. This result in increasingly strong trade relationships with some suppliers, cobalt from D.R. Congo, lithium from Australia and Chile, nickel from Indonesia and Philippines.

Some examples show how geopolitics and national strategies can shape global TCM trade flows. There has been a huge increase of aluminum supplies from Russia since 2021, potentially due to the trade restrictions Europe imposed to Russia after its invasion of Ukraine, resulting in reorientation of trade flows toward China — same happening for other products like oil (Grekou et al., 2023). Regarding Indonesian nickel, Chinese imports have drastically decreased due to the ban on raw nickel exports in 2014 and 2020,[10] aimed at developing Indonesian domestic refining activities in order to capture a larger share of added value.

Finally, an important point is the strong relationship between D.R. Congo and China which together, as supplier and importer respectively, account for the vast majority of the global cobalt trade (80% of

10. See : https ://www.iea.org/policies/16084-prohibition-of-the-export-of-nickel-ore

globally traded ores and 81% of globally traded cobalt mattes and unwrought in 2022). This tight link is the result of the Chinese international strategy that we will describe right after, and is an important source of concern for the Northern core demanding countries wishing to diversify their cobalt supplies.

TABLE 6 – Share of Chinese FDI in total FDI Inflows and share of Chinese FDI directed toward the Mining sector

Country	Share of Chinese FDI in FDI Inflows	Share of Chinese FDI toward the mining sector
Argentina	07.43%	15.13%
Australia	16.06%	33.27%
Brazil	06.92%	07.35%
Canada	07.70%	14.49%
Chile	06.01%	43.44%
Democratic Republic of Congo	48.22%	98.30%
Indonesia	12.91%	39.77%
Jamaica	10.70%	25.64%
Japan	08.17%	00.00%
Kazakhstan	14.52%	00.63%
Mexico	00.59%	14.44%
Mongolia	24.56%	44.85%
Norway	08.34%	00.00%
Peru	23.41%	63.44%
Philippines	10.29%	51.24%
Russia	06.60%	07.12%

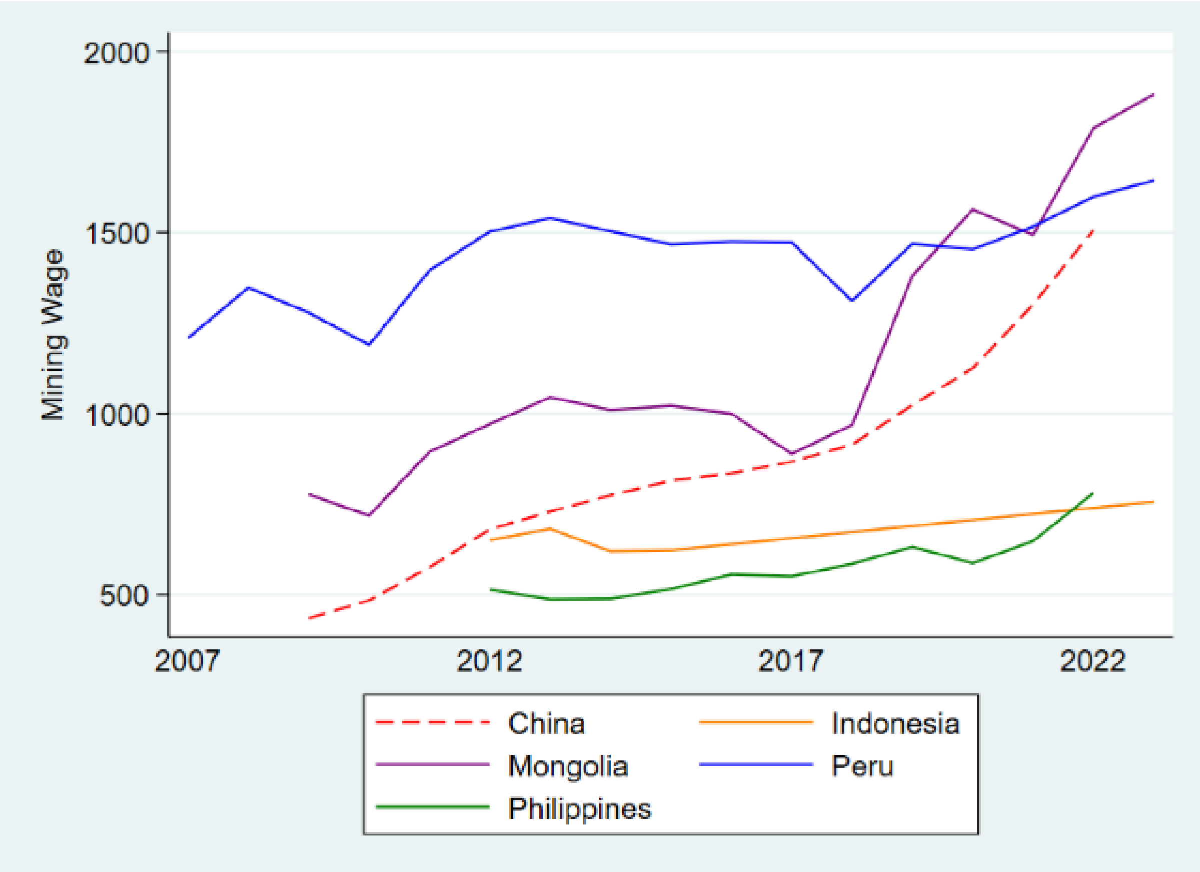
Source : UNCTAD FDI data ; American Global Investment Tracker for chinese FDI

In order to secure supplies of minerals it produces little or none, China largely imports from other mining countries, but also largely invest toward the latter, especially targeting the mining sector. This large international pattern of investment toward mining is a key component of China's strategy (Bonnet et al., 2022).

As Table 6 shows, Chinese FDI inflows account for a significant share of the total FDI inflows for several of these host mining countries over the 2005-2020 period. During this period, Chinese FDI accounted for around 10 to 15% of total FDI inflows in Australia, Indonesia, and Philippines ; almost a quarter of total inflows in Mongolia and Peru, and almost half of total FDI inflows in D.R. Congo. Moreover, these FDI flows are significantly targeted toward the mining sector. For the countries mentioned, more than a third, sometimes half, of Chinese FDI is directed toward the host country mining sector. Once again D.R. Congo is a very important country as almost all of Chinese FDI went toward the mining sector. Therefore, between 2005 and 2020, almost half of total FDI inflows in DRC was Chinese investments in the mining sector only.

Recent studies on company-level investments in the mining sector show the strong position of Chinese mining companies abroad. Faubert et al. (2024) build, for different minerals, a production-weighted holding rate, expressing the share of the world production ensured by multinational mining companies from different countries. It confirms the crucial role of China as, in 2022, Chinese mining companies ensure 28% of world cobalt production (operating essentially in DRC), 17% of world copper production (operating essentially in Chile, Peru and Mongolia, in addition to domestic extraction), 19% of world lithium production (in Australia, Argentina and Chile) and 18% of world nickel production (in Indonesia and Philippines). In an earlier study, Leruth et al. (2022) also showed the strong position of Chinese mining companies operating abroad and accounting for significant shares of the global production. Moreover, these two papers discuss the nature of Chinese investors and companies operating abroad. Faubert et al (2024) show the predominance of strategic investors in the Chinese multinational mining companies, accounting for respectively 100%, 77% and 48% of Chinese investors' holdings in firms extracting copper, lithium and cobalt. These strategic investors are long-term investors, not only driven by short-term financial returns, but moved by strategic or geopolitical interest to wield decision-making or governance power. In line, Leruth et al. (2022) show that most of Chinese mining multinationals are etiher state-owned companies (Zijin Mining Group, Jinchuan Group for example), therefore directly responding to (geo)political objectives of the Chinese state, or indirectly "private" companies with potential public holdings or decision-making power.

Figure 4 – Average monthly earnings in the mining sector, in 2021 PPP USD



Source : ILOSTAT

Now we must assess in which geopolitical and economic conditions these trade and investment relationships take place. [11]
First, regarding wage differentials, Figure 4 shows the evolution of average monthly earnings in the mining sector of China and its main mineral suppliers. When, operating in, or importing from, foreign mining countries, China does not systematically benefit from cheaper wages. Mining wages are indeed far cheaper in Indonesia, Philippines, and likely in DRC too. [12]
Regarding prices differentials now, figures are available in Appendix 2. Generally, the import prices paid

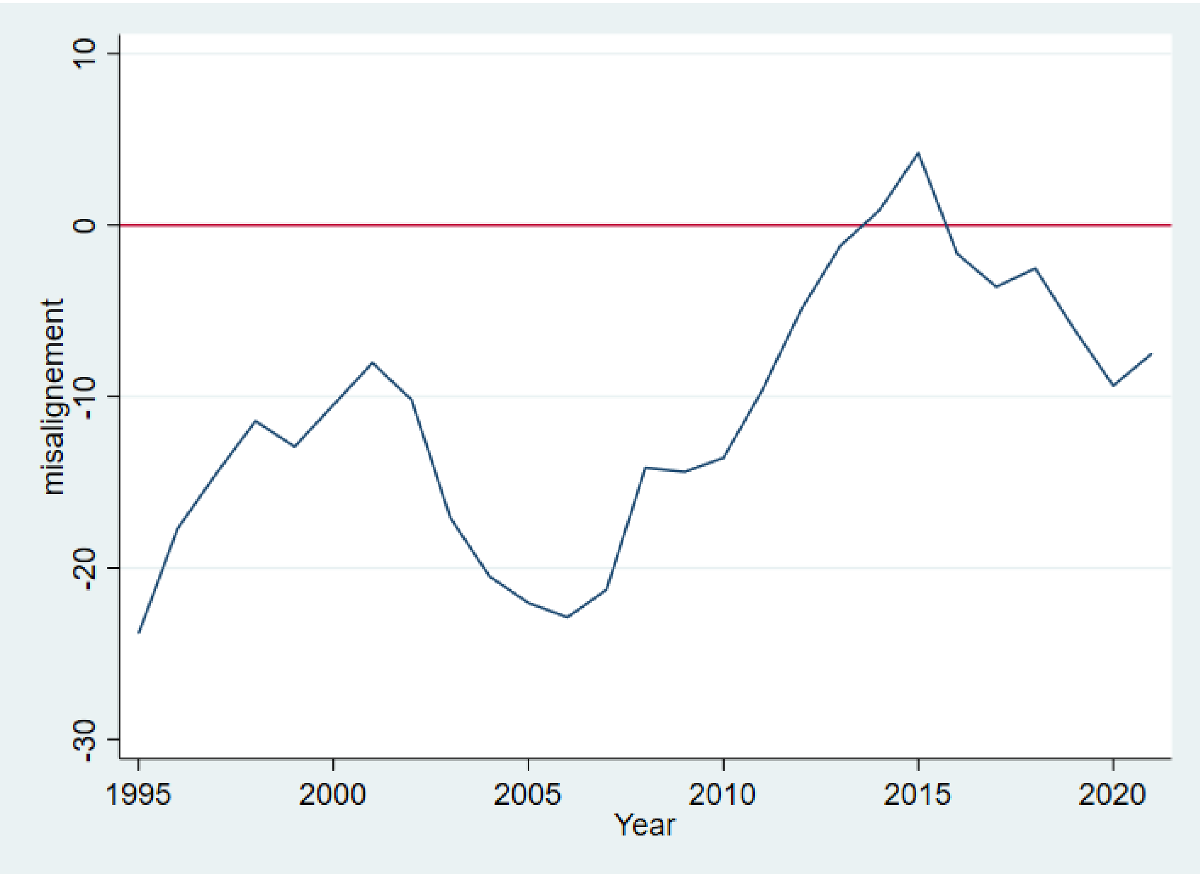
11. In order to assess the economic dimension of the EUE, value-added is generally considered as an important indicator. Unfortunately, precise and complete data on the repartition of value-added of the whole TCM and LCT GVC is not accessible. Therefore, this section is limited to assessment of the economic conditions in which extraction and trade takes place, namely wage differentials, price differentials and currency power. In the same idea, terms of trade are difficult to calculate as the TCM/LCT importing countries generally don't export the latter at all.

12. ILOSTAT data for DRC mining wage is only available for the year 2012 and is 70/month 2021 PPP USD which is extremely weak. But these wages are significantly higher in Peru or in Mongolia, and especially in Australia, under ILOSTAT data for mining wages in Australia is available only under the previous ISIC revision, but the average mining wage in Australia (on average over the 2001-2021 period) is 5800/month 2021 PPP USD, which is much higher than in China and/or its other mining suppliers.

by China are very close to the global market prices of the London Metal Exchange. [13] So regarding our data, there does not seem to be any kind of exorbitant economic exploitation between China and its mining suppliers over the prices issue. However, this point must be nuanced. First, there is potentially a significant part of the trade realized "over the counter", for which import prices paid by China are unknown and could potentially be lower than the global market price.

Then, we have already mentioned the imperfection of global markets and their inability to determine a "fair" price to compensate the socio-environmental externalities of both the exploitation of nature and the missed opportunities for the periphery, in terms of value-added and material development, of exporting raw materials. For example, regarding the carbon emissions externality only, France Stratégie (2020) has estimated the carbon footprint of metal production, from mining to refining, and shows that the implementation of a 60 USD carbon tax could significantly increase the price of some of the critical metals retained, especially aluminum (by 60%) and zinc (by 9%). But this is still hypothetical and today global markets do not take such an externality into account at all, and the carbon externality is just one among many other in the mining and refining sector.

FIGURE 5 – Chinese yuan misalignment



A value under zero means an undervaluation of the Chinese yuan, Source : EQCHANGE database from CEPII (Couharde et al. 2018)

13. One major exception is the DRC cobalt imported by China which seems to be paid at a significantly lower price. Cobalt is a complex case because our import data for refined cobalt (under code HS97 850510 in the UN comtrade data) corresponds to both cobalt mattes (around 50% of pure metal) and unwrought cobalt (99.8% of pure metal) combined. However refined cobalt traded under the LME corresponds to 99.8% pure cobalt only. Therefore, it could be cobalt mattes traded between DRC and China, explaining the price differential.

Finally, regarding currencies, the Chinese yuan is significantly undervalued since the early 2000s, despite a progressive revaluation between 2005 and 2015 (see Figure 5). Therefore, China does not benefit from an "overpowered" currency to easily buy foreign natural resources and goods. One point of nuance once again is that a significant part of the minerals' and metals' global trade could actually be labelled in USD, potentially benefitting China and its large reserves of USD (resulting from its trade surplus with the US).
Regarding geopolitics, Table 20 in Appendix shows the geopolitical influence of China over the mining supplying countries, using the Foreign Bilateral Influence Capacity index, which is constructed based on economic, diplomatic, military and political variables (Moyer et al., 2021). [14] The index ranges from 0 to 1. Therefore, overall, China's influence on its mining supplier countries is not very strong, with the exception of Indonesia and Russia, where the index does exceed 0.2. What is noteworthy, however, is the very strong growth of China's geopolitical influence over the period 2005-2020. This is in line with the assessment of China as a rising regional and global economic, and increasingly geopolitical, power (Moyer et al., 2021). Despite this dynamic, China has not been very influent in general over the TCM mining countries during this timespan.

3.2 US material supply sources and macroeconomic conditions

Copper ore is really the only TCM the US significantly extracts and exports, accounting for around 5% of the global ore production (USGS, 2024), it is historically an important resource for the US mining industry, and it might represent a strategic asset for the US in this new scramble for TCM. However, for other products, the US relies on foreign resources.

Indeed, as seen above (see Figure 1 and Figure 2), the US are not a major global importer of TCM but it still benefits from supplies from other mining countries. Table 7 shows US' main suppliers for each TCM the US significantly imports. For all products except copper ore, the US is by far net importer. Moreover, the US mainly imports refined metals, even refined copper from neighbouring countries as it does not necessarily have the domestic refining capacities. The US supplies are quite concentrated as, for each material, the first two suppliers always represent more than 50% of all US imports (except for processed cobalt which is more diversified). There are some very strong reliances to China for processed silicon or to Canada for several metals. The privileged partners are neighbouring countries, from the Americas (Canada, Mexico, Argentina, Chile, Peru, Brazil, and Jamaica), outside these continents there are only three exceptions (Norway, Russia and China). Finally, it is worth noting that besides Canada and Norway, all supplier countries are developing economies generally included in the "Global South"; China being the in-between exception here as a semi-periphery. Therefore, depending on the country, these supplies represent an unbalanced relationship of EUE, a strategic issue of dependency, or a balanced relationship of partnership. In dynamics, Norway, Canada and Mexico are important and constant suppliers, and the imports from Jamaica and Argentina for the related materials have increased. For these countries, the US is a major TCM importing country, resulting in a strong interdependence. The US relies on material supplies from these countries, and the latter relies on the US for export revenues. The two main exceptions are China and Russia, which are considered as foreign entity of concerns, rival or adversary economies. Since 2016 the US imports of Russian aluminum have drastically decreased to almost zero in 2022, strengthening the role of Canada as the main aluminum supplier for the US. This

14. "The FBIC Index's core input variables are as follows : 1) goods trade; 2) foreign aid; 3) arms trade; 4) diplomatic exchange (i.e., presence of embassies); 5) shared intergovernmental organization memberships; 6) trade agreements; and 7) military alliances. The FBIC Index also uses country-level data for 8) GDP and 9) military spending as denominators for the dependence indicators." For details, see Moyer et al (2021).

Table 7 – US' main TCM suppliers

Products	US Suppliers	% of US Imports	% of Supplier's Exports
Bauxite (aluminum ore)	Jamaica	40%	92.8%
	Brazil	22.5%	30.8%
Aluminum processed	Canada	54.6%	74.5%
	Russia	28.3%	20%
Cobalt processed	Norway	20.2%	53.3%
	Canada	14%	15.13%
Copper cathode	Chile	45.4%	13.8%
	Canada	28.4%	90.8%
Graphite raw	China	36.8%	10%
	Mexico	23.8%	88%
Lithium carbonates	Chile	58%	19.5%
	Argentina	42%	64.5%
Nickel unwrought	Canada	50%	41.9%
	Norway	15.3%	17.2%
Silicon carbides	China	68.6%	39.45%
Zinc ore	Peru	46%	3%
Zinc unwrought	Canada	59.7%	90%
	Mexico	10.9%	58.85%

Shares of the total on the 1995-2022 timespan. Source : BACI

is an important example of recent decoupling from an adverse country on a critical material supply, although regarding China the supplies have not really decreased for processed silicon.

Table 8 – Share of US FDI in total FDI inflows and share of US FDI directed toward the mining sector

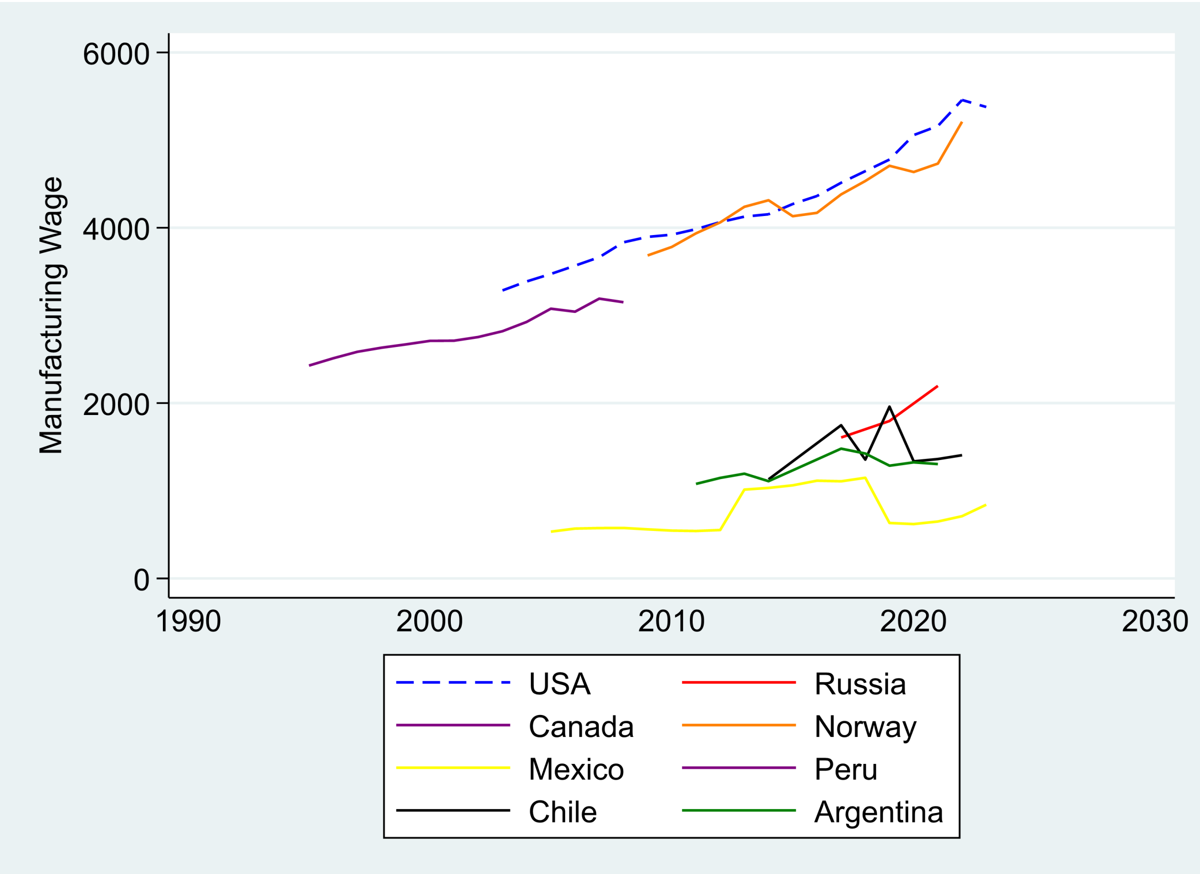
Country	Share of US FDI in FDI Inflows	Share of US FDI toward the mining sector
Argentina	9.68%	35.34%
Brazil	8.68%	16.35%
Canada	25.77%	13.69%
Chile	11.58%	18.65%
Jamaica	2.61%	0.00%
Mexico	14.59%	10.88%
Mongolia	0.71%	0.00%
Norway	41.09%	20.56%
Peru	8.53%	61.43%

Source : UNCTAD FDI data ; Bureau of Economic Analysis for US FDI

Like China, US companies have invested significantly in supplying mining countries between 2005 and 2020, especially in Canada, Norway and Mexico where US FDI represent an important share of total FDI inflows during this period. However, in general, US FDI are less targeted at the mining sector than the Chinese FDI in its mining supplying countries, with the exception of Argentina and Peru where respectively 35% and 61% of US FDI are directed at the mining sector. According to Faubert et al. (2024), US companies hold an important share of the world production for several minerals, 27% of world copper (thanks to its own domestic extraction, and its historical major copper mining companies operating in Chile, Peru and Indonesia) and 31% of world lithium (with operations in Argentina and

Chile). However, unlike China, the US has almost no "strategic investors" (Faubert et al., 2024). This is the main difference between US and Chinese FDI, already discussed by Leruth et al (2022). The US investments are fully private, and the US mining multinational companies (Freeport McMoran, Albermarle or Livent) are mostly owned by passive private hedge funds like BlackRock or Vanguard, that only follow short-term low-risk returns objectives (Leruth et al., 2022). Chinese FDI toward mining countries are targeted at this sector, following geo-strategic objectives of securing supplies, while US FDI follow economic objectives of short-term returns and profits. These financial objectives are contradictory with the industrial objectives of securing critical materials, necessitating strategic, long-term and riskier FDI.

FIGURE 6 – Average monthly earnings in the manufacturing sector in 2021 PPP

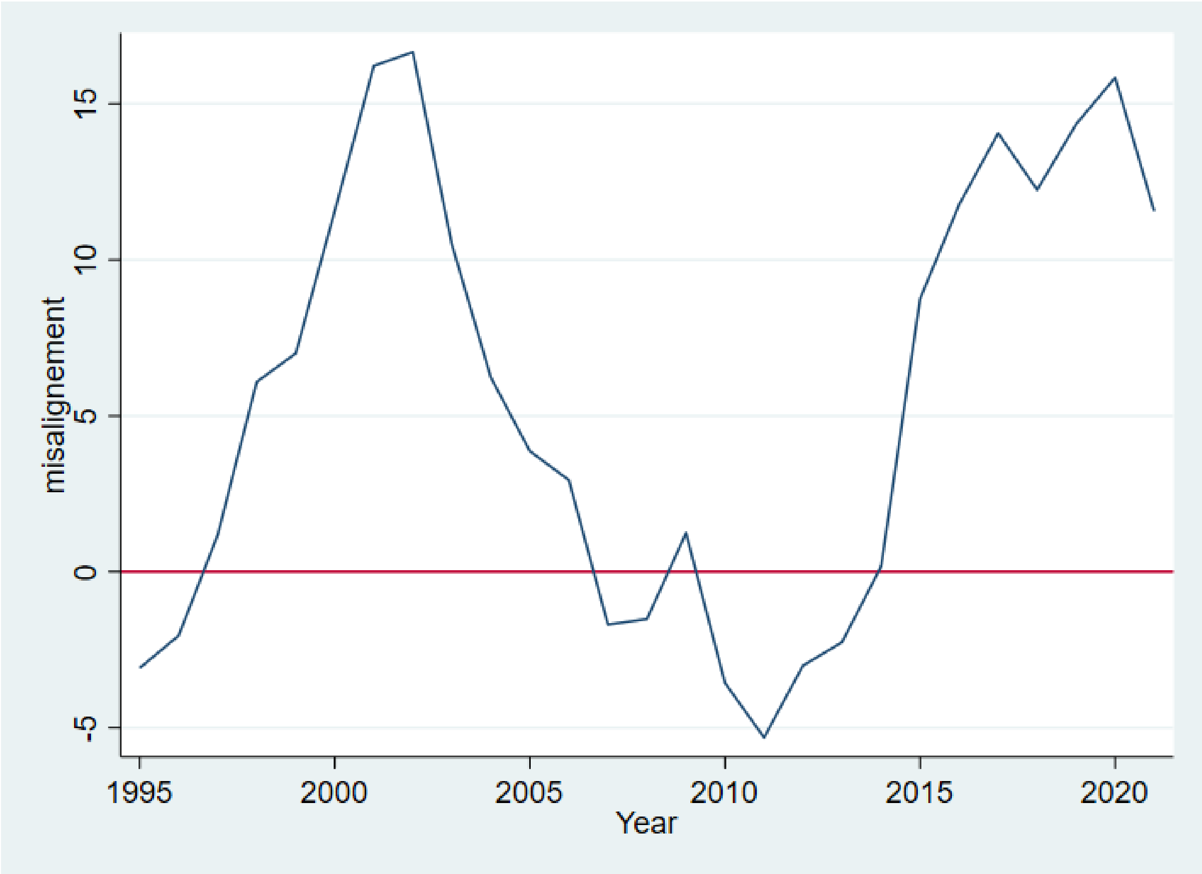


Source : ILOSTAT

Regarding the economic conditions in which trade takes place between the US and its suppliers, the US strongly benefits from uneven economic conditions. Figure 6 shows that the US has much higher wages than its supplying countries, at the exception of Canada and Norway, the latter being Northern wealthier countries with high wages and standards of living. These exceptions are important as Canada and Norway are significant suppliers for several minerals, and most importantly, part of the US friend-shoring strategy we will detail later. But besides these two, the US suppliers for TCM are emerging countries of the Global South, with lower wages and price levels.

From the economic point of view, the great unevenness between US and its suppliers mostly reside in the status of the USD. The US sovereignly issues its currency, which is largely overvalued, and there-

Figure 7 – USD misalignment



A value over zero means an overvaluation of the US dollar. Source : EQCHANGE database from CEPII (Couharde et al., (2018))

fore dominant in the global trade. The exorbitant privilege of the USD is naturally verified in its TCM supplies as well, and just as any goods, the US can easily finance a TCM trade deficit.
Regarding geopolitical influence, the overall US influence on its suppliers is important and significantly higher than that of China on its suppliers (Table 20 in Appendix). US influence is particularly strong on Canada and in Latin America, historical trade partners and geographically close countries. Over the 2005-2020, US influence has increased in some countries (Brazil, Chile) but also has significantly decreased in others (Argentina, Peru, that regarding mining, have hosted more and more Chinese investments). The dynamics are therefore less important for China, which has been a rising global economic and geopolitical power, but of course the US still generally remains the most influent country.

However, where the US really appears as an ultimate core country, is when regarding at its LCT supplies and deployment that almost entirely relies on China.
Since years, the strong core accumulation in the US generally relies on the "Chimerica" relationship. From the material point of view, China's industry, fueled by cheap labor and coal, supplied US material accumulation. From the monetary point of view, the US benefitted from the exorbitant privilege of its currency to finance its trade deficit, while China recycled its USD reserves in US Treasury bonds, reinforcing its status as the global key currency (Svartzman et al., 2022). Moreover, the US largely benefits from the cheap wages and low socio-environmental standards in the Chinese industry.
This strong relationship between US and China is perfectly incarnated in the TCM and low-carbon

macroeconomics, as China is the top supplier of LCT at a global scale and mainly toward the US, and vice-versa, the US is the top importer of LCT at a global scale and mainly from China. The large majority of LCT global trade is realized from China to the US and as a result, the US knows the highest deployment of LCT per capita (see Table 4).

3.3 The rising semi-periphery and the ultimate but challenged core

Table 9 summarizes the different data and indicators used so far in this paper to assess the EUE patterns, and to specify the socio-economic, ecological and technological characteristics that define the position occupied by China, the US and the mining peripheries in this multi-tiered international hierarchical structure.
The "mining peripheries" is of course an heterogenous block with countries with their own specific history, economic structure and geoeconomic relationships. This heterogeneity will be addressed in Section 4) when addressing national strategies. Still, these peripheries are similar enough to be considered as a whole, from a material point of view, as being large net supplyers of TCM, and from an economic point of view, as being emerging or developing economies (to the exception of Australia and Canada). The characteristics displayed in Table 9 represent aggregate averages for these peripheral countries. Moreover, no other countries display core-like characteristics or semi-periphery-like characteristics as markedly as the US and China.
Indeed, Section 2) highlighted the realization of EUE patterns through the international TCM and LCT supply chain, because of verified uneven global distribution of ecological costs, TCM material flows and LCT deployment. However this section 3) details the three-tiered structuration of such EUE with two specific countries, China and the US, and their economic and geopolitical relationships with the mining countries.

First, regarding China, and in line with recent literature, I argue that the latter must be considered as a semi-periphery, and this characterization is particularly relevant in the TCM and LCT GVC.
China has set up a large investment strategy at a global scale (driven by private but also public interests) in order to promote mining activities in, and to secure TCM supplies from, its main mining suppliers. Then, China is by far the main importer of minerals and refined metals at a global scale. Finally, China records the world's largest deployment of LCT in absolute terms (see Table 4). In regard with the theoretical framework presented earlier, the export of capital (and capitalism), the import of materials (or embedded nature) and the domestic technological deployment, are clear charasteristics of energy/ecological imperialism (Musso et al., 2020 ; Frame, 2022) resulting in an EUE (Hornborg, 2009 ; Hornborg, 2014 ; Ciccantell, 2020). Indeed, China seems to benefit from an actual material accumulation based on foreign labor and nature, to the economic and ecological detriment of its supplying mining peripheries.
However, China does not exert a very strong economic or geopolitical domination over its supplying mining peripheries (weaker prices and currencies, limited capital penetration besides the mining sector and moderate geopolitical influence). Then, China also massively exploits its own domestic nature and labor. Finally, China is the major manufacturer of finished LCT or components at a global scale and massively exports toward Northern economies. It seems that China is not only a weak or limited core, but also, and perhaps above all, an extractive and productive periphery that ensure significant transfers of high added-value and high material-intensity technologies toward the Northern core.

In line with Li (2021), Frame (2022) and Tausch (2025), and especially in regard to its position within

	USA	China	Mining peripheries
Material flows			
Minerals	Low surplus	High surplus	High deficit
Metals	Low surplus	High surplus	High deficit
Technology	High surplus	High deficit	/
Economic position			
Wage differentials	High positive differentials	Country specific	High negative differentials
Currency valuation	High overvaluation	High to low undervaluation	High undervaluation
FDI toward foreign mining	Moderate capital control	High capital control	Low capital control
Ecology and technology			
Ecological costs	Low costs	High costs	High costs
Technological deployment	High deployment	High deployment	Low deployment
Geopolitical influence			
Bilateral influence on supplyers	High influence	Moderate but growing influence	Low influence

TABLE 9 – Summary of the main structural indicators of an EUE in the TCM GVC, pointing at the macroeconomic, ecological and technological hierarchy between the US (core), China (semi-periphery) and mining supplying countries (periphery) in general.

the TCM and LCT GVC, China is a semi-periphery, at an intermediate position.
China records important physical trade surplus of minerals and metals from the TCM mining countries and benefits here from the EUE. Even if its economic dimension is limited (no significant wage, price or currency differentials with the mining countries, moderate economic and geopolitical influence), from an ecological and material point of view, the mining countries have to assume the socio-environmental costs of extraction while China benefits from the deployment of highly material intensive LCT. Therefore, China's supply of TCM from D.R. Congo, Philippines or Peru, to name a few, might represent the most striking examples of TCM-related EUE between China and supplying peripheries.
However, at the same time, China is itself an important mining and processing country, as well as being the major manufacturer and supplier of LCT and components toward the Northern core, the latter benefitting both from the economic and ecological dimensions of an EUE with China. European countries and mainly the US benefit from cheap labor and nature embedded in Chinese LCT products.

Regarding the US, and the geopolitical and economic conditions in which it trades with its TCM suppliers, the US largely benefits from wage and exchange rate differentials, in addition of externalizing the negative socio-environmental consequences of mining and refining, far from its domestic standards for environmental and labor protection. At the exception of Canada and Norway, which are other core Northern advanced economies, and as the current hegemonic core nation, the US are much likely to benefit from a significant EUE from its mining suppliers.
This dominant position is the result of its economic and monetary hegemony since the end of the World War II. Moreover, the US has a typical core-like political history of mining and foreign mineral sourcing,

as detailed in section 7.1) in the Appendix. The history of U.S. mining power can be broadly divided into three phases : (i) a domestic mining boom between 1870 and 1970 ; (ii) the post-WWII consolidation of global hegemony through extensive control over extractive peripheries in the Global South ; and (iii) since the 2000s, an increasing concentration of mineral supply reliance on China.
Therefore, if the US benefits from the EUE regarding its direct TCM supplying countries, the largest share of material appropriation is concentrated through the sourcing of downstream finished LCT products from China.
As shown earlier, the Chimerica analysis is totally relevant regarding TCM and LCT as China is a major extractive and productive periphery for the US. The majority of LCT global trade is realized from China to the US (see Figure 3), as a result the US benefit from the largest LCT deployment per capita (see Table 4). All of this has allowed the US to externalize the socio-environmental costs of extraction, refining, and manufacturing, bearing only the monetary cost within an uneven ecological, economic, and monetary relationship with China that remains largely to the U.S.'s advantage.

Finally, the other mining peripheries assume the heavy ecological costs associated to mining/refining, know large external transfers of domestic labor and nature, generally happening under uneven economic, financial, monetary, and geopolitical conditions. This results in the under-compensation of extractive activities negative externalities, as well as unsustainable economic structure and under-development of material and technological capacities.

This assessment clearly indicates a three-tiered international structure in which the TCM-related EUE takes form, and if the US acts a traditional accumulative and exploitative core, and most of the mining countries as traditional extractive and exploited peripheries, the central place of China as a semi-periphery completely shatters the binarity of the classical EUE theoretical framework.
Now, over the past few years, US hegemony is more and more challenged by China, and finds itself in a concerning situation of dependence toward the latter. Moreover, the different mining peripheries have their own strategies in order to cope with their under-optimal position. We assess the recent shifting geo-economic strategies, especially in the US but also in the rest of the Northern core, as well as in the Southern extractive peripheries, and investigate how it could potentially affect or modify the TCM and LCT macroeconomics and the resulting EUE patterns described above.

4 National strategies in shifting geo-economics

We have described how the TCM and LCT GVC follow patterns of EUE, mainly around China as a strong semi-periphery. However, there are crucial geopolitic and geoeconomic issues interacting with TCM and LCT as these materials and products are highly strategic. As explained earlier, they are high value-added technological products, crucial for energy and decarbonization stakes, as well as for digital high-tech (ADEME, 2024) or for the defense industry (Danino-Perraud, 2019). Moreover, the early 2020's are marked by important geopolitical and geo-economic tensions, disruptions and reconfigurations. Therefore, the EUE literature meets with the recent works on geoeconomic fragmentation (Aiyar et al., 2023).

China, as a strong semi-periphery in this GVC, seeks to continue its strategy described earlier, reinforcing trade and investment partnerships with supplying countries, as well as its domestic mining and industrial production in order to maintain its domination over the world supply of LCT. As of right now there is no clear signs of a shifting strategy for China, however the latter is likely to capitalize on its dominant position on this “generative sector” to maintain its massive economic ascent (Ciccantell, 2020) and assert its place as a core country in the world-economy. In addition of securing TCM supplies, China could offshore some of its production in peripheral countries in South-East Asia to reduce production costs, maximize profits but also avoid international sanctions tariffs or trade barriers. China has already offshored some of its solar PVs assembling in Vietnam, Malaysia and Thailand to bypass US’ tariffs (Basore et al., 2022), or offshored nickel refining capacities in Indonesia to avoid the latter’s raw ore export ban (Wiradikarta, 2024). China could also “weaponize” its dominant position on TCM refining and LCT production, using it as a geopolitical asset or mean of pressure, as it did in 2010-12 during the well-known “rare earth crisis”. It has been considered that China used its quasi-monopoly on rare earth elements production as a “geopolitical weapon” to settle a maritime conflict with Japan. At that time, Japan faced important economic consequences because of the disruption of trade flows and price increases penalizing the Japanese rare earths dependent industrial sectors. Finally, China could potentially use its dominant position to assert international credibility of its domestic currency, as historically, the international key currency has always been tightly linked to the key energy commodity (the coal-sterling nexus during the British hegemony, the oil-dollar nexus during the current US hegemony) (Aglietta et al., 2019). Therefore, one could imagine a TCM-yuan nexus in a new world economy hierarchy where China challenges the US hegemony, just like China has started to contract bilateral oil supply agreements labeled in yuan with various supplyers (Iran, Russia, Gulf States). If this scenario is still hypothetical, as TCM are largely traded in dollars over international market places, and as the Chinese will to assert a yuan hegemony in the world monetary system is not totally confirmed, there is however a strategy to internationalize its currency, potentially aiming at digitalization and more multilateralism (Aglietta et al., 2022), where its dominant position over the TCM GVC could play an significant role.

Regarding the US, there is much more to say on its strategies in this shifting geo-economics, that could modify its TCM and LCT supply patterns. Indeed, we mentioned the fact that after benefitting from the Chimerica relationship for years, the US now finds itself in a critical strategic reliance on China, in a context of increasing economic and geopolitical rivalry with the latter. The more China pursues its economic ascent, the more it leans toward becoming a core, the more it challenges the US hegemony. Whether it be in terms of material consumption (as we have shown earlier), international economic influence (through the BRI and the international investment and lending Chinese strategy) or even attempts of de-dollarization and internationalization of the yuan (Aglietta et al., 2022).

Therefore, the US has recently and increasingly asserted a geopolitical and economic rivalry with China, alongside the will to decouple from it, to reduce trade reliance especially regarding strategic or critical materials or technologies. Hence the growing literature on the new trade war and the geo-economic fragmentation around these two blocs, highlighting, since several years, a relative slowing of global flows of goods, a sharp increase in trade restrictions, as well as in protectionist or decoupling rethorics both in the public and private spheres (Aiyar et al., 2023). The US-China rivalry is central in this geo-economic fragmentation, and decoupling has actually started, even if currently it is still very limited, and only diluting ultimate dependence on China (as “countries that increased exports to the US also increased imports from China in the same sector”, see Freund et al., 2023).

Additionally, the TCM issue is central in this geo-economic fragmentation (Hache et al., 2024), and especially in the US-China rivalry. Indeed, since the 2010 REE crisis, there has been a renewed awareness on criticality and reliance on minerals/metals from the successive US governments. Several reports on criticality, supply chain assessments, and critical minerals listings have been published since then by the different administrations, in addition of public policies in order to diversify and secure critical material supplies (Humphries, 2019). Under the Trump I administration, reliance on critical minerals are considered as a defense and national security issue, in a 2017 decree first, then as an "unusual and extraordinary

threat" in a 2020 decree declaring a state of emergency. Emphasis is put on military and high-technology, China being clearly considered as a threat and an adversary. The Biden administration have added the issue of LCT material requirements, especially through the Inflation Reduction Act, which was designed with two objectives in sight, the promotion of LCT deployment, and the onshoring, securing and diversification of supply chains. [15] Trump II administration marked a partial rupture, with an anti-ecological backlash limiting the promition of LCT deployment. However, it reinforced efforts to decouple from China, reshore production, and regain control over foreign mineral resources (e.g., Greenland, Ukraine, D.R. Congo), driven less by ecological concerns than by geo-economic objectives, profit-seeking motives, and other material applications in digital and defense sectors.
Whether it be for military, technological, energetic or economic objectives, there is in the US a clear political will to onshore and promote a domestic industrial supply chain, to reduce reliance on rival countries and especially China, and to secure material supplies from chosen countries.

Specifically, there are three perspectives, linked and complementary, for the US, and by extension for other core countries in general, like the European Union for example.

— *i) Decoupling from China and "Foreign Entities of Concern"*
  First, securing supplies and reducing reliance on foreign entities of concern, especially China. For energetic, military and technological reasons, the displayed national material security objectives for the US relies on a decoupling, or at least a drastic reduction of strategic reliance, from China regarding TCM and LCT imports. For now, this process may have started but is still very limited, despite the growing geopolitical tensions and the displayed "trade war" rethoric, the US-China decoupling is far from being fully realized (Freund et al., 2023). However, in this wake, a reduction of TCM and LCT imports from China (or other important mining countries like Russia, also considered by the US administration as a "Foreign Entity of Concern") represents a material limit to the deployment of LCT in the US. More generally, cutting down trade with China or any other undesirable extractive periphery means giving up on material inflows of minerals/metals/technologies for all sectors. In this perspective, if trade between US and China slows down, this could lead to a mitigation of the realization of the EUE between these two countries. However this displayed objective goes against the de facto Chimerica cooperation that happened for years and it will take time, political and economic will to be realized, to restructure these global supply chains.

— *ii) EUE from the Global South*
  The second perspective of the US strategy would consist in securing supplies from its existing, and from new, mining peripheries in the Global South. For most of its supplier countries, the US benefits from uneven economic and monetary conditions (especially cheap foreign wages and currencies), and important asymmetrical material flows, therefore perpetuating an EUE with Global South extractive peripheries. Indeed, there is a vast literature studying the historical and the current general EUE between the US and South-American countries for example (Munoz et al., 2011 ; Alonso-Fernandez et al., 2022). The potential increasing TCM sourcing from these countries, and the increased geoeconomic competition between US and China for control over

15. Indeed, the IRA promoted the domestic extraction of critical minerals, the domestic production of LCT and low-carbon energy, and set up a number of requirements on the different tax credits, especially regarding the origin of critical materials. For example, regarding electric vehicles, the consumer tax credits were enabled depending on a threshold percentage of critical minerals extracted or processed in the United States or in a free trade agreement country or a critical mineral agreement country, with an ineligibility for vehicles that have battery components manufactured or assembled by a foreign entity of concern, China likely to be one of them (IRA Guidebook, 2023).

extractive peripheries, would be a source of reproduction but also of aggravation of the existing EUE patterns. However, it would be difficult for the US to secure partnerships and supplies where China is already deeply grounded, in Africa or South-East Asia for example. But still, in this perspective, one can argue that the TCM sourcing, in unchanged conditions, perpetuating EUE patterns, is a source of environmental injustice and therefore represents a political limit to a project of a fair global energy transition.

— *iii) Reshoring and friendshoring with the Global North*

The third perspective for the US stems from this material limit induced by decoupling from China. In order to maintain, and to secure TCM and technologies supplies, the US will develop reshoring and friendshoring strategies. Reshoring of mining and manufacturing activities have recently been largely promoted in the US by protectionist policies since the first Trump administration and under the Biden administration as well. Regarding domestic mining activity, since 2022, concrete actions, [16] and huge amounts have been took to revitalize and boost the domestic mining sector. [17] However, the onshoring strategy faces two main limits. First, the issue of the social acceptability of domestic mining activities, as it means the reshoring of the related socio-environmental negative externalities. [18] Second, the geological limit, as the US territory is not endowed with all the TCM and there has been a structural decline in ore grades in mines operating in the U.S. for almost 40 years (Hammond et al., 2022).

Hence this onshoring strategy is coupled with a friendshoring strategy, a strategic strengthening of trade relations with allied, or at least chosen, partner countries because of their economic and political proximity with the US, in order to secure TCM and technologies supplies. For example, the US have signed a Critical Minerals Agreement with Japan in 2023, enabling Japanese metals to comply with IRA restrictions. The US are also part of the Minerals Security Partnership that aims to "diversify and stabilize global supply chains" as well as promoting investment, ESG standards and recycling within a club of a dozen of countries, plus the EU, all developed countries from the Global North, sometimes described as a "NATO for minerals and metals" (Vivoda, 2023). In this club, Australia and Canada are important mining countries, Japan and Norway significant refining countries, and Germany and South Korea important LCT manufacturing countries. However, this strategy faces some tradeoffs and limits as well. First, friendshoring represents an economic tradeoff, as these mining countries have higher economic and ecological standards, there is no easy and cheap foreign resource appropriation, and material accumulation in the US will therefore happen at a much higher price. Then, conceptually, if better, as more balanced, economic, monetary and ecological conditions of TCM extraction, refining and trade between the US and allies, could eventually mitigate the EUE mechanism. But this mitigation is likely to stay very limited as the logic of exploiting and commodifying nature would remain fundamentally unchanged. The environmental consequences of mining activities remain major and are underestimated or overlooked in the capitalist framework, despite environmental standards, the ecological dimen-

16. The first Trump administration has sought to reduce environmental constraints on mining companies, and accelerate the permitting process by adding the mining sector to the industries eligible for fast track permitting under the FAST-41 law, originally intended to simplify and speed up the permitting process for utility projects streamline. In May 2023, under the Biden administration, South 32 was the first mining project to beneficiate from the Fast-41 law, for the silver, lead, zinc and manganese Hermosa Mine in Arizona.

17. Under the IRA, 250 M USD is granted to the Department of Defense, to invest in critical mineral mining or processing projects ; the Department of Exterior is instructed to ensure 40B USD of loans ; and the Department of Treasury to ensure a 10% tax credit, for critical minerals mining and processing (IRA guidebook, 2022).

18. Two important case studies, the Rosemont copper project in Arizona (LeGouill, 2017) and the Thacker Pass lithium project in Nevada (Rodeiro, 2023), can provide a good understanding of the complex legal struggles, the opposing interests, the environmental claims from locals, in addition to recalling the colonial history of US mining, when native tribes constitute oppositions based on cultural and sovereignty concerns.

sion of the EUE is not easily reducible. [19] Depending on the effective level of cooperation between these countries, as well as the levels of material consumption, and the equity of the allocation of material flows, this perspective could result in an unconventional North-North EUE, more or less mitigated : from fair exchanges and symmetrical material flows between core countries, resulting in the minimization of the EUE, to relatively unfair exchanges and asymmetrical flows resulting in the semi-peripheralization, regarding this specific GVC of some countries within the core. Finally, there are geological and material limits, as it is unlikely that in the short term, these countries have the sufficient resource endowments and the mining and manufacturing capacities to reach their own demand. As shown above, the entire TCM and LCT GVC is centered around China's dominance and it would take much time, efforts and coordinated policies to shift this GVC around these Northern allied countries.

Regarding this third perspective, these policies suffer some instability, as in the US for example. If there has been a certain continuity between the onshoring/friendshoring strategy between the Trump administrations and the Biden administration, the objectives differed, while the Trump administrations emphasized the national security, defense and high-tech issues, the Biden administration emphasized on the climate emergency and the LCT. The second Trump administration has disrupted the initiatives of the previous administration, such as the IRA, as climate and LCT deployment are no longer a government's priority. There is also a breakdown in certain diplomatic methods and relations, which could have an impact on "mineral diplomacy" and friendshoring initiatives, regarding the tariffs applied to Canada in early 2025 for example. However, the second Trump administration is likely to ease the mining permitting processes in order to promote domestic extraction, not really to fuel the TCM demand for the LCT, nor to reduce the EUE with China and its peripheries, but to ensure material sovereignty and maximize profits from extractive activities. But this would have for consequences the US domestic extraction of TCM, like the several copper projects in Arizona or lithium projects in Nevada for example (LeGouill, 2017 ; Rodeiro, 2023 ; Riofrancos, 2023). Finally, the second Trump administration could also adopt more direct methods to expand its commodity frontier, referring to the Trump's imperial statements on the mineral-rich territories of Greenland, Ukraine or D.R. Congo. It is still too early in the second Trump administration, and it is hard to distinguish between publicity stunts and real political projects, but what is sure is that this a source of uncertainty and instability in the climate and LCT US policies, the only constant will still be the economic profitability.

It seems that in periods of hegemony, the core seeks to optimize supply inflows and maximize earnings from the realization of the EUE. However in period of challenged hegemony and reliance, it seeks instead to secure supply inflows even if this means a redirection or restructuring of the EUE benefits. These strategies and policies can present inner contradictions, regarding the onshoring of socio-environmental costs as well as the monetary costs induced to a reconfiguration of the global supply chains, these strategies are not exactly compatible with a liberal capitalist framework, hence the resurgence of state-driven policies, that still have to coexist with private interests. This is the inner contradictions of "green capitalism" within the "security-sustainability nexus" (Riofrancos, 2023). Despite the uncertainty and the inner contradictions, these strategies and the shifting geo-economics around TCM and LCT are major and need to be studied as it could end up in a modification or a redirection of trade flows and therefore of EUE patterns, more than a reduction of the latter. From a "direct" North-South EUE, without passing through China, to a North-North EUE, between the US and Australia and/or Canada for example, or even to an "internal" domestic EUE between extractive and non-extractive regions. Indeed, there can be asymmetrical material flows and appropriation patterns within a national economy. Extractive regions

19. "Smart-mining" or "sustainable mining" are highly criticized concepts, even considered as an oxymoron for some (Kirsch, 2010 ; Goodland, 2012). The literature has shown that mining is inherently unsustainable (SystExt, 2023).

can undergo a subnational resource curse (Cust et al., 2016) while richer regions benefit from this extraction and pursue significant economic development, resulting in an internal EUE typical of semi-periphery (Ciplet et al., 2019), [20] China for example, has rich coastal areas with high levels of material accumulation, and poorer internal extractive regions (Tausch et al, 2025). The Environmental Justice stakes are also very high in some countries of the Global North, which would like to reshore extractive activities, to the benefit of the wealthiest regions and urban centers powered by low-carbon electricity, but to the detriment of local Indigenous People living near/in extractive regions (in USA (Rodeiro, 2023), Australia or Canada (Horowitz et al., 2024)).

Regarding Global South extractive peripheries, these mining countries can, if political independence and stability is ensured, take political ownership of these issues, think about national economic natural resource management and develop related industries in order to build a more favorable balance of power with the core countries. There is a huge opportunity to maximize and capture the national mining revenues and invest them in other sectors in order to diversify the economy and/or to develop an industrial sector on the following stages of the GVC, where much of the value-added lies. There are several examples of mining countries trying to work in this direction. In 2024, Chile's government created the state-owned National Lithium Company in order to partially and progressively nationalize the lithium production, as it did with copper, Codelco being a fully state-owned company and one of the world's largest copper mining company. Indonesia's government progressively banned exports of raw nickel ore in order to promote the development of metallurgical sectors, to capture more added value and export refined and transformed nickel metal. Other examples come even closer to resource nationalism. In Bolivia, the lithium resources and the related mining and industrial sectors have been nationalized, accepting selected and limited international partnerships only, the national company learned, by doing, to develop a small but sovereign battery-grade lithium national production (Mariette, 2021). Mining activities can also be part of a strategy aiming at economic and political independence for Indigenous people. Like the Kanak people in New Caledonia, which follows the "nickel doctrine" which aims at developing nickel mining and refining activities, even if it faces several difficulties and failures, in order to capture value-added and revenues, while still thinking on diversifying the local activities to prepare for a "post-nickel" economy (Demmer, 2018).

Besides these examples, there is an issue of limited room of manoeuvre for these extractive peripheries that have to cope with this unfavourable hierarchical global economic system, as well as external commercial and financial dependence. As Alami et al. (2025) explains, in this context of geoeconomic fragmentation and tightening of global industrial policy, only large emerging countries with sufficient political and fiscal space could capitalize on some specific strategic asset in order to ensure a key intermediate position in the international economic structure. In the same idea, Ciccantell (2020) develops the concept of "generative sector", a key strategic industrial sector that drive the economic ascent of a rising economy in the hierarchical international economic structure. A strong positioning on the TCM and LCT GVC could be such an asset for the current peripheries.

Therefore, in the short run, capturing revenues and value-added, diversify and climb up the value chain, reduce the opportunity costs associated with the EUE, can be beneficial in order to ensure a key strategic position, in order to "ascent" to a semi-peripheral position (like China) and potentially to a core position (like Japan did). However, at short-term, such ascent comes with the heavy socio-environmental costs of extraction and, above all, at a longer term, such strategy can be considered as illusory, as it stays in the current framework of the inherently unsustainable and unfair "zero-sum" world economic system, where

20. "In doing so, the semi-peripheries developed decidedly bimodal or mixed economies, with extremely modern sectors and vast internal regions continuing to live in pre-modern conditions (Hecht, Anderson, and May 1988)". (Ciplet et al., 2019).

not every nation can be in the core (Hornborg, 2009).

This section has shown that the TCM and LCT global value chains are evolving within a shifting geo-economic landscape, where each country pursues distinct national strategies shaped by its position in the international hierarchical structure and guided by its own interests. These complex strategic interactions could, in the short term, alter, redirect, mitigate, or exacerbate the patterns of TCM-related EUE discussed in Section 2, potentially reshaping the relative positions of the US China, and mining peripheries, presented in Section 3.

However, in the longer term, it appears that as long as these strategies remain framed within logics of material-technological accumulation and high economic growth, TCM-related EUE are unlikely to be significantly reduced in absolute terms. A truly global and "fair" low-carbon transition would therefore require deeper, more structural and radical policy shifts, which will be addressed in the conclusion.

5 Conclusion

The heavy socio-environmental costs associated to mining activities, as well as the uneven global material allocation of TCM and LCT, pose an ethical limit to a “fair” global transition. The huge international TCM trade flows characterize significant EUE patterns between TCM extractive peripheries, mainly in the Global South, and richest core countries in the Global North, deploying and accumulating LCT. China is in-between, playing a crucial role as a semi-periphery, both suffering and benefitting from the EUE, while the US have definitely been an ultimate core in this GVC the past ten years.

However, the geo-economic fragmentation and the shifting geopolitics and national strategies around TCM as a national energy and industrial security issue can have a significant impact on these EUE patterns, not likely reducing such EUE but potentially modifying its directions. At the same time, the fast-growing demand for TCM is likely to pressure every resource endowments and motivate extraction, both in the core and the periphery, so it is also much likely that the TCM-related EUE patterns will be strongly exacerbated everywhere.

Therefore, a "fair" global ecological transition seems incompatible with the current capitalist, growth-seeking and extractivist world economic system. It seems necessary to step out of this unsustainable framework, aim for an i) **ecological** transition, not only focused on carbon emissions reduction, but on the preservation of living in general, and ii) a strong energetic and material sufficiency, as well as international balanced cooperation. In order to achieve this, in line with a “global sustainability by cooperation” (Althouse et al., 2020), core countries from the Global North have to rethink their model of material accumulation and energy consumption. Turning to the emerging peripheries of the Global South, all efforts must be made to ensure a sustainable development that does not repeat the unsustainable patterns of capitalist development. A strong global cooperation could enable organized degrowth of material flows in the core and sustainable development in the periphery (Althouse et al., 2020 ; Hickel, 2021), which would be the best case scenario in order to mitigate and adapt to climate change, while still protecting all living as well as environmental justice.

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7 Appendix

7.1 Political history of US national and international mining and supply strategies.

The US is an important mining country and has always benefited from a geologic asset, with a vast and resourceful territory. Between the 1870s and the 1970s, almost a century of highly favorable political, legislative, geological and industrial context enabled intense extractivism within the domestic commodity frontier. The colonization of the Western territories gave access to new deposits, the General Mining Act in 1872 favored prospection and exploitation, and the mining industry boomed, especially around steel in the North East, benefitting from large deposits of coal and iron, and around copper in the South West, benefitting from cheap Mexican labor and qualified mining engineers from the Tucson University of Arizona founded in 1885 (LeGouill, 2019 ; Black, 2018).
Therefore, regarding base industrial metals, the US was, in 1970, a major global actor in both mining and refining (11.9% /19.3% of global iron mining/smelting ; 26.3%/23.3% of global copper mining/smelting ; 37.3% of global aluminum smelting and 20.1% of global steel smelting, from USGS 1970 yearbook). The US thus enjoyed a certain degree of metallic sovereignty, fueling the strong industrial and material development of this country during the 20th century, participating toward its rise to global hegemony (Mitchell, 1983 ; Ciccantell et al., 2020).
Then, the 1970s and the 1990s marked a relatively sharp decline of the US domestic mining industry. In the 1970s, the legal context became less favorable, with the hardening of the permitting process to exploit deposits, and environmental laws that penalized the highly polluting refining sector (Legouill, 2019 ; Hammond et al., 2022). Geological resource depletion also played a role, as there has been a structural decline in ore grades in mines operating in the U.S. for almost 40 years, leading to increasing costs of extraction for decreasing amounts of pure metal in the end (Hammond et al., 2022). Then, in the 1990s, U.S. public policy began to lose interest in domestic mining. The collapse of the USSR in 1991 put an end to the hypothesis of conflict and competition with the Soviet bloc. Then, the development of globalization has led to the internationalization of US mining companies and increased imports of ores and metals, to the detriment of domestic extraction (Hache et al., 2022). These structural changes resulted in a significant decline of the US mining activity and a rise in US reliance on foreign mining countries (Net import reliance in the US in 1995 : copper (6%), aluminium (25%), zinc (41%). Net import reliance in the US in 2022 : copper (41%), aluminium (54%), zinc (76%). Source : USGS mineral yearbooks).

In parallel of its domestic decline, the US had to expand its mineral commodity frontier abroad. The issue of accessing foreign raw materials supplies was already a growing concern for the US material security and economic development at that time, as evidenced by the President's Materials Policy Commission, or the "Paley Commission", report of 1952 (Riofrancos, 2023). The most striking example of this strategy during the second half of the 20th century is the Point Four Program. In the context of the Cold War, in order to compete with the USSR and to secure material supplies to fuel its economic ascent, the US actively promoted natural resources exploitation and mining activities around the world, notably in emerging countries, in the Global South peripheries. Led by the Department of Interior, the Point Four Program was a vast foreign policy strategy, mixing public and private initiatives, from financial to technical assistance on field, strongly tinted with interventionist ideology. This Program succeeded as it resulted in the multiplication of mining projects, as well as diplomatic and trade relationships, throughout the Global South peripheries (Black, 2016 ; Black, 2018). More specifically in Latin America, the imposition of a work organization model, a technological model and a political model, enabled US mining companies to dominate, and to access resources (Legouill et al., 2019). Or more directly, the

1973 coup in Chile, supported by the CIA, had the consequence to open up Chile's copper resources to US companies and markets, or the US support of the Indonesian government's bloody colonization of West Papua, which has enabled Freeport McMoran's subsidiary to exploit the Grasberg mine since 1967, the third largest copper mine in the world (Izoard, 2024). The US has an important history of resource imperialism or related international strategies fueling its strong position in the World-Ecology System. Then, more recently, since the 1980's, the Global South emerging countries have undergone a complete conversion to the neoliberal economic principles, through the Washington Consensus and the related structural adjustments. As explained earlier, the contemporary liberalization of global trade and global finance replicates, through purely economic mechanisms, the EUE between the Northern core and Southern peripheries. Moreover, some authors evoke a "commodities consensus" in Latin America, leading to its "re-primarization" and extractivism, materially benefitting the core and the US. In this context, the US is hegemonic, at the top of economic, monetary, financial, technological and military global hierarchy in addition of being geopolitically and economically influent at a global scale. Therefore, the US largely benefits from the EUE with Global South peripheries in the current neoliberal world-system where it is positioned as the most powerful core country. Offshoring and outsourcing enabled to restore profit while maintaining cheap material supplies.

However, the US has increasingly positioned on the very downstream of the GVC, importing goods and finished products with the most embedded value, labor and nature. And regarding the TCM and LCT GVC, the US has "neglected" control over upstream activities in the periphery, relying heavily on China as a supplying semi-periphery. This results in a paradoxical situation for the US, being both an accumulative and exploitative core toward China, while at the same time being largely strategically dependant on the latter, because of reduced control and supply from the primary extractive peripheries. Therefore, the US now aims at reviving domestic mining and regain direct financial and political control over foreign extractive activities, in order to reduce direct reliance toward China and regain its predominant core position not only downstream but all along the GVC.

7.2 Tables and figures.

Table 10 – Main mining countries by mineral

Minerals	**Main producing countries (1997-2020, % of world production)**	**Main producing countries (2020, % of world production)**	**Main uses in LCT**
Bauxite	Australia (17%), China (12%), Guinea (11%)	Australia (27%), China (24%), Guinea (23%)	Wind and solar energy infrastructures, electricity networks
Cobalt	D.R. Congo (52%), Zimbabwe (8%), Canada (8%), Russia (8%)	D.R. Congo (73%), Russia (7%), Australia (4%)	Power storage batteries for electric vehicles
Copper	Chile (36%), USA (10%), Peru (9%), China (7%)	Chile (32%), Peru (12%), China (9%)	Electricity networks, wind turbines, solar PVs, electric vehicles
Graphite	China (70%), Indonesia (12%)	China (79%), Brazil (6.5%)	Power storage batteries for electric vehicles and storage grids
Lithium	Australia (40%), Chile (30%), China (10%)	Australia (48%), Chile (26%), China (16%)	Power storage batteries for electric vehicles and storage grids
Nickel	Russia (17%), Indonesia (14%), Canada (12%), Australia (11%)	Indonesia (36%), Philippines (16%), Russia (13%)	Power storage batteries for electric vehicles
Silicon	China (59%), Russia (10%), Norway (6%)	China (70%), Russia (7%), Brazil (5%)	Solar PVs, electric vehicles
Zinc	China (29%), Australia (12%), Peru (11%)	China (31%), Peru (10%), Australia (10%)	Wind turbines

Source : United States Geological Survey for production data ; International Energy Agency for uses.

Table 11 – Materials and Products HS6 codes

Material	Stage	Product	HS-6 code
Aluminium	raw	Ores and concentrates	260600
	processed	Unwrought not alloyed	760110
Cobalt	raw	Ores and concentrates	260500
	processed	Unwrought and mattes	810510
Copper	raw	Ores and concentrates	260300
	processed	Unwrought cathodes	740311
Graphite	raw	Natural graphite	250410
Lithium	raw	Unprocessed lithium minerals	253090
	processed	Carbonates	283691
Nickel	raw	Ores and concentrates	260400
	processed	Unwrought not alloyed	750210
Silicon	raw	Silicon sands	250510
	processed	Carbides	284920
Zinc	raw	Ores and concentrates	260800
	processed	Unwrought not alloyed	790111
Li-ion Batteries	finished technologies	Lithium-ion accumulators	850760
Solar panels	finished technologies	Photosensitive semiconductor devices, including photovoltaic cells whether or not assembled in modules or made up into panels	854140
Wind turbines	technological components	Generating sets, wind-powered	850231

Under the UN COMTrade HS 2017 classification. Regarding Cobalt under 810510 code, UN COMTRADE data aggregates "unwrought" (actual cobalt pure metal) with "mattes" (intermediary metallurgical products with a much lower purity level), see footnote 8.

Table 12 – Exports of minerals in percentage of world trade (2017-2022)

	Bauxite	**Cobalt**	**Copper**	**Graphite**	**Lithium**	**Nickel**	**Zinc**
Australia	26%	/	4%	/	19%	/	18%
Chile	/	/	15%	/	/	/	1%
China	/	1%	/	43%	9%	/	/
D.R. Congo	/	80%	1%	/	/	/	/
Guinea	49%	/	/	/	/	/	/
Indonesia	10%	9%	4%	/	1%	16%	/
Madagascar	/	/	/	12%	/	/	/
Mozambique	/	/	/	14%	/	/	/
New-Caledonia	/	/	/	/	/	12%	/
Peru	/	/	17%	/	/	/	16%
Philippines	/	2%	/	/	/	64%	/
Papua New Guinea	/	/	24%	/	/	/	/

Source : BACI

Table 13 – Imports of minerals in percentage of world trade (2017-2022)

	Bauxite	Cobalt	Copper	Graphite	Lithium	Nickel	Zinc
United Arab Emirates	/	14%	/	/	/	/	/
China	74%	44%	41%	15%	28%	83%	28%
France	1%	1%	/	1%	14%	/	2%
Japan	/	/	10%	10%	4%	6%	7%
South Korea	/	2%	4%	10%	1%	6%	15%
Philippines	/	6%	10%	/	/	/	/
United States	3%	/	/	10%	3%	/	/
Zambia	/	24%	/	/	/	/	/

Source : BACI

Table 14 – Exports of metals in percentage of world trade (2017-2022)

	Aluminum	Cobalt*	Copper	Lithium	Nickel	Silicon	Zinc
Argentina	1%	/	/	18%	/	/	/
Australia	9%	1%	4%	/	18%	/	11%
Canada	12%	3%	2%	/	13%	/	9%
Chile	/	/	23%	63%	/	/	/
China	/	1%	3%	5%	2%	43%	1%
D.R. Congo	/	76%	11%	/	/	/	/
India	13%	/	1%	/	/	1%	8%
South Korea	/	1%	3%	2%	/	/	10%
Norway	/	1%	/	/	12%	4%	4%
Russia	15%	2%	7%	/	18%	5%	1%

Source : BACI. Regarding Cobalt, UN COMTRADE data aggregates "unwrought" (actual cobalt pure metal) with "mattes" (intermediary metallurgical products with a much lower purity level), see footnote 8.

Table 15 – Imports of metals in percentage of world trade (2017-2022)

	Aluminum	Cobalt	Copper	Lithium	Nickel	Silicon	Zinc
China	5%	79%	35%	31%	25%	1%	13%
Germany	4%	1%	5%	4%	7%	16%	7%
Japan	10%	3%	/	14%	5%	9%	1%
South Korea	8%	1%	4%	22%	5%	7%	2%
Netherlands	9%	2%	3%	2%	13%	3%	7%
United States	15%	3%	8%	8%	11%	17%	13%

Source : BACI. Regarding Cobalt, UN COMTRADE data aggregates "unwrought" (actual cobalt pure metal) with "mattes" (intermediary metallurgical products with a much lower purity level), see footnote 8.

Table 16 – Exports of LCT in percentage of world trade (2017-2022)

	Li-ion batteries	**Solar panels**	**Wind turbines**
China	41%	60%	18%
Denmark	/	/	21%
Germany	6%	2%	31%
Japan	9%	1%	/
Malaysia	3%	11%	/
Poland	9%	/	1%
South Korea	16%	4%	/
Spain	/	/	13%
Vietnam	1%	7%	1%

Source : BACI

Table 17 – Imports of LCT in percentage of world trade (2017-2022)

	Li-ion batteries	**Solar panels**	**Wind turbines**
France	3%	1%	7%
Germany	15%	5%	3%
India	2%	10%	/
Japan	3%	7%	2%
Netherlands	4%	7%	5%
United Kingdom	2%	1%	9%
United States	19%	19%	9%

Source : BACI

Table 18 – EJ conflits, land use and mining related deforestation in the main TCM mining countries

Countries	**EJA conflicts (all minerals & TCM only)**	**Land use (in % of total area) (all minerals)**	**Mining-Related Deforestation (in km2) (all minerals)**
ARG	41 (23)	2 301 (0.08%)	/
AUS	2 (1)	8 482 (0.11%)	714
BRA	44 (10)	5 915 (0.07%)	1 654
CAN	20 (13)	5 087 (0.05%)	1 108
CHL	34 (34)	4 562 (0.6%)	/
CHN	24 (24)	10 364 (0.1%)	/
COD	11 (9)	426 (0.02%)	/
IDN	24 (6)	8 020 (0.42%)	3 537
JAM	2 (2)	25 (0.23%)	/
KAZ	/	2 082 (0.08%)	/
MEX	44 (24)	932 (0.05%)	/
MNG	6 (3)	782 (0.05%)	/
PER	54 (33))	3 539 (0.28%)	689
PHL	35 (19)	302 (0.1%)	/
RUS	17 (11)	11 770 (0.07%)	1 276
USA	21 (15)	8 188 (0.08%)	860

Source : Maus et al. (2022) for land use ; WWF extracted forests (2023) for mining-related deforestation ; Environmental Justice Atlas (Temper et al., 2018) for the environmental justice conflicts

Table 19 – Energy cost and rock to metal ratio for the whole production process (from extraction to pure metal production)

Metals	**Energy consumption (GJ/t)**	**Rock to metal ratio (RMR)**
Aluminum	212 GJ	7
Cobalt	322 GJ	859
Copper	64 GJ (hydro) / 33 GJ (pyro)	513
Graphite	/	/
Lithium	433 GJ	1 634 (hard rock resources)
Nickel	194 GJ (hydro) / 114 GJ (pyro)	250
Silicon	/	3
Zinc	48 GJ (electrolytic) / 36 GJ (pyro)	71

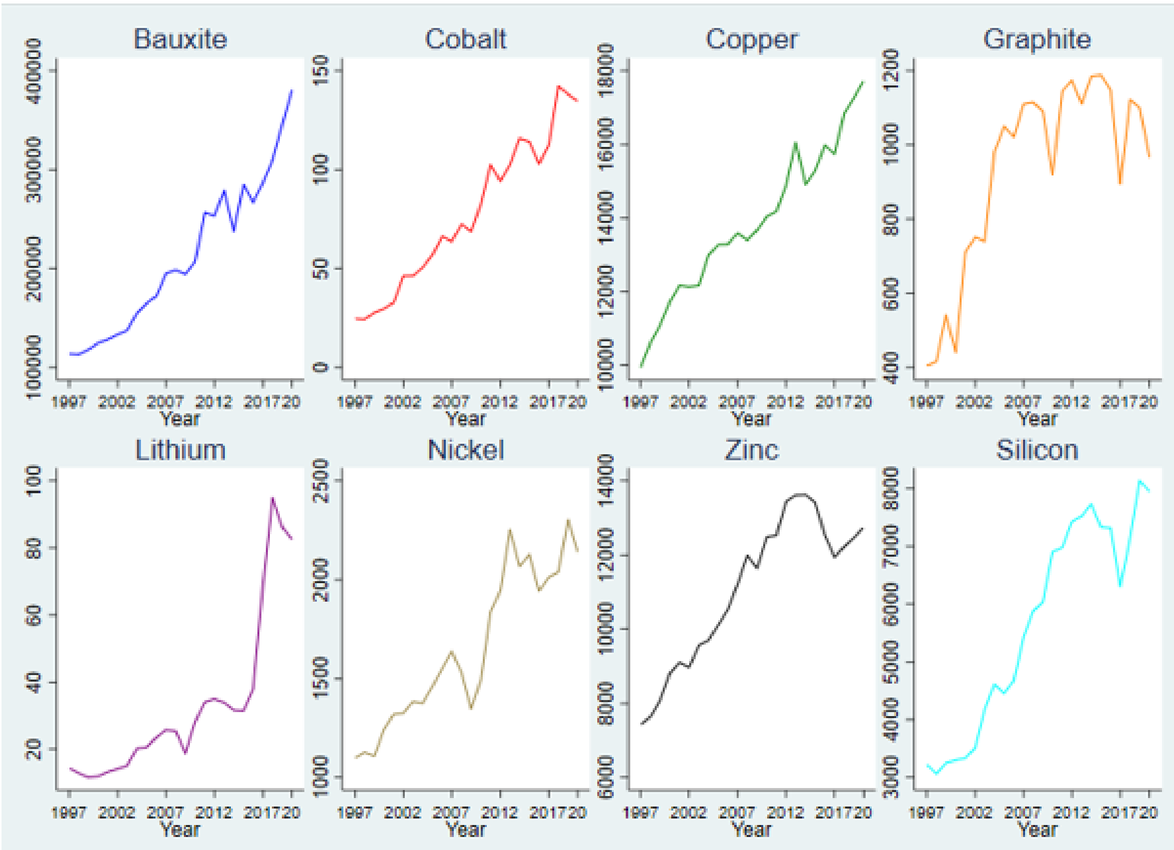
Nassar et al. (2022) for the rock-to-metal ratio ; Court et al. (2015) for the energy consumption

TABLE 20 – FBIC index from US and China for the TCM supplying countries

Country	fbic from US	growth fbic from US	trade agreement	fbic from China	growth fbic from China	trade agreements with China
Argentina	0.2763	-14.60019	0	0.05826	58.43007	0
Australia	0.3541	27.94403	4	0.10080	139.6943	1.5
Brazil	0.3000	22.68494	0	0.07191	169.7177	0
Canada	0.6720	0.27570	8	0.05480	99.35686	0
Chile	0.3820	42.86116	4	0.11379	118.2012	4
China	0.1133	-4.22115	.	.	.	.
Democratic Republic of the Congo	0.0911	116.9944	0	0.06873	152.7798	0
Indonesia	0.2060	40.69059	0	0.21213	257.0401	8
Jamaica	0.3053	10.86528	0	0.06959	87.67208	0
Japan	0.4074	-7.31889	0	0.10091	21.97623	0
Kazakhstan	0.1040	-24.9077	0	0.11100	138.5302	0
Mexico	0.7251	-0.72763	8	0.06173	198.1897	0
Mongolia	0.4782	-51.1844	0	0.14863	95.44815	0
Norway	0.2607	11.13738	0	0.03246	113.6951	0
Peru	0.3663	-22.5426	3.75	0.11107	273.9317	3
Philippines	0.3789	-9.11941	0	0.12725	73.26874	0
Russia	0.0475	21.31518	0	0.24249	43.52661	0

Source : FBIC (Moyer et al., 2021)

FIGURE 8 – Mining production trends



Source : United States Geological Survey